Fan Heat and Pump Heat:

Sources and Significance

How these two thermodynamic phenomena—long thought to be similar—occur quite differently in air and hydronic systems

Editor's note: This is Part 1 of a two-part series. See Page 5 for the story behind the article.

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Coming out of college, most engineers in the HVAC field have a strong basic understanding of the principles of thermodynamics, fluid mechanics, and heat transfer. In the years that follow, however, that understanding tends to give way to an increasing reliance on rules of thumb, code requirements, and computerized calculations. This is understandable, considering the pressures of designing, installing, and making operational complex systems on tight schedules. But in some cases, engineers must be able to fall back on fundamentals to understand a problem. Certainly, that is the case with fan heat and the seemingly similar concept of pump heat.

In air-handling systems, fan heat—energy imparted by supply and return fans—causes airstream temperature to rise, compromising energy efficiency and system performance. Misconceptions of the nature of this temperature rise abound in the design community. Pump heat is even less recognized and understood.

This article will discuss the source and significance of fan heat and pump heat.

FAN HEAT AND PUMP HEAT DEFINED

Fan heat and pump heat originally were defined in terms of their effect on cooling load. In their landmark textbook on HVAC systems,[1] Willis H. Carrier, Realto E. Cherne, Walter A. Grant, and William A. Roberts said of fan heat: "The fan horsepower used in moving air results in heat that becomes part of the room sensible load, provided the fan is on the leaving-air side of the conditioner. If the fan is on the entering-air side, the fan heat becomes part of the refrigeration load, but not of the room sensible heat." Of pump heat, they observed, "The power of the chilled-water circulating pump is a heat gain similar to that of the fan, but is added to the total heat since it affects only the refrigerating load."

The concepts of fan heat and pump heat revolve around energy input being converted to heat and appearing as heat gain in circulating fluid systems. It is interesting to note that neither the current editions of the ASHRAE handbooks nor the companion volume on terminology[2] define these terms.

JOULE'S EXPERIMENTS

As a junior engineer working for a consulting engineering firm in 1975, I sought to determine why a design discharge temperature of 55 F could not be achieved on the leaving-air side of one of a high-rise office building's largest air-handling units—a high-pressure draw-through unit with filters, heating coil, cooling coil, and supply fan providing conditioned air for a two-pipe induction-unit system with induction terminals in perimeter offices. As I measured temperature and flow, the

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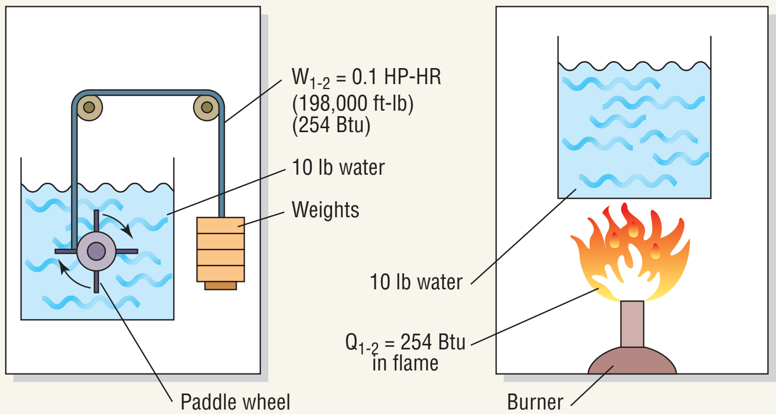
facility's chief engineer claimed he knew the source of the problem: high-pressure drops occurring across dirty filters and clogged preheat coils. Because of the friction taking place, he reasoned, the pressure drops were causing air to heat up on its

Nomenclature

$Q_{1\text{-}2}$	Heat added to a system (fluid) between conditions 1 and 2 (British thermal units per pound or British thermal units)
$U, \Delta U$	Internal energy or change in internal energy in a process (British thermal units per pound or British thermal units)
$W_{1\text{-}2}$	Work done by a system between states or locations 1 and 2 (foot-pounds per pound or foot-pounds)
J	Mechanical equivalent of heat (778.2 ft-lb per British thermal unit)
$T, \Delta T$	Fluid temperature or temperature change in a process (degrees Fahrenheit or degrees Rankine)
C_p	Specific heat capacity at constant pressure (British thermal units per pound, degrees Rankine)
C_v	Specific heat capacity at constant volume (British thermal units per pound, degrees Rankine)
m	Mass of fluid (pounds)
V	Volume (cubic feet)
P	Fluid pressure (pounds per square foot)
ρ	Fluid density (pounds per cubic foot)
v	Fluid specific volume (cubic feet per pound)
Z	Elevation of fluid above a datum plane (feet)
V	Fluid velocity (feet per second)
g	Acceleration of gravity (32.2 ft per second squared)
$h, \Delta h$	Fluid enthalpy or enthalpy change (British thermal units per pound or British thermal units)
k	Ratio of specific heat capacities ($C_p \div C_v$) (dimensionless)
$S, \Delta S$	Fluid entropy or change in fluid entropy (British thermal units per pound, degrees Rankine)
R	Gas constant (for air, 53.3 ft-lb per pound, degrees Rankine)
hp	Horsepower (33,000 ft-lb per minute)
cfm	Volumetric airflow (cubic feet per minute)
$TP, \Delta TP$	Total pressure or rise in total pressure (inches water gauge)
η_f	Fan efficiency (dimensionless)
ΔP	Head loss in water stream (feet) or air stream (inches water gauge)
bhp	Actual shaft horsepower input to a process
Hd	Head across a pump (feet)
η_p	Pump efficiency (dimensionless)
Q	Volumetric flow rate (gallons per minute)

