# Application Guideline

## Return Fan Capacity Control via Speed Control

October 2006

This guideline explores five speed control strategies commonly used to control return fan capacity in a variable air volume system application. While targeted at commercial building applications, the concepts discussed will apply in nearly any application where return fan capacity must be modulated.

The guideline is divided into a fundamentals chapter, followed by a chapter focusing on each of the targeted capacity control strategies. Each chapter is arranged to present the issues faced by the designer, the installer and the operating team and includes a strategy specific technical discussion, DDC system point list, narrative control sequence and troubleshooting table.

While the focus of the guideline is on return fan speed/capacity control, it would be impossible to discuss this topic without also considering how the return fan impacts building pressurization, economizer operation, and ventilation. Thus the interaction of the return fan with these other HVAC processes is touched upon as each strategy is discussed. Additional supplemental information on these topics is provided in the form of appendices. Also, definitions for terms used in the guide can be found in the Glossary of Terms at the end of the guide. Links to additional outside resources can be found in the Additional Resources section of the References.

## Table of Contents

# 1. Introduction and Fundamentals

## Purpose and Overview of Content

This NBCIP Application Guideline is intended to guide designers, installers and facilities staff in the selection, design, installation, and operation of a number of common return fan speed/capacity control strategies. Five return fan strategies are considered:

- Speed Tracking Control
- Flow Tracking Control
- Building Pressure Control
- Discharge Pressure Control
- Mixed Air Plenum Pressure Control

Table 1-1 contrasts these strategies.

Just as a successful HVAC process requires the integration of its various components into a system, the successful development and implementation of any return fan speed/capacity control strategy requires the integration of designers, installing contractors, and operators. For each strategy, the guideline presents the design considerations from each of these perspectives. Then, it addresses implementation issues so that any design goals are realized when components of the system are assembled in the field. Finally, the guideline addresses the elements that must be monitored and maintained on a daily basis to ensure that the original design intent persists.

The reader is encouraged to become familiar with the information in each section, regardless of his or her particular area of expertise. Understanding the issues that must be dealt with by the other members of the team will equip each individual to be better able to successfully integrate their requirements with those of the team as a whole.

The focus of this guideline is on return fan speed/capacity control. However, it would be impossible to discuss this topic without also considering how the return fan impacts building pressurization, economizer operation, and ventilation. Therefore, a brief review of each is included so that these issues will be considered when implementing a particular return fan speed/capacity control strategy.

Most of the topics discussed will address commercial and institutional building HVAC systems with Variable Speed Drive (VSD) speed/capacity control of the return fans implemented in a Direct Digital Control (DCC) system environment. However, many of the concepts discussed can also be applied to HVAC and fan systems in process environments and also to fans where capacity is controlled by other technologies such as inlet guide vanes and/or situations where the control processes are implemented via pneumatic and discrete electric and electronic controls.

Each chapter of the guideline begins with a two-page table that includes a generic air handling unit system diagram illustrating the general configuration of a variable air volume (VAV) fan system. The system components, sensors, etc. that are particular to the strategy being discussed are highlighted. This has been done to allow the hardware and configuration differences between the various strategies to be quickly assessed and contrasted. The table also provides an overview of the content of the chapter by capturing the key points in a consistent format that is replicated throughout the guideline. Table 1-1 reflects the chapter structure, in that each table heading is a chapter subheading.

The guideline also includes a number of appendices that explore technical issues related to return fan capacity control such as infiltration and exfiltration, outdoor air control, and economizer operation for the reader interested in more detail. This information is also envisioned as providing a foundation for additional guideline development by NBCIP in the future.

Each chapter also includes a control strategy, sequences of operation, a points list and a troubleshooting guideline. These are designed to address the issues that might be encountered with return fan capacity control in general as well as with a given strategy in particular.

In addition to the list of references at the end of the guideline, relevant resources for each chapter will be listed in a section labeled "Useful Resources" at the end of each chapter.

*Table 1-1*

## Return Fan Speed/Capacity Control Strategy Comparison

| Strategy | Description<br>Fundamental Principle of Operation | Comparison Characteristics | Rating<br>Low | <br>Moderate | <br>High |
|---|---|---|---|---|---|
| Speed Tracking Control | **Description:** Return fan speed is controlled in direct proportion to the supply fan speed or the supply fan speed command.<br><br>**Fundamentals:** Once the correct supply to return fan volume ratio has been set and the speeds associated with it have been determined, the desired flow relationship can be maintained by controlling the return fan speed based in proportion to supply fan speed | **Application Complexity** | ✓ | | |
| | | **Potential for Negative IEQ Impact** | | | ✓ |
| | | **Potential for Negative Energy Impact** | | | ✓ |
| | | **Potential for Integration/Interaction Problems** | | ✓ | |
| | | **First Cost** | ✓ | | |
| | | **Maintenance Cost** | ✓ | | |
| | | **Energy Cost** | | | ✓ |
| | | | Low | Moderate | High |
| Flow Tracking Control | **Description:** Return fan speed is controlled based on flow measurements to maintain a differential between supply and return flow.<br><br>**Fundamentals:** Via conservation of mass, the desired minimum outdoor air flow rate can be maintained by measuring the supply flow rate, subtracting the desired outdoor air flow rate from it, and controlling the return fan to deliver the resulting flow. | **Application Complexity** | | | ✓ |
| | | **Potential for Negative IEQ Impact** | | ✓ | |
| | | **Potential for Negative Energy Impact** | ✓ | | |
| | | **Potential for Integration/Interaction Problems** | | ✓ | |
| | | **First Cost** | | | ✓ |
| | | **Maintenance Cost** | | | ✓ |
| | | **Energy Cost** | ✓ | | |
| | | | Low | Moderate | High |
| Building Pressure Control | **Description:** Return fan speed is controlled based on building static pressure to maintain a positive pressure relationship relative to the outdoor pressure.<br><br>**Fundamentals:** Controlling return fan speed based on building static pressure can help to leverage the potential benefits associated with beyond minimum outdoor air flow rates in buildings served with economizer equipped air handling systems by ensuring a positive building pressure. | **Application Complexity** | | ✓ | |
| | | **Potential for Negative IEQ Impact** | ✓ | | |
| | | **Potential for Negative Energy Impact** | ✓ | | |
| | | **Potential for Integration/Interaction Problems** | | | ✓ |
| | | **First Cost** | | ✓ | |
| | | **Maintenance Cost** | | ✓ | |
| | | **Energy Cost** | | ✓ | |
| | | | Low | Moderate | High |
| Discharge Pressure Control | **Description:** Return fan speed is controlled to maintain a fixed return fan discharge static pressure and controls the relief damper position to maintain building pressure.<br><br>**Fundamentals:** Holding a fixed pressure on the discharge plenum of the return fan allows it to respond to changes in the relief and return damper positions, which, in turn are driven by the economizer temperature control process and the building static pressure control process. | **Application Complexity** | | ✓ | |
| | | **Potential for Negative IEQ Impact** | ✓ | | |
| | | **Potential for Negative Energy Impact** | ✓ | | |
| | | **Potential for Integration/Interaction Problems** | | | ✓ |
| | | **First Cost** | | ✓ | |
| | | **Maintenance Cost** | | ✓ | |
| | | **Energy Cost** | | ✓ | |
| | | | Low | Moderate | High |
| Mixed Air Plenum Control | **Description:** Return fan speed is controlled to maintain a fixed mixed air plenum static pressure.<br><br>**Fundamentals:** If a constant mixed air plenum pressure is maintained, the minimum outdoor air flow will be constant regardless of supply flow rate since the pressure difference across the minimum outdoor air damper is constant. | **Application Complexity** | | ✓ | |
| | | **Potential for Negative IEQ Impact** | | | ✓ |
| | | **Potential for Negative Energy Impact** | | | ✓ |
| | | **Potential for Integration/Interaction Problems** | | | ✓ |
| | | **First Cost** | | ✓ | |
| | | **Maintenance Cost** | | ✓ | |
| | | **Energy Cost** | | ✓ | |

## Basic Control Strategy: Fundamental Principles

To create a consistent context for understanding the topics in this guideline, a number of terms related to return fan speed/capacity control have been defined in the *Glossary of Terms.* Many of the fundamental concepts associated with return fan speed/capacity control can be understood simply by reading through these definitions. In addition, some concepts are further discussed and illustrated in subsequent appendices of this guideline.

The definition of a return fan in the *Glossary of Terms* provides an overview of its function in a typical HVAC system. The return fan capacity/speed control strategies (for the purposes of this guideline) are defined in Table 1-1.

## Return Fans and Capacity Control

This guideline outlines methods of controlling the return fan's capacity by controlling its speed.

Because the flow capacity required from the return fan is directly related to the flow rate produced by the supply fan, systems in which the supply flow varies in the course of normal operation will require some way to vary the capacity of the return fan. Otherwise, operating problems will ensue, and lead to discomfort, energy waste, loss of Indoor Environmental Quality (IEQ), and, in extreme cases, damage to the system and building.

There is a direct relationship between fan speed and capacity. According to fan affinity laws:

$$Q_2 = Q_1 \times \left(\frac{N_2}{N_1}\right)$$

$$\text{Where:}$$

$$Q_1 \text{ and } Q_2 = \text{Flow at conditions 1 and 2}$$

$$N_1 \text{ and } N_2 = \text{Fan speed at conditions 1 and 2}$$

In other words, if fan speed is increased, more air will be moved. If fan speed is decreased, less air will be moved. This technique preserves the fan's efficiency. There are a number of ways fan speed control can be accomplished, including the use of the following:

- Variable speed drives (VSD)
- Eddy current clutches
- Mechanical clutches

Discussions of these devices can be found in the *Glossary of Terms*.

## A Few Words on Capacity Control Technologies

Over the past 15-20 years VSD technology has evolved significantly and great improvements have been made in reliability, efficiency, and reductions in size and first cost. These developments have made VSD technology the first choice for new projects for controlling fan capacity through variations in the fan speed.

Other techniques for controlling a fan's capacity include:

- Discharge dampers
- Inlet vanes
- Variable blade pitch

Discussions of these additional techniques can be found in the *Glossary of Terms*.

Since many new construction projects are actually renovations of areas served by existing systems and may not include central system improvements like upgrading to VSDs for fan capacity control, the information in this guideline can also be used to support the design and installation of systems using other technologies. In addition, facilities engineers, operators, and commissioning providers will find the information useful when working with a variety of applications beyond the VSD focus.

## When to Apply Return Fan Speed/Capacity Control

The need to control return fan speed usually evolves out of a need to match the return flow rates to the supply fan flow rates associated with a VAV system. The supply fan volume in this type of system is modulated in response to a variable parameter in the area served; typically the heating or cooling load. This is further discussed in the *Glossary of Terms*.

Variable speed return fans may also be found:

- On incremental volume systems where the supply fan capacity is varied in steps rather than modulated over a range of flows.
- On constant volume systems where the system resistance changes associated with filter loading on the supply or return side cause unacceptable system flow variations

and the drives can be used to adjust system performance as the filters load.

- On constant volume systems where very precise pressure relationships need to be maintained and the drives can be used to precisely tune fan performance to subtle variations in operating conditions.

In all of these instances, the need to vary the return fan speed is still the result of the need to accommodate variations in the supply fan performance.

### When Not to Apply a VSD for Return Fan Speed/Capacity Control

The ability of a VSD to precisely vary the flow produced by a fan may make it seem like the ideal balancing device for every situation. However, while it is true that a drive may make final balancing adjustments simply a matter of turning a knob rather than changing a sheave, the utility achieved should be considered in light of several factors that could be viewed as undesirable, including:

- Drive Efficiency: ***Even the best VSD is less than 100% efficient*** (see Figure 1). VSDs represent a fixed loss in the system that increases with the speed reduction they provide. This loss would not exist if the speed reduction was achieved by a sheave change.
- Complexity: ***Variable speed drives used purely for balancing purposes may represent complexity without commensurate benefit when contrasted with a sheave change.*** This complexity can translate directly to added first cost, added training cost, increased potential for failure and an increased potential for operator error.

The bottom line is that while a variable speed drive may represent a perfect control device for modulating flow on a variable flow system, it may represent a less than ideal balancing device on a constant volume system that has little potential for flow variation in normal operation.

### Return Fan Integration Issues with the HVAC System and Building

Because of the integrated nature of HVAC systems and the buildings they serve, it is nearly impossible to discuss return fan capacity control without considering it in that context. At a fundamental level, this comes back to the conservation of mass. This balance is of critical importance and is heavily influenced by the return fan in the following areas in most buildings:

#### *At the Return Fan Discharge Plenum and Mixed Air Plenum*

Ideally, conservation of mass at the return fan discharge plenum means that the amount of air leaving the discharge plenum via the relief dampers and return dampers exactly equals the amount of air placed into the plenum by the return fan. However, problems with the return fan capacity control system, the minimum outdoor air flow regulation system and/or the control of the economizer process can trigger a condition where the amount of air exiting the return fan discharge plenum exceeds the amount of air placed into the plenum by the return fan. In this situation, conservation of mass means that outdoor air will be introduced into the system via reverse flow through the relief louvers.

#### *At the Zone Level*

Conservation of mass at the zone level means that the amount of air entering the zone exactly equals the amount of air leaving the zone. The path via which the air movement occurs (to or from either adjacent zones or the exterior of the building) controls the pressure relationship between the zones. Designers endeavor to establish proper pressure relationships by targeting the magnitude and direction of flow between zones required to establish them. For instance, a designer might indicate that an operating room have 150 cfm more supply air than return air while the adjacent corridor has 150 cfm more return air than supply air (on a per room basis). The 150 cfm number may have been based on past experience or derived from the anticipated pressure drop that would occur if 150 cfm flowed out of the OR via cracks around the door. In a perfect world, when the balancer established the required flows, the exfiltration through the cracks would in fact set up the desired pressure relationship. In the real world, quality of construction issues often foil the design intent, requiring an intense crack detection and caulking process by the general contractor (subsequent to "intense" discussions with the design team and owner). In any case, the performance of the return fan has a direct impact on controlling these relationships.

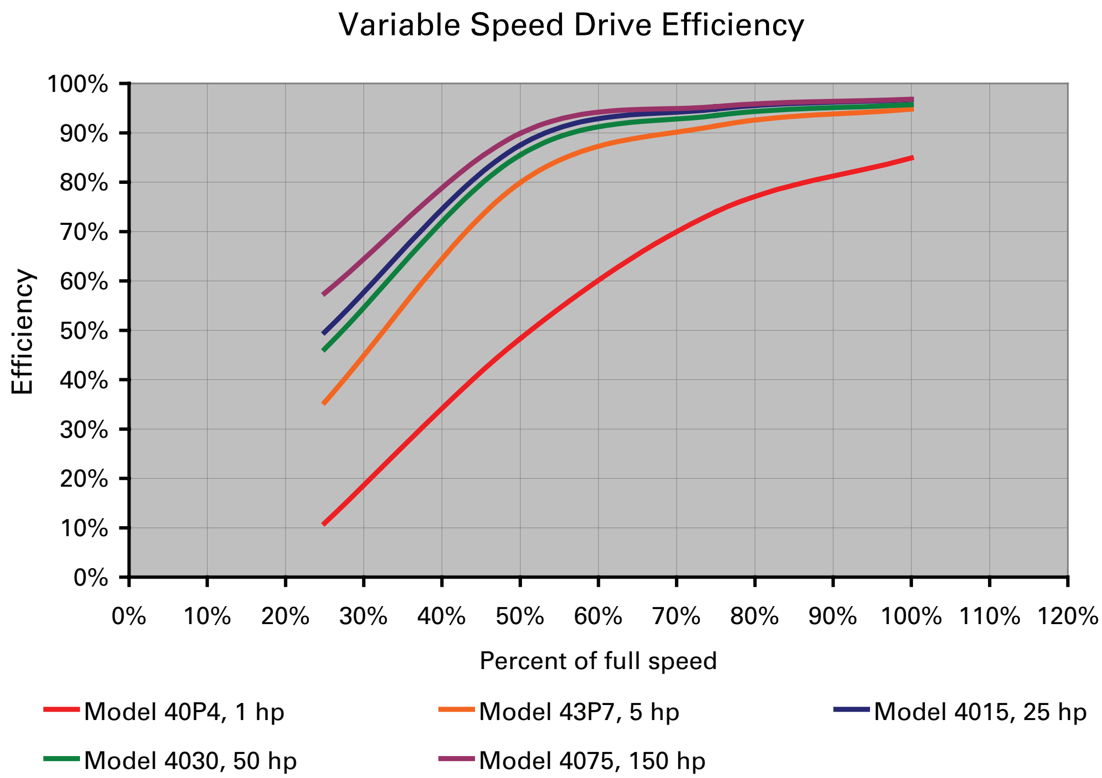



*Figure 1 – Variable speed drive efficiency versus size and load (Courtesy Saftronics). Note how efficiency generally improves with increasing size. However, there can be exceptions to this rule as can be seen here when the efficiency of the 25 hp drive is compared with the 50 hp drive in this particular product line.*

### At the Envelope Level

Conservation of mass applied at the boundary of the building envelope implies that the amount of air entering the building from the exterior will exactly equal the amount of air exiting the building from the interior. Return fan performance can have an influence in this area on two important fronts:

- Via conservation of mass, the difference between an air handling system's supply and return flow will directly impact the minimum outdoor air flow into the system.
- When the air handling system is operating on an economizer cycle, the return fan also has a role to play in moving the relief air associated with economizer operation out of the building.

The impact of the return fan as it operates on these fronts can manifest itself in a number of ways including:

- Influencing infiltration and exfiltration. This topic is discussed in greater detail in *Appendix 1: Infiltration and Exfiltration.*
- Impacting the performance of the economizer process. This topic is discussed in greater detail in *Appendix 2: Economizer Theory and Operation.*
- Impacting the performance of the minimum outdoor air flow regulation strategy. This topic is discussed in greater detail in *Appendix 3: Minimum Outdoor Air Flow Regulation.*
- Impacting the performance of building exhaust systems via its impact on the minimum outdoor air flow regulation strategy. This can be a critical consideration in laboratories, hospitals, and other applications with high exhaust flow requirements.
- Impacting the general flow of air into and out of the building and between zones and systems serving the building. This topic is discussed in detail in *Appendix 9 – Minimum Outdoor Air Requirements and Their Impact on Return Fan Capacity Control.*
- Impacting the performance of the building pressure control strategy. This topic is elaborated upon later in this chapter.

When selecting and applying a return fan capacity/speed control strategy, it is important to recognize the potential interactions on all of these fronts and to assess their impacts on the system and building served by the return fan. It is also important to recognize that the phenomenon listed above are interactive with each other.

## Building Static Pressure Control

Achieving control of building static pressure can have a significant impact on comfort, IEQ, structure and finishes, and even security. In many ways, building static pressure reflects the aggregated impact of the interaction of the factors mentioned in the preceding topic. Thus, it can be seen that the interaction of a return fan capacity control process with the air handling system it serves and the other systems in the building can have a significant direct impact on building static pressure. In fact, one of the return fan capacity control strategies discussed in this guideline is based on building static pressure. In the other cases, coordinating the return fan control strategy with an active building pressure control strategy can yield benefits on many fronts.

The most common building pressure control strategy involves controlling the relief dampers based on building static pressure. A discussion of this approach can be found in *Chapter 4: Building Pressure Control*.

## Return Fan Control Considerations: Hardware Issues

Properly designed and implemented control system hardware and software are essential to the success of any return fan control strategy. On the hardware side, the following topics merit consideration as the design evolves:

- Damper interlocks: Depending on the specifics of their implementation, all of the strategies in this guideline are subject to conditions, either due to a failure mode or a transient condition, where the return fan could attempt to operate with both the return and relief dampers closed. It is also possible for large return or relief damper assemblies to suddenly close as the result of a failure of some kind. Where the dampers serve as smoke isolation dampers in addition to control dampers, sudden closure can be the result of a fire alarm or smoke management or control cycle. Irrespective of the trigger, sudden, rapid damper closures can generate air hammer, causing significant damage to the system. Damper interlocks, static pressure safety switches, and pressure relief doors can be used independently or in concert to mitigate the problems that can occur in these situations.
- Sensor selection and application: Robust, reliable inputs are critical to the success of all of the control strategies, making sensor selection critically important. Accuracy is a key consideration of the selection process. It is also important to remember that the best sensor in the world will fail to perform as anticipated if it is improperly applied or installed. The pressure, flow and other sensors employed by any return fan capacity/speed control strategy need to be carefully selected for compatibility with the approach under all operating conditions, installed in a manner that supports the design intent, and inspected and maintained as necessary to ensure that the design intent persists.

  All of these topics are discussed in detail in the *Control Design Guide*, which is listed under *Additional Web Resources* in the *References* section of this guideline.
- Pneumatic controls: While most new applications will be supported by DDC control systems, many retrofit applications will interact with an interface to a pneumatic control system. This can present a problem because the flow and pressure data required by many strategies are difficult to measure with pneumatic technology. Fortunately, there are a number of ways to address such a requirement including using high end, process grade pneumatic transmitters and controllers, providing stand-alone electronic controllers, or selecting a strategy like speed or signal tracking where control can be achieved without measuring parameters like pressure or flow.

Additional, detailed discussion of these topics can be found in *Appendix 5: Control System Hardware and Software*.

## Return Fan Control Considerations: Software Issues

The black box nature of computer based control systems can lend an aura of difficulty and mystery to their design, implementation and maintenance that can be intimidating to the design and operating team. Fortunately, design success is not as dependent upon familiarity with computers and DDC technology as it is upon familiarity with the HVAC process and clear communication of its requirements to the implementing contractor(s). There are several simple but important steps that can be taken by the designer to facilitate this process. These steps have the added benefit of laying the foundation for operator understanding of the control requirements, methodologies and intent, paving the way for the persistence of the design intent.

- *Control points lists*: Points lists provide a way for the designer to communicate to the construction team exactly what is needed to control, monitor, diagnose and maintain the return fan capacity/speed control strategy. These lists concisely convey key information regarding sensor requirements, alarm requirements, and trending requirements to the installing contractors, providing a level playing field for bidding and ensuring that the system will have the features necessary for commissioning and on-going operation.
- *Narrative sequences*: A detailed narrative sequence complements a points list and helps ensure that the intent of the design is communicated to the implementing contractors and operators. This communication is essential for a successful start-up and for the persistence of the operating strategy. A well executed narrative sequence will be more than a one-line summary of the operating strategy. It will also address critical details that are essential to the sequence's success like required inputs and outputs, set points, alarm requirements, scheduling requirements, energy tracking requirements, failure modes (and the desired system response when they occur), and interlock and safety requirements.
- *Operator interface requirements*: Even a well thought out, well executed control system design will not persist for long if there are no provisions made for operator access and adjustment. Thus, operator interface requirements should be integral with any control system design and specification. The specified requirements should address:
  1 Hardware issues like memory, back-up capability, and printing capability.
  2 Software issues like trending, graphic interface requirements, and supplementary supporting software requirements.
  3 Usability features like set point adjustment, security levels and graphic layering.

Additional, detailed discussion of these topics can be found in *Appendix 5: Control System Hardware and Software.*

### Return Fan Electrical and Drive System Considerations

Because variable speed drives are typically used to achieve variable air flow, it is important for the design engineer to understand variable speed drives and how to apply them. This understanding should be conveyed to the construction and operating team in the contract documents by addressing issues that are critical to the design intent including:

- Technical requirements for the drive technology employed on the project.
- Requirements for bypass contactors in situations where redundancy is deemed critical. Integral to this is information describing how the interlock and safety systems are intended to perform when the drive is in bypass. Hard-wired interlocks that function under all possible combinations of Hand-Off-Auto and Invertor-Bypass selector switch positions are recommended for all critical safeties.
- Requirements for control system interfaces and outputs from the drive to the control system, including network cards, onboard controllers, and programmable inputs and outputs.
- Operator interface requirements, including selector switch and graphic display needs.
- Motor requirements to ensure compatibility with the drive technology, including shaft grounding where deemed desirable. For retrofit projects, it is important to bear in mind that existing motors may not exhibit long term compatibility with variable frequency technology. The result may be a significantly higher failure rate when served by a VSD compared to a constant, synchronous speed application.
- Motor requirements to ensure that the motor provided has adequate starting torque and the horsepower necessary to operate the fan.

- Distribution system interface requirements including IEEE 519 analysis requirements, isolation requirements, and the installation details necessary to ensure that the harmonics produced by the drive do not adversely impact the load served by the drive or the system connected to it.
- Belt and sheave requirements, including requirements to replace the adjustable pitch sheaves provided for start-up with fixed pitch sheaves as the final step in the balancing process. The final sheaves should be sized to allow the VSD to deliver design flow when operating at 100% speed. Such an approach can go a long way towards maximizing belt life and optimizing over-all drive system efficiency.
- Minimum motor speed requirements related to ensuring that the desired minimum flow rates can be achieved and the required pressure relationships are maintained. In some applications, motor cooling requirements may also come into play when assessing the minimum allowable operating speed for a motor/VSD combination.

Additional, detailed discussion of these topics can be found in *Appendix 6: Electrical and Drive System Considerations.*

## Return Fan Duct System Considerations

There are several duct system issues that have a direct impact on the performance of any return fan capacity control system.

### *Damper Installation*

Damper sizing and installation can have a major impact on return fan performance, as is discussed in *Appendix 2: Economizer Theory and Operation.* While it may be convenient to install economizer dampers to match the configuration and size of each duct where they are located, taking the time to size them and configure them properly will go a long way toward ensuring the maximum performance (see Figure 2).

Parallel blades often provide better opportunity for mixing in an economizer process because of their directional characteristics. However, they have a different characteristic curve (see Figure 3) from opposed blade dampers which should be taken into account in applications where the two types are used in the same economizer section.

*Figure 2 – Economizer outdoor air (left) and return air (right) dampers with different configurations and mounting arrangements can cause performance problems with the economizer process.*

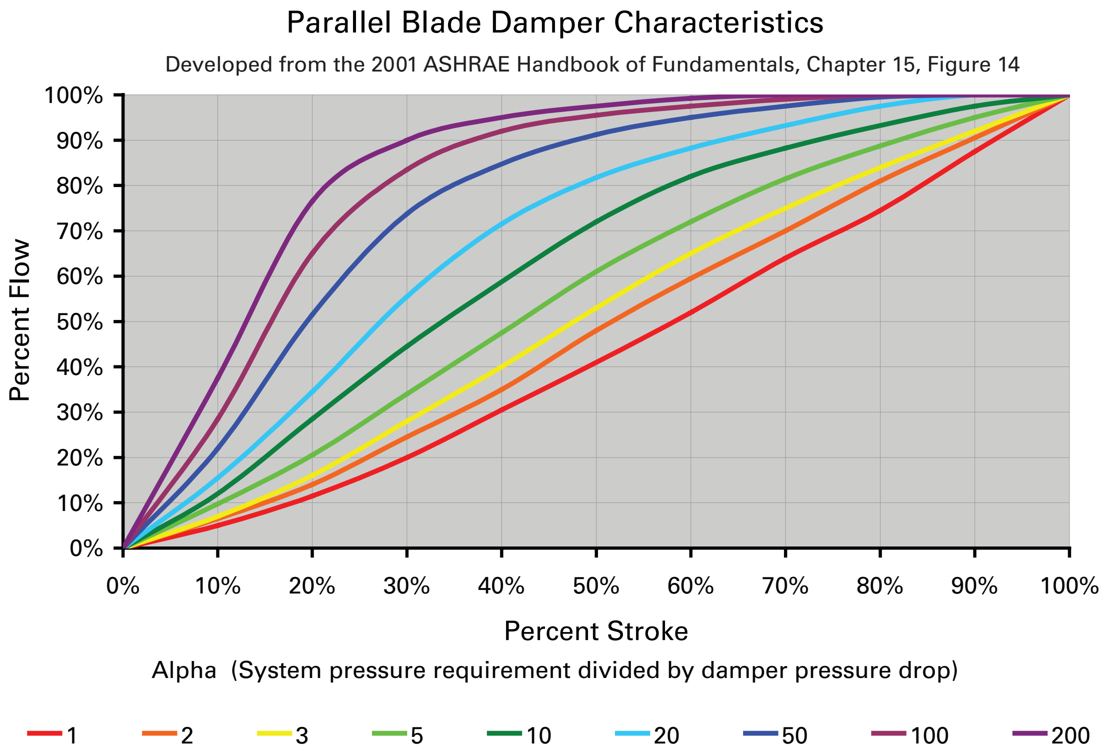
Linkage arrangements can also affect damper performance, a topic which is discussed and illustrated in *Appendix 2: Economizer Theory and Operation*.

It is also important to make sure that the dampers are installed per the manufacturer's requirements including:

- Square and plumb to prevent racking and binding during the operating stroke.
- Reinforced as necessary to withstand the system's operating pressures in all modes. Many multi-section dampers require reinforcing plates between sections or some other form of extra support beyond simply bolting the frames together.

### *Return Versus Relief Path*

Many return fans also serve as relief fans in that the system's return and relief dampers are located on the discharge side of the fan. When this is the case, the fan's performance will be impacted by the operation of both the return and relief dampers as well as the flow through both pathways. Thus, it is important to design the system so the pressure drop from the discharge of the return fan *to* the return damper (where the pressure capabilities of the supply fan will take over) is nearly identical to the pressure drop from the discharge of the return fan *through* the relief damper under design conditions. Otherwise, the return fan operation might be subject to another variable as the dampers change position and flows through the various duct pathways vary.



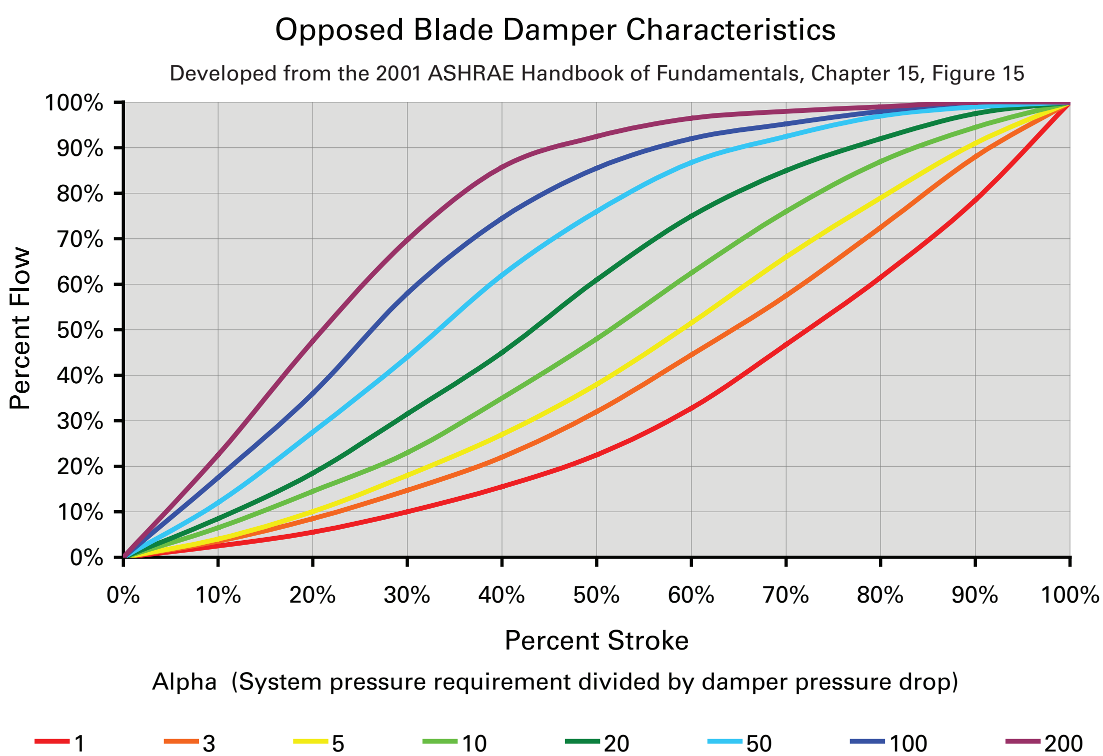




*Figure 3 – Opposed blade (top) and parallel blade (bottom) dampers have different characteristics. Note that in these graphs, percent stroke is percent of damper blade stroke. This may be different than the percent actuator stroke and the percent of output from the control system. See Appendix 2 and the Control Design Guide listed under References for additional information on damper sizing and linearity and the relationship between command and damper position.*

## The Relationship Between Design, Installation, and Operation

In many ways, the fundamental premise behind this guideline could be summarized as follows:

*Know your job; understand everyone else's.*

It takes a team of people with a variety of skills to successfully design, implement and operate a system. Everyone has a specialized but inter-related function to perform if the overall success of the system is to be ensured.

One of the earliest and most important steps in the overall process is the documentation of the project's design intent. *Capturing* the owner's requirements and intentions in a way that will *convey* them to the design, implementation, and operating teams and pave the way to *achieving* them in the operating facility is the essence of design intent. Practical, proven methods of achieving this include:

- Floor plans and design details
- Equipment and construction specifications
- Control system diagrams, points lists and narrative sequences
- Coordination reviews, meetings and drawings

Construction observation by the project's designer and commissioning provider provides a powerful mechanism to ensure that the ideas captured by the design documents are conveyed to the field in a manner that will allow them to be achieved. Bringing the designer's perspective to the field ensures that their ideas are reflected in the systems as implemented. Bringing the commissioning provider to the construction process ensures that operations and maintenance and integration will be implemented in a manner that addresses integration requirements and provides an operable and maintainable system into the future.

Performing a thorough review of the shop drawings and submittals for a project is also an important step in the capture-convey-achieve process. These documents represent the dividing line between the point in time when something is an idea only documented with drawings and words, and a physical reality. Changing the former is usually much easier than the latter. Taking the time to be sure that reality will match the expectations and needs of all parties, including the designer, the contractor and the operating staff can go a long way towards preventing installation and operational problems down the road.

### *Prestart and Start-up Checklists*

Checklists are important commissioning tools that ensure that the manufacturer's installation requirements have been met. Taking the time to make sure that all of the checklist requirements have been met paves the way for a smooth, trouble-free start-up and facilitates the functional testing process that will follow.

### *Functional Testing*

Functional testing is a critical step in the start-up and commissioning of any system. If a commissioning provider is involved in the project, they will likely have some specific tests to perform on the return fan capacity control system. If not, the information presented in *Appendix 4: Tuning Outdoor Air Flow to Design Specifications* will provide guidance for testing to ensure that design intent is realized.

Additional, detailed discussion of these topics can be found in *Appendix 7: The Relationship Between Design, Installation and Operation.*

## Maintaining and Adapting Design Intent

Many of the issues that present themselves to the installing contractors as the system is brought on line are ongoing operations and maintenance issues. In fact, the checklists and tests performed as a part of the commissioning process can be valuable operations and maintenance tools. The initial test data provides a baseline for comparison, and the procedures themselves provide a template for ongoing commissioning of the system.

Becoming involved in the design and construction process is an ideal way for the operating team to get up to speed on the systems they will inherit when a project reaches completion. By participating in the design review process, the operating team can bring a unique perspective to the process that will ensure that operation and maintenance needs are addressed in a timely fashion when the impact on the budget is minimal or even beneficial. Participating in the construction observation process allows the operating team to learn things about their systems that will be less obvious once finishes are in place.

Interacting with the contractors, particularly the control contractor and commissioning provider, will provide valuable insight into the operating characteristics of their systems beyond any formal training provided by the contract.

Once the building is up and running, the following items are worthy of consideration for return fans and their capacity control systems:

- *Motor Replacement*: Not all motors are created equal. If a new motor is required, it is important to make sure that it matches the original motor's capabilities for starting torque. Also, since the order of connection of the leads on a three phase motor has a direct impact on its direction of rotation, the phase rotation of the new motor needs to match the phase rotation of the existing motor.
- *Fan Wheel Cleanliness*: A dirty fan wheel is a more massive fan wheel, and a more massive fan wheel requires a motor with a higher starting torque capability. A little bit of dirt accumulated over the relatively large area represented by a fan wheel can add up to a significant increase in the fan wheel's moment of inertia (also referred to as $WR^2$). Keeping the fan wheel clean can go a long way towards preventing nuisance overload trips that start to mysteriously occur after several years of operation.
- *VSD Bypass Operation*: Operating a return fan with the VSD in bypass can have impacts on several operational fronts. Thus, the operating team should be fully aware of the issues and their implications in their facility prior to operating a VSD equipped return fan in bypass.
- *Sensor and Actuator Calibration*: Return fan control systems are no different from any other in that robust, reliable operation is dependent upon accurate, calibrated sensors and actuators. The limit switches and permissive interlocks associated with protecting the fan from damaging operating conditions are particularly critical.

  It is also important to remember that sensors may drift out of calibration over time. As a result, they will require periodic recalibration to ensure accurate measurements over their service life.
- *Minimum Outdoor Air Flow Verification*: HVAC systems are large, dynamic machines with a multitude of moving parts. As such, the effects of wear over time will shift their performance. Systems that performed per design subsequent to initial start-up and testing will tend to degrade over time. Failure to perform as designed can be a critical problem for return fan speed/capacity control systems, especially if the loss of performance leads to a loss of IEQ and efficiency. Periodically repeating the testing discussed in *Appendix 4: Tuning Outdoor Air Flow to Design Specifications* will ensure that the design intent persists and good IEQ is maintained under all operating conditions.

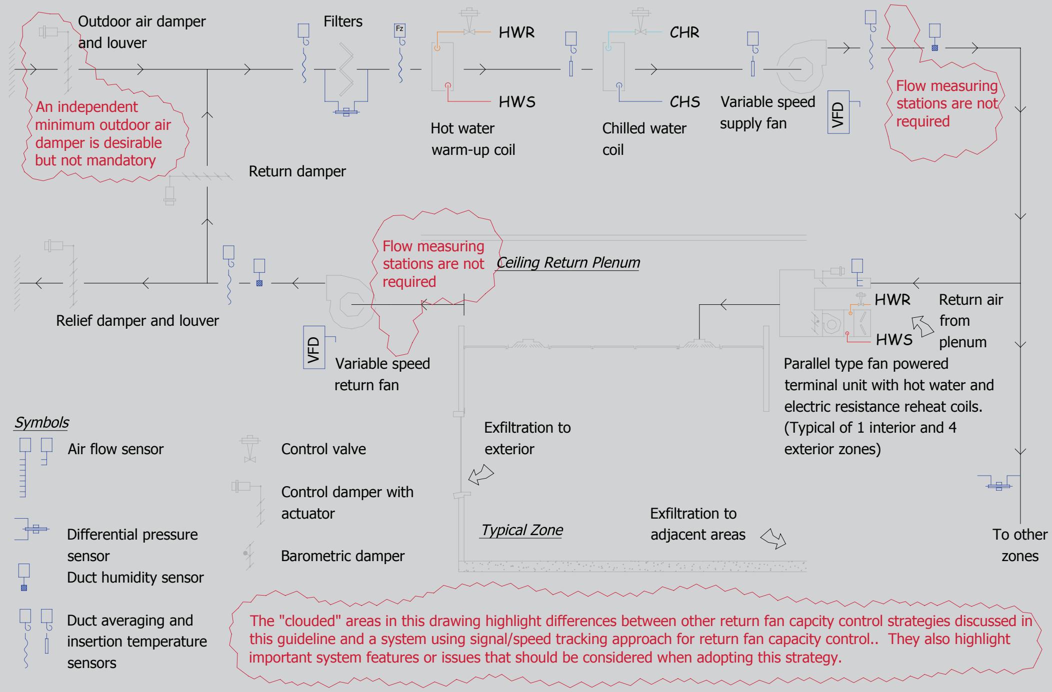
Additional, detailed discussion of these topics can be found in *Appendix 7: The Relationship Between Design, Installation and Operation.*

# Chapter 2 ■ Speed Tracking Control

This chapter will discuss speed tracking based control, a strategy that adjusts the return fan speed as a function of the supply fan speed. The simplicity of the strategy makes it a good choice for less advanced building control systems and smaller air handlers. The two common ways to achieve the strategy are signal tracking, which sets the return fan speed based on a signal that controls the supply fan speed, and speed tracking, which sets the return fan speed based on the measured speed of the supply fan. In this guideline, the techniques will be referred to collectively as "speed tracking control strategies."

## Contents

# Speed Tracking Control




*A Typical VAV Air Handling System with Speed Tracking Control*

# General Description

This approach controls the return fan speed based on the supply fan speed. It can be accomplished in a number of ways. Two common ways are signal tracking, which sets the return fan speed based on a signal that controls the supply fan speed and speed tracking, which sets the return fan speed based on the measured speed of the supply fan. In this guideline, the technique will be referred to collectively as "speed tracking control strategies." Most applications incorporate a constant of proportionality between the fan speeds called the "bias" or "speed ratio." Some applications incorporate several bias factors and apply each factor over a portion of the supply fan speed range to accommodate non-linearities that change with operating flow. Systems that control supply and return fan inlet guide vanes with the same signal will perform in a manner similar to this strategy.

## Advantages

- Minimal control device requirements
- Simple straightforward programming
- Simple and low cost

## Limitations

- No direct control over ventilation rate
- Not well suited for complex buildings
- No control over building pressurization

## Application Considerations

| Characteristic | Low | Medium | High |
|---|---|---|---|
| Application Complexity | ✓ | | |
| Potential for Negative IEQ Impact | | | ✓ |
| Potential for Negative Energy Impact | | | ✓ |
| Potential for Integration/Interaction Problems | | ✓ | |
| First Cost | ✓ | | |
| Maintenance Cost | ✓ | | |
| Energy Cost | | | ✓ |

## Key Design Issues & Considerations

- Consider the ventilation requirements versus the strategy's ability to meet those requirements under all operating conditions. A fixed speed differential does not necessarily guarantee a fixed outdoor air percentage. The design intent should be clear regarding minimum outdoor air flow requirements under all operating conditions.
- There are subtle differences between speed tracking (the return fan follows what the supply fan actually did) and signal tracking (the return fan follows what the supply fan was told to do) that can influence the system's performance, responsiveness, stability and tunablity. These factors should be considered by the designer and reflected in the design intent.
- Bias/speed ratio provision and requirements should be reflected in the design intent.
- Designers should have an understanding of the fan curves of both the actual supply fan and return fan systems they are working on.

## Key Installation Issues & Considerations

- Systems with multiple bias settings may require additional hardware features or drive programming capabilities to accommodate the extra settings.
- Setting the system up to ensure adequate minimum outdoor air under all operating conditions will require testing at multiple points and close coordination between trades.

## Key Operating Issues & Considerations

- Periodic retesting to ensure adequate minimum air flow under all operating conditions should be performed. Retesting is critical after any major building renovation, especially if it impacts the building envelope, the HVAC processes for areas surrounding those served by the system, or the ventilation requirements of the loads served by the system.

Speed tracking control adjusts the return fan speed as a function of the supply fan speed in order to introduce the desired amount of outdoor air. This strategy does not control building static pressure, which is controlled by the relief damper, independent of the fan control.The simplicity of this strategy makes it a good choice for less advanced building control systems and smaller air-handlers.

Additional information generally applicable to all return fan speed control strategies can be found in *Chapter 1: Introduction and Fundamentals*. Additional useful resources outside of this guideline are listed at the end of the chapter.

## 2.1 General Description

In this strategy, fan volume is directly related to fan rotational speed. The difference between the flow moved by the supply fan and the flow moved by the return fan is the amount of outdoor air brought into the system.

If the curve shape and other characteristics of a supply and return fan could be perfectly matched under all operating conditions, then varying the return fan speed in direct proportion to the supply fan speed would maintain a fixed minimum outdoor air percentage. This presumes that the maximum fan speeds have been set as necessary to provide the design supply and minimum outdoor air flow. However, perfectly matched fans are seldom possible in reality. The result of this is often a significant variation in minimum outdoor air flow under different operating conditions when speed tracking is employed. This is discussed in detail in *Appendix 8: Theoretical Versus Actual Performance*.

The term "bias" is generally applied to the ratio that is maintained between the supply and return fan speeds. Additional discussion regarding this topic will be found later in this section under Bias.

### Variations

There are several variations of this strategy in common use.

#### *Signal Tracking*

Under this variation, return fan speed/capacity modulation is based on the output signal that is used to control the supply fan speed.

Signal tracking relies on a control system output signal rather than a process input parameter. In most cases, software is used to implement signal tracking, as the control system monitors the signal to the supply fan and generates an independent output to control the return fan. However, there are implementations where the supply and return fan variable speed drives are both driven by the same output.

#### *Speed Tracking*

Under this variation, return fan speed/capacity modulation is based on the measured supply fan speed.

In this scenario, a speed feedback signal from the supply fan variable speed drive is monitored by the DDC system and then used to control the return fan speed via an independent output. In some implementations the supply fan speed feedback signal is hard wired directly to the return fan drive.

#### *Return Fan Inlet Guide Vane or Blade Pitch Modulation*

Under this variation, return fan capacity is controlled by modulating its inlet guide vanes or blade pitch via the same output signal that is used to control the supply fan inlet guide vanes, supply fan blade pitch or supply fan speed. The variable return air volume is obtained entirely by varying the configuration of the inlet guide vanes or the pitch of the fan blades while the fan speed remains constant.

This approach, a form of signal tracking, is typically encountered in older systems installed prior to the widespread acceptance of variable speed drives. It may also be found where a retrofit upgraded the supply fan capacity modulation technology from inlet vanes to a variable speed drive but did not address the return fan capacity control technology.

An important but subtle difference between speed tracking and signal tracking is that a system responding based on supply fan speed will be responding to the integrated effects of lags in the system including fan inertia, fan acceleration and deceleration delays and other factors. Putting it another way, a system that is tracking supply fan speed is responding to what the supply fan did or is doing. As a result, the return fan response is a more accurate reflection of the conditions that have actually been produced by the supply fan.

But, the lags and other factors reflected in the speed signal amount to feedback that can make the system more difficult to tune. In contrast, a system that is tracking the supply fan command signal is responding to what the supply fan has been asked to do. This means that there will be less lag time and feedback in the input to the return fan drive. But if something happens that de-couples the supply fan speed from the control signal (for instance, if an operator takes manual control of the fan speed), then the return fan is following a signal that may or may not reflect the actual operating condition.

## 2.2 Advantages

The main advantage of supply fan speed tracking based control of the return fan is that a minimal number of control devices and points are needed. The control programming is also very straightforward. Lower technology control systems such as stand-alone electronic and electro-pneumatic systems can be used to implement speed tracking. Smaller air-handling systems in non-critical applications can benefit from the simple, low-cost approach of this strategy.

## 2.3 Limitations

Speed tracking based return fan control operates solely on the basis of the supply fan drive performance. Thus, it operates as an open loop control strategy in the context of the HVAC system served because there is no direct feedback into the control process to account for any changes in the system, the loads, the HVAC process or the building envelope. In fact, most buildings experience changes in some or all of these areas on a daily if not hourly basis as discussed in *Chapter 1: Introduction and Fundamentals*. These changes can produce variations in the building air flow patterns and other parameters associated with the HVAC process which may not be reflected in the response and performance of the supply fan capacity control system. Thus, the fundamental assumption that maintaining a constant differential between the supply and return fan speeds will maintain the correct outside air volume may not be true in all circumstances.

Speed tracking based strategies tend to maintain a fixed minimum outdoor air percentage. This can be a desirable feature in situations where the ventilation requirement varies in a direct relationship with the supply flow requirement. Some non-perimeter office environments with no heating loads exhibit a pattern where net cooling load will vary directly with the occupancy. However, in situations where the ventilation requirement is fairly constant, regardless of the supply flow, maintaining a fixed minimum outdoor air *percentage* will actually reduce the minimum outdoor air *flow* as the supply flow requirement drops off. A fully occupied theater during a lecture might be an example of such a load: The occupancy, and thus the ventilation requirement, are at design. But if lights are dimmed and the event takes place in the evening during the winter, the cooling load might be significantly below design. Thus, these strategies are undesirable for such an application. The inability of this control strategy to directly control the ventilation flow rate limits its application. The error between the design ventilation flow rate and the actual flow rate delivered to the building using this strategy is proportional to the size of the air-handling unit. Also, as the square footage increases, the zone count increases, and holes in the building envelope, (i.e., doors and windows), are more numerous, maintaining positive building static pressure throughout the space served becomes more difficult. For all these reasons, speed tracking may lead to over or under ventilation for some medium-size air handling systems (10,000 – 25,000 cfm) and most large air handling systems (larger than 25,000 cfm).

The system curve and the fan curve for a typical supply fan are significantly different than the return fan. This system/fan curve mismatch between fans results in incorrect tracking under basic speed tracking control strategies. It is necessary to establish a bias to correct for fan curve mismatch. This topic is further discussed later in this chapter under *Control System Considerations – Software*.

## 2.4 Application Considerations

### Application Complexity

While speed tracking control strategies offer low cost and simple approaches to the return fan capacity/speed control problem, there are often energy penalties and other issues which should be considered before choosing the strategy.

### Potential for Negative IEQ Impact

Because speed tracking strategies do not directly control the minimum outdoor air flow, buildings served by these strategies are more prone to:

- Infiltration and the ensuing comfort issues. (Smaller, simpler systems with low turn-down requirements will be less likely to experience problems than larger systems with complex control strategies and distribution systems and high turn-down requirements.)
- Under-ventilation. (As a result, systems and buildings served by speed tracking strategies are also more prone to IEQ problems.)
- Poor fan tracking due to fan curve mismatch results in: the inability to control outside air flow; highly negative space pressures and the resulting infiltration; or excessive space pressures, all of which have a potential for a negative IEQ impact.

### Potential for Negative Energy Impact

The tendency toward infiltration and the tendency to over-ventilate by design as a hedge against under-ventilation during operation make speed tracking control strategies less efficient than some other alternatives. Specific areas of energy penalties are:

- Infiltration loads increase when unconditioned air is drawn into the building at the perimeter due to poor building static pressure control.
- Excess HVAC process loads due to the potential to over-ventilate.
- Excessive return fan energy due to maintaining a (sometimes unnecessary) constant ratio of return air to supply air. For estimating purposes, it can be assumed that a speed tracking strategy may result in a 2-5% increase in return fan energy consumption when contrasted with other strategies.

Since the strategy lends itself to smaller systems, the magnitude of the penalty represented by the inefficiency may not be large.

### Potential for Integration/ Interaction Problems

Because of their simplicity, speed tracking strategies do not combine well with some of the complexities of day to day building operations. In the following situations, they should be employed with caution or abandoned in favor of an alternative strategy:

- Situations where stack effect is significant.
- Situations where variable exhaust flow rates or variable ventilation requirements exist.
- Situations where the potential for infiltration and/or exfiltration is significant.
- Situations where direct control of the minimum outdoor air and ventilation rate is necessary to ensure IEQ or proper inter-space pressure relationships.
- Situations where building static pressure control is critical.

### First Cost

Implementation of speed tracking based control strategies will have the lowest first cost when contrasted to the alternatives. Few if any additional sensors or wiring will be required beyond what would have been installed to provide fundamental control of the supply and return fan drives. Similarly, very little additional programming will be required beyond what would be needed at the most fundamental level.

### Maintenance Cost

Due to their simplicity and minimal control hardware requirements, the maintenance costs associated with speed tracking strategies will tend to be low. However, the need to periodically retest the performance of larger and more complex systems that employ the strategy for proper ventilation flow delivery will tend to add to the maintenance cost. This issue is discussed in greater detail in Section 2.7-Key Operating Issues and Considerations.

### Energy Cost

Despite the low first costs and potentially low maintenance costs, factoring in the lifetime energy use for an air handling system using this strategy could result in the highest life cycle cost of any of the strategies discussed in this guideline. But, the efficiency losses mentioned above under Potential for Negative Energy Impact are related to system size, hours of operation, and climate. Thus a small, simple system with a low turn-down requirement and minimal operating hours in a mild climate may still exhibit an attractive life cycle cost when contrasted with the added first costs, maintenance costs and complexity associated with some of the other strategies. In fact, for a small, simple system, the long term advantages of simplicity may justify a modest energy penalty, especially if the operating simplicity ensures persistence. Many of the other options, while capable of delivering better energy efficiency, will fail to energy intensive states if their more complex control systems and operating strategies are poorly understood and maintained.

On the other hand, a larger system with a high turn-down requirement and a significant number of operating hours in an extreme climate may pay a significant energy penalty if this operating strategy is utilized. In this case, the added first costs and maintenance costs associated with some of the more complex strategies may yield a more attractive life cycle picture via the improved efficiency delivered.

## 2.5 Key Design Issues and Considerations

Many of the issues discussed in the subsequent sections on installation and operation are intertwined with the decisions made during the design process. Thus, reviewing those sections to understand the challenges that will be faced during fabrication, start-up and operation can be crucial to a successful design. *Appendix 7: The Relationship Between Design, Installation and Operation* includes a discussion of a general nature on this topic. The following information is particular to speed tracking strategies.

### Infiltration and Over-Ventilation

*Appendix 8: Theoretical Versus Actual Performance* contrasts the theoretical performance of a speed tracking strategy based on the design condition with what actually happens in the system as the loads vary. In the example, the design intent was to have the system set up for a constant minimum outdoor air flow rate of 5,000 cfm. In such a circumstance, the designer typically has specified this outdoor air quantity to balance the building's exhaust and pressurization requirements, with the exhaust being more significant in most cases. A reduction in minimum outdoor air flow below design will compromise the mass flow balance at the building envelope. Specifically, if the minimum outdoor air flow rate drops below the design requirement, as is the case in the example, infiltration is likely to occur, especially if the imbalance is associated with the operation of a constant volume toilet exhaust fan. If unanticipated by the designer, the infiltration will show up as an unanticipated energy burden in addition to being a comfort and potential IEQ issue.

If the designer anticipated the problem, they might increase the design minimum outdoor air flow rate to ensure that it always met or exceeded the building's exhaust and pressurization requirements, even if it degraded under some operating conditions, to mitigate any comfort and IEQ issues. However, the system will still bear an energy burden at the air handling unit location since additional outdoor air must be conditioned as a part of the unit's HVAC process.

In either case, an analysis similar to the one used in the example can be used to identify the potential infiltration or excess outdoor air requirement. This quantity can then be used to assess the energy penalty it represents via degree-day calculations, bin calculations or computer modeling.

### Moving More Return Air Than Necessary

Building Static Pressure and Return Fan Discharge Plenum based control strategies tend to better-optimize the amount of return air moved than speed tracking strategies. Consulting the chapters in this guideline that deal with these strategies will provide additional insight into the savings potential.

### Control System Considerations – Hardware

As stated previously, speed tracking control strategies typically have a low implementation cost due to the modest control system requirements. Most of the control system hardware considerations discussed in *Chapter 1: Introduction and Fundamentals* and in *Appendix 5: Return Fan Control System Hardware and Software Issues* apply, including:

- Variable speed drive interlock issues.
- Economizer control integration issues.
- Minimum outdoor air control issues.
- Building pressurization control integration issues.
- Return and relief damper interlock issues.

## Control System Considerations – Software

Points lists, narrative sequences and logic diagrams are important tools to convey design intent to the implementing and operating staff. These topics are discussed in *Chapter 1: Introduction and Fundamentals* and *Appendix 5: Return Fan Control System Hardware and Software*. The following applies specifically to this strategy.

### *Control System Points List*

The example provided at the end of this chapter can be edited to meet the needs of a project using speed tracking for return fan control. Editing considerations should include:

- Coordination with the requirements of the narrative sequence and any logic diagrams.
- Clarification regarding whether the return fan drive will be interfaced to the supply fan speed signal or command via a hardwired interface or a software-based interface.
- Clarification on if and how speed will be measured and what the units of measure should be (rpm, Hz, percent maximum, etc).

### *Narrative Control Sequence*

The example provided at the end of the chapter can be edited to meet the needs of a project using speed tracking for return fan control. Editing considerations should include:

- Coordination with the requirements of the points list and any logic diagrams.
- Clarification regarding whether the actual supply fan speed or the speed command to the supply fan will be used for the controlling input to the return fan drive. See *Variations* at the beginning of this chapter for additional information regarding the differences between these two approaches.

### Bias

For a speed tracking strategy to provide some measure of minimum outdoor air flow control, the differential between supply and return fan capacity (which is controlled by their respective speeds) must be maintained as the system operating point varies over time. The term “bias” is generally applied to the ratio that is maintained between the supply and return fan speeds. An initial assessment of the required value must be made by the designer. Verification and tuning are critical steps in the implementation and operational phases of the system’s life.

While simple in concept, there are some complexities associated with implementing and maintaining bias in an operating system, specifically:

- Unless the supply and return fans are the same with matching fan curves and identical design operating points, it is highly unlikely that they will have the same design speed and that there will be a one to one correlation between any speed changes required as the system operates.
- As can be seen from the example in *Appendix 8: Theoretical Versus Actual Performance*, it is likely that a bias setting that provides the required performance at one condition will not provide it at another as the system operating point shifts.

The units of measurement used to determine the bias make a difference. Maintaining a fixed rpm differential is quite different than maintaining the return fan speed as a fixed percentage of the supply fan speed. To understand this, contrast the two in the context of the Figure A8-1 in *Appendix 8: Theoretical Versus Actual Performance*. The design supply to return fan speed difference is 432 rpm. This translates to a return fan speed that is 52% of the supply fan speed at design. If the return fan is controlled for a constant *rpm* difference relative to the supply fan, its speed when the supply fan stabilizes at 80% load will be 371 rpm. In contrast, if the return fan is controlled at a constant percentage of supply fan speed, its speed when the supply fan stabilizes at 80% load will be 415 rpm. Since each approach will yield different results, the designer should determine which approach will best meet the needs of the project. Also, the installing contractor should be aware that there can be subtle differences and ensure that the implementation truly reflects the design intent.

A bias setting that provides the desired flow relationship at one operating condition may not provide the same desired relationship at another. To deal with this, a designer has several options:

- Adjust the bias to provide a satisfactory minimum outdoor air flow rate at the worst case condition. As discussed under *Application Complexity*, this degrades system efficiency.
- Provide multiple bias settings for multiple operating conditions. This approach works particularly well with incremental volume systems where the system will only operate at specific flow conditions rather than over an infinite range of flow conditions.
- Provide a bias setting using a curve fit or look-up table. Many DDC systems support curve fits and look up tables. However, some that do support it only support it under an optional software package. Thus, if the designer intends to use this approach it is important that the project specifications reflect the requirement so the bidding contractors include any optional software packages in their bid.
- Allow the bias to influence the minimum outdoor air damper position in addition to the relationship between return fan and supply fan speed. This approach defeats one of the primary advantages of this strategy by adding complexity to its programming, implementation, and operation.

Regardless of how the bias is adjusted and applied, using the fan sheaves to set the bias for the design operating point will optimize overall efficiency and controllability as discussed in *Appendix 6: Electrical and Drive System Considerations* under *Maximizing Efficiency*.

### Air Handling System Considerations

Many of the air handling system considerations discussed in *Chapter 1: Introduction and Fundamentals* apply to this strategy, including:

- Economizer damper selection, sizing, and installation.
- Return flow path versus relief flow path pressure losses.
- Integration with HVAC system and building functions and processes including building and zone level pressurization, mixed air and economizer process control, including the potential to pressurize the mixed air plenum and the potential to reverse air flow through the relief system, building static pressure control, and minimum outdoor air flow regulation.

Issues related to a mismatch between supply and return fan curve characteristics are generally most prevalent at conditions of high turn down/low airflow where minimum motor speed settings prevent further speed reduction by the return fan.

### Electrical System Considerations

Many of the electrical system considerations discussed in *Chapter 1: Introduction and Fundamentals* apply to this strategy, including:

- Variable speed drive application, networking, and interlock issues.
- Motor selection and application issues.

## 2.6 Key Installation Issues and Considerations

Many of the design issues discussed in the preceding section and the operating issues discussed in the next section have a direct bearing on system installation. Therefore, reviewing the design intent for the strategy and its operating requirements is a crucial step in successfully installing and starting up the system. *Appendix 7: The Relationship Between Design, Installation and Operation* includes a discussion of a general nature on this topic. The information in this chapter is particular to speed tracking based control strategies.

Successful performance hinges on integrating the bias settings and on other factors addressed by the designer with their implementation effort in the field. *Figure A8-1 in Appendix 8: Theoretical Versus Actual Performance* and its related discussion illustrate some of the operational issues associated with ensuring adequate minimum outdoor air flows in a VAV system that uses speed tracking to control the return fan. From the design side, the system needs to be assessed and designed to ensure that maintaining the required minimum outdoor air flow rate can be realistically achieved. To ensure overall success on all fronts, the design issues must be complemented by the following efforts in the field:

### Adequate Equipment Procurement

A thorough shop drawing review process can go a long way toward ensuring that the design intent is reflected in the equipment provided. A discussion of important areas to target is included in *Chapter 1: Introduction and Fundamentals* under *The Relationship Between Design, Installation, and Operation*.

### Locating and Installing Sensors in the Field

Because speed based control strategies generally do not require additional sensors beyond what would be provided for fundamental control of the variable speed drives, there are few sensor location and installation issues to consider beyond those discussed in *Chapter 1: Introduction and Fundamentals* under *Hardware Issues*.

In some instances where multiple bias settings are required, additional external potentiometers must be added to the variable speed drive to accommodate the additional settings. In these cases, the additional devices should be coordinated with the drive supplier during the shop drawing review process. The increasing implementation by drive manufacturers of fully programmable features is making the need to add external devices to set drive parameters a thing of the past.

### Pre-start and Start-up Checklist Considerations

The pre-start and start-up considerations for speed tracking strategies are no different from the general requirements for any other strategy. See *Chapter 1: Introduction and Fundamentals* under *The Relationship Between Design, Installation, and Operation* for additional information.

### Testing Considerations

Perhaps the most important aspect of implementing the speed tracking return fan control strategy is the system setup and testing associated with ensuring proper minimum outdoor air flow. Ensuring a fixed speed differential between the supply and return fans does not necessarily guarantee that the intended minimum outdoor air flow rate will be maintained, as can be seen from the example in *Appendix 8: Theoretical Versus Actual Performance*.

Usually, setting up the system and testing it involves close coordination between the mechanical contractor, the controls contractor and the balancing contractor to tune the drives, the fan speeds and the bias settings. A detailed description of the considerations and test process can be found in *Appendix 4: Tuning Outdoor Air Flow to Design Specifications*. Typically, the ultimate goal of the testing process is to determine the appropriate bias or biases required to ensure adequate minimum outdoor air flow under all operating conditions. Bear in mind that the IEQ and efficiency benefits associated with multipoint testing will only be realized in a system that is capable of accepting multiple bias settings. Otherwise, the bias will need to be set for the worst case operating point and the system will tend to over or under-ventilate under other conditions.

## 2.7 Key Operating Issues and Considerations

Many of the issues discussed in the preceding paragraphs in terms of design and installation will ultimately become operational issues. Reviewing and understanding key design and implementation issues will allow the operating staff to develop an understanding of the design intent for the strategy and its implementation. This can be a crucial step in successfully operating a system regardless of the control approach employed.

### Operating and Monitoring the Process

The trouble shooting table, control sequence and points list included at the end of this chapter will provide a good starting point for developing an understanding of the operating details associated with this strategy. In addition, they illustrate where the operating staff interfaces with the control system to adjust and monitor it. Additional information applicable to the operation of all return fan control strategies can be found in *Appendix 7: The Relationship Between Design, Installation and Operation*.

## 2.8 Speed Tracking Control Troubleshooting Table

While not all inclusive, Table 2-1 illustrates many of the more common problems that can occur with a speed tracking control strategy and the associated corrective actions. Some troubleshooting issues will be general in nature while others will be specific to a particular system by virtue of the control sequence and wiring configuration associate with it. The Table 2-1 is based on the system illustrated at the beginning of the chapter with a control sequence as described in *Section 2.9. Sample Narrative Sequence of Operations*.