For water, C_v = 1.0 Btu per lb-deg F



(a) Work added

$$Q_{1\text{-}2} = \Delta U + \frac{W_{1\text{-}2}}{J}$$

With no external heat loss or gain,

$$Q_{1\text{-}2} = 0$$

$$\Delta U = \frac{-W_{1\text{-}2}}{J}$$

$$mC_v\Delta T = \frac{-W_{1\text{-}2}}{J}$$

$$\Delta T = \frac{-W_{1\text{-}2}}{mC_vJ}$$

Because work done on a system is negative,

$$\Delta T = \frac{(198{,}000)}{(10)(1.0)(778.2)}$$

$$\Delta T = 25.4 \text{ F}$$

(b) Heat added

With no external work, $W_{1\text{-}2} = 0$

$$Q_{1\text{-}2} = \Delta U + \frac{W_{1\text{-}2}}{J}$$

$$\Delta U = Q_{1\text{-}2}$$

$$mC_v\Delta T = Q_{1\text{-}2}$$

$$\Delta T = \frac{Q_{1\text{-}2}}{mC_v}$$

$$\Delta T = \frac{(254)}{(10)(1.0)}$$

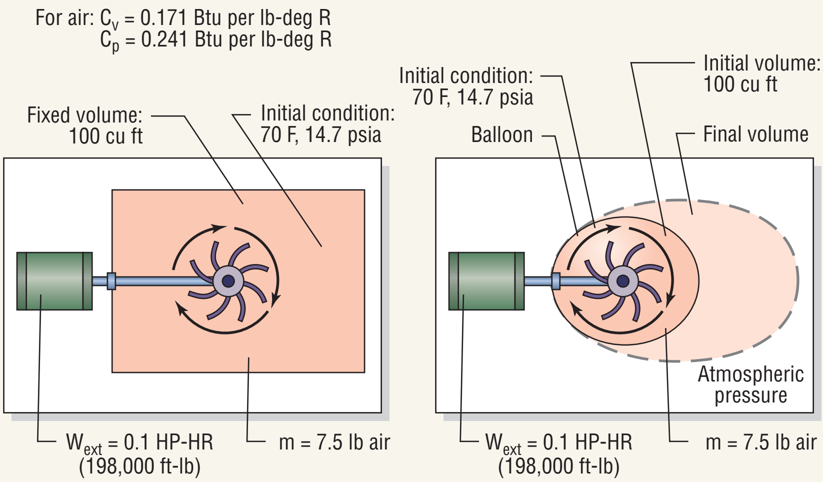
$$\Delta T = 25.4 \text{ F}$$

FIGURE 1. Joule's experiment—the mechanical equivalent of heat.

way through the devices, thus raising the supply-air temperature. In the years since, a number of papers and articles espousing the idea that pressure drop causes heat gain in air-duct systems have appeared in technical journals. This article will show that, in reality, heat does not appear at the point of pressure drop in an air-duct system. It does, however, appear at that point in a hydronic system.

The confusion has much to do with the basic concept that friction generates heat. In about 1840, James Prescott Joule conducted a series of experiments to identify the relationship between mechanical energy (work) and heat energy, the most famous of which is depicted in Figure 1(a).[3] In this experiment, Joule used falling weights to turn a paddle in a container of water. The resulting friction heated the water. By measuring the temperature change, Joule determined the heat supplied to the water. He knew the height to which the weight had been raised and, therefore, the work (or energy) in foot-pounds that had been imparted to the water. From his painstaking experiments, Joule derived a value for the mechanical equivalent of heat, *J*, of 772.5 ft-lb per British thermal unit, which is within 1 percent of the currently accepted value of 778.2 ft-lb per British thermal unit.