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Fails To Start | Loss of Power | • Verify the integrity of the power supply from the motor back to the source. If tripped circuit breakers or blown fuses are encountered, determine and correct the cause of the fault prior to restoring power. |
| | Interlock Problem | • After verifying that the fan can be safely run alone, switch the fan to "Hand" and observe the results.<br>■ If the fan still fails to start, the problem is most likely in the safety interlock circuit (fire alarm, relay, smoke detector, etc.). Investigate and correct interlock problems in the safety interlock circuit associated directly with the return fan.<br>■ If the fan runs, the problem is most likely in the interlocks associated with scheduled operation of the fan and other automation requirements. Verify the controlling software that cycles the fan in the "Auto" mode as well as any hardwired interlocks with other equipment like the supply fan. A safety trip that is preventing a supply fan start (freezestat, static switch, smoke detector, etc.) could prevent a return fan start if the return fan is interlocked via hardwiring or software to only run when the supply fan runs.<br>• If the fan fails to run in "Hand" or "Auto" and the drive is equipped with a "Bypass" option, switch the fan to "Bypass" after verifying that it is safe for the fan to run at full speed.<br>■ If the fan starts and runs in bypass, the problem is most likely in the VSD itself (see below).<br>■ If the fan fails to start in the bypass mode, the problem is probably one of the other issues listed in this table. |
| | VFD Failure | • Verify the integrity of the drive circuitry using the manufacturer's troubleshooting guidelines as published in the operation and maintenance manual. |
| | Drive System Failure | • Verify the integrity of the drive belts and sheaves or couplings. |

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Fails To Start (cont'd) | Motor Failure | • Verify that proper voltage exist at the motor terminals on all phases.<br>• Isolate the motor from the power system and all controllers, drives, starters, etc.<br>  ■ Spin the motor shaft by hand to assess the integrity of the bearings. The shaft should spin freely and smoothly. Investigate and correct any unusual noise, jams or restrictions to free movement.<br>  ■ Inspect the motor connections for security and signs of overheating or resistive connections. Correct any discrepancies found.<br>  ■ Megger test the motor to measure the insulation resistance to ground. Correct any grounded conditions before reapplying power to the motor. Usually this will involve removing the motor and sending it out for repair.<br>• If the motor spins freely, the connections are good, and there are no grounds, cautiously reapply power (monitor the inrush current during this process) and verify:<br>  ■ The motor starts and comes up to speed.<br>  ■ The motor inrush current drops off as the motor comes up to speed.<br>  ■ The current on all phases is balanced and does not exceed the motors nameplate rating.<br>• If the motor currents are over nameplate disconnect the load and restart the motor. Verify the following:<br>  ■ No-load motor amps are approximately 50 to 70% full load amps for 900 – 1200 rpm motors (Some may be higher), approximately 30% full load amps for 1800 rpm motors and are approximately 20 to 30% full load amps for 3600 rpm motors. If the no load currents are balanced and within the limits listed above, the motor is probably being overloaded (see below).<br>  ■ If the no-load currents are out of balance or exceed the limits listed above, the motor windings are probably shorted and the motor will need to be removed and repaired.<br>• If the motor currents are severely imbalanced (in excess of 10% different) check the following:<br>  ■ Verify that the voltage supplied to the motor is within 5% of the line voltage rating. Investigate and correct the cause of any observed low voltage condition.<br>  ■ Verify that the phase to phase voltages are balanced and are within 5% of the line voltage of each other. If the phase voltages are balanced but the currents are imbalanced, there is probably a short in the motor winding and the motor will need to be removed and repaired. |

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Fails To Start (cont'd) | Overload Trip | • If a new motor has been installed on the fan, verify that the moment of inertia rating (WR$^2$) of the new motor is equal to or better than the motor it replaced (see Appendix 6: Electrical and Drive System Considerations for additional information.)<br>• Verify that the wiring connections to the overload relay are tight. Loose wiring connections represent a resistive load that can generate heat and trigger a false overload trip.<br>• Inspect and clean the fan wheel as necessary. Dirt on the fan wheel increases its moment of inertia and can cause start-up problems to "suddenly" appear in a fan that has been running satisfactorily (see *Chapter 1: Introduction and Fundamentals – Maintaining and Adapting Design Intent - Fan Wheel Cleanliness* for additional information.) |
| Return Fan Fails To Stop | Fan Remains in Operation Despite a Safety Trip That Should Directly Shut Down the Fan | • Safety trips intended to directly affect the return fan should shut down and lock out the fan irrespective of the position of any Hand-Off-Auto switches or Inverter-Bypass switches. If a fan remains in operation after a safety trip, investigate and correct problems in the safety interlock circuit. |
| | Fan Remains in Operation Despite a Supply Fan Shut Down Due to a Safety Trip | • Verify that the drive is in "Auto". If the drive is in "Auto" and continues to operate when it should be off, investigate and correct problems in the control logic associated with supply fan interlocks. |
| | Fan Remains in Operation When It Should Be Off Based on Schedule | • Verify that the drive is in "Auto". If the drive is in "Auto" and continues to operate when it should be off, investigate and correct problems in the control logic associated with the return fan start-stop functions. |
| Return Fan Speed Does Not Vary | Return Fan Speed Does Not Vary Despite Supply Fan Speed Variations | • If the return fan VSD is equipped with a bypass system, verify that the system is in "Inverter" (VSD active) and not "Bypass" (VSD bypassed and out of the circuit).<br>• Verify that the return fan VSD speed control selection is in the position that causes the drive to follow a remote speed command. Typically this is the "Auto Speed Command" position. This selection may be made via a selector switch or via a keypad, depending on the drive design, manufacturer, and vintage.<br>• Verify that the speed control signal is available at the return fan VSD input terminals.<br>• Verify that the bias settings are as required to control the ratio of supply fan to return fan speed. The preliminary settings specified by the designer were most likely optimized and tuned to the installed system during the commissioning process. These settings should be reflected in the commissioning report. |

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Speed Does Not Vary (cont'd) | Return Fan and Supply Fan Speeds Do Not Vary | • Verify that the supply fan VSD is in "Auto" and not in a mode that would cause it to run at a fixed speed. If the supply fan is in "Auto" and its speed does not vary the problem could be:<br>■ A problem in the supply fan speed control system or related logic. Detailed troubleshooting of the supply fan speed control system is beyond the scope of this guide, but in general terms the procedure will be similar to that described above under Return Fan Speed Does Not Vary Despite Supply Fan Speed Variations.<br>■ A load condition that exceeds the supply fan's capacity may exist. This could be caused by a number of factors including a load condition in excess of design, a supply flow restriction, or conditions that have compromised the capabilities of the cooling or heating utility systems that condition the supply air (low refrigerant, high chilled water supply temperature, high cooling coil discharge air temperature, low heating coil discharge air temperature, low steam supply pressure, low hot water supply temperature, etc.). Troubleshooting of these issues is beyond the scope of this guideline. |
| Pressure Relationships are Negative or Overly Positive Either Relative to the Outdoors or Relative to Adjacent Areas | Pressure Relationships are Negative or Overly Positive Regardless of the Operating Status of the Return Fan and its Related Air Handling System | • The problem is most likely not related to the return fan and is more likely related to:<br>■ Issues in a different system in the building.<br>■ Stack effect.<br>■ An imbalance between make up air either due to improper adjustment and balancing or due to the operation of an exhaust system without its associated make up system or vice-versa.<br>■ Problems with a building static pressure control system that operates independently of the air handling system in question.<br>■ Modification or changes have been made to the building's envelope, functions, or occupancy patterns. |

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Pressure Relationships are Negative or Overly Positive Either Relative to the Outdoors or Relative to Adjacent Areas (cont'd) | Negative or Overly Positive Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling System | • If the building is overly positive, and this was identified during initial testing after installation, verify that the RF is not oversized relative to the capacity of the other exhaust fans in the building. Verify that the RF VSD low limits are not higher than they could be or that there isn't another software low limit preventing the return fan from modulating as low as possible (typically around 10-15 Hz).<br>• Verify the integrity of the minimum outdoor air control system including that minimum outdoor air is being introduced into the system in the proper quantities.<br>• Verify that the economizer damper system is functioning properly including:<br>■ Maximum outdoor air, return air, and relief air dampers operate freely and through their full stroke<br>■ Maximum outdoor air, return air, and relief air dampers operate with the correct relationship to each other (return dampers close as the maximum outdoor air dampers open, etc.)<br>• Verify that any building pressure control components of the return fan/air handling system control process are functioning properly (if so equipped).<br>• Verify that the return fan bias setting or settings are correct and as tuned during the commissioning process. See *Appendix 4: Tuning Outdoor Air Flow to Design Specifications* for information on making these adjustments if it is necessary to re-tune the system.<br>• Verify that the return fan sheave or motor sheave have not been replaced with new sheaves with a different pitch diameter than the sheaves that were installed when the system was commissioned and tuned.<br>• Verify that the pitch diameter on a fan or motor equipped with an adjustable pitch sheave has not changed.<br>• Verify that there is not a restriction in the outdoor air intake system such as a louver that has become obstructed, turning vanes that have been obstructed by debris, etc. Bear in mind that the pressure drop represented by a restriction is a function of flow rate. Thus, a restriction in a VAV system may present a problem that seems to come and go as the flow rate increases and decreases.<br>• Determine if modifications have been made to the building's envelope, functions, or occupancy patterns in the area served by the return fan and its related air handling system or systems. Significant modifications in any of these areas may require re-assessment of the return fan capacity control system's bias settings and/or re-tuning of the system's minimum outdoor air flow. See *Appendix 4: Tuning Outdoor Air Flow to Design Specifications* and *Appendix 8: Theoretical Versus Actual Performance* for additional information. |

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Minimum Outdoor Air Flow Does Not Meet Requirements | Minimum Outdoor Air Flow Problems Exist Regardless of the Operating Status of the Return Fan and its Related Air Handling System | • The issues in this category will be similar to the issues discussed above under *Pressure Relationships Are Negative or Overly Positive Regardless of the Operating Status of the Return Fan and its Related Air Handling System*. |
| | Minimum Outdoor Air Flow Problems Appears to be Related to the Operation of the Return Fan and its Related Air Handling System | • In small buildings or large complex buildings, problems with minimum outdoor air flow in one system may not manifest themselves as problems with pressure relationships in the building even though in theory, they should. For small buildings, this is usually because leakage rates between zones or through the envelope are large enough that they prevent the issue from showing up as a pressure relationship problem. In larges complex buildings, the volume of the building or the interactions with other systems can mask the problem and prevent it from showing up as a pressure relationship issue. However, most of the issues are the same as those discussed above under *Negative or Overly Positive Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling System*. |
| Mixed Air Plenum is Positive | Bias setting not appropriate for the current operating condition | • As illustrated in *Appendix 8 - Theoretical Versus Actual Performance,* it is likely that the bias required to maintain the desired relationship between supply and return flow. If the return flow exceeds the supply flow, it is possible for the return fan to pressurize the mixed air plenum under some operating conditions, especially if the operating condition does not have the relief damper open. To solve this problem, it may be necessary to modify the bias setting used for the system or provide multiple bias settings as is discussed earlier in this chapter under *Control System Considerations – Software*. |
| | Problem with the relief damper control system | • If the relief damper control system has failed and the relief damper position is not appropriate for the current system operating state, then the return fan may be able to pressurize the mixed air plenum even though the intended relationship between supply fan speed and return fan speed is being maintained. This is especially true if the failure that is preventing the relief dampers from opening is also preventing the outdoor air dampers from opening. |
| | Wrong reference used for mixed air plenum pressure measurement | • If the air handling system equipment room serves as a return plenum on the inlet side of the return fan, then it may be possible for the mixed air plenum to be positive relative to the equipment room, even though it is negative relative to the out-of-doors. Verify mixed air plenum pressure relative to the out-of-doors. |

## 2.9 Sample Points List

The following tables illustrate a points list for the return fan speed tracking control. It can be used as a starting point for similar systems employing speed tracking control strategies. It was developed using the points list tool contained in the *Control Design Guide*. This publicly available resource can be downloaded from www.PECI.org/FTGuide and used to develop a points list with characteristics similar to those illustrated for an entire system or project. Note that sensor accuracy references the end to end accuracy of the sensing system.

| Point Name | Sensor Information | | |
|---|---|---|---|
| | System and Service | Sensor/Interface Device[6] | |
| | | Type | Accuracy |
| **Analog Inputs** | | | |
| AH1SpdFb | AHU 01 Drive Speed Feedback | VFD programmable output | +/-1.0%FS |
| RF1SpdFb | AHU 01 Return Fan 1 Speed Feedback | VFD programmable output | +/-1.0%FS |
| RF1kW | RF1 kW | VFD programmable output | +/-1.0%FS |
| **Analog Outputs** | | | |
| RF1Spd | AHU 01 Return Fan 1 Speed Control Command | 4-20 ma output | +/-1.0%FS |
| **Digital Inputs** | | | |
| RF1POO | Return Fan 01 Proof of Operation | Current switch | N/A |
| RF1SSwSt | Return Fan 1 Selector Switch Status | Auxilliary contact | N/A |
| VFD1SSwSt | Supply Fan 1 VFD Selector Switch Status | Auxilliary contact | N/A |
| **Digital Outputs** | | | |
| AH1RFSS | AHU 01 Return Fan Start/Stop Command | Interface relay | N/A |
| **Virtual Points** | | | |
| RF1Hrs | RF 01 Accumulated Hours of Operation | Calculation based on proof of operation input | N/A |
| RF1kWh | RF1 kWh | Calculation based on kW input | N/A |
| RF1SpdPGn | RF1 Speed Control Loop Proportional Gain | Manually set | N/A |
| RF1SpdIGn | RF1 Speed Control Loop Integral Gain | Manually set | N/A |
| RF1SpdDGn | RF1 Speed Control Loop Derivative Gain | Manually set | N/A |
| RF1DesBs | RF1 Design Condition Bias Setting | Manually set | N/A |
| RF180%Bs | RF1 80% of Design Condition Bias Setting | Manually set | N/A |
| RF1MDsBs | RF1 Minimum Full Occupancy Load Bias Setting | Manually set | N/A |
| RF1MOcBs | RF1 Minimum Partial Occupancy Load Bias Setting | Manually set | N/A |
| **Hard Wired Points** | | | |
| RF1Fire | RF 01 Fire Alarm Shut Down Relay | Relay by fire alarm contractor | N/A |
| AH1VFDAux | AH1 VFD Auxilliary Contact | Auxilliary contact | N/A |

| Point Name | Alarm and Trending Information, General Notes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Features | | | | | | | | | | | Notes |
| | Alarms | | | | Trending | | | | | | | |
| | Limit | | Warning | | Samples[1] | Commissioning[5] | | | Operating[5] | | | |
| | Hi | Lo | Hi | Lo | | Time[2] | Local[3] | Archive[4] | Time[2] | Local[3] | Archive[4] | |
| **Analog Inputs** | | | | | | | | | | | | |
| AH1SpdFb | None | None | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | |
| RF1SpdFb | N/A | N/A | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | |
| RF1kW | N/A | N/A | N/A | N/A | 15 | 15 min1 | X | X | 15 min | X | X | |
| **Analog Outputs** | | | | | | | | | | | | |
| RF1Spd | N/A | N/A | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | |
| **Digital Inputs** | | | | | | | | | | | | |
| RF1POO | Note 9 | None | None | None | 15 | COV | X | X | COV | X | | Note 7 |
| RF1SSwSt | Note 10 | None | None | None | 2 | COV | X | X | COV | X | | Note 11 |
| VFD1SSwSt | Note 10 | None | None | None | 2 | COV | X | X | COV | X | | Note 11 |
| **Digital Outputs** | | | | | | | | | | | | |
| AH1RFSS | Note 9 | None | None | None | 15 | COV | X | X | COV | X | | |
| **Virtual Points** | | | | | | | | | | | | |
| RF1Hrs | None | None | 1,000 hr. | None | None | None | None | None | None | None | None | Note 8 |
| RF1kWh | None | None | None | None | None | None | None | None | None | None | None | Note 8 |
| RF1SpdPGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1SpdIGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1SpdDGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1DesBs | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF180%Bs | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1MDsBs | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1MOcBs | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| **Hard Wired Points** | | | | | | | | | | | | |
| RF1Fire | Open | None | None | None | None | None | None | None | None | None | None | Note 14 |
| AH1VFDAux | Note 15 | None | None | None | None | None | None | None | None | None | None | Note 13 |

**Notes**

1. Samples indicates the minimum number of data samples that must be held in the local controller if it is trending the point. This may be based on the Operating trending requirements. Higher sample capabilities tends to minimize archiving frequency.
2. Time indicates the required sampling time for the trending function (1 min = 1 sample per minute, 4 min = 1 sample every 4 minutes).
3. A check in the local column indicates that the trending only needs to be running in the local controller and the most recent value can write over the last value when the trend buffer fills up.
4. A check in the archive column indicates that the trend data must be archived to the system hard disc when trend buffer fills up so that a continuous trend record is maintained.
5. Commissioning trending requirements only need to be implemented during the start-up and warranty year. After the start-up and warranty process, the control contractor should set the trending parameters to the operating requirements listed.
6. See the specifications for additional requirements and details regarding sensor and interface device requirements.
7. Adjust to detect a belt or coupling failure by showing failure to run with the belt or drive coupling removed and the motor running.
8. Accumulate on a monthly basis and archive the monthly total to the hard disk on the last day of the month at midnight.
9. Provide an alarm if the equipment is running when it is commanded off. Provide an additional alarm if the equipment is not running when it is commanded on. Include time delays to accommodate system start-ups.
10. Issue and alarm if the manual override switch/Hand-Off-Auto switch is not in Auto.
11. If the DDC system provides this function as a standard feature in the firmware and software supporting its I/O boards, an independent contact on the override switch and associated physical point is not required.
12. Typical of all control loops. Provide commandable points for adjustment of loop setpoints, tuning parameters, and bias settings. Limit access to Lead Operator or higher.
13. Arrange contact to close any time the AHU1 supply fan is in operation under VFD control or in bypass.
14. Fire alarm shut down relays are furnished and installed by the fire alarm supplier and located at the motor starter location. Control wiring through the fan start circuit shall be by the electrical contractor. The control contractor shall coordinate with the electrical contractor to ensure that the intended operating sequence is achieved.
15. Furnished and installed by the fire alarm supplier and wired to their system. Coordinate as required for proper installation and verification.

## 2.10 Sample Narrative Sequence of Operations

The following narrative sequence is an example that applies to the return fan speed tracking control. It can be used as a starting point for similar systems employing speed tracking control strategies. Note that this sequence is an example written around the system illustrated at the beginning of the chapter. It does not necessarily address every issue that would need to be addressed by every conceivable system utilizing this return fan capacity control strategy. For instance:

- There are a number of different methods that could be used to control the building relief dampers when this strategy is employed.
- Smaller fans may not require as many safety interlocks to prevent damage to dampers or plenums if the return fan starts with all of the dampers on its discharge closed or if all of the dampers fail closed with the return fan in operation.
- Variable speed drive programming requirements will vary with system complexity, drive type, and Owner preferences and requirements.
- Alarm and alert message requirements can vary significantly from system to system and facility to facility depending on Owner preference, system configuration and the loads served.

Also note that this example only addresses the return fan and its drive system. It does not address issues like the control of the relief, return, and outdoor air dampers, which are highly interactive with the return fan capacity control strategy but which are also very system and project specific. When an edited version of this sequence is applied to a system, it is critical that the designer address the integration of the other HVAC processes that occur in the system with the return fan capacity control issues identified in this narrative.

### Return Fan Variable Speed Drive Control

#### *Overview*

Return fan speed and return fan capacity are directly related. This control strategy exploits this characteristic and controls the return fan speed in direct relationship to supply fan speed. In order to ensure adequate outdoor air ventilation under all load conditions, multiple bias settings are employed, thereby providing different ratios of return fan speed to supply fan speed for different operating conditions. The bias settings listed in the following sequence are based on design calculations and shall be fine-tuned to the building's operating characteristics via field testing and adjustment during the commissioning process. This tuning shall be a coordinated effort between the testing and balancing contractor, the mechanical contractor, the control contractor and the commissioning provider supplemented by consultation from the designer when necessary. Building static pressure is not controlled by the fan speed tracking function, but by the relief damper tied directly to the building static pressure.
For additional details on this control strategy, including installation, commissioning, and operating tips, refer to the application guideline titled *Return Fan Capacity Control via Speed Control* published by the National Building Controls Information Program and available for free download at www.buildingcontrols.org.

#### *Speed Control*

A programmable output on the supply fan variable speed drive is set up to provide a 4-20 mA input to the control system that is directly proportional to supply fan speed. This supply fan speed is multiplied by a bias factor which is indicated in the table below. The resulting speed becomes the setpoint for the return fan speed variable speed drive's control loop.

The control loop is contained in the return fan variable speed drive and is set up as a PID loop. A tendency towards a return fan speed that is below setpoint causes the return fan speed to increase. A tendency towards a return fan speed that is above setpoint causes the return fan speed to decrease. The drive speed control shall be via a discrete hardwired interface between the control system and the drive. Network level interfaces between the control system and drive shall not be permitted for this function.

*Table 2-2*

| Return Fan Bias Settings | | |
|---|---|---|
| Supply Fan Speed | Bias setting [1] | Comment |
| 895 rpm | 0.52 | Full load design point |
| 803 rpm | 0.44 | 80% full load design point; it is anticipated that a significant number of operating hours will be in this range |
| 521 rpm | 0.40 | Minimum anticipated load condition with full occupancy |
| 350 rpm | 0.65 | Minimum anticipated load condition, partial occupancy |

[1] Bias is the return fan speed / supply fan speed.

Control loop tuning parameters and variable speed drive acceleration times, deceleration times, minimum and maximum speeds shall be adjusted and optimized during the commissioning process.

### Start Stop Control and Proof of Operation

The return fan variable speed drive shall be commanded on by a hardwired interlock any time the supply fan variable speed drive is in operation. It shall also be possible to command the drive on via the DDC system using a command from the operator's console.

A current switch sensing current to the variable speed drive shall provide a contact closure for proof of operation purposes any time the return fan motor is operating under load. The current switch shall be adjusted so that the proof of operation is not indicated if the motor is running but the belts have broken and thus the fan is not turning.

### Variable Speed Drive Interlocks

The following interlocks shall be provided for the return fan variable speed drive:

- External, Hardwired

  A start-stop interlock to the supply fan shall be hardwired into the variable speed drive control circuit. These interlocks shall function regardless of the status of the drive Hand-Off-Auto and Inverter-Bypass selector switches.

  A fire alarm shut down relay shall be wired into the circuit and arranged to shut down the fan on a building fire alarm condition per the programming requirements of the fire alarm system. Coordinate with Division 16 as required for wiring and programming of the fire alarm relay. Coordinate with Division 16 for the location and field installation of the duct mounted smoke detectors.

- External, Software based

  The return fan variable speed drive shall be commanded to 0 Hz any time the return fan is not in operation as indicated by the return fan status input.

- Internal

  The return fan shall be shut down and locked out if a motor overload condition is sensed in the drive or bypass mode. Manual reset at the drive location shall be required to resume normal operation.

### Outputs to the DDC System

The following outputs shall be provided from the variable speed drive to the automation system. These outputs may be provided by discrete hardwired interfaces or by a network level interface at the contractor's discretion. The final installed condition shall be reflected in the "as-built" drawings.

- Drive speed feedback in Hz
- Drive kW

### *Alarms: Operator*

Operator alarms shall be delivered to the operator's console and logged on a dedicated alarm printer as they occur. The following operator alarms shall be provided:

- Indicate *AHU1 return fan failure to start or run* if the fan is not running when it should be, including a failure to start when commanded on for any reason or a shutdown that occurs when the fan should be operating per the operating sequence given the current conditions.
- Indicate *AHU1 return fan failure to stop or remain shut down* if the fan is running when it should not be, including a failure to stop when commanded off for any reason or any operation that occurs when the fan should be off per the operating sequence given the current conditions.
- Indicate *AHU1 measured return fan speed to supply fan speed bias does not match setpoint* if the supply fan has been running for 5 minutes or more (initial setting, adjustable) and the difference between the measured bias and the desired setpoint is greater than 5% (initial setting, adjustable). Suppress this alarm if the supply fan status is off.

### *Alerts: Facility Management*

Facility management alarms shall be directed to a weekly report, generated for the director of engineering and made available for viewing under their log-in. The following alarms shall be provided:

- Indicate During the past week the *AHU1 return fan operated for a significant period of time when the supply fan was not operating* if the return fan operates more than one hour (initial setting, adjustable) when the supply fan is not operating. Reset the timer at the end of the week.
- Indicate *During the past week the AHU1 return fan has failed to operate for a significant period of time when the supply fan was operating* if the supply fan operates for more than one hour (initial setting, adjustable) when the return fan is not operating. Reset the timer at the end of the week.
- Indicate *During the past week, the AHU1 return fan speed did not vary significantly on one or more days* if the return fan speed does not vary by more than ± 5 Hz (initial setting, adjustable) between 30 minutes after start-up and the shut down time during any day on which the system operated.

### *Totalization*

The following totalization functions should be provided and the data should be archived to the system hard drive on a daily basis:

- Return fan hours of operation based on the proof of operation input for the current week, the current month, and the current year.
- Return fan kWh based on the kW input from the variable speed drive for the current week, the current month and the current year.

## 2.11 Case Study

Albert Einstein once said that "things should be made as simple as possible but no simpler." On a recent project, this appeared to be the case, at least with regard to minimum outdoor air flow control. The system was an incremental volume multizone system that ran at full speed during occupied hours and 50% speed during unoccupied hours. The minimum outdoor air flow requirement was 50% under both operating modes due to the occupancy of the building. Given the simple performance requirement, the designer selected signal tracking as a simple, effective control strategy for the return fan. He also elected to use a simple minimum position signal approach to regulating minimum outdoor air flow.

Unfortunately, the economizer dampers were simply sized to match the face area of the intake louver rather than to provide a linear flow versus stroke characteristic. As a result, a retrocommissioning team working with the owner several years after the installation was complete hit the energy savings jackpot. The owner's operating staff were key players in diagnosing the problem and implementing a fix.

In the course of the investigation phase of the project, field testing revealed that the simple 50% damper signal command sent to the damper assembly to provide 50% outdoor air was just a bit too simple. It was actually providing 85-95% outdoor air due to the characteristics of the oversized dampers. This was bad news as it meant that the energy required to treat the over-design outdoor air flow consumed any savings realized by the design's reduced air flows during unoccupied hours.

The good news was that the project team was able to modify the outdoor air damper assembly and improve the damper flow control characteristics. Figure 2-1 illustrates the relatively simple modification that was performed. Additional good news was that there were five similar units on site, which allowed the operating staff to multiply their savings six-fold by replicating the process on the remaining units.

*Figure 2-1.*

*Top left – The modified damper. The far left section has been dedicated to the economizer function by disconnecting it from the other two sections. The far right section has been dedicated to the minimum outdoor air function by disconnecting it from the other two sections and adding a damper actuator (bottom right). The middle section has been permanently closed. Top right – Disconnecting the sections to actuate independently was simply a matter of loosening up a coupling and sliding it over. Bottom Left – This static pressure piloted pneumatic switching relay made interlocking the minimum outdoor air damper with the supply fan operation easy to accomplish with no wiring required. The relay is piped to sense the static pressure across the cooling coil. When it senses pressure, it connects main air pressure to its output, which in turn, is connected to the normally closed minimum outdoor air damper actuator that was added (bottom right). Since there is only pressure drop across the cooling coil when air flow is created by the fan operation, this arrangement will only open the minimum outdoor air damper when the fan runs.*

## 2.12 Additional Resources

Additional guidance can be found in *Installation and Maintenance of V-Belt Drives*, another useful tool that is provided as a free resource from the TB Woods Company at http://www.tbwoods.com/pdf/VBD-IM_InstallationandMaintenance.pdf

*ASHRAE Guideline 16*, which can be found at www.ashrae.org, provides guidance on the selection and sizing of economizer dampers.

*ASHRAE Standard 62-2004*, which can be found at www.ashrae.org, provides guidance on establishing ventilation rates.

Energy Design Resources Briefs – The two briefs mentioned specifically in this guideline are:

- Economizers – http://www.energydesignresources.com/resource/28/
- Design Review – http://www.energydesignresources.com/resource/26/

However, the Energy Design Resources Web contains a wealth of information related to HVAC design, including topics on VAV systems and Drives that can provide valuable references for other aspects of projects where return fan capacity control is applied.

The *Functional Testing Guide*, which can be found at www.peci.org/ftguide/ contains the theory behind the testing associated with the commissioning process as well as sample tests and guidance documents to help the user develop their own tests. A large portion of the guide is focused on air handling systems including a chapter dedicated to return, relief, and exhaust systems and a chapter on integrated operation and control. The site also includes a check list tool that can help the user identify testing requirements and/or do design review. And a *Control System Design Guide*, which will help the user understand the control system design process and the sensors and hardware associated with control systems. The point lists included in this guideline were generated with the point list tool included in the *Control Design Guide*.

The *Adjustable Speed Drives Directory*, available at www.epri.com, provides an overview of variable speed drive technology and a list of manufacturers.

Control Spec Builder, which can be found at www.ctrlspecbuilder.com/sb/welcome.nsf is an interactive tool that will help the user perform many of the important steps in the control design process including specifications, sequences, schematics, point lists, trends, alarms, and other key requirements.

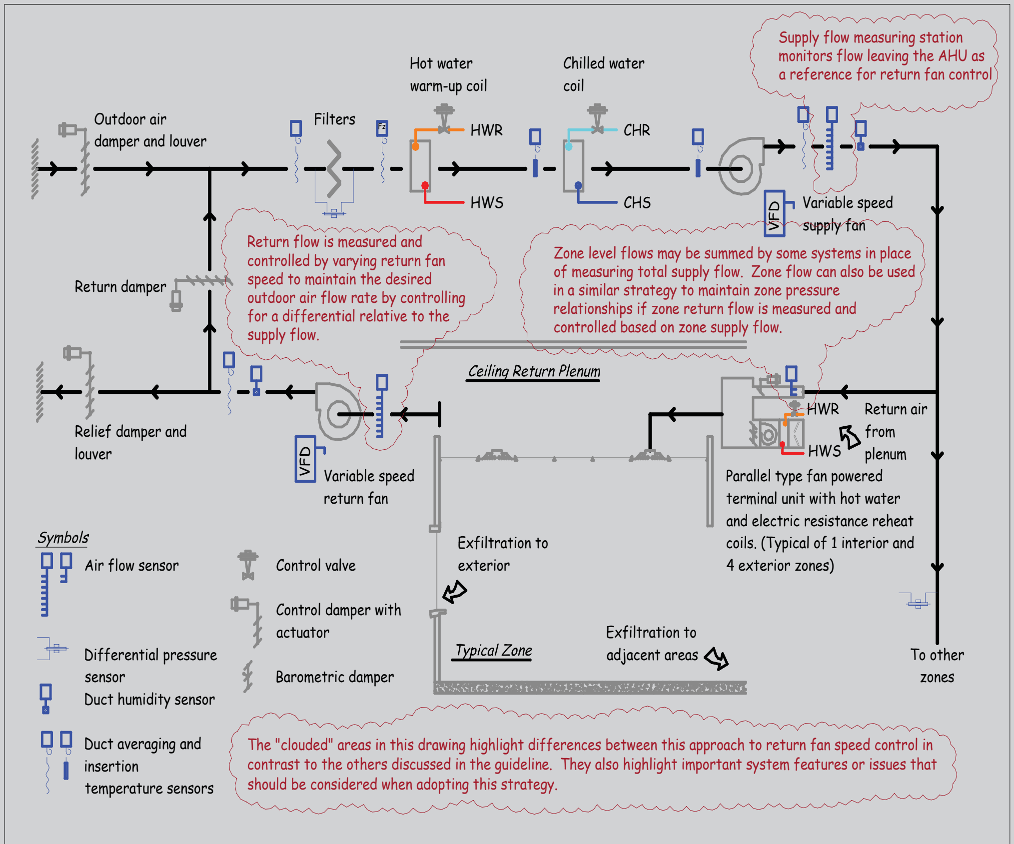
*Improving Fan System Performance: A Sourcebook for Industry* is available at www1.eere.energy.gov/industry/bestpractices/pdfs/fan_sourcebook.pdf. This resource, jointly developed by DOE and AMCA contains a wealth of information on fans and fan systems including fan performance, fan system components, fan system maintenance, and fan system troubleshooting and economics.

# Chapter 3 ▪ Flow Tracking Control

This chapter will discuss speed tracking based control, a strategy that adjusts the return fan speed as a function of the supply fan speed. The simplicity of the strategy makes it a good choice for less advanced building control systems and smaller air handlers. The two common ways to achieve the strategy are signal tracking, which sets the return fan speed based on a signal that controls the supply fan speed, and speed tracking, which sets the return fan speed based on the measured speed of the supply fan. In this guideline, the techniques will be referred to collectively as "speed tracking control strategies."

## Contents

# Speed Tracking Control




*A Typical VAV Air Handling System with Flow Tracking Based Control*

# General Description

This chapter will discuss flow tracking control, a strategy that modulates return fan speed based on measured supply and return flow. Because the strategy is based on measured flow rates, it has the potential to deliver better control of minimum outdoor air quantity and building pressure when contrasted with some of the other strategies. Thus it is more suited to complex buildings where its added cost and complexity can be justified by the benefits.

## Advantages

- Near direct control of minimum outdoor air flow and building and zone pressure relationships.
- Monitoring and positive verification of supply and return flow rates.

## Limitations

- Dependent on accurate flow measurement; this can be technically difficult to achieve.
- Complex and costly relative to other strategies.
- Can be highly interactive with other system and building processes.

## Application Considerations

| Characteristic | Low | Medium | High |
|---|---|---|---|
| Application Complexity | | | ✓ |
| Potential for Negative IEQ Impact | | ✓ | |
| Potential for Negative Energy Impact | ✓ | | |
| Potential for Integration/Interaction Problems | | ✓ | |
| First Cost | | | ✓ |
| Maintenance Cost | | | ✓ |
| Energy Cost | ✓ | | |

## Key Design Issues & Considerations

- Accurate flow measurement is essential. While simple in concept, real-time flow measurement is technically complex to achieve and requires careful attention to the details of the sensing system design and application to ensure reliable results.
- Consider the system's ventilation requirements and performance under all load conditions. By design, this strategy will tend to maintain a fixed minimum outdoor air *volume* rather than *percentage*. If this is not appropriate for all of the system's operating conditions, then multiple flow differential setpoints will be required.

## Key Installation Issues & Considerations

- Subtle but important differences in theory and technology mean that flow measurement equipment substitutions need to be carefully assessed to ensure identical performance under all operating conditions.
- The sensitivity of flow measurement accuracy to straight duct at the measuring point means that field configuration changes made to ductwork to accommodate existing conditions require careful review by the design team to ensure the accuracy of the flow measuring system is not compromised.
- Envelope and duct leakage can have a significant impact on the performance of the strategy.
- A loss of input signal will typically cause a return fan that is controlled by this strategy to drive to full speed. Fans that are capable of delivering pressures that exceed the duct pressure class for the ductwork on their discharge or the inlet side of the supply system may require additional safety system to protect them in the event of this occurrence.

## Key Operating Issues & Considerations

- Periodic retesting to ensure adequate minimum air flow under all operating conditions should be performed. Retesting is critical after any major building renovation, especially if it impacts the building envelope, the HVAC processes for areas surrounding those served by the system, or the ventilation requirements of the loads served by the system.

Flow tracking control is a strategy that modulates return fan speed based on measured supply and return flow rates. Because of its potential for better control of minimum outdoor air flow and building pressurization, it is more suited to complex buildings where its added cost and complexity can be justified in terms of the benefits.

Additional information generally applicable to all return fan speed control strategies can be found in *Chapter 1: Introduction and Fundamentals*. Additional useful resources outside of this guideline are listed at the end of the chapter.

## 3.1 General Description

In this strategy, the return fan capacity is controlled by measuring the supply flow and controlling the return fan to deliver a flow that is equal to the supply flow minus the desired minimum outdoor air quantity. As a result, near direct control of minimum outdoor air flow is achieved. The strategy may also provide a more positive approach to building pressure control relative to some of the other strategies, albeit an indirect one.

### Variations

This approach can also be applied at the zone level to control pressure relationships relative to adjacent zones. By measuring zone supply and return flows and modulating dampers as necessary to maintain a positive or negative flow differential, the zone pressure can be controlled at a positive or negative value relative to the surroundings.

While more costly and complex to design, install, and maintain, this variation may merit consideration:

- If zone level flow or pressure relationships are critical to the function in the zone or;
- Where zone relationships could be adversely impacted by conditions in adjacent zones.

Facilities implementing this variation may endeavor to use the DDC system to collate the zone data to develop the total supply and return flow rates for the system. These flow rates are then be used for return fan capacity control in lieu of directly measured totals.

## 3.2 Advantages

This control strategy has the potential to control outside air flow rates and building and zone level pressure relationships better than some of the other control strategies outlined in this guideline. It may be applied successfully to virtually any type of facility, from offices to medical facilities and clean rooms. However, it is best suited for larger and/or more complex facilities or systems; particularly those serving critical processes and/or where minimum outdoor air flow requirements and related direct exhaust and exfiltration requirements vary significantly due to variable occupancy, variable equipment use or other factors. In these situations, the strategy's added complexity and cost can typically be justified in terms of the benefits provided relative to some of the other approaches described in this guideline.

## 3.3 Limitations

The most prevalent factors that may limit the successful application of this control strategy include:

- Flow measurement errors, particularly in systems where differential pressure based flow measurement is used. Related to this are the system's turn-down requirements and the impact of those requirements on the flow measuring equipment.
- Changes in building dynamics that occur over time. Examples include day to day operating variables like prevailing winds and stack effect as well as the changes that occur over time as the equipment and building envelope age.
- Dynamic interactions with other system processes that impact flow rates. Examples include active minimum outdoor air control, economizer control, building pressure control, and zone level flow control processes.

## 3.4 Application Considerations

### Application Complexity

While simple in concept, the application of this strategy has the potential to be complex and interactive for the reasons listed as its limitations; specifically, measurement issues and building and system dynamics issues. These topics will be discussed in greater detail later in the chapter.

### Potential for Negative IEQ Impact

By providing direct control of the supply and return flow rates, this strategy also provides near direct control of the minimum outdoor air flow rate. As a result, the strategy has the potential to deliver better IEQ via better ventilation and better control over building pressurization than some of the other strategies. However, for this benefit to be realized the design basis for the flow differential maintained by the strategy must be sound and the issues noted as the limitations of the strategies must be acknowledged and addressed from design, through start-up and operation.

### Potential for Integration/ Interaction Problems

As noted under limitations, this strategy can be particularly prone to problems related to the dynamic interactions between its control loops and other control loops associated with the system and with building dynamics. This potential increases with the number of flow control loops that are used to implement the strategy; i.e., a system that uses total flow leaving and entering the AHU will be less prone to integration and interaction problems than one that measures and controls based on supply and return flow from each floor or zone served by the system.

### First Cost

In new construction, this control strategy has the potential to have a moderate to high first cost because flow sensors, especially those with high accuracy and precision at reduced flow conditions, are relatively expensive compared to other sensor types. Additional duct work may also be necessary to ensure proper air flow across the flow sensor and accurate measurement. Project costs will also increase if variable ventilation or exhaust control strategies are implemented or flow measurements are made on a zone by zone or floor by floor basis.

In a retrofit application, this control strategy may be cost prohibitive if major duct modifications are necessary to ensure accurate flow measurements.

### Maintenance Cost

The near direct control of minimum outdoor air flow provided by this strategy coupled with the availability of the measured supply and return flow data used for control will tend to minimize the need for periodic retesting to verify proper ventilation performance. However, many of the flow measuring technologies that might be employed by this strategy require regular maintenance and calibration to ensure performance and accuracy, offsetting some of the savings associated with the reduced need to re-test. This sensor maintenance burden will increase in direct proportion to the number of flow measuring elements employed by the application.

### Energy Cost

The potential of this strategy to provide better control of minimum outdoor air flow and building pressurization means that the strategy offers the potential to optimize the energy burden associated with these functions. However, as is the case with all of the strategies discussed in this guideline, failure to perform as intended can lead to energy waste on a number of fronts including:

- Increased heating/cooling requirements due to infiltration.
- Increased heating or cooling requirements due to over-ventilation.
- Increased fan energy requirements due to moving air in excess of what is required.

A potential energy burden that is unique to this strategy is related to the flow measurement function. Specifically, if the system in question has a high turn down requirement and uses a velocity pressure based flow measuring technology, it may be necessary to reduce the duct size at the flow measuring element location in order to ensure a measurable velocity pressure under all operating conditions. With appropriate attention to fitting design, the impact of the higher velocity section and the related transitions can be minimized. The *ASHRAE Handbook – Fundamentals* and the *ASHRAE Duct Fitting Database* can be used as guidelines for developing efficient duct/ fitting solutions to this problem. However, in the limit, the transitions and high velocity duct section represent an air handling energy burden that would not exist with the other strategies discussed in this guideline.

## 3.5 Key Design Issues and Considerations

Many of the issues discussed in the subsequent sections on installation and operation are intertwined with the decisions made during the design process. Thus, reviewing those sections to understand the challenges that will be faced during fabrication, start-up and operation can be crucial to a successful design. *Appendix 7: The Relationship Between Design, Installation and*

*Operation* includes a discussion of a general nature on this topic. The following information is particular to the flow tracking strategy.

### The Impact of Flow Measurement Accuracy on Outdoor Air Quantity

Accurate measurement of both air streams is extremely critical for successful implementation of flow tracking control in terms of maintaining the required outdoor air flow. This is compounded by the fact that by nature, the strategy uses the difference between two large measured variables (supply and return flow) as the indicator of a small variable (outdoor air flow). As a result, small errors in supply or return flow measurements can result in significant errors in outside air flow, especially in systems with high supply flow rates (Kettler 1995, Elovitz, 1995) Table 3-1 illustrates this effect for a 10,000 cfm system with an intended minimum outdoor air flow rate of 1,000 cfm.

*Table 3-1. The Impact of Supply and Return Flow Measurement Errors on Outdoor Air Flow*

| Item | Actual Flow, cfm | Error (*See Note*) | Indicated Flow, cfm |
|---|---|---|---|
| Supply Flow | 10,000 | +1% | 10,100 |
| Return Flow | 9,191 | -1% | 9,100 |
| Difference (*Outdoor air flow*) | 809 | -19% | 1,000 |

*Note; Error refers to measurement error for supply and return flow and the error in achieved value for the outdoor air flow*

There are several things worth noting with regard to the information in the table:

- The relatively small <u>*absolute*</u> difference in flow (-191 cfm) is a relatively large <u>*percentage*</u> (-19%) relative to the desired outdoor air flow rate of 1,000 cfm.
- Given that tracking control systems generally work using the indicated flow, in this particular situation, such a system will be under-ventilating by 19% under the operating condition illustrated.
- In real world applications, a 1% error in flow measurement is virtually unachievable; i.e., the problem illustrated in the table would most likely be much more significant in an operating system.

In an operating air handling system, air flow measurements tend to be "noisy" i.e., there is a lot of variability due to the low level of the signal being measured and system dynamics like turbulence and other factors. Since turbulence can be significant factor impacting measured flow accuracy, it is likely that in the long term, there are times when the system illustrated in the table will over-ventilate as well as under-ventilate. As a result, the transient variations in outdoor air flow may not adversely impact indoor environmental quality (IEQ) and efficiency in the long term.

Experience and the literature suggests that the weighted average of outside air flow over an extended time period is a much better indicator of IEQ, and this control strategy has been demonstrated to effectively meet the latter criteria (Elovitz 1995). For instance, economizer equipped systems in mild climates may spend most of their operating hours utilizing significantly more than the minimum outdoor air quantity via the economizer process. Thus, the long term impact of under or over ventilating would be less significant in terms of IEQ and energy efficiency than it would be for a system in a severe climate like Key West Florida. This topic is discussed in greater detail in *Appendix 2: Economizer Theory and Operation* and *Appendix 9: Minimum Outdoor Air Requirements and Their Impact on Return Fan Capacity Control*.

A more pressing concern with regard to outdoor air flow fluctuations is the impact it will have on building and zone pressure relationships and the related comfort, IEQ and energy issues. This topic is discussed in greater detail in *Appendix 9: Minimum Outdoor Air Requirements and their Impact on Return Fan Capacity Control*.

### Control System Considerations – Hardware

The system diagram included with the summary pages at the beginning of the chapter illustrates the control system hardware needed to implement this strategy effectively. Most of the control system hardware considerations discussed in *Chapter 1: Introduction and Fundamentals* and in *Appendix 5: Control System Hardware and Software* apply, including:

- Variable speed drive interlock issues.
- Economizer control integration issues.

- Minimum outdoor air control issues.
- Building pressurization control integration issues.
- Return and relief damper interlock issues.

The following issues are unique to the flow tracking strategy:

- Flow measurement application considerations.
- Flow measurement technology selection.
- Loss of input failure mode.

Each of the topics will be discussed in detail in the subsequent paragraphs.

### *Flow Measurement Application Considerations*

Irrespective of the technology selected for flow measurement, there are several issues that need to be considered. In fact, the project's needs and capabilities with regard to these issues may direct the selection of the technology to be employed. Specifically they are:

- Sensor location
- Flow traverse grid methodology
- Turbulence
- System turndown ratio

#### Sensor Location

It is common knowledge that flow measurement accuracy is dependent upon a uniform velocity profile. Typically, this involves providing a length of straight duct ahead of and leaving the measurement location. Requirements vary with the manufacturer as well as the technology but a general rule of thumb requires 10 equivalent straight duct diameters (no fittings) ahead of the sensor and five equivalent duct diameters after it.

It can be difficult to achieve the prescribed straight duct run for a flow measuring element in the field without planning during design phase. Field observation during the construction phase is also critical to ensure that the design requirements are not compromised as existing conditions are encountered and addressed. In some situations, the following strategies may find application if difficulty is encountered in providing suitable lengths of straight duct.

- *Provide Flow Straightening Vanes:* Some manufacturers have developed and tested flow straightening vanes with their flow sensors and will guarantee accuracy if they are applied ahead of the element in short duct runs. However, the elements themselves require some physical space and they introduce a energy burden into the system via the pressure drop they represent.
- *Measure Flow in the Fan Inlet Cone:* Measuring technologies have been developed that allow flow to be measured in a fan's inlet cone. Typically, the velocity will be higher at this location relative to others in the system. However, the fan shaft, bearing supports, drive system, belt and inlet guards, and other hardware typically found on the fan inlet create disturbances in the velocity profile and can impact accuracy.

It may also be possible to minimize the impact of the issues discussed above by careful selection and application of the flow measuring technology utilized by the system. This will be discussed below under *Flow Measurement Technology Selection*.

#### Flow Traverse Grid Methodology

Duct air flow is typically measured by measuring velocities on a grid across the plane of the duct and then averaging the velocities to determine flow. Over the years, a number of sampling methodologies have been developed for determining the grid dimensions:

- *Equal Area:* This method was developed in the early 1950s for measuring flow in rectangular ducts. In general terms, the method uses equal distances between measurement points with constraints placed on the maximum distance allowed between any two points.
- *Log-Linear:* This method was developed for measuring flow in circular ducts concurrently with the equal area method. There are two variations. In general terms, the preferred approach takes 6 non-uniformly spaced readings across the diameter of the duct. Three sets of readings are taken with the traverse lines intersecting each other at 60° angles at the duct centerline. If access is limited, an alternative approach takes 10 non-uniformly spaced readings across the duct diameter. Two sets of readings are taken with

the traverse lines intersecting each other at a 90° angle at the duct centerline. The intent of the non-uniformly spaced readings is to account for the impact of friction along the duct wall.

- *Log-Tchebycheff:* This method was developed for rectangular and round ducts by a mathematician of the same name (pronounced "che-boo-chef") in the 1970s (MacFerran 1999). Like the log-linear method, it uses non-uniformly spaced readings in an effort to account for the impact of duct wall friction on velocity. It yields similar results to the log-linear method in round ducts. In rectangular ducts, it yields results that are consistently lower than the equal area method, purportedly due to its accommodation of the impact of duct friction via its grid arrangement. However, limited research contrasting the two techniques suggests that the velocity profile and number of sampling points have a greater impact on accuracy than the approach used to define the sampling grid (Klaassen 2001).

The Log-Tchebycheff approach is the method recommended in the current literature and has been adopted as the method of choice or an acceptable option by most standards and certification agencies.

Many manufacturers offer flow sensing arrays configured per log-Tchebycheff requirements. Some also offer equal area configurations or proprietary arrangements with stated accuracies based on in-house or third party testing.

Figure 3-1 contrasts a traverse made with the equal area method with the same traverse made using the log-Tchebycheff method.

### Turbulence

When discussing turbulence in the context of flow measurement, it is important to distinguish between fully developed turbulent flow, with its characteristic "D" shaped velocity profile and the random flow patterns and distortion of the flow profile produced by fittings, duct transitions, and protuberances into the airstream. The former is desirable in terms of ensuring consistent, repeatable, flow measurements while the latter will generally have a negative impact on measurement accuracy. The specific nature of the impact of turbulence on flow measurement varies with the technology employed. This will be discussed below under *Flow Measurement Technology Selection*.

### Turndown Ratio

By nature, VAV systems see a variation in flow. This flow variation can have an impact on both flow profile and turbulence. For instance, an elbow upstream of a flow measuring station will introduce turbulence into the air stream to all but the lowest of flow conditions encountered by a typical HVAC system. At high flow rates, this turbulence will be much more significant than what is encountered at low flow rates both in terms of magnitude of the disturbance and persistence after the element generating the disturbance. In addition, the distortion of the velocity profile produced by the elbow can be more exaggerated and persistent at higher flow rates.

Turndown also has an impact that is unique to systems using a velocity pressure based measurement technology due to "square law" effects. This topic is discussed in greater detail in *Appendix 5: Return Fan Control System Hardware and Software Issues*.

## *Flow Measurement Technology Selection*

There are two fundamental technologies used for flow measurement in current practice:

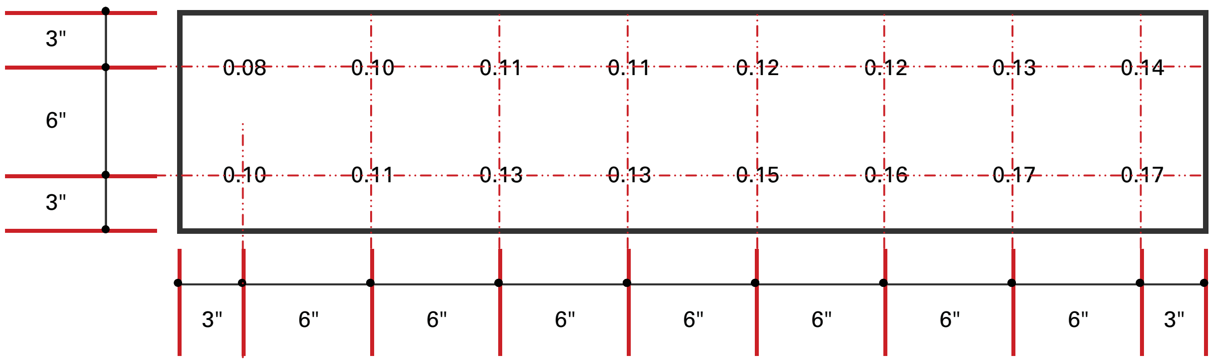
- Velocity pressure based measurement
- Thermal dispersion based measurement

### Velocity Pressure Based Measurement

Velocity pressure based flow measurement is a time-proven approach. When VAV fan systems first began to penetrate the commercial building market, velocity pressure based air flow measurement was the only practical method available for use. As a result, it is the predominant technology found on existing systems (frequently coupled with pneumatic sensing and control technology). The technology is also used in new systems but will typically be coupled with DDC technology, yielding superior results when contrasted with pneumatics.

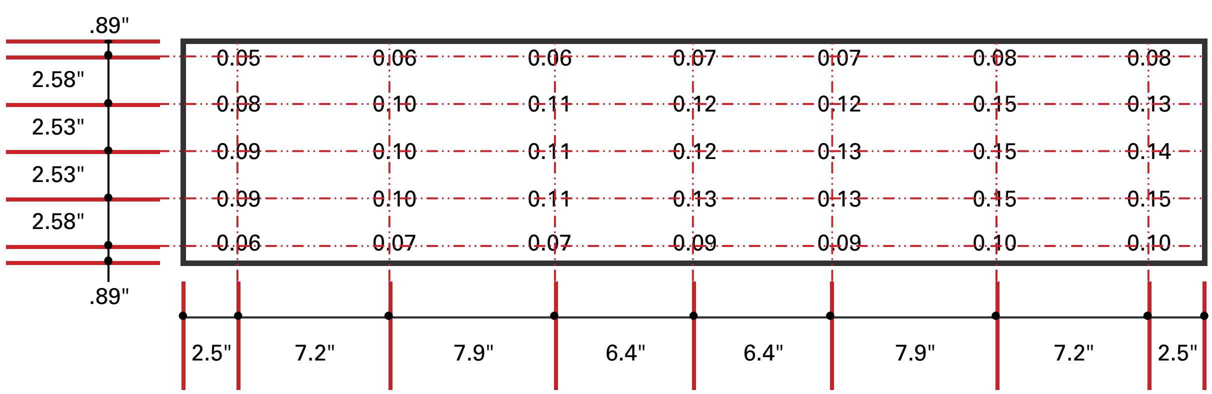
Velocity pressure based technology places a pitot tube array at the desired sensing location

*A 12″ x 48″ Duct Traversed by the Equal Area Method*




| Column | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Row 1 | Velocity Pressure, in.w.c. | 0.08 | 0.10 | 0.11 | 0.11 | 0.12 | 0.12 | 0.13 | 0.14 |
| | Velocity, fpm | 1,160 | 1,241 | 1,316 | 1,352 | 1,387 | 1,387 | 1,455 | 1,519 |
| Row 2 | Velocity Pressure, in.w.c. | 0.10 | 0.11 | 0.13 | 0.13 | 0.15 | 0.16 | 0.17 | 0.17 |
| | Velocity, fpm | 1,264 | 1,346 | 1,423 | 1,460 | 1,531 | 1,599 | 1,665 | 1,665 |
| Duct cross-sectional area | | 4.00 square feet | | | | | | | |
| Average velocity pressure | | 0.13 inches water column | | | | | | | |
| Velocity based on average VP | | 1,430 feet per minute | | | | | | | |
| Average velocity | | 1,423 feet per minute | | | | | | | |
| Flow | | | | | | | | | |
| Average velocity pressure basis | | 5,721 cubic feet per minute | | | | | | | |
| Average velocity basis | | 5,693 cubic feet per minute | | | | | | | |

*A 12″ x 48″ Duct Traversed by the Log-Tchebycheff Method*




| Column | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| Row 1 | Velocity Pressure, in.w.c. | 0.05 | 0.06 | 0.06 | 0.07 | 0.07 | 0.08 | 0.08 |
| | Velocity, fpm | 887 | 948 | 1,006 | 1,060 | 1,060 | 1,161 | 1,112 |
| Row 2 | Velocity Pressure, in.w.c. | 0.08 | 0.10 | 0.11 | 0.12 | 0.12 | 0.15 | 0.13 |
| | Velocity, fpm | 1,162 | 1,241 | 1,314 | 1,384 | 1,397 | 1,526 | 1,463 |
| Row 3 | Velocity Pressure, in.w.c. | 0.09 | 0.10 | 0.11 | 0.12 | 0.13 | 0.15 | 0.14 |
| | Velocity, fpm | 1,179 | 1,257 | 1,331 | 1,407 | 1,434 | 1,561 | 1,499 |
| Row 4 | Velocity Pressure, in.w.c. | 0.09 | 0.10 | 0.11 | 0.13 | 0.13 | 0.15 | 0.15 |
| | Velocity, fpm | 1,187 | 1,265 | 1,338 | 1,421 | 1,460 | 1,573 | 1,543 |
| Row 5 | Velocity Pressure, in.w.c. | 0.06 | 0.07 | 0.07 | 0.09 | 0.09 | 0.10 | 0.10 |
| | Velocity, fpm | 970 | 1,033 | 1,092 | 1,175 | 1,227 | 1,277 | 1,252 |
| Duct cross-sectional area | | 4.00 square feet | | | | | | |
| Average velocity pressure | | 0.10 inches water column | | | | | | |
| Velocity based on average VP | | 1,277 feet per minute | | | | | | |
| Average velocity | | 1,390 feet per minute | | | | | | |
| Flow | | | | | | | | |
| Average velocity pressure basis | | 5,106 cubic feet per minute | | | | | | |
| Average velocity basis | | 5,559 cubic feet per minute | | | | | | |

*Figure 3-1. An Equal Area and Log-Tchebycheff Traverse of the Same Duct*

and utilizes the array to measure the velocity pressure of the air stream. Velocity pressure is then converted to velocity by the control system and then multiplied by the duct area at the sensing location to obtain a flow rate.

One of the most significant limitations of this technology is signal degradation that occurs at high turn-downs due to "square law" effects, as mentioned under *Flow Measurement Application Considerations*. Turbulence can also have a significant negative impact on velocity based measurements because the measurements assume that the velocity vector in the measured flow is absolutely perpendicular to the measuring element. Turbulence introduces a variable that undermines this assumption on two fronts.

- The flow eddies associated with turbulent flow cause the flow at the sensing element to be less than perpendicular to the element. As a result the true velocity pressure may not be measured.
- The turbulent flow patterns themselves vary with time and system flow. As a result the irregularities mentioned in the previous bullet also vary with time and load condition.

Most manufacturers of sensing arrays have developed proprietary total and static pressure sensing arrangements that can mitigate some of the effects of minor turbulence.

### Thermal Dispersion-Based Measurements

Thermal dispersion based flow measuring elements operate based on the relationship between flow and convective heat transfer. There are two general approaches in common use:

- The amount of current required to maintain a heated wire at a constant temperature as flow varies is measured and used as an indication of flow.
- Two temperature sensing elements are located in the air stream to be measured. One is heated and one is not heated. The difference in temperature between the two elements as flow varies is an indication of flow rate.

This technology has the advantage of providing a signal that is a linear function of flow and of being sensitive to low flow rates. Thus it is better suited to systems with high accuracy and large turn down requirements. The technology is historically more costly than velocity pressure based approaches, but advances in electronics and the broader application of the technology are driving the cost down. In addition, when the true costs of obtaining a robust, reliable velocity pressure based flow measurement are considered, thermal dispersion technology may be more cost effective than it appeared when first considered.

Like velocity pressure based measurements, the technology is also susceptible to the effects of turbulence, but for a different reason. For thermal dispersion sensors, turbulence can impact the heat transfer coefficient and thus the basis of the measurement. This means that fittings located in the immediate vicinity of a thermal dispersion sensor can cause it to read high because the turbulence they create increases the heat transfer from the sensing element relative to the conditions that exist without the fitting, which are typically the basis for calibration. As a result, most thermal based sensors have straight duct installation requirements similar to those associated with velocity pressure based sensors.

At least one manufacturer has exploited the sensitivity of thermal dispersion technology to turbulence by developing a sensor configuration that produces a predictable level of turbulence at the sensing element in excess of what would be caused by a duct obstruction. As a result, their sensor is relatively immune to the effect of fittings in the immediate vicinity and requires much less straight duct to produce an accurate flow reading.

### Loss of Input Failure Mode

One of the more common failure modes for any control system is a loss of input. In the case of a flow tracking based control strategy, a loss of the input measuring return fan flow would typically look like a condition where the control point (supply to return flow differential) had increased above set point. This would cause the return fan to run up to full speed, regardless of the requirements of the system. For this reason, over-pressurization safeties like limit switches, static pressure switches, and pressure relief doors may merit additional consideration for application with this strategy when contrasted with strategies like building static pressure control where a loss of input will cause the fan to go to minimum speed. Additional discussion on these safety interlocks can be found in *Chapter 1: Introduction and Fundamentals*.

## Control System Considerations – Software

Points lists, narrative sequences and logic diagrams are important tools to convey design intent to the implementing and operating staff. These topics are discussed in *Chapter 1: Introduction and Fundamentals* and *Appendix 5: Return Fan Control System Hardware and Software Issues*. The following information applies specifically to this strategy.

### *Converting Velocity Pressure to Flow*

The equation used to convert velocity pressure to flow is illustrated in Equation 3-1.

$$V = 4{,}005\sqrt{P_V}$$

Where:

$V$ = Velocity in feet per minute

$4{,}005$ = A units conversion constant suitable for typical HVAC applications. For absolute accuracy, this constant should be adjusted for the temperature and barometric pressure at the test point.

$P_V$ = Velocity pressure in inches water column

*Equation 3-1. The relationship between velocity and velocity pressure*

As discussed earlier under *Flow Traverse Grid Methodology*, a duct traverse involves measuring *velocities* on a grid across the plane of the duct and then averaging the *velocities* to determine flow. The difference between averaging velocities and averaging velocity pressures is a subtle but important one that needs to be addressed when the actual parameter measured in the duct is velocity pressure.

Mathematically speaking, the velocity pressure based measurement of flow in a duct can be correctly assessed via Equation 3-2. Note that each of the velocity pressures is converted to velocity and then the velocities are averaged. This will not yield the same result as averaging the velocity pressures and then using the average velocity pressure to assess velocity and flow rate. The latter, incorrect calculation is illustrated mathematically in Equation 3-3 so that it can be contrasted with the correct approach illustrated in Equation 3-2.

The impact of using the wrong calculation technique can be observed by contrasting the flow calculated on an average *velocity pressure* basis with the flow calculated on an average *velocity* basis in Figure 3-1. The error increases as the number of measurement points increases. It will

$$Q = \left[\frac{\left(4{,}005\times\sqrt{P_{V1}}\right)+\left(4{,}005\times\sqrt{P_{V2}}\right)\ldots+\left(4{,}005\times\sqrt{P_{Vn}}\right)}{n}\right]\times A$$

$$= \left[\frac{V_1+V_2\ldots+V_n}{n}\right]\times A$$

Where:

$Q$ = Flow rate in cubic feet per minute

$\left(4{,}005\times\sqrt{P_{V1}}\right) = V_1$ = Velocity in feet per minute, calculated from velocity pressure per Equation 3-1

$n$ = The number of sample points in the traverse grid

$A$ = Duct cross-sectional area at the traverse location in square feet

*Equation 3-2; Correctly Assessing Flow via a Traverse Measuring Multiple Velocity Pressures*

$$Q = 4{,}005\times\sqrt{\frac{\left(P_{V1}+P_{V2}\ldots+P_{Vn}\right)}{n}}\times A$$

Where:

$Q$ = Flow rate in cubic feet per minute

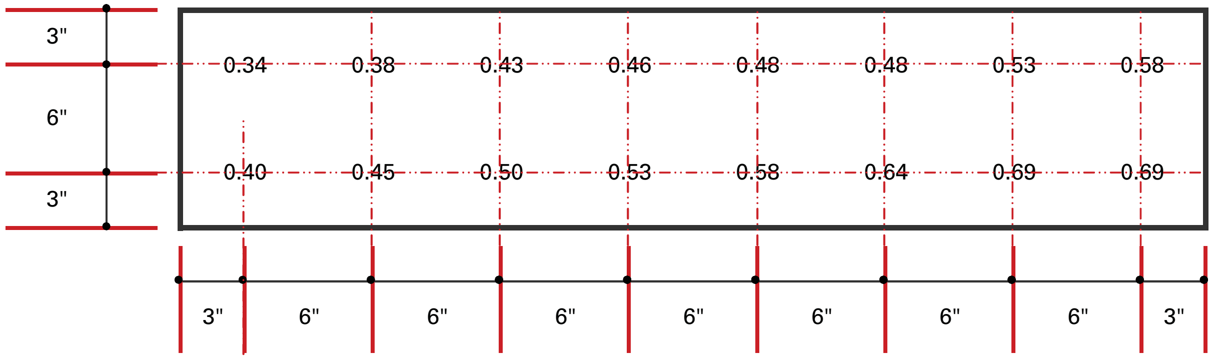
$P_{Vn}$ = Velocity in inches water column measured at each traverse point

$n$ = The number of sample points in the traverse grid

$A$ = Duct cross-sectional area at the traverse location in square feet

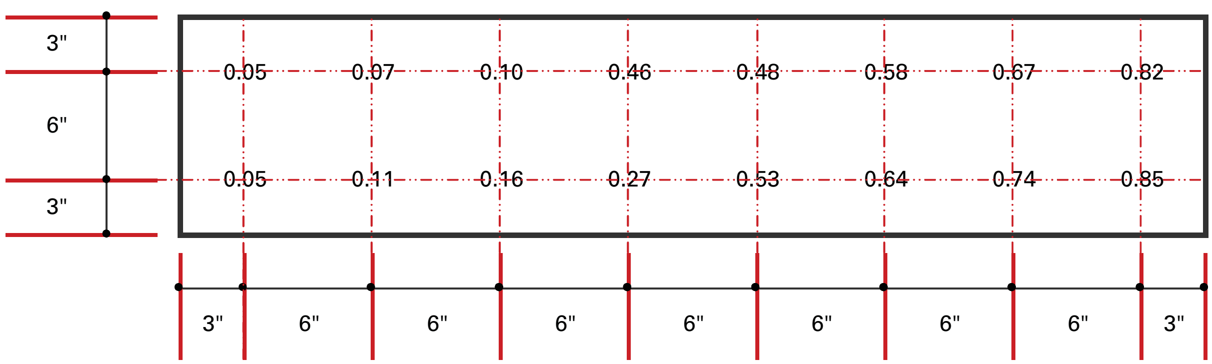
*Equation 3-3; Incorrectly Assessing Flow via a Traverse Measuring Multiple Velocity Pressures*

*The Figure 3-1 duct with a flow increase simulated .*




| Column | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Row 1 | Velocity Pressure, in.w.c. | 0.05 | 0.07 | 0.10 | 0.46 | 0.48 | 0.58 | 0.67 | 0.82 |
| | Velocity, fpm | 877 | 1,074 | 1,241 | 2,704 | 2,774 | 3,039 | 3,282 | 3,617 |
| Row 2 | Velocity Pressure, in.w.c. | 0.05 | 0.11 | 0.16 | 0.27 | 0.53 | 0.64 | 0.74 | 0.85 |
| | Velocity, fpm | 923 | 1,306 | 1,599 | 2,065 | 2,920 | 3,199 | 3,455 | 3,694 |
| Duct cross-sectional area | | 4.00 square feet | | | | | | | |
| Average velocity pressure | | 0.41 inches water column | | | | | | | |
| Velocity based on average VP | | 2,565 feet per minute | | | | | | | |
| Average velocity | | 2,361 feet per minute | | | | | | | |
| Flow | | | | | | | | | |
| Average velocity pressure basis | | 10,260 cubic feet per minute | | | | | | | |
| Average velocity basis | | 9,442 cubic feet per minute | | | | | | | |

*The Figure 3-1 duct with additional velocity profile distortion and increased flow simulated.*




| Column | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Row 1 | Velocity Pressure, in.w.c. | 0.34 | 0.38 | 0.43 | 0.46 | 0.48 | 0.48 | 0.53 | 0.58 |
| | Velocity, fpm | 2,321 | 2,481 | 2,632 | 2,704 | 2,774 | 2,774 | 2,909 | 3,039 |
| Row 2 | Velocity Pressure, in.w.c. | 0.40 | 0.45 | 0.50 | 0.53 | 0.58 | 0.64 | 0.69 | 0.69 |
| | Velocity, fpm | 2,529 | 2,692 | 2,846 | 2,920 | 3,063 | 3,199 | 3,329 | 3,329 |
| Duct cross-sectional area | | 4.00 square feet | | | | | | | |
| Average velocity pressure | | 0.51 inches water column | | | | | | | |
| Velocity based on average VP | | 2,860 feet per minute | | | | | | | |
| Average velocity | | 2,846 feet per minute | | | | | | | |
| Flow | | | | | | | | | |
| Average velocity pressure basis | | 11,442 cubic feet per minute | | | | | | | |
| Average velocity basis | | 11,385 cubic feet per minute | | | | | | | |

*Figure 3-2. The impact of higher velocities and distorted flow profiles on the error created by using average velocity pressure instead of velocity to assess flow.*

also increase with increasing velocity and can be especially significant if the flow profile is distorted as is illustrated in Figure 3-2, which simulates the effect of higher flow rates and a distorted flow profile on the readings taken in the Figure 3-1 duct.

The bottom line is that the designer should specify the calculation technique that is to be used for calculating velocity and then verify that this has been properly implemented in the installed system to ensure the best possible results. Related to the calculation is a hardware issue that will be discussed in the next section.

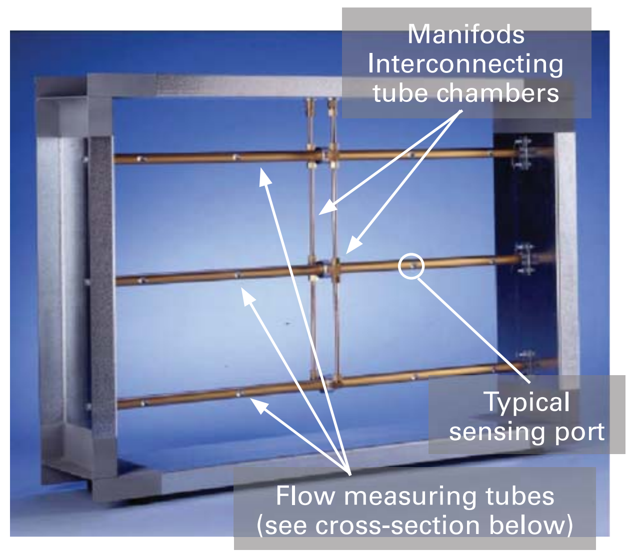
## Measuring Velocity at Multiple Points

The issues discussed in the preceding section are primarily software issues in current technology systems; i.e., the conversion of velocity pressure to velocity and the calculation of flow typically occur in the DDC system software and/or in the firmware of the transmitters used to provide inputs to the system. However, it is important to realize that the configuration of hardware used to extract the information from the air stream can have an impact on the calculation similar to that described in the preceding section.

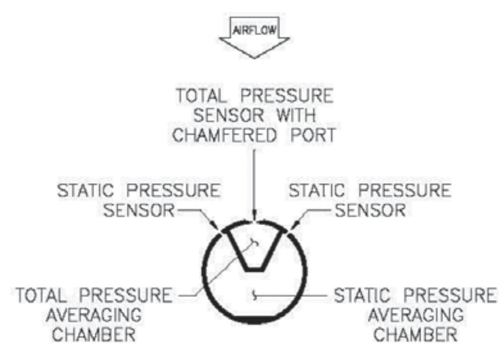
To understand these hardware based impacts, consider the physical construction of a typical flow traverse station as illustrated in Figure 3-3.Note that the array is constructed from multiple tubes with a cross section as illustrated. Each tube has multiple ports, all of which are interconnected by the chamber to which they are referenced. As a result:

- The pressure in each chamber reflects the effect of the pressures at all of the sensing ports associated with it.[1]
- In the array shown, the pressure in the two chambers in each tube reflect static and total pressures influenced by all of the static and total pressure ports in the tube rather than individual values for each port.
- If the flow tubes are interconnected with a manifold, as is the case in the illustration, then the static and total pressures measured at the manifold connections reflect values influenced by all of the ports and all of the tubes rather than individual values for each port.

The manufacturer's literature indicates that the ports on the device pictured are spaced on an equal area basis. But, because the velocity calculated from the measured parameter is based on the aggregated effect of the pressures seen by all of the ports on the array, it may not reflect the result that would be achieved with an actual, point by point equal-area based traverse. Rather, it most likely reflects something along the lines of the result that would be achieved by a calculation based on average velocity pressure rather than average velocity.




*Air flow measuring assembly*




*Typical flow measuring tube cross-section*

*Figure 3-3. Construction features of a typical velocity pressure type flow traverse station (Courtesy www.AirMonitor.com)*

[1] This has the effect of quasi-averaging the pressures but probably is not a true average. In theory, if there are different pressures present at each of the ports, then there will be some flow between the ports with higher pressures and the ports with lower pressures. If there is flow in the chamber, then there will be pressure drop related to that flow, which will be reflected in the pressure measured in the chamber.

Most manufacturers provide calibration information for their equipment, including a guarantee of their stated accuracy if the equipment is properly applied. The manufacturer of the equipment used in the illustration certifies their equipment per AMCA Publication 611 and the AMCA Certified Ratings Program and provides the sample test data demonstrating such, as is illustrated in Figure 3-4.

**Test Results – Rectangular Stations**

| Reference Volume, ACFM | Reference Velocity, AFPM | % Accuracy | Airflow Resistance IN w.c. |
|---|---|---|---|
| 35,134 | 4,015 | 0.53 | .082 |
| 31,391 | 3,488 | 0.45 | .064 |
| 26,018 | 2,891 | 0.39 | .044 |
| 19,456 | 2,162 | 0.23 | .028 |
| 13,971 | 1,552 | 0.10 | .013 |
| 8,832 | 981 | –1.40 | .005 |

*Figure 3-4 – Certification test data for the flow measuring station illustrated in Figure 3-3. (Courtesy www.AirMonitor.com)*

Thus, if:

- the equipment is applied within the application constraints defined by the certification procedure and the manufacturer, and;
- the certified accuracy of the measured signal, when combined with the impact of other elements in the signal chain, is satisfactory for the needs of the project;

then satisfactory results can be anticipated.

The bottom line is that the significance of the detail under discussion (and others like it) will vary from project to project. In the end, most engineering solutions are the result of compromises from perfection that are made based on the requirements of the project, the capabilities of the operating team, the available budget and the limitations of the technology to be applied. Compromises that yield acceptable results on one project may yield totally unacceptable results on a different one. By understanding the details of a given technology and their implications when the technology is applied, a designer can make an informed decision, compromising where appropriate while applying rigorous technical solutions where necessary.

In the case of our example, there are a number of ways to deal with the impact of the manifolds interconnecting the sensing points.

- *Use the Assembly as Shown*: If the project's requirements and parameters are such that the certified accuracy is acceptable and the product can be applied as necessary to ensure the certified accuracy, then using the product should provide acceptable results. One example of such a situation might be an office building air handling system of modest complexity with a modest turn down requirement, space for the necessary straight ductwork required for accuracy, and a low velocity duct system.
- *Provide Independent Pressure Sensors for Each Flow Tube*: Providing one sensor per flow tube instead of one sensor per assembly may improve the accuracy of the system because the result would more closely approach the result achieved from a true pitot tube traverse. However, unless one flow tube were provided for each measuring point (12 sensors for an array with an equivalent number of ports to the one shown in Figure 3-3), the result will still be theoretically un-equivalent to a true traverse. And, the addition of pressure sensors can drive the project costs upward quickly due to the direct sensor costs and the additional I/O requirement they represent at the DDC system controller.
- *Consider an Alternative Technology*: Thermal dispersion based measurement provides an alternative to the velocity pressure based approach associated with our example. (This technology is described earlier in the chapter under *Thermal Dispersion Based Measurements*). One advantage of thermal dispersion is that the data from each sensor in the array is a reflection of velocity rather than velocity pressure. As a result, averaging the output from each sensor simply averages velocity, an approach that duplicates the technique used for a pitot tube traverse. Some of the thermal dispersion products currently offered perform this averaging process in their electronics package, providing a single output that truly reflects the average velocity seen by the array.

### Control System Points List

The example provided at the end of this chapter can be edited to meet the needs of a project using flow tracking for return fan control. Editing considerations should include:

- Coordination with the requirements of the narrative sequence and any logic diagrams.
- Clarification regarding the technique used to traverse the duct at the flow measurement locations, including sensing technology, velocity calculation and averaging technique, traverse grid requirements, end-to-end accuracy requirements, and turn-down capabilities.
- Clarification regarding the hardware requirements of any additional safeties provided to protect the system for a loss of input from the return fan discharge static pressure sensor.

### *Narrative Control Sequence*

The example provided at the end of the chapter can be edited to meet the needs of a project using flow tracking for return fan control. Editing considerations should include:

- Coordination with the requirements of the points list and any logic diagrams.
- Clarification regarding velocity calculation and averaging techniques and requirements.
- Clarification regarding system turn-down requirements.
- Clarification regarding the operation of any additional safeties provided to protect the system for a loss of input from the return fan discharge static pressure sensor.
- Clarification regarding the supply to return flow differential that will be maintained; i.e., is it fixed under all operating conditions or does the set point change as a function of an operating parameter?

Irrespective of the exact flow differential requirements, using the fan sheaves to set the differential for the design operating point with the variable speed drive operating at 100% speed will optimize overall efficiency and controllability as discussed in *Appendix 6: Electrical and Drive System Considerations* under *Maximizing Efficiency*. This contingency can be addressed in the narrative sequence, but should also be noted in the commissioning and testing and balancing section of the specification to ensure it is accommodated by all trades working on the project.

### Air Handling System Considerations

Many of the air handling system considerations discussed in *Chapter 1: Introduction and Fundamentals* apply to this strategy, including:

- Economizer damper selection, sizing, and installation.
- Return flow path versus relief flow path pressure losses.
- Integration with HVAC system and building functions and processes including building and zone level pressurization and minimum outdoor air flow regulation.

### Electrical System Considerations

Many of the electrical system considerations discussed in *Chapter 1: Introduction and Fundamentals* apply to this strategy including:

- Variable speed drive application, networking, and interlock issues.
- Motor selection and application issues.

## 3.6 Key Installation Issues and Considerations

Many of the design issues discussed in the preceding section and the operating issues discussed in the next section have a direct bearing on system installation. Therefore, reviewing the design intent for the strategy and its operating requirements is a crucial step in successfully installing and starting up the system. *Appendix 7: The Relationship Between Design, Installation and Operation* includes a discussion of a general nature on this topic. The information in this chapter is particular to flow tracking strategies.

To ensure overall success on all fronts, the design issues must be complemented by field efforts focused on the issues discussed in the following paragraphs.

### Adequate Equipment Procurement

A thorough shop drawing review process can go a long way toward ensuring that the design intent is reflected in the equipment provided. A discussion of important areas to target is included in *Chapter 1: Introduction and Fundamentals* under The Relationship Between Design, Installation, and Operation.

Of particular importance to flow tracking strategies is the equipment used to measure flow. Substitutions that appear to be equivalent on the surface may turn out to be significantly different when subject to scrutiny. For example, a velocity pressure based sensing array that has been proposed as a substitution for a thermal dispersion based array may appear to have similar number of sensing points, grid arrangement, and accuracy. However, a thorough review of the proposed substitution may reveal that:

- Accuracy statements for the velocity pressure based array are in terms of percent of full scale while accuracy statements for the thermal dispersion array are in terms of percent of reading.
- Accuracy statements for the velocity pressure based array do not include the effects of the transducers used to convert velocity pressure to velocity while the accuracy statements for the thermal dispersion array reflect an output that is proportional to velocity.
- The velocity pressure based array may quasi-average a number of velocity pressure points for conversion to velocity while the thermal dispersion array averages a velocity reading for each point.
- The velocity pressure based array may require longer lengths of straight duct to achieve its rated accuracy when contrasted with the thermal dispersion based device. Increasing the amount of straight duct run can be difficult to accomplish in the field and may add cost.
- The velocity pressure based array may require flow straightening elements to work with the available straight duct lengths provided for a thermal based array. The flow straighteners may represent an added first cost for the component as well as an ongoing operating cost due to the pressure loss associated with them. In addition, the pressure loss may tax the capabilities of the fans selected for the project if it is significant enough.

The technical details behind the issues outlined above are discussed in detail in *Section 2.5 - Key Design Issues and Considerations*. From the installation standpoint, understanding the technical details is not as important as recognizing that substituting one flow measuring technology for another may cause a significant deviation from the design intent which will manifest itself as a start-up and operational problem.

## Locating and Installing Sensors in the Field

Flow tracking control strategies are highly dependent on accurate, reliable, repeatable, robust flow measurement for success. And, as was discussed in *Section 2.5 - Key Design Issues and Considerations*, flow measurement is dependent on a uniform velocity profile. Typically, this is ensured by providing adequate straight duct sections at the sensor location on the drawings by the designer. If provisions of this type have not been directly addressed by the design documents, then field coordination with the designer will be necessary to correctly identify proper sensor location.

Occasionally construction changes or other physical constraints identified during installation may prevent a system from being installed exactly as shown on drawings. Again close coordination with the designer is necessary to determine an acceptable solution. For example, the addition of a straightening vane assembly may be appropriate in situations where ideal duct configuration simply cannot be achieved. Coordinating such a field modification with the designer will ensure that the added pressure drop associated with the straightening vanes will not over-burden the fan system.

Flow sensors can be particularly sensitive to orientation, particularly orientation relative to the direction of flow. Be sure to mount the sensor per manufacturer's recommendations and use the manufacturer's jigs if necessary to ensure proper alignment.

Vibration can also be problematic for sensors and is another area where flow sensors can be particularly prone to problems. For example, mounting a sensor or transmitter on the side of a duct that is vibrating significantly ("drumming") may lead to inaccurate measurements.

Additional general information regarding sensor installation is discussed in *Chapter 1: Introduction and Fundamentals* under *Hardware Issues*.

## Duct and Envelope Leakage Impacts

Supply duct leakage may impact the amount of air delivered to the respective spaces served by the HVAC system and disrupt the balance between ventilation, exhaust, and building pressure. This is especially true if the leakage occurs downstream of the supply flow measurement. In this case, the return fan may remove more air from the space than is appropriate because it is controlling based on the measured supply flow versus the delivered supply flow (measured flow minus the leakage downstream of the flow measuring station). Systems designed to measure supply flow at the zone level may be less susceptible to control problems of this type. But, such an approach does not overcome the waste of conditioned air and fan energy associated with duct leakage.

A similar concern pertains to return duct or plenum leakage if total flow is measured close to or directly at the return fan. For example if outside air from an adjacent plenum is drawn into the return plenum through a leak, then:

- the measured flow may not reflect the true return flow from the space.
- the ventilation/exhaust/pressure balance will be altered but may not be reflected in return fan control.

Finally, the integrity of the building envelope can have a significant impact on the performance of this strategy. Operable windows can also have a significant impact as described in *Appendix 7: The Relationship Between Design, Construction, and Operation*.

### Velocity Pressure Probe Contamination

Frequently, the sensing orifices on the probes used to measure velocity pressure are relatively small and susceptible to obstruction, especially if they are in an unfiltered air stream like the return or exhaust air. This can also be a problem in new construction if due diligence has not been paid to protecting the duct systems from construction debris and/or systems have been operated temporarily without adequate filtration.[1] Cleaning sensing arrays is discussed in *Section 3.7 - Key Operating Issues and Considerations*.

### Pre-start and Start-up Checklist Considerations

The pre-start and start-up considerations for flow tracking strategies are no different from the general requirements for any other strategy. See *Chapter 1: Introduction and Fundamentals* under *The Relationship Between Design, Installation, and Operation* for additional information.

### Testing Considerations

Usually, setting up the system and testing it involves close coordination between the mechanical contractor, the controls contractor and the balancing contractor to tune the drives, the fan speeds and the flow differential settings. A detailed description of the considerations and test process can be found in *Appendix 4: Tuning Minimum Outdoor Air Flow*. Typically, the ultimate goal of the testing process is to determine the appropriate flow differential set point or set points required to ensure adequate minimum outdoor air flow under all operating conditions. Bear in mind that the IEQ and efficiency benefits associated with multiple flow differential set points testing will only be realized in a system that is capable of varying the minimum outdoor air quantity in a repeatable reliable manner. Lacking such a capability, the system should be set for the flow differential that meets the highest minimum outdoor air requirement and then tested to ensure that this requirement is achieved under all operating modes.

## 3.7 Key Operating Issues and Considerations

Many of the issues discussed in the preceding paragraphs in terms of design and installation will ultimately become operational issues. Reviewing and understanding key design and implementation issues will allow the operating staff to develop an understanding of the design intent for the strategy and its implementation. This can be a crucial step in successfully operating a system regardless of the control approach employed. *Appendix 7: The Relationship Between Design, Installation and Operation* includes a discussion of a general nature on this topic. The information in this chapter is particular to flow tracking strategies.

### Operating and Monitoring the Process

The troubleshooting table, control sequence, and points list included at the end of this chapter will provide a good starting point for developing an understanding of the operating details associated with this strategy. In addition, they illustrate

[1] Frequently, the dust generated by drywall sanding operations, terrazzo and concrete grinding operations or other construction activities is finer than the dust that will be encountered by the system under normal operation and for which the filters were selected. *The Functional Testing Guide* listed in the reference section contains additional information on filtration and other issues associated with temporary operation.

where the operating staff interfaces with the control system to adjust and monitor it. Additional information applicable to the operation of all return fan control strategies can be found in *Appendix 7: Design, Installation and Operation*.

Air handling systems that employ flow tracking strategies are particularly prone to problems created by additions, renovations or changes to adjacent spaces or the building envelope. In general terms, any modification or change:

- that allows air that would normally be returned to exit the area served by some other path; or
- that allows air from some other source to enter the return system and be measured as part of the system return air; or
- that diverts supply air down stream of the flow measuring station to an area not served by the associated return fan;

will invalidate the flow differential set point or set points originally identified for the system. As a result, minimum outdoor air flow and pressurization problems will be created as the return fan attempts to control at a flow differential that is no longer correct.

Many of the concepts discussed in *Appendix 4: Tuning Outdoor Air Flow to Design Specifications* will prove useful for the operating staff as they tune the system to the changing requirements of the area it serves.

### Velocity Pressure Probe Contamination

As mentioned in *Section 3.6 - Key Installation Issues and Considerations*, the orifices in the sensing arrays can become plugged with contaminants over time, especially in unfiltered air streams. Experience has shown that occasional inspection and cleaning may be required. One common approach used to accomplish this is to blow the tubing and manifolds out with compressed air. When using this approach, caution should be exercised:

- Signal transmitters should be disconnected from the manifold because they will not tolerate the pressures generated by the compressed air.
- By design, the tubing, extrusion, and fittings used to fabricate the sensing manifolds only see pressures in the inches of water column range. While the materials and assemblies used can probably tolerate pressures that are much higher than that, it would be prudent to regulate the pressure used to 10-15 psig or less. If there is a question about pressure tolerance, the manufacturer should be consulted.

The "canned air" sold by office supply stores for cleaning out computer keyboards and circuit boards offers another alternative for blowing out sensing arrays that is less likely to cause damage. However, even with this approach, the transmitters should be disconnected from the array during the cleaning operation.

### Legacy Systems with Pneumatic Controllers and Calculation Relays

Operators and commissioning providers dealing with existing flow tracking systems may find themselves confronted with a bewildering array of pneumatic instruments. Implementing flow tracking control via pneumatic technology can be a complex control problem involving pneumatic relays performing functions like square root extraction, addition, and signal selection. The problem is compounded by the problems associated with measuring and transmitting the very low velocity pressures produced in a typical system at low flow rates via a mechanical means. Reliable operation of this technology is absolutely dependent upon frequent calibration and maintenance of the pneumatic technology. Annual inspection, adjustment and calibration by a qualified service technician should be considered a minimum requirement with three to six month inspection intervals warranted in applications where the performance of the technology is critical to the loads served and/or IEQ.

Given the significant improvements in performance and persistence of accuracy that can be obtained via current technology sensing systems when combined with DDC, existing pneumatic flow control technology should be targeted for upgrade as soon as practical. If a full upgrade of the building or system to DDC is not warranted or deemed viable in the immediate future, simply upgrading the portion of the system that measures and controls flow to eliminate the pneumatic transmitters, calculation relays, and controllers can often be justified in terms of reduced maintenance and improved performance and reliability.

If the existing pneumatic technology must be retained, then process grade repair/replacement parts should be considered when the need arises.

## 3.8 Troubleshooting Table

While not all inclusive, this table illustrates many of the more common problems that can occur with a flow tracking return fan control strategy and the associated corrective actions. Some troubleshooting issues will be general in nature while others will be specific to a particular system by virtue of the control sequence and wiring configuration associated with it. The following table is based on the system illustrated at the beginning of the chapter with a control sequence as described in *Section 3.10 - Sample Narrative Sequence of Operations*.

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Fails To Start | Loss of Power | • Verify the integrity of the power supply from the motor back to the source. If tripped circuit breakers or blown fuses are encountered, determine and correct the cause of the fault prior to restoring power. |
| | Interlock Problem | • After verifying that the fan can be safely run alone, switch the fan to "Hand" and observe the results.<br>■ If the fan still fails to start, the problem is most likely in the safety interlock circuit (fire alarm, relay, smoke detector, etc.). Investigate and correct interlock problems in the safety interlock circuit associated directly with the return fan.<br>■ If the fan runs, the problem is most likely in the interlocks associated with scheduled operation of the fan and other automation requirements. Verify the controlling software that cycles the fan in the "Auto" mode as well as any hardwired interlocks with other equipment like the supply fan. A safety trip that is preventing a supply fan start (freezestat, static switch, smoke detector, etc.) could prevent a return fan start if the return fan is interlocked via hardwiring or software to only run when the supply fan runs.<br>• If the fan fails to run in "Hand" or "Auto" and the drive is equipped with a "Bypass" option, switch the fan to "Bypass" after verifying that it is safe for the fan to run at full speed.<br>■ If the fan starts and runs in bypass, the problem is most likely in the VSD itself (see below).<br>■ If the fan fails to start in the bypass mode, the problem is probably one of the other issues listed in this table. |
| | VSD Failure | • Verify the integrity of the drive circuitry using the manufacturer's troubleshooting guidelines as published in the operation and maintenance manual. |
| | Drive System Failure | • Verify the integrity of the drive belts and sheaves or couplings. |

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Fails To Start (cont'd) | Motor Failure | • Verify that proper voltage exist at the motor terminals on all phases.<br>• Isolate the motor from the power system and all controllers, drives, starters, etc.<br>■ Spin the motor shaft by hand to assess the integrity of the bearings. The shaft should spin freely and smoothly. Investigate and correct any unusual noise, jams or restrictions to free movement.<br>■ Inspect the motor connections for security and signs of overheating or resistive connections. Correct any discrepancies found.<br>■ Megger test the motor to measure the insulation resistance to ground. Correct any grounded conditions before reapplying power to the motor. Usually this will involve removing the motor and sending it out for repair.<br>• If the motor spins freely, the connections are good, and there are no grounds, cautiously reapply power (monitor the inrush current during this process) and verify:<br>■ The motor starts and comes up to speed.<br>■ The motor inrush current drops off as the motor comes up to speed.<br>■ The current on all phases is balanced and does not exceed the motors nameplate rating.<br>• If the motor currents are over nameplate disconnect the load and restart the motor. Verify the following:<br>■ No-load motor amps are approximately 50 to 70% full load amps for 900 – 1200 rpm motors (Some may be higher), approximately 30% full load amps for 1800 rpm motors and are approximately 20 to 30% full load amps for 3600 rpm motors. If the no load currents are balanced and within the limits listed above, the motor is probably being overloaded (see below).<br>■ If the no-load currents are out of balance or exceed the limits listed above, the motor windings are probably shorted and the motor will need to be removed and repaired.<br>• If the motor currents are severely imbalanced (in excess of 10% different) check the following:<br>■ Verify that the voltage supplied to the motor is within 5% of the line voltage rating. Investigate and correct the cause of any observed low voltage condition.<br>■ Verify that the phase to phase voltages are balanced and are within 5% of the line voltage of each other. If the phase voltages are balanced but the currents are imbalanced, there is probably a short in the motor winding and the motor will need to be removed and repaired. |

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Fails To Start (cont'd) | Overload Trip | • If a new motor has been installed on the fan, verify that the moment of inertia rating ($WR^2$) of the new motor is equal to or better than the motor it replaced (see *Appendix 6: Electrical and Drive System Considerations* for additional information.)<br>• Verify that the wiring connections to the overload relay are tight. Loose wiring connections represent a resistive load that can generate heat and trigger a false overload trip.<br>• Inspect and clean the fan wheel as necessary. Dirt on the fan wheel increases its moment of inertia and can cause start-up problems to "suddenly" appear in a fan that has been running satisfactorily (see *Chapter 1: Introduction and Fundamentals – Maintaining and Adapting Design Intent - Fan Wheel Cleanliness* for additional information.) |
| Return Fan Fails To Stop | Fan Remains in Operation Despite a Safety Trip That Should Directly Shut Down the Fan | • Safety trips intended to directly affect the return fan should shut down and lock out the fan irrespective of the position of any Hand-Off-Auto switches or Inverter-Bypass switches. If a fan remains in operation after a safety trip, investigate and correct problems in the safety interlock circuit. |
| | Fan Remains in Operation Despite a Supply Fan Shut Down Due to a Safety Trip | • Verify that the drive is in "Auto". If the drive is in "Auto" and continues to operate when it should be off, investigate and correct problems in the control logic associated with supply fan interlocks. |
| | Fan Remains in Operation When It Should Be Off Based on Schedule | • Verify that the drive is in "Auto". If the drive is in "Auto" and continues to operate when it should be off, investigate and correct problems in the control logic associated with the return fan start-stop functions. |
| Return Fan Speed Does Not Vary | Return Fan Speed Does Not Vary Despite Supply Fan Speed Variations | • If the return fan VSD is equipped with a bypass system, verify that the system is in "Inverter" (VSD active) and not "Bypass" (VSD bypassed and out of the circuit).<br>• Verify that the return fan VSD speed control selection is in the position that causes the drive to follow a remote speed command. Typically this is the "Auto Speed Command" position. This selection may be made via a selector switch or via a keypad, depending on the drive design, manufacturer, and vintage.<br>• Verify that the speed control signal is available at the return fan VSD input terminals.<br>• Verify that the differential flow set point or set points are as required to control the ratio of supply fan to return fan speed. The preliminary settings specified by the designer were most likely optimized and tuned to the installed system during the commissioning process. These settings should be reflected in the commissioning report. |

<table>
<tr><th>Symptoms</th><th>Possible Cause</th><th>Recommendation</th></tr>
<tr><td rowspan="2">Return Fan Speed Does Not Vary (cont’d)</td><td>Return Fan Speed Does Not Vary Despite Supply Fan Speed Variations</td><td><ul><li>Verify that the return fan is in fact moving air. One method of doing this is to take manual control of the fan speed and carefully ramp it up and down to see if the indicated flow rate changes. (Exercise caution to ensure that you don’t inadvertently create excessive building, zone or duct pressure relationships). If changes in speed do not produce flow or changes in flow, then the problem may be a belt failure or an issue with the return system that is affecting the return fan’s ability to move return air through the system like a closed fire damper. If the return fan is moving air, then the problem could be an issue related to the integrity of the return system, like an open service door after the flow measuring station, but ahead of the return fan which is allowing the fan to move a lot of air without measuring the air flow.</li><li>Verify that the supply flow is in fact varying with the changes in supply fan speed. There should be a fairly direct correlation between supply flow and supply fan speed. If there isn’t, investigate and correct. Possible issues include fire/ smoke dampers that should be open but are closed, problems with the coordination of the outdoor air and return air dampers associated with the economizer process, an erroneous supply fan speed signal, and belt failures.</li></ul></td></tr>
<tr><td>Return Fan and Supply Fan Speeds Do Not Vary</td><td><ul><li>Verify that the supply fan VSD is in “Auto” and not in a mode that would cause it to run at a fixed speed. If the supply fan is in “Auto” and its speed does not vary the problem could be:<ul><li>A problem in the supply fan speed control system or related logic. Detailed troubleshooting of the supply fan speed control system is beyond the scope of this guide, but in general terms the procedure will be similar to that described above under Return Fan Speed Does Not Vary Despite Supply Fan Speed Variations.</li><li>A load condition that exceeds the supply fan’s capacity may exist. This could be caused by a number of factors including a load condition in excess of design, a supply flow restriction, or conditions that have compromised the capabilities of the cooling or heating utility systems that condition the supply air (low refrigerant, high chilled water supply temperature, high cooling coil discharge air temperature, low heating coil discharge air temperature, low steam supply pressure, low hot water supply temperature, etc.). Troubleshooting of these issues is beyond the scope of this guideline.</li></ul></li></ul></td></tr>
</table>

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Speed Varies Under Some Operating Conditions, But Not Under Others | All issues listed under *Return Fan Speed Does Not Vary* | • Investigate and correct as described under *Return Fan Speed Does Not Vary*. |
| | The condition occurs during mild weather when the system is using a significant amount of outdoor air via its economizer cycle | • Look for alternative relief paths that could have been created by the building occupants like open operable windows on a nice day or doors propped open to facilitate a move. |
| Pressure Relationships are Overly Negative or Positive Either Relative to the Out-of-doors or Relative to Adjacent Areas | Minimum outdoor air damper properly sized, but the maximum outdoor air damper is oversized. | • Assess the damper performance characteristics under all operating modes. The minimum outdoor air/economizer damper system needs to represent a pressure drop that is significant relative to the system pressure drop under all operating conditions. Dampers that are properly sized when the system is at design flow may be marginal when the system has turned down to 50-75% of design capacity. |
| | Overly Negative or Positive Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling System | • Verify the integrity of the minimum outdoor air control system including that minimum outdoor air is being introduced into the system in the proper quantities.<br>• Verify that the economizer damper system is functioning properly including:<br>■ Maximum outdoor air, return air, and relief air dampers operate freely and through their full stroke<br>■ Maximum outdoor air, return air, and relief air dampers operate with the correct relationship to each other (return dampers close as the maximum outdoor air dampers open, etc.)<br>• Verify that any building pressure control components of the return fan/air handling system control process are functioning properly (if so equipped).<br>• Verify that the return fan flow differential set point or set points that control the ratio of return flow to supply flow are correct and as tuned during the commissioning process. See *Appendix 4: Tuning Outdoor Air Flow to Design Specifications* for information on making these adjustments if it is necessary to re-tune the system.<br>• Verify that the return fan sheave or motor sheave have not been replaced with new sheaves with a different pitch diameter than the sheaves that were installed when the system was commissioned and tuned.<br>• Verify that the pitch diameter on a fan or motor equipped with an adjustable pitch sheave has not changed. |

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Pressure Relationships are Overly Negative or Positive Either Relative to the Out-of-doors or Relative to Adjacent Areas (cont'd) | Overly Negative or Positive Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling System (cont'd) | • Determine if modifications or changes have been made to the building's envelope, functions, or occupancy patterns in the area served by the return fan and its related air handling system or system. Significant modifications in any of these areas may require re-assessment of the return fan capacity control system's differential flow set point or set points and/or re-tuning of the system's minimum outdoor air flow. See *Appendix 4: Tuning Outdoor Air Flow to Design Specifications* and *Appendix 8: Theoretical Versus Actual Performance* for additional information. |
| Minimum Outdoor Air Flow Does Not Meet Requirements | Minimum Outdoor Air Flow Problems Exist Regardless of the Operating Status of the Return Fan and its Related Air Handling System | • The issues in this category will be similar to the issues discussed above under *Overly Negative or Positive Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling System*. |
| | Minimum Outdoor Air Flow Problems Appears to be Related to the Operation of the Return Fan and its Related Air Handling System | • In small buildings or large complex buildings, problems with minimum outdoor air flow in one system may not manifest themselves as problems with pressure relationships in the building even though in theory, they should. For small buildings, this is usually because leakage rates between zones or through the envelope are large enough that they prevent the issue from showing up as a pressure relationship problem. In large complex buildings, the volume of the building or the interactions with other systems can mask the problem and prevent it from showing up as a pressure relationship issue. However, most of the issues are the same as those discussed above under *Negative or Overly Positive Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling System*. |

## 3.9 Sample Points List

The following tables illustrate a points list for the return fan in the system illustrated at the beginning of the chapter and can be used as a starting point for similar systems employing flow tracking control strategies. It was developed using the points list tool contained in the Control Design Guide. This publicly available resource can be downloaded from www.PECI.org/FTGuide and used to develop a points list with characteristics similar to those illustrated for an entire system or project.

| Point Name | Sensor Information | | |
|---|---|---|---|
| | System and Service | Sensor/Interface Device[6] | |
| | | Type | Accuracy |
| **Analog Inputs** | | | |
| AH1SVel | AHU 01 Supply Velocity | Thermal dispersion array | 3% of reading |
| AH1RVel | AHU 01 Return Velocity | Thermal dispersion array | 3% of reading |
| RF1SpdFb | AHU 01 Return Fan 1 Speed Control Feedback | VFD programmable output | +/-1.0%FS |
| RF1kW | RF1 kW | VFD programmable output | +/-1.0%FS |
| **Analog Outputs** | | | |
| RF1Spd | AHU 01 Return Fan 1 Speed Control Command | 4-20 ma output | +/-1.0%FS |
| **Digital Inputs** | | | |
| RF1POO | Return Fan 01 Proof of Operation | Current switch | N/A |
| RF1SSwSt | Return Fan 1 Selector Switch Status | Auxilliary contact | N/A |
| VFD1SSwSt | Supply Fan 1 VFD Selector Switch Status | Auxilliary contact | N/A |
| **Digital Outputs** | | | |
| AH1RFSS | AHU 01 Return Fan Start/Stop Command | Interface relay | N/A |
| **Virtual Points** | | | |
| AHU1SFlo | AHU 01 Supply Flow | Calculation based on measured velocity | N/A |
| AHU1RFlo | AHU 01 Return Flow | Calculation based on measured velocity | N/A |
| RF1Hrs | RF 01 Accumulated Hours of Operation | Calculation based on proof of operation input | N/A |
| RF1SpdPGn | RF1 Speed Control Loop Proportional Gain | Manually set | N/A |
| RF1SpdIGn | RF1 Speed Control Loop Integral Gain | Manually set | N/A |
| RF1SpdDGn | RF1 Speed Control Loop Derivative Gain | Manually set | N/A |
| AHU1FDMx | AHU 01 Supply/return flow differential set point, all zones occuppied | Manually set | N/A |
| AHU1FDMn | AHU 01 Supply/return flow differential set point, Z1-4 only occuppied | Manually set | N/A |
| **Hard Wired Points** | | | |
| RF1Fire | RF 01 Fire Alarm Shut Down Relay | Relay by fire alarm contractor | N/A |
| AH1VFDAux | AH1 VFD Auxilliary Contact | Auxilliary contact | N/A |

| Point Name | Alarm and Trending Information, General Notes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Features | | | | | | | | | | | Notes |
| | Alarms | | | | Trending | | | | | | | |
| | Limit | | Warning | | Samples[1] | Commissioning[5] | | | Operating[5] | | | |
| | Hi | Lo | Hi | Lo | | Time[2] | Local[3] | Archive[4] | Time[2] | Local[3] | Archive[4] | |
| **Analog Inputs** | | | | | | | | | | | | |
| AH1SVel | None | None | None | None | 15 | 1 min | X | X | None | None | None | Note 15 |
| AH1RVel | None | None | None | None | 15 | 1 min | X | X | None | None | None | Note 15 |
| RF1SpdFb | N/A | N/A | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | |
| RF1kW | N/A | N/A | Note 26 | Note 26 | 15 | 15 min1 | X | X | 15 min | X | X | |
| **Analog Outputs** | | | | | | | | | | | | |
| RF1Spd | N/A | N/A | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | |
| **Digital Inputs** | | | | | | | | | | | | |
| RF1POO | Note 13 | None | None | None | 15 | COV | X | X | COV | X | | Notes 7,9 |
| RF1SSwSt | Note 10 | None | None | None | 2 | COV | X | X | COV | X | | Notes 10, 11 |
| VFD1SSwSt | Note 10 | None | None | None | 2 | COV | X | X | COV | X | | Notes 10, 11 |
| **Digital Outputs** | | | | | | | | | | | | |
| AH1RFSS | Note 13 | None | None | None | 15 | COV | X | X | COV | X | | |
| **Virtual Points** | | | | | | | | | | | | |
| AHU1SFlo | None | None | None | None | 15 | 1 min | X | X | 4 min | X | X | Note 16 |
| AHU1RFlo | None | None | None | None | 15 | 1 min | X | X | 4 min | X | X | Note 16 |
| RF1Hrs | None | None | 1,000 hr. | None | None | None | None | None | None | None | None | Note 8 |
| RF1SpdPGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1SpdIGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1SpdDGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| AHU1FDMx | None | None | None | None | None | None | None | None | None | None | None | Note 17 |
| AHU1FDMn | None | None | None | None | None | None | None | None | None | None | None | Note 17 |
| **Hard Wired Points** | | | | | | | | | | | | |
| RF1Fire | Open | None | None | None | None | None | None | None | None | None | None | Note 14 |
| AH1VFDAux | None | None | None | None | None | None | None | None | None | None | None | Note 13 |

**Notes:**

1. Samples indicates the minimum number of data samples that must be held in the local controller if it is trending the point. This may be based on the operating trending requirements. Higher sample capabilities tends to minimize archiving frequency.
2. Time indicates the required sampling time for the trending function (1 min = 1 sample per minute, 4 min = 1 sample every 4 minutes).
3. A check in the local column indicates that the trending only needs to be running in the local controller and the most recent value can write over the last value when the trend buffer fills up.
4. A check in the archive column indicates that the trend data must be archived to the system hard disc when trend buffer fills up so that a continuous trend record is maintained.
5. Commissioning trending requirements only need to be implemented during the start-up and warranty year. After the start-up and warranty process, the control contractor should set the trending parameters to the operating requirements listed.
6. See the specifications for additional requirements and details regarding sensor and interface device requirements.
7. Adjust to detect a belt or coupling failure by showing failure to run with the belt or drive coupling removed and the motor running.
8. Accumulate on a monthly basis and archive the monthly total to the hard disk on the last day of the month at midnight.
9. Provide an alarm if the equipment is running when it is commanded off. Provide an additional alarm if the equipment is not running when it is commanded on. Include time delays to accommodate system start-ups.
10. Issue an alarm if the manual override switch/Hand-Off-Auto switch is not in Auto.
11. If the DDC system provides this function as a standard feature in the firmware and software supporting its I/O boards, an independent contact on the override switch and associated physical point is not required.
12. Typical of all control loops. Provide commandable points for adjustment of loop setpoints, tuning parameters, and bias settings. Limit access to Lead Operator or higher.
13. Arrange contact to close any time the AHU1 supply fan is in operation under VFD control or in bypass and hardwire to start the fan.
14. Fire alarm shut down relays are furnished and installed by the fire alarm supplier and located at the motor starter location. Control wiring through the fan start circuit shall be by the electrical contractor. The control contractor shall coordinate this effort to ensure that the desired sequence is provided.
15. Flow measuring arrays to be configured for a log-Tchebycheff traverse grid with a 4-20 ma output that represents the true mathematical average of the velocities measured at each point on the grid. The array shall be capable of the indicated accuracy over its entire range. The range shall be 300 fpm to 2,800 fpm. Coordinate with the sheet metal contractor to ensure adequate straight duct to meet the manufacturers requirements for flow profile uniformity. See the specifications for additoinal details.
16. Caculate flow based on the measured duct vecolity and the field measured cross sectional area at the flow measuring element.
17. See the sequence of operation for set points. Coordinate with the testing and balancing and commissioning providers to tune these settings along with the minimum outdoor air flow and building pressurization during start-up and the warranty year.

## 3.10 Sample Narrative Sequence of Operations

The following narrative sequence is an example that applies to the return fan shown in the system diagram at the beginning of the chapter. It can be used as a starting point for similar systems employing flow tracking control strategies.

### Return Fan Variable Speed Drive Control

#### *Overview*

Return fan speed and return fan capacity are directly related. In addition, the differential between return flow and supply flow has a direct bearing on the outdoor air brought into the building and building pressure relationships. As a result, assuming that the economizer dampers and relief dampers are properly sized and controlled, modulating the speed of the return fan to maintain a specific flow differential relative to the supply flow will help to ensure that a VAV system's ventilation and pressurization requirements are maintained as the supply flow varies in response to the load variations. For additional details on this control strategy, including installation, commissioning, and operating tips, refer to the application guideline titled *Return Fan Capacity Control via Speed Control* published by the National Building Controls Information Program and available for free download at www.buildingcontrols.org.

#### *Speed Control*

Thermal dispersion type flow measurement arrays in the supply and return mains from the air handling unit provide an input to the control system that is directly proportional to the average velocity at the flow measuring location based on a log-Tchebycheff traverse of the ducts. The return fan shall be controlled to maintain the flow differential (relative to the supply flow) indicated in Table 3-2 below based on the current operating condition.

The control loop is contained in the controller serving the return fan variable speed drive (all inputs and outputs associated with the control process are hardwired to the controller) and is set up as a PID loop. A tendency towards a return fan speed that is below set point causes the return fan speed to increase. A tendency towards a return fan speed that is above set point causes the return fan speed to decrease.

Drive speed control shall be via a discrete hardwired interface between the control system and the drive. Network level interfaces between the control system and drive shall not be permitted for this function.

Control loop tuning parameters and variable speed drive acceleration times, deceleration times, minimum and maximum speeds shall be adjusted and optimized during the commissioning process.

*Table 3-2. Return Fan Flow Differential Settings*

| Return Fan Flow Differential Settings | | |
|---|---|---|
| Supply Flow, cfm | Flow Differential, cfm | Comment |
| 10,000 | 3,000 | Full load design point. |
| 8,500 | 3,000 | 80% full load design point; it is anticipated that a significant number of operating hours will be in this range. |
| 5,750 | 3,000 | Minimum anticipated load condition with all zones in the occupied mode (maximum occupancy, see note below). |
| 3,000 | 500 | Minimum anticipated load condition with zone VAV1-1 in the occupied mode and all other zones (VAV1-2, VAV1-3, VAV1-4, and VAV1-5) in the unoccupied mode (minimum occupancy, see note below). |

*Note: Unoccupied zones are driven to 0 cfm by a zone level schedule. See the AHU1 occupied/unoccupied control sequence for additional information regarding zone occupancy control as well as its coordination with the outdoor air damper minimum position signal.*

Coordinate minimum speed settings for the fan with the motor and VSD supplier to ensure adequate motor cooling while achieving the lowest possible speed to minimize the step change that occurs when the fan starts. Anticipate an initial setting of 5 Hz based on the drive/motor combination specified.

### *Start Stop Control and Proof of Operation*

The return fan variable speed drive shall be commanded on by a hardwired interlock any time the supply fan variable speed drive is in operation. It shall also be possible to command the drive on via the DDC system using a command from the operator's console.

A current switch sensing current to the variable speed drive shall provide a contact closure for proof of operation purposes any time the return fan motor is operating under load. The current switch shall be adjusted so that the proof of operation is not indicated if the motor is running but the belts have broken and thus the fan is not turning.

### *Variable Speed Drive Interlocks*

The following interlocks shall be provided for the return fan variable speed drive:

- External, Hardwired

  A start-stop interlock to the supply fan shall be hardwired into the variable speed drive control circuit. These interlocks shall function regardless of the status of the drive Hand-Off-Auto and Inverter-Bypass selector switches.

  A fire alarm shut down relay shall be wired into the circuit and arranged to shut down the fan on a building fire alarm condition per the programming requirements of the fire alarm system. Coordinate with Division 16 as required for wiring and programming of the fire alarm relay. Coordinate with Division 16 for the location and field installation of the duct mounted smoke detectors.

- External, Software based

  The return fan variable speed drive shall be commanded to 0 Hz any time the return fan is not in operation as indicated by the return fan status input.

- Internal

  The return fan shall be shut down and locked out if a motor overload condition is sensed in the drive or bypass mode. Manual reset at the drive location shall be required to resume normal operation.

### *Outputs to the DDC System*

The following outputs shall be provided from the variable speed drive to the automation system. These outputs may be provided by discrete hardwired interfaces or by a network level interface at the contractor's discretion. The final installed condition shall be reflected in the "as-built" drawings.

- Drive speed feedback in Hz
- Drive kW

### *Alarms: Operator*

Operator alarms shall be delivered to the operator's console and logged on a dedicated alarm printer as they occur. The following operator alarms shall be provided:

- Indicate AHU1 return fan failure to start or run if the fan is not running when it should be, including a failure to start when commanded on for any reason or a shutdown that occurs when the fan should be operating per the operating sequence given the current conditions.
- Indicate AHU1 return fan failure to stop or remain shut down if the fan is running when it should not be, including a failure to stop when commanded off for any reason or any operation that occurs when the fan should be off per the operating sequence given the current conditions.
- Indicate AHU1 measured flow differential does not match set point if the supply fan has been running for 5 minutes or more (initial setting, adjustable) and the difference between the measured flow and the desired set point is greater than 5% (initial setting, adjustable). Suppress this alarm if the supply fan status is off.

### *Alarms: Facility Management*

Facility management alarms shall be directed to a weekly report, generated for the director of engineering and made available for viewing under their log-in. The following alarms shall be provided:

- Indicate *during the past week the AHU1 return fan operated for a significant period of time when the supply fan was not operating* if the return fan operates more than one hour (initial setting, adjustable) when the supply fan is not operating. Reset the timer at the end of the week.
- Indicate *during the past week the AHU1 return fan has failed to operate for a significant period of time when the supply fan was operating* if the supply fan operates for more than one hour (initial setting, adjustable) when the return fan is not operating. Reset the timer at the end of the week.
- Indicate *during the past week, the AHU1 return fan speed did not vary significantly on one or more days* if the return fan speed does not vary by more than ± 5 Hz (initial setting, adjustable) between 30 minutes after start-up and the shut down time during any day on which the system operated.

### *Totalization*

The following totalization functions should be provided and the data should be archived to the system hard drive on a daily basis:

- Return fan hours of operation based on the proof of operation input for the current week, the current month, and the current year.
- Return fan kWh based on the kW input from the variable speed drive for the current week, the current month and the current year.

## 3.11 Case Study

The following case study relates to an existing VAV air handling unit designed to control the return fan speed based on flow tracking. AHU3 consists of two supply and two return fans operating in parallel in their respective air streams. Because a few of the zones served by the unit were occupied around the clock, the air handling system operated continuously. During periods when most zones were unoccupied, the VAV boxes in the unoccupied zones would eventually modulate to a minimum air flow position as the loads dropped away. While this did reduce the supply and return flow below what was seen during occupied hours, the residual air flow and ventilation associated with drifting down to and then holding at minimum flow still represented a significant and unnecessary fan energy and reheat energy burden.

As an energy conservation measure, a decision was made to implement scheduling at a zone level by forcing the VAV box primary air dampers completely closed when the zone they served was unoccupied rather than simply allowing them to drift to minimum flow. This would allow the duct static pressure control loop to reduce the supply fan speed and related flow as soon as a zone was not in use. In addition, the flow reduction would be larger than was achieved in the past since minimum flow in the unoccupied zones had been eliminated. It was anticipated that the return fans would simply follow the supply fans and maintain the necessary flow differential via the flow tracking control logic. The result of the modification is illustrated in Figure 3-5 for one of the two parallel fan sets.

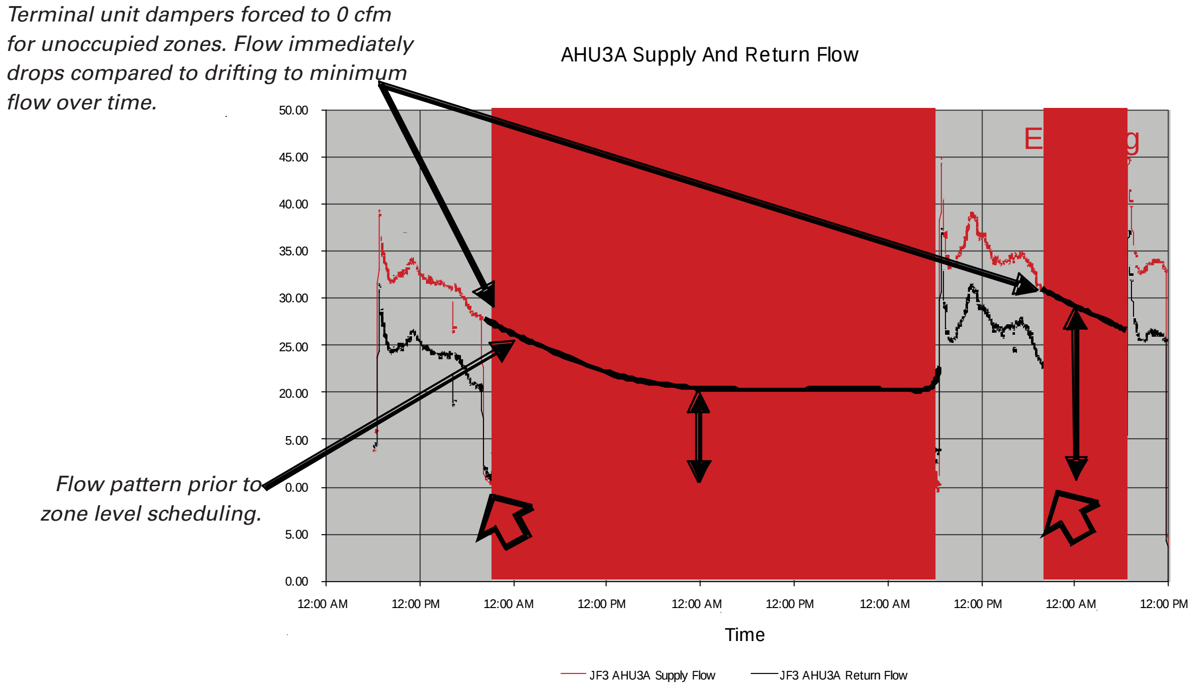



*Figure 3-5. Good news and bad news; When AHU3's control system software was modified to force its VAV units to 0 cfm during unoccupied hours, there was an immediate reduction in flow with commensurate savings in fan and reheat energy compared to previous patterns (gray arrows). Unfortunately, the new turndown requirement revealed a calibration problem with the velocity pressure based flow measuring stations that caused the return flow to track above rather than below the supply fan flow during unoccupied hours.*

As can be seen from Figure 3-5, the flow rate during unoccupied hours was reduced considerably from previous patterns. However, operation at a new flow rate that was significantly lower than the system had seen in the past introduced a new problem. Specifically, the reduction in air flow lowered the velocity pressure at the return flow measuring station by an order of magnitude compared to the conditions before modification. This is illustrated in Table 3-3. This led to an inability to accurately measure return air flow and control return fan speed, which was the underlying cause behind the problem illustrated in Figure 3-5. The problem was solved via a combination of equipment upgrades and calibration.

| Parameter | | Return Flow Measuring Station Conditions | |
|---|---|---|---|
| | | | |
| Peak | | | |
| | Velocity, fpm | 2,600 | 2,600 |
| | | | |
| Minimum | | | |
| | Velocity, fpm | 1,026 | 342 |
| | | | |

*Table 3-3. AHU3 Return Fan Flow Measuring Station Parameters At Different Operating Conditions.*

## 3.12 Additional Resources

Additional guidance can be found in these sources:

*Installation and Maintenance of V-Belt Drives*, another useful tool that is provided as a free resource from the TB Woods Company at http://www.tbwoods.com/pdf/VBD-IM_InstallationandMaintenance.pdf

Functional Testing Guide – http://www.peci.org/ftguide/ under the Testing Guide: Fundamentals to the Field topic.

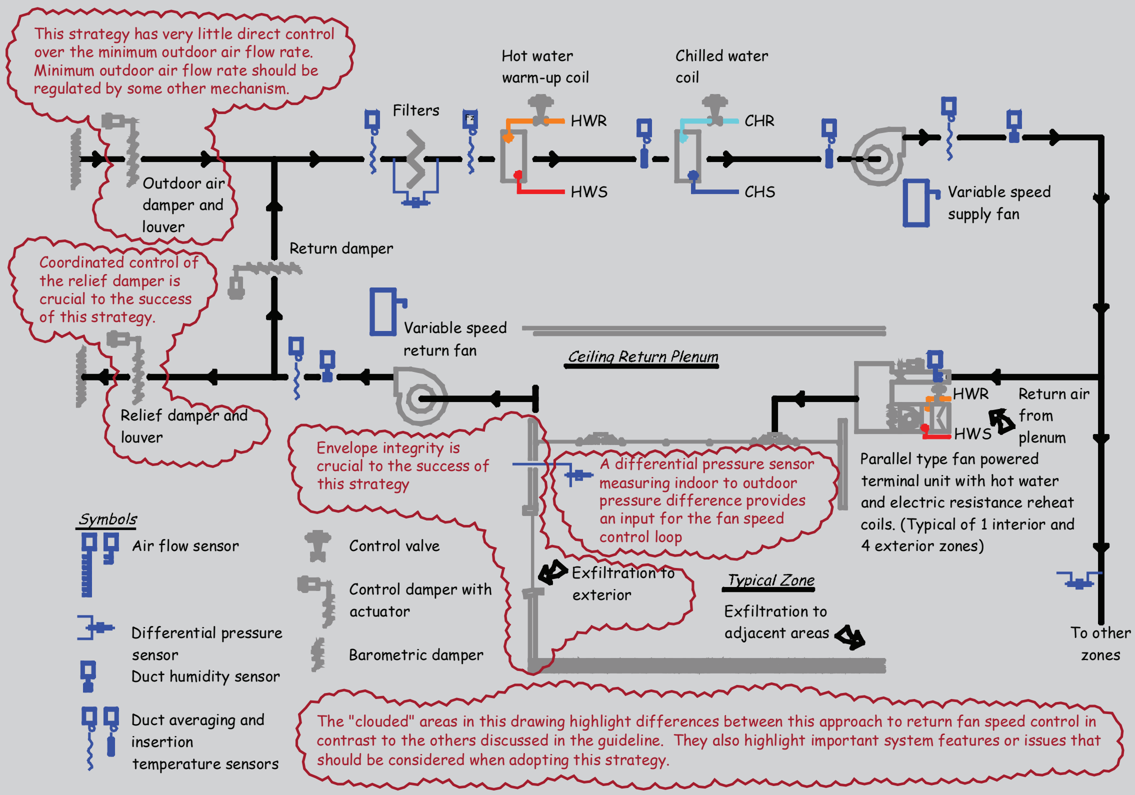
Control System Design Guide – http://www.peci.org/ftguide/ under the Control System Design Guide topic.

# Chapter 4 ■ Building Pressure Control

This chapter will discuss building pressure control of return fan speed. There are several variations of this approach where-in the building static pressure is used to control the relief dampers and the return fan is controlled by one of the other strategies in this guideline or where the return fan and relief dampers are controlled in sequence to maintain the desired static pressure in one area of the building relative to another area rather than the outside.

## Contents

## Building Pressure Control




*A Typical VAV Air Handling System with Building Static Pressure Based Control*

## General Description

This strategy modulates return fan speed as required to maintain a building static pressure setpoint and thus, assuming a working make up system, will provide direct and potentially superior control of building static pressure when contrasted with some of the other approaches discussed in this guideline. The typical pressure reference is the building interior relative to the exterior, but the strategy has also been employed to control pressure in one area relative to another. Variations on this strategy can be used to control the relief dampers, either in concert with the return fan or independently, with the return fan being controlled by one of the other strategies described in this guideline. The strategy is highly dependent upon the integrity of the building envelope and may not function as anticipated if the building is leaky.

## Advantages

- Direct control of building pressure mitigates the adverse impacts of environmental dynamics like wind and stack effect.
- Low to moderate life cycle cost.

## Limitations

- Envelope integrity is critical to the success of this strategy, thus it may not be well suited for leaky buildings or buildings with operable windows.
- Little direct impact on minimum outdoor air flow regulation.

## Application Considerations

| Characteristic | Low | Medium | High |
|---|---|---|---|
| Application Complexity | | ✓ | |
| Potential for Negative IEQ Impact | ✓ | | |
| Potential for Negative Energy Impact | ✓ | | |
| Potential for Integration/Interaction Problems | | | ✓ |
| First Cost | | ✓ | |
| Maintenance Cost | | ✓ | |
| Energy Cost | | ✓ | |

## Key Design Issues & Considerations

- A coordinated effort from design through construction to ensure the integrity of the building envelope is crucial to success. In retrofit applications, assessment of the envelope prior to proceeding with design may be desirable.
- This strategy can be highly interactive with the traffic through entry ways in the building and the effects of wind. The location of the pressure reference points used as inputs to the control process should take this into account and should utilize termination heads designed to minimize these effects.
- Relief damper and return fan control need to be carefully coordinated.
- Minimum outdoor air flow regulation needs to be addressed as a separate consideration.
- The building pressure setpoint needs to be selected with consideration to a number of variables including climate, building environment and function and code issues.
- The sensing technology needs to be suitable for the very low, bi-directional pressures.

## Key Installation Issues & Considerations

- Vigilance regarding envelop integrity during construction is crucial and beneficial on numerous fronts beyond the success of this control strategy.
- Verification in multiple operating modes is desirable. Using trend analysis to observe the nature of the response of the building after initial set-up can minimize effort and provide superior results.

## Key Operating Issues & Considerations

- Changes in the building that impact the integrity of the envelope can have a major impact on the performance of this strategy.

Building pressure control adjusts the return fan speed to maintain a positive building static pressure relative to the atmosphere. By its very nature, this strategy has the potential to minimize infiltration driven IEQ and comfort related issues.

Additional information generally applicable to all return fan speed control strategies can be found in *Chapter 1: Introduction and Fundamentals*. Additional useful resources outside of this guideline are listed at the end of the chapter.

## 4.1 General Description

As is the case with all of the return fan capacity control strategies in this guideline, this strategy is built on the fundamental relationship between fan capacity and rotational speed. The unique aspect of this strategy is that it assumes a relationship between the building's pressure, relative to atmosphere and the amount of air being moved by the return fan, either for recirculation or relief from the building. It also assumes that the supply system is introducing the proper amount of outdoor air into the building in the first place. Based on these assumptions, the strategy functions to increase the return fan speed if the building pressure increases above setpoint and decrease the return fan speed if the pressure decreases below setpoint.

The integrity of the building envelope is critical to the success of this strategy; if the building leaks so badly that it can not be pressurized, then the return fan or fans will have nothing measurable for use as an input to the building pressure speed control loop.

### Variations

There are several variations of this strategy in common use.

#### *Return Fan Controlled to Maintain a Space Pressure Relationship*

There have been instances where a strategy similar to this strategy has been used to maintain a specific space pressure relationship between adjacent zones rather than an indoor to outdoor pressure relationship.

#### *Relief Damper Modulation*

A common variation on the building pressure control strategy is to modulate the relief damper to maintain building static pressure. The return fan speed is modulated based on one of the other strategies discussed in this guideline.

#### *Multiple Building Pressure Sensors*

Another minor variation on the building pressure control strategy is to use multiple building static pressure sensors and control the return fan to maintain the lowest measurement at the required setpoint.

## 4.2 Advantages

When properly designed and implemented, this approach can be applicable to all building sizes and classes.

The primary benefit offered by this strategy relative to the others included in this guideline is its ability to directly control infiltration and exfiltration through the building envelope. This is a desirable feature in virtually all climates and a required feature in some. Specifically, as the differential between the outdoor and indoor temperature and humidity increases, the need to control infiltration and exfiltration also increases. In cold winter climates uncontrolled infiltration can lead to burst pipes and other equipment failures in addition to comfort complaints. In hot and humid climates, infiltration must be controlled to prevent condensation, mold growth, and the degradation of the materials utilized in the building's envelope and structure. A detailed discussion of infiltration and exfiltration and the related issues can be found in *Appendix 1: Infiltration and Exfiltration*.

Another benefit of this control strategy is that it accommodates the dynamic nature of buildings and the environment they are located in. Many factors including wind, outside air temperature, operable components of the building envelope (doors and windows), the ventilation rate, and VAV supply air distribution vary continuously and have an impact on building static pressure. Actively measuring and controlling based on building static pressure minimizes and mitigates the adverse impact these variables can have on air migration through the envelope.

## 4.3 Limitations

Envelope integrity is critical to the success of this strategy. A building that is so leaky that it can not be pressurized will provide no feedback mechanism for controlling return fan speed and the strategy will fail to deliver the desired results. Thus, if the strategy is being employed on a new construction project, extra vigilance during construction with regard to the integrity of the envelope is warranted. For large complex structures, incorporating some sort of envelope leakage test into the commissioning process may also be desirable.

This strategy may not provide satisfactory performance in facilities with operable windows due to the significant and unpredictable breech of the envelope represented by the open windows.

If this strategy is being considered in an existing building undergoing renovation or retrofit, assessing envelope integrity via inspection or test may be desirable prior to finalizing the design.

It is also important to recognize that a return fan that is controlled based on building static pressure has little or no direct impact on the minimum outdoor air flow introduced into the building when contrasted with some of the other approaches discussed in this guideline. This can be an advantage and a disadvantage.

- On a positive note, it is less likely that the operation of the return fan in such a system will cause problems with minimum outdoor air flow.
- On the other hand, implementing this strategy in concert with some other minimum outdoor air control strategy is critical if adequate ventilation is to be ensured when contrasted with approaches like flow tracking or mixed air plenum control. In both of those strategies, the controlled parameter (supply/return flow differential and mixed air plenum pressure, respectively) can have a very significant and direct influence on ventilation.

## 4.4 Application Considerations

### Application Complexity

While simple in concept, building pressure control can become complex to implement for a number of reasons including:

- The need to interact with multiple systems with variable operating requirements and schedules serving different areas of the building.
- The need to provide multiple building static pressure reference points to accommodate variable operating contingencies.[1]
- The need to accommodate significant variations in the integrity of the building envelope due to highly variable traffic rates through doorways, operable windows, or large operable openings like loading dock doors.

When faced with these challenges, buildings or systems located in dry and/or moderate climates may provide satisfactory service via one of the other simple strategies discussed in this guideline. In climates where the potential provided by this strategy to positively control infiltration is deemed desirable or a "must have," the project design requirements and budget should reflect the complexities that are introduced by the factors listed above.

### Potential for Negative IEQ Impact

Because building pressure based return fan control will, by its nature, directly minimize infiltration, it has one the lowest potentials for negative impact on IEQ out of all of the strategies discussed in this guideline. Specifically, minimizing infiltration is one of the best ways to ensure comfort during the heating season. In addition, minimizing infiltration, especially at street level where urban pollution and contaminants are in greatest concentration, can be a significant factor in ensuring indoor air quality, a major component of overall IEQ.

Despite these strong suites, it is important to realize that this strategy must be used in concert with other ventilation assurance strategies to maximize indoor air quality.

### Potential for Integration/ Interaction Problems

Because building pressurization can impact all of the air handling systems in a building, building pressure control has the potential to propagate disturbances in one system to all of the other systems that are influenced by building pressure.

In addition, events that temporarily modify the integrity of the building envelope can ripple out

[1]The static pressure reference points and static pressure sensor location are often two different physical locations. The reference points are the physical points in the building where the indoor and outdoor pressures are measured (referenced). Ideally, the sensor that is connected to the reference points and converts the measured pressure to an input signal for the control system is located in an accessible location as close as possible to the reference points. However, in most instances, there will be a significant length of tubing between the sensor and one or both of the reference point locations. Ensuring that this tubing is leak free is an important consideration when measuring building static pressure.

and impact all of the systems using building static pressure as a reference. An example of such a disturbance is the effect that opening and closing doors can have on building pressure, which is illustrated in Figure 4-1. While the data in the figure was collected in a test mode rather than a normal operating mode and thus is not an exact portrayal of a building in normal operation, it does illustrate how significant the impact of a door opening can be on building pressures and the related flow patterns it produces.

The impact of door operation on building pressure can become even more complex when doors open and close multiple times, especially if the pattern is not consistent. This topic will be discussed in greater detail later in this chapter in *Section 4.5 - Key Design Issues and Considerations*.

## First Cost

A building pressure approach to return fan capacity control, while simple in concept, can be more costly than some of the other simple control strategies like speed/signal tracking and mixed air plenum pressure control. Factors that can add to its cost and complexity include:

- The need to interact with multiple systems.
- The need to provide multiple building static pressure reference points to accommodate variable operating contingencies.

When faced with these challenges, buildings or systems located in dry and/or moderate climates may realize satisfactory, cost effective service via one of the other simple strategies discussed in this guideline.

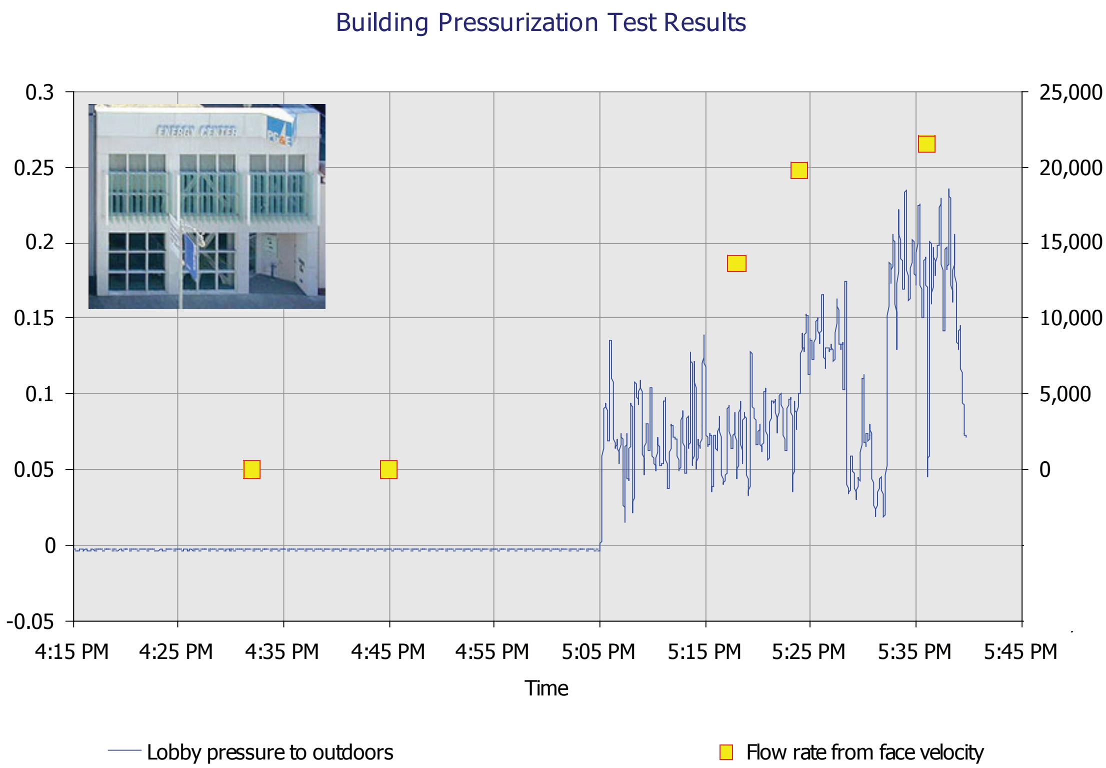



*Figure 4-1. The Impact of Opening a Loading Dock Door on Building Pressure.*

*This data set, taken during a building pressurization test for a low rise, 26,000 square foot facility shown in the photo inset demonstrates the impact that operating a door can have on building pressurization. At the time, the air handling system in the building was being operated on 100% outdoor air with all exhaust and relief systems shut down to assess the leakage potential of the envelope. Notice how the pressure drops from 0.15 in.w.c. to below 0.05 in.w.c. between 5:25 and 5:35 pm when a 12' x 11' loading dock door is opened. At the time, the system was delivering about 20,000 cfm of air into the building, which was pressurizing it to approximately 0.15 in.w.c. When the door opens, much of the air exits through it rather than through cracks in the building envelope and the building pressure drops. The flow through the door was estimated to be between 7,000 and 10,000 cfm.*

### Maintenance Cost

Due to the minimal control hardware requirements, the maintenance costs associated with building pressure control strategies will tend to be low relative to more hardware intensive strategies like flow tracking. Systems that use multiple building static reference points will require a proportionally higher maintenance effort.

Because this strategy is less likely to have a direct impact on minimum outdoor air flow, the need to retest to verify proper ventilation flow delivery will be less than that associated with some of the other strategies discussed in this guideline. However, retesting the minimum outdoor air flow regulation approach used in conjunction with this strategy periodically is still advisable. Maintenance issues are discussed in greater detail in *Section 2.7. - Key Operating Issues and Considerations*.

### Energy Cost

If implemented properly, building pressure control has the potential to be at least as energy efficient as all of the other return fan strategies discussed in this guideline. In some instances, it may offer superior performance (Sellers et al., 2004a). Efficiency gains relative to other strategies are achieved on two fronts:

- By maintaining a positive building pressure, the strategy minimizes infiltration and the load it represents on the perimeter HVAC systems. If this positive pressure is achieved by virtue of extra outdoor air brought in by an economizer process to handle the loads associated with internal heat gains, then in effect the perimeter heating load is offset by heat recovered from the building interior. Specifically, cool air delivered to the building interior is warmed to space temperature via the internal gains. This air is then exfiltrated through the envelope, which acts as a form of relief system for the economizer process. If air were infiltrating through the envelope, then it would represent a heating load that would be a burden on the HVAC system serving the perimeter.
- Because air is relieved through the envelope rather than by being transported back to the air handling unit location for discharge through the relief louvers, the amount of air handled by the return fan is reduced. Handling less air equates to using less energy, with the magnitude of the savings being directly related to reduction in return flow.

## 4.5 Key Design Issues and Considerations

Many of the issues discussed in the subsequent sections on installation and operation are intertwined with the decisions made during the design process. Thus, reviewing those sections to understand the challenges that will be faced during fabrication, start-up and operation can be crucial to a successful design. *Appendix 7: The Relationship Between Design, Installation and Operation* includes a discussion of a general nature on this topic. The following information is particular to systems using a building pressure based approach to return fan capacity control.

### Envelope Integrity

As stated previously, envelope integrity is critical to the success of a return fan control strategy that is based on maintaining a positive building pressure. Research suggests that building leakage is surprisingly independent of factors like age, method of construction, materials and other factors that one would intuitively expect to influence leakage (Sellers et al., 2004a). In addition to the intentional envelop penetrations (and thus, leakage paths) represented by entry-ways and loading docks, other unintentional but significant leakage sources can occur where envelope and/or structural components join together (Sellers et al., 2004a). There have been instances where the cumulative effect of intentional and unintentional envelope breeches has been so great that it is not possible to pressurize the building's interior without first addressing the gaps and cracks in the envelope.

Operable windows can represent a significant and variable compromise of the envelope. This may not be much of an issue in a small facility in a mild climate; the windows will simply become a relief path for the economizer process on a mild day and the return fan will move towards minimum speed as the number of open windows increases and building pressure drops. For a large complex facility in an extreme climate and/or with critical pressure relationship requirements, operable windows may not be the best option.

Vestibules are a desirable feature in most building, especially in cold climates. They can be especially helpful in buildings endeavoring to maintain a positive building static pressure due to the buffer they create between the interior environment and the opening of doors to the exterior. To deliver the full benefit, the vestibule needs to be long enough that the exterior door closes before the interior door opens under normal traffic rates. If both doors are open simultaneously, much of the buffering benefit is lost. In large complex and high-rise buildings, providing an independent system to handle the lobby and vestibule can be advantageous, especially if the system is capable of conditioning significant quantities of outdoor air for pressurization purposes (Sellers et al., 2004a).

The bottom line is that building pressure return fan control strategies are prone to problems related to a lack of integrity in the building envelope. This fact needs to be considered and addressed during the design and construction process, and requires a coordinated effort among many of the design professionals and trades people involved in the design and fabrication of the facility.

### Stack Effect

For buildings taller than a few stories, the hydrostatic pressure differentials created by the indoor to outdoor temperature and density differentials acting on the "column of air" within a building also affect the building operating pressure. Figure 4-2 illustrates this phenomenon with measured data from a low rise and high rise building. Commonly called stack effect, this phenomenon becomes more pronounced as the building height increases and will be influenced by seasonal temperature differences as well. When the ambient temperature is below the buildings internal temperature, stack effect causes infiltration in the lower levels and exfiltration in the upper levels. In the summer time, the effect is reversed.

Irrespective of the season, there will be an elevation at some point in the building where there is no infiltration or exfiltration. This is commonly called the neutral plane. In essence, the building pressure control strategy endeavors to force the neutral plane to a location where the impacts of infiltration are minimized. A typical target is to force it to the bottom of the building by endeavoring to maintain a positive pressure in the lobby during the winter months.

### Humidified Environments and Humid Climates

When contemplating humidity in relationship to building static pressure it is important to remember that the *vapor pressure differential* controls the migration of water vapor rather than the air pressure difference. In accordance with Dalton's Law, water will migrate from an area of higher vapor pressure to an area of lower vapor pressure even if the area of lower vapor pressure is at a higher air pressure.

The bottom line is that maintaining building pressure differentials should not be considered the primary method of preventing condensation. This issue needs to be addressed by the proper selection, application, and configuration of the materials comprising the building envelope so that the envelope assembly prevents inappropriate moisture migration (via air leakage or vapor diffusion) and includes provisions to drain way any condensation that does occur. Since the integrity of air barriers and vapor retarders cannot be guaranteed, building pressure relationships provide an additional control mechanism that can minimize the potential for problems where there are intentional or unintentional breeches of the envelope.

### Control System Considerations – Hardware

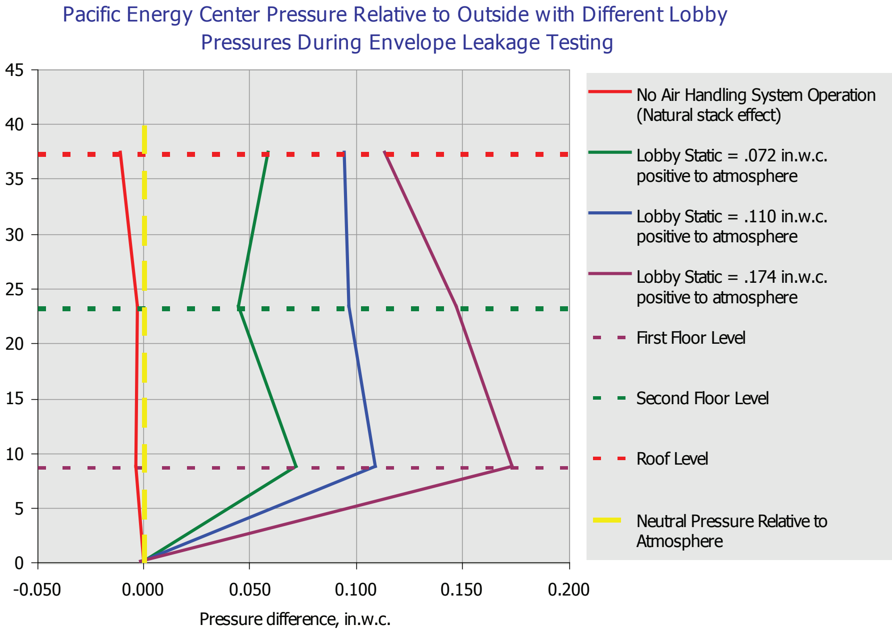
Most of the control system hardware considerations discussed in *Chapter 1: Introduction and Fundamentals* and in *Appendix 5: Control System Hardware and Software Issues* apply, including:

- Variable speed drive interlock issues.
- Economizer control integration issues.
- Return and relief damper interlock issues.
- Minimum outdoor air control issues.
- Building pressurization control integration issues.

The following issues are unique to the building pressure control strategy:

- Traffic rates through doors and other envelope penetrations.
- Locating indoor and outdoor pressure reference points and their associated transmitter.
- Very low differential pressure measurement technology.

Each of the topics will be discussed in detail in the subsequent paragraphs.



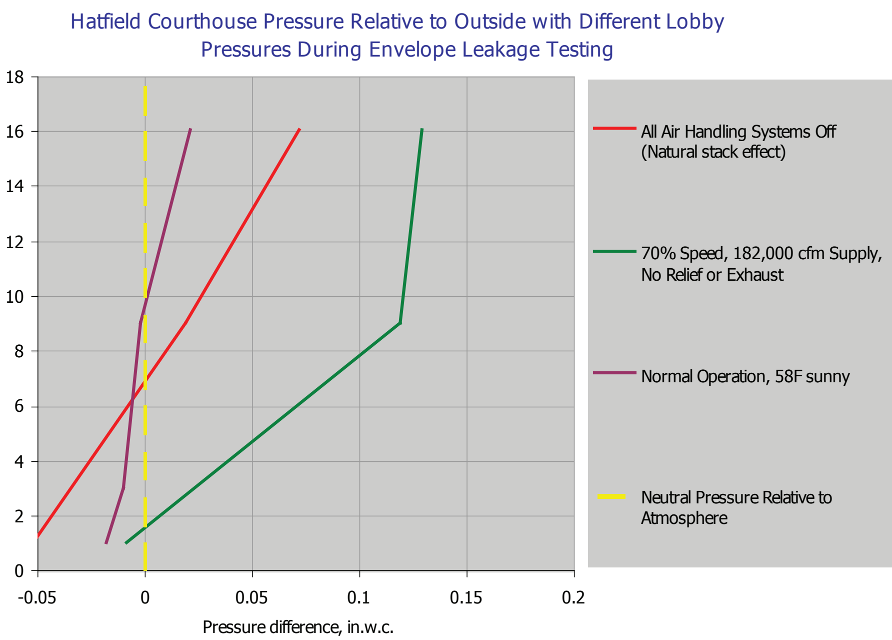




*Figure 4-2. Pressure Gradients in a Low Rise and a High Rise Building with Different Lobby Pressures.*

*The data in both of these graphs was obtained during envelope testing. In the Pacific Energy Center, a door at basement level was cracked open during the test, which tended to reference the basement level to atmosphere without excess flow and locked the neutral plane at that level. In the Courthouse, all doors were closed during the test and thus, the test shifted the neutral plane. Note that even the low rise building on a mild day exhibited some stack effect. Also notice that in the less leaky low rise building, operation of the supply system immediately pressurized the lobby level. But, in the very leaky high rise, even with 182,000 cfm of supply air and no relief or exhaust, the neutral plane was still above the lobby level. Finally, the inflection point in the 70% speed curve for the high rise building turned out to be a clue to where a problem was. In essence, the test data was indicating that it was much more difficult to pressurize the building above the 8th floor level than below that level. Subsequent inspections revealed a significant leak that short circuited the equipment room return plenum to the outdoor air intake plenum in the 8th floor mechanical space.*

### *Traffic Rates through Doors and Other Envelope Penetrations*

Traffic rates through the doors and other entryways into the building can have a significant impact on controllability for a building pressure control system. Each time a door opens, the amount of air entering or leaving the building at the door location increases and the buildings ability to maintain a positive internal pressure relative to the environment decreases, as is illustrated in Figure 4-1. These pressure change events can have operational impacts on a number of fronts. Consider the entry lobby to an office building.

- During the early morning, midday, and early evening hours, employees entering and exiting the building will cause numerous door operations over a short time frame.
- Each door operation will impact the reference pressure being used by the control system. But, the pattern will, in all likelihood, be erratic. If one person goes through the door by themselves, the event will most likely be of short duration and magnitude. In contrast, if a group of people go through the door, the event will be prolonged and produce a larger drop in lobby pressure, especially if one of the people politely holds the door open for the others before entering themself.
- The traffic rate through the door may drop to virtually zero during the mid morning and afternoon hours and at night.

A fan system using building pressure measured in the entry lobby will have to deal with all of the entry door traffic patterns, not just the status-quo that exists during periods of low activity. If it is a VAV system, then the response to the different traffic patterns will change as a function of the current system operating point, adding another variable to the already complex system response characteristic.

If the building is served by multiple systems, another set of variables is added to the mix. Even if only one system is directly associated with the lobby, all of the systems can interact with each other through the common denominator of building static pressure. Systems serving adjacent zones will interact with each other via the doorways and corridors interconnecting the zones. Systems on adjacent floors will interact via the elevator shafts, return air shafts and stairwells interconnecting the floors.

The bottom line is that at a fundamental level, all of the fan systems in the building are in parallel with each other, sharing a common intake reference (the outdoors) and a common discharge reference (the building interior). As a result, they will interact with each other through their common points of connection. This fact is worthy of consideration as the design of a building pressure control system evolves and is implemented in the field. Robust, responsive, precise control systems and components are critical if the system is to deal with the numerous interactive variables it will be confronted with in the course of day to day operation.

### *Locating Indoor and Outdoor Pressure Reference Points and their Associated Transmitter*

The location of the reference points used for determining building static pressure can be crucial to the success of this strategy. The location of the actual sensing mechanism itself is also important in terms of maintenance considerations. All of these issues should be addressed by the designer in the design documents and coordinated with the installer during construction. When determining the best location for the sensor, there are several important issues to consider:

- The space most prone to infiltration in the winter often is the best location for the indoor pressure reference. Typically, this is the ground floor entrance area. Controlling the building pressure at this point will minimize infiltration in this area. In humid environments, infiltration during the summer may also be a consideration and require a separate sensing location, set point, or both. Leaky buildings in humid climates may require a minimum level of system operation around the clock to maintain a positive pressure and dehumidify air that does infiltrate to prevent condensation and the resulting water damage and IEQ problems. (Sellers et al., 2004a)
- The indoor pressure reference point should be as immune as possible to the effects of wind through envelope penetrations, pressure differentials generated by normal supply or return air flow, and the piston effect created by elevator movement. The transient effects of air velocity can be minimized by using a sensing head that physically dampens the fluctuations in measured pressure.

Positioning the indoor reference so that it is exposed to the effects of traffic through exterior doors can have advantages and disadvantages. On the positive side, the mechanism most likely to cause an adverse pressure relationship to be generated will be immediately sensed. On the negative side, the highly variable nature of this input can cause controllability problems as was discussed previously. Careful consideration of these issues may lead to referencing interior pressure (the pressure in an adjacent interior space to the main entrance area or lobby rather than in the lobby itself) especially if the lobby does not have a vestibule. The reference should normally not be taken in the drop ceiling of a return air plenum.

- The transmitter should be mounted in close proximity to the reference pressure sensing locations to minimize the compromises that can occur in accuracy and response time due to long runs of tubing. If long runs are unavoidable consider the following options to mitigate potential problems:

  1. Use oversized tubing to minimize the pressure drops that occur due to transient flow conditions. This will also tend to dampen random pressure pulses, providing a more stable input.
  2. Use copper tubing with soldered joints.
  3. Leak test the tube run after installation to verify its integrity.
  4. Consider using two pressure sensors, one at the indoor reference and one at the outdoor reference and generate the differential pressure based on computations in the DDC controller.
  5. Consider using thermal dispersion based sensors, which use flow direction and velocity in a tube interconnecting the two pressure zones as a proxy for differential pressure.

- The transmitter itself must be in an accessible location and not above a hard ceiling or any ceiling of excessive height.

- The terminations of the tubing at the sensed location should be provided with sensing heads designed for the purpose. Frequently, pneumatic tubing is run from the transmitter and simply poked through a ceiling tile in an unsecured fashion. Maintenance activity in this area can pull the tubing out of the tile and leave it dangling in the ceiling, invalidating the input. Sensing heads design for the purpose of measuring building and ambient pressures provide a secure and obvious termination for the tubing from the transmitter and can also provide shielding and/or buffering of the pressure pulses created by door activity and wind. Figure 4-3 illustrates several of the sensing heads offered by one manufacturer.

*Figure 4-3. Typical Building and Outdoor Air Pressure Sensing Heads.*

*Outdoor air (above) and space pressure (below) (Images courtesy www.AirMonitor.com)*

- In extremely variable environments, there may be some benefit gained in installing outdoor sensors on each face of the building and piping them to a common manifold to average out variable wind effects.
- The physical distance that frequently exists between the building static pressure transmitter and the return fan it controls makes it tempting to use the control network as a means of transmitting the input signal instead of hardwiring it to the controller serving the return fan. This practice should be avoided for the reasons discussed in *Appendix 5: Control System Hardware and Software Issues*.

### *Very Low Differential Pressure Measurement Technology*

Matching the range of a sensor to the anticipated signal range that it will measure is an important control system design consideration as discussed in *Appendix 5: Control System Hardware and Software Issues*. For building pressure based control systems, this issue can be worthy of additional consideration for a number of reasons.

- Typical control setpoints for building static pressure control systems are in the range of 0.01 - 0.10 in.w.c. Thus, a transmitter with a full scale range of 0.20 to 0.25 in.w.c. is desirable for this application. Repeatedly measuring pressures of this magnitude accurately and reliably in a cost-effective manner can be difficult although technological advances are constantly bringing improvements to market in this area.
- Although the intent of building pressure based control is to maintain a positive pressure, in a real time operating environment, negative pressure differentials will be encountered. Typically this occurs during off hours due to stack effect or due to an operational problem. In the former case, avoiding the nuisance over-range alarms that can occur when a transmitter with no negative pressure measuring capabilities is subjected to a negative pressure is desirable. In the latter case, having the ability to detect and issue an alarm as a result of the undesirable operating condition can be an advantage. The bottom line is that providing a sensor with a bi-directional measurement capability is desirable in this application.

### *Electronic Measurement*

In the current market, electronic sensors are the obvious choice for measurements of this type. There currently are a number of technologies available that can address the issues listed above while directly measuring differential pressure. Thermal dispersion based sensors offer another option for measuring very low differential pressures using velocity as a proxy for pressure differential. The technology works by connecting the two pressure zones with a tube. The pressure differential between the zones causes a flow to occur through the tube. This flow is typically measured via one of two approaches:

- The amount of current required to maintain a heated wire at a constant temperature as flow varies is measured and used as an indication of flow.
- Two temperature sensing elements are located in the air stream to be measured. One is heated and one is not heated. The difference in temperature between the two elements as flow varies is an indication of flow rate.

Regardless of the approach used, the flow can be correlated to differential pressure, allowing the sensors to be used to measure very low differential pressures. Sensors of this type are frequently used for isolation rooms and other sensitive applications where the ability to resolve pressures to 0.0001 in.w.c. is required. But their low range sensitivity and bi-directional capability make them worthy of consideration for building static pressure measurement applications.

### *Pneumatic Measurement*

In retrofit applications, designers are still, on occasion, forced to deal with a pneumatic control system. In these situations, specifying a high quality process grade transmitter should be considered. A detailed discussion of this topic can be found in *Appendix 5: Control System Hardware and Software Issues.*

### Relief Damper Control

Coordination of the control of the relief dampers is an important consideration for applications using building pressure strategies. Consider a situation where the relief dampers are controlled by the same signal controlling the outdoor air and return air dampers operating at 50% outdoor air. If conditions are such that the building static pressure set point is being met due to air being relieved through the building envelope, the control system will drive the return fan towards minimum speed.[2] Under these conditions it may be possible for the supply fan to pull outdoor air into the building through the relief louver and partially open relief and return dampers in addition to the outdoor air louver. This has several operational implications:

- The quality of the air at the relief location may be undesirable for introduction into the building.
- The system will essentially be operating as a 100% outdoor air system.

Segregating the control of the relief damper from the economizer process will help to mitigate this issue. Common approaches include:

- Sequencing the relief dampers with the return fan speed. This will be discussed in detail in the next section.
- Sequencing the relief dampers to maintain a positive relief plenum pressure. The set point is based on the pressure required to deliver 100% relief at design conditions.

### Control System Considerations – Software

Point lists, narrative sequences and logic diagrams are important tools to convey design intent to the implementing and operating staff. These topics are discussed in *Chapter 1: Introduction and Fundamentals* and *Appendix 5: Control System Hardware and Software Issues*. The following applies specifically to this strategy.

### *Control System Points List*

The example provided at the end of this chapter can be edited to meet the needs of a project using building pressure for return fan control. Editing considerations should include:

- Coordination with the requirements of the narrative sequence and any logic diagrams.
- Clarification regarding the location of the indoor and outdoor pressure reference points, including any special hardware requirements and multiple sensor requirements.
- Clarification regarding the type of technology that will be used for measuring differential pressure.

### *Narrative Control Sequence*

The example provided at the end of the chapter can be edited to meet the needs of a project using building pressure for return fan control. Editing considerations should include:

- Coordination with the requirements of the points list and any logic diagrams.
- Clarification regarding the required set point.
- Clarification regarding the interface between the relief dampers and the return fan operation, if any.

Each of these topics will be discussed in further detail in the following paragraphs.

### *Set Point Selection*

It is appropriate for the designer to specify the initial set point anticipated for the system. This helps to establish and document the design intent, although it may be necessary to modify the initial specification during the commissioning process to tune the system to the actual building characteristics.

Set point requirements can vary and should take a number of factors into consideration including the following:

- *Indoor to Outdoor Humidity Relationship:* One of the primary reasons for controlling infiltration or exfiltration is to prevent condensation from occurring within the envelope materials.

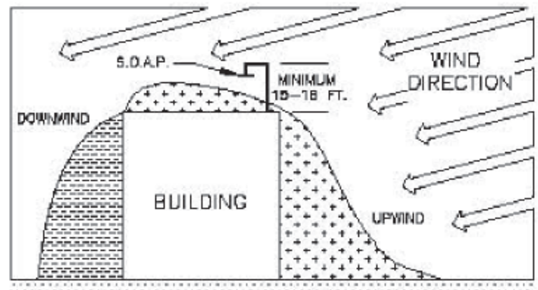
  *For a building located in a humid climate, it is generally desirable to maintain a positive building pressure at all times. A positive set point in the range of 0.05 to 0.10 in.w.c may be appropriate to minimize infiltration in the top floor (summer operation), and the bottom floor (winter operation).*

  *For a building in a dry climate that is humidified or has a significant latent load it is often desirable to maintain a neutral or slightly negative pressure in the range of 0.00 to -0.05 in.w.c, relative to outdoors. This will minimize exfiltration and the potential condensation of warm indoor air inside the exterior wall cavities.*

[2] Conditions that could cause this might include low load conditions, open operable windows or loading dock doors, etc.

*In a mild to dry climate or for a non-humidified building in a cold climate, condensation may not be as much of a concern, and maintaining a slightly positive building static pressure, 0.00 to 0.05 in.w.c. may be desirable. This will minimize infiltration and improve comfort on the perimeter zones, especially in locations with entryways.*

- *Wind:* The impact of wind can be significant but highly variable and difficult to predict as can be seen from Figure 4-4. In locations where there is a predictable prevailing wind, accommodating its impact on building pressurization via set point selection may be appropriate. In areas where it can be highly variable, the impact may be better accommodated or mitigated by the selection and configuration of the outdoor air pressure reference, as was discussed previously under *Locating Indoor and Outdoor Pressure Reference Points and their Associated Transmitter* and illustrated in Figure 4.3.
- *Building Functions:* The functions occurring within a building may influence the selection of the building pressurization set point. For example, the operating rooms in a surgical suite will most likely need to be positive relative to both the clean corridor and dirty corridor serving them. The clean corridor will most likely need to be positive relative to the dirty corridor and the dirty corridor may need to be positive relative to atmosphere to prevent infiltration via an emergency exit door that is located in it. Clean rooms and labs may have similar pressure cascade requirements that influence the selection of the building pressurization set point.
- *Sound:* Selecting a building pressurization setpoint that forces the neutral plane to the lobby level in a high-rise building can create positive pressures that are high enough on the upper floors to cause whistling through the cracks, operable windows and doors to observation decks. Thus, it may be necessary to compromise on a setting that minimizes infiltration at the lobby level while preventing occupant complaints in other areas.
- *Elevator Door Pressure Differential:* Elevator shafts can act like chimneys through the building, exposing the elevator doors to the full indoor to outdoor pressure differential.




| WIND VELOCITY MILES PER HOUR | UPWIND SIDE INCHES W.C. | DOWNWIND SIDE INCHES W.C. |
|---|---|---|
| 10 | 0.035 | −0.015 |
| 15 | 0.088 | −0.025 |
| 20 | 0.14 | −0.050 |
| 25 | 0.22 | −0.065 |
| 30 | 0.30 | −0.090 |
| 35 | 0.42 | −0.125 |
| 40 | 0.54 | −0.180 |
| 45 | 0.70 | −0.260 |
| 50 | 0.85 | −0.340 |
| 55 | 1.06 | −0.425 |
| 60 | 1.28 | −0.540 |
| 65 | 1.70 | −0.700 |

*Figure 4-4. The Impact of Wind on Building Pressurization (Image courtesy of www.AirMonitor.com)*

Most manufacturers specify a maximum pressure differential that can be accommodated before elevator door operation is affected. This requirement may influence or even dictate the final building pressure set point. (Trane)

- *Americans with Disabilities Act (ADA) and Security Requirements:* Building static pressure also influences the force required to operate external doors. ADA requirements dictate the maximum allowable force required to operate an entry door and thus, may constrain the maximum allowable building static pressure, especially if the doors are large. Excessive pressures can also over-power door closers and latching systems, causing doors to blow open and creating security problems in some locations. In most situations, ADA and security issues will limit the maximum allowable building pressure to 0.15 in.w.c. or less. The direction in which the door swings relative to the positive or negative pressure will dictate whether ADA or security concerns are the controlling factor. For instance, a door that swings out will have an ADA limitation if the building is negatively pressurized since the pressure will tend to hold the door closed. It will have a security limitation if the building is positively pressurized since the pressure will tend to blow the door open. If the door in question were to swing in, then a positive pressure will create an ADA limitation and a negative pressure will create a security concern.

### *Sequencing the Relief Damper and Return Fan*

An efficiency opportunity unique to the building pressure control strategy involves sequencing the relief dampers with the return fan to control building pressure. This also mitigates the potential for inducing reverse flow through the relief dampers discussed in the previous section.

When economizer equipped fan systems are operating on an economizer cycle, some or all of the air handled by the return fan is discharged through the system's relief louver, with the amount varying as a function of the operating state of the economizer. Given:

- the variable flow nature of the VAV systems typically associated with variable speed return fans; and
- the square law relationship between pressure and flow in the return airflow path; and
- the fact that by its nature, a building pressure based return fan control process will exfiltrate some of the relief air through cracks in the building envelope;

There will most likely be conditions when the required level of relief can be accomplished by simply opening the relief dampers without the operation of the return fan. When conditions reach the point where the relief dampers are wide open and the building pressure begins to exceed set point, then the return fan can be placed in operation and its speed varied as necessary to maintain pressure by relieving air through the open relief dampers.

The energy saving benefit associated with reduced return fan operation when employing this strategy may justify the added complexity and merit its consideration as the design develops.

### *Sheave and VFD Adjustment Coordination for Design Conditions*

As is the case with all of the return fan strategies discussed in this guideline, using the fan sheaves to set up the return fan to maintain the desired static pressure at the design operating condition with the variable speed drive operating at 100% speed will optimize overall efficiency and controllability as discussed in *Appendix 6: Electrical and Drive System Considerations* under *Maximizing Efficiency*. This contingency can be addressed in the narrative sequence, but should also be noted in the commissioning and testing and balancing section of the specification to ensure it is accommodated by all trades working on the project.

### Air Handling System Considerations

Many of the air handling system considerations discussed in *Chapter 1: Introduction and Fundamentals* apply to this strategy, including:

- Economizer damper selection, sizing, and installation.
- Return flow path versus relief flow path pressure losses.
- Integration with HVAC system and building functions and processes including building and zone level pressurization and minimum outdoor air flow regulation.

### Electrical System Considerations

Many of the electrical system considerations discussed in *Chapter 1: Introduction and Fundamentals* apply to this strategy including:

- Variable speed drive application, networking, and interlock issues.
- Motor selection and application issues.

## 4.6 Key Installation Issues and Considerations

Many of the design issues discussed in the preceding section and the operating issues discussed in the next section have a direct bearing on system installation. Therefore, reviewing the design intent for the strategy and its operating requirements is a crucial step in successfully installing and starting up the system. *Appendix 7: The Relationship Between Design, Installation and Operation* includes a discussion of a general nature on this topic. The information in this chapter is particular to building pressure control strategies.

To ensure overall success on all fronts, the design issues must be complemented by field efforts focused on the issues discussed in the following paragraphs.

### Adequate Equipment Procurement

A thorough shop drawing review process can go a long way toward ensuring that the design intent is reflected in the equipment provided. A discussion of important areas to target is included in *Chapter 1: Introduction and Fundamentals* under *The Relationship Between Design, Installation, and Operation*. Of particular importance with regard to a building pressure control strategy is the technology used to measure building static pressure and the provisions made for terminating the sensing lines at the location selected for pressure reference. These topics are discussed in detail earlier in this chapter under *Key Design Issues and Considerations – Control Considerations – Hardware*. The shop drawings should reflect the requirements of the contract documents for these items. If the contract documents do not directly address these issues, then it will be desirable to address them during the shop drawing review and approval process to prevent problems down the road.

### Locating and Installing Sensors in the Field

As was discussed earlier in the chapter under *Key Design Issues and Considerations – Control Considerations – Hardware*, the location of the pressure references used in a building pressure approach is critical to success and should be addressed in the design documents. However, existing conditions can raise issues that compromise the design intent and must be resolved in the field. Ideally this should be accomplished in consultation with the designer to ensure that the intent is not compromised.

If the design documents do not directly address the location of the pressure references, the issue should be brought up with the designer as soon as possible. This will ensure the intent of their design can be realized before construction progress makes access to the optimal location difficult and/or expensive.

Related to the issue of sensor installation is filtering of the input. Building static pressure signals can be very "noisy" due to door activity and the low level parameter being measured. If the return fan tries to follow each and every deviation, no matter how small, operational difficulties can arise, as is illustrated in the case study at the end of the chapter. Filtering the building static pressure input so that it reflects the average condition rather than the instantaneous condition can improve control system stability and prevent nuisance alarms. Most current technology systems provide filtering capabilities as a standard feature. Lacking that, capacitors or inductors can be wired into the input signal circuit to dampen out minor variations and smooth the input. Stand alone filtering modules offered by several process control manufacturers offer a similar capability in a non-custom, more easily documented and implemented arrangement if so desired.

### Monitoring Envelope Integrity During Construction

Given that:

- the integrity of the building envelope is critical to the success of this strategy; and
- the integrity of even the best of envelope designs is ultimately determined by the field conditions under which it is fabricated;

Close monitoring of the quality of the fabrication process is in everyone's best interest. Frequently, the installing contractor's field manager is in a good position to monitor the envelope fabrication process as they work on the site on a daily basis. Alternatively, this task can be contractually assigned to a commissioning provider as part of the overall commissioning and quality control process.

### Pre-start and Start-up Checklist Considerations

The pre-start and start-up considerations for building pressure control strategies are no different from the general requirements for any other strategy with one exception. For systems where long tubing runs are required to connect the building static pressure sensor to one or both of the reference points, the designer may have specified that the tubing be leak tested to verify its integrity as was discussed under *Key Design Issues and Considerations*. Such a test should be accomplished while the tubing system is accessible for inspection and repair in the event that a leak is identified.

See *Chapter 1: Introduction and Fundamentals* under *The Relationship Between Design, Installation, and Operation* for additional information regarding general pre-start and start-up considerations.

## Testing Considerations

Typically, setting up the system and testing it involves close coordination between the mechanical contractor, the controls contractor and the balancing contractor to tune the drives, fan speeds, and setpoints as necessary to deliver the desired level of building pressurization. Given the highly variable nature of the factors that impact a systems ability to pressurize the building as intended and the tendency of envelope integrity to decay over time, the following items should be considered as a test plan is developed.

- Independent measurements should be taken at the pressure reference point to confirm the intended pressurization requirements are being met. This should be done for various system operating modes including minimum flow, maximum flow, minimum outdoor air, and 100% outdoor air. If there are multiple systems serving the building, pressurization should also be verified under all of the anticipated operating modes. This may involve checking each of the operating states listed previously with the maximum number of systems on line and the minimum number of systems on line and at one or more points in between.
- Confirming the mechanical system can deal with seasonal issues like stack effect may require seasonal testing under some or all of the different operating modes identified in the preceding bullet.
- In large, complex buildings, it may be appropriate to document building pressure at other critical points in the building in addition to the reference point. Consider entrances and other breaches in the building envelope located on different exposures, yet served by the same air handling unit. If this testing reveals problems maintaining building pressurization, adjustments in the sensor location or set point may be necessary.

Contemplation of the multiple operating modes and seasonal contingencies listed in the preceding bullets can be daunting for good reason. Performing forced response testing to verify all of the potential operating scenarios that might occur in a complex building would be a significant undertaking. This is an area where an approach that:

- Verifies performance in one or two critical operating modes via forced response testing and then;
- Exploits the data logging capabilities of the building's control system or independently deployed data loggers to identify and assess issues identified by the natural response of the building as it moves through its various operating modes and the seasons;

Can reduce labor requirements and provide a more accurate picture of the issues that need to be addressed.

Because envelop integrity is crucial to the success of this strategy, utilizing some sort of envelope testing strategy as a part of the commissioning process may be desirable for a number of reasons.

- The test results provide a baseline for assessing the integrity of the envelope as the building ages and goes through renovations if the test is repeated as a part of a continuing or ongoing commissioning process.
- Performed as an *assessment test* rather than an *acceptance test*, the data gathered may provide useful insights into where problems may lie as was the case with the high-rise illustrated in Figure 4-2. If the test can be performed after the envelope is substantially complete but before final finishes are in place, any problems identified will be easier and less costly to repair.

Finally, because pressurization based control systems have little direct impact on the minimum outdoor air flow rate, the testing and commissioning involved to set up a system of this type does not necessarily ensure that the proper ventilation rates for the system have been set up. Thus, an independent testing process targeted at verification of ventilation should be included in the commissioning process. A detailed description of the considerations and test process required to ensure proper minimum outdoor air flow can be found in *Appendix 4: Tuning Outdoor Air Flow to Design Specifications*.

## 4.7 Key Operating Issues and Considerations

Many of the issues discussed in the preceding paragraphs in terms of design and installation will ultimately become operational issues. Reviewing and understanding key design and implementation issues will allow the operating staff to develop an understanding of the design intent for the strategy and its implementation. This can be a crucial step in successfully operating a system regardless of the control approach employed.

### Operating and Monitoring the Process

The control sequence and points list included at the end of this chapter will provide a good starting point for developing an understanding of the operating details associated with this strategy. In addition, they illustrate where the operating staff interfaces with the control system to adjust and monitor it. Additional information applicable to the operation of all return fan control strategies can be found in *Appendix 7: The Relationship Between Design, Installation and Operation*.

Any air-handling system that employs this strategy and is affected directly by additions or renovations or indirectly by changes to adjacent spaces or the building envelope should receive attention before and after these changes are completed.

Pre-renovation assessment considerations might include:

- Documentation of the envelope integrity, ventilation rates, and pressure relationships to provide a baseline for comparison subsequent to renovation.
- Identification of alternative operating strategies to be employed during periods in the renovation cycle when pressurization will be compromised or impossible, thereby invalidating a pressurization based control strategy.
- Coordination of the existing requirements with the design intent and requirements of the new areas and systems created by the renovation.
- Budgeting and planning for modifications of the existing system in the renovation that may render the current operating strategy ineffective due to changes in the envelope or the relocation of major envelope breeches like lobbies and other entry-ways.

Post renovation assessment considerations might include:

- Re-evaluation of the ventilation flow rate, building pressure relationships, and building static pressure.
- Testing and balancing as necessary to re-establish the supply, minimum outdoor air flow and return flow relationships and the associated static pressure and minimum outdoor air flow set points.
- Testing and balancing under variable load conditions to ensure that the relationships established under the preceding bullet hold under all anticipated operating conditions.

Many of the concepts discussed in Appendix 4: Tuning Outdoor Air Flow to Design Specifications will prove useful for the operating staff as they tune the system to the changing requirements of the area it serves.

Building Pressure Control Troubleshooting Table

While not all inclusive, this table illustrates many of the more common problems that can occur with a building pressure control strategy and the associated corrective actions. Some troubleshooting issues will be general in nature while others will be specific to a particular system by virtue of the control sequence and wiring configuration associate with it. The following table is based on the system illustrated at the beginning of the chapter with a control sequence as described in Section 4.10 Sample Narrative Sequence of Operations.

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Fails To Start | Loss of Power | • Verify the integrity of the power supply from the motor back to the source. If tripped circuit breakers or blown fuses are encountered, determine and correct the cause of the fault prior to restoring power. |
| | Interlock Problem | • After verifying that the fan can be safely run alone, switch the fan to "Hand" and observe the results.<br>■ If the fan still fails to start, the problem is most likely in the safety interlock circuit (fire alarm, relay, smoke detector, etc.). Investigate and correct interlock problems in the safety interlock circuit associated directly with the return fan.<br>■ If the fan runs, the problem is most likely in the interlocks associated with scheduled operation of the fan and other automation requirements. Verify the controlling software that cycles the fan in the "Auto" mode as well as any hardwired interlocks with other equipment like the supply fan. A safety trip that is preventing a supply fan start (freezestat, static switch, smoke detector, etc.) could prevent a return fan start if the return fan is interlocked via hardwiring or software to only run when the supply fan runs.<br>• If the fan fails to run in "Hand" or "Auto" and the drive is equipped with a "Bypass" option, switch the fan to "Bypass" after verifying that it is safe for the fan to run at full speed.<br>■ If the fan starts and runs in bypass, the problem is most likely in the VSD itself (see below).<br>■ If the fan fails to start in the bypass mode, the problem is probably one of the other issues listed in this table. |
| | VSD Failure | • Verify the integrity of the drive circuitry using the manufacturer's troubleshooting guidelines as published in the operation and maintenance manual. |
| | Drive System Failure | • Verify the integrity of the drive belts and sheaves or couplings. |

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Fails To Start (cont'd) | Motor Failure | • Isolate the motor from the power system and all controllers, drives, starters, etc.<br>■ Spin the motor shaft by hand to assess the integrity of the bearings. The shaft should spin freely and smoothly. Investigate and correct any unusual noise, jams or restrictions to free movement.<br>■ Inspect the motor connections for security and signs of overheating or resistive connections. Correct any discrepancies found.<br>■ Megger test the motor to measure the insulation resistance to ground. Correct any grounded conditions before reapplying power to the motor. Usually this will involve removing the motor and sending it out for repair.<br>• If the motor spins freely, the connections are good, and there are no grounds, cautiously reapply power (monitor the inrush current during this process) and verify:<br>■ The motor starts and comes up to speed.<br>■ The motor inrush current drops off as the motor comes up to speed.<br>■ The current on all phases is balanced and does not exceed the motors nameplate rating.<br>• If the motor currents are over nameplate disconnect the load and restart the motor. Verify the following:<br>■ No-load motor amps are approximately 50 to 70% full load amps for 900 – 1200 rpm motors (Some may be higher), approximately 30% full load amps for 1800 rpm motors and are approximately 20 to 30% full load amps for 3600 rpm motors. If the no load currents are balanced and within the limits listed above, the motor is probably being overloaded (see below).<br>■ If the no-load currents are out of balance or exceed the limits listed above, the motor windings are probably shorted and the motor will need to be removed and repaired.<br>• If the motor currents are severely imbalanced (in excess of 10% different) check the following:<br>■ Verify that the voltage supplied to the motor is within 5% of the line voltage rating. Investigate and correct the cause of any observed low voltage condition.<br>■ Verify that the phase to phase voltages are balanced and are within 5% of the line voltage of each other. If the phase voltages are balanced but the currents are imbalanced, there is probably a short in the motor winding and the motor will need to be removed and repaired. |

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Fails To Start (cont'd) | Overload Trip | • If a new motor has been installed on the fan, verify that the moment of inertia rating ($WR^2$) of the new motor is equal to or better than the motor it replaced (see *Appendix 6: Electrical and Drive System Considerations* for additional information.)<br>• Verify that the wiring connections to the overload relay are tight.  Loose wiring connections represent a resistive load that can generate heat and trigger a false overload trip.<br>• Inspect and clean the fan wheel as necessary. Dirt on the fan wheel increases its moment of inertia and can cause start-up problems to "suddenly" appear in a fan that has been running satisfactorily (see *Chapter 1:  Introduction and Fundamentals – Maintaining and Adapting Design Intent - Fan Wheel Cleanliness* for additional information.) |
| Return Fan Fails To Stop | Fan Remains in Operation Despite a Safety Trip That Should Directly Shut Down the Fan | • Safety trips intended to directly affect the return fan should shut down and lock out the fan irrespective of the position of any Hand-Off-Auto switches or Inverter-Bypass switches. If a fan remains in operation after a safety trip, investigate and correct problems in the safety interlock circuit. |
| | Fan Remains in Operation Despite a Supply Fan Shut Down Due to a Safety Trip | • Verify that the drive is in "Auto". If the drive is in "Auto" and continues to operate when it should be off, investigate and correct problems in the control logic associated with supply fan interlocks. |
| | Fan Remains in Operation When It Should Be Off Based on Schedule | • Verify that the drive is in "Auto". If the drive is in "Auto" and continues to operate when it should be off, investigate and correct problems in the control logic associated with the return fan start-stop functions. |
| Return Fan Speed Does Not Vary | Return Fan Speed Does Not Vary Despite Supply Fan Speed Variations | • If the return fan VSD is equipped with a bypass system, verify that the system is in "Inverter" (VSD active) and not "Bypass" (VSD bypassed and out of the circuit).<br>• Verify that the return fan VSD speed control selection is in the position that causes the drive to follow a remote speed command. Typically this is the "Auto Speed Command" position. This selection may be made via a selector switch or via a keypad, depending on the drive design, manufacturer, and vintage.<br>• Verify that the speed control signal is available at the return fan VSD input terminals.<br>• Verify that the building pressure set point is as required. The preliminary settings specified by the designer were most likely optimized and tuned to the installed system during the commissioning process. These settings should be reflected in the commissioning report.. |

<table>
<tr><th>Symptoms</th><th>Possible Cause</th><th>Recommendation</th></tr>
<tr><td rowspan="2">Return Fan Speed Does Not Vary (cont'd)</td><td>Return Fan Speed Does Not Vary Despite Supply Fan Speed Variations</td><td>• Verify that the building pressure set point is achievable given the current integrity of the building envelope. If a major new breech of the envelope has occurred, intentional or otherwise, the supply system may no longer be able to pressurize the building, invalidating a pressure based control strategy.<br>• Verify that the return fan is in fact moving air. One method of doing this is to take manual control of the fan speed and carefully ramp it up and down to see if the indicated flow rate changes. (Exercise caution to ensure that you don't inadvertently create excessive building, zone or duct pressure relationships). If changes in speed do not produce flow or changes in flow, then the problem may be a belt failure or an issue with the return system that is affecting the return fan's ability to move return air through the system like a closed fire damper. If the return fan is moving air, then the problem could be an issue related to the integrity of the return system, like an open service door after the flow measuring station, but ahead of the return fan which is allowing the fan to move a lot of air without measuring the air flow.<br>• Verify that the supply flow is in fact varying with the changes in supply fan speed. There should be a fairly direct correlation between supply flow and supply fan speed. If there isn't, investigate and correct. Possible issues include fire/ smoke dampers that should be open but are closed, problems with the coordination of the outdoor air and return air dampers associated with the economizer process, an erroneous supply fan speed signal, and belt failures.</td></tr>
<tr><td>Return Fan and Supply Fan Speeds Do Not Vary</td><td>• Verify that the supply fan VSD is in "Auto" and not in a mode that would cause it to run at a fixed speed. If the supply fan is in "Auto" and its speed does not vary the problem could be:<br>■ A problem in the supply fan speed control system or related logic. Detailed troubleshooting of the supply fan speed control system is beyond the scope of this guide, but in general terms the procedure will be similar to that described above under Return Fan Speed Does Not Vary Despite Supply Fan Speed Variations.<br>■ A load condition that exceeds the supply fan's capacity may exist. This could be caused by a number of factors including a load condition in excess of design, a supply flow restriction, or conditions that have compromised the capabilities of the cooling or heating utility systems that condition the supply air (low refrigerant, high chilled water supply temperature, high cooling coil discharge air temperature, low heating coil discharge air temperature, low steam supply pressure, low hot water supply temperature, etc.). Troubleshooting of these issues is beyond the scope of this guideline.</td></tr>
</table>

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Pressure Relationships are Negative or Overly Positive Either Relative to the Outdoors or Relative to Adjacent Areas | Pressure Relationships are Negative or Overly Positive Regardless of the Operating Status of the Return Fan and its Related Air Handling System | • The problem is most likely not related to the return fan and is more likely related to:<br>■ Issues in a different system in the building.<br>■ Stack effect.<br>■ An imbalance between make up air either due to improper adjustment and balancing or due to the operation of an exhaust system without its associated make up system or vice versa.<br>■ Problems with a building static pressure control system that operates independently of the air handling system in question.<br>■ Modifications or changes have been made to the building's envelope, functions, or occupancy patterns. |
| | Negative or Overly Positive Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling System | • Verify that the static pressure control set point has not been changed and that the components associated with the control process (reference sensing ports, transmitter, wiring, I/O board) are not obstructed and are functioning properly.<br>• Verify the integrity of the minimum outdoor air control system including that minimum outdoor air is being introduced into the system in the proper quantities.<br>• Verify that the economizer damper system and related relief dampers are functioning properly including:<br>■ Maximum outdoor air, return air, and relief air dampers operate freely and through their full stroke.<br>■ Maximum outdoor air, return air, and relief air dampers operate with the correct relationship to each other (return dampers close as the maximum outdoor air dampers open, etc.).<br>■ Verify that the process controlling the relief dampers, if different from the process controlling the economizer, is functioning properly.<br>• Verify that the minimum outdoor air flow control process is functioning properly. See *Appendix 4: Tuning Outdoor Air Flow to Design Specifications* for information on testing if it is necessary to re-tune the system.<br>• Verify that the return fan sheave or motor sheave have not been replaced with new sheaves with a different pitch diameter than the sheaves that were installed when the system was commissioned and tuned.<br>• Verify that the pitch diameter on a fan or motor equipped with an adjustable pitch sheave has not changed. |

| Symptoms | Possible Cause | Recommendation |
|---|---|---|
| Pressure Relationships are Negative or Overly Positive Either Relative to the Outdoors or Relative to Adjacent Areas | Negative or Overly Positive Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling System | • Verify that there is not a restriction in the outdoor air intake system or relief system such as a louver that has become obstructed, turning vanes that have been obstructed by debris, etc. Bear in mind that the pressure drop represented by a restriction is a function of flow rate. Thus, a restriction in a VAV system may present a problem that seems to come and go as the flow rate increases and decreases.<br>• Determine if modifications have been made to the building's envelope, functions, or occupancy patterns in the area served by the return fan and its related air handling systems. Significant modifications in any of these areas may require re-assessment of the building static pressure set point and/or re-tuning of the system's minimum outdoor air flow. See *Appendix 4: Tuning Outdoor Air Flow to Design Specifications* and *Appendix 8: Theoretical Versus Actual Performance* for additional information. |
| Minimum Outdoor Air Flow Does Not Meet Requirements | Minimum Outdoor Air Flow Problems Exist Regardless of the Operating Status of the Return Fan and its Related Air Handling System | • The issues in this category will be similar to the issues discussed above under *Pressure Relationships are Negative or Overly Positive Regardless of the Operating Status of the Return Fan and its Related Air Handling System.* |
| | Minimum Outdoor Air Flow Problems Appears to be Related to the Operation of the Return Fan and its Related Air Handling System | • In small buildings or large complex buildings, problems with minimum outdoor air flow in one system may not manifest themselves as problems with pressure relationships in the building even though in theory, they should. For small buildings, this is usually because leakage rates between zones or through the envelope are large enough that they prevent the issue from showing up as a pressure relationship problem. In large complex buildings, the volume of the building or the interactions with other systems can mask the problem and prevent it from showing up as a pressure relationship issue. However, most of the issues are the same as those discussed above under *Negative or Overly Positive Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling System*. |

## 4.9 Sample Points List

The following tables illustrate a points list for the return fan in the system illustrated at the beginning of the chapter and can be used as a starting point for similar systems employing building pressure control strategies. It was developed using the points list tool contained in the *Control Design Guide*. This publicly available resource can be downloaded from www.PECI.org/FTGuide and used to develop a points list with characteristics similar to those illustrated for an entire system or project.

| Point Name | Sensor Information | | |
|---|---|---|---|
| | System and Service | Sensor/Interface Device [6] | |
| | | Type | Accuracy |
| **Analog Inputs** | | | |
| BldgStat | Building Static Pressure | Thermal dispersion; -0.10 to 0.10 in.w.c. | ±2% of range |
| RF1SpdFb | AHU 01 Return Fan 1 Speed Control Feedback | VFD programmable output | +/-1.0% FS |
| RF1kW | RF1 kW | VFD programmable output | +/-1.0% FS |
| **Analog Outputs** | | | |
| RF1Spd | AHU 01 Return Fan 1 Speed Control Command | 4-20 ma output | +/-1.0%FS |
| AH1Rel | Relief Damper Command | 4-20 ma output | +/-1.0% FS |
| **Digital Inputs** | | | |
| RF1POO | Return Fan 01 Proof of Operation | Current switch | N/A |
| RF1SSwSt | Return Fan 1 Selector Switch Status | Auxilliary contact | N/A |
| VFD1SSwSt | Supply Fan 1 VFD Selector Switch Status | Auxilliary contact | N/A |
| **Digital Outputs** | | | |
| AH1RFSS | AHU 01 Return Fan Start/Stop Command | Interface relay | N/A |
| **Virtual Points** | | | |
| RF1Hrs | RF 01 Accumulated Hours of Operation | Calculation based on proof of operation input | N/A |
| RF1SpdPGn | RF1 Speed Control Loop Proportional Gain | Manually set | N/A |
| RF1SpdIGn | RF1 Speed Control Loop Integral Gain | Manually set | N/A |
| RF1SpdDGn | RF1 Speed Control Loop Derivative Gain | Manually set | N/A |
| StatSet | Building Static Pressure Set Point | Manually set; initial value = 0.05 in.w.c. | N/A |
| **Hard Wired Points** | | | |
| RF1Fire | RF 01 Fire Alarm Shut Down Relay | Relay by fire alarm contractor | N/A |
| AH1VFDAux | AH1 VFD Auxilliary Contact | Auxilliary contact | N/A |

| Point Name | Alarm and Trending Information, General Notes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Features | | | | | | | | | | | Notes |
| | Alarms | | | | Trending | | | | | | | |
| | Limit | | Warning | | Samples [1] | Commissioning [5] | | | Operating [5] | | | |
| | Hi | Lo | Hi | Lo | | Time [2] | Local [3] | Archive [4] | Time [2] | Local [3] | Archive [4] | |
| **Analog Inputs** | | | | | | | | | | | | |
| BldgStat | Note 15 | Note 16 | None | None | 15 | 1 min | X | X | None | None | None | Note 18 |
| RF1SpdFb | N/A | N/A | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | |
| RF1kW | N/A | N/A | Note 26 | Note 26 | 15 | 15 min1 | X | X | 15 min | X | X | |
| **Analog Outputs** | | | | | | | | | | | | |
| RF1Spd | N/A | N/A | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | |
| AH1Rel | N/A | N/A | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | Note 17 |
| **Digital Inputs** | | | | | | | | | | | | |
| RF1POO | Note 13 | None | None | None | 15 | COV | X | X | COV | X | | Notes 7,9 |
| RF1SSwSt | Note 10 | None | None | None | 2 | COV | X | X | COV | X | | Notes 10, 11 |
| VFD1SSwSt | Note 10 | None | None | None | 2 | COV | X | X | COV | X | | Notes 10, 11 |
| **Digital Outputs** | | | | | | | | | | | | |
| AH1RFSS | Note 13 | None | None | None | 15 | COV | X | X | COV | X | | |
| **Virtual Points** | | | | | | | | | | | | |
| RF1Hrs | None | None | 1,000 hr. | None | None | None | None | None | None | None | None | Note 8 |
| RF1SpdPGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1SpdIGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1SpdDGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| StatSet | None | None | None | None | None | None | None | None | None | None | None | Note 17 |
| **Hard Wired Points** | | | | | | | | | | | | |
| RF1Fire | Open | None | None | None | None | None | None | None | None | None | None | Note 14 |
| AH1VFDAux | None | None | None | None | None | None | None | None | None | None | None | Note 13 |

**Notes:**

1. Samples indicates the minimum number of data samples that must be held in the local controller if it is trending the point. This may be based on the operating trending requirements. Higher sample capabilities tends to minimize archiving frequency.
2. Time indicates the required sampling time for the trending function (1 min = 1 sample per minute, 4 min = 1 sample every 4 minutes).
3. A check in the local column indicates that the trending only needs to be running in the local controller and the most recent value can write over the last value when the trend buffer fills up.
4. A check in the arcnive column indicates that the trend data must be archived to the system hard disc when trend buffer fills up so that a continuous trend record is maintained.
5. Commissioning trending requirements only need to be implemented during the start-up and warranty year. After the start-up and warranty process, the control contractor should set the trending parameters to the operating requirements listed.
6. See the specifications for additional requirements and details regarding sensor and interface device requirements.
7. Adjust to detect a belt or coupling failure by showing failure to run with the belt or drive coupling removed and the motor running.
8. Accumulate on a monthly basis and archive the monthly total to the hard disk on the last day of the month at midnight.
9. Provide an alarm if the equipment is running when it is commanded off. Provide an additional alarm if the equipment is not running when it is commanded on. Include time delays to accommodate system start-ups.
10. Issue an alarm if the manual override switch/Hand-Off-Auto switch is not in Auto.
11. If the DDC system provides this function as a standard feature in the firmware and software supporting its I/O boards, an independent contact on the override switch and associated physical point is not required.
12. Typical of all control loops. Provide commandable points for adjustment of loop setpoints, tuning parameters, and bias settings. Limit access to Lead Operator or higher.
13. Arrange contact to close any time the AHU1 supply fan is in operation under VFD control or in bypass and hardwire to start the fan.
14. Fire alarm shut down relays are furnished and installed by the fire alarm supplier and located at the motor starter location. Control wiring through the fan start circuit shall be by the electrical contractor. The control contractor shall coordinate this effort to ensure that the desired sequence is provided.
15. Issue an alarm if the building static pressure exceeds .10 inches w.c. During commissioning, coordinate the final set point with tests to ensure compliance with ADA requirements and the capabilities of door closers and latching systems.
16. Issue an alarm if the building static pressure drops below 0.0 inches w.c. for 5 or more consecutive minutes. During commissioning, coordinate the time delay to accommodate the variability associated with normal start-up and shut down. Supress the alarm when AHU1 is not in operation.
17. Coordinate the control of the relief damper with the return fan speed per the sequence of operation. Verify coordination and tuning during the commissining process.
18. Provide a flush mounted static pressure sensing head at the indoor sensing location and an outdoor pressure sensing head at the outdoor location. Sensing heads to be as manufactured by Tek-Air or Air Monitor Corporation or approved equal. Locate the transmitter in the phone equipment room adjacent to the lobby in an accessible location. Provide copper sensing lines from the sensor heads to the transmitter. Utilize soft copper to minimize the number of joints. Use compression or solder fittings for any joints and connections that are necessary.

## 4.10 Sample Narrative Sequence of Operations

The following narrative sequence is an example that applies to the return fan shown in the system diagram at the beginning of the chapter. It can be used as a starting point for similar systems employing building pressure control strategies.

### Return Fan Variable Speed Drive Control

#### *Overview*

This control sequence functions based on the following premises:

- Return fan speed and return fan capacity are directly related.
- The supply system associated with the return fan is introducing the correct amount of outdoor air into the building, either as required for minimum ventilation or as required by the needs of an economizer process.
- Building pressure is directly related to the amount of air moved by the return fan, either for recirculation by the supply side of its associated system or for discharge from the building.

In general terms, the strategy increases the return fan speed as building pressure increases and decreases the return fan speed as building static pressure decreases. The operation of the return fan is sequenced with the operation of the relief dampers to optimize energy consumption and prevent reverse flow through the relief louver.

For additional details on this control strategy, including installation, commissioning, and operating tips, refer to the application guideline titled *Return Fan Capacity Control via Speed Control* published by the National Building Controls Information Program and available for free download at www.buildingcontrols.org.

#### *Speed Control*

A thermal dispersion based differential pressure sensor provides a 4-20 ma output that is proportional to building static pressure. Mount the indoor sensing head in the ceiling of the lobby over the reception desk. Mount the outdoor sensing head in the open meter pit serving the gas meter that is located adjacent to the main entry.

The building pressure signal is used as an input to a PID based building static pressure control loop. The output of the loop is used to modulate the relief dampers in sequence with the return fan speed. As building static pressure deviates above set point (adjustable, initial setting = 0.05 in.w.c. positive relative to the outdoors), the relief dampers are modulated from closed to open. Further deviation causes the return fan to start at minimum speed and then ramp up as necessary to maintain set point. Pressure deviations below set point reverse the sequence.

Drive speed control shall be via a discrete hard wired interface between the control system and the drive. Network level interfaces between the control system and drive shall not be permitted for this function.

Control loop tuning parameters and variable speed drive acceleration times, deceleration times, minimum and maximum speeds shall be adjusted and optimized during the commissioning process.

Coordinate minimum speed settings for the fan with the motor and VFD supplier to ensure adequate motor cooling while achieving the lowest possible speed to minimize the step change that occurs when the fan starts. Anticipate an initial setting of 5 Hz based on the drive/motor combination specified.

#### *Start Stop Control and Proof of Operation*

The return fan variable speed drive shall be commanded on by a hard wired interlock any time the supply fan variable speed drive is in operation. It shall also be possible to command the drive on via the DDC system using a command from the operator's console.

A current switch sensing current to the variable speed drive shall provide a contact closure for proof of operation purposes any time the return fan motor is operating under load. The current switch shall be adjusted so that the proof of operation is not indicated if the motor is running but the belts have broken and thus the fan is not turning.

### Variable Speed Drive Interlocks

The following interlocks shall be provided for the return fan variable speed drive:

- External, Hard wired

  A start-stop interlock to the supply fan shall be hard wired into the variable speed drive control circuit. These interlocks shall function regardless of the status of the drive Hand-Off-Auto and Inverter-Bypass selector switches.

  A fire alarm shut down relay shall be wired into the circuit and arranged to shut down the fan on a building fire alarm condition per the programming requirements of the fire alarm system. Coordinate with Division 16 as required for wiring and programming of the fire alarm relay. Coordinate with Division 16 for the location and field installation of the duct mounted smoke detectors.

- External, Software based

  The return fan variable speed drive shall be commanded to 0 Hz any time the return fan is not in operation as indicated by the return fan status input.

- Internal

  The return fan shall be shut down and locked out if a motor overload condition is sensed in the "drive mode." Manual reset at the drive location shall be required to resume normal operation.

### Outputs to the DDC System

The following outputs shall be provided from the variable speed drive to the automation system. These outputs may be provided by discrete hard wired interfaces or by a network level interface at the contractor's discretion. The final installed condition shall be reflected in the "as-built" drawings.

- Drive speed feedback in Hz
- Drive kW

### Alarms: Operator

Operator alarms shall be delivered to the operator's console and logged on a dedicated alarm printer as they occur. The following operator alarms shall be provided:

- Indicate *AHU1 return fan failure to start or run* if the fan is not running when it should be, including a failure to start when commanded on for any reason or a shutdown that occurs when the fan should be operating per the operating sequence given the current conditions.
- Indicate *AHU1 return fan failure to stop or remain shut down* if the fan is running when it should not be, including a failure to stop when commanded off for any reason or any operation that occurs when the fan should be off per the operating sequence given the current conditions.
- Indicate *Lobby static pressure is not positive* if the supply fan has been running for five minutes or more (initial setting, adjustable) and the lobby pressure is not positive for five consecutive minutes or more (initial setting, adjustable). Suppress this alarm if the supply fan status is off.

### Alarms: Facility Management

Facility management alarms shall be directed to a weekly report, generated for the director of engineering and made available for viewing under their log-in. The following alarms shall be provided:

- Indicate *During the past week the AHU 1 return fan operated for a significant period of time when the supply fan was not operating* if the return fan operates more than one hour (initial setting, adjustable) when the supply fan is not operating. Reset the timer at the end of the week.
- Indicate *During the past week the AHU1 return fan has failed to operate for a significant period of time when the supply fan was operating* and the relief dampers were 100% open if the building static pressure set point was exceeded by 10% for 5 consecutive minutes (initial settings, adjustable) and the return fan fails to operate when the supply fan is operating with the relief dampers 100% open. Reset the timer at the end of the week.
- Indicate *During the past week, the AHU1 return fan operated with the relief dampers less than 100% open* if the return fan operated for more than 15 minutes with the relief dampers less than 100% open (initial setting, adjustable). Reset the timer at the end of the week.

- Indicate *During the past week, the AHU1 return fan speed did not vary significantly on one or more days* if the return fan speed does not vary by more than ± 5 Hz (initial setting, adjustable) between 30 minutes after start-up and the shut down time during any day on which the system operated.

### *Totalization*

The following totalization functions should be provided and the data should be archived to the system hard drive on a daily basis:

- Return fan hours of operation based on the proof of operation input for the current week, the current month, and the current year.
- Return fan kWh based on the kW input from the variable speed drive for the current week, the current month and the current year.

## 4.11 Case Study

This incident is actually an event that occurred in the context of a supply fan static pressure control loop. The return fan was controlled by a speed tracking strategy with multiple bias settings to accommodate the different supply fan operating modes. It is used as a case study for the building static pressure strategy because it is an excellent illustration of how sensitive building pressure control systems can be to breeches in the building envelope, especially when equipped with state of the art electronic or computer based control systems capable of detecting and responding to very small changes in the measured parameter. Building pressure based return fan capacity/speed control systems are highly susceptible to similar operational issues.

In the early 1980s, as variable speed technology was beginning to become cost effective in the commercial building industry, a nominal 40,000 cfm constant volume reheat system serving a hospital emergency room (ER), radiology suite, and lobby was retrofitted with an eddy current type variable speed drive. Two position dampers were added to the supply and return ducts serving the radiology suite and lobby. The dampers were controlled by a time clock so that they were open for the normal radiology suite and lobby hours of operation, but closed when the areas were not occupied. Manual over-ride switches allowed re-activation for non-normal operating hours. The setting of the dampers in the closed position was adjusted to provide the proper pressure relationships during the unoccupied hours. These changes allowed the constant volume fan system to be operated as an incremental volume fan system, maintaining constant flow to the emergency room around the clock, but shutting down flow to the other areas and saving reheat and fan energy during unoccupied hours.

The supply fan drive was controlled based on duct static pressure at a remote point in the duct system, specifically in the duct leading to a diffuser in the corridor that connected the emergency room with the patient wing. This location was selected because field testing indicated that controlling for a duct pressure of approximately 0.15 in.w.c. at this location would maintain the desired flow to the ER and also would ensure a positive pressure relationship relative to the patient wing. At the time the project was implemented, electronic sensing and control technologies were also beginning to emerge as viable and cost effective strategies for commercial buildings. As a result, the designer elected to use a stand alone electronic PID controller to control the supply fan drive, even though the rest of the air handling system was controlled via pneumatic technology. This made the interface to the eddy current clutch controllers much easier to accomplish and facilitated the use of a linear variable differential transformer (LVDT) type pressure sensor with a range of 0.00 - 0.50 inches w.c. This device had superior range, resolution and response characteristics when contrasted with those typically found in the available pneumatic product lines at the time.

The modification work proceeded smoothly as did the start-up once the learning curve associated with the new control technology was overcome. But, as the modified system began to operate on a day-to-day basis, an interesting problem emerged. Several times a day, the supply fan speed would begin to hunt. The oscillations were random in nature and would last 20 to 30 minutes and then disappear. The events occurred every day, regardless of the climate conditions and were so predictable that the operating engineers would joke about being able to set their watches by them.

The initial suspicion was that the step change introduced into the system when the dampers to the unoccupied zones opened was triggering the problem since it seemed to occur on a regular basis and at about the time the clocks would trigger the occupied cycle. But, closer investigation revealed three facts that shot down the theory.

1. The morning event actually started 10 - 15 minutes before the time clocks commanded the lobby and radiology damper open.
2. The evening event actually occurred 30 - 60 minutes before the time clocks commanded the lobby and radiology dampers closed.
3. There was an event that occurred late at night well after the dampers were closed and well before the time that the dampers opened.

After a lot of loop tuning, troubleshooting, and head scratching, the assistant facilities director had an insight that led to the solution of the problem; specifically, he noted that the hunting occurred around the time of a shift change. It turned out that the door used as an employee entrance was in the corridor that interconnected the ER and patient wing, within 10 to 15 feet of the diffuser that had the duct static pressure sensor in its supply duct. An investigation based on the assistant director's insight revealed that:

- Because the building was positive relative to the outside, opening the employee entrance door caused the local building pressure to drop.
- This drop in pressure showed up as a change in static pressure of about 0.03 inches w.c. in the supply duct at the duct static pressure sensor location used to control the supply fan speed.
- The duration of the change in pressure was a function of the length of time the door was open, ranging from 5 - 10 seconds if only one person went through the door to 30 - 45 seconds if a group of people were leaving.
- Irrespective of the duration, the supply transmitter picked up the change and dutifully transmitted it to the controller which endeavored to change the speed of the supply fan and correct for the deviation from set point. All of this happened nearly instantaneously.
- Unlike the controller, the fairly massive fan wheel in the 40,000 cfm fan system took some time to accelerate in response to the change in input. In fact, close observation revealed that by the time the fan had started to ramp up, the door was closed and the duct static pressure was driving above set point due to the increasing fan speed.
- The control system would endeavor to make a correction in the opposite direction. If nothing else happened at the door, things would stabilize after a few cycles, which typically took several minutes. But, if someone opened the door again before things had settled out, another upset would occur and the instability would persist.

The bottom line was that when a shift change occurred, the door opening events occurred more frequently than the system settling time, driving the system into a period of random instability that would disappear when the shift change was over and the door operations ceased.

Correcting the problem was fairly simple; a capacitor installed across the input to the controller filtered out the short duration voltage spikes produced by the pressure fluctuations that occurred when the door opened and closed quickly. But, it allowed gradual and persistent trends to be reflected at the controller input. As a result, the system was responsive to the changes that occurred when the time clock closed the dampers, but rode through the minor pressure changes produced by the shift change. As a side benefit, aside from learning a lot about system dynamics and integrated operation, the design engineer also learned that electrolytic capacitors are polarity sensitive and make a really loud bang if you hook them up backwards, even on a low voltage control input.

## 4.12 Additional Resources

Additional guidance can be found in *Installation and Maintenance of V-Belt Drives*, another useful tool that is provided as a free resource from the TB Woods Company at http://www.tbwoods.com/pdf/VBD-IM_InstallationandMaintenance.pdf

For more information on Building Pressurization test procedures that can be implemented in the field to assess envelope integrity see:

Sellers D, Friedman H, Luskay L, Haasl T, Moore E (2004a). "Commissioning and Envelope Leakage: Using HVAC Operating Strategies to Meet Design and Construction Challenges." *Proceedings of the 2004 ACEEE Summer Study on Building Efficiency*.

For additional information on stack effect, see the *Glossary of Terms* at the end of this guideline and this reference:

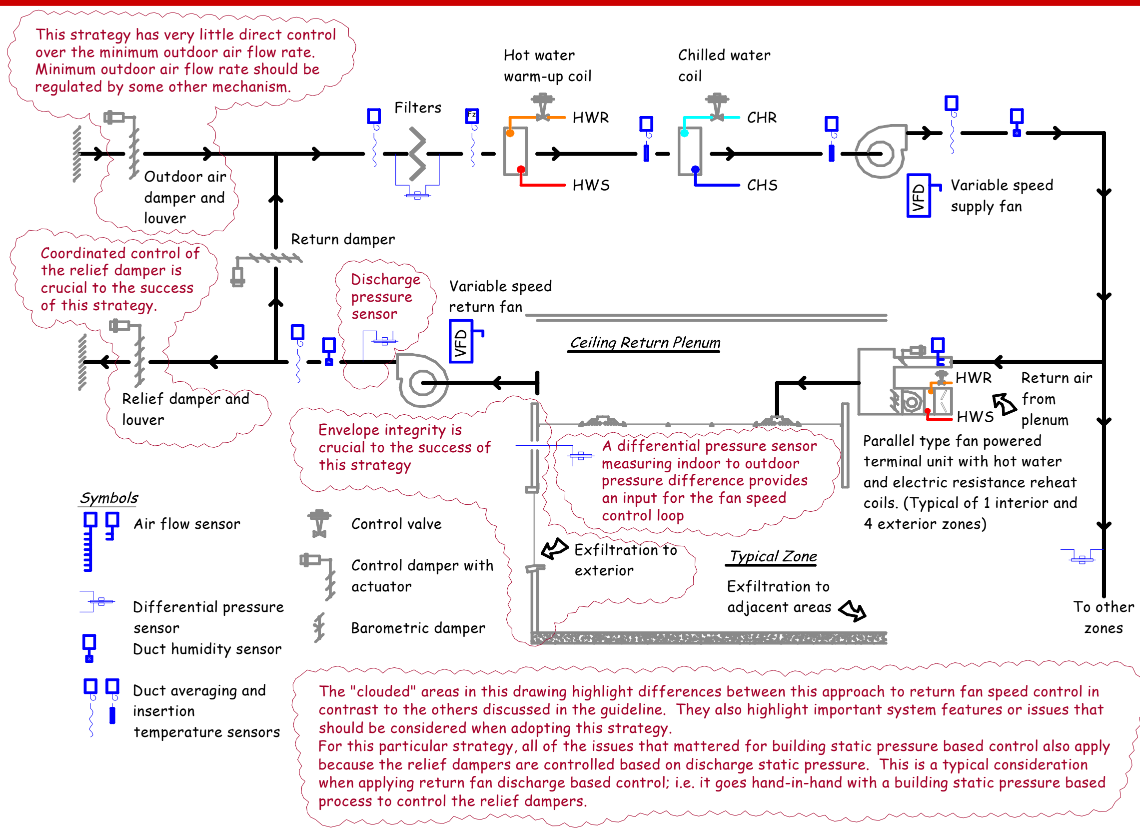
Stanke, Dennis (2002). "Managing the Ins and Outs of Commercial Building Pressurization."

# 5. Discharge Pressure Control

This chapter will discuss discharge pressure control of return fan speed. Most implementations of this approach are very similar to the building pressure based approach discussed in *Chapter 4*. It is also important to note that this approach is the method of choice in *ASHRAE Guideline 16P - Selecting Outdoor, Return, and Relief, Dampers for Air-side Economizer Systems*.

## Chapter 5 Contents

## Discharge Pressure Control




*A Typical VAV Air Handling System with Return Fan Discharge Pressure Based Control*

## General Description

This strategy modulates return fan speed as required to maintain a constant discharge static pressure, thereby serving as a constant pressure air source for the economizer and relief damper control processes. It is typically used in conjunction with a building pressure based control strategy for the relief dampers, but can provide superior response characteristics when contrasted with an approach that uses building pressure to control the return fan speed directly, an approach which is described in *Chapter 4: Building Pressure Control* of this guideline. It also accommodates situations where multiple systems exist and a common building static pressure control process is utilized, allowing the benefits of that strategy to be realized without having it be dependent upon any individual air handling system.

## Advantages

- All the advantages of a building static pressure based approach with the potential for a better response characteristic.
- Can accommodate multiple systems using a common building static pressure based control strategy.

## Limitations

- No strategy specific limitations, but because it must be applied in conjunction with some sort of control process for the relief system, and because that process is typically building pressure based, the limitations discussed in *Chapter 4: Building Pressure Control* of this guideline should be considered.

## Application Considerations

| Characteristic | Low | Medium | High |
|---|---|---|---|
| Application Complexity | | ✓ | |
| Potential for Negative IEQ Impact | ✓ | | |
| Potential for Negative Energy Impact | ✓ | | |
| Potential for Integration/Interaction Problems | | | ✓ |
| First Cost | | ✓ | |
| Maintenance Cost | | ✓ | |
| Energy Cost | | ✓ | |

## Key Design Issues and Considerations

- This strategy must be applied with some sort of relief damper control strategy. Typically, a building static pressure based approach is used. *Chapter 4: Building Pressure Control* of this guideline provides a detailed discussion of applicable considerations associated with controlling a return fan based on building pressure. Most of these considerations will apply to any building pressure based control approach.

- A loss of input signal failure will typically cause a return fan that is controlled by this strategy to drive to full speed. Fans that are capable of delivering pressures that exceed the duct pressure class for the ductwork on their discharge or the inlet side of the supply system may require additional safety systems to protect them in the event of this occurrence.

- The discharge pressure sensor should be located at a point in the duct system where a stable, fully developed flow profile is achieved or in a plenum downstream of the fan.

## Key Installation Issues and Considerations

- This strategy must be applied with some sort of relief damper control strategy. Typically, a building static pressure based approach is used. *Chapter 4: Building Pressure Control* of this guideline provides a detailed discussion of applicable considerations associated with controlling a return fan based on building static pressure. Most of these considerations will apply to any building static pressure based control approach.

- Testing in the 100% outdoor air and 100% relief air mode can be critical for ensuring performance in all operating modes

## Key Operating Issues and Considerations

- This strategy must be applied with some sort of relief damper control strategy. Typically, a building static pressure based approach is used. *Chapter 4: Building Pressure Control* of this guideline provides a detailed discussion of applicable considerations associated with controlling a return fan based on building static pressure. Most of these considerations will apply to any building static pressure based control approach and thus, apply to this strategy.

# 5. Discharge Pressure Control

This control strategy modulates return fan speed and capacity to maintain a constant pressure in the discharge air plenum of the return fan. Given the close-coupled nature of the fan and its controlling sensor, the control strategy is one of the most responsive of all of the strategies discussed in this guideline.

Additional information generally applicable to all return fan speed control strategies can be found in *Chapter 1: Introduction and Fundamentals*. Additional useful resources outside of this guideline are listed at the end of the chapter.

## 5.1. General Description

As is the case with all of the return fan capacity control strategies in this guideline, this strategy is built on the fundamental relationship between fan capacity and rotational speed. The unique aspect of this strategy is that it assumes that if the discharge pressure of the return fan is maintained at a fixed value that is high enough to either:

- deliver the design return flow through the return dampers to the economizer process; or

- deliver the design relief flow through the relief dampers and louvers to the building exterior;

then the performance of the fan will be matched to the needs of the supply system it serves.

When this strategy is employed, the relief dampers are typically controlled based on building static pressure or a building pressure relationship between two adjacent zones. It is this secondary control relationship that provides a nearly direct connection between the pressure at the discharge of the return fan and a parameter that reflects the variable flow operation of the supply fan.

Because of this building pressure control aspect, the characteristics and application considerations for a return fan discharge based strategy are very similar to those associated with the building pressure based approach discussed in *Chapter 4: Building Pressure Control*. Thus, the reader is encouraged to review *Chapter 4* in addition to this chapter when applying this strategy.

As was the case for building pressure control, this strategy has a less direct impact on minimum outdoor air flow when contrasted with strategies like flow tracking or mixed air plenum pressure control where the fan's control parameter has a direct impact on outdoor air flow. But, discharge pressure control can be very interactive with the economizer process and would exhibit a similar type and level of interaction with an active minimum outdoor air control process. This interactivity will be discussed in greater detail under *Key Design Issues and Considerations*.

### Variations

The variations on this strategy are related to how the relief dampers are controlled rather than to the control of the return fan speed. The two most common approaches for relief damper control are:

- *Building pressure based* where the dampers are modulated to maintain a pressure relationship relative to the building exterior. This approach is the method of choice in *ASHRAE Guideline 16P - Selecting Outdoor, Return, and Relief, Dampers for Air-side Economizer Systems*.

- *Zone pressure based* where the dampers are modulated to maintain a pressure relationship between adjacent zones in the building.

Properly implemented and adjusted, either of these approaches will provide excellent results when combined with discharge static pressure based control of the return fan.

## 5.2. Advantages

When properly designed and implemented, this approach can be applicable to all building sizes and classes.

The primary benefits offered by this strategy are very similar to those to those associated with the direct static pressure based approach discussed in *Chapter 4: Building Pressure Control,* specifically*;*

- An ability to directly control infiltration and exfiltration through the building envelope.

- The ability to accommodate the dynamic nature of buildings and the environment they are located in.

The characteristics that make this strategy stand out from a building static pressure based approach are:

- The close coupled return fan discharge pressure control loop has the potential for a much quicker response to a change when contrasted with a building static pressure based loop. As a result, the control process has the potential to be more responsive.
- The independent return fan control loop allows a building with multiple air handling systems to control each system independently of the others while over-all building static pressure is controlled by a separate non-air handling unit specific process. This allows more flexibility in terms of air handling unit scheduling.

## 5.3. Limitations

There are no real limitations on system size or type to which this control strategy can be applied. Compared to the building static pressure control strategy, this strategy is slightly more expensive due to the installation and maintenance of both the building static pressure sensors and plenum pressure sensor. The control algorithm is also more complex which will increase programming costs, but the return fan plenum pressure control strategy typically yields better overall system performance. This will be discussed in greater detail under *Key Design Issues and Considerations*.

Approaches that apply this strategy and endeavor to control the relief dampers based on the pressure in the relief plenum tend to perform poorly. This approach to relief damper control can be encountered in systems where the equipment room is treated as a relief plenum. Typically, the problems encountered are related to the fact that the discharge of the return fan and the relief plenum are virtually the same point. Thus, there are two different control processes endeavoring to control the same parameter and the potential for adverse interactions and instability is high.

Approaches that endeavor to control the relief damper based on the same signal as is used to control the economizer dampers will also tend to perform poorly when applied in conjunction with this strategy because the return fan control process becomes virtually open loop when the system is operating on 100% outdoor air.

Proper economizer damper sizing is critical to the success of this strategy. Oversized economizer dampers will have a non-linear response that, in extreme cases, approaches that of a two position damper. Non-linearity in the economizer process can ripple out and make the return fan discharge static pressure control loop and building static pressure control loop difficult to control. Economizer theory and operation is discussed in detail in *Appendix 2: Economizer Theory and Operation*.

The pressure drop characteristics of the relief path relative to the return path are particularly important to this strategy. If the pressure required to deliver the design air flow through the relief damper to the building exterior is significantly different from what is required through the return damper to the mixed air plenum, then the return fan discharge static pressure setpoint will be inappropriate for on path or the other. This topic is discussed in greater detail in *Chapter 1: Introduction and Fundamentals*.

## 5.4. Application Considerations

### Application Complexity

Relative to the building pressure based approach, the complexity of this strategy is increased by the addition of the discharge static pressure control loop and the added interaction potential it represents. However, this added control loop may provide other benefits that justify it or may minimize or eliminate complexity elsewhere in the building.

### Potential for Negative IEQ Impact

The negative IEQ impact potential of this strategy is very similar to that associated with a building static pressure based approach. Specifically, it is primarily related to how well the control process is able to manage building pressure relationships and the related potential for infiltration and/or air movement between adjacent zones.

### Potential for Integration/Interaction Problems

At a system level, the addition of a control loop relative to some of the other approaches adds to the potential for integration and interaction problems. However, for complex buildings with multiple systems, the net effect may be an improvement in the ability to control building static pressure because the added loop provides a buffer between the building static pressure control process and the control of each air handling unit's return fan.

### First Cost

In new construction, this control strategy has the potential to have a moderate first cost as a result of the additional sensor and programming required when contrasted with the speed tracking, building pressure and mixed air pressure based strategies. However, the additional hardware and software costs are typically not as significant as those associated with a flow tracking based strategy.

In a retrofit application, this control strategy may be cost prohibitive if a building static pressure control process is not already in place and outside, return, and relief air damper control cannot be separated easily. The cost impact will be compounded if additional control system Input/Output points are not available, or if the installation of a building differential pressure sensor is problematic.

### Maintenance Cost

Maintenance cost considerations for this strategy are very similar to those associated with a building static pressure based approach although the additional sensor and control loop represent an incremental cost addition.

### Energy Cost

The energy related costs and benefits of this strategy are very similar to those associated with the building static pressure based approach. Specifically;

- Return fan energy will tend to be optimized.
- Perimeter heating loads will tend to be minimized.

For a detailed discussion of these topics refer to the *Energy Cost* section of *Chapter 4: Building Pressure Control.*

## 5.5. Key Design Issues and Considerations

Many of the issues discussed in the subsequent sections on installation and operation are intertwined with the decisions made during the design process. Thus, reviewing those sections to understand the challenges that will be faced during fabrication, start-up and operation can be crucial to a successful design. *Appendix 7: Design, Installation and Operation* includes a discussion of a general nature on this topic. The following information is particular to discharge pressure return fan control strategies.

### The Return Fan Discharge Plenum as a Constant Pressure Supply for Economizer and Relief Processes

From a functional standpoint, implementing this strategy causes the discharge of the return fan to become a constant pressure source of air for the air handling system's relief and economizer processes. The following discussion will assume that:

- The system's economizer process modulates the return and outdoor air dampers to maintain a temperature setpoint; and
- The system's relief process is controlled by building static pressure.

From the economizer's perspective:

- If the economizer control process requires more return air and less outdoor air to maintain setpoint, it closes the outdoor air damper and opens the return damper. As a result, air begins to flow from the return fan discharge into the mixed air plenum, raising the temperature. In turn, the pressure at the discharge of the return fan drops and the fan speeds up to move more air and maintain the desired setpoint.
- If the economizer control process requires less return air to maintain setpoint, it closes the return damper, restricting the flow from the return fan discharge into the mixed air plenum. As a result, the pressure at the discharge of the return fan rises and the fan

slows down to move less air and maintain the desired setpoint.

From the relief system's perspective:

- If the building static pressure drops, the building static pressure control process closes the relief damper, reducing air flow from the return fan discharge to the building exterior. As a result, the pressure at the discharge of the return fan increases and the fan slows down in an effort to maintain setpoint. This moves less air back from the occupied zone and tends to increase its pressure relative to the surroundings or building exterior, satisfying the building static pressure control setpoint.

- If the building static pressure rises, the building static pressure control process opens the relief damper, increasing air flow from the return fan discharge to the building exterior. As a result, the pressure at the discharge of the return fan drops and the fan speeds up in an effort to maintain setpoint. This moves more air back from the occupied zone and tends to decrease its pressure relative to the surroundings or building exterior, satisfying the building static pressure control setpoint.

Of course, in an operating fan system, the economizer and relief processes tend to operate in concert; changes in outdoor air flow that occur as the result of economizer modulation create changes in building pressure that cause the relief system to respond. Thus, in a typical system, the return fan is most likely reacting to the response of both processes simultaneously. And the fan's response feeds back into the other two control processes.

The bottom line is that the design of a system employing this strategy needs to consider and address all of these factors to be successful.

- Economizer and minimum outdoor air dampers need to be sized to provide a linear response characteristic.

- The relief and return flow paths should have similar pressure drop characteristics.

- The impact of the interactions between the various control loops in the system need to be considered and addressed.

- The impact of the interactions between the system, the building envelope, and other systems needs to be considered and addressed.

## Building Static Control via Multiple Loops versus a Single Loop

As indicated previously, the added complexity associated with an additional control loop in the building static pressure control process may have benefits in terms of improving the overall response of the control process. This is illustrated in Figure 5-1 which is the result of a simulation which contrasted a system with the return fan speed controlled directly by building static pressure (the approach discussed in *Chapter 4: Building Pressure Control*) and a fan controlled based on discharge static pressure with the relief dampers controlled by building static pressure.

The bottom line is that the cascaded control loops can improve the fan's response to changes in the building's operating environment. But, this comes at a cost; two cascaded control loops are a much more complex affair to tune and maintain than one loop. However, experience has shown that the benefit is often worth the cost.

## Control System Considerations – Hardware

Most of the control system hardware considerations discussed in *Chapter 1: Introduction and Fundamentals* and in *Appendix 5: Control System Hardware and Software* apply, including:

- Variable speed drive interlock issues.

- Economizer control integration issues.

- Return and relief damper interlock issues.

- Minimum outdoor air control issues.

- Building pressurization control integration issues.

Because the strategy typically relies on building pressure based control of the relief dampers, the control system considerations associated with building pressure based control of return fan speed also apply:

- Traffic rates through doors and other envelope penetrations.

- Locating indoor and outdoor pressure reference points and their associated transmitter.

- Very low differential pressure measurement technology.

Each of the topics is discussed in detail in *Chapter 4: Building Pressure Control.*

The following issues are unique to the discharge pressure control strategy:

- Loss of input failure mode.

- Fan discharge static pressure sensor selection and location.

Each of these topics is discussed in more detail in the following paragraphs.

*Loss of Input Failure Mode*

One of the more common failure modes for any control system is a loss of input. In the case of a discharge pressure control strategy, a loss of the input measuring fan discharge static pressure would typically look like a condition where the control point was below setpoint. This would cause the fan to run up to full speed, regardless of the requirements of the system. For this reason, over-pressurization safeties like limit switches, static pressure switches, and pressure relief doors may merit additional consideration for application with this strategy when contrasted with strategies like building static pressure control where a loss of input will cause the fan to go to minimum speed. Additional discussion on these safety interlocks can be found in *Chapter 1: Introduction and Fundamentals*.

*Fan Discharge Static Sensor Selection and Location.*

The discharge static pressure sensor should be selected so that the normal operating point (typically, the setpoint) is at approximately 50% of the sensor's span. While the return fan discharge pressure will typically be a positive value, providing a sensor with bi-directional capabilities will allow an alarm to be generated if the return fan discharge plenum becomes negative, an event associated with the failure of the return fan or its drive system and the induction of outdoor air through the relief system. For most applications a sensor with a range of -0.50 to 0.50 inches w.c. will be appropriate.

Obtaining a pressure indication that is a true indicator of fan discharge static pressure requires that the fan discharge velocity profile be taken into account. A sensor that is located at the physical discharge of the fan will be subject to the flow disturbances created by the non-uniform flow profile that exists at that location. As a result, the turbulence will make the signal even more erratic than a typical air pressure measurement, increasing the requirements for filtering and making the loop more difficult to tune. It will also not represent the actual static pressure that will be achieved because the velocity conversion associated with this process has not taken place.

A more stable and accurate reading will be obtained either:

- At or beyond the 100% effective duct length and before any fittings introduce turbulence and distortions of their own.

- In a discharge plenum.

The design should reflect the required location by specifying it and making the physical provisions necessary to accommodate it.

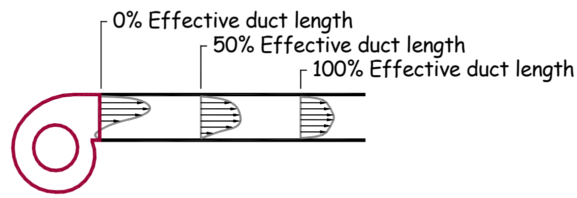



*Figure 5-2 – Fan Discharge Velocity Profile*

## Control System Considerations – Software

Points lists, narrative sequences and logic diagrams are important tools to convey design intent to the implementing and operating staff. These topics are discussed in *Chapter 1: Introduction and Fundamentals* and *Appendix 5: Control System Hardware and Software*. *Chapter 4: Building Pressure Control* contains a discussion of software considerations that should be considered for the building static pressure control process that goes hand-in-hand with the discharge pressure control strategy. The following applies specifically to discharge pressure control.

*Discharge Static Pressure Setpoint Selection*

It is important that the discharge static pressure setpoint that is selected be high enough to ensure that the return fan can deliver the full design flow to either of the following locations:

- *The Mixed Air Plenum when Operating On Minimum Outdoor Air/Full Recirculation*: In this mode, the return fan must provide enough energy to move the design air flow from its discharge through any fittings or velocity conversions to the inlet side of the return dampers. From that point, the supply fan is typically selected to provide the energy necessary to move the air into the mixed air plenum, either via the return damper or the outdoor air intake system.

- *The Exterior of the Building When Operating On 100% Outdoor Air/Full Relief:* In this mode, the return fan must provide the energy necessary to move the design flow of air from its discharge through any fittings or velocity conversions to the building exterior. This path typically includes the relief damper, relief louver, and the velocity head loss associated with discharging the air from the building.

Ideally, the pressure requirement through each of these paths should be identical, as was discussed previously. In reality, physical constraints imposed by existing conditions probably make one path critical in terms of setting the setpoint. This assessment should be made as a part of the design process and then verified by the commissioning process.

*Control System Points List*

The example provided at the end of this chapter can be edited to meet the needs of a project using discharge pressure return fan control. Editing considerations should include:

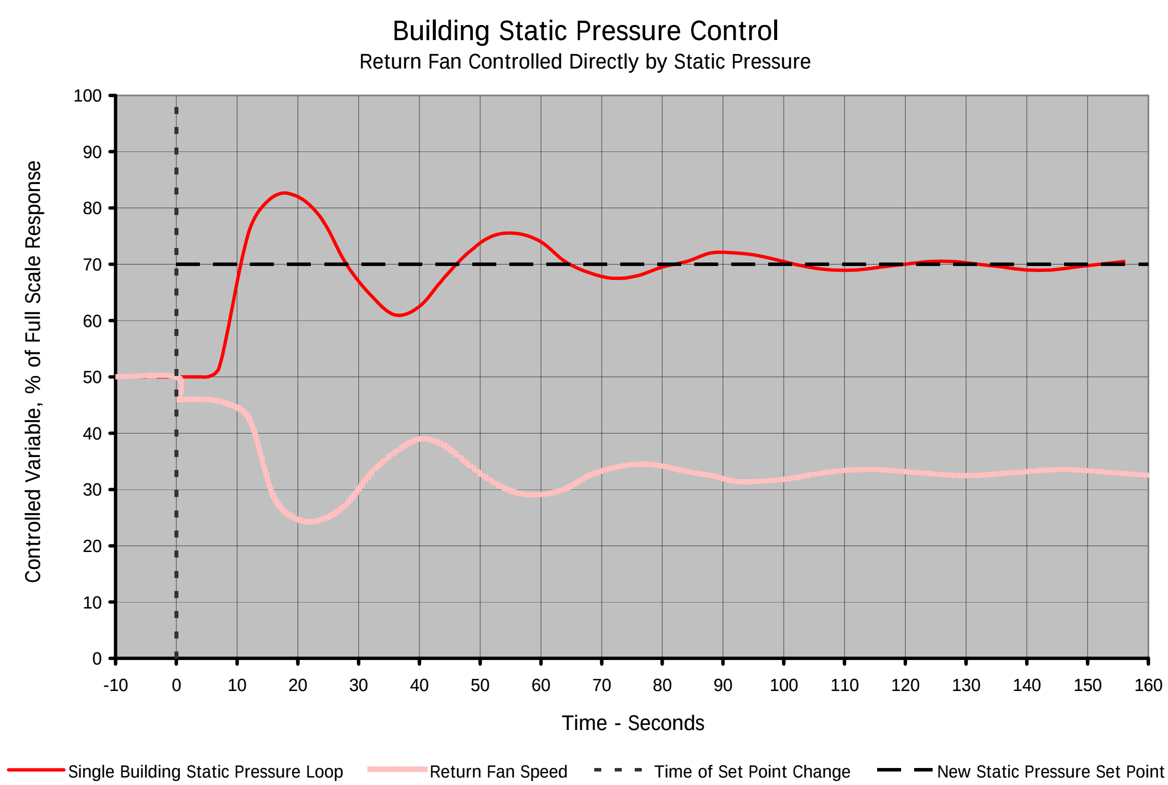



*Figure 5-1A – Response of a Building Static Pressure Control Loop to a Step Change in Static Pressure Set Point*

The data in these two figures illustrates the output of a simulation that contrasts controlling building static pressure directly via return fan speed (Figure 5-1A) versus a cascaded loop where building pressure is controlled via the relief dampers while the return fan speed is controlled based on discharge static pressure (Figure 5-1B). Note that in the first case (5-1A), the fan speed changes immediately when the set point is changed because the set point no longer matches the control point.

The magnitude of the change is a direct function of the control loop's tuning parameters. But, 6-7 seconds pass between the point in time when the setpoint change is made and the point when the building static pressure responds. The lull is due to transportation delays and other lags associated with a change in fan speed telegraphing its way through the building to create an impact on building static pressure. In essence, it took about 5 seconds for the fan's control loop to "see" the result of the initial fan speed change because it took that long for the change in flow associated with speed change to cause a reaction that could be detected as a change in building static pressure. Since building static pressure is the input to the return fan speed control loop, the fan can only respond as quickly as the control system can detect a change in static pressure. And, until it "sees" a reaction, the loop's integral gain gradually increases the fan speed, ultimately contributing to the overshoot evident in the first response cycle and lengthening the time it takes the system to settle out at the new operating condition.

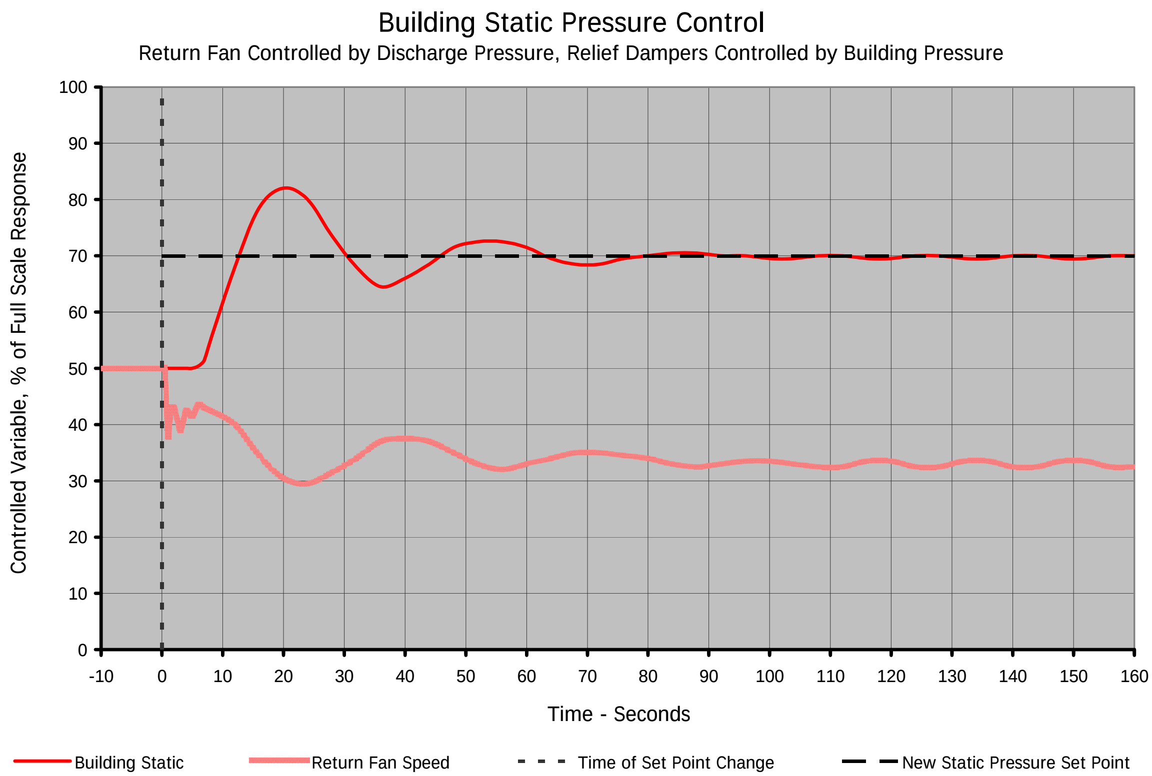



*Figure 5-1B – Response of a Cascaded Building Static Pressure Control Loop to a Step Change in Static Pressure Set Point*

In contrast, when the static pressure setpoint is changed in the cascaded loop arrangement (5-1B)the fan tracks the change in its discharge static pressure produced by the motion of the relief dampers, which is fairly immediate. Specifically, when the building static pressure set point is changed, the relief dampers move causing an immediate change in the return fan's discharge pressure. This change becomes an input to the return fan control loop and the fan, in turn, responds immediately. Because there is very little lag between when the fan changes speed the discharge sensor "sees" the resulting change in static pressure, the fan's control loop "sees" the results of its speed change much more quickly than the relief damper control loop "sees" the result of the fan speed change as a building static pressure change. Thus, instead of continuing increase speed until the static pressure changes, the return fan is nearly stable at a new operating point when the static pressure control loop begins to "see" the impact of the fan speed change. The net result is that overshoot is minimized and the time it takes to stabilize at the new operating conditions is shortened.

- Coordination with the requirements of the narrative sequence and any logic diagrams.
- Clarification regarding the location of the discharge pressure sensor.
- Clarification regarding the hardware requirements of any additional safeties provided to protect the system for a loss of input from the return fan discharge static pressure sensor.
- Clarification regarding the points required for controlling the relief system, which is typically based on building static pressure when this strategy is employed. A discussion of points list considerations for building static pressure based control applications can be found in *Chapter 4: Building Pressure Control*.

*Narrative Control Sequence*

The example provided at the end of the chapter can be edited to meet the needs of a project using discharge pressure return fan control. Editing considerations should include:

- Coordination with the requirements of the points list and any logic diagrams.
- Clarification regarding the operation of any additional safeties provided to protect the system for a loss of input from the return fan discharge static pressure sensor.
- Clarification regarding the discharge static pressure setpoint.
- Clarification regarding the interface between return fan speed control and building static pressure when this strategy is employed.

As is the case with all of the return fan strategies discussed in this guideline, using the fan sheaves to set up the return fan to maintain the desired static pressure at the design operating with the variable speed drive operating at 100% speed will optimize overall efficiency and controllability as discussed in *Appendix 6: Electrical Distribution and Drive* under *Maximizing Efficiency*. This contingency can be addressed in the narrative sequence, but should also be noted in the commissioning and testing and balancing section of the specification to ensure it is accommodated by all trades working on the project.

### Air Handling System Considerations

Many of the air handling system considerations discussed in *Chapter 1: Introduction and Fundamentals* apply to this strategy, including:

- Economizer damper selection, sizing, and installation.
- Return flow path versus relief flow path pressure losses.
- Integration with HVAC system and building functions and processes including building and zone level pressurization and minimum outdoor air flow regulation.

The issues related to ensuring similar static pressure requirements:

- from the fan discharge to the return dampers; and
- from the fan discharge to the building exterior;

should be addressed by the duct design in addition to being addressed by the setpoint discussion in the narrative sequence.

### Electrical System Considerations

Many of the electrical system considerations *discussed in Chapter 1: Introduction* and *Fundamentals* apply to this strategy including:

- Variable speed drive application, networking, and interlock issues.
- Motor selection and application issues.

## 5.6. Key Installation Issues and Considerations

Many of the design issues discussed in the preceding section and the operating issues discussed in the next section have a direct bearing on system installation. Therefore, reviewing the design intent for the strategy and its operating requirements is a crucial step in successfully installing and starting up the system. *Appendix 7: Design, Installation and Operation* includes a discussion of a general nature on this topic. The information in this chapter is particular to discharge pressure control.

Because building static pressure control goes hand-in-hand with discharge pressure control of the return fan, the topics discussed in *Chapter 4: Building Pressure Control* under *Key Installation Issues and Considerations* should also be considered and addressed if applicable when implementing a discharge pressure control strategy.

To ensure overall success on all fronts, the design issues must be complemented by field efforts focused on the issues discussed in the following paragraphs.

#### Adequate Equipment Procurement

A thorough shop drawing review process can go a long way toward ensuring that the design intent is reflected in the equipment provided. A discussion of important areas to target is included in *Chapter 1: Introduction and Fundamentals* under *The Relationship Between Design, Installation, and Operation*.

#### Locating and Installing Sensors in the Field

The location of the discharge static pressure sensor should reflect the technical issues discussed under *Key Design Issues and Considerations*. Ideally, these requirements should be addressed by the design documents. If they aren't then they should be coordinated with the designer in the field. If existing conditions preclude an installation as required by the design documents, consulting with the designer as a part of the process used to resolve the problem is also desirable.

#### Pre-start and Start-up Checklist Considerations

The pre-start and start-up considerations for speed tracking strategies are no different from the general requirements for any other strategy. See *Chapter 1: Introduction and Fundamentals* under *The Relationship Between Design, Installation, and Operation* for additional information.

#### Safety Interlock Testing and Coordination

Any additional safeties provided to protect the system from a loss of input failure should be verified, including coordination of the safety set point with normal operating conditions to prevent nuisance safety trips.

#### Testing Considerations

Usually, setting up the system and testing it involves close coordination between the mechanical contractor, the controls contractor and the balancing contractor to tune the drives, the fan speeds and the various setpoints associated with return fan control and the related ventilation and pressurization issues. A detailed description of the considerations and test process can be found in *Appendix 4: Tuning Minimum Outdoor Air Flow*.

As is discussed in the referenced appendix, the ultimate goal of the testing process is to determine the appropriate setpoints required to ensure proper and safe operation under all operating conditions. For a return fan discharge pressure control strategy, two critical operating modes that should be considered are design flow operation with 100% return air (full recirculation) and design flow with 100% relief (full economizer operation). Data collected while testing these two functions can be used to tune the discharge static pressure setpoint per the discussions under *Key Design Issues and Considerations – Discharge Static Pressure Setpoint Selection*.

### 5.7. Key Operating Issues and Considerations

Many of the issues discussed in the preceding sections in terms of design and installation will ultimately become operational issues. In addition, because building static pressure control goes hand-in-hand with discharge pressure return fan control, many of the design and installation issues discussed in *Chapter 4: Building Pressure Control* also apply. Reviewing and understanding key design and implementation issues will allow the operating staff to develop an understanding of the design intent for the strategy and its implementation. This can be a crucial step in successfully operating a system regardless of the control approach employed.

### Operating and Monitoring the Process

The control sequence and points list included at the end of this chapter will provide a good starting point for developing an understanding of the operating details associated with this strategy. In addition, they illustrate where the operating staff interfaces with the control system to adjust and monitor it. Additional information applicable to the operation of all return fan control strategies can be found in *Appendix 7: Design, Installation and Operation*.

Any air-handling system that employs this strategy and is affected directly by additions or renovations or indirectly by changes to adjacent spaces or the building envelope should receive attention before and after these changes are completed.

Pre-renovation assessment considerations might include:

- Documentation of the envelope integrity, ventilation rates, and pressure relationships to provide a baseline for comparison subsequent to renovation.
- Identification of alternative operating strategies to be employed during periods in the renovation cycle when pressurization will be compromised or impossible, thereby invalidating the discharge pressurization based control strategy.
- Coordination of the existing requirements with the design intent and requirements of the new areas and systems created by the renovation.
- Budgeting and planning for renovation modifications that might render the existing system ineffective in the current operating strategy due to changes in the envelope or the relocation of major envelope breeches like lobbies and other entry-ways.

Post renovation assessment considerations might include:

- Re-evaluation of the ventilation flow rate, building pressure relationships, and building static pressure.
- Testing and balancing as necessary to re-establish the supply, minimum outdoor air flow and return flow relationships and the associated building static, return fan discharge static, and outdoor air flow control set points.
- Testing and balancing under variable load conditions to ensure that the relationships established under the preceding bullet hold under all anticipated operating conditions.

Many of the concepts discussed in *Appendix 4: Tuning Minimum Outdoor Air Flow* will prove useful for the operating staff as they tune the system to the changing requirements of the area it serves.

## 5.8. Discharge Pressure Control Troubleshooting Table

*While not all inclusive, this table illustrates many of the more common problems that can occur with a return fan discharge pressure strategy and the associated corrective actions. Some troubleshooting issues will be general in nature while others will be specific to a particular system by virtue of the control sequence and wiring configuration associated with it. The following table is based on the system illustrated at the beginning of the chapter with a control sequence as described in Section 5-10 Sample Narrative Sequence of Operations.*

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Fails To Start | Loss of Power | • Verify the integrity of the power supply from the motor back to the source. If tripped circuit breakers or blown fuses are encountered, determine and correct the cause of the fault prior to restoring power. |
| | Interlock Problem | • After verifying that the fan can be safely run alone, switch the fan to "Hand" and observe the results.<br>♦ If the fan still fails to start, the problem is most likely in the safety interlock circuit (fire alarm, relay, smoke detector, etc.). Investigate and correct interlock problems in the safety interlock circuit associated directly with the return fan.<br>♦ If the fan runs, the problem is most likely in the interlocks associated with scheduled operation of the fan and other automation requirements. Verify the controlling software that cycles the fan in the "Auto" mode as well as any hardwired interlocks with other equipment like the supply fan. A safety trip that is preventing a supply fan start (freezestat, static switch, smoke detector, etc.) could prevent a return fan start if the return fan is interlocked via hardwiring or software to only run when the supply fan runs.<br>• If the fan fails to run in "Hand" or "Auto" and the drive is equipped with a "Bypass" option, switch the fan to "Bypass" after verifying that it is safe for the fan to run at full speed.<br>♦ If the fan starts and runs in bypass, the problem is most likely in the VFD itself (see below).<br>♦ If the fan fails to start in the bypass mode, the problem is probably one of the other issues listed in this table. |
| | VFD Failure | • Verify the integrity of the drive circuitry using the manufacturer's troubleshooting guidelines as published in the operation and maintenance manual. |
| | Drive System Failure | • Verify the integrity of the drive belts and sheaves or couplings. |
| | Motor Failure | • Isolate the motor from the power system and all controllers, drives, starters, etc.<br>♦ Spin the motor shaft by hand to assess the integrity of the bearings. The shaft should spin freely and smoothly. Investigate and correct any unusual noise, jams or restrictions to free movement. |

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| | | ♦ Inspect the motor connections for security and signs of overheating or resistive connections. Correct any discrepancies found.<br>♦ Megger test the motor to measure the insulation resistance to ground. Correct any grounded conditions before reapplying power to the motor. Usually this will involve removing the motor and sending it out for repair.<br>• If the motor spins freely, the connections are good, and there are no grounds, cautiously reapply power (monitor the inrush current during this process) and verify:<br>♦ The motor starts and comes up to speed.<br>♦ The motor inrush current drops off as the motor comes up to speed.<br>♦ The current on all phases is balanced and does not exceed the motor's nameplate rating.<br>• If the motor currents are over nameplate disconnect the load and restart the motor. Verify the following:<br>♦ No-load motor amps are approximately 50 to 70% full load amps for 900 – 1200 rpm motors (Some may be higher), approximately 30% full load amps for 1800 rpm motors and are approximately 20 to 30% full load amps for 3600 rpm motors. If the no load currents are balanced and within the limits listed above, the motor is probably being overloaded (see below).<br>♦ If the no-load currents are out of balance or exceed the limits listed above, the motor windings are probably shorted and the motor will need to be removed and repaired.<br>• If the motor currents are severely imbalanced (in excess of 10% different) check the following:<br>♦ Verify that the voltage supplied to the motor is within 5% of the line voltage rating. Investigate and correct the cause of any observed low voltage condition.<br>♦ Verify that the phase to phase voltages are balanced and are within 5% of the line voltage of each other. If the phase voltages are balanced but the currents are imbalanced, there is probably a short in the motor winding and the motor will need to be removed and repaired. |
| | Overload Trip | • If a new motor has been installed on the fan, verify that the moment of inertia ($WR^2$) of the new motor is equal to or better than the motor it replaced (see *Appendix 6: Electrical and Drive System Considerations* for additional information.)<br>• Verify that the wiring connections to the overload relay are tight. Loose wiring connections represent a resistive load that can generate heat and trigger a false overload trip. |

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| | | • Inspect and clean the fan wheel as necessary. Dirt on the fan wheel increases its moment of inertia and can cause start-up problems to "suddenly" appear in a fan that has been running satisfactorily (see *Chapter 1: Introduction and Fundamentals – Maintaining and Adapting Design Intent - Fan Wheel Cleanliness* for additional information.) |
| Return Fan Fails To Stop | Fan Remains in Operation Despite a Safety Trip That Should Directly Shut Down the Fan | • Safety trips intended to directly affect the return fan should shut down and lock out the fan irrespective of the position of any Hand-Off-Auto switches or Inverter-Bypass switches. If a fan remains in operation after a safety trip, investigate and correct problems in the safety interlock circuit. |
| | Fan Remains in Operation Despite a Supply Fan Shut Down Due to a Safety Trip | • Verify that the drive is in "Auto." If the drive is in "Auto" and continues to operate when it should be off, investigate and correct problems in the control logic associated with supply fan interlocks. |
| | Fan Remains in Operation When it Should Be Off Based On Schedule | • Verify that the drive is in "Auto." If the drive is in "Auto" and continues to operate when it should be off, investigate and correct problems in the control logic associated with the return fan start-stop functions. |

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Speed Does Not Vary | Return Fan Speed Does Not Vary Despite Supply Fan Speed Variations. | • If the return fan VFD is equipped with a bypass system, verify that the system is in "Inverter" (VFD active) and not "Bypass" (VFD bypassed and out of the circuit).<br>• Verify that the return fan VFD speed control selection is in the position that causes the drive to follow a remote speed command. Typically this is the "Auto Speed Command" position. This selection may be made via a selector switch or via a keypad, depending on the drive design, manufacturer, and vintage.<br>• Verify that the speed control signal is available at the return fan VFD input terminals.<br>• Verify that the discharge static pressure signal is available and calibrated.<br>• Verify that the building pressure and return fan discharge set point is as required. The preliminary settings specified by the designer were most likely optimized and tuned to the installed system during the commissioning process. These settings should be reflected in the commissioning report.<br>• Verify that the building static pressure set point is achievable given the current integrity of the building envelope. If a major new breech of the envelope has occurred, intentional or otherwise, the supply system may no longer be able to pressurize the building, invalidating a pressurization based control strategy.<br>• Verify that the return fan discharge static pressure set point is achievable given the current integrity of the building envelope. If there is a significant difference between the requirement for full relief flow and the requirement for full return flow, then a setting based on one condition may not be achievable in the other condition.<br>• Verify that the return fan is in fact moving air. One method of doing this is to take manual control of the fan speed and carefully ramp it up and down to see if the indicated flow rate changes. (Exercise caution to ensure that you don't inadvertently create excessive building, zone or duct pressure relationships). If changes in speed do not produce flow or changes in flow, then the problem may be a belt failure or an issue with the return system that is affecting the return fan's ability to move return air through the system like a closed fire damper. If the return fan is moving air, then the problem could be an issue related to the integrity of the return system, like an open service door after the flow measuring station, but ahead of the return fan which is allowing the fan to move a lot of air with out measuring the air flow.<br>• Verify that the supply flow is in fact varying with the |

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| | | changes in supply fan speed. There should be a fairly direct correlation between supply flow and supply fan speed. If there isn't, investigate and correct. Possible issues include fire/smoke dampers that should be open but are closed, problems with the coordination of the outdoor air and return air dampers associated with the economizer process, an erroneous supply fan speed signal, and belt failures. |
| | Return Fan And Supply Fan Speeds Do Not Vary | • Verify that the supply fan VFD is in "Auto" and not in a mode that would cause it to run at a fixed speed. If the supply fan is in "Auto" and its speed does not vary the problem could be:<br>♦ A problem in the supply fan speed control system or related logic. Detailed troubleshooting of the supply fan speed control system is beyond the scope of this guide, but in general terms the procedure will be similar to that described above under Return Fan Speed Does Not Vary Despite Supply Fan Speed Variations.<br>♦ A load condition that exceeds the supply fan's capacity may exist. This could be caused by a number of factors including a load condition in excess of design, a supply flow restriction, or conditions that have compromised the capabilities of the cooling or heating utility systems that condition the supply air (low refrigerant, high chilled water supply temperature, high cooling coil discharge air temperature, low heating coil discharge air temperature, low steam supply pressure, low hot water supply temperature, etc.). Troubleshooting of these issues is beyond the scope of this guideline. |
| Pressure Relationships are Negative or Overly Positive Either Relative to the Outdoors or Relative to Adjacent Areas | Pressure Relationships are Negative or Overly Positive Regardless of the Operating Status of the Return Fan and its Related Air Handling System | • The problem is most likely not related to the return fan and is more likely related to:<br>♦ Issues in a different system in the building.<br>♦ Stack effect.<br>♦ An imbalance between make up air either due to improper adjustment and balancing or due to the operation of an exhaust system without its associated make up system or vice versa.<br>♦ Problems with a building static pressure control system that operates independently of the air handling system in question.<br>♦ Modification or changes have been made to the building's envelope, functions, or occupancy patterns. |
| | Negative or Overly Positive Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling | • Verify that the static pressure control setpoint has not been changed and that the components associated with the control process (reference sensing ports, transmitter, wiring, I/O board) are not obstructed and are functioning properly.<br>• Verify the integrity of the minimum outdoor air control |

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| | System | system including that minimum outdoor air is being introduced into the system in the proper quantities.<br>• Verify that the economizer damper system and related relief dampers are functioning properly including:<br>♦ Maximum outdoor air, return air, and relief air dampers operate freely and through their full stroke.<br>♦ Maximum outdoor air, return air, and relief air dampers operate with the correct relationship to each other (return dampers close as the maximum outdoor air dampers open, etc.).<br>♦ Verify that the process controlling the relief dampers, if different from the process controlling the economizer, is functioning properly.<br>• Verify that the minimum outdoor air flow control process is functioning properly. See *Appendix 4: Tuning Minimum Outdoor Air Flow* for information on testing if it is necessary to re-tune the system.<br>• Verify that the return fan sheave or motor sheave have not been replaced with new sheaves with a different pitch diameter than the sheaves that were installed when the system was commissioned and tuned.<br>• Verify that the pitch diameter on a fan or motor equipped with an adjustable pitch sheave has not changed.<br>• Verify that there is not a restriction in the outdoor air intake system or relief system such as a louver that has become obstructed, turning vanes that have been obstructed by debris, etc. Bear in mind that the pressure drop represented by a restriction is a function of flow rate. Thus, a restriction in a VAV system may present a problem that seems to come and go as the flow rate increases and decreases.<br>• Determine if modifications have been made to the building's return path, relief path, envelope, functions, or occupancy patterns in the area served by the return fan and its related air handling systems. Significant modifications in any of these areas may require re-assessment of the building static pressures and return fan discharge pressure set points and/or re-tuning of the system's minimum outdoor air flow. See *Appendix 4: Tuning Minimum Outdoor Air Flow* and *Appendix 8: Theoretical Versus Actual Performance* for additional information. |
| Minimum Outdoor Air Flow Does Not Meet | Minimum Outdoor Air Flow Problems Exist Regardless of the Operating Status | • The issues in this category will be similar to the issues discussed above under Pressure Relationships are Negative or Overly Positive Regardless of the Operating |

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| Requirements | of the Return Fan and its Related Air Handling System | Status of the Return Fan and its Related Air Handling System. |
| | Minimum Outdoor Air Flow Problems Appears to be Related to the Operation of the Return Fan and its Related Air Handling System | • In small buildings or large complex buildings, problems with minimum outdoor air flow in one system may not manifest themselves as problems with pressure relationships in the building even though in theory, they should. For small buildings, this is usually because leakage rates between zones or through the envelope are large enough that they prevent the issue from showing up as a pressure relationship problem. In larges complex buildings, the volume of the building or the interactions with other systems can mask the problem and prevent it from showing up as a pressure relationship issue. However, most of the issues are the same as those discussed above under *Negative or Overly Positive Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling System*. |

## 5.9. Sample Points List

The following tables illustrate a points list for the return fan in the system illustrated at the beginning of the chapter and can be used as a starting point for similar systems employing return fan discharge pressure control strategies. It was developed using the points list tool contained in the *Control Design Guide*. This publicly available resource can be downloaded from [www.PECI.org/FTGuide](http://www.PECI.org/FTGuide) and used to develop a points list with characteristics similar to those illustrated for an entire system or project.

| Point Name | Sensor Information | |
|---|---|---|
| | System and Service | Sensor/Interface Device |
| | | Type |
| **Analog Inputs** | | |
| RF1DStat | AHU 01 Return Fan 1 Discharge Static Pressure | Low range DP; -0,50 - 0.50 in.w.c. |
| BldgStat | Building Static Pressure | Thermal dispersion; -0.10 to 0.10 in.w.c. |
| RF1SpdFb | AHU 01 Return Fan 1 Speed Control Feedback | VFD programmable output |
| RF1kW | RF1 kW | VFD programmable output |
| **Analog Outputs** | | |
| RF1Spd | AHU 01 Return Fan 1 Speed Control Command | 4-20 ma output |
| AH1Rel | Relief Damper Command | 4-20 ma output |
| **Digital Inputs** | | |
| RF1POO | Return Fan 01 Proof of Operation | Current switch |
| RF1SSwSt | Return Fan 1 Selector Switch Status | Auxilliary contact |
| VFD1SSwSt | Supply Fan 1 VFD Selector Switch Status | Auxilliary contact |
| **Digital Outputs** | | |
| AH1RFSS | AHU 01 Return Fan Start/Stop Command | Interface relay |
| **Virtual Points** | | |
| RF1Hrs | RF 01 Accumulated Hours of Operation | Calculation based on proof of operation input |
| RF1SpdPGn | RF1 Speed Control Loop Proportional Gain | Manually set |
| RF1SpdIGn | RF1 Speed Control Loop Integral Gain | Manually set |
| RF1SpdDGn | RF1 Speed Control Loop Derivative Gain | Manually set |
| StatSet | Building Static Pressure Set Point | Manually set; initial value = 0.05 in.w.c. |
| RF1DSet | RF1 Discharge Static Set Point | Manually set; initial value = 0.18 in.w.c. |
| **Hard Wired Points** | | |
| RF1Fire | RF 01 Fire Alarm Shut Down Relay | Relay by fire alarm contractor |
| AH1VFDAux | AH1 VFD Auxilliary Contact | Auxilliary contact |

| Point Name | Alarm and Trending Information, General Notes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Features | | | | | | | | | | | Notes |
| | Alarms | | | | Trending | | | | | | | |
| | Limit | | Warning | | Samples[1] | Commissioning[5] | | | Operating[5] | | | |
| | Hi | Lo | Hi | Lo | | Time[2] | Local[3] | Archive[4] | Time[2] | Local[3] | Archive[4] | |
| **Analog Inputs** | | | | | | | | | | | | |
| RF1DStat | 0.35 in.w.c. | 0.00 in.w.c. | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | |
| BldgStat | Note 15 | Note 16 | None | None | 15 | 1 min | X | X | None | None | None | Note 18 |
| RF1SpdFb | N/A | N/A | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | |
| RF1kW | N/A | N/A | Note 26 | Note 26 | 15 | 15 min1 | X | X | 15 min | X | X | |
| **Analog Outputs** | | | | | | | | | | | | |
| RF1Spd | N/A | N/A | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | |
| AH1Rel | N/A | N/A | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | Note 17 |
| **Digital Inputs** | | | | | | | | | | | | |
| RF1POO | Note 13 | None | None | None | 15 | COV | X | X | COV | X | | Notes 7,9 |
| RF1SSwSt | Note 10 | None | None | None | 2 | COV | X | X | COV | X | | Notes 10, 11 |
| VFD1SSwSt | Note 10 | None | None | None | 2 | COV | X | X | COV | X | | Notes 10, 11 |
| **Digital Outputs** | | | | | | | | | | | | |
| AH1RFSS | Note 13 | None | None | None | 15 | COV | X | X | COV | X | | |
| **Virtual Points** | | | | | | | | | | | | |
| RF1Hrs | None | None | 1,000 hr. | None | None | None | None | None | None | None | None | Note 8 |
| RF1SpdPGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1SpdIGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1SpdDGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| StatSet | None | None | None | None | None | None | None | None | None | None | None | Note 17 |
| RF1DSet | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| **Hard Wired Points** | | | | | | | | | | | | |
| RF1Fire | Open | None | None | None | None | None | None | None | None | None | None | Note 14 |
| AH1VFDAux | None | None | None | None | None | None | None | None | None | None | None | Note 13 |

**Notes:**

1. Samples indicates the minimum number of data samples that must be held in the local controller if it is trending the point. This may be based on the operating trending requirements. Higher sample capabilities tends to minimize archiving frequency.
2. Time indicates the required sampling time for the trending function (1 min = 1 sample per minute, 4 min = 1 sample every 4 minutes).
3. A check in the local column indicates that the trending only needs to be running in the local controller and the most recent value can write over the last value when the trend buffer fills up.
4. A check in the archive column indicates that the trend data must be archived to the system hard disc when trend buffer fills up so that a continuous trend record is maintained.
5. Commissioning trending requirements only need to be implemented during the start-up and warranty year. After the start-up and warranty process, the control contractor should set the trending parameters to the operating requirements listed.
6. See the specifications for additional requirements and details regarding sensor and interface device requirements.
7. Adjust to detect a belt or coupling failure by showing failure to run with the belt or drive coupling removed and the motor running.
8. Accumulate on a monthly basis and archive the monthly total to the hard disk on the last day of the month at midnight.
9. Provide an alarm if the equipment is running when it is commanded off. Provide an additional alarm if the equipment is not running when it is commanded on. Include time delays to accommodate system start-ups.
10. Issue an alarm if the manual override switch/Hand-Off-Auto switch is not in Auto.
11. If the DDC system provides this function as a standard feature in the firmware and software supporting its I/O boards, an independent contact on the override switch and associated physical point is not required.
12. Typical of all control loops. Provide commandable points for adjustment of loop setpoints, tuning parameters, and bias settings. Limit access to Lead Operator or higher.
13. Arrange contact to close any time the AHU1 supply fan is in operation under VFD control or in bypass and hardwire to start the fan.
14. Fire alarm shut down relays are furnished and installed by the fire alarm supplier and located at the motor starter location. Control wiring through the fan start circuit shall be by the electrical contractor. The control contractor shall coordinate this effort to ensure that the desired sequence is provided.
15. Issue an alarm if the building static pressure exceeds .10 inches w.c. During commissioning, coordinate the final set point with tests to ensure compliance with ADA requirements and the capabilities of door closers and latching systems.
16. Issue an alarm if the building static pressure drops below 0.0 inches w.c. for 5 or more consecutive minutes. During commissioning, coordinate the time delay to accommodate the variability associated with normal start-up and shut down. Supress the alarm when AHU1 is not in operation.
17. Coordinate the control of the relief damper with the return fan speed per the sequence of operation. Verify coordination and tuning during the commissining process.
18. Provide a flush mounted static pressure sensing head at the indoor sensing location and an outdoor pressure sensing head at the outdoor location. Sensing heads to be as manufactured by Tek-Air or Air Monitor Corporation or approved equal. Locate the transmitter in the phone equipment room adjacent to the lobby in an accessible location. Provide copper sensing lines from the sensor heads to the transmitter. Utilize soft copper to minimize the number of joints. Use compression or solder fittings for any joints and connections that are necessary.
19. Provide a static probe located down stream of the return fan discharge in an area where the fan discharge velocity profile is fully developed and free from the effect of fittings. As an alternative, the probe can be locaed in the return fan discharge plenum. Coordinate the final location and associated set point with the designer. Static probes shall be as manufactured by Dwyer or

## 5.10. Sample Narrative Sequence of Operations

The following narrative sequence is an example that applies to the return fan shown in the system diagram at the beginning of the chapter. It can be used as a starting point for similar systems employing return fan discharge pressure control strategies.

### Return Fan Variable Speed Drive Control

*Overview*

This control sequence functions based on the following premises:

- Return fan speed and return fan capacity are directly related.
- The supply system associated with the return fan is introducing the correct amount of outdoor air into the building, either as required for minimum ventilation or as required by the needs of an economizer process.
- Building pressure is controlled by modulating the relief dampers based on building static pressure. This is described in detail in the building static pressure control operating sequence narrative.
- The outdoor air and return air dampers are controlled by the economizer process in coordination with the discharge temperature control process. This is described in detail in the discharge temperature control operating sequence narrative.
- The return fan functions to move air to its discharge and provide a constant pressure air source for use by the building static pressure control process and the economizer process.

In general terms, the strategy increases the return fan speed as its discharge pressure drops and decreases the return fan speed as its discharge pressure rises. The primary reasons the discharge pressure will vary are because of modulation of the relief dampers via the building static pressure control process or modulation of the economizer dampers via the discharge temperature control process.

For additional details on this control strategy, including installation, commissioning, and operating tips, refer to the application guideline titled *Return Fan Capacity Control via Speed Control* published by the National Building Controls Information Program and available for free download at www.buildingcontrols.org.

*Speed Control*

A differential pressure transmitter measures return fan discharge pressure at a point where the velocity profile is fully developed (see the floor plan on sheet M-5 for the sensor location). The output of this transmitter provides an input for monitoring the discharge pressure and for a PID control loop. The output of the control loop modulates the return fan speed and capacity as necessary to maintain the mixed air plenum pressure setpoint of 0.18 in.w.c. positive relative to ambient (initial setting, adjustable) by commanding the return fan variable speed drive. A tendency towards a discharge pressure that is below setpoint causes the return fan speed to increase. A tendency towards a discharge pressure that is above setpoint causes the return fan speed to decrease.

Drive speed control shall be via a discrete hardwired interface between the control system and the drive. Network level interfaces between the control system and drive shall not be permitted for this function.

Control loop tuning parameters and variable speed drive acceleration times, deceleration times, minimum and maximum speeds shall be adjusted and optimized during the commissioning process.

Coordinate minimum speed settings for the fan with the motor and VFD supplier to ensure adequate motor cooling while achieving the lowest possible speed to minimize the step change that occurs when the fan starts. Anticipate an initial setting of 5 hz based on the drive/motor combination specified.

*Start Stop Control and Proof of Operation*

The return fan variable speed drive shall be commanded on by a hardwired interlock any time the supply fan variable speed drive is in operation. It shall also be possible to command the drive on via the DDC system using a command from the operator's console.

A current switch sensing current to the variable speed drive shall provide a contact closure for proof of operation purposes any time the return fan motor is operating under load. The current switch shall be adjusted so that the proof of operation is not indicated if the motor is running but the belts have broken and thus the fan is not turning.

*Variable Speed Drive Interlocks*

The following interlocks shall be provided for the return fan variable speed drive:

- External, Hardwired

  A start-stop interlock to the supply fan shall be hardwired into the variable speed drive control circuit. These interlocks shall function regardless of the status of the drive Hand-Off-Auto and Inverter-Bypass selector switches.

  A fire alarm shut down relay shall be wired into the circuit and arranged to shut down the fan on a building fire alarm condition per the programming requirements of the fire alarm system. Coordinate with Division 16 as required for wiring and programming of the fire alarm relay. Coordinate with Division 16 for the location and field installation of the duct mounted smoke detectors.

- External, Software based

  The return fan variable speed drive shall be commanded to 0 hz any time the return fan is not in operation as indicated by the return fan status input.

- Internal

  The return fan shall be shut down and locked out if a motor overload condition is sensed in the drive or bypass mode. Manual reset at the drive location shall be required to resume normal operation.

*Outputs to the DDC System*

The following outputs shall be provided from the variable speed drive to the automation system. These outputs may be provided by discrete hardwired interfaces or by a network level interface at the contractor's discretion. The final installed condition shall be reflected in the "as-built" drawings.

- Drive speed feedback in hz
- Drive kW

*Alarms: Operator*

Operator alarms shall be delivered to the operators console and logged on a dedicated alarm printer as they occur. The following operator alarms shall be provided:

- Indicate *AHU1 return fan failure to start or run* if the fan is not running when it should be, including a failure to start when commanded on for any reason or a shutdown that occurs when the fan should be operating per the operating sequence given the current conditions.
- Indicate *AHU1 return fan failure to stop or remain shut down* if the fan is running when it should not be, including a failure to stop when commanded off for any reason or any operation that occurs when the fan should be off per the operating sequence given the current conditions.
- Indicate *AHU1 return fan discharge pressure is below setpoint; check for fan or drive system failure or input failure* if the supply fan has been running for 5 minutes or more (initial setting, adjustable) and the discharge pressure is 0.00 in.w.c. or less (initial setting, adjustable). Suppress this alarm if the supply fan status is off.
- Indicate *AHU1 return fan discharge pressure is too high; check for drive problems, relief damper control problems or economizer control problems* if the supply fan has been running for 5 minutes or more (initial setting, adjustable) and the discharge pressure is 0.35 in.w.c. or more (initial setting, adjustable). Suppress this alarm if the supply fan status is off.

*Alarms: Facility Management*

Facility management alarms shall be directed to a weekly report, generated for the director of engineering and made available for viewing under their log-in. The following alarms shall be provided:

- Indicate *During the past week the AHU1 return fan operated for a significant period of time when the supply fan was not operating* if the return fan operates more than one hour (initial setting, adjustable) when the supply fan is not operating. Reset the timer at the end of the week.
- Indicate *During the past week the AHU1 return fan has failed to operate for a significant period of time when the supply fan was operatin*g if the return fan fails to operate for more than one hour (initial setting, adjustable) when the supply fan is operating. Reset the timer at the end of the week.
- Indicate *During the past week, the AHU1 return fan speed did not vary significantly on one or more days* if the return fan speed does not vary by more than ± 5 hz (initial setting, adjustable) between 30 minutes after start-up and the shut down time during any day on which the system operated.

*Totalization*

The following totalization functions should be provided and the data should be archived to the system hard drive on a daily basis:

- Return fan hours of operation based on the proof of operation input for the current week, the current month, and the current year.
- Return fan kWh based on the kW input from the variable speed drive for the current week, the current month and the current year.

## 5.11. Case Study

A recent project demonstrated the level of performance that can be achieved with a return fan discharge pressure control strategy along with design characteristics that lead to success and some of the typical field issues that were identified and resolved. The system had the following characteristics:

- The return fan was part of a modular VAV rooftop unit.
- Pressure independent terminal reheat VAV boxes were provided for each zone.
- The supply and return fans were each provided with a VFD.
- Minimum outside air was controlled by measuring air flow through factory-designed outside air damper-flow station. There was not a dedicated minimum outside air damper assembly; rather the entire outdoor air damper section modulated to meet minimum ventilation and economizer requirements. The return dampers modulated in coordination with the outside air dampers.
- The minimum outside air setpoint was adjusted based on occupancy sensors and CO2 measurements. If a zone was unoccupied, the VAV box damper was closed and the minimum ventilation air requirement for that zone was subtracted from the minimum outside air flow rate setpoint.
- An atmospheric reference for building pressure control was mounted on the HVAC unit. The equipment manufacturer's outside pressure sensing head, a device intended to minimize wind influence, was less effective than hoped for. The building interior reference was located in the front lobby.

The following observations were made during system start-up and commissioning.

During colder months, the minimum ventilation air flow matched the setpoint very well. As the supply fan speed increased or decreased to meet zone loads, the outside air dampers would modulate closed or open, as necessary to maintain the desired minimum outside air flow. As ambient temperatures increased, the needs of the economizer process tended to exceed the needs of the ventilation process. When this was the case, outside air dampers modulated in coordination with the return dampers as necessary when the economizer cycle was enabled.

As originally implemented, the building static pressure signal that controlled the relief dampers was used without any buffering or filters. This resulted in an unstable control process due to the variability of the signal.[1] Signal dampening techniques were used to smooth out the input signal, which helped to reduce damper oscillations.

The discharge pressure return fan speed control process tracked return fan discharge plenum pressure very well. As the relief dampers and return dampers modulated in response to building pressure and the requirements of the economizer, fan speed was varied to maintain a constant plenum pressure.

## 5.12. Additional Resources

Additional guidance can be found in *Installation and Maintenance of V-Belt Drives,* another useful tool that is provided as a free resource from the TB Woods Company at [http://www.tbwoods.com/pdf/VBD-IM_InstallationandMaintenance.pdf](http://www.tbwoods.com/pdf/VBD-IM_InstallationandMaintenance.pdf)

---

[1] For a detailed discussion of a problem of this type, see the case study included in *Chapter 4: Building Pressure Based Control*.

Guidance on integrating this strategy with an economizer process can be found in *ASHRAE Guideline 16P Selecting Outdoor, Return, and Relief, Dampers for Air-side Economizer Systems*, which can be downloaded at www.ASHRAE.org.

# 6. Mixed Air Plenum Control

This chapter will discuss mixed air plenum pressure based control, an approach which uses the static pressure in the mixed air plenum to control the return fan speed. This approach is less common than some of the other approaches; it is indirect, subtle, and not well understood.

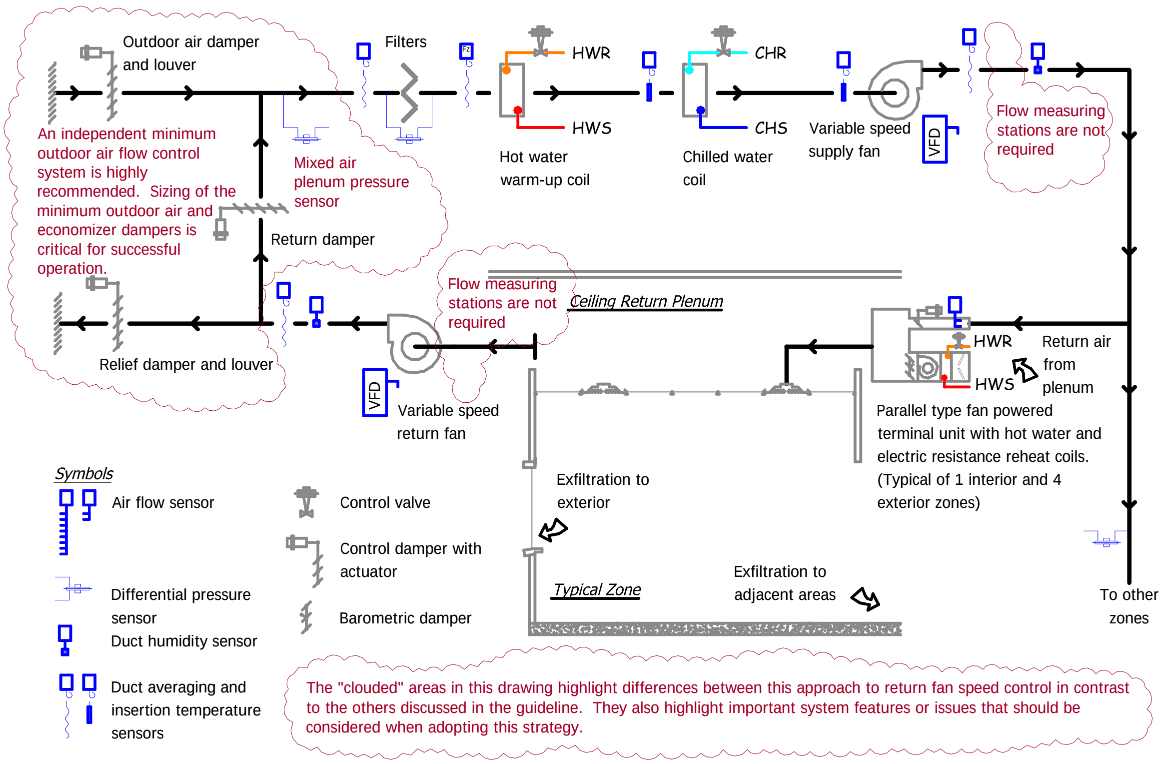
By its nature, this approach will tend to deliver a constant *volume* rather than a constant *percentage* of minimum outdoor air as supply flow varies in a VAV application. This may be an advantage in situations where the ventilation requirement does not vary with load and/or where a fixed minimum outdoor air volume is required to ensure proper zone to zone or building pressure relationships. However it is important to recognize that the strategy does not control either of these parameters directly. In fact, if care is not exercised in the selection and sizing of the minimum outdoor air and economizer damper systems on the air handling system where it is applied, this strategy will fail to perform, yielding unacceptable return fan capacity control and triggering problems with minimum outdoor air and building pressurization control. Complex buildings and/or air handling system configurations can exacerbate these problems, especially if they have high turn-down requirements.

This approach has minimal requirements in terms of hardware and programming when contrasted with some of the other strategies. Thus, in a new construction environment, it will tend to have a lower first cost, making it an attractive choice for small systems and systems with minimal complexity and/or turn-down requirements. Because it is highly dependent on proper minimum outdoor air and economizer damper sizing and configuration, it can be a more expensive alternative in a retrofit application if the existing system requires modification in those areas.

There are also two variations of this approach wherein the mixed air plenum pressure is used to control the outdoor air or return air damper while the return fan is controlled by any one of the other approaches discussed in this guideline.

## Chapter 6 Contents

# Mixed Air Plenum Control




*A Typical VAV Air Handling System with Mixed Air Pleum Pressure Based Control*

## General Description

This approach controls the return fan speed based on the static pressure in the mixed air plenum. There are also two variations of this approach documented in the literature in which the mixed air plenum static pressure is used to control the outdoor air or return air damper while the return fan speed is controlled by one of the other strategies discussed in this guideline. The variations depend on the movement of the return our outdoor air dampers in response to mixed air plenum pressure to create a detectable change in other system parameters which are then used to indirectly control the return fan.

## Advantages

- Minimal control device requirements.
- Well suited for applications requiring a constant ventilation rate.

## Limitations

- Tends to maintain a constant minimum outdoor air flow instead of a constant percentage.
- Subject to complex system interactions.

## Application Considerations

| Characteristic | Low | Medium | High |
|---|---|---|---|
| Application Complexity | | ✓ | |
| Potential for Negative IEQ Impact | | | ✓ |
| Potential for Negative Energy Impact | | | ✓ |
| Potential for Integration/Interaction Problems | | | ✓ |
| First Cost | | ✓ | |
| Maintenance Cost | | ✓ | |
| Energy Cost | | ✓ | |

## Key Design Issues and Considerations

- The sizing of the minimum outdoor air and economizer dampers, while important for all applications, is critical for this application. This is complicated by the variations in damper performance that occur in VAV systems due to the variation in flow with load through the economizer system and the relationship between damper velocity, pressure drop and performance.
- This strategy is subject to subtle but complex system interactions under different operating modes. For instance the feedback path changes when a system operating on an economizer cycle reaches the 100% outdoor air mode. These interactions can make the strategy difficult to tune and troubleshoot.
- Consider the ventilation requirements in terms of a constant *volume* versus a constant *percentage* of minimum outdoor air. This strategy will tend to maintain a constant volume under all conditions unless some sort of setpoint reset strategy is employed.

## Key Installation Issues and Considerations

- Subtle differences in the as installed versus as designed configurations of the economizer damper hardware can make major differences in the way the strategy performs.
- Setting the system up to ensure adequate minimum outdoor air under all operating conditions will require testing at multiple points and close coordination between trades.

## Key Operating Issues and Considerations

- Periodic retesting to ensure adequate minimum air flow under all operating conditions should be performed. Retesting is critical after any major building renovation, especially if it impacts the building envelope, the HVAC processes for areas surrounding those served by the system, or the ventilation requirements of the loads served by the system.

# 6. Mixed Air Plenum Control

This approach to return fan speed/capacity control uses the pressure in the mixed air plenum to directly or indirectly control the return fan speed. This approach is less common than some of the other approaches; it is indirect, subtle, and not well understood.

Additional information generally applicable to all return fan speed control strategies can be found in *Chapter 1: Introduction and Fundamentals*. Additional useful resources outside of this guideline are listed at the end of the chapter.

## 6.1. General Description

As is the case with the other strategies discussed in this guideline, the goal of this control strategy is to coordinate the flow variation in the return system with the flow variation in the supply system in a manner that ensures the required outdoor air flow rate is maintained. The fundamental principle behind the strategy is that there is a specific and predictable relationship between flow and differential pressure across a fixed orifice. When applied to an air handling system, the outdoor air intake system represents the fixed orifice. Controlling the system for a constant mixed air plenum pressure relative to the atmosphere imposes a known differential pressure across the orifice and thus produces a predictable flow.

In general terms, the strategy functions as follows:

- The mixed air plenum pressure setpoint is based on the pressure drop necessary to move the desired minimum outdoor air flow through the intake system with the AHU on minimum outdoor air.
- The return fan is controlled so that it speeds up as the plenum pressure drops below setpoint and slows down as the plenum pressure rises above setpoint.
- If the supply flow increases from a steady state condition and nothing else changes, the initial tendency will be for more outdoor air to come in through the intake system since the return flow is regulated to a large extent by the operation of the return fan. The increasing flow through the intake system tends to drop the mixed air plenum pressure below setpoint. The control system detects this and increases the return fan speed, moving more return air into the plenum. Assuming a tuned loop, the tendency will be to stabilize at a higher supply and return flow rate and with the desired minimum outdoor air flow rate.
- If the supply flow decreases from a steady state condition and nothing else changes, the initial tendency will be for less outdoor air to come in through the intake system since, as was the case in the preceding bullet, the return flow will tend to be regulated by the operation of the return fan. The decreasing flow through the intake system tends to allow the mixed air plenum pressure to rise towards atmospheric pressure and above setpoint. The control system detects this and reduces the return fan speed, moving less return air into the plenum. Assuming a tuned loop, the tendency will be to stabilize at a lower supply and return flow rate and with the desired minimum outdoor air flow rate.

Because the fundamental principle behind this strategy is founded on a relationship between flow rate and differential pressure, this strategy will tend to maintain a constant minimum outdoor air flow rather than a constant minimum outdoor air percentage.

### Variations

In addition to the technique described in the preceding section where return fan speed is controlled directly based on mixed air plenum pressure, there are two other mixed air plenum pressure based control strategies in use:

- Return fan speed/capacity modulation based on one of the other processes described in this application guideline while the minimum outdoor air damper is modulated directly as a function of mixed air plenum pressure.
- Return fan speed/capacity modulation based on one of the other processes

described in this application guideline while the return damper is modulated directly as a function of mixed air plenum pressure and the requirements of the economizer cycle.

## 6.2. Advantages

Properly implemented, this approach can help ensure a constant minimum outdoor air volume (not percentage) under the variable operating conditions associated with economizer and VAV operation.

Mixed air plenum static pressure based control may be advantageous when:

- The ventilation load remains constant over the entire operating interval while the thermal load varies significantly.
- The pressure relationships that must be maintained are critical.
- The systems served are constant volume or near constant volume systems where only minor adjustments in fan speed are necessary.

This approach also has one of the lowest hardware costs, especially in new construction making it an option worth considering for smaller systems and projects where budget constraints may be present.

## 6.3. Limitations

The constant minimum outdoor air volume advantage listed in the preceding section can be a disadvantage if there is a variable ventilation load. This limitation can be mitigated if indicators of the variable ventilation requirement are used to reset the mixed air plenum setpoint.

This approach is also very susceptible to a number of design and operating complexities, which are enumerated in the following section.

## 6.4. Application Considerations

### Application Complexity

In a real air handling system, especially a VAV air handling system equipped with a return fan and an economizer cycle, there are several factors that complicate the relationship between mixed air plenum pressure and minimum outdoor air flow.

- The mixed air plenum is actually connected to two different orifices; the outdoor air intake system and the return air connection. Flow through both of these pathways will impact its pressure relative to atmosphere.
- The pressure in the mixed air plenum is impacted by two different reference pressures; atmospheric pressure and the return fan discharge pressure. The strategy exploits this fact as a mechanism to control the return fan.
- The two orifices referenced in the first bullet are only fixed when the system is on minimum outdoor air. When the economizer process is active, they vary in size in an inverse relationship to each other. Ideally, this relationship will be such that the net orifice area represented by both pathways is constant; this strategy assumes that this is the case. In reality, this is very difficult to achieve and is highly dependent the sizing and linearity of the outdoor air and return air dampers.

These complexities are expanded upon below as a part of the discussion on integration and interaction problems.

### Potential for Negative IEQ Impact

All things being equal, properly applied and implemented, this strategy will have little measurable impact on comfort relative to the other strategies. And, assuming filtration and dehumidification issues are properly addressed in the over-all HVAC process, this strategy may show a tendency towards improved IEQ given its tendency to ensure constant minimum outdoor air volumes under all operating conditions.

### Potential for Integration/Interaction Problems

As indicated above, the success of the strategy is dependent on the integration of the return fan speed control system with the economizer dampers. If the damper system is not sized to provide a linear control characteristic, then it can no longer be assumed that the mixed air plenum pressure relative to atmospheric pressure is fairly constant under all operating modes. If the pressure is not constant, then the assumed relationship between return flow, outdoor air flow and supply flow will also be invalid.

Related to the preceding; experience and the literature indicate that this approach is best implemented with a minimum outdoor air control strategy that utilizes an independent minimum outdoor air damper.

A subtle but potentially significant interaction issue associated with this particular strategy is that when the system reaches a 100% outdoor air condition, the process becomes virtually open loop because the return fan discharge is disconnected from the mixed air plenum by virtue of the closed return air damper. This may cause problems with the return flow tracking the supply flow, especially if there are significant variations in supply flow in the 100% outdoor air mode.

Finally, the variable flow rates encountered in a VAV system compound the complexities alluded to the preceding bullets.

All of these issues are explored in greater detail in *Section 6.5. Key Design Issues and Considerations*.

### First Cost

In new construction, this approach can be one of the lowest first cost options available. The fan speed control strategy as a direct function of mixed air plenum pressure can be achieved for the cost of a differential pressure sensor, the control system hardware, and the control programming required. This low first cost assumes that the dampers and other hardware required to successfully control minimum outdoor air flow in a compatible manner would have been provided regardless of the approach.

In a retrofit application, it may be necessary to modify the existing maximum outdoor air damper to provide a more linear characteristic, add an independent minimum outdoor air damper, or both. Obviously, all of these scenarios can impact first cost. However, the additional costs will typically be modest in contrast to those associated with some of the more hardware intensive return fan speed control strategies like fan volume/flow tracking.

### Maintenance Cost

Due to the minimal control hardware requirements, the maintenance costs associated with mixed air plenum pressure based tracking strategies will tend to be low. However, the need to periodically retest the performance of larger and more complex systems that employ the strategy for proper ventilation flow delivery will tend to add to the maintenance cost. This issue is discussed in greater detail in *Section 2.7- Key Operating Issues and Considerations*.

### Energy Cost

There are three general areas where mixed air plenum static pressure based control may increase energy consumption relative to other approaches:

*Fan Energy*

This approach is dependent upon a properly sized minimum outdoor air and economizer damper system. Proper sizing of the damper systems is related to pressure drop, with higher pressure drops being associated with more linear characteristics. Fan energy is also a direct function of system static pressure. Thus, the pressure drop required to allow the minimum outdoor air and economizer dampers to regulate flow predictably will impose an energy burden on the fan system that would not exist under different circumstances. This consideration is mitigated by the fact that the economizer process is also dependent upon proper damper sizing. Thus, it might be argued that any economizer equipped system would bear the burden of the energy consumption associated with the economizer damper pressure drop, regardless of how return fan speed was controlled.

*Heating and Cooling Energy*

When properly implemented, this approach will tend to ensure constant minimum outdoor air flows. If this is a requirement of the system, then there is not an energy penalty associated with this. However, if the ventilation requirements of the system are variable, then the constant minimum outdoor air flow rate regardless of the load condition may represent an unnecessary energy burden. Conversely it may provide improved IAQ; thus, represent a value for the added energy expenditure.

*Control Process Feedback Path*

The third energy impact is with regard to the control process feedback path when the economizer process drives the system to 100% outdoor air operation. One of the fixes that could be implemented to address the change in feedback path is the implementation of a minimum position signal for the return damper. Even in the best of cases, this will result in some warm return air being re-circulated, which will dilute the cooling effect of the supply outside air and most likely result in the use of more mechanical cooling.

## 6.5. Key Design Issues and Considerations

Many of the issues discussed in the subsequent sections on installation and operation are intertwined with the decisions made during the design process. Thus, reviewing those sections to understand the challenges that will be faced during fabrication, start-up and operation can be crucial to a successful design. *Appendix 7: Design, Installation and Operation* includes a discussion of a general nature on this topic. The following information is particular to return fans controlled based on mixed air plenum pressure.

### Integration with the Economizer Process

The performance of this strategy is highly dependent upon the success of the minimum outdoor air and economizer control processes and related damper sizing issues; it is particularly important that the dampers and mixing section requirements associated with these functions be addressed by the contract documents. A detailed discussion of these topics can be found in *Appendix 2: Economizer Theory and Operation*.

To understand the ramifications of failing to address these issues, consider what happens when a mixed air plenum pressure control based system equipped with oversized economizer dampers moves from minimum outdoor air towards an economizer process.

1. The maximum outdoor air damper begins to open as the return damper begins to close. This event and its ramifications are discussed in detail in *Appendix 2: Economizer Theory and Operation* under *Damper Sizing and Linkage Arrangement*.

2. Due to the low resistance through the now open maximum outdoor air damper, the mixed air plenum pressure will suddenly rise impacting the return fan speed control loop.

3. The interaction of the supply fan speed control loop as it tries to respond to the sudden flow increase will further impact the mixed air plenum pressure, which can trigger a cascading instability to the return fan speed control loop and other control loops in the system. Frequently, this can degrade rapidly to a situation similar to that depicted in Figure 2 of *Appendix 2: Economizer Theory and Operation*.

A condition similar to that described under item 2 above will occur as a result of the oversized return dampers. Specifically, when on minimum outdoor air, the return dampers may never generate a pressure drop that is in the range of the pressure drop through the minimum outdoor air damper alone, allowing the return fan to pressurize the minimum outdoor air plenum. As a result, the return fan speed will drive to its minimum setting and remain there since the control loop would interpret the lack of negative mixed air pressure as too much return air. This may be the exact opposite of the real situation and could easily lead to problems with over-pressurization of the building, including doors that blow open, whistling, and capacity reductions on the supply side if the building or portions of the building are particularly tight. The building static pressure control issues could ripple out through the building static pressure control system, causing further interactive instability.

## 100% Outdoor Air Operation

A subtle but significant limitation of the mixed air plenum pressure based approach shows up in operating modes where the economizer process places the system on 100% outdoor air. The feedback path for the control process changes when the return damper closes fully to allow 100% outdoor air economizer cooling. When the unit is not on 100% outdoor air (the return damper is at least partially open), the return fan speed can affect the mixed air plenum pressure by a direct path. Specifically;

1. Changes in return fan speed change the return fan discharge pressure.
2. Changes in return fan discharge pressure change the pressure difference across the return damper.
3. Changes in the pressure difference across the return damper will have a direct impact on flow through the damper.
4. Flow through the damper will have a direct impact on the mixed air plenum pressure.

With the return damper fully closed during 100% outside air economizer operation, the direct path is disrupted. Now, the return fan's impact on the mixed air plenum pressure is via the much longer, subtler path associated with supply fan performance and the impact of building pressurization. Specifically;

1. Changes in the mixed air plenum pressure will only be a function of the supply fan flow rate.
2. Supply fan flow rate will vary with load in VAV systems and, for any given load condition, can impact or be impacted by building pressurization.

To gain some insight into the effect of building pressurization on this process, consider a VAV system with oversized economizer dampers that has achieved a steady state operating mode at a near design load condition while on minimum outdoor air. If things are working correctly, the supply and return fan speeds would be near maximum. If the outdoor conditions changed to the point where the integrated economizer cycle allows the system to switch to 100% outdoor air, then system will move through the sequence of events enumerated previously under *Integration with the Economizer Process*. As a result of the oversized outdoor air dampers minimizing the pressure drop to the mixed air plenum, the return fan speed drives to minimum while the supply fan speed attempts to deliver the air volume required by the load condition. Since this change minimizes the amount of air being returned by the return fan for discharge from the building via the relief damper system, the building pressure will tend to increase as the system tries to find a new stable operating point where the flow into the building is matched by the flow out of the building via envelope leakage. At this point, a couple of scenarios can occur.

1. *The Pressurized Building Pushes the Supply Fan Up Its Curve:* If nothing else changes, the increasing building pressure will tend to push the supply fan up its curve. This will reduce flow, which will reduce the pressure drop through the outdoor air intake system and raise the mixed air plenum pressure. The increase in mixed air plenum pressure will be seen as too much return air and will tend to keep the return fan at a low speed.
2. *Pressurization of the Building by the Supply Fan Shifts the Return Fan Operating Point:* Because the supply and return fans are placed in series when the system is in the 100% outdoor air mode, and because the pressurized building serves as a common reference point for the supply fan discharge and the return fan suction, the typically more powerful supply fan will tend to influence the performance of the return fan. (In extreme cases, it may actually try to push more air through it.) This will tend to increase flow out of the building, regardless of the return fan speed.
3. *Exterior Doors Blow Open:* The doors to the building might blow open if the pressure developed by the supply fan becomes high enough. If this reduction in resistance on the supply side causes the supply fan to move out of its curve and deliver beyond design flow, then the

mixed air plenum pressure will drop to the point where the return fan speed increases and the system may stabilize at a satisfactory operating point. This result is far from guaranteed.

The significance and impact of the issues related to a mixed air plenum pressure based control strategy during 100% outdoor air operation generally fall into three categories:

- Systems that use the variation of this strategy to modulate the return damper, based on mixed air plenum pressure, may experience fewer problems since the return damper is influenced by other factors besides the economizer process. For instance, a minimum return position can be incorporated into the control cycle to ensure that the feedback path is never changed. However, this will dilute the benefit of the economizer and could impose an energy penalty on the system.

- Feedback issues are more significant in tight buildings than if the building tends to leak. Similarly, the tendency for people to open operable windows on a nice day (i.e. a day typically associated with operating on 100% outdoor air) may make the building temporarily leaky and mitigate the problem.

- Systems that spend a significant amount of their time on 100% outdoor air due to climate conditions and impact of an integrated economizer will be more subject to the effects of the feedback phenomenon than systems that spend more of their operating hours in non-100% outdoor air modes.

All of these issues will tend to be much more significant for large complex systems and/or large complex buildings.

### Integration with VAV Systems with High Turn Down Ratios

Applying the mixed air plenum pressure based strategy to a VAV system with a large turn down ratio may yield less than optimal performance on a number of fronts.

*Damper Linearity Variations with Flow*

A system with a reasonably linear damper characteristic at design flow may have a marginal characteristic at 50% load because the pressure drop through the damper system will vary exponentially with flow. In general, damper linearity is dependent upon the pressure drop through the damper being significant relative to the pressure drop through the system the damper serves, as is discussed in *Appendix 2: Economizer Theory and Operation.*

*Speed Regulation While Operating on 100% Outdoor Air*

Because of the issues discussed previously under *100% Outdoor Air Operation*, systems that must deal with significant flow variations and spend a significant amount of time operating at or near 100% outdoor air may have marginal performance at best. An example of such a situation might occur with a fan system operating in the Los Angeles, California area. An examination of the climate data for the LA area as presented in Figure 1 of *Appendix 2* reveals that an air handling system with a discharge setpoint of 55°F and an integrated economizer cycle would spend a significant amount of time operating with 100% outdoor air due to the mild climate.

### Control System Considerations – Hardware

Most of the control system hardware considerations discussed in *Chapter 1: Introduction and Fundamentals* and in *Appendix 5: Control System Hardware and Software* apply, including:

- Variable speed drive interlock issues
- Economizer control integration issues
- Minimum outdoor air control issues
- Building pressurization control integration issues
- Return and relief damper interlock issues

The control hardware for this approach is minimal, consisting of the return fan variable speed drive and the mixed air plenum pressure sensor.

The mixed air plenum pressure sensor should be located so that the pressure drop of the filters is not included in the measurement. Filter pressure drop will vary with the filter loads and negate the intent of the control process; i.e. ensuring a constant minimum outdoor air percentage by maintaining a constant mixed air plenum pressure.

A sensor with the ability to measure both positive and negative pressures is desirable. Even though the normal operating mode will result in a negative mixed air plenum pressure, stack effect during the off cycle and some failure modes could result in a positive mixed air plenum pressure. Utilizing a sensor with bi-directional capabilities will prevent the positive pressures from being interpreted as invalid or over range data, eliminating nuisance control system sensor failure alarms during the off cycle. This type of sensor will also allow alarms to be generated for failure modes that result in positive plenum pressures.

## Control System Considerations – Software

Points lists, narrative sequences and logic diagrams are important tools to convey design intent to the implementing and operating staff. These topics are discussed in *Chapter 1: Introduction and Fundamentals* and *Appendix 5: Control System Hardware and Software*. The following applies specifically to this strategy.

*<u>Control System Points List</u>*

The example provided at the end of this chapter can be edited to meet the needs of a project using mixed air plenum pressure for return fan control. Editing considerations should include:

- Coordination with the requirements of the narrative sequence and any logic diagrams.
- Clarification regarding whether the mixed air plenum pressure setpoint is:

  1. A fixed value targeting a fixed minimum outdoor air volume under all operating conditions or:
  2. A reset value targeting a variable outdoor air flow based on occupancy or some other parameter.

- In the case of item 2 above, clarification will be required regarding how the resetting parameter is to be measured.
- Clarification on if and how speed will be measured and what the units of measure should be (rpm, hz, percent maximum, etc).

*<u>Narrative Control Sequence</u>*

The example provided at the end of the chapter can be edited to meet the needs of a project using mixed air plenum pressure for return fan control. Editing considerations should include:

- Coordination with the requirements of the points list and any logic diagrams.
- Clarification regarding a fixed or variable mixed air plenum pressure setpoint, as discussed above under *Control System Points List*.
- Clarification regarding whether the return fan speed will be controlled directly based on mixed air plenum pressure, or indirectly using one of the variations listed earlier in this chapter.
- If one of the variations on the strategy is selected, clarification will need to be provided regarding how the mixed air plenum pressure related control functions for each component will be integrated with the other functions they serve. For instance, if the return damper is modulated to maintain the mixed air plenum pressure, are there any issues that need to be addressed with regard to economizer operation, failure modes, position when the system is off, smoke exhaust cycle operation, etc.?

### Air Handling System Considerations

Many of the air handling system considerations discussed in *Chapter 1: Introduction and Fundamentals* apply to this strategy, including:

- Economizer damper selection, sizing, and installation
- Return flow path versus relief flow path pressure losses

### Electrical and Drive System Considerations

Many of the electrical system considerations discussed in *Chapter 1: Introduction and Fundamentals* apply to this strategy including:

- Variable speed drive application, networking, and interlock issues.
- Motor selection and application issues.

As is the case for any of the strategies, adjusting/selecting the fan sheaves to provide design flow with the drives running at full speed will optimize overall efficiency and controllability as discussed in *Appendix 6: Electrical Distribution and Drive* under *Maximizing Efficiency*.

## 6.6. Key Installation Issues and Considerations

Many of the design issues discussed in the preceding section and the operating issues discussed in the next section have a direct bearing on system installation. Therefore, reviewing the design intent for the strategy and its operating requirements is a crucial step in successfully installing and starting up the system. *Appendix 7: Design, Installation and Operation* includes a discussion of a general nature on this topic. The information in this chapter is particular to the mixed air plenum pressure based control strategy.

To ensure overall success on all fronts, the design issues must be complimented by the following efforts in the field:

### Adequate Equipment Procurement

A thorough shop drawing review process can go a long way toward ensuring that the design intent is reflected in the equipment provided. A discussion of important areas to target is included in *Chapter 1: Introduction and Fundamentals* under *The Relationship Between Design, Installation, and Operation*.

### Locating and Installing Sensors in the Field

As mentioned previously under *Control System Considerations – Hardware,* it is important to make sure the sensing locations selected in the field allow true mixed air plenum pressure to be sensed independent of the influence of the filtration system. In addition, the sensor location topics discussed in *Chapter 1: Introduction and Fundamentals* under *Hardware Issues* should also be considered.

### Installing and Configuring the Economizer and Minimum Outdoor Air Dampers to Ensure a Linear Flow versus Stroke Characteristic

As mentioned previously, the performance of this strategy is highly dependent upon the success of the minimum outdoor air and economizer control processes and related damper sizing issues. Important installation considerations include:

- *Design versus Installed Damper Type:* To achieve the design performance, the installed damper must have characteristics that are similar to those anticipated by the designer when the damper was sized. For instance, if an opposed blade damper was substituted for a parallel blade damper or an airfoil blade design was substituted for a conventional design, then installed equipment may have very different performance characteristics when contrasted with those anticipated by the design.
- *Design versus Installed Damper Configuration:* Configuration issues like the damper size and aspect ratio can have a direct impact on the damper characteristics. Blade rotation and the relative location of

the outdoor air damper with respect the return damper can impact mixing performance and, if improperly handled, can lead to instability in the economizer control process which can ripple out to other control processes in the system, including the return fan speed control process.

- *Design versus Installed Actuator and Linkage Arrangement:* The geometry of the actuator and linkage system can have a direct impact on damper characteristics. For instance the percent stroke versus percent blade rotation characteristic of a piston actuator driving a damper through a crank arm will be different from a shaft mounted direct drive actuator.

All of these topics are discussed in greater detail in *Appendix 2: Economizer Theory*.

### Pre-start and Start-up Checklist Considerations

The pre-start and start-up considerations for mixed air plenum pressure based strategies are no different from the general requirements for any other strategy. See *Chapter 1: Introduction and Fundamentals* under *The Relationship Between Design, Installation, and Operation* for additional information.

### Testing Considerations

Perhaps the most important aspect of implementing a mixed air plenum pressure based return fan control strategy is the system setup and testing associated with ensuring proper minimum outdoor air flow. The physical realities of the installed equipment can often yield field results that differ from the theoretical expectations. This is illustrated in the example in *Appendix 8: Theoretical versus Actual Performance*, which contrasts the expected performance and actual performance of a speed tracking based strategy. While the exact operating profile that a mixed air plenum pressure based strategy might experience as it followed the supply flow changes might vary somewhat from what is illustrated, the concept still applies. That is, satisfactory performance assessed at one point in the operating spectrum may not ensure satisfactory performance under all possible operating scenarios. This reality will exist from moment the system is design through its start-up and operational life, and thus must be addressed by the responsible parties during all of those phases.

Given that this control strategy is highly dependent upon the performance of the economizer and minimum outdoor air dampers and that damper performance will vary with flow, it is strongly recommended that a multi-point testing approach be used for this strategy. Test points should include 5 to 10 operating points spread out across the system operating spectrum (minimum supply flow/load to maximum supply flow/load). If a fixed outdoor *percentage* is to be maintained, then the test should verify that such is the case since this strategy will tend to produce a fixed outdoor air *volume* unless specific measures are included to reset the mixed air plenum pressure setpoint under different operating modes. Finally, if the initial testing does not occur under conditions that challenge and prove the stability of the economizer control process (usually extreme cold), using trending or a return visit to the site to verify economizer stability and thus the stability and performance of the mixed air plenum pressure based return fan control process is recommended.

Usually, setting up the system and testing it involves close coordination between the mechanical contractor, the controls contractor and the balancing contractor to tune the drives, the fan speeds and the bias settings. A detailed description of the considerations and test process can be found in *Appendix 4: Tuning Minimum Outdoor Air Flow*.

## 6.7. Key Operating Issues and Considerations

Many of the issues discussed in the preceding paragraphs in terms of design and installation will ultimately become operational issues. Reviewing and understanding key design and implementation issues will allow the operating staff to develop an understanding of the design intent for the strategy and its implementation. This can be a crucial step in successfully operating a system regardless of the control approach employed.

However, it is important to acknowledge that there is a subtle but important difference between the design information conveyed by the control sequence and the realities of an operating building. By its nature a control sequence will describe the response that *should* occur in a system for any conceivable operational trigger or event. In contrast, the operating team is often challenged to discover what specific trigger or event *caused* the operating state with-which they are dealing. Towards that end, a trouble shooting table has been included in this chapter which correlates an operating symptom with its possible cause and corrective action.

## Operating and Monitoring the Process

The control sequence and points list included at the end of this chapter will provide a good starting point for developing an understanding of the operating details associated with this strategy. In addition, they illustrate where the operating staff interfaces with the control system to adjust and monitor it.

Additional information applicable to the operation of all return fan control strategies can be found in *Appendix 7: Design, Installation and Operation*.

## 6.8. Troubleshooting Table

*While not all inclusive, this table illustrates many of the more common problems that can occur with a mixed air plenum pressure based return fan capacity control strategy and the associated corrective actions. Some troubleshooting issues will be general in nature while others will be specific to a particular system by virtue of the control sequence and wiring configuration associated with it. The following table is based on the system illustrated at the beginning of the chapter with a control sequence as described in Section 6.10. Sample Narrative Sequence of Operations.*

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| Return Fan Fails To Start | Loss of Power | • Verify the integrity of the power supply from the motor back to the source. If tripped circuit breakers or blown fuses are encountered, determine and correct the cause of the fault prior to restoring power. |
| | Interlock Problem | • After verifying that the fan can be safely run alone, switch the fan to "Hand" and observe the results.<br>♦ If the fan still fails to start, the problem is most likely in the safety interlock circuit (fire alarm, relay, smoke detector, etc.). Investigate and correct interlock problems in the safety interlock circuit associated directly with the return fan.<br>♦ If the fan runs, the problem is most likely in the interlocks associated with scheduled operation of the fan and other automation requirements. Verify the controlling software that cycles the fan in the "Auto" mode as well as any hardwired interlocks with other equipment like the supply fan. A safety trip that is preventing a supply fan start (freezestat, static switch smoke detector, etc.) could prevent a return fan start if the return fan is interlocked via hardwiring or software to only run when the supply fan runs.<br>• If the fan fails to run in "Hand" or "Auto" and the drive is equipped with a "Bypass" option, switch the fan to "Bypass" after verifying that it is safe for the fan to run at full speed.<br>♦ If the fan starts and runs in bypass, the problem is most likely in the VFD itself (see below).<br>♦ If the fan fails to start in the bypass mode, the problem is probably one of the other issues listed in this table. |
| | VFD Failure | • Verify the integrity of the drive circuitry using the manufacturer's troubleshooting guidelines as published in the operation and maintenance manual. |
| | Drive System Failure | • Verify the integrity of the drive belts and sheaves or couplings. |
| | Motor Failure | • Isolate the motor from the power system and all controllers, drives, starters, etc.<br>♦ Spin the motor shaft by hand to assess the integrity of the bearings. The shaft should spin freely and smoothly. Investigate and correct any unusual noise, jams or restrictions to free movement.<br>♦ Inspect the motor connections for security and signs of overheating or resistive connections. Correct any |

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| | | discrepancies found.<br>♦ Megger test the motor to measure the insulation resistance to ground. Correct any grounded conditions before reapplying power to the motor. Usually this will involve removing the motor and sending it out for repair.<br>• If the motor spins freely, the connections are good, and there are no grounds, cautiously reapply power (monitor the inrush current during this process) and verify:<br>♦ The motor starts and comes up to speed.<br>♦ The motor inrush current drops off as the motor comes up to speed.<br>♦ The current on all phases is balanced and does not exceed the motors nameplate rating.<br>• If the motor currents are over nameplate disconnect the load and restart the motor. Verify the following:<br>♦ No-load motor amps are approximately 50 to 70% full load amps for 900 – 1200 rpm motors (Some may be higher), approximately 30% full load amps for 1800 rpm motors and are approximately 20 to 30% full load amps for 3600 rpm motors. If the no load currents are balanced and within the limits listed above, the motor is probably being overloaded (see below).<br>♦ If the no-load currents are out of balance or exceed the limits listed above, the motor windings are probably shorted and the motor will need to be removed and repaired.<br>• If the motor currents are severely imbalanced (in excess of 10% different) check the following:<br>♦ Verify that the voltage supplied to the motor is within 5% of the line voltage rating. Investigate and correct the cause of any observed low voltage condition.<br>♦ Verify that the phase to phase voltages are balanced and are within 5% of the line voltage of each other. If the phase voltages are balanced but the currents are imbalanced, there is probably a short in the motor winding and the motor will need to be removed and repaired. |
| | Overload Trip | • If a new motor has been installed on the fan, verify that the starting torque capability of the new motor (often referred to in the motor and fan spec sheets as WR2) is equal to or better than the motor it replaced (see *Appendix 6: Electrical and Drive System Considerations* for additional information.)<br>• Verify that the wiring connections to the overload relay are tight. Loose wiring connections represent a resistive load that can generate heat and trigger a false overload trip.<br>• Inspect and clean the fan wheel as necessary. Dirt on the fan wheel increases its moment of inertia and can cause start-up problems to "suddenly" appear in a fan that has been running satisfactorily (see *Chapter 1: Introduction and Fundamentals –* |

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| | | *Maintaining and Adapting Design Intent - Fan Wheel Cleanliness* for additional information.) |
| Return Fan Fails To Stop | Fan Remains in Operation Despite a Safety Trip That Should Directly Shut Down the Fan | • Safety trips intended to directly affect the return fan should shut down and lock out the fan irrespective of the position of any Hand-Off-Auto switches or Inverter-Bypass switches. If a fan remains in operation after a safety trip, investigate and correct problems in the safety interlock circuit. |
| | Fan Remains in Operation Despite a Supply Fan Shut Down due to a Safety Trip | • Verify that the drive is in "Auto." If the drive is in "Auto" and continues to operate when it should be off, investigate and correct problems in the control logic associated with supply fan interlocks. |
| | Fan Remains in Operation When it Should Be Off Based On Schedule | • Verify that the drive is in "Auto." If the drive is in "Auto" and continues to operate when it should be off, investigate and correct problems in the control logic associated with the return fan start-stop functions. |
| Return Fan Speed Does Not Vary | Return Fan Speed Does Not Vary Despite Supply Fan Speed Variations. | • If the return fan VFD is equipped with a bypass system, verify that the system is in "Inverter" (VFD active) and not "Bypass" (VFD bypassed and out of the circuit).<br>• Verify that the return fan VFD speed control selection is in the position that causes the drive to follow a remote speed command. Typically this is the "Auto Speed Command" position. This selection may be made via a selector switch or via a keypad, depending on the drive design, manufacturer, and vintage.<br>• Verify that the speed control signal is available at the return fan VFD input terminals.<br>• Verify that the mixed air plenum pressure setpoint is appropriate and/or matches the design requirement.<br>• Verify that the supply flow is in fact varying with the changes in supply fan speed. There should be a fairly direct correlation between supply flow and supply fan speed. If there isn't, investigate and correct. Possible issues include fire/ smoke dampers that should be open but are closed, problems with the coordination of the outdoor air and return air dampers associated with the economizer process, an erroneous supply fan speed signal, and belt failures |
| | Return Fan And Supply Fan Speeds Do Not Vary | • Verify that the supply fan VFD is in "Auto" and not in a mode that would cause it to run at a fixed speed. If the supply fan is in "Auto" and its speed does not vary the problem could be:<br>♦ A problem in the supply fan speed control system or related logic. Detailed troubleshooting of the supply fan speed control system is beyond the scope of this guide, but in general terms the procedure will be similar to that described above under *Return Fan Speed Does Not Vary Despite Supply Fan Speed Variations*.<br>♦ A load condition that exceeds the supply fan's capacity may exist. This could be caused by a number of factors including a load condition in excess of design, a supply flow restriction, or |

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| | | conditions that have compromised the capabilities of the cooling or heating utility systems that condition the supply air (low refrigerant, high chilled water supply temperature, high cooling coil discharge air temperature, low heating coil discharge air temperature, low steam supply pressure, low hot water supply temperature, etc.). Troubleshooting of these issues is beyond the scope of this guideline. |
| Return fan speed varies under some operating conditions, but not under others | All issues listed under *Return Fan Speed Does Not Vary* | Investigate and correct as described under *Return Fan Speed Does Not Vary* |
| | Minimum outdoor air damper properly sized but the maximum outdoor air damper is oversized | Assess the damper performance characteristics under <u>*all*</u> operating modes. The minimum outdoor air/economizer damper system needs to represent a pressure drop that is significant relative to the system pressure drop under all operating conditions. Dampers that are properly sized when the system is at design flow may be marginal when the system has turned down to 50-75% of design capacity. |
| Building Pressure Relationships are Negative or Overly Positive Either Relative to the Outdoors or Relative to Adjacent Areas | Building Pressure Relationships are Negative or Overly Positive Regardless of the Operating Status of the Return Fan and its Related Air Handling System | • The problem is most likely not related to the return fan and is more likely related to:<br>♦ Issues in a different system in the building<br>♦ Stack effect<br>♦ An imbalance between make up air either due to improper adjustment and balancing or due to the operation of an exhaust system without its associated make up system or vice versa.<br>♦ Problems with a building static pressure control system that operates independently of the air handling system in question.<br>♦ Modification or changes have been made to the building's envelope, functions, or occupancy patterns. |
| | Negative or Overly Positive Building Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling System | • Verify the integrity of the minimum outdoor air control system including that minimum outdoor air is being introduced into the system in the proper quantities. Bear in mind that in many instances the return fan capacity control system <u>*is*</u> the minimum outdoor air control system; i.e. there may not be an active minimum outdoor air control system.<br>• Verify that the economizer damper system is functioning properly including:<br>♦ Maximum outdoor air, return air, and relief air dampers operate freely and through their full stroke<br>♦ Maximum outdoor air, return air, and relief air dampers operate with the correct relationship to each other (return dampers close as the maximum outdoor air dampers open, etc.)<br>• Verify that any building pressure control components of the return fan/air handling system control process are functioning properly (if so equipped). |

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| | | • Verify that the mixed air plenum pressure setpoint is correct and as tuned during the commissioning process. See *Appendix 4: Tuning Minimum Outdoor Air Flow* for information on making these adjustments if it is necessary to re-tune the system.<br>• Verify that the return fan sheave or motor sheave have not been replaced with new sheaves with a different pitch diameter than the sheaves that were installed when the system was commissioned and tuned.<br>• Verify that the pitch diameter on a fan or motor equipped with an adjustable pitch sheave has not changed.<br>• Verify that there is not a restriction in the outdoor air intake system such as a louver that has become obstructed, turning vanes that have been obstructed by debris, etc. Bear in mind that the pressure drop represented by a restriction is a function of flow rate. Thus, a restriction in a VAV system may present a problem that seems to come and go as the flow rate increases and decreases.<br>• Related to the preceding, verify that the mixed air plenum pressure sensor is measuring plenum pressure ahead of the filters. The mixed air plenum pressure based control strategy is vulnerable to problems if the mixed air plenum pressure is sensed down stream of the filters. This is because the filters represent a pressure drop that varies with both flow rate and time as the filters load.<br>• Determine if modification or changes have been made to the building's envelope, functions, or occupancy patterns in the area served by the return fan and its related air handling systems. Significant modifications in any of these areas may require re-assessment of the system's mixed air plenum pressure setpoint and/or re-tuning of the system's minimum out door air flow. See *Appendix 4: Tuning Minimum Outdoor Air Flow* and *Appendix 8: Theoretical versus Actual Performance* for additional information. |
| Minimum Outdoor Air Flow Does Not Meet Requirements | Minimum Outdoor Air Flow Problems Exist Regardless of the Operating Status of the Return Fan and its Related Air Handling System | The issues in this category will be similar to the issues discussed above under *Pressure Negative or Overly Positive Regardless of the Operating Status of the Return Fan and its Related Air Handling System*. |
| | Minimum Outdoor Air Flow Problems Appear to be Related to the Operation of the Return Fan and its Related Air Handling System | In small buildings or large complex buildings, problems with minimum outdoor air flow in one system may not show up as problems with pressure relationships in the building. However, most of the issues are the same as those discussed above under *Negative or Overly Positive Pressure Relationships Appear to be Related to the Operation of the Return Fan and its Related Air Handling System*. |
| | Constant minimum outdoor air | By their nature, mixed air plenum pressure based strategies will tend to deliver a constant minimum outdoor air volume. This may or may |

| Symptom | Possible Cause | Recommendation |
|---|---|---|
| | *percentage* is desired versus a constant minimum outdoor air *volume*. | not be appropriate given the nature of the load. |

## 6.9. Sample Points List

The following tables illustrate a points list for the return fan in the system illustrated at the beginning of the chapter and can be used as a starting point for similar systems employing mixed air plenum pressure based control strategies. It was developed using the points list tool contained in the *Control Design Guide*. This publicly available resource can be downloaded from www.PECI.org/FTGuide and used to develop a points list with characteristics similar to those illustrated for an entire system or project.

| Point Name | Sensor Information | | |
|---|---|---|---|
| | System and Service | Sensor/Interface Device[6] | |
| | | Type | Accuracy |
| **Analog Inputs** | | | |
| AH1MAPr | AHU 01 Mixed Air Plenum Static Pressure | Low range differential pressure transmitter | +/-0.05 in.w.c. |
| RF1SpdFb | AHU 01 Return Fan 1 Speed Control Feedback | VFD programmable output | +/-1.0%FS |
| RF1kW | RF1 kW | VFD programmable output | +/-1.0%FS |
| **Analog Outputs** | | | |
| RF1Spd | AHU 01 Return Fan 1 Speed Control Command | 4-20 ma output | +/-1.0%FS |
| **Digital Inputs** | | | |
| RF1POO | Return Fan 01 Proof of Operation | Current switch | N/A |
| RF1SSwSt | Return Fan 1 Selector Switch Status | Auxilliary contact | N/A |
| VFD1SSwSt | Supply Fan 1 VFD Selector Switch Status | Auxilliary contact | N/A |
| **Digital Outputs** | | | |
| AH1RFSS | AHU 01 Return Fan Start/Stop Command | Interface relay | N/A |
| **Virtual Points** | | | |
| RF1Hrs | RF 01 Accumulated Hours of Operation | Calculation based on proof of operation input | N/A |
| RF1SpdPGn | RF1 Speed Control Loop Proportional Gain | Manually set | N/A |
| RF1SpdIGn | RF1 Speed Control Loop Integral Gain | Manually set | N/A |
| RF1SpdDGn | RF1 Speed Control Loop Derivative Gain | Manually set | N/A |
| AH1MAPrStPt | AH1 Mixed Air Plenum Pressure Set Point | Manually set | N/A |
| **Hard Wired Points** | | | |
| RF1Fire | RF 01 Fire Alarm Shut Down Relay | Relay by fire alarm contractor | N/A |
| AH1VFDAux | AH1 VFD Auxilliary Contact | Auxilliary contact | N/A |

| Point Name | Alarm and Trending Information, General Notes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Features | | | | | | | | | | | Notes |
| | Alarms | | | | Trending | | | | | | | |
| | Limit | | Warning | | Samples[1] | Commissioning[5] | | | Operating[5] | | | |
| | Hi | Lo | Hi | Lo | | Time[2] | Local[3] | Archive[4] | Time[2] | Local[3] | Archive[4] | |
| **Analog Inputs** | | | | | | | | | | | | |
| AH1MAPr | None | None | Note 27 | Note 27 | 15 | 1 min | X | X | 4 min | X | X | |
| RF1SpdFb | N/A | N/A | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | |
| RF1kW | N/A | N/A | Note 26 | Note 26 | 15 | 15 min1 | X | X | 15 min | X | X | |
| **Analog Outputs** | | | | | | | | | | | | |
| RF1Spd | N/A | N/A | N/A | N/A | 15 | 1 min | X | X | 4 min | X | X | |
| **Digital Inputs** | | | | | | | | | | | | |
| RF1POO | Note 13 | None | None | None | 15 | COV | X | X | COV | X | | Notes 7,9 |
| RF1SSwSt | Note 10 | None | None | None | 2 | COV | X | X | COV | X | | Notes 10, 11 |
| VFD1SSwSt | Note 10 | None | None | None | 2 | COV | X | X | COV | X | | Notes 10, 11 |
| **Digital Outputs** | | | | | | | | | | | | |
| AH1RFSS | Note 13 | None | None | None | 15 | COV | X | X | COV | X | | |
| **Virtual Points** | | | | | | | | | | | | |
| RF1Hrs | None | None | 1,000 hr. | None | None | None | None | None | None | None | None | Note 8 |
| RF1SpdPGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1SpdIGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| RF1SpdDGn | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| AH1MAPrStPt | None | None | None | None | None | None | None | None | None | None | None | Note 12 |
| **Hard Wired Points** | | | | | | | | | | | | |
| RF1Fire | Open | None | None | None | None | None | None | None | None | None | None | Note 14 |
| AH1VFDAux | None | None | None | None | None | None | None | None | None | None | None | Note 13 |

**Notes:**

1. Samples indicates the minimum number of data samples that must be held in the local controller if it is trending the point. This may be based on the operating trending requirements. Higher sample capabilities tends to minimize archiving frequency.
2. Time indicates the required sampling time for the trending function (1 min = 1 sample per minute, 4 min = 1 sample every 4 minutes).
3. A check in the local column indicates that the trending only needs to be running in the local controller and the most recent value can write over the last value when the trend buffer fills up.
4. A check in the archive column indicates that the trend data must be archived to the system hard disc when trend buffer fills up so that a continuous trend record is maintained.
5. Commissioning trending requirements only need to be implemented during the start-up and warranty year. After the start-up and warranty process, the control contractor should set the trending parameters to the operating requirements listed.
6. See the specifications for additional requirements and details regarding sensor and interface device requirements.
7. Adjust to detect a belt or coupling failure by showing failure to run with the belt or drive coupling removed and the motor running.
8. Accumulate on a monthly basis and archive the monthly total to the hard disk on the last day of the month at midnight.
9. Provide an alarm if the equipment is running when it is commanded off. Provide an additional alarm if the equipment is not running when it is commanded on. Include time delays to accommodate system start-ups.
10. Issue an alarm if the manual override switch/Hand-Off-Auto switch is not in Auto.
11. If the DDC system provides this function as a standard feature in the firmware and software supporting its I/O boards, an independent contact on the override switch and associated physical point is not required.
12. Typical of all control loops. Provide commandable points for adjustment of loop setpoints, tuning parameters, and bias settings. Limit access to Lead Operator or higher.
13. Arrange contact to close any time the AH1 supply fan is in operation under VFD control or in bypass and hardwire to start the fan.
14. Fire alarm shut down relays are furnished and installed by the fire alarm supplier and located at the motor starter location. Control wiring through the fan start circuit shall be by the electrical contractor. The control contractor shall coordinate this effort to ensure that the desired sequence is provided.

## 6.10. Sample Narrative Sequence of Operations

The following narrative sequence is an example that applies to the return fan shown in the system diagram at the beginning of the chapter. It can be used as a starting point for similar systems employing mixed air plenum pressure based control strategies.

### Return Fan Variable Speed Drive Control

*Overview*

Return fan speed and return fan capacity are directly related. In addition, the pressure in the mixed air plenum will have a direct impact on the flow rate through the outdoor air and return air damper systems. Assuming the dampers are properly sized for a linear characteristic, holding the mixed air plenum pressure at a constant value will ensure a constant minimum outdoor air percentage. By measuring the mixed air plenum pressure and controlling the return fan speed to hold it at a constant value, the capacity of the return fan can be matched to the requirements of the air handling system as the supply fan capacity control system varies supply flow to match load and the economizer control system varies the economizer damper position to maintain the desired mixed air temperature. For additional details on this control strategy, including installation, commissioning, and operating tips, refer to the application guideline titled *Return Fan Capacity and Speed Control* published by the National Building Controls Information Program and available for free download at www.buildingcontrols.org.

*Speed Control*

A differential pressure transmitter measures mixed air plenum pressure upstream of the filters and relative to the outdoors. The output of this transmitter provides an input for monitoring the plenum pressure and for a PID control loop. The output of the control loop modulates the return fan speed and capacity as necessary to maintain the mixed air plenum pressure setpoint of 0.30 inches w.c. negative relative to atmosphere (initial setting, adjustable) by commanding the return fan variable speed drive. A tendency towards a mixed air plenum pressure that is below setpoint causes the return fan speed to increase. A tendency towards a mixed air plenum pressure that is above setpoint causes the return fan speed to decrease. Drive speed control shall be via a discrete hardwired interface between the control system and the drive. Network level interfaces between the control system and drive shall not be permitted for this function.

Control loop tuning parameters and variable speed drive acceleration times, deceleration times, minimum and maximum speeds shall be adjusted and optimized during the commissioning process.

*Start Stop Control and Proof of Operation*

The return fan variable speed drive shall be commanded on by a hardwired interlock any time the supply fan variable speed drive is in operation. It shall also be possible to command the drive on via the DDC system using a command from the operator's console.

A current switch sensing current to the variable speed drive shall provide a contact closure for proof of operation purposes any time the return fan motor is operating under load. The current switch shall be adjusted so that the proof of operation is not indicated if the motor is running but the belts have broken and thus the fan is not turning.

*Variable Speed Drive Interlocks*

The following interlocks shall be provided for the return fan variable speed drive:

- External, Hardwired

A start-stop interlock to the supply fan shall be hardwired into the variable speed drive control circuit. These interlocks shall function regardless of the status of the drive Hand-Off-Auto and Inverter-Bypass selector switches.

A fire alarm shut down relay shall be wired in to the circuit and arranged to shut down the fan on a building fire alarm condition per the programming requirements of the fire alarm system. Coordinate with Division 16 as required for wiring and programming of the fire alarm relay. Coordinate with Division 16 for the location and field installation of the duct mounted smoke detectors.

- External, Software based

The return fan variable speed drive shall be commanded to 0 hz any time the return fan is not in operation as indicated by the return fan status input.

- Internal

The return fan shall be shut down and locked out if a motor overload condition is sensed in the drive or bypass mode. Manual reset at the drive location shall be required to resume normal operation.

*Outputs to the DDC System*

The following outputs shall be provided from the variable speed drive to the automation system. These outputs may be provided by discrete hardwired interfaces or by a network level interface at the contractor's discretion. The final installed condition shall be reflected in the "as-built" drawings.

- Drive speed feedback in hz
- Drive kW

*Alarms: Operator*

Operator alarms shall be delivered to the operators console and logged on a dedicated alarm printer as they occur. The following operator alarms shall be provided:

- Indicate *AHU1 return fan failure to start or run* if the fan is not running when it should be, including a failure to start when commanded on for any reason or a shutdown that occurs when the fan should be operating per the operating sequence given the current conditions.
- Indicate *AHU1 return fan failure to stop or remain shut down* if the fan is running when it should not be, including a failure to stop when commanded off for any reason or any operation that occurs when the fan should be off per the operating sequence given the current conditions.
- Indicate *AHU1 mixed air plenum pressure does not match setpoint* if the supply fan has been running for 5 minutes or more (initial setting, adjustable) and the difference between the measured mixed air plenum pressure and the desired setpoint is greater than 10% (initial setting, adjustable). Suppress this alarm if the supply fan status is off.

*Alarms: Facility Management*

Facility management alarms shall be directed to a weekly report, generated for the director of engineering and made available for viewing under their log-in. The following alarms shall be provided:

- Indicate *During the past week the AHU 1 return fan operated for a significant period of time when the supply fan was not operating* if the return fan operates more than one hour (initial setting, adjustable) when the supply fan is not operating. Reset the timer at the end of the week.

- Indicate *During the past week the AHU1 return fan has failed to operate for a significant period of time when the supply fan was operatin*g if the return fan fails to operate for more than one hour (initial setting, adjustable) when the supply fan is operating. Reset the timer at the end of the week.

- Indicate *During the past week, the AHU1 return fan speed did not vary significantly on one or more days* if the return fan speed does not vary by more than ± 5 hz (initial setting, adjustable) between 30 minutes after start-up and the shut down time during any day on which the system operated.

*Totalization*

The following totalization functions should be provided and the data should be archived to the system hard drive on a daily basis:

- Return fan hours of operation based on the proof of operation input for the current week, the current month, and the current year.

- Return fan kWh based on the kW input from the variable speed drive for the current week, the current month and the current year.

## 6.11. Case Study

Several VAV systems utilizing mixed air plenum static pressure based return fan speed control serving a Midwestern office building experienced problems when the details addressed by the design were not reflected in the final installation. The designer selected mixed air plenum pressure based control for the VAV system return fans. They were careful to size the economizer dampers and to arrange the mixing boxes to promote mixing.

Unfortunately, he did not spend a commensurate amount of time reviewing shop drawings and monitoring construction and start-up. When the first cold snap hit, his irate client called to inform him that the building was inoperable due to problems with the freeze stats and mixing boxes. The inability to keep the air handling systems on line left employees in the core of the building hot, employees on the perimeter cold and placed the computer systems serving a network of distribution centers in jeopardy of shut down.

Upon arriving on site to investigate, the engineer found the systems exhibiting problems that were happening faster than he could track them. Systems would start, fans would surge up to speed and slow down erratically, dampers would drive open, flows would change, fans would surge some more, freeze stats would trip, and the process would repeat for as long as anyone was willing to press the reset button. Ultimately the problem was traced to a few key issues:

- Factory mixing boxes had been substituted for the field erected mixing boxes shown on the drawings as a cost savings measure. The mixing boxes were applied at the low end of their design envelope; thus, the damper velocities were low and the damper characteristics where non linear. In addition, they provided little distance for mixing to occur.

- The specified mixed air low limit cycle was not provided.

- The mixed air static pressure sensor was of lower accuracy than specified. In addition, the system had been programmed to only read the sensor's data if it changed by 0.10 in.w.c. Since the design setpoint was 0.25 in.w.c., things could be well on their way to "out of control" before the sensor reported a change.

The problems were solved by:

- Disabling damper blades to increase velocities and improve linearity and adding baffles to the mixing box to promote mixing.

- Correcting the control deficiencies.

The project would have gone more smoothly if the design details were addressed during installation. While a thorough design process was a good start, it needed to be supported by good submittal review and informed construction and start-up observation. Due to the integrated nature of HVAC systems, a problem in one area can have serious consequences throughout the entire HVAC system.

## 6.12. Additional Resources

Additional guidance on V-belt drives can be found in *Installation and Maintenance of V-Belt Drives,* another useful tool that is provided as a free resource from the TB Woods Company at http://www.tbwoods.com/pdf/VBD-IM_InstallationandMaintenance.pdf

# Appendix 1: Infiltration and Exfiltration

Because of the integrated nature of HVAC systems and the buildings they serve, it is nearly impossible to discuss return fan capacity control without considering its impact on infiltration and exfiltration at the building envelope boundary. At a fundamental level, this comes back to the conservation of mass, or stated simply: If things are to remain in balance, "the goes intas gotta equal the goes outas."[1]

Applied at the boundary of the building envelope, conservation of mass means that the amount of air entering the building from the exterior will exactly equal the amount of air exiting from the interior. When things are out of balance, infiltration and exfiltration occur.

## Infiltration and Exfiltration

Because the return fan impacts pressure relationships at the zone and building envelope levels, it will have a strong influence on infiltration and exfiltration. This can be both a blessing and a curse. With proper manipulation, a designer can use these phenomena to ensure comfort, safety and cleanliness. But, if uncontrolled, these phenomena can lead to problems that will negatively impact comfort, energy, indoor environmental quality (IEQ), product quality, safety, security, and even the integrity of the envelope itself.

### Interior Zone Infiltration and Exfiltration

For interior zones, infiltration and exfiltration will be from and to adjacent zones. As a result, the quality of the air thus conveyed will generally be controlled by the HVAC processes serving the surrounding areas and usually does not represent an IEQ challenge. The exceptions to this generalization are:

- Health care facilities in which air moving from a non-sterile area like a corridor to a sterile area like an operating room could cause infection control problems.
- Laboratories and process facilities where air moving from a dirty area to a clean area could contaminate experiments or product.
- Locations such as chemical storage rooms where negative pressure relative to the surroundings is used to control or contain hazardous or noxious fumes or materials.

### Exterior Zone Infiltration and Exfiltration

Conditions are more complicated for exterior zones where interactions with the ambient environment can also occur via infiltration and exfiltration through the building envelope. Air that is infiltrated from the outdoors will be unconditioned since it enters the building without passing through an HVAC process. If ambient conditions are at or near the desired zone conditions, then infiltration may not be an issue. But most of the time, the difference between the desired indoor conditions relative to that of the infiltrating air in terms of temperature, moisture content and cleanliness makes the exchange undesirable and can lead to problems on a number of fronts:

*Excess Heating and Cooling Load:* If the air that is infiltrating into a zone (or exfiltrating across a zone) is at a temperature or humidity that is significantly different from the zone's, then it can tax the capabilities of the zone conditioning equipment and result in comfort complaints and unanticipated energy consumption if control is lost. Comfort is strongly influenced by air motion. The drafts produced by infiltration and exfiltration, particularly infiltration at the perimeter on a cold day, can produce comfort complaints.

*Noise:* High rates of infiltration or exfiltration through cracks around windows and doors can cause whistling, leading to additional occupant complaints.

*Access:* High negative differential pressures across the building envelope can make exterior doors difficult to open. This can lead to citations for lack of compliance with the Americans with Disabilities Act and may even lead to litigation. It may also pose a life safety threat if the pressure differential makes the doors in an escape route difficult to open from the inside. Requirements limiting the maximum force required to open a door can be found in numerous codes.

1 Dr. Albert W. Black, personal conversation.

*Security:* High positive differential pressures across the building envelope can prevent exterior doors from closing once they are open. In extreme cases, excessive positive pressure can actually blow doors open. Either way, the open doors can pose a security challenge.

Beyond the operational difficulties listed above, infiltrating air can cause problems with the building envelope on a number of fronts including:

- Condensation when humid air encounters surfaces cooled to temperatures below its dew point.
- Structural and performance degradation due to condensation in wall and ceiling cavities.
- Mold and mildew growth due to moisture accumulation from condensation in wall and ceiling cavities.
- Damage to finishes due to condensation, as well as staining from the dirt carried in with the infiltrating air.

In contrast, air that is exfiltrated from an exterior zone seldom represents an environmental quality control problem in the occupied area. In fact, exfiltration is often used to help ensure zone environmental quality by ensuring that air warmed by the building's internal gains is forced out through the cracks in lieu of cold air being drawn in. This has the added advantage of saving energy since the perimeter infiltration load is eliminated. As long as the outdoor air flow brought into the building to pressurize it does not exceed the amount that would be coming in via an economizer process, the approach essentially uses the internal gains to offset infiltration loads.

In some instances, return fan energy will also be saved with exfiltration because less air needs to be moved back from the occupied zone to the relief location.

To achieve these benefits, coordinate the return fan capacity/speed control strategy with the operation of the economizer and its relief system so that:

1 The building cracks are allowed to function as the relief system until a positive building pressure is achieved throughout the building, especially at its primary point of entry.

*and*

2 The relief systems are allowed to modulate as necessary to control the pressure at a suitable value once a positive pressure is achieved throughout the building. Refer to Sellers et al. (2004a), Sellers et al. (2004b), and Friedman et al. (2004) for case studies and testing procedures on envelope leakage.

Exfiltration from an exterior zone is only one term in the conservation of mass equation at the building envelope. The infiltration that may occur to offset it can create an environmental quality issue at some other location in the building if it is not understood by the designer and addressed by the HVAC system design. In addition, air that is exfiltrating through the envelope can lead to envelope failures similar to those listed above if it encounters a surface at or below its dew point. This can be an important consideration for humidified buildings located in cold environments.

## The Bottom Line on Uncontrolled Infiltration and Exfiltration

Controlling infiltration and exfiltration is a critical design issue, especially in extreme climates. Keeping integration and interaction in mind while dealing with the design, construction and operational details associated with variable speed return fans will minimize the potential for difficulties on a number of fronts including comfort, IEQ, and building security. The exact nature of a variable speed return fan's impact on these areas will vary with the specifics of the control strategy. The information in Table 1 of *Chapter 1: Introduction and Fundamentals* provides an overview of the potential impacts and contrasts them with the other strategies. Strategy specific details can be further explored by reading the associated chapter of the guideline. Proper return fan application and control is very important. Failure can lead to problems for the building owner ranging from tenant dissatisfaction to envelope failures and litigation.

Typically, an HVAC designer endeavors to design and control the building's supply, return and the exhaust systems in a manner that will allow them to achieve some level of control over infiltration and exfiltration. However, this effort is complicated by a number of factors, some being the result of HVAC processes and others being the result of natural phenomenon.

Examples of HVAC processes that cause complications include economizers, minimum outdoor air flow regulation, building static pressure control, VAV system operation, and exhaust hoods. Examples of natural phenomena that add complexity include stack effect and variations in wind speed and direction. All of these topics are discussed in the Glossary of Terms. The following appendices will explore economizers, minimum outdoor air flow regulation, and building static pressure control in greater detail. They are active control processes that can be highly interactive with the operation and control of the return fan.

# Appendix 2: Economizer Theory and Operation

When an air handling system equipped with a return fan is operating on an economizer cycle, the return fan is frequently used to move the extra air brought in for free cooling to a point where it can be ejected from the building. In this way, it is essentially functioning as a relief fan in addition to a return fan as the economizer modulates from minimum outdoor air toward 100% outdoor air. When the economizer reaches the 100% outdoor air position, the return fan's role changes to that of a relief fan. Ensuring a smooth operating cycle and flow balance under these highly variable operating conditions requires careful attention on the part of the designer to the selection of the fan, the design of the economizer and the return and relief duct system, and the control of the return fan, the economizer process and the relief system.

## Economizer Cycles

Because many buildings experience internal gains on a year-round basis, economizer cycles are frequently implemented on many air handling systems as a way to provide efficient cooling by using cool, seasonally available outdoor air rather than mechanical processes. A detailed discussion of economizer processes is beyond the scope of this guideline. But because of the integrated relationship between the components of an HVAC system, and because the performance of the return fan can have a significant impact on the economizer process, there are several return fan speed control issues that need to be assessed in the context of an economizer process. For a more detailed look at economizers, refer to *Chapter 3 of the Functional Testing Guide* or the Energy Design Resources Design Brief titled *Economizers*.

Economizer related factors that should be considered in the context of return fan speed are discussed in the following sections.

## Economizer Operating Profile

Figure A2-1 compares different climates to show the number of hours per year that occur at different temperatures. In the illustration, a wide variation can be seen in both the number of hours at a given temperature and the range of temperatures normally encountered at each location.

These load profiles can have significant implications for some return fan speed control strategies due to the interactive nature of HVAC processes.

- Systems that spend many hours operating on an economizer cycle will be much more subject to economizer induced problems than those with a limited number of hours under economizer operation. For instance, a typical office building system in Key West, Florida will probably spend very few hours per year in an economizer process because the high humidity and temperature conditions will typically make cooling return air much more economical than cooling outdoor air.
- The temperature conditions under which economizer operation occurs can come into play in two general ways:
    1. Because the issues that lead to many of the operating difficulties with economizers are related to their operation at low ambient temperatures, systems operating on an economizer cycle in cold climates like Anchorage, Alaska will be more prone to economizer induced instability than systems in more moderate climates like Portland, Oregon.
    2. Systems in mild climates where the ambient temperature is frequently plus/minus 10-15°F of the desired supply temperature will spend a majority of time on or near 100% outdoor air. These systems may also have many hours of integrated economizer operation. In addition to minimizing the potential for economizer induced instability, systems operating in these environments are generally less prone to IEQ issues. In fact, one could argue that the minimum outdoor air regulation is irrelevant once economizer operation is initiated since by definition, the process is bringing in outdoor air quantities in excess of those required for ventilation.

Given the climate, it may be difficult to even justify equipping a system in Key West with an economizer. The location was picked for illustrative purposes in the context of the example rather than to illustrate design practice in the area.

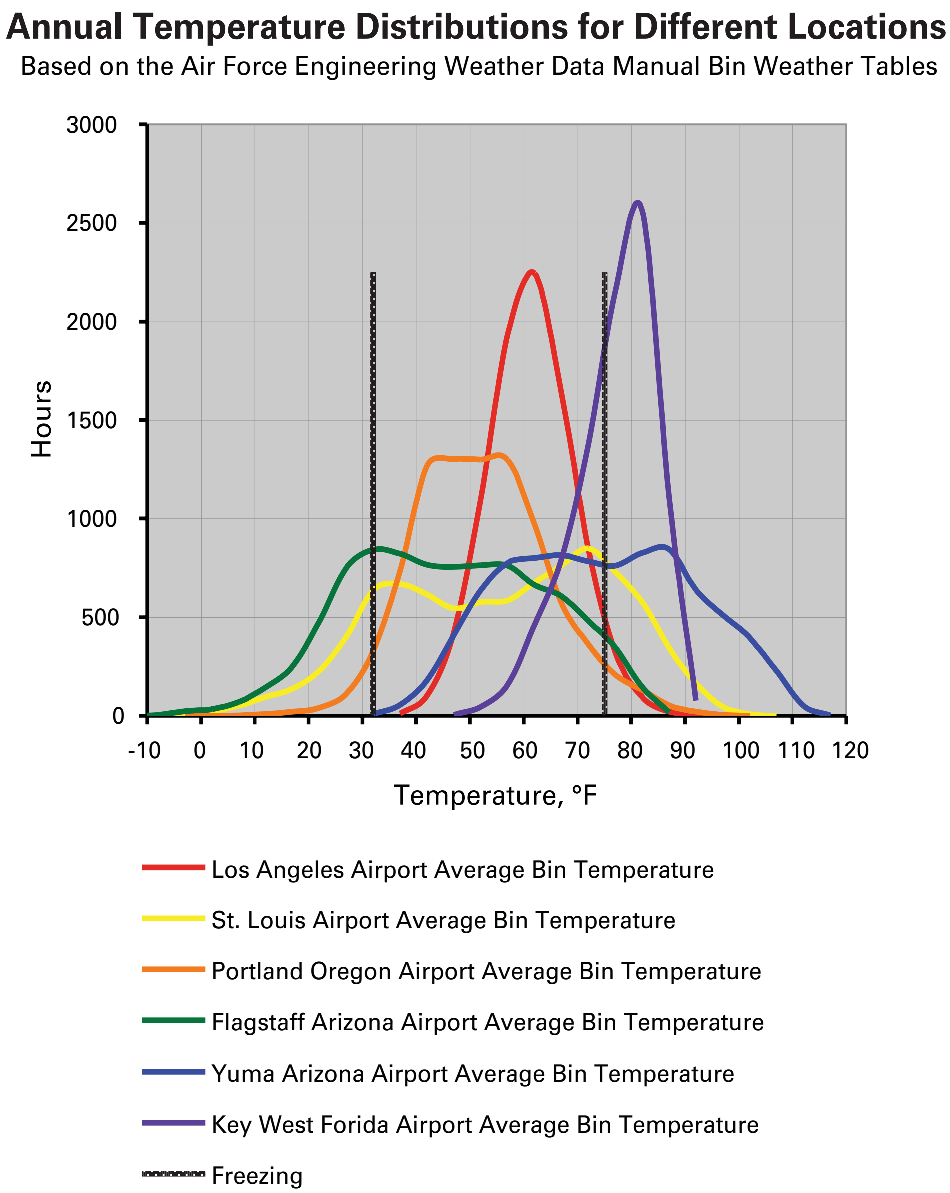



*Figure A2-1. Temperature Patterns for Different Climates. (Source: Portland Energy Conservation/Facility Dynamics Engineering)*

## Economizer Stability

It is not unusual for instability in one control loop to ripple out to other control loops in an HVAC system because they are so highly interactive. This is illustrated in Figure A2-2. Notice how the instability disappears when the heating water valve is forced closed, revealing the root cause of the problem in all of the other loops was an out-of-tune preheat coil control loop.

The pressure and flow variations associated with economizer instability frequently impact the stability of the supply and return fan capacity control loops, as was the case for the rooftop unit whose operation is illustrated in Figure A2-2. In fact, the supply and return flow rates were so out of sync that the outdoor air plenum was pressurized during some of the larger spikes. As a result, the outdoor air sensor was subjected to the warm return air which triggered brief chiller plant starts.

Issues that impact economizer stability are discussed in the following paragraphs.

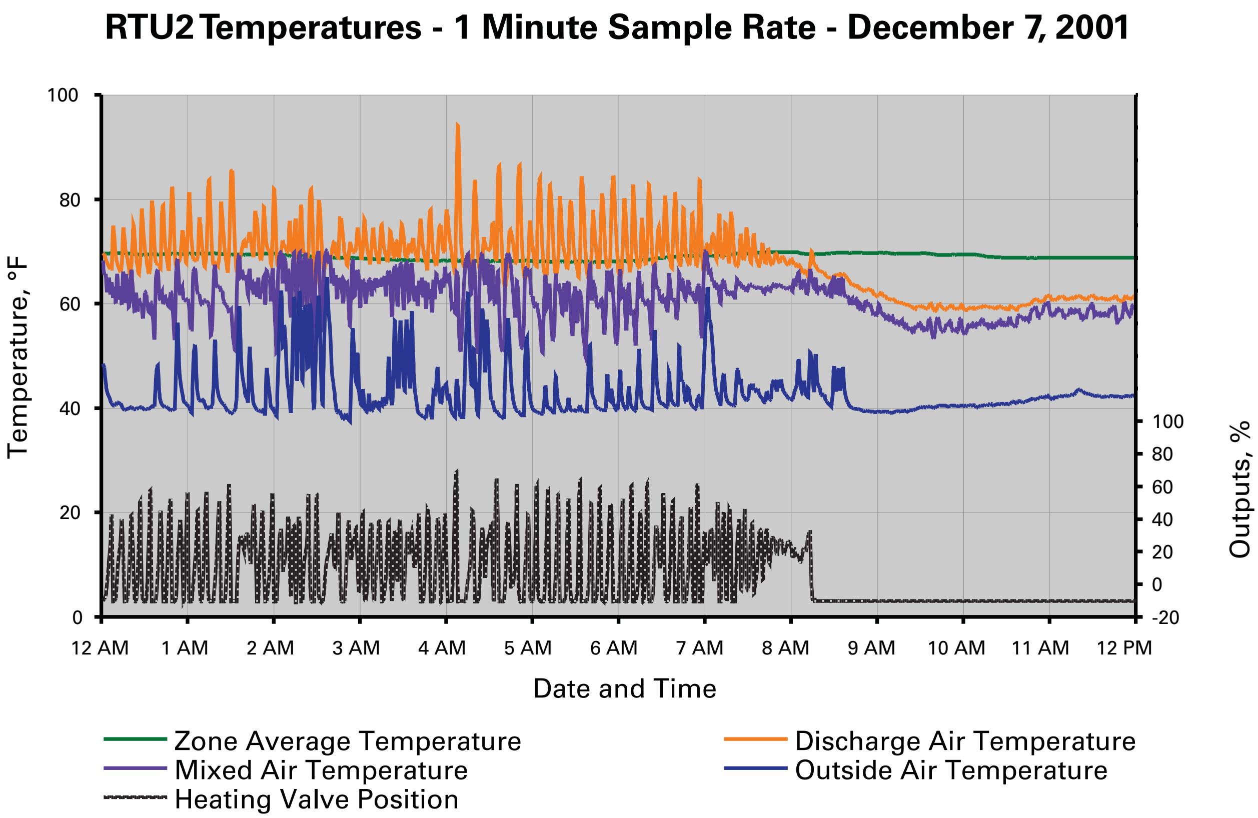



*Figure A2-2. Cascading Instability in a Modular Rooftop AHU (Source: Portland Energy Conservation/Facility Dynamics Engineering)*

## Damper Sizing and Linkage Arrangement

The linearity of the relationship between damper actuator stroke and damper position can have a major impact on economizer stability. Linearity is a function of both the damper sizing as well as the linkage arrangement, and attention in both of these areas is essential to the success of any economizer strategy.

Figure A2-3 illustrates the characteristic curves for parallel blade dampers. Opposed blade dampers have similar curves. In this figure, the dark green (far right) curve would be considered a linear characteristic and the dark purple (far left) curve would be considered a two position characteristic. Thus, a small damper authority (large alpha) is associated with a damper that does not have much resistance relative to the system it serves. Note the following:

- As a damper with a two position characteristic begins to open, it will cause a major flow change with only a minor position change.
- A linear characteristic requires a significant damper pressure drop relative to the system.

The fact that the outdoor air damper modulates from open to closed as the return damper modulates from closed to open in a typical economizer arrangement further compounds the over-sizing problems. Consider the following scenario for a system with over-sized economizer dampers. Bear in mind that these dampers will have two-position characteristic curves.

- The system begins to move off of the minimum outdoor air setting toward economizer operation. When this occurs, the outdoor air portion of the assembly moves from minimum flow toward maximum flow while the return section moves from maximum flow toward minimum flow.
- Since the dampers are over-sized and therefore non-linear, the small change in outdoor air damper position will cause a significant change in outdoor air flow because the dampers will be operating on the left portion of the dark purple curve in Figure A2-3.

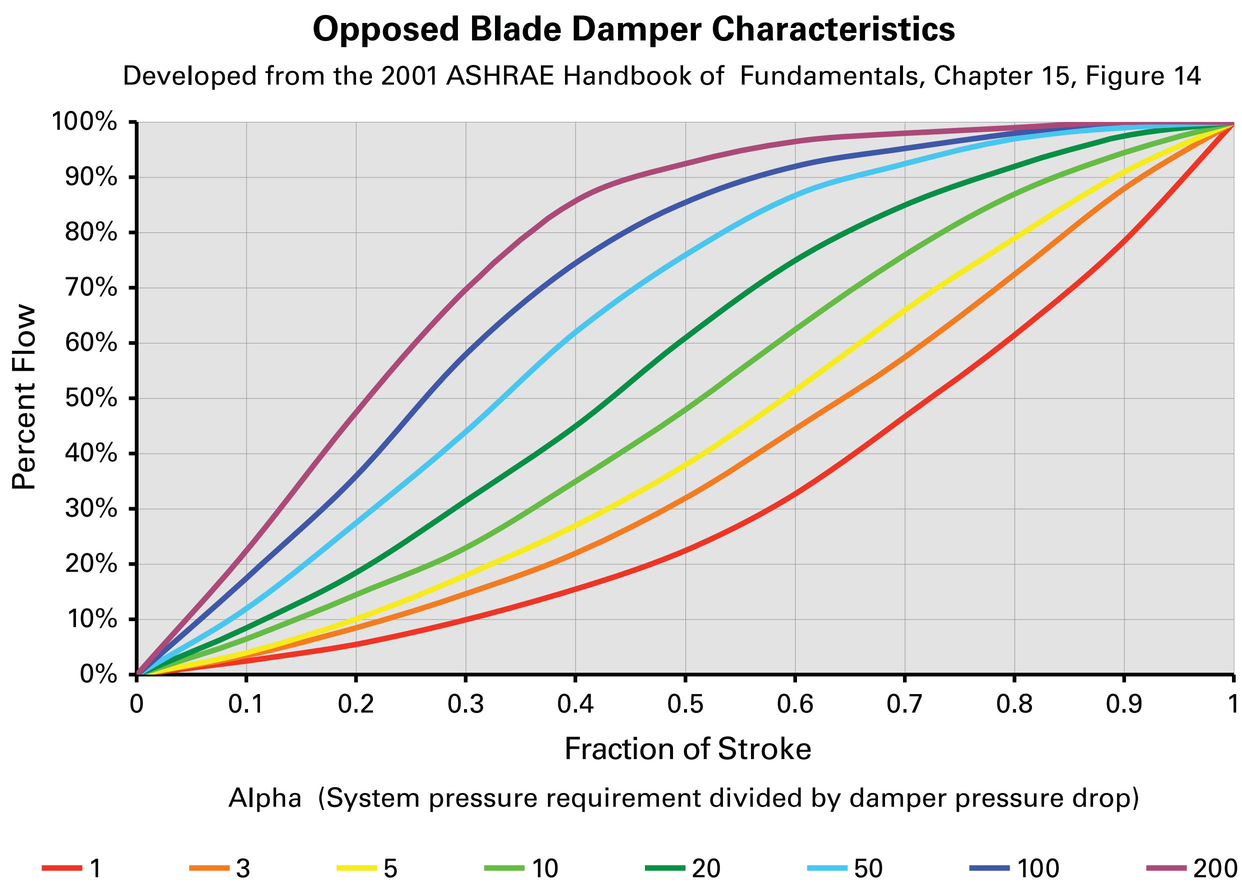



*Figure A2-3. Parallel Blade Damper Characteristic Curves. A fraction of stroke of 0 represents a closed damper and a fraction of stroke of 1 represents an open damper. (Source: Portland Energy Conservation/Facility Dynamics Engineering)*

- In an opposite but similar manner, the return damper portion will move slightly from fully open toward closed. But, the return dampers start from a wide open position and thus are at the right side of the dark purple curve in Figure A2-3. Thus, a small change in their position will have very little impact on return flow.
- The combined effect of the motion of the two dampers is a net decrease in system resistance. As a result, the supply fan flow will increase as the fan operating point shifts out on its curve. This can trigger a number of interactions in most systems, the specifics of which will vary with the nature of the system and its fan capacity control strategies. Frequently, these interactions feed back into the economizer, triggering instability that ripples out into other control loops in the system.

Linkage arrangements can also contribute to non-linearity, especially for actuators that are not mounted concentrically with the damper blade shafts. This effect is illustrated in Figure A2-4.

Additional information on damper sizing, actuators, and linkage arrangements can be found in Chapter 3 of the *Functional Testing Guide* and in *ASHRAE Guideline 16-2003*.

### Mixing Performance

Even if the damper provided for an economizer were sized and installed for perfectly linear performance, the system would still be fighting an uphill battle. This is because the mixing process itself is inherently non-linear, as illustrated in Figure A2-5.

Mixing performance is particularly critical in cold climates and will vary with the outdoor air and return air percentages even in a well designed system. Poor performance can lead to instability and other problems that can cascade out to the return fan speed control loop.

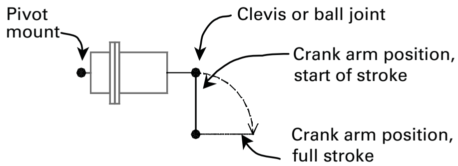
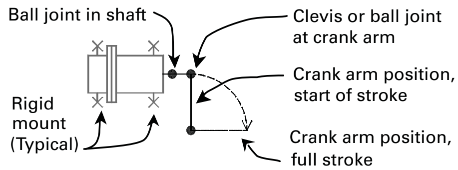
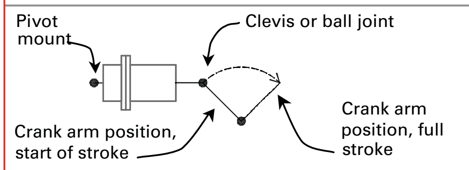
| Mounting Arrangement | Percent Actuator Stroke at the Indicated % Blade Rotation: 0% (0°) | 25% (22-1/2°) | 50% (45°) | 75% (67-1/2°) | 100% (90°) | Maximum Deviation from Linear (Note 1) | Maximum Reduction in Actuator Force (Note 2) |
|---|---|---|---|---|---|---|---|
|  | 0% | 32% | 62% | 85% | 100% | 12% | 66%; this occurs at full stroke. 100% is available at the start of the stroke. |
|  | 0% | 29% | 56% | 79% | 100% | 6% | 43%; this occurs at full stroke. 100% is available at the start of the stroke. |
|  | 0% | 24% | 50% | 78% | 100% | -1% and +3% | 29%; this occurs both at the start of the strake and at full stroke. 100% is available at 42% of the stroke. |

*Figure A2-4. The Relationship Between Linearity and Linkeage Arrangement (Source: Portland Energy Conservation/Facility Dynamics Engineering)*

The fact that parallel blade dampers can direct the flow of air passing through them can give them an advantage over opposed blade dampers in a mixing application. Arranging the dampers so the outdoor air stream and return air stream are directed into each other as the dampers rotate closed will promote turbulence and mixing.

Even with perfect damper sizing and configuration, the air handling system needs to be arranged to provide some physical distance for mixing to occur prior to encountering a coil. Frequently, the filter section and coil access sections can provide this distance. For field erected economizers, the mixing section can be located at a point in the duct system that is remote from the unit. Frequently, an added benefit of this approach is that the elbows located between the mixing box and AHU will also promote mixing. Where mixing distances are limited by physical constraints, air blenders can be used although they incur a modest penalty in the form of pressure drop.

Figure 6 illustrates these concepts. The April 2002 ASHRAE Journal includes a procedure for sizing the minimum outdoor air damper and economizer damper. While it specifically targets one of the variations on the mixed air plenum pressure control return fan speed, the information provides useful guidance applicable to all strategies. Damper sizing guidance can also be found in *ASHRAE Guideline 16-2003*. Damper sizing and mixing are discussed from a commissioning perspective in Chapter 3 of the *Functional Testing Guide*.

In some situations, the mixing box provided in a manufacturer's standard product line will not adequately address these issues and it will be necessary to provide a field erected mixing box even though the rest of the system uses modular or packaged equipment. Usually, this situation will be the result of an application with a mixing box module at the low end of its design flow range, where the damper velocities are relatively low compared to the high end of the application range for the module size. Such a requirement should be clearly addressed in the drawings and specifications.

## Controlling the Relief Dampers

Economizer equipped systems require relief dampers in addition to outdoor air and return air dampers. The dampers are required to provide an exit path for the extra air brought into the building by the economizer process. Because the relief dampers are located on the discharge of the return fan, they have a direct bearing on its performance.

Traditionally, an economizer's outdoor air and return air dampers are controlled to provide a mixed air or supply air temperature that will satisfy the cooling load for the system. The relief dampers

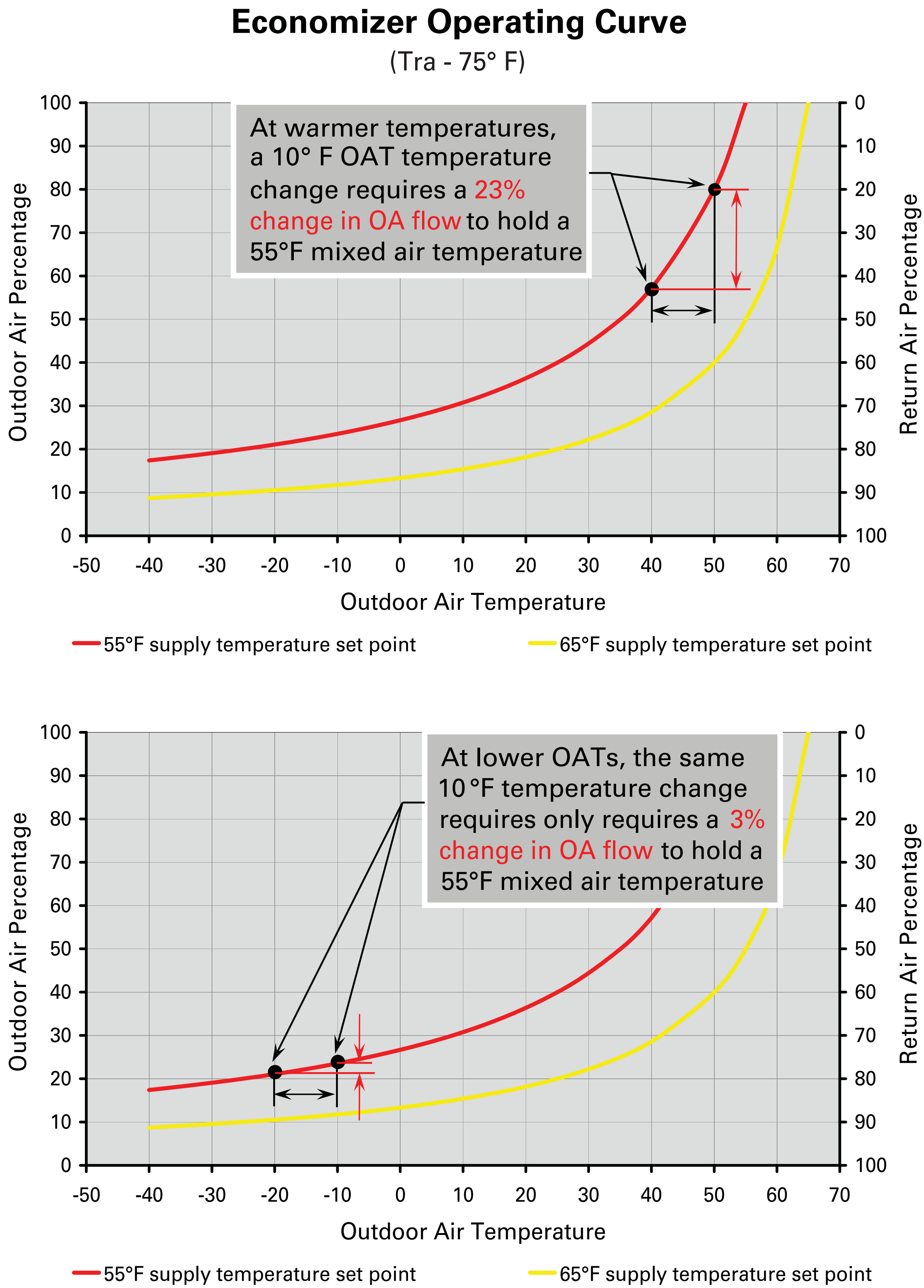



*Figure A2-5. Economizer Non-Linearity (Source: Portland Energy Conservation/Facility Dynamics Engineering)*

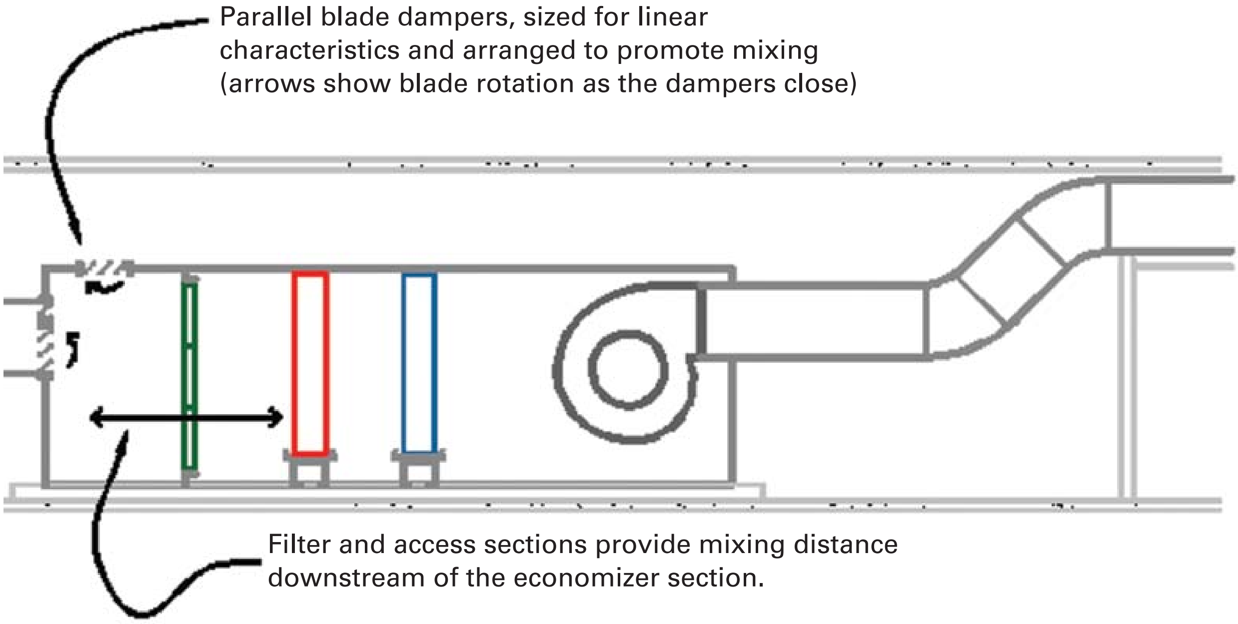



*Figure A2-6. Cofiguring an AHU Economizer Section to Promote Mixing (Source: Portland Energy Conservation/Facility Dynamics Engineering)*

are often controlled by the same signal since there is a direct relationship between the outdoor air flow and relief requirement. This is a simple approach that can work well for constant volume systems. However, it is important to remember that in an economizer process, the outdoor air dampers are positioned by a temperature control process that is driven by load. In contrast, the relief dampers address the building pressure control problem that is the outfall of the economizer process. Because VAV systems vary both flow and temperature in response to the load they serve, the traditional relief damper control approach begins to provide less than optimal results.

This can best be understood by examining what happens on a day when the outdoor temperature equals the required system supply temperature but the load is significantly below design—50% below for an example. To exaggerate the problem, assume that the system uses variable speed relief fans that are controlled by the same signal that controls the economizer's outdoor air and return air dampers (so that when the system is on 100% outdoor air, then the relief fans will be at 100% speed). On such a day, the outdoor air dampers would be fully open and the return air dampers would be fully closed since the outdoor air is at the required temperature setpoint and thus requires no mixing with return air. But, since the load is only 50% of design, the supply flow, which equates to the outdoor air flow in this scenario, is 50% of design. The traditional economizer control process will have the relief fans running at 100% speed. As a result, the fans will be attempting to remove the design air flow from a building that is only being supplied with 50% of the design flow. The building pressure will become extremely negative, and many associated problems will follow.

The bottom line is that many VAV applications will benefit from a strategy that controls the relief dampers independently from the economizer control signal. Building static pressure based control is one approach to this and is discussed further in *Chapter 4: Building Pressure Control*.

## Economizer Control Strategies

Economizer control strategies can have a direct impact on economizer performance and stability.

- *Change-over strategies and their associated dead bands:* Improperly selected or implemented change-over strategies can trigger instability with ripple problems similar to those illustrated in Figure A2-3.

- *Low-limit control systems and their integrated operation with system startup in cold weather:* The transient conditions associated with startups are some of the most challenging aspects of HVAC systems. Systems without a properly implemented mixed air low-limit process can be particularly challenging and unstable during startup due to the variation in mixed air plenum pressure that occurs as the flow in the system changes. For instance, as the demand for cooling (flow) is reduced, the mixed air plenum pressure will increase (become less negative) relative to the outdoors as the supply and return fan speed decrease. This is because the pressure difference between the outdoors and the mixed air plenum is generated by the pressure drop associated with flow through the outdoor and return air dampers. As the flow drops off, so does the pressure. The result of this reduced differential between outdoor and mixed air plenum is a reduction in outdoor air flow. This decline will increase as fan speed decreases, assuming there is no change in the outside air damper position. It will also be non-linear due to the square law.

# Appendix 3: Minimum Outdoor Air Flow Regulation

At their core, most return fan speed/capacity control strategies are targeted at maintaining adequate ventilation/minimum outdoor air flow to the system they serve. Under actual operating conditions, controlling the amount of outside air drawn into an air handling system can be difficult, especially in VAV systems.

As stated in the *Glossary of Terms*, minimum outdoor air flow is directly related to code-enforced ventilation requirements and may include make up air associated with various processes like kitchen hoods and lab hoods. The operation of the return fan is directly linked to the minimum outdoor air flow, the control of which is critical to IEQ. Ensuring that the control of the return fan does not negatively impact minimum outdoor air flow is one of the primary goals of any return fan capacity control strategy.

## Minimum Outdoor Air Flow and Energy

Conditioning outdoor air will represent a major load under some conditions in most climates. The magnitude of the annual energy consumption associated with this is a function of the local environment as discussed previously and illustrated in Figure 2 of *Appendix 2*: *Economizer Theory and Operation*.

Ventilation requirements are a major component of most minimum outdoor air flow settings. These requirements are typically determined prescriptively or are based on an analysis of contaminant sources, contaminant concentration targets, and perceived acceptability for contaminant concentrations. The latter procedure is typically called an IAQ based design process. Prescriptive approaches tend to be more energy intensive than IAQ based approaches since the settings must cover the worst case. But, they are conservative and less design intensive and are often the procedure of choice. ASHRAE 62-2004 provides guidance for both processes. Generally, one of the versions of ASHRAE 62 will be accepted by most code authorities.

## Maintaining a Fixed Minimum Outdoor Air Percentage vs. a Fixed Minimum Outdoor Air Flow

It is important to recognize that there is a difference between maintaining a fixed percentage of minimum outdoor air and maintaining a fixed flow rate. Ultimately, the designer endeavors to control the outdoor air flow rate. If the characteristics of the design are such that the required flow rate varies with supply flow, then maintaining a fixed percentage of outdoor air may be adequate. On the other hand if the outdoor air flow rate must remain constant despite variable operating conditions, then the system must be designed to operate in this manner.

This issue is particularly important with regard to the selection of a control strategy for return fans in VAV systems because some strategies (speed tracking, for example) tend to maintain a fixed percentage while others (flow tracking, for example) tend to maintain a fixed flow. It is important that the characteristics of the strategy be tailored to the requirements of the project.

## Passive vs. Active Minimum Outdoor Air Flow Control

All of the return fan control strategies discussed in this guideline are passive minimum outdoor air flow control strategies in that none of them use a measurement of outdoor air flow as a direct input to their control process. Rather, they measure and control other parameters which are then assumed to yield the desired results. Stated another way, they are open loop rather than closed loop processes with regard to the control of minimum outdoor air flow. While theoretically sound, their underlying assumptions regarding minimum outdoor air flow can be compromised by the numerous variables encountered in day-to-day operations. Thus, it is often prudent to supplement the return fan capacity control strategy with monitoring or active control of the minimum outdoor air flow in situations where:

- The air handling system is complex.
- The building is complex.

- There are wide variations in the ambient environment.
- There are wide variations in the system or building operating conditions.
- Pressure relationships are critical
- The risks and liabilities associated with a failure to maintain the required minimum outdoor air flow are high.

Many times, building codes will make this decision for the designer. For instance, the 1998 International Building Code requires a control system to regulate the outdoor air to meet the requirements of the code. ASHRAE 62-1989 and 62-1999 both contain a general requirement that provisions be made to maintain acceptable indoor air quality when the space is occupied and the air volume is reduced (Sellers, 2000). ASHRAE 62-2004 further clarifies these requirements in stating that:

- *"Ventilation systems shall be designed to be capable of providing the required ventilation rates in the breathing zone whenever the zones served by the system are occupied, including all full- and part-load conditions."*

  *and*

- *"The system shall be designed to maintain the minimum outdoor airflow as required by Section 6 under any load condition. Note: VAV systems with fixed outdoor air damper positions must comply with this requirement at minimum supply airflow."*

These requirements need to be taken into account during design when considering a passive minimum outdoor air control for VAV systems and their related return fan capacity control strategies.

## Passive Minimum Outdoor Air Flow Control Techniques

Common approaches to passive minimum outdoor air flow control include:

- *Providing a Minimum Position Setting to the Economizer Outdoor Air Damper:* This strategy assumes that there is a linear relationship between flow and damper command, and thus is highly dependent upon damper sizing and linearity.
- *Providing an Independent Minimum Outdoor Air Damper:* This approach provides a separate flow path and damper for the minimum outdoor air. Ideally, the flow path will include a manual damper to facilitate setting the desired flow rate. The approach provides better, more persistent results than the minimum position signal approach and thus is recommended as a minimum level of control.
- *Providing an Independent Minimum Outdoor Air Damper with Multiple Positions*: This approach takes the concept in the preceding bullet a step further by providing multiple independent damper positions triggered by multiple operating conditions. For example, the damper might be positioned to lower flow rate when scheduled zones remain unoccupied at the same time as other areas become occupied. While not an active control strategy since it does not measure and control flow directly, it can be a significant improvement over the other approaches for systems with variable requirements and low budgets.

Passive minimum outdoor air flow control is best suited for constant volume systems. However, these approaches are often encountered in the field on VAV systems. In these situations, it is imperative that the contract language include provisions for testing and verification of the minimum outdoor air flow rates.

## Active Minimum Outdoor Air Flow Control Techniques

Because VAV systems are variable by nature, when passive control techniques are used the variations can produce changes in the parameters that drive minimum outdoor air flow. Because of this, VAV systems are prime candidates for active minimum outdoor air flow monitoring and control. These strategies can have the added benefit of improving overall efficiency in some situations because they precisely tailor the ventilation to the current requirements rather than worst case prescriptive requirements.

Common approaches to active minimum outdoor air flow control include:

- *Providing an Independent Damper that is Controlled Based on Carbon Dioxide or Volatile Organic Compounds (VOCs):* This approach offers the most potential for efficiency since the minimum outdoor air flow rate is controlled based on the need for ventilation rather than prescriptive values. A common variation on this approach is to have the flow setpoint reset based on $CO_2$ or VOCs.

In all cases the system must be designed and implemented properly to ensure that the design intent is met. Considerations include:

- Flow measuring elements must be sized to accurately measure the minimum anticipated flow.
- Flow measuring elements must have a sufficient amount of straight duct before and after to ensure a good velocity profile.
- The pressure drop required to move the necessary flow through the measurement and regulating assembly must be available under all operating conditions.
- Active control elements used in the intake system must be suitable for use in 100% outdoor air environments where they will be subject to freezing conditions*, dust, and moisture. Or, they need to be installed so they are protected to the extent necessary to meet the manufacturer's requirements.

Additional detailed discussion regarding active control of minimum outdoor air flow can be found in Schell, 2001 and 2002, and Brennan, 1999 in the *References* section.

* This can be particularly important with pneumatic actuators since cold ambient temperatures can condense water out of the supply air.

### *Packaged Outdoor Air Measurement and Control Systems*

As can be surmised from the discussion in the preceding appendices, return fan speed/capacity control is very sensitive to and dependent upon the outdoor air and economizer control processes. Several manufacturers now offer packaged outdoor air measurement and control systems that can be incorporated into the economizer sections of packaged equipment. These assemblies are based on technologies similar to those employed in VAV terminal units. They may offer an attractive alternative to a field erected economizer with an independent minimum outdoor air damper, especially for smaller modular air handling systems. Potential advantages include:

- A sole-source accountability for controlling outdoor air flow while minimizing potential coordination and integration issues between the control system contractor, the sheet metal contractor and the air handling unit manufacturer. In some instances, these assemblies are offered directly by air handling unit manufacturers, further reducing (but not eliminating) the potential for integration problems.
- Active measurement based control of minimum outdoor air flow.
- The potential for active control in the economizer cycle since the dampers provided have been targeted at regulating and controlling minimum outdoor air flow. Note that the sizing and coordination issues with the return and relief damper assemblies still need to be addressed outside of the package solution in most situations.

### *Outdoor Air Induction through the Relief Louvers*

A common phenomenon associated with VAV fan systems and related directly the control of the return fan is the induction of outdoor air into the system via the relief louvers. This phenomenon has been witnessed by the authors of this guideline and others (Seem, 1998).

Intake of air via a relief location can be a serious issue. Many times, relief louvers are located in a manner that will subject the system to air that is contaminated or has undesirable psychrometric properties. For this flow pattern to occur, the return fan discharge pressure must be lower than the ambient pressure at the relief louver location. This can be the result of a number of factors including:

- Return fan capacity control problems
- Minimum outdoor air flow regulation problems
- A significant difference between the pressure required to move outdoor air from the intake louver through the intake system to the mixed air plenum (the desired route) versus through the relief louver and the relief/return system to the mixed air plenum (the undesired route). In this situation, the relief system can become the “defacto” path of least resistance to the outside under some operating conditions, regardless of the designer’s intent.

Some return fan control strategies are more prone to this type of problem than others. Thus, the potential impact of such a problem is an important design consideration. Systems where this type of problem could present serious consequences in terms of IEQ, safety, or other critical operating areas should implement a strategy that is less prone to the problem.

## Ensuring the Persistence of Design Minimum Outdoor Air Flow Rates

Irrespective of the system type or operating strategy, taking steps to ensure that the design requirement is met initially and continues to be met over the life of the system should be a high priority of both the initial commissioning process as well as any ongoing commissioning efforts. Appendix 4: *Tuning Minimum Outdoor Air Flow* focuses on this topic.

# Appendix 4: Tuning Minimum Outdoor Air Flow to Design Specifications

Regardless of the minimum outdoor air flow strategy employed in the system, coordinating it with the operation of the return fan and supply fan capacity control system is crucial to success. Tuning and verification of these functions should be prime targets in the system commissioning and operation process. These efforts should be supported and supplemented by testing and balancing to measure, adjust, and verify the minimum outdoor air flow rate.

## Selecting the Test Point or Points

The standard practice is for the Test and Balance (TAB) contractor to verify the minimum outdoor air flow necessary for at least one operating point, and many times the system design flow condition is selected. In contrast, recently released ASHRAE Guideline 62-2004 requires that "The system shall be designed to maintain the minimum outdoor airflow as required by [62-2004] under any load condition" and that "VAV systems with fixed outdoor air damper positions must comply with this requirement at minimum supply airflow." In the former case, the assumption is that setting the system for the required minimum outside air flow rate at one key condition will ensure it for all operating conditions. The example illustrated in Figure 1 in *Appendix 8: Theoretical Versus Actual Performance* demonstrates that in many instances, this may be a bad assumption and that verification and tuning at multiple operating points is desirable. Such verification could be viewed as crucial to ensuring the requirements of ASHRAE 62-2004 are met. Of course, additional testing and tuning requires more time and a larger budget than a single point adjustment, and a balance must be struck between perfection and financial reality.

Ideally, the designer should determine the best compromise between budget and theory for a given system and include specifications detailing those requirements in the contract documents. However, it is not unusual for the language in the documents to be fairly vague, leaving the decision to the implementing party. While the issue is the same, the challenge is often along different lines; balancing the need to meet the intent of the documents and any legal requirements imposed by codes and standards with the desire to be low bidder and obtain the work. In either case, the following guidelines may prove useful in striking a compromise.

- *Analyze system performance at key or critical operating points:* An analysis similar to the one in Figure 1 in *Appendix 8: Theoretical Versus Actual Performance* will often reveal a trend which points to the worst case. This is especially true if the analysis is performed at the limiting conditions for the process, i.e., design conditions and minimum flow. The results of the analysis can be used to target a single point test condition that will ensure adequate minimum outdoor air flow in the worst case and err on the high side the rest of the time.
- *Test and tune at the most common flow condition:* It is not unusual for VAV systems with fairly flat load profiles in mild climates or in climates with a narrow daily range to spend the vast majority of their operating hours in a narrow portion of their flow range. As a rule of thumb, this range will be 65 – 75% of design capacity. Usually, this is because the loads served do not vary significantly, or the climate has a significant number of operating hours in a narrow range of conditions. For this type of system, a single point test at the most common operating condition will ensure proper performance for most of the operating hours.
- *Test and tune at the limits in addition to the most common flow condition:* Supplementing the test discussed in the previous bullet with additional tests at limiting conditions like minimum flow and design flow will go a long way toward ensuring adequate performance over the desired operating range. Many times, this added insurance is well worth the cost, especially if IEQ is questioned and litigation ensues.
- *Test and tune at 5 to 10 operating points spread out over the entire range of operation*: This approaches the theoretical ideal, but also represents the highest cost to implement. If the application is significant enough to warrant testing at this level, then it may also warrant a

more robust return fan speed control strategy coupled with a robust minimum outdoor air flow control strategy. For incremental volume systems, this is the strategy of choice since, by nature, there will be very specific operating points with very specific supply and return flow conditions associated with them.

To achieve the efficiency benefits associated with multipoint testing, in addition to ensuring adequate minimum outdoor air flow, a system that is capable of accepting multiple return fan speed setpoints settings will be required. Otherwise the setpoint will need to be set for the worst case operating point and the system will tend to over-ventilate under other conditions.

## Testing at Multiple Points

It is important that multipoint test processes reflect actual system operating conditions to the extent possible. Ramping the supply fan speed up and down over its operating range without addressing the position of the terminal unit dampers will provide unsatisfactory results. Ideally, a demand for different flow rates should be created by manipulating the terminal units, thereby forcing the supply fan capacity control system to adjust the fan to deliver at those conditions.

DDC control systems make multi-point testing easy to accomplish by stepping the terminal unit dampers through different positions using global commands. In contrast, terminal units that are controlled by discrete pneumatic, electric or electronic thermostats will require multiple trips to the individual thermostats to step the system through a range of operating conditions. This can significantly increase the time required to perform a multi-point test, especially if the building is occupied and the tenants inadvertently spoil the test by re-adjusting the thermostat setpoints because they are uncomfortable at the test condition.

The trending capabilities of DDC systems can also be leveraged to assess the minimum outdoor air flow in real time by using conservation of mass to compare the predicted mixed air temperature with the actual mixed air temperature given the current outdoor air and return air temperatures. For this approach to yield viable results:

- The temperature sensors used as inputs need to be closely calibrated relative to each other.
- The return air to outdoor air temperature difference needs to be at least 10°F for outdoor air fractions less than 40%
- The return air to oudoor air temperature difference needs to be at least 7°F for outdoor air fractions greater than 40.

## Ambient Conditions and Forced Testing Procedures

Many systems have performance requirements and responses that vary with the season. Economizer processes and VAV air handling systems are two good examples. Since these processes are intertwined with most return fan capacity control applications, a thorough verification of the return fan's control system will involve testing under different seasonal scenarios. Generally, there are two approaches to this problem.

- *Test extensively under the conditions of initial start-up and throughout the commissioning process:* Anticipate and schedule additional testing at the remaining seasonal extremes and/or swing seasons. Usually, this will involve two or three return visits to the site by the commissioning contractor, supplemented by training for the operators to help them anticipate and deal with changes due to the change in seasons. This approach has the best chance of truly tuning the system to the operating realities of the building but will take nearly a year to fully implement.
- *Force system parameters to simulate different seasonal conditions:* This approach allows the testing to be completed during the commissioning process but is not as robust as actual seasonal testing. This is because forcing an input can verify logic and trends towards the proper response, but, the actual system response for most HVAC processes is highly dependent upon things like thermal lags that are virtually impossible to simulate.

During extreme summer or winter weather conditions, the design and capacity of the installed systems may make testing at high outdoor air percentages difficult or even dangerous to the equipment. As a result, it may be necessary to perform additional testing subsequent to start-up as soon as conditions permit to ensure reliable performance even if the testing process must be from forced parameters.

## Additional Resources

Additional guidance on all of the topics in this appendix can be found in the *General Precautions and Preparations* chapter of the *Functional Testing Guide*.

# Appendix 5: Return Fan Control System Hardware and Software Issues

Most return fan speed/capacity control strategies will only be as good as the control system that supports them. This appendix provides guidance regarding important control system considerations that should be addressed by the return fan control strategy design. At the end of the appendix, additional useful references are listed.

## Damper Interlocks

Depending on the specifics of their implementation, all of the strategies in this guideline are subject to conditions where the return fan could attempt to operate with both the return and relief dampers closed, either due to a failure mode or a transient condition. Typically the relief and outside dampers would both be specified as normally-closed and the return dampers would be normally-open in order to prevent both the relief and return dampers from being closed simultaneously. However, the possibility does exist that the return and relief dampers could be closed simultaneously. If the relief damper is connected to a normally-closed actuator and either the actuator fails or the control system signal is lost while the system is operating on 100% outdoor air, the relief damper would close when the return damper was closed. Systems that segregate the control of the relief dampers from the economizer process are also at risk.

Generally, the cause for concern is excessive static pressure either due to the fan being forced up its curve or due to air hammer. It is common for a fan to have a peak on its operating curve that is significantly above the pressure class of the duct. If a return fan were to operate with both the relief damper and the return damper closed, a flow restriction could be created which would push the fan up its curve, which could generate more pressure than the duct is designed to contain. Arguably a properly functioning variable speed drive will mitigate this sort of occurrence. Nevertheless, if the drive has been placed in bypass or if the failure that caused both dampers to be closed has also affected the drive control loop, then the system can be quickly and seriously damaged.

If the potential for operation with both the return and relief dampers closed exists, one or more of the following design approaches may merit consideration:

- Select the duct pressure class so that all ductwork downstream of the return fan is rated for a pressure in excess of the return fan curve peak.
- Provide a permissive interlock circuit using limit switches that sense damper blade position. This ensures that the return fan will not be allowed to start or remain operational unless the return or relief damper is open to a position that will prevent the problem.
- Provide a manual reset static pressure switch downstream of the return fan.
- Provide drive interlocks designed to function in all possible selector switch positions (hand, auto, inverter and bypass).
- Take steps to ensure that the drive acceleration times and braking functions are utilized to their full advantage.

None of the solutions described above will effectively deal with air hammer, which is a pressure pulse phenomenon very similar to water hammer. Air hammer is generated when air moving in a duct system is suddenly stopped. Pressure relief doors are the most effective means of dealing with this issue.

## Sensor Accuracy

Sensor accuracy is an important component of any control process and needs to be addressed on two fronts.

*Accuracy Rating Criteria*

The frame of reference for the accuracy rating needs to be identified. For instance is the stated accuracy percent of reading or percent of full span input? The more common approach is to state accuracy in terms of full span. However, it is quite common for a sensor to be applied in a situation where it does not normally operate at its full span rating. For example, a sensor rated for a span of 0 to 1.00 inch w.c. with an accuracy of ±1% of full span might be applied to in a situation where the normal anticipated signal will be .2 inches w.c.. If the sensor is not operating at the full scale input, then the accuracy relative to the operating point will be reflected by the following formula (Smith).

$$A_{Op} = A_{FS} \times \left( \frac{Span_{Full}}{Span_{Op}} \right)$$

Where :

$$A_{Op} = \text{Accuracy at the operating condition}$$

$$A_{Op} = \text{Accuracy at full span}$$

$$Span_{Full} = \text{Full span input (consisten t units)}$$

$$Span_{Op} = \text{Operating input (consisten t units)}$$

Solving this formula for the sensor under discussion reveals that the accuracy in terms of the .2 in.w.c. operating point is ±5%. In other words the user could anticipate that the observed reading reflected reality by ±.01 in. w.c. (±1% of 1.00 in.w.c, the full span of the instrument) which is ±5% of .2 in.w.c.

*Accuracy Rating Components:*

It is important to understand what components are included in a sensor's accuracy rating. Common components include:

- Non-linearity
- Hysterysis
- Repeatability
- Thermal drift
- Temperature effect
- Mounting effect

If the sensing element is coupled with a transmitter, then the transmitter itself could contribute to the over-all loss of accuracy in any or all of the areas listed above. Additional inaccuracies can be added by the signal processing equipment and wiring between the sensor and the controller and operator work station. Thus it is important to understand what is and isn't included in a sensors statement of accuracy, especially when comparing products.

There are two methods in general use for looking at the combined effect of these error sources (Smith):

- *Maximum deviation* adds up the contribution of each element.

*Probable deviation* adds up the squares of the contribution of each element and than takes the square root of the resulting sum.

The bottom line is that overall system accuracy at all operating points must be evaluated in order to properly select an individual sensor or flow measurement technology. Sensors with high precision, temperature compensation, or self-calibration features will mostly likely be more costly. But the cost is often justified when a realistic picture of the delivered accuracy is painted in light of the needs of the system to be served.

All of these topics are discussed in detail in the *Control Design Guide*, which is listed under Additional Web Resources in the References section of this guideline.

## Sensor Selection and Installation

In addition to accuracy, there are several issues that should be considered when selecting and installing sensors for return fan capacity control applications. For most of the applications discussed in this guideline the sensors required will be measuring flow or pressure.

For pressure measurements, the following should be considered:

- *Apply Pressure Sensors as Pressure Transmitters vs. Signal Converters*: Most current technology devices that measure pressure and generate an input that is acceptable to a DDC control system are designed to measure a relatively low pressure and convert it to an electronic signal. The electronic signal will generally be more robust and immune to problems when transmitted over a long distance when compared to extending tubing to transmit the actual pressures over a long distance.

Thus, it is desirable to select pressure sensors with robust electronic outputs (4-20 milliamps or 2-10 vdc for instance) and locate them in close proximity to the sensing location to keep the sensing tubing runs short. This will exploit their signal transmitting capabilities in addition to their signal conversion capabilities. This is in contrast to locating the sensors in the control panel and running the tubing from the field sensing location to the control panel.

- *Ensure Freedom from Unwanted Pressure Effects*: It is important that the sensing probes that provide the pressure input to the sensors be located in a manner that allows them to truly sense the desired parameter. For instance, sensors designed to measure static pressure should be installed in a manner that does not subject the probe to the influence of velocity pressure. This is best accomplished by using appropriate sensing heads and judiciously selecting their placement. Outdoor ambient pressure references should take the potential of wind influence into account.

- *Ensure Independence from Other Variable Pressure Drops*: Care should be exercised when locating probes so that when sensing pressure, they are unaffected by pressure drops caused by events outside of fan capacity and speed control. For example, one strategy highlighted in this guideline controls the return fan based on mixed air plenum pressure. In most systems, the filters will be located in the mixing plenum or at the point where the air exits the mixing plenum. If a mixed air plenum pressure sensor is piped to measure pressure after the filters, the increase in pressure drop as the filters load will affect the return fan control, as it should. If the sensor is piped to sense pressure ahead of the filters, changes associated with filter loading will not be picked up, even though these changes will impact the return fan control requirements.

- *Match the Performance of the Sensor to the Application*: For best accuracy, sensors should be selected to match the requirements of the application. Using a sensor with a range of 0-10 inches w.c. to measure a pressure that is typically 0.10 inches w.c. will provide less desirable results than using a sensor with a span that places the anticipated measurement under normal operating conditions in the middle and the maximum anticipated pressure slightly below the top.

In some instances, the flow measurements will involve measuring a velocity pressure signal and converting it to flow. In this case, the considerations discussed for pressure sensors will also apply. In addition, the effects of the square law must be taken into consideration. Velocity is a function of velocity pressure as defined by Equation A5-1.

$$V = 4{,}005\sqrt{P_V}$$

Where :

$V$ = Velocity in feet per minute

$4{,}005$ = A units conversion constant suitable for typical HVAC applications

$P_V$ = Velocity pressure in inches water column

*Equation A5-1 – The relationship between velocity and velocity pressure*

Examination of the equation reveals that the velocity pressure is a non-linear function of velocity. Specifically, if the flow in a given section of duct is reduced by 50%, the velocity pressure (i.e. the signal used by a velocity pressure based measuring system) is reduced to 25% of its original value. As a result, the velocity pressure available for measurement at low flow conditions in a system with a large turn down ratio can be quite small. Such a system may require special attention during the design of the control system to ensure a usable signal is available under all flow conditions. Alternatives include:

- Downsizing ducts at flow measuring locations to ensure a readable signal is available under all flow conditions.

- Providing a low range transmitter and a high range transmitter for the flow measuring element and selecting the appropriate transmitter based on the nominal supply fan speed or some other indicator of load.

- Using a signal measurement technology like a hot wire anemometer that is immune to square-law effects.

Additional considerations regarding flow measurement will be found in *Appendix 3* under *Active Minimum Outdoor Air Flow Control Techniques* and in *Chapter 3: Flow Tracking Control*.

## Control Loop Integrity

It is important to consider where the input and output connections interface to the control loop they serve. It is not uncommon for the input sensor associated with the control of a process to be located a considerable distance from the controller it serves. For example, a fan system utilizing building static pressure to control the return fan my be located on the upper floor of a high-rise building while the sensing element measuring the building pressure is located on the first floor. In these situations, it is tempting to connect the input to the closest available controller and use the control network to transmit the information to the controller at the other end of the building. However, there are several pitfalls to this approach related to the network becoming a part of the control loop:

- A network failure will result in an open control loop; i.e. a control process with no input. Such a failure can lead to equipment damage or may even cause safety problems.

- Variable traffic rates on the network can introduce variable and unacceptable time delays in the input to the controller. These variables can make the controller difficult or impossible to tune for robust reliable operation.

The bottom line is that inputs to control process should always reside on the same controller as the outputs they serve. This contingency should be reflected in the design documents and verified in the field as a part of the commissioning and inspection process.

## Pneumatic Controls

Despite the movement towards DDC control in the industry, pneumatic controls, and particularly pneumatic actuation systems, are frequently encountered. In an informal survey conducted recently by the authors, when asked "How long do you think it will be until pneumatics are phased out of your facilities", the response from facilities engineers ranged from "15-20 years" to "never."

Pneumatic controls will typically be encountered in the following situations:

- Existing systems where a retrofit project is modifying a portion of the system or facility but not the entire system or facility and the existing pneumatic control system must be expanded or interfaced with.

- Existing systems or facilities where the budget or technical capabilities of the owner will only support pneumatic control solutions.

- New and existing facilities where the speed and actuating power associated with pneumatic actuators make them an attractive alternative to electric actuators.

Thus, it is not out of the question that a designer will need to adapt one of the strategies outlined in this guideline to work with a pneumatic control system for either sensing or actuation purposes or both.

Generally less accurate and robust than electronic sensors, pneumatic transmitters can provide reasonable service for some applications, especially the higher end two-pipe and process grade transmitters. The 3-15 psi output signal from a two pipe transmitter will be less susceptible to problems than the static pressure input, even though both signals are transmitted in tubing.

Unlike their electronic counterparts pneumatic transmitters rely on mechanical systems to convert the measured parameter to a force that can repeatably, reliably, and accurately move a pneumatic relay. The forces required to accomplish this are many orders of magnitude larger than those required to accomplish the same function electronically.

To understand this, consider a pneumatic transmitter that must measure the very low differential pressure signals typically associated with velocity pressure based flow measurement or building static pressure control. Differential pressure measurements are typically made by applying the differential pressure to a diaphragm and using the motion of the diaphragm to actuate the mechanism. The force generated by a diaphragm is a direct function of its area. A quick survey of the options available currently in the commercial market will reveal that the sensors have diaphragms with diameters in the range of 3 to 4 inches (areas of 7.0 to 12.5 inches respectively) where-as the products offered in the process control arena have diaphragm diameters in the range of 6 to 8 inches or more (28 to 50 inches or more respectively). The sensors featuring the larger diaphragms have an obvious advantage when it comes to generating a force with a very small pressure. Process grade transmitters also have the advantage of being two pipe instruments and thus not subject to the limitations associated with the one pipe approach typically employed in the commercial arena.

Most pneumatic sensors need to be connected to a controller to provide feedback control. The devices typically used for this are termed "receiver controllers" since they receive a signal from a remote transmitter, compare it to a setpoint, and generate a control output as necessary in an effort to make the control point match the setpoint. These devices come in a wide array of quality levels, control capabilities (including PID), and price ranges. If pneumatic controls are mandated, the added cost for a process grade controller is usually warranted. However, a high quality process grade pneumatic controller is a beautiful but complex piece of machinery and may overwhelm operating staff. If pneumatic controls are mandated because the owner wishes to avoid the perceived cost and complexity of DDC technology, then a control strategy like speed tracking, that can be implemented without any flow or pressure sensors for the return fan, may be in order.

Pneumatic actuation is typically associated with inlet guide vanes. However, signal converters are available that can convert a pneumatic signal to an electronic signal like 4-20 milliamps or 1-5 vdc and allow it to control a variable speed drive. It is not uncommon to encounter this technology in existing systems where variable speed drives were installed to replace inlet guide vanes.

## Control System Point Lists

A control system point list can be a powerful tool for conveying control system design intent. Properly implemented a point list can:

- *Identify Point Requirements:* This is the obvious function of a point list. What's not always obvious without one is what points are required for non-control functions like commissioning and operation. Without a point list to clarify the requirements, these points may not be included in a project that is competitively bid, despite the best intentions of the designer and contractors.

- *Establish a Point Naming Convention:* Establishing a naming convention up front can go a long way towards providing a workable control system down the line. If the points that are added will be a part of an existing system, then consistency with the existing naming convention can be ensured. For new projects, conventions that make sense to the operating team can be developed and conveyed. This is a great way to get the operating staff involved in the project's early stages.

- *Establish Sensor Requirements:* The point list provides a ready means to specify sensor type and accuracy requirements. Adding a comments column allows special requirements to be addressed.

- *Establish Alarm Requirements:* Alarms provide a powerful tool for ensuring the persistence of design intent, which is often key to the persistence of efficiency. Current technology DDC systems have powerful alarm capabilities that are often under-utilized simply due to lack of direction. The point list provides an ideal format for defining alarm requirements and is another good way to get the operating staff involved with the project.

- *Establish Trending Requirements:* Current technology DDC systems have powerful trending capabilities that can be essential tools to commissioning and operations.

But, achieving the fullest benefit requires a system that can track a significant amount of data and move it through the network efficiently. Generally, these requirements are ample memory in the controllers, a properly configured operator workstation and a robust network architecture, most of which can be had for a relatively modest cost given the capabilities of current technology. But, in a competitive bidding environment, they will not be provided, no matter how modest the cost, without definition of the requirements on the project drawings. The point list provides a simple and effective mechanism for conveying these requirements. By indicating for each point what the trending and archiving requirements are (and then enforcing those requirements), the designer can go a long way towards bringing the full benefit of current control technology to the client.

## Narrative Sequences and Logic Diagrams

A detailed narrative sequence complements a points list and helps ensure that the intent of the design is communicated to the implementing contractors and operators. This communication is essential for a successful start-up and for the persistence of the operating strategy.

The narrative sequence needs to be more than a simple statement of intent. Consider the following narrative for a return fan speed tracking control strategy:

> *The return fan speed shall be controlled by tracking the supply fan speed.*

At first glance, this seems like all that is necessary. After all, it conveys the essence of how the return fan is to be controlled, the designer's intent, in a concise statement. But, for the system to operate successfully, there are many other details that need to be addressed. Here are a few examples:

- *Is the return fan tracking an output that is the indication of the supply fan's speed or the command going to the supply fan's capacity control system?* There are differences between the two that will impact how the VFDs are configured and the system's failure modes.
- *What difference in speed should be maintained by the control system?* For most speed tracking strategies, the speed difference is intended to control the system's minimum outdoor air flow, an important design and operating parameter.
- *Is the speed difference fixed or does it vary as a function of load or some other parameter?* Due to air handling system dynamics, operating at a fixed speed differential may not guarantee the desired minimum outdoor air flow rate under all operating conditions.

The answers to these questions are critical to the success of the design and will define its operating characteristics. While it is possible to address them in the field, they are design issues that are best addressed by the designer based on direct knowledge of the systems requirements rather than the field staff who may not be familiar with all the issues and who might second guess the designer's intent.

A narrative control sequence provides an excellent way to communicate all of the relevant design requirements to the field. In addition to addressing the details of the automatic operating sequence, the narrative should:

- Provide an overview of the system and its design intent.
- Document safety interlock requirements, including clarification on which interlocks should be hard wired and which can be accommodated in software.
- Document the desired failure mode response to events like power failures, loss of input signal, etc.
- Document how the system should function if selector switches are placed in hand, including which interlocks are still effective and how related equipment should respond if it is not placed in auto at the same time.
- Document scheduling requirements including any special sequences that need to be executed to start up the system.

- Document any special calculations like energy consumption or flow that are to be performed by the system, including the calculation technique.

- Document any special alarm requirements; for instance it may be desirable to have an alarm trigger an operator message detailing the required response in addition to documenting the problem.

- Support and supplement the point list by clarifying any important details regarding sensor requirements, sensor location, trending requirements, etc.

## Operator Interface Issues

Developing a solid control system design is a key factor in the facility operating equation, but not the only factor. Making the control process and data understandable and easily accessible to the operators is also important if the design intent is to persist. Items to consider include:

- *Provide more than a bare-bones operator interface:* Most DDC systems can actually be accessed and even programmed through a low level computer or hand held device. But data entry with such a device can be difficult and the information is often presented in a cryptic manner. Given the low cost of current technology PCs, the added cost of providing one with enhancements to support operations will be well worth the investment. Savings will accrue to the contractor because the start-up and commissioning process will be streamlined. Savings will accrue to the owner because persistence will be enabled.

- *Include a graphical user interface:* Many DDC systems can be accessed and controlled without graphics. But for most people, "a picture is worth a thousand words." Providing a graphic interface, including specifications for the graphics that are required, will go a long way towards making the system more user friendly.

- *Set up the work station to be more than just a control system tool:* Most control systems can run their interface software concurrently with other applications. Including word processing software in the operator work station's requirements will allow the operators to maintain an electronic log and write reports for management. Including a spreadsheet application will allow them to mine the trend data that is available from the system and perform calculations to support troubleshooting. Including a viewer for drawing files from programs like Viso® or AutoCAD® will allow them to access the electronic versions of the documents for the building. Including the actual drawing software will allow them to annotate changes on the drawings as the facility is modified.

- *Make important operating parameters adjustable:* Few things are more frustrating for an operator than knowing what a problem is but being unable to fix it because he or she cannot get to the parameter that needs to be changed. Specifying that all setpoints and tuning parameters are to be operator accessible and can be commanded without re-programming will help prevent this sort of frustration. Password protection should be specified to ensure that only experienced, trained operators can make changes to critical parameters.

- *Provide plenty of memory for data archiving:* Trending and memory go hand in hand. To maximize the benefits that trending has to offer, make sure to provide enough disc space to store data. Supplement this by providing training for the operators so they know how to access and archive the data.

- *Provide a method for backing up the system:* The programming information stored in a functioning control system represents a major investment in development labor. All if it can be lost in a heartbeat if the system experiences a hard drive problem or some other fault if the data has never been backed up. All computer based systems should include a convenient way to back up their data. This should be supplemented with a written procedure and training for the operators so they can maintain a current back-up when operational changes are made to setpoints and other parameters.

- *Involve the operators in database and graphic development:* By bringing the operating staff into the control system development process early on, everyone wins. The operators get a system that is tailored to their needs and thought patterns. The contractor is exposed to the owner's preferences at the point when it is easy and cost effective to accommodate them. All of this helps to ensure that the designer's intent is achieved and persists.

## Additional Resources

Additional guidance on all of the topics in this appendix can be found in the *Control System Design Guide, which* provides detailed information on this topic as well as a spreadsheet tool that can be used to create a point list. Each chapter in this guideline includes one of theses points list for the strategy that it discusses, as applied to the system illustrated in the opening pages of the chapter.

CtrlSpecBuilder is another useful tool that is provided as a free resource from Automated Logic at [www.ctrlspecbuilder.com](http://www.ctrlspecbuilder.com). Included are routines that will help you build narrative sequences, develop point lists, and define other specification requirements.

A more detailed example contrasting a statement of intent with the details required to make it a working control sequence can be found in the Energy Design Resources brief titled *Design Review.*

# Appendix 6: Electrical and Drive System Considerations

Since variable frequency drives are typically used to achieve variable air flow, it is important for the design engineer to understand variable speed drives and how to apply them. General information on their application to air handling systems can be found in this appendix. At the end of the appendix, additional useful resources are listed.

## Variable Speed Drive (VSD) Technology

The VSDs typically applied in commercial HVAC systems are designed to work with standard squirrel cage induction motors. Most will contain four building blocks.

- A rectifier that converts the incoming AC power to DC.
- A filter that smoothes the DC power.
- An inverter that converts the DC power back to AC power with a variable frequency and voltage for use by the induction motor. The inverter contains solid state switching devices like transistors, thyristors, and gate turn-off thyristors to obtain the desired output.
- A controller that regulates the rectifier and inverter based on the requirements of the load and the operator or external control system. Generally speaking a constant voltage to frequency ratio is maintained over most of the output range.

There are a number of technologies that are used to accomplish the functions associated with these fundamental building blocks (Stebbins, 2000):

- Current source inverters control the current delivered to the load in addition to the voltage and frequency. They are typically applied for large single motor applications and the impedance of the motor is an important factor in their operation.
- Variable voltage inverters function independently of the motor they serve. In fact, one drive can serve multiple motors. They can include current limiting circuitry and were common in the 1980s.
- Pulse-width modulation inverters, which have become the dominant technology in the HVAC industry. They employ a constant voltage DC bus in the rectifier which is then pulsed on and off to create a replica of the AC waveform at the output of the inverter.

## Variable Speed Drive (VSD) Features and Options

Variable speed drives come with a wide array of features and options, many of which are useful for HVAC applications.

- *Bypass switches* allow the drive to be isolated from the power system and motor for service while the motor runs at full speed as a conventional motor. This can provide some measure of redundancy and comfort to owners and operators who are concerned about the potential for the high technology represented by the drive to fail. However, it should be used with care since the fan will run at full speed regardless of the needs of the system. This can create operational problems due to flow imbalance and over-pressurization problems. In the latter case, the problems can be so severe as to cause duct failures. When bypass switches are provided, it is often desirable to make sure the interlock wiring is arranged so that safety interlocks and operating controls will be effective, regardless of the operating mode.
- *External interlock terminals* allow safeties and operating interlocks to be interfaced with the drive in a manner that will shut it down regardless of the status of selector switches like the Hand-Off-Auto switch or the Inverter-Bypass switch. These terminals should not be confused with interlock terminals that will only affect the drive when it is running in auto. This can be of critical importance in the case of safety interlocks.
- *Programmable outputs* are becoming more common and allow many drive parameters to be sent to dedicated terminals for use by external devices. For example, a programmable output might be used to provide the supply fan speed as an output from the supply fan drive for use by the return fan drive in a speed tracking control strategy.

- *Network interface cards* allow drives to communicate directly with control systems at a network level rather than via discrete inputs and outputs. Such a connection can make a wealth of operating information available to the facilities staff including drive amps, kW, kWh, speed, faults, etc. However, even though it may be possible to achieve all of the required control functions and interfaces via a network level connection to the control system, it is recommended that the inputs and outputs associated with control loops be made as discrete connections between the drive and the controller sending the commands. This will ensure that a network communications failure does not cause an open control loop problem. It will also ensure that the loop tuning is not upset by changes in the loop time constant associated with varying traffic rates on the communications bus. Similar considerations apply to inputs to the controller.
- *On board controllers* allow the variable speed drive to monitor an input, such as duct static pressure, and control the drive in response to it without the need for a controlling command from an external control system. This can be an advantage in situations where drives are being added to a facility that does not have DDC control capabilities. This controller should not be confused with the on-board controller included in most drives used to regulate the drive output based on the internal drive parameters that are a direct or indirect indication of the drive speed.  In other words, in most cases an operating drive utilizes some sort of internal control loop to regulate its own speed. The HVAC process parameters that we typically think of as controlling the drive are actually adjusting the setpoint of this internal control process in response to the requirements of the HVAC system.
- *Displays* allow drive operating parameters to be displayed locally. Many manufacturers offer programmable features that allow the user to select the parameters to be displayed. Displays are becoming almost standard since they are used to set up the drive. But, some drives feature a removable display and keypad. This can be a security feature in some applications. But, it can also be a way to get low in a competitive bidding environment where a display is not specified. In the latter case, the operating team can find themselves confronted with multiple drives and only one portable display/keypad to operate with and no budget to buy additional units. This hardship can be avoided by making sure the specifications require a display and keypad for every drive.
- *Over-speed capability* provides some operating flexibility for solving problems and adapting to future requirements. Many drives are capable of driving the motors they serve above synchronous speed (60 Hz), in some cases up to 120 Hz or more. This can be especially handy in direct drive fans where there are no sheaves to allow the ratio between motor speed and fan speed to be adjusted. The feature can be used to fine tune a system or squeeze a little extra capacity out of a system where the motor is not fully loaded at the original design condition. Before proceeding, it is important to verify that the fan class will support operation at a higher speed and that bearings, belts, sheaves and couplings can tolerate the higher speeds. Also bear in mind that for fans, motor horsepower varies with the cube of the speed, all other things being equal. As a result, it will not take much of a speed change to load a motor that is running near its nameplate. But, in some instances, this extra cushion is all that is necessary to adapt to a new operating condition or solve an operating problem.

## Distribution System Considerations

Variable speed drives are an integral part of the electrical distribution system and can have a major impact on its operation.

The circuitry in variable speed drives can generate distortion on the distribution system serving the drive. The amount of distortion generated by a given drive in a given application can be the function of a number of variables including the size and configuration of the distribution system, the technology used by the drive and the size of the drive and the load it serves. This distortion can have a significant negative impact on the distribution system if it is severe enough (Fuhr, n.d).

Increasing the number of drives will increase the potential for problems. But, drives are not the only source of waveform distortion in modern electrical distribution systems. Electronic ballasts, desktop computers and other electronic equipment can all contribute to the problem. In the case of a VSD, the problem can be mitigated by installing an isolation transformer, line reactor or similar device on the incoming line. These devices may also provide some protection for the drive circuitry from transients and surges in the distribution system, which can affect the operation and reliability of the drive and even cause a failure. But, these devices add cost and complexity to the project which may or may not be necessary if the characteristics of a specific drive and the distribution system are considered. Performing an IEEE 519 analysis of the distribution system will help the design team identify the need for additional protection. In some instances, this analysis is assigned to the contractor in the specifications since the need for protection can be very much influenced by the specifics of the drive's design.

The technology used to vary motor speed by VSDs also creates a distorted wave form on the output side of the drive with voltages, frequencies and wave forms that are much different than the pure sinusoidal wave form associated with the utility supply. If not properly addressed, these distortions can cause problems with the motor and the leads between the drive and the motor. Motor issues are further discussed in the next subsection. Lead issues can vary with the drive technology and thus should be addressed to meet the requirements of the drive manufacturer for the equipment that is installed. In general, the drives should be located as close as possible to the motor they serve to minimize the length of conduit and wire between the drive and motor. This can add cost to a project for motors that are located outside since the drives must be supplied in weather proof enclosures. Since the drives generate heat, it is often necessary to ventilate these enclosures. This is a much more costly undertaking when the weather proof integrity of the enclosure must be maintained, in contrast to a drive in an indoor location.

## Motor Considerations

Most of the motor issues associated with return fan capacity control are related to applying the motors with VSDs. A detailed discussion of this topic can be found in *How to Match AC Motors and Variable Speed Drives* (Jackson and Liggett, 2002) as well as the other references cited in this appendix.

### Variable Speed Drive Issues

Motors that are controlled by VSDs are subject to stresses that would not exist in a non-VSD application. In general terms, these effects exist because the output waveform of a VSD is not a pure sine wave and includes high frequency currents and voltages. Specifics vary as a function of the technology used by the drive, but in general terms, the harmonic content can impact the motor on several fronts:

- *Heat generated by the harmonic losses associated with the motor's iron laminations and copper windings raises the motor's temperature, shortening its life (Houdek, n.d).*
- *Efficiency is reduced by the losses generated by the harmonics (Houdek, n.d.).*
- *Audible noise generated by the high frequency harmonic content can annoy occupants and tenants situated in the vicinity of the drive (Houdek, n.d.).*
- *Voltage spikes stress the insulation in the motor, leading to premature failures in motors not designed for use with VSDs (Stone et al., 1999).*
- *Eddy currents induced in the laminations and shaft of the motor cause pitting and premature bearing failures as they flow through the bearings to ground (Boyanton, n.d.).*

Fortunately, the technology associated with drives is constantly advancing and improving in areas that address these problems. And, there are non-drive technologies that can be applied to deal with these issues, most of which are best invoked at the time of design.

- *Load reactors can be installed on the load side of the drive to mitigate the harmonic problems that cause motor heating, efficiency losses, and audible noise.*

- *Adjusting the carrier frequency in a pulse width modulated drive can also be a way of dealing with audible noise. Many drives allow this setting to be adjusted in the field.*
- *Shaft grounding systems can be provided for motors associated with variable speed drives to provide a means for eddy currents to reach ground without going through the bearings.*

Specifying that the motors provided on a project be rated for use with variable speed drives is recommended for any project where drives will be applied. Many designers are also requiring that the motor and drive supplier coordinate with each other to ensure compatibility and minimize problems.

### VSDs and Retrofit Applications

When an existing fan and motor are upgraded to use a VSD, all of the issues mentioned in the preceding paragraphs will need to be addressed with regard to the motor. Generally, two approaches are used:

- *Upgrade the existing motor to a VSD compatible motor:* This approach will minimize potential problems but will add cost and eliminate an asset (the motor) which may be serviceable in the new application.
- *Relocate the motor to a different service in the retrofit:* For instance, if the retrofit includes a new fixed speed pump or fan with a horsepower requirement matching the existing motor, then the existing motor can be installed on the new equipment and a new VSD-compatible motor provided for the return fan.
- *Make an informed decision to re-use the existing motor:* There is a difference between walking blindly into trouble and taking a calculated risk, like in the case of applying a drive to an existing motor. The severity of drive induced motor problems can vary over a wide spectrum as a function of a number of factors including drive technology, motor quality, the distribution system, and the duty cycle. A quality existing motor may provide satisfactory service in a VSD application for many years. Making a decision to re-use a motor that appears serviceable may be a viable alternative, especially if the owner participates in the decision and the operating staff is trained regarding the potential problems as a part of the commissioning process. If the motor does fail, then it can be upgraded to a better match for the VSD at that time.

## Starting Torque

Because of their low static requirements, return fans tend to be low horsepower, low speed, large wheel diameter selections when contrasted with the supply fan they serve. The fan selection affects the motor selection in two ways:

- *Motor horsepower: It must be matched to the fan selection's brake horsepower requirement. This is an obvious consideration and is typically addressed satisfactorily.*
- *Motor starting torque: In addition to running the fan at speed, the motor must be capable of accelerating the fan wheel and shaft up to the operating speed. The name for this parameter is moment of inertia and it is expressed mathematically as WR2, where W is the mass of the wheel and R is the perpendicular distance to the axis of rotation (Greenheck, n.d.).*

Moment of inertia is usually not a factor for large fans running at high static pressures. But for large volume, low static pressure applications like return fans, a motor capable of maintaining speed may not be able to accelerate the wheel fast enough to prevent motor damage. A slow acceleration time allows the in-rush current associated with a motor start to persist longer than is desirable. High inrush currents lead to high motor winding temperature and premature motor failures. If the overloads have been properly set, the motor will be protected but will never get to start because the overloads will trip before the wheel is up to speed.

## Drive Sheave and Belt Considerations

For most HVAC applications, fans are driven by belts. Direct drive applications are encountered where simplicity, maintenance or cost are issues. Direct drives may also be encountered in clean room applications where the particles associated with belt wear could contaminate the clean space. The remainder of this section will focus on issues associated with belt driven fans.

### Fixed Versus Adjustable Sheaves

Adjustable pitch sheaves allow the speed of the device they serve to be changed. This is typically accomplished by varying the width of the groove in the pulley which, in turn, controls how far down into the groove the belt rides (see Figure A6-1).

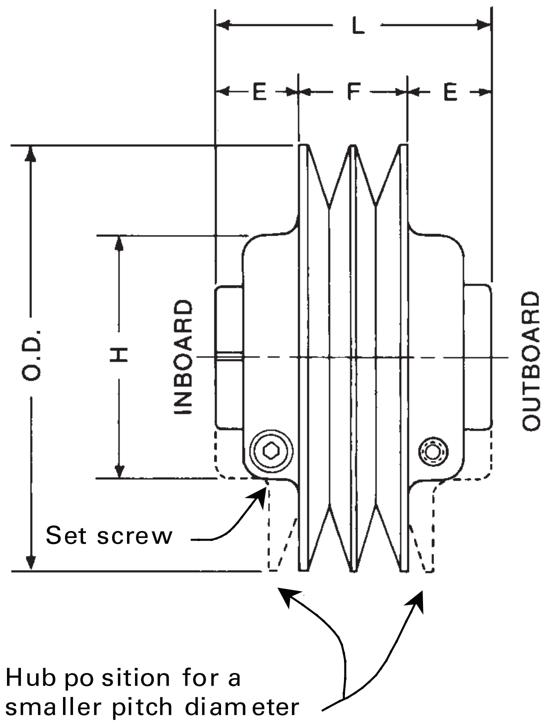



***Figure A6-1***

***A typical adjustable pitch sheave. Loosening the set screws allows the outer hubs to be moved relative to the center hub. This widens the groove so that the belt runs lower in it, effectively reducing the pitch diameter and increasing the rotational speed assuming no change in the belt speed. (Courtesy: ???)***

Adjustable pitch sheaves provide the advantage of flexibility, but add an additional first cost. They also tend to have a higher operational cost. If the belt rides below the top of the sheave there will be increased belt wear. They also work against persistence since the speed setting can be lost if the set screws come loose or are inadvertently loosened during a belt change.

Best practice is to specify equipment with adjustable sheaves to facilitate initial set up and balancing and then provide an allowance or unit cost in the contract to compensate the balancer for installing a fixed pitch sheave once the final speed requirement is known.

### Maximizing Efficiency

By far, V-belts are the industry standard for HVAC applications and have an efficiency loss of approximately 3% associated with them. Cogged belts may provide for some improvement in this area but add cost and complexity that may not be warranted in typical HVAC applications.

Regardless of the type of sheave provided, selecting them so the design supply, return, and outdoor air flows are achieved with the variable speed drives operating at full speed will optimize overall efficiency and controllability. Efficiency is maximized because for most drives, efficiency is highest at full speed and declines as speed is reduced (see Figure 1-1 in *Chapter 1: Introduction and Fundamentals*). Control is maximized because the full speed range of the drive is available for control in contrast to a situation where only some of the speed range of the drive has been used to set the design flow. For example, if the balancer used the drive to slow a fan down 10% to achieve design flow, then only 90% of the drive's turn down capability is available for control purposes. In contrast, if the balancer uses the fan sheaves to adjust the fan speed to design flow with the drive operating at full speed, then 100% of the drive turn-down capability is available for control purposes.

## Minimum Speed Settings

Minimum speed for both supply and return fans should be such that the desired flow relationship can be maintained under all operating conditions. For example, assume the minimum speed for the return fan is set at 10 Hz based on the motor manufacturer's recommendation. Then the minimum supply fan speed must be coordinated in order to maintain the differential necessary to maintain proper system flow rates. In most applications, the speed of the supply fan will be higher than the return fan but the final setting is very dependent upon the fan performance characteristics and the sheave ratios of the individual fans.

## Additional Resources

Additional guidance on all of the topics in this appendix can be found in *Installation and Maintenance of V-Belt Drives*, another useful tool that is provided as a free resource from the TB Woods Company at http://www.tbwoods.com/pdf/VBD-IM_InstallationandMaintenance.pdf.

*The Adjustable Speed Drives Directory, the Control System Design Guide* and the *Functional Testing Guide* also include detailed information on different drive technologies and their applications in addition to a directory of manufacturers and products.

# Appendix 7: The Relationship Between Design, Installation and Operation

Designers must understand the details, nuances, and physics behind the performance of the machinery and systems they are designing. But they also must be aware of the challenges and requirements that the implementers and operators will face as they fabricate, install, and operate the systems. The same could be said of the implementer and operator with regard to their particular area of expertise: everyone has a specialized but inter-related function to perform if the overall success of the system is to be ensured. This appendix will explore some of these relationships as the final step in paving the way to successful operation. At the end of the appendix, additional useful resources are listed.

## Design Intent

> *If design intent were put on display at the National Conference on Building Commissioning, people would be lined up for miles to see it because everyone has heard of it but nobody has ever really seen exactly what it is.*
>
> -A National Conference on Building Commissioning Attendee

Design intent is a key concept and a hot topic in the commissioning industry. Yet, as the commissioning provider stated above, it is elusive and difficult to capture and define. In general terms, the concept is to capture the owner's requirements and intentions in a way that will convey them to the design, implementation, and operating teams and pave the way to achieving them in the operating facility.

It could be said that a well developed set of contract documents might provide a reasonable statement of design intent. In fact, one could argue that if they do not, the entire project is at risk since, in current practice, the contract documents are the primary mechanism for conveying intent from the design team to the construction team, and ultimately to the operating team. Presentation can be a critical step if the goals of the owner are to be conveyed in this manner by the design team to the implementation and operating teams. The following paragraphs briefly explore key points with regard to conveying intent in the contract documents.

### Floor Plans

Floor plans are the primary mechanism used to convey the physical arrangement of components to the trades people installing the system. It is important to remember that they endeavor to depict a three dimensional world in two dimensions and that those two dimensions are scaled down considerably from reality. For instance, a typical 0.5 mm pencil line on a 1/16" = 1' scale drawing would be about 4" wide if its width were scaled up to real world dimensions. Obviously then, some issues will arise when floor plans are used to convey information to the field. The items covered in the next several paragraphs can help alleviate problems that may occur.

### Details

Details can help resolve questions on a number of fronts. Providing an isometric of a complex duct or piping connection can add a great deal of clarity. Providing large scale detail of a complex assembly can allow important information to be conveyed that would otherwise be lost if the line width is bigger than the item being drawn.

### Flow Diagrams, Points Lists, and Narrative Sequences

Flow diagrams complement the point lists and narrative sequences by presenting the system arrangement in a logical way. This is in contrast to the physical arrangement conveyed in the floor plans. By freeing the presentation from the changes in direction, size, etc. required to fit the system into the available space, the functionality of the system can be clearly conveyed and understood by everyone involved with the project.

### Specifications

While a picture is said to be worth a thousand words, there comes a point in most technical projects where words are the most efficient recourse for conveying information. That is where specifications come into play, as they provide a forum for conveying the project's performance parameters, contractual organization, and legal requirements. In doing so, they complement and clarify the drawings and other information, binding it into one contractual package.

From a technical standpoint, one over-arching rule might be said to apply:

> *Specify what you need and enforce what you specify.*

While some of the legal and "boiler plate" issues in the specifications are general in nature, many of the technical details are specific to the project and should be conveyed as such. And, in most instances, even the legal and "boiler plate" requirements will benefit from some editing to ensure compliance with the specifics of a given project. After all, it is called a *Specification*, not a *General Statement of Intent*, for a reason.

Tailoring the specifications to the real needs of the project provides a firm foundation for enforcement, a key factor complementing the written word. Un-enforced and/or un-enforceable specification requirements can create problems technically, contractually and legally. Enforcing the requirements of a well written specification only makes sense; after all, if you didn't need it, you wouldn't have asked for it, right?

## Coordination

Coordination will be a re-occurring theme for the life of any project. The owner must coordinate with the designer to make sure their requirements are understood and addressed, and the design team must coordinate amongst themselves to be sure the needs of the various specialties complement each other rather than interfere. Similar coordination is required between the construction team members as well as with the design team to ensure the requirements of the contract documents are implemented as intended. Finally, the entire team from owner to designer to contractor must coordinate with each other as the project comes on line to make sure the systems meet the design intent and that the operating staff has the information and other tools they need to run the facility.

Ideally, many of the coordination issues could be addressed in detail by the designer via the contract documents. However, in the current economic and construction market, designers faced with the challenges of tight design budgets and/or timelines must often delegate coordination issues to the contractors who will be performing the work. This approach can be viable if all of the necessary factors are clearly addressed in the contract documents, but such an effort goes beyond simply specifying in general terms.

Regardless of how coordination issues are addressed, considerations for return fan control systems include:

- Ensuring that the responsibility for sizing and selecting the equipment like dampers is clearly delineated.
- Ensuring that the application range and ratings of equipment like sensors, actuators and drives are compatible with the performance characteristics of the system served.
- Ensuring that the sensing and actuating systems incorporated in any packaged equipment are compatible with the sensing and actuating capabilities of the control system specified.
- Ensuring that the system and equipment room layout provides sufficient space for the assembly and proper installation including any entering or leaving straight duct requirements for flow sensors and maintenance and service requirements.
- Ensuring that any power requirement is coordinated with the electrical design and related contract documents.
- Ensuring that the shop drawing requirements will support a package that clearly and accurately conveys all of this information for review, approval and use in the field.

The shop drawing issue raised in the last bullet requires support from the designer during the construction phase to succeed. The effort should go beyond simply verifying that the product is from a manufacturer listed in the specifications. It should also verify that all of the coordination issues have been addressed and some quick cross checks have been performed, especially if the selection process had been delegated to others or the equipment is a substitution and differs from the basis of design.

Control systems are an area where interfaces between multiple trades occur on many projects. For instance the mixed air plenum pressure sensor required for a mixed air plenum pressure control strategy might be furnished by the control contractor, installed by the pipe fitters and wired by the project electrician. While legal considerations generally dictate that the designer not specify means and methods to the contractors bidding the work, it is generally desirable to include language in the contract documents that ensure that all parties understand their involvements with the components of the control system. This will allow them to ensure that their bid and scope of work reflects the coordination required for a successful installation. Frequently, this can be addressed by a paragraph in each section of the specification that references the control sequences and point lists and requires that the contractors bidding each section include any necessary coordination in their price.

## Implementation

Ideally, the designer's involvement should not stop with the completion of the design documents. Ongoing involvement with the design as it proceeds into construction and start-up can be rewarding and informative for the designer and beneficial for all parties. Including field involvement in the designer's scope of work and fee will typically reward the owner with benefits that pay for themselves many times over. By anticipating the inevitable "surprises" that arise when theory and reality come face to face, the intent of the design is not compromised. Design team involvement in field implementation can be particularly beneficial in the following areas:

### Construction Observation

Who better to verify that reality reflects concept than the designer. And what better way to ensure that than to have the designer periodically review the installation as it progresses in the field. It is important to begin this involvement early in the process before the final finishing work of other trades obscure important details, making them difficult to observe or correct. Important field verification issues for return fan capacity control systems include:

- *Configuration of the economizer dampers*: The location and relationship of the outdoor air and return air dampers relative to each other is important. These issues are covered in detail in *Appendix 2: Economizer Theory and Operation*.
- *Return and relief flow path duct fabrication details:* Ideally, the pressure losses through both flow paths should be similar. A minor change in the way a duct fitting is fabricated can have a significant impact on the pressure loss and thus a significant impact on the performance of the system in some operating modes. This topic is also discussed in detail in *Appendix 2: Economizer Theory and Operation*.

Including the commissioning provider in the construction observation process can also provide benefits that pay for the costs many times over. By nature, the design team will focus on verifying the issues related to their particular specialty as they move through the construction site while a commissioning provider will focus on integration issues. For example, the architect might check that the correct shaft wall has been installed for a fire rated shaft, the mechanical designer will verify that the fire damper is properly situated in the shaft (both important verifications), and the commissioning provider will observe that the damper is 5 feet above a hard ceiling, 10 feet from the framing rough-in for the access door and that the top plate for a wall is zip screwed to the duct access panel (see Figure A7-1).

***Figure A7-1***

***An integration issue between the framing contractor, the sheet metal contractor and the operator, who will ultimately pay the price if the problem is not corrected before it is hidden by finishes. (Courtesy: ???)***

### Submittals and Shop Drawings

A thorough shop drawing review process can go a long way towards ensuring that the design intent is reflected in the equipment provided. Areas to target include:

- *Sizing and configuration of the economizer dampers:* Damper sizing is critical to economizer performance, as was discussed earlier in this section.

- *Variable speed drive options and interlock arrangements:* Most drive manufacturers offer a variety of configuration options in addition to a number of places to interface with hardwired interlock circuits. Carefully matching these details to the design requirements can be critical to the overall success of the project. Issues with variable speed drives are discussed earlier in *Chapter 1: Introduction and Fundamentals*.

Even if the designer is not involved in construction observation, the preceding items are worthy of consideration by the implementer. In addition, the implementer should consider the following items if they are not covered by an independent commissioning process.

### Checklists

Checklists provide a valuable method to track the installation process. Most manufacturers offer checklists tailored to their products. Commissioning providers frequently provide checklists with an integration perspective that include both the equipment specific issues for a given component as well as the issues associated with integrating the component into the system. Items that relate to return fans and their capacity control systems include:

- Verification of the integrity of wiring connections, including that the wires are on the correct terminals and the connections are tight.
- Verification of belt tension prior to start-up and after initial run-in.
- Verification and coordination of factory start-ups to ensure that the manufacturer's requirements are met and warranties are not violated, especially in situations where temporary operation is being considered.

### Functional tests

Functional testing is a critical step in the start-up and commissioning of any system. If a commissioning provider is involved in the project, they will no-doubt have some very specific tests to perform on the return fan capacity control system. Lacking that, the information presented in *Appendix 4: Tuning Outdoor Air Flow to Design Specifications* will provide guidance for ensuring that design intent is realized.

## Maintaining and Adapting Design Intent

Many of the issues dealt with by the installing contractors as they bring the systems on line are also ongoing operations and maintenance issues. In fact, the checklists and tests performed as a part of the commissioning process can be valuable operations and maintenance tools. The initial test data provides a baseline for comparison, and the procedures themselves provide a template for ongoing commissioning of the system.

Becoming involved in the design and construction process is an ideal way for the operating team to get up to speed on the systems they will inherit when a project reaches completion. By participating in the design review process, the operating team can bring a unique perspective to the process that will ensure that operation and maintenance needs are addressed in a timely fashion and when the impact on the budget is minimal or even beneficial, i.e., cost saving. Participating in the construction observation process allows the operating team to learn things about their systems that will be less obvious once finishes are in place. Interacting with the contractors, particularly the control contractor and commissioning provider, will provide valuable insight into the operating characteristics of their systems beyond any formal training provided by the contract.

Once the building is up and running, the following items are worthy of consideration for return fans and their capacity control systems.

### Motor Replacement

When motors are replaced, it is important to make sure that the new motor is suitable for use with the variable speed drive and has similar starting torque characteristics. These measures will ensure that the design intent is preserved and minimizes the potential for the operating difficulties associated with a mismatch. However, it is important to understand that a motor that meets all of the requirements of the original design may not be a stock motor or the lowest cost option in a competitive bidding environment unless all of the requirements are clearly delineated.

When a motor is replaced, the connections to the existing motor are disconnected and must be reconnected to the new motor. For a three-phase motor, this introduces the possibility of changing the direction of rotation of the motor if the leads are not connected in the same phase sequence as in the original motor. This is because the direction of rotation for a three-phase motor is established by the phase rotation, which, in turn, is established by the order in which the phase conductors are connected to the motor windings. Thus, when a motor is changed, it is important to verify rotation. If the rotation is in the wrong direction, it can be changed by switching any two phase leads. Note that for VSD equipped motors, this change must be made downstream of the drives due to the operating characteristics of the drive.

### Dirty Fan Wheels

Per the discussions earlier in this appendix under Motor Replacement, the motors provided for fans, particularly return fans, must provide not only the horsepower required for operation at speed, but also the torque required to accelerate the wheel up to operating speed. The torque required to accelerate the fan wheel is a function of the mass of the fan wheel and shaft among other things. Return fans typically handle unfiltered air, and can become dirty over time. While this dirt may appear insignificant, it can actually add enough mass to the fan wheel that the moment of inertia changes to a value that is beyond the capabilities of the motor. This is especially true of large fan wheels that are started across the line or with minimum acceleration settings in the VSD. When this happens, the starter or drive may suddenly start tripping on overload. The problem will seem mysterious because verifying all of the typically suspect parameters like overload settings, motor connection security, etc. will not solve it. When this situation is encountered, cleaning the fan wheel may be the “silver bullet” leading to success.

### Drive Operation in Bypass

Many drives have bypass switches that allow the drive electronics to be bypassed, connecting the motor directly across the line. In addition to being aware of the design issues associated with this feature, the operating staff needs to understand exactly how the drive is interlocked when operating in this mode. It is also important to recognize that it may be necessary to manually manipulate the return fan speed if the supply fan is being operated in bypass or vice versa.

Similarly, nearly all drives allow the start-stop command and speed command to be over-ridden by manual commands and/or selector switch settings at the drive. When operating any drive in this manner, it is important to consider the impact on the rest of the system, including any related VSDs. For example, if an operator elects to take manual control of the return fan speed, then it may also be advisable to take control of the supply fan speed to ensure that the required ventilation rates and pressure relationships are maintained in the facility.

### Calibration

Verifying calibration of all sensors and actuators is an obvious and essential measure for ensuring proper operation and persistence of design intent.

### Limit Switches and Permissive Interlock Circuits

If provided, limit switches are critical to ensuring that the system is not damaged by a failure of a damper actuator or interlock. Thus, it is important to periodically verify that the limit switches are free to actuate and that the fans cannot start or remain in operation unless dampers are in safe positions.

### Verify Economizer and Minimum Outdoor Air Flow Control Performance

The story in the case study presented at the end of *Chapter 6: Mixed Air Plenum Control* illustrates the problems that occurred in one system when the economizer performance was neglected from the outset. Similar problems can occur in previously well-functioning systems if sensors are not calibrated and the economizer damper systems and their related linkages and actuators are not inspected, adjusted, and lubricated.

The operation of the minimum outdoor air flow control system is integral with the operation of the economizer and subject to the same potential to degrade. This function is also highly interactive with the return fan capacity control strategy. Periodically repeating the testing discussed earlier in *Appendix 4: Tuning Outdoor Air Flow to Design Specifications* will ensure that the design intent persists and good IEQ is maintained under all operating conditions.

## Verify Performance Prior and Subsequent to Building Additions or Renovations

Any air-handling system that is affected directly by additions or renovations or indirectly by changes to adjacent spaces or the building envelope should receive attention before and after these changes are completed. This is especially true for VAV systems and their related return fan speed control processes. Changes can be the result of:

- *Intentional Building Modifications:* It is not unusual for a building modification to be developed and implemented without consideration of the impact it will have on the existing building and systems serving it. Facilities groups should make a point of proactively ensuring that the existing systems are considered and adjusted as necessary to accommodate building renovations and expansions. Such an effort should include documenting existing performance, budgeting for any necessary modification to existing systems from the start (including the necessary design work), supporting the design team in their effort to assess the potential impacts, and monitoring the design development and construction process to ensure the necessary issues are identified and addressed.
- *Temporary Conditions:* Renovation and expansion processes can temporarily breech zone separations and compromise the integrity of the building envelope, creating temporary operating problems in terms of pressure and ventilation control. The operating team should anticipate issues of this type anytime a construction processes is contemplated and coordinate with the day to day construction operations in an effort to minimize the impact on the existing, occupied building.
- *Occupant Induced Modifications:* Operable windows are a prime example of an occupant induced modification that can reek havoc on VAV systems and their associated return fan capacity control strategies. For example, if a system is operating at or near 100% outdoor air on an integrated economizer cycle on a mild day, the return fan frequently is functioning as a relief fan, removing the extra air brought into the building for "free cooling" by bringing it back to the relief louver for discharge. If building leakage or open windows are providing the necessary relief path for the excess air, then, the return fan may create negative pressure in some portions of the building as it pulls outdoor air in through cracks and open windows in an effort to satisfy its capacity control strategy. This can quickly lead to comfort and IEQ complaints from building occupants located in the immediate vicinity of the infiltration path.
- *Long Term Effects:* Over time, the pressure separations represented by internal partitions and the building envelope can degrade, modifying the pressure relationships created by the original flow settings. Sealants deteriorate, weather-stripping ages and deteriorates, and the impact of numerous minor penetrations made to accommodate new piping and wiring add up. Because the changes are minor and cumulative, the impact may not be noticed initially until they are significant enough to generate a complaint, IEQ issue or code compliance problem.

To minimize and mitigate the impact of the changes that might occur in a building, the operating team should periodically re-assess the performance of the system, especially if there has been a renovation or expansion project. Periodic and post renovation assessment considerations might include:

- Re-evaluation of the ventilation flow rate, building pressure relationships, and envelope integrity and building static pressure.
- Testing and balancing as necessary to re-establish the supply, minimum outdoor air flow and return flow relationships and the associated bias settings.
- Testing and balancing under variable load conditions to ensure that the relationships established under the preceding bullet hold under all anticipated operating conditions.

## The Operational Impacts of Design Compromises

Most engineering solutions are the result of compromises from perfection that are made based on the requirements of the project, the capabilities of the operating team, the available budget and the limitations of the technology to be applied. Compromises that yield acceptable results on one project may yield totally unacceptable results on a different one. Compromises that worked satisfactorily when a building or system was first brought on line may fail to perform as the building is modified or ages over time or the loads served by the system and thus, the demands placed upon it change. Taking the time to understand the design issues and related compromises that might apply to a given system can be a valuable troubleshooting and diagnostic aid for commissioning providers and operators as they deal with the evolving, real-time performance of the systems they work with and the demands that are placed on them over their operating life.

## Troubleshooting Charts

Troubleshooting charts provide a helpful tool for the operating team. In fact, if troubleshooting charts do not exist, they can often be created from the system logic diagrams by working through them in reverse order. In most cases, a logic chart will depict the actions that must occur and the order in which they must occur for a particular event to be initiated. In contrast, troubleshooting often involves starting with an event that did not occur as expected and tracing back through the system until the component that failed to actuate is discovered.

## Additional Resources

*Chapters 2* and *3* of the *Control System Design Guide* contain detailed information and recommendations regarding calibration and accuracy issues. The *Integrated Operation and Control* chapter of the *Functional Testing Guide* includes a relative calibration procedure which also may prove useful.

# Appendix 8: Theoretical versus Actual Performance

HVAC concepts that appear to be perfectly sound to yield the desired results under design conditions may fail to perform under the unforgiving, highly variable, highly interactive scrutiny of reality. Sometimes, the deviations from the anticipated performance are minor, insignificant, or even helpful. Other times, the failure to achieve design intent under all operating conditions can lead to significant problems. Complicating the matter is that the predicted results for any control strategy applied to a given HVAC system are highly dependent on the dynamics of the system as its various components interact and as the system itself interacts with the building and the environment. Fortunately, the interactions will follow the laws of physics and thus, can be analyzed and predicted.

The following example explores the performance of the speed/signal tracking strategy in a particular system as it goes through a step-change in operating states. While focused on only one of the five strategies covered in the guideline, the technique illustrated could be applied to any one of them to assess its performance in a given situation.

### A Speed Signal Tracking Example

When applied, speed tracking strategies attempt to exploit the fan affinity law that relates flow to fan speed in an effort to maintain a constant minimum outdoor air percentage. Specifically:

$$Q_2 = Q_1 \times \left(\frac{N_2}{N_1}\right)$$

Where :

$Q_1$ and $Q_2$ = Flow at conditions 1and 2

$N_1$ and $N_2$ = Fan speed at conditions 1and 2

The assumption is that if the supply fan and return fan speeds are set to provide the correct minimum outdoor air percentage at design, then the direct relationship between flow and speed described by the fan affinity law will ensure that the desired minimum outdoor air percentage is maintained under all operating conditions. But, for the fan affinity law to apply, the system must be unmodified and operating on the same system curve.

Unfortunately, the operation of the terminal units in a VAV system is constantly changing its system curve. This effect, combined with the techniques commonly used to control the supply fan in a VAV system can undermine the “direct relationship between flow and fan speed” theory. Figure 1 illustrates this phenomenon for a 25,000 cfm fan system. The characteristics of the system are as follows:

- The system serves an average low rise building with a lot of open office area.
- The system design intent is to provide a constant 5,000 cfm minimum outdoor air flow.
- The return fan drive tracks the supply fan drive speed and has been adjusted to provide 20% minimum outdoor air at design conditions.
- The supply fan drive is controlled to maintain a fixed static pressure at the fan discharge.
- The supply fan static requirement includes 1.5 in.w.c. of internal static (static accounted for with-in the AHU casing) and 2.0 in.w.c. of external static (static in the outdoor air intake and supply duct system), most of which is in the supply duct system.

Consider what happens if the system is operating at design flow and experiences a load change that reduces the flow requirement by 20%. For the purposes of this discussion, we will assume that this load change occurs in one step; perhaps a VAV terminal unit being forced to 0 cfm when the zone it serves goes unoccupied. Similar issues arise when a system goes through a gradual reduction in flow brought on by the throttling of a VAV terminal.

*<u>Step 1 – The VAV Terminal Unit Throttles</u>*

The system upset occurs when a 5,000 cfm VAV terminal unit drives fully closed. This is a

20% reduction in supply flow demand. Initially, the throttling forces the supply fan up its curve by an amount approximately equal to the VAV zones flow rate. Assuming nothing else changes in the system, a new system curve is generated which passes through this point. Note several important points at this juncture:

- Since nothing changed on the return system*, the return fan's performance is unchanged.
- Since the return fan's performance is unchanged, the minimum outdoor air quantity drops towards 0%.

Because this step increased the discharge static above setpoint, it will be transitory and of short duration due to the action of the discharge static pressure control system that modulates supply fan capacity.

*Step 2 – Supply Fan Speed Reduction*

The discharge static pressure control system detects the increase in static pressure associated the VAV terminal throttling and reduces the supply fan speed to the discharge static pressure setpoint. Assuming that nothing has changed in the system, the supply fan speed change moves the fan's performance down the system curve generated with the VAV unit throttled. Note the following:

- The supply flow is now 17,650 cfm (29% of design). Assuming nothing changed, this is 9% below the current demand.
- The supply fan speed changed 12%.
- The return fan speed tracked the supply fan speed directly and changed 12%.

---

* The reduction in supply flow probably changed the pressure in the occupied zone slightly and thus, influenced the return fan's performance. For the purposes of our discussion, we will assume that the pressure change was nearly undetectable and thus was insignificant. This is a reasonable assumption given typical building leakage rates and the open office nature of the area served.

- The 12% reduction in return fan speed reduced the return flow to 17,650 cfm.

Since the return and supply flow are still virtually identical, the minimum outdoor air flow rate is still virtually zero.

Because the reduction in flow associated with the supply fan speed change drops the capacity delivered by the system to less than the demand, this condition will also be transitory. The reduction in capacity relative to demand will cause the other terminal units in the system to shift their damper positions moving through a series of system curves to a new stable operating point.

*Step 3 – Supply Flow Increases to Match Demand*

Assuming the load in the remaining occupied zones is unchanged from what it was at the beginning of the example there will generally be a cycle where:

- The VAV terminal unit dampers drive open.
- The opening dampers result in a reduction in discharge static pressure below setpoint.
- The reduction in discharge static below setpoint leads to an increase in supply fan speed.
- The increase in supply fan speed re-establishes control at setpoint.

This cycle will continue in an analog fashion until the system stabilizes. Note the following with regard to the system once stability has been achieved.

The supply fan speed stabilizes at 10% below the original speed while the flow stabilizes at 20% below the original flow. This apparent disparity between actual performance and that anticipated by the underlying theory behind speed and signal tracking is because the system curve has changed by virtue of the actions of the VAV terminals. Projections using the fan affinity laws based on the original operating point and system curve are not valid for points on the new system curve. The new system curve is the direct result of the changes in the flow versus. pressure characteristic of the duct system which were the result of the movement of the VAV terminal unit dampers. The new fan operating point (the intersection of the fan curve with the system curve) is the direct result of the way the supply fan control system responds to the flow and pressure changes created in the system when the VAV terminal units move their dampers.

- The return fan speed stabilizes at 10% below the original speed and the return flow stabilizes at 10% below the original flow, in perfect agreement with the fan affinity laws. Since nothing changed the pressure versus. flow relationship for the return duct system, the return fan performance shifts up and down the original system curve. The fan affinity laws apply and the performance is as anticipated by the underlying assumption behind speed and signal tracking strategies.

- The minimum outdoor air percentage stabilizes at 10% rather than the 20% intended by the design. This disparity occurs due to the difference between the supply fan's responses to the load change versus the return fan, as discussed in the preceding bullets.

When applying speed tracking strategies, designers need to be aware of the issues discussed above and illustrated in Figure 1. Performing an analysis similar to the one illustrated may provide insight into the suitability and potential problems associated with a particular strategy in a particular application. Generally, the following rules of thumb apply:

- Systems with larger outdoor air percentages will show less deviation from design than systems with small percentages.

- Systems with low static requirements and particularly, low external static requirements will be more immune to problems than systems with high static requirements.

- Systems which control the supply fan for pressures at remote points in the system will be more immune to problems than systems that control for a static pressure at the fan discharge.

- Systems with similar fans and similar fan curve shapes will be more immune to problems than systems with different fan types and different fan curve shapes.

### Good News/Bad News

Interestingly enough, the minimum outdoor air flow reduction that occurs as the system in the example reduces total flow could be a good thing or it could be a bad thing. For instance, if the terminal unit throttled closed because the zone it served was unoccupied, and the occupancy in that zone represented a 50% reduction in occupancy for the area served by the system, then the shift in operating characteristics has caused the system to reduce it's ventilation rate in accordance with the need and thus yields a benefit. In contrast, if the flow rate reduction is not related to occupancy level, then the system shift in operating point

| Step | Flow | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Supply | | Return | | Outdoor Air | | OA Deviation from Design | |
| | cfm | % Change | cfm | % Change | cfm | % of Supply | cfm | % of Supply |
| Desgin | 25,000 | Base case | 20,000 | Base case | 5,000 | 20% | Base case | Base case |
| 1 | 20,000 | 20% | 20,000 | 0% | 0 | 0% | -5,000 | -20% |
| 2 | 17,650 | 29% | 17,650 | 12% | 0 | 0% | -5,000 | -20% |
| 3 | 20,000 | 20% | 17,933 | 10% | 2,067 | 10% | -2,933 | -10% |

| Step | Speed | | | | | |
|---|---|---|---|---|---|---|
| | Supply | Return | Change from Base Case | | | |
| | | | Supply | | Return | |
| | rpm | rpm | rpm | % | rpm | % |
| Desgin | 895 | 463 | Base case | Base case | Base case | Base case |
| 1 | 895 | 463 | 0 | 0% | 0 | 0% |
| 2 | 790 | 409 | -105 | -12% | -54 | -12% |
| 3 | 803 | 415 | -92 | -10% | -48 | -10% |

Exfiltration to adjacent areas

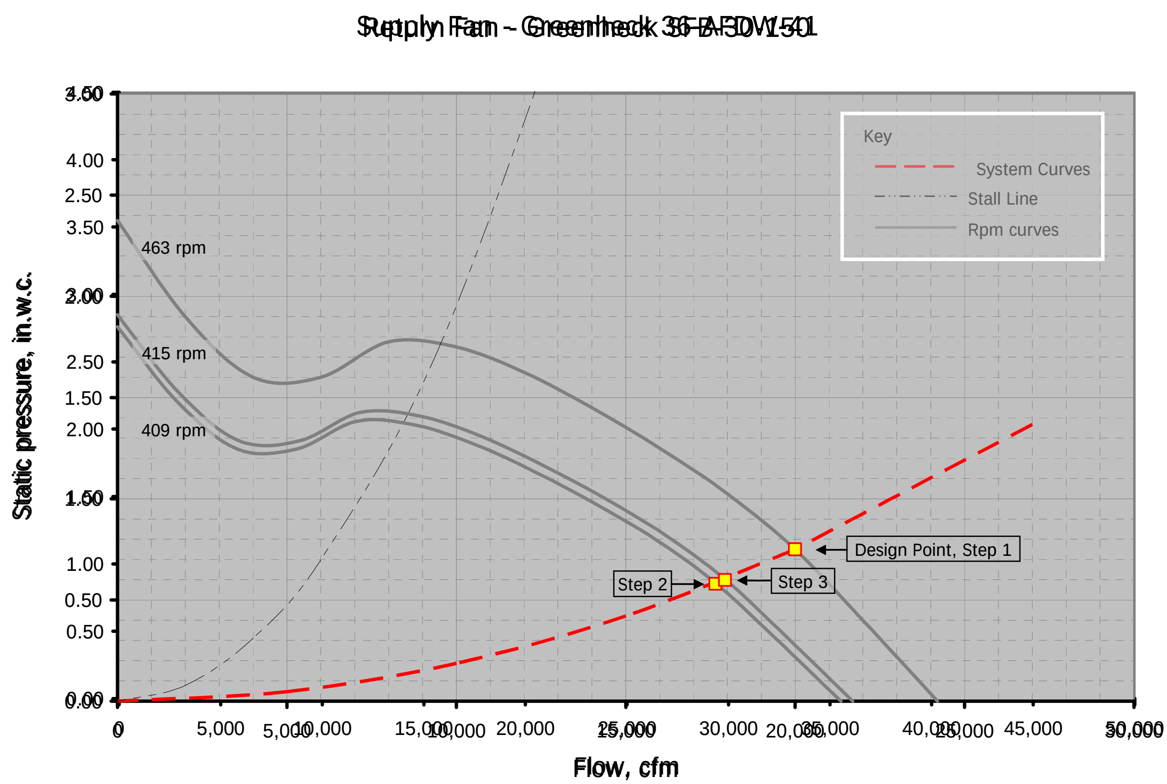



*Figure 6 (Continued on opposite page)– Supply and return flows in a fan system with signal/speed tracking based return fan control as the system goes through a step change in supply flow. Refer to the text for a discussion of the various steps shown in the fan curves and summarized in the tables.*

results in the potential to under ventilate any time the system is on minimum outdoor air. How much of an issue this represents depends on how much time the system will spend operating on minimum outdoor air.  For example a system in San Diego equipped with an integrated economizer cycle may spend most of its time operating on 100% outdoor air due to the mild environment that exists there. In contrast, a system operating in a hot and humid environment like Key West or a Midwestern environment with hot humid summers and cold winters may spend a significant amount of time on minimum outdoor air.

Performing a detailed analysis of a given system's dynamics under all conceivable operating conditions would be daunting, and mostly likely not cost effective.  In contrast, assessing system performance under a few critical operating conditions (peak load, minimum load, start-up, shut-down, step change in load, etc.) may provide valuable insights and target areas worthy of further analysis.

# Appendix 9: Minimum Outdoor Air Requirements and their Impact Return Fan Capacity Control

Determining the proper outdoor air flow requirement for an HVAC system is a critical part of any HVAC design process. It is also integral to the control of the return fan speed on VAV system since the flow returned will have a significant impact on the outdoor air flow rate introduced into the system. While a detailed discussion of the procedure used to determine outdoor air flow requirements is beyond the scope of this guideline, a brief overview of some of the key elements which have a direct bearing on the performance requirements of the return fan will be presented in this appendix. In addition, examples will be presented, illustrating how the outdoor air flow requirement and the exhaust and exfiltration requirements that complement it influence return fan operation.

Detailed information on determining outdoor air requirements for ventilation purposes can be found in ASHRAE Standard 62.2-2004 and the companion application guideline. Most code dictated ventilation requirements can be traced directly or indirectly back to a version of this ASHRAE standard.

### *HVAC System Outdoor Air Components*

In general terms, the minimum outdoor air requirement for most commercial HVAC systems is composed of the components listed below. Note that since outdoor air represents mass flow into the building, each outdoor air component has a complementary process that represents mass flow exiting the building, thus maintaining a mass flow balance:

- *Ventilation Air:* This is air that is introduced into the building for the purposes of diluting pollutants from occupants, building materials, or processes. Generally, this air is directly exhausted via toilet exhaust fans, janitor's closet exhaust fans or similar systems. However, there are instances where it has been handled via a fixed relief setting at the economizer relief damper.

  Typically, the ventilation requirement in commercial buildings is driven by occupancy; more occupants equal more ventilation. The simplest approach to addressing this need is to arrange the system to provide ventilation for the design occupant density under all conditions, regardless of the actual occupant density. The reality is that the occupant density in most buildings will vary and, if the ventilation requirement can be tailored to the actual occupant density, significant energy savings can be achieved in many climates. Demand controlled ventilation strategies and provisions in code that allow ventilation rates to be modified based on less than peak occupancy open the doorway to capturing these savings. But, achieving the result typically adds to the design and operating complexity of the system, as will be illustrated in the examples at the end of this appendix.

- *Make-up Air:* This is air that is brought into the building to replace air that is exhausted by a process like a kitchen exhaust hood or a lab hood. In some cases, ventilation air can be transferred from an adjacent zone/system to the zone with the process, minimizing the need for handling and treating additional outdoor air. This approach is illustrated in one of the examples at the end of this appendix.

- *Pressurization Air:* This is air that is brought into the building to ensure positive pressurization relative to the out-of-doors. This pressurization may be reflected as a direct positive pressure differential between a perimeter zone served by the system and the exterior of the building. Or, it may be reflected as a positive pressure relative to an adjacent interior zone which in turn is positive to the exterior of the building. This air exits the building via an exfiltration process. Exfiltration (and its counterpart; infiltration) are discussed in *Appendix 1: Infiltration and Exfiltration*.

The bottom line is that the minimum outdoor air introduced into a building is critical for ensuring a safe, comfortable and efficient environment by diluting contaminants, ensuring adequate make-up for processes that require exhaust, and controlling infiltration.

*The Return Fan and Minimum Outdoor Air*

As is discussed through-out the guideline, the return fan has a critical role to play in maintaining adequate building ventilation and pressurization. Generally, this role is manifested on two fronts which will be discussed in the following sections.

*Maintaining the Mass Flow Balance at the Mixed Air Plenum*

In an HVAC system, the mixed air plenum represents a node where the conservation of mass equation applies and must be satisfied. This means that for the designer's intended outdoor air fraction to be realized, the return fan needs to deliver sufficient air to complement the minimum outdoor air flow and balance the conservation of mass equation; i.e. the mass flow represented by the supply stream leaving the mixing plenum will be the sum of the mass flows represented by the return and outdoor air streams entering it.

Assuming a fixed supply flow, if the return flow is too low, then the outdoor air flow will be too high and will typically cause unnecessary energy consumption. If the return flow is too high, then the outdoor air flow will be too low, representing the potential for IEQ problems. Thus, one of the primary drivers behind return fan capacity control is to ensure that the return air delivered to the mixing plenum is the exact complement of the minimum outdoor air requirement, ensuring efficiency and minimizing the potential for IEQ issues.

Interestingly enough, the only time this matters on an economizer equipped system is when the system is at its minimum outdoor air condition. Generally, this will occur during climate extremes:

- When it is extremely cold, the economizer control process will drive the system towards minimum outdoor air as it mixes return and outdoor air to satisfy its discharge or mixed air temperature setpoint.
- When it is extremely warm and/or humid, an integrated economizer process will stop using more than the minimum outdoor air requirement because the extra outdoor air no longer represents a "free cooling" source.

These topics and their implications are discussed in *Appendix 2: Economizer Theory and Operation.*

*Maintaining the Mass Flow Balance at the Zone Level*

Just as was the case for the mixed air plenum, the space served by the HVAC system represents a node where the conservation of mass equation applies and must be satisfied. However, it's more complicated than the mixed air plenum since the number of streams entering and leaving the space can exceed three.

Air can enter the space via a number of routes including:

- *The supply stream*, which is nearly always present and includes the minimum outdoor air fraction.
- *Infiltration from the building exterior*, which generally is unconditioned air and frequently represents an IEQ problem in terms of comfort, contaminants and condensation.
- *Infiltration from adjacent zones*, which may include conditioned air transferred by design or unintentionally from other HVAC systems as well as outdoor air that infiltrated through the adjacent zone. The return fan associated with a different system serving the adjacent zone can influence the node via this path.

Air can exit the node via a number of routes including:

- *The return stream,* which is usually but not always present. This route is the means by which the system's return fan will influence the node.
- *Direct exhaust via hoods, toilet exhaust and other positive processes,* which have ideally, but not always, been anticipated by the design.
- *Exfiltration to the building exterior,* which may be for pressurization purposes and

intentional by design or unintentional due to changes that have occurred in the building subsequent to design, system problems (including loss of control of the return fan) or issues not adequately addressed by the design.

- *Exfiltration to adjacent zones,* which may be intentional or unintentional as discussed in the preceding bullet. The system's return fan can influence the system serving the adjacent zone via this path.

These topics and their implications are discussed in greater detail in *Chapter 1* of the Guideline and in *Appendix 1: Infiltration and Exfiltration*. The common denominator is that all of them impact zone to zone and building pressure relationships.

Because the return fan is associated with one of the more common and primary exit routes listed above, it will have a direct and significant impact on inter-zonal and building pressure relationships. It follows then that in a VAV application, where the supply flow into the node varies, controlling the return fan in a consistent manner to complement the supply flow will be critical in terms of ensuring proper inter-zonal and building pressure relationships.

The interaction of the return fan with inter-zonal and building pressure relationships will be critical and exist under all operating conditions, unlike the return fan's interactions with the mixed air plenum, which are more critical when the system is on minimum outdoor air.

The remainder of this appendix will be devoted to three examples illustrating the concepts discussed to this point. The first two examples depict an individual HVAC system serving a total building when:

- Direct exhaust exceeds minimum ventilation rate and;

- Minimum ventilation rate exceeds direct exhaust.

The third example illustrates what happens when multiple HVAC systems serve adjacent zones.

### *Direct Exhaust Requirements Exceed Ventilation Requirements*

This example is based on an individual HVAC system serving all zones in the building with the following requirements on a design day:

- *Supply Flow* – 10,000 cfm based on the sensible cooling requirements of the zones served.

- *Ventilation Flow* – 2,000 cfm based on the type of occupancy, the number of occupants, and the requirements of the governing codes.

- *Toilet Exhaust* – 1,000 cfm based on code requirements for exhaust in the restroom and janitor's closets.

- *Process Exhaust* – 3,000 cfm based on the requirements of exhaust hoods in the kitchen.

As can be seen from the tabulation above, 4,000 cfm will be directly exhausted from the building via the toilet and kitchen hood exhaust systems. To keep the building pressure relationships neutral, conservation of mass dictates that 4,000 cfm of outdoor air be introduced into the building. The ventilation requirement provides 2,000 cfm of the necessary flow. But and additional 2,000 cfm of make up air will be necessary to achieve a neutral pressure relationship, bringing the total minimum outdoor air requirement up to 4,000 cfm.

If the designer wanted to ensure a neutral or slightly positive pressure relationship relative to the outdoors, they might elect to bring in outdoor air in excess of the 4,000 cfm value assessed above. The exact amount required can be difficult to identify and will be a function of a number of factors including how air tight the building is, stack effect, wind speed and direction, and the traffic rate through the building entry-ways to name a few. Assessment techniques include rules of thumb, past experience, and techniques similar to those used to identify infiltration loads.

Once the outdoor minimum outdoor air flow requirement has been identified, the design return fan flow requirement can be identified. In the case of this example, the design return flow requirement is as identified in Table a9-1.

If 500 cfm of additional outdoor air were added to the minimum outdoor air flow requirement to provide some measure of positive pressurization, then the resulting design return flow requirement would become 5,500 cfm as is summarized in Table A9-2.

| Flow | | Comment |
|---|---|---|
| 10,000 | cfm | Supply flow (starting point for the return flow requirement) |
| (4,000) | cfm | Direct exhaust (to be subtracted from the return flow requirement) |
| 6,000 | cfm | Resulting design return flow |

*Table A9-1 – Design Return Flow Requirement with No Building Pressurization Air (Option A in Figure A9-1)*

| Flow | | Comment |
|---|---|---|
| 10,000 | cfm | Supply flow (starting point for the return flow requirement) |
| (4,000) | cfm | Direct exhaust (to be subtracted from the return flow requirement) |
| (500) | cfm | Pressurization air exfiltrated via cracks and other openings(to be subtracted from the return flow requirement) |
| 5,500 | cfm | Resulting design return flow |

*Table A9-2 – Design Return Flow Requirement with Building Pressurization Air (Option B in Figure A9-1)*

Figure A9-1 illustrates these flow relationships diagrammatically; including the flow differential setpoints that would be used if the system were controlled by a flow tracking strategy (see Chapter 3 of the guideline for a detailed discussion of this strategy).

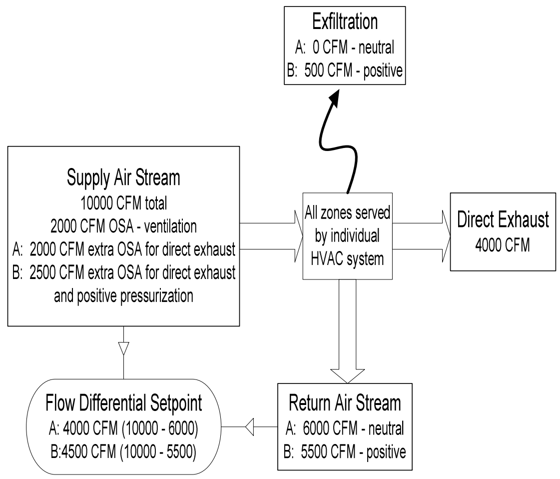



*Figure A9-1 – Direct Exhaust Requirements Exceed Ventilation Requirements*

The real trick in this situation and for any VAV system where the return flow must complement the supply flow under varying conditions is to utilize a control strategy that is capable of meeting the needs of the system under all load conditions, not just the design condition. This is the over-arching goal of any return fan speed control strategy. But, the exact nature of the goal will vary from situation to situation and needs to be assessed and identified as the design is developed.

For example, in the situation under discussion, it will be necessary to assess if the direct exhaust requirement is the same under all operating conditions or varies with time. For instance if the kitchen exhaust hood is manually controlled and only runs when the kitchen staff needs it, then some mechanism will need to be in place to:

- Identify if the kitchen exhaust hood is or is not operating.
- Adjust the setpoints in the return fan control strategy to reflect the current operating condition (full kitchen exhaust or no kitchen exhaust or something in between if there are multiple hoods).
- Adjust the minimum outdoor air flow to reflect the current operating condition, especially if an active minimum outdoor air control strategy is employed.

When the day to day and hour to hour operating variables are considered, the requirements for the return fan capacity control strategy can become quite demanding. Taking our current example a step further, suppose that the kitchen exhaust hood does operate intermittently based on the needs of the kitchen staff. If demand controlled ventilation is included in the project, allowing the minimum outdoor air flow to be adjusted to reflect the number of occupants, then both the return fan and toilet exhaust requirements will be impacted.

Assuming demand controlled ventilation is not a project requirement, but the intermittent kitchen exhaust fan operation is, then the design return fan capacity when the hood is not operating will be as illustrated in Table A9-3.

| Flow | | Comment |
|---|---|---|
| 10,000 | cfm | Supply flow (starting point for the return flow requirement) |
| (1,000) | cfm | Toilet exhaust (this is the exhaust flow that would exist if the 3,000 cfm kitchen hood were not in operation) |
| 9,000 | cfm | Resulting design return flow |

*Table A9-3 – Design Return Flow Requirement with No Building Pressurization Air and No Kitchen Hoods in Operation*

In this scenario, 1,000 cfm of the return flow would need to exit the building via a fixed relief damper barometric campers or exfiltration to ensure that the design ventilation requirement of 1,000 cfm is met. If the air exits the building via exfiltration or barometric dampers at the zone, then the return fan will not have to handle that air and the return fan size drops by 1,000 cfm from what is show in Table A9-2.

The variable kitchen exhaust requirement has implications in terms of system complexity, first cost, and energy. On the one hand, the designer could identify all contingencies and design the system to deal with them. Properly implemented, this approach would yield best efficiency but would have significant complexity and first cost in terms of the control system. On the other hand the designer could elect to simply run the kitchen hood any time the HVAC system serving it was in operation. This would simplify the control system complexity and minimize the return fan first cost. But, the continuous need to condition and move 3,000 cfm of outdoor air that was only needed on an intermittent basis would represent a significant energy burden over the life of the system.

Irrespective of the exact solution to the challenge presented by this example, the technique used to control the return fan will be on the critical path to success. In most situations, if the designer takes the time to assess system outdoor air and exhaust requirements under all operating modes, the appropriate return fan capacity control strategy will soon become evident.

For instance, in the case of the example under discussion;

- If the operation of the kitchen exhaust hood is intermittent, and;
- Demand controlled ventilation is employed due to a highly variable occupancy, and;
- The climate is extreme;

then the cost and complexity of a flow tracking strategy for the return fan may be justified in terms of the operating savings that could be achieved (see *Chapter 3: Flow Tracking Control*).

On the other hand;

- if the ventilation requirement is constant and;
- the kitchen hood operates anytime the HVAC system serving it operates;

then a mixed air plenum pressure based control strategy may be attractive due to its relatively low first cost and its tendency to maintain a constant minimum outdoor air volume under all load conditions when properly implemented (see *Chapter 6: Mixed Air Plenum Control*).

The bottom line is that the selection and implementation of an appropriate return fan control strategy can be impacted by a number of variables. In turn, the interactions of the return fan with the system and building it serves can have a significant impact on minimum outdoor air flow control and building pressurization. Identifying specific solutions to problems of the type discussed in this section is beyond the scope of the guideline. However, the issues are raised to illustrate how critical the analysis of the system requirements is and encourage the reader:

- *If they are designers;* to perform such an analysis as a part of the process they used to identify and develop the appropriate return fan control strategy for the system they are designing and clearly communicate their requirements in the contract documents.

- *If they are implementers;* to be aware of the fact that that the details of the design may be crucial to success and that a rigorous commissioning process will go along way towards identifying and resolving the inevitable field issues that will arise and the design progresses from concept to reality.

- *If they are operators;* to recognize that operational changes that move away from the original design concept, either intentionally or accidental, may require that the control strategy be revisited and retuned to adapt to the new conditions.

*Appendix 8: Theoretical versus Actual Performance* examines the performance of a speed tracking strategy as the system goes through a change in operating state, contrasting what actually will happen with what might be anticipated by less informed observer and will provide additional insights into the issues discussed in this section.

The remaining examples illustrate two additional scenarios that frequently must be dealt with by return fan capacity control systems.

*Ventilation Requirements Exceed Direct Exhaust Requirements*

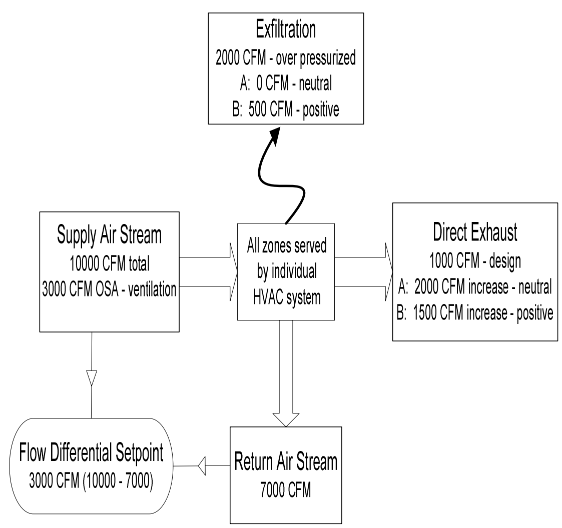
This example is based on an individual HVAC system serving all zones in the building with the following requirements on a design day:

- *Supply Flow* - 10,000 cfm based on the sensible cooling requirements of the zones served.

- *Ventilation Flow* – 3,000 cfm based on the type of occupancy, the number of occupants, and the requirements of the governing codes.

- *Toilet Exhaust* – 1,000 cfm based on code requirements for exhaust in the restroom and janitor's closets.

Figure A9-2 and Tables A9-4 through A9-6 illustrate some of the options that could be used to address this situation. As can be seen from the tabulation above, it is the intent of the design to bring in 2,000 cfm more outside air than is being directly exhausted. Depending on the integrity of the building envelope, this may or may not represent a significant pressurization problem if not addressed directly by the design.




*FigureA9- 2 – Ventilation Requirements Exceed Direct Exhaust Requirements*

| Flow | | Comment |
|---|---|---|
| 10,000 | cfm | Supply flow (starting point for the return flow requirement) |
| (1,000) | cfm | Direct exhaust (to be subtracted from the return flow requirement) |
| (2,000) | cfm | Exfiltration through the envelope (additional outdoor air that must be relieved to ensure ventilation requirements are met) |
| 7,000 | cfm | Resulting design return flow |

*Table A9-4 – Design Return Flow Requirement with a High Exfiltration Rate and No Building Pressurization Air (Base case in Figure A9-2)*

One approach for accommodating the high exfiltration requirement associated with the base case in Figure A9-2 would involve using barometric dampers from the zone or ceiling plenum serving it to the out-of-doors. This would be a simple, cost effective approach that would keep the building positively pressurized, but not excessively so. A similar result could be achieved by using a fixed relief damper at the air handling unit. But this would require that the return fan handle the extra 2,000 cfm, increasing its size and cost and potentially adding to the complexity of the control of the fan and economizer.

Another option is summarized below in Table A9-5.

| Flow | | Comment |
|---|---|---|
| 10,000 | cfm | Supply flow (starting point for the return flow requirement) |
| (3,000) | cfm | Increased direct exhaust to match ventilation requirement (to be subtracted from the return flow requirement) |
| 7,000 | cfm | Resulting design return flow |

*Table A9-5 – Design Return Flow Requirement with Increased Direct Exhaust (Option A in Figure A9-2)*

Under this option, the direct exhaust rate is increased to accommodate the ventilation requirement. This will cost some energy in terms of exhaust fan power, but may have some advantages relative to the approach presented in Table A9-4.

- Direct exhaust has the potential to provide a more positive assurance that the intended air flows will be achieved when contrasted with relying on a high exfiltration rate.
- One approach used successfully by designers to handling the increased direct exhaust flow is to transfer additional air through the restrooms to the toilet exhaust system. Given that the loads in restrooms are typically quite low, the high air transfer rates through them often means that tolerable comfort conditions can be maintained with out the cost of a zone of control.

Option B in Figure A9-2 represents a compromise between the base case and Option A and is summarized below in Table A9-6.

| Flow | | Comment |
|---|---|---|
| 10,000 | cfm | Supply flow (starting point for the return flow requirement) |
| (2,500) | cfm | Increased direct exhaust to partially match ventilation requirement (to be subtracted from the return flow requirement) |
| (500) | cfm | Remaining ventilation air is exfiltrated to provide positive pressurization (to be subtracted from the return flow requirement) |
| 7,000 | cfm | Resulting design return flow |

*Table A9-6 – Design Return Flow Requirement with Increased Direct Exhaust and Some Exfiltration (Option B in Figure A9-2)*

Under this scenario some of the extra ventilation air is relieved, reducing the direct exhaust requirement and providing some measure of assurance of a positive building pressure.

*Multiple HVAC Systems Serve Adjacent Zones*

This example is based on a building with two individual HVAC system serving adjacent zones. Design day requirements for each system are as follows:

System 1

- *Supply Flow* - 10,000 cfm based on the sensible cooling requirements of the zones served.
- *Ventilation Flow* – 2,000 cfm based on the type of occupancy, the number of occupants, and the requirements of the governing codes.
- *Toilet Exhaust* – 1,000 cfm based on code requirements for exhaust in the restroom and janitor's closets.
- *Process Exhaust* – 3,000 cfm based on the requirements of exhaust hoods in the kitchen. Note that when combined with the toilet exhaust, there is a total direct exhaust requirement of 4,000 cfm.

System 2

- *Supply Flow* - 10,000 cfm based on the sensible cooling requirements of the zones served.
- *Ventilation Flow* – 3,000 cfm based on the type of occupancy, the number of occupants, and the requirements of the governing codes.
- *Toilet Exhaust* – 1,000 cfm based on code requirements for exhaust in the restroom and janitor's closets.

When considered separately in the context of the zones they serve, each system contains an imbalance between the outdoor air brought in for ventilation purposes and the air that will be directly exhausted. System 1 has a 2,000 cfm deficit of outdoor air and System 2 has a requirement for 2,000 more cfm of outdoor air than is exhausted from the areas it serves.

| System 1 Flow | | System 2 Flow | | Total Flow | | Comment |
|---|---|---|---|---|---|---|
| 10,000 | cfm | 10,000 | cfm | 20,000 | cfm | Supply flow (starting point for the return flow requirement) |
| (1,000) | cfm | (4,000) | cfm | (5,000) | cfm | Direct exhaust (to be subtracted from the return flow requirement in each system) |

| | | | |
|---|---|---|---|
| (2,000) cfm | 2,000 cfm | 0 cfm | Air transferred from System 2 zones to System 1 zones to provide make-up for direct exhaust from System 1 zones (to be subtracted from the return flow requirement in System 2; Offsets direct exhaust in System 1, increasing the return flow in that system) |
| 7,000 cfm | 8,000 cfm | 15,000 cfm | Resulting design return flow |

*Table A9-7 – Transfer Air from System 2 Zones to System 1 Zones; No Additional Outdoor Air (Figure A9-3 Option A)*

However, looking at the two systems holistically opens the door to some solutions to the imbalance problem. Figure A9-3 and Tables A9-7 and A9-8 illustrate some of the options.

Both options involve transferring air from System 2 to System 1 via transfer ducts or some other mechanism. The goal is to allow excess ventilation air (relative to the direct exhaust requirement) in System 2 to offset the deficit created by System 1's direct exhaust requirement relative to its ventilation requirement. Under Option A (tabulated in Table A9-7) no additional outdoor air is required and a neutral pressure relationship is crated relative to the outdoors.

Creating a positive pressure relationship relative to the outdoors requires that additional outdoor air be brought into the building. Option B, (tabulated in Table A9-8) is intended to pressurize each space with respect to the outside. By limiting the System 2 to System 1 air transfer to 1,500 cfm, 500 is available for pressurizing the portion of the building served by System 2. Increase System 1's minimum outdoor air flow by 1000 CFM, when combined with the transfer air from System 2, allows the direct exhaust in System 1's zones to be addressed while providing 500 additional cfm for pressurization purposes.

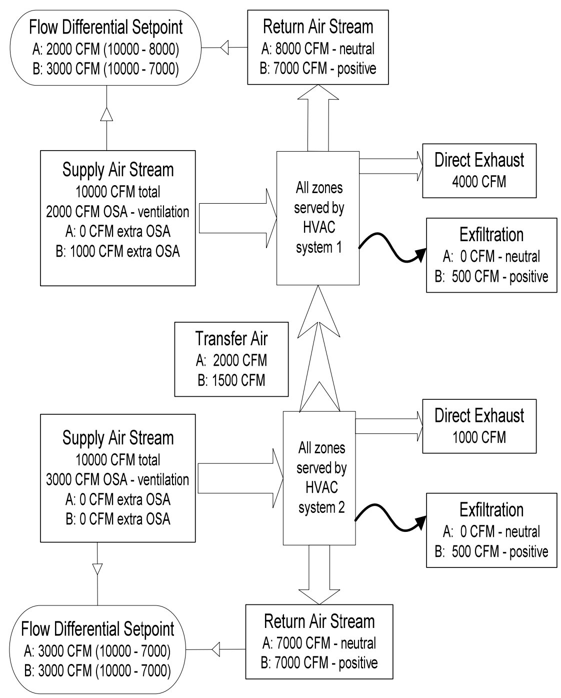



*Figure A9-3 – Multiple Air Handling Systems*

| System 1 Flow | System 2 Flow | Total Flow | Comment |
|---|---|---|---|
| 10,000 cfm | 10,000 cfm | 20,000 cfm | Supply flow (starting point for the return flow requirement) |
| (1,000) cfm | (4,000) cfm | (5,000) cfm | Direct exhaust (to be subtracted from the return flow requirement in each system) |

| | | | | | | |
|---|---|---|---|---|---|---|
| (1,500) | cfm | 1,500 | cfm | 0 | cfm | Air transferred from System 2 zones to System 1 zones to provide make-up for direct exhaust from System 1 zones (to be subtracted from the return flow requirement in System 2; Offsets direct exhaust in System 1, increasing the return flow in that system) |
| (500) | cfm | (500) | cfm | (1,000) | cfm | Remaining ventilation air is exfiltrated to provide positive pressurization (to be subtracted from the return flow requirement) |
| 7,000 | cfm | 7,000 | cfm | 14,000 | cfm | Resulting design return flow |

*Table A9-8 – Transfer Air from System 2 Zones to System 1 Zones but also Pressurize the Building Relative to the Outdoors (Figure A9-3 Option B)*

# Glossary of Terms

The following terms are defined to create a consistent context for understanding the topics in this guideline. They are listed in alphabetical order. Many of the fundamental concepts associated with return fan speed/capacity control can be understood simply by reading through these definitions.

In some instances, a more formal and detailed definition can be found in the handbooks, guidelines, standards, and other resources produced by organizations such as ASHRAE, ASTM, NFPA, AMCA, ARI, SMACNA and others.

*AMCA:*
Air Movement and Control Association

*ARI:*
American Refrigeration Institute

*ASHRAE:*
American Society of Heating, Refrigerating and Air-Conditioning Engineers

*ASD:*
Adjustable Speed Drive

*ASTM:*
American Society for Testing Materials

*Barometric Damper (also called a Gravity Damper):*
A damper whose actuation is dependent upon pressure differences acting in opposition to counter-balances. A true gravity damper utilizes no external actuating mechanism, although pneumatically or electrically powered actuators positioned in response to the output from a differential pressure controller can provide a similar function.

Dampers of this type are frequently used to:

- Relieve air brought into the building by an economizer cycle
- Control pressure relationships between adjacent areas
- Provide back draft protection at fan discharges and openings in the building envelope

*Building Pressurization:*
The introduction of sufficient outdoor air into the building envelope to ensure that the pressure in the building exceeds atmospheric pressure, thus minimizing infiltration. The operation of the return fan can have a direct impact on building pressurization.

*Constant Air Volume System:*
An air handling system wherein the supply flow remains constant or nearly constant for all operating conditions. This type of system typically will not require any form of speed or capacity control for the supply or return fans other than the initial setting of the sheaves by the balance contractor. Some constant volume systems are equipped with variable speed drives for balancing purposes, which while convenient, may waste energy due to the drive losses when contrasted with a sheave adjustment.

*DDC System:*
This acronym evolved from the terms Direct Digital Control System and Distributed Digital Control System, but in the industry jargon is now generally used to refer to any computer/software based control system utilizing a network of microprocessor based controllers, with electronic inputs and outputs. Other acronyms with similar or near similar meanings which are often used interchangeably with the term DDC include:

- BCS (Building Control System)
- BEMS (Building Energy Management System)
- BMS (Building Management System)
- EMS (Energy Management System)
- EMCS (Energy Management and Control System)
- ECS (Energy Control System)
- SCADA (Supervisory Control and Data Acquisition System)

Many of the preceding terms actually have very specific and non-equivalent definitions in a pure technical discussion.

*Dew Point ($t_{dp}$): –*
The temperature at which water will begin to condense out of an air sample if you were to cool it at constant pressure; i.e. the point at which dew will form. It is important to know this for the indoor and outdoor environment you are serving with your system because any surface at or below that temperature will accumulate condensation, which is usually undesirable, especially if it is inside a wall or ceiling cavity. If the air in your sample is at dew point, the dry-bulb temperature, wet-bulb temperature, and dew point are all numerically equal.

*Discharge Dampers:*
An approach to fan capacity control under which a damper in the fan outlet is used to throttle the fan. The approach is low cost, but it is also one of the least desirable in terms of efficiency and noise because at best, it forces the fan up its system curve, increasing the fan static pressure and moving the operating point away from the peak efficiency point and into potentially unstable operating regions. A damper located directly on the fan discharge also incurs a system effect penalty, further degrading performance.

*Economizer Cycle:*
An HVAC process under which outdoor air in excess of that required for ventilation is brought in by the air handling system for the purposes of eliminating or minimizing the mechanical cooling necessary to handle the load. Temperature control is achieved by mixing return air from the building with the outdoor air to achieve the desired mixed air or supply air temperature. In most cases, the process requires some sort of relief system to allow the excess air brought into the building to exit without creating a pressurization problem. The process must also be coordinated with the ventilation requirements to ensure that there is always enough outdoor air brought into the building to meet the ventilation requirements. In addition, the control of the process must be coordinated with the other heat transfer elements in the system like the preheat coil and cooling coil to prevent energy waste. A detailed discussion of economizers can be found in the Functional Testing Guide and the Energy Design Resources Design Brief, Economizers.

*Economizer Change-over Interlocks:*
Interlocks designed to disable the operation of the economizer when it no longer provides benefit in terms of a reduction in the energy required to cool the air handled by the system. The interlock system is designed to compare a parameter (typically outdoor air temperature or outdoor air enthalpy) to a set point or another parameter and return the economizer dampers to the minimum outdoor air position when economizer operation is no longer desirable. When conditions are again suitable for using outdoor air, the interlock allows the dampers to move from the minimum outdoor air position as necessary to satisfy the economizer process. In current technology systems, the interlock can be implemented in software or via discrete hardware elements.

*Exfiltration:*
Air that is expelled from a building through cracks and openings in the envelope by a positive pressure in the building relative to the atmosphere.

Generally, exfiltration is considered desirable as long as it is not excessive, especially in contrast to infiltration. If air is exfiltrated from the building, control of the building environment is maintained because only conditioned, treated air is introduced from the exterior to the interior. In addition to having a direct impact on IEQ, exfiltration can have an indirect impact in this area. In hot and humid environments, the indirect effect is related to the fact that exfiltration through cracks in the envelope construction minimizes the potential that humid outdoor air will be brought in through those cracks, leading to the potential for condensation and condensation related problems when the air comes into contact with surfaces cooled below its dewpoint by the operation of the buildings HVAC systems. The reverse is true in a cold environment with a humidified indoor environment. In this case, relatively humid indoor air exfiltrating through the envelope could lead to condensation issues when it comes into contact with surfaces cooled below its dewpoint by heat transfer to the cold ambient environment.

In cold environments, exfiltration also helps ensure that pipes will not be frozen due to exposure to jets of sub-freezing air infiltrating through cracks in the envelope. Exfiltration also tends to improve comfort on the perimeter zones in this situation since the occupants are not exposed to similar effects.

Exfiltration is related to building pressurization and stack effect. In addition, return fan operation can have a direct impact on exfiltration.

*Exhaust Air:*
Air that is removed from the building in direct relationship to its ventilation needs. Examples include toilet exhaust, elevator machine room exhaust, and lab hood exhaust.

*Exhaust Fan:*
A fan dedicated to the removal of exhaust air.

*Freezestat:*
A safety device used to protect water and steam coils that are not designed to deal with sub-freezing air from exposure to such by shutting down the air handling system and closing any outdoor air dampers. Manual reset is typically required and a hard wired installation is highly desirable. A detailed discussion of freezestats can be found in the Functional Testing Guide and the Energy Design Resources Design Brief, *Economizers*.

*Hard Coded:*
Programming where setpoints and other parameters are embedded in the code and therefore must be accessed by opening the program file if they are to be changed. This is in contrast to programming where variables are used for setpoints and other operational parameters in the programming code. This allows the operators to manipulate the program by simply changing the value of the variable rather than having to open and modify the program. Hard coded parameters are much more difficult (and potentially dangerous) to access and therefore tend to be persistent. They are best used for parameters that require infrequent modification once properly set or where uninformed modification could cause significant operating problems. Examples include limit settings and calculation constants. Variable parameters should be used for settings that will be frequently adjusted in the day to day operation of the building. In most current technology systems, access to these parameters can still be controlled by only allowing operators with high level passwords access to them.

*Hard Wired:*
A control device that can perform its function without any dependence on a computer or software based control strategy, thus is immune to computer failure or programming errors. It is highly recommended that all safety functions be hard wired functions.

*IAQ:*
Indoor Air Quality

*IEQ:*
Indoor Environmental Quality, of which IAQ is a component, also includes the impact of temperature, lighting, sound and other environmental issues.

*Incremental Air Volume System:*
An air handling system in which the flow rate varies in increments such as full flow, 50% flow, etc. This is often accomplished by using a multi-speed motor or by two position dampers in the distribution system coupled with a more conventional VSD/supply static control technique. The motors or dampers are typically controlled by schedules or other functions in the space served. These systems tend to be used either as a cost effective way to achieve VAV-like operation or where constant volume operation is required to ensure proper pressure relationships but where different zones on a large system have different use patterns. When applied, this type of system will require some method to match the return fan capacity to the supply fan capacity and the information in this guideline may be of value.

*Infiltration:*
Air that is drawn into a building through cracks and openings in the envelope by a negative pressure in the building relative to the atmosphere; essentially the opposite of exfiltration, discussed previously.

Like exfiltration, infiltration is related to building pressurization and stack effect. In addition, return fan operation can have a direct impact on infiltration.

*Inlet Guide Vanes:*
An approach to fan capacity control that modifies fan performance by changing the direction at which the incoming air enters the fan wheel, often referred to as changing the swirl." Movable vanes in the eye of the fan are positioned in unison to direct the air. By changing the angle at which the air enters the wheel, the velocity vectors associated with the wheel are changed and thus the performance changes. This performance change is often accomplished with a minimal degradation in efficiency and thus is more desirable than a discharge damper approach which throttles the fan rather than modifying the performance by affecting the physics occurring in the wheel. Ideally, a fan wheel should be designed to use matching inlet vanes tailored to its specific characteristics. But, it is common to apply off the shelf guide vane assemblies to off the shelf fans, sacrificing some performance for a first cost savings.

The vanes can require a significant amount of power to move, thus pneumatic actuation is preferred although electric actuation can also be accomplished on smaller installations. Although they are becoming less common, inlet vanes can still be found in new construction on smaller systems, where first cost factors make variable speed technology less attractive, or where the owner's maintenance staff can not support variable speed technology. They are also frequently encountered on existing systems where the designer may be forced to accommodate them in a retrofit because the budget will not support an upgrade to variable speed technology.

*Integrated Economizer Cycle:*
An economizer control process wherein the system is allowed to remain in 100% outdoor air mode[1] in conjunction with the operation of the mechanical cooling system as long as it will take less energy to cool the outdoor air stream when contrasted with the mixed condition that would be achieved with minimum outdoor air and return air.

*Figure G-1 – Inlet vanes in an existing fan undergoing repair (Courtesy: Portland Energy Conservation/Facility Dynamics Engineering)*

*Make-up Air:*
Air that is brought into the building by a fan system to replace air that is exhausted by a process like a kitchen exhaust hood or a lab hood. In some instances, it is simply included in the minimum outdoor air setting of the fan system serving the area. In other instances, it is addressed by a separate system dedicated to the function. The latter approach has the advantage of allowing operating economy to be achieved because the make up and exhaust processes can be cycled based on the function they serve independently from the comfort conditioning HVAC processes in the area. This is especially common in the case of kitchen hoods.

[1] 100% outdoor air operation will occur in a properly functioning economizer process when the outdoor air temperature is at or above the required supply air temperature.

*Minimum Outdoor Air:*
The outdoor air that must be brought into the system to handle the ventilation requirements of the building. This amount may vary with building use and the system operating conditions (either intentionally or unintentionally) or may be fixed any time the system is in operation (again, either intentionally or unintentionally). Maintaining the proper minimum outdoor air quantity is crucial in terms of ensuring proper indoor air quality, proper inter-space pressure relationships, and proper building pressurization. It is directly related to meeting code enforced ventilation requirements and may include make up air associated with various processes like kitchen hoods and lab hoods.

*NFPA:*
National Fire Protection Association

*Non-integrated Economizer Cycle:*
An economizer process where the economizer operation is terminated and mechanical cooling started when the outdoor temperature alone cannot provide the required supply temperature.

*Outdoor Air:*
Air from the local, ambient environment introduced into the building either intentionally by an HVAC process or unintentionally by infiltration and stack effect.

*Relief Air:*
Air which is expelled from the building having been brought in by an economizer cycle.

*Relief Fan:*
A fan which is applied in conjunction with an economizer cycle and located in the relief path from a building, not to be confused with a return fan. Return fans often function as relief fans during the economizer process, but a true relief fan will never function as a return fan. Relief fans are applied when the return path from the occupied zone to the air handling unit has an insignificant pressure drop (thus requiring no return fan) but the restrictions in the relief path to the building exterior would cause the building to become over-pressurized when the economizer cycle was operating on high percentages of outdoor air if no fan were provided. Without a relief fan, the supply fan must pressurize the occupied zone to a pressure that is high enough to overcome the relief path restrictions. If this pressure exceeds 0.10 – 0.15 inches w.c., a variety of problems can ensue, including a reduction in supply flow and doors that are blown open.

There may or may not be a correlation between the number of relief fans and the number of return fans. In some instances, one fan will be provided for each air handling system but in others such a correlation may not exist. There are advantages and disadvantages to both approaches that depend on a variety of factors including controllability and first cost.

The relief fan is selected and controlled to move the relief air through the relief path and maintain an acceptable level of building pressurization. The design capacity is related to the system flow rate on a 100% outdoor air cycle and the capacity requirement will vary directly with the percentage of outdoor air introduced into the building by the economizer cycle. It will also be influenced by other factors like stack effect, minimum outdoor air flow rate, building pressurization, and envelope integrity. This is in contrast to a return fan application, where the fan’s capacity is directly related to the supply flow associated with the system or systems it serves.

Control of relief fan operation is beyond the scope of this guideline, however, many of the principles associated with return fan capacity and speed control can be applied to relief fan capacity and speed control. Additional information on this topic can be found in the return fan definition below.

*Return Fan:*
A fan which is applied in an air handling system when the restrictions in the return air flow path from the occupied zone to the air handling unit would cause the building to become over-pressurized. Without a return fan, the supply fan must pressurize the occupied zone to a value that is high enough to overcome the return path restrictions. If this pressure exceeds 0.10 – 0.15 inches w.c., a variety of problems can ensue, including a reduction in supply flow and doors that are blown open.

For many air handling systems, the relief location is at the air handling unit location, thus the return fan also functions as a relief fan when the system is operating on an economizer cycle. But, unlike the relief fan the capacity required of the return fan is related directly to the current supply flow rate but is also influenced by factors such as the minimum outdoor air requirement, stack effect, building pressurization, and envelope integrity.

There may or may not be a correlation between the number of supply fans and the number of return fans in a building. In some instances, one fan will be provided for each air handling system but in others one fan may serve multiple units. There are advantages and disadvantages to both approaches that depend on a variety of factors including controllability and first cost.

*Safety Interlock:*
A control process designed to prevent building occupants or equipment from being harmed by undesired system operating conditions or events.

Interlocks provided for human safety are typically referred to as Life Safety interlocks and are usually highly regulated by building codes. Examples include interlocks with fire alarm systems, engineered smoke control cycles, and hazardous gas detection systems.

Interlocks provided to protect HVAC machinery are selected at the designer's discretion and are typically a function of the capabilities of the equipment, the local environment, and the system's failure modes. Examples include limit switches on dampers, freezestats, pressure relief doors, and static pressure limit switches.

Return fans frequently are protected by interlocks designed to prevent damage due to over-pressurization. They are also typically interlocked directly or indirectly with the life safety functions associated with the air handling system they serve. In engineered fire and smoke management or control systems, return fans may have a crucial roll to play with regard to exhausting smoke from a building or maintaining pressure relationships to control or manage the spread of fire and smoke.

*SMACNA:*
Sheet Metal and Air Conditioning Contractors National Association

*Stack Effect (Also termed Chimney Effect):*
The tendency of a tall building to act like a chimney or smoke stack. When the building is warmer than the ambient environment, the air in the building is less dense than the air outside at ground level. Thus, outdoor air tends to enter the building through cracks and open doors on the lower levels. This air then moves upward through the building via shafts and other vertical openings, and exits the building through cracks and openings in the upper levels. The flow pattern reverses during the summer months when the temperatures inside the building are cooler than the ambient environment. Return fan operation can have a direct impact on stack effect.

The flow rates associated with stack effect will be a function of a number of different variables including:

- Indoor/outdoor temperature difference
- Building height
- Envelope integrity, including unintentional leaks as well as openings like doors, windows, and intake and exhaust dampers/louvers
- Number and size of vertical shafts and their connection to each other and to building spaces
- Outdoor air flow rate
- Exhaust and relief flow rate
- Air handling system operation

It is also important to recognize that since air is flowing into the building at one level and out of the building at another level, there is a point at some level in the building where the pressure differential relative to the atmosphere is zero. There will be no flow into or out of the building at that level. This point is called the neutral pressure plane and its location will vary as a function of the parameters listed above.

*System Curve:*
For a given duct system operating at a given flow rate, there will be a specific resistance or pressure loss associated with moving the air through the duct system. If the flow rate changes, the resistance to flow will also change. For most systems, this relationship is approximately as follows:

$$P_2 = P_1 \times \left(\frac{Q_2}{Q_1}\right)^2$$

Where :

$Q_2$ and $Q_1$ = Flow at conditions 1 and 2

$P_1$ and $P_2$ = Static pressure at conditions 1 and 2

Frequently, this relationship is termed the square law since pressure varies with the square of the flow. A plot of this relationship is a parabola which is referred to as the system curve.

A fan's performance requirement is determined by plotting the intersection of the system curve with the fan's performance curve. Anything that is done to modify the system, e.g. a fitting is changed, a damper position is changed, a VAV terminal unit modulates, will alter the system and thus generate a new system curve. A VAV system actually operates on a family of system curves ranging from the curve associated with minimum flow to the curve associated with design flow.

*System Effect:*
The degradation of fan performance as the direct result of its interface with the duct system serving it. The test method used to rate fans assumes a fully developed uniform velocity profile at the fan outlet, which takes some finite length of duct to achieve. A similar assumption is made with regard to the inlet condition. If a duct fitting is placed in the system too close to the fan inlet or outlet, the uniform profile will be disrupted and the fan performance will be degraded. How much degradation occurs is a function of a number of factors including the characteristics of the fitting, the proximity to the fan and the geometry of the fitting relative to the fan discharge velocity profile. The loss in performance is termed system effect and is accounted for as if it were a static or total pressure loss when selecting the fan.

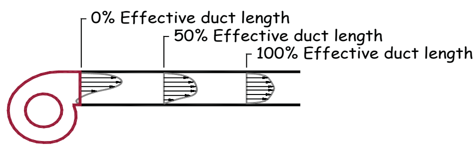



*Figure G-2 – Fan Discharge Velocity Profiles (Courtesy: ????)*

*Terminal Equipment:*
Equipment installed at the end of an HVAC system's supply distribution system to control zone environmental conditions. The most common are units that control the flow and or temperature of air supplied to the zone in response to the load. In some instances flow is also influenced by the zone pressure relationship to adjacent areas. VAV boxes, fan powered VAV boxes, and reheat coils are all examples of this type of equipment. In some instances terminal equipment can also include zone humidification and filtration equipment. This type of equipment is typically found in hospitals, labs, and process environments, but may also be found on occasion in commercial buildings like libraries or museums.

Equipment of this type is usually found on the supply side of the distribution system, but in situations where flow is varied and pressure relationships are critical, the flow regulation equipment may also be installed on the return side of the zone.

Return fan capacity and speed control is directly related to the performance of this equipment in situations where the terminal equipment varies airflow.

*Turn-down Ratio:*
The ratio of the minimum capacity at which a system is expected to operate to the peak capacity at which it is expected to operate. A VAV system with a design flow rate of 50,000 cfm which also needed to be able to operate at the 10,000 cfm level during periods of low occupancy would have a turn-down ratio of 1:5 or 20%. In general terms, systems with high turn down requirements will be more difficult to control over their entire operating range in contrast to systems with a low turn down requirement.

This is generally because many heat transfer and pressure characteristics can vary significantly with flow, often in a non-linear manner. In addition, many of the variables are interactive, compounding the effect. It is not uncommon for a system which has been commissioned and tuned to deliver satisfactory performance at a particular capacity level to become unstable when conditions change and drive it to a different operating point.

Return fan speed and capacity control strategies must deal directly with turn-down issues to operate satisfactorily. And the variable performance of the return fan can trigger turn-down issues in other portions of the system as its capacity changes in response to the control algorithm.

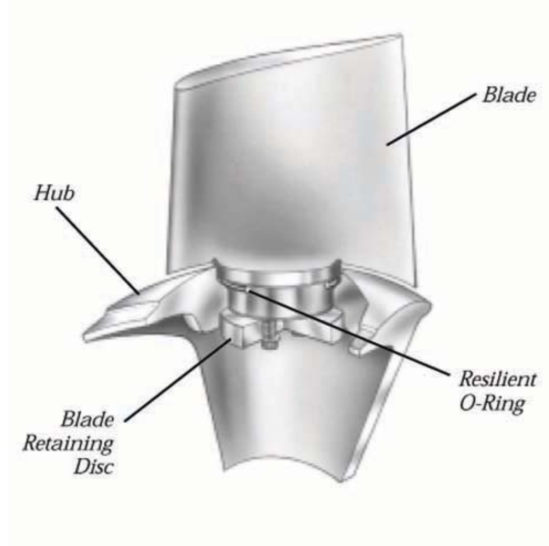
*Variable Air Volume System (Frequently termed VAV Systems):*
An air handling system wherein the supply flow varies as a function of some process requirement. Usually the driving requirement is cooling load, but systems where the volume varies as a function of the heating load or pressurization requirements can also be found.

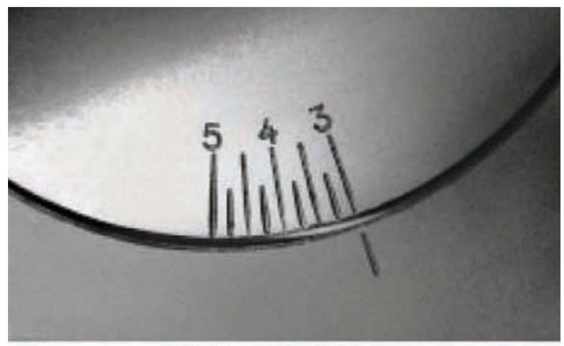
In load driven applications, varying the flow can have a major impact on the energy required to serve the process on several fronts.

- Fan energy is saved because the amount of air moved varies with the load. This is a powerful, non-linear relationship and all other things being equal, a 25% reduction in flow translates to a 58% reduction in fan horsepower. The need in most systems to maintain some fixed discharge pressure at the inlet to the terminal units detracts from this some, but there are still significant savings to be realized.
- Control energy is saved in most applications since the need for less capacity is matched by a reduction in available capacity. This is in contrast to constant volume system approaches like reheat, multizone, or double duct where the need for a reduction in capacity is addressed by imposing a false load on the system. For instance a constant volume reheat system operating at part load eliminates unnecessary cooling capacity by heating the supply air at the terminal location with a reheat coil.
- HVAC process energy is saved at the air handling system since the flow through the heat transfer equipment is reduced with load.

*VFD (also called an Inverter):*
Variable Frequency Drive; a variable speed drive technology that varies the speed of an alternating current (a.c.) motor by varying the frequency of the ac power applied to it. In general terms, the drive circuitry rectifies the incoming a.c. utility power into pulsed direct current (d.c.; hence the term inverter), modifies the frequency and voltage, then coverts the power back to a.c. for use by the motor. There are a variety of technologies used to accomplish the rectification and wave form modification.

*Variable Pitch:*
A method of fan capacity control commonly applied to axial fans. Under this approach, the pitch of the blades is varied, which changes the angle of attack of the blade (the angle between the blade and the air stream velocity vector) and thus, the performance of the fan. The blade pitch variation can be purely manual; i.e. accomplished only by hand when the fan is not operating. Or, it can be automatic, allowing the capacity of the fan to be varied while in operation. In most instances, the mechanisms used to accomplish this are complex and require significant attention to ensure reliable performance. They also require a lot of power to actuate and thus, a source of pneumatic air is typically required when this technology is employed.




Blade set at 30° angle

Blade angle adjustment tool

*Figure G-3 – Manually adjustable blades in a vane axial fan (Courtesy: Twin City Fan)*

*Variable Speed Drive:*
Any technology used to vary the speed of a motor. VFDs are one form of variable speed drive, but not all variable speed drives are VFDs, even though in the industry, the terms tend to be used interchangeably. There are a surprising number of approaches to varying motor speed ranging from mechanical systems to synchronous motors to clutches. Many of these are limited to industrial sites and process control applications where the power requirements, first costs, and maintenance issues can be handled and justified. Non-VFD variable speed technologies which may be encountered in commercial HVAC systems include:

- *Eddy Current Clutches:* This technology uses a motor driving a rotor that is equipped with a variable magnetic field. The rotor spins around an armature, which is connected to the output shaft. By varying the strength of the magnetic field, the slip between the rotor and armature is varied and thus the output speed. The technology is much less efficient than current technology VFDs, but represented a more cost effective approach to achieving a variable speed output 15 to 20 years ago. Because brushes were used to transmit power to the rotor, the technology tended to be maintenance intensive in contrast to VFD technology.
- *Mechanical Clutches:* There was a period of time when the VAV system approach was evolving as a practical technology, (driven primarily by the need to save energy) but when the cost of electrically varying motor speed using a VFD was very cost prohibitive, perhaps by a factor of 5 to 10 relative to today's market. During that time a mechanical variable speed technology was employed in some systems that varied the speed of the output shaft by varying the pitch of one of the drive pulleys. In fact, the approach was often termed a pulley pincher because of how it worked. The approach was not very efficient and prone to maintenance problems and thus quickly faded from the market as other variable speed technologies evolved and became more cost effective.

The reduction in cost that has occurred for VFDs in the past 10 to 15 years make them the technology of choice in the current market. However, the older technologies can still be encountered on existing installations where a designer, faced with a retrofit and a tight budget may have to make do with what is there.

*Ventilation Air:*
Air that is introduced into the building for the purposes of diluting pollutants from occupants, building materials, or processes. In most cases the ventilation rate will be controlled by code requirements and is reflected in the minimum outdoor air and make up air settings of the building's air handling equipment. In turn, many codes reference a version of ASHRAE Standard 62 for most occupancies and various NFPA codes for certain hazardous occupancies including transformer vaults, chemical storage rooms and various process environments.

# References


Boyanton, Hugh. (n.d.). “Electrical Discharge Machining Of Bearings.” Shaft Grounding Systems, Inc. www.shaftgroundingsystems.com

Brennan, Terry M. (1999, July). “Measurements to Solve IAQ Problems.” *Heating, Piping and Air Conditioning (HPAC).*

Brennan, Terry M. (1999, Spring). Indoor Air Quality Primer. *Heating, Piping and Air Conditioning (HPAC) Ventilation Guide.*

Dougan, David S. (2004, January). “Airflow Measurement for HVAC Systems; Technology Comparison.” *Automated Buildings*.

Elovitz, David. (1995). “Minimum Outside Air Control Methods for VAV Systems.” *ASHRAE Transactions*, SD-95-2-1.

Fuhr, Bob. (n.d.) “An Introduction to Power System Harmonics.” *Power Systems Engineerin*g, www.powerstudies.com

Felker, Larry. (2002, April). “Minimum Outside Air Damper Control.” *ASHRAE Journal*.

Greenheck Fan Corporation. (n.d.). “Motor Starting Torque.” *Engineering Bulletin*. www.greenheck.com.

Houdek, John A. (n.d.). Load Reactors Increase VFD System Performance & Reliability. MTE Corporation. www.mtecorp.com

Jackson, Stewart and Liggett, F. (2002, July). “How to Match Motors to Variable Speed Drives.” *Plant Engineering*. http://www.reliance.com/pdf/misc/225412.pdf

Joliet Technologies. (n.d.). “Adjustable Speed Drives: What are they? How do they work?” *Application Information*. http://www.joliettech.com/adjustable_speed_drives-application_information.htm

Kettler, John. (1995). “Minimum Ventilation Control for VAV Systems: Fan Tracking vs. Workable Solutions.” *ASHRAE Transactions, SD-95-2-3.*

Kettler, John. (1998, May). “Controlling Minimum Ventilation Volume in VAV Systems.” *ASHRAE Journal.*

Kettler, John. (2004). “Return Fans or Relief Fans: How to Choose?” *ASHRAE Journal.*

Klaassen, Curtis, House, John. (2001, March). “Equal Area vs. Log-Tchebycheff.” *Heating, Piping and Air Conditioning*

MacFerran, Ernest. (1999, December). “Equal Area vs. Log-Tchebycheff.” *Heating, Piping and Air Conditioning*

Puttgen, Hans. B. (1991, December). “Adjustable Speed Drives Directory - Third Edition.” CU-7544, Research Projects 2951-9 and 2951-12. Georgia Institute of Technology, School of Electrical Engineering, Published by Electric Power Research Institute www.epri.com

Rosenberg, Michael. (2004). “Building Pressurization Control.” *Proceedings of the 12th National Conference on Building Commissioning.*

Schell, Mike and Dan Int-Hout (2001, February). “Demand Control Ventilation Using CO2.” *ASHRAE Journal.*

Schell, Mike. (2002). “Real Time Ventilation Control.” *HPAC*.

Seem, John E., House, J. Klaassen, C. (1998, February). “Leave the Outdoor Air Damper Wide Open.” *ASHRAE Journal*.

Sellers, David, Williams, J. (2000) “A Comparison of the Ventilation Rates Established by Three Common Building Codes in Relationship to Actual Occupancy Levels and the Impact of these Rates on Building Energy Consumption.” *ACEEE 2000 Summer Study Proceedings.*

Sellers, David, Friedman, H., Luskay, L., Haasl, T., Moore, E. (2004a). “Commissioning and Envelope Leakage: Using HVAC Operating Strategies to Meet Design and Construction Challenges.” *Proceedings of the 2004 ACEEE Summer Study on Building Efficiency*.

Sellers, David, Friedman, H., Luskay, L., Haasl, T., Moore, E. (2004b). “A Test Procedure for Assessing Envelope Leakage in Commercial Buildings: The Issues, the Process and the Results.” *Proceedings of the 12th National Conference on Building Commissioning*.

Smith, R.B. (1990). “Importance of Flow Transmitter Selection in Return Fan Control of VAV Systems.” *ASHRAE Transactions,* T-90-17-4.

Stanke (2002). “Managing the Ins and Outs of Commercial Building Pressurization.”

Stebbins, Wayne. (2000). “Adjustable Speed Drive Selection and Application.” *Energy User News - Fundamental Series Item.* http://www.energyusernews.com/CDA/Article_Information/Fundamentals_Item/0,2637,8170,00.html

Stone, G.C., Campbell, S.R., Seddirw, H.G. (1999). “Adjustable Speed Drive Surges: How They Affect Motor Stator Windings.” *IEEE Transactions*, Paper 0-7803-5293-9/99.

“Coping with Air Pressure Problems in Tall Buildings.” Trane Engineering News Letter,

Taylor, Steven. (2000, September). “Comparing Economizer Relief Systems.” *ASHRAE Journal.*

## Additional Web Resources

ASHRAE Guideline 16 – www.ashrae.org

ASHRAE Standard 62-2004 – www.ashrae.org

Energy Design Resources Briefs – The two briefs mentioned specifically in this guideline are:

*Economizers* – http://www.energydesignresources.com/resource/28/

*Design Review* – http://www.energydesignresources.com/resource/26/

However, the Energy Design Resources Web contains a wealth of information related to HVAC design, including topics on VAV systems and Drives that can provide valuable references for other aspects of projects where return fan capacity control is applied.

Functional Testing Guide – http://www.peci.org/ftguide/ under the Testing Guide: Fundamentals to the Field topic.

Control System Design Guide – http://www.peci.org/ftguide/ under the Control System Design Guide topic.

The Adjustable Speed Drives Directory – www.epri.com