Joule's experiment clearly illustrates the First Law of Thermodynamics: When energy is transferred across the



(a) Constant volume **(b) Constant pressure**

For each container control volume, the mechanical-equivalent-of-heat concept in Figure 1 indicates:

(a)

$$Q_{1\text{-}2} = \frac{W_{ext}}{J} = \frac{198{,}000}{778.2} = 254 \text{ Btu}$$

Because no work is done by the control volume, $W_{1\text{-}2} = 0$

$$Q_{1\text{-}2} = \Delta U + W_{1\text{-}2}$$

$$Q_{1\text{-}2} = \Delta U$$

$$Q_{1\text{-}2} = mC_v\,(T_2 - T_1)$$

$$T_2 = T_1 + \frac{Q_{1\text{-}2}}{mC_v}$$

$$T_2 = 530 + \frac{254}{(7.5)(0.171)}$$

$$T_2 = 728 \text{ R} = 268 \text{ F}$$

$$\frac{P_2}{P_1} = \frac{T_2}{T_1} \text{ (volume constant)}$$

$$P_2 = \frac{(14.7)(728)}{530} = 20.2 \text{ psia}$$

(b)

$$Q_{1\text{-}2} = \Delta U + \frac{W_{1\text{-}2}}{J} \qquad Q_{1\text{-}2} = \Delta U + {}_1\!\int^2 \frac{pdv}{J}$$

$$Q_{1\text{-}2} = (U_2 - U_1) + \frac{P_2v_2}{J} - \frac{P_1v_1}{J}$$

$$h = U + \frac{Pv}{J}$$

$$Q_{1\text{-}2} = h_2 - h_1$$

$$Q_{1\text{-}2} = mC_p(T_2 - T_1) \qquad T_2 = T_1 + \frac{Q_{1\text{-}2}}{mC_p}$$

$$T_2 = 530 + \frac{254}{(7.5)(0.241)}$$

$$T_2 = 670 \text{ R} = 210 \text{ F}$$

$$\frac{V_2}{V_1} = \frac{T_2}{T_1} \text{ (pressure constant)}$$

$$V_2 = \frac{(100)(670)}{530} = 126 \text{ cu ft}$$

FIGURE 2. Joule's experiment using air.

boundaries of a system, the energy of the system changes by a like amount. The increase in energy is equal to the decrease in energy of its surroundings. Stated in equation form:

$$Q_{1\text{-}2} = \Delta U + \frac{W_{1\text{-}2}}{J} \qquad (1)$$

Stated in words, the heat transferred to a system from State 1 to State 2 during a process is equal to a change in internal energy from initial to final conditions, plus the work done by the system during the process.

Whether work is done on a liquid, with friction occurring between the liquid and the paddle wheel, or a liquid is heated directly by a flame of equal energy, the result of the temperature rise is the same. In Figure 1(a) and Figure 1(b), however, the experiment was performed with an incompressible liquid—water—with the only boundary condition being atmospheric pressure. This experiment cannot be duplicated easily with a compressible gas without setting other limiting conditions, as can be seen in Figure 2(a) and Figure 2(b).

In Figure 2, work was done on the air in each vessel, with the equivalent effect of adding heat. In Figure 2(a), volume was held constant, while the mechanical energy and resulting heat input increased the temperature and pressure of the air, with no work done by the air. In Figure 2(b), pressure was held constant, with the heat input causing an increase in volume, as well as temperature—although the increase in temperature was smaller than in the constant-volume case. While heating a gas at constant volume merely increases the internal energy (because no work is being done by the gas), heating at constant pressure is accompanied by expansion and, thus, conversion of part of the heat supplied to the gas into mechanical work. The heat supply must cover this work, in addition to the increase in internal energy. Under these conditions, more heat must be supplied for every degree of temperature rise than in the case of heating at constant volume. In other words, the specific heat at constant pressure, C_p, is larger than the specific heat at constant volume, C_v.

These examples show that the addition of mechanical work to a gas can have several outcomes, depending on the constraints imposed by the system. Though the assumption of incompressibility may be reasonable for ideal gases in normal HVAC applications, air still will behave as a gas in all processes and follow all of the thermodynamic relationships of gases. To analyze the effects of work on an air system, as well as work's relationship to frictional effects, all of the properties of air as a gas, including its compressibility, must be considered.

DUCT-SYSTEM FRICTION LOSS

Air is known to lose pressure as it passes through a duct system. Losses in pressure are characterized as either frictional, meaning they relate to fluid viscosity and the roughness of confining duct walls, or dynamic, meaning they relate to stream turbulence and eddying flow created by turns or obstructions in ductwork. For simplicity, and because they fundamentally relate to the viscous effects of turbulence in a fluid, all losses in this discussion will be termed "frictional." To examine friction loss effectively, one must know the levels of energy throughout a system. For this, the steady-flow energy equation and concept of throttling process are useful.

Obtained from the First Law of Thermodynamics, which considers both mechanical and thermal energy, the steady-flow energy equation states that the amount of heat added to a fluid as it passes through a system is equal to the change in energy content of the fluid, plus any work done by the fluid. Valid for compressible and incompressible fluids both with and without frictional effects, it is stated per pound of fluid flowing in a system as follows[4]:

$$\frac{W_{1\text{-}2}}{J} + Q_{1\text{-}2} + \frac{P_1 v_1}{J} + \frac{Z_1}{J} + U_1 + \frac{V_1^2}{2gJ} = \frac{P_2 v_2}{J} + \frac{Z_2}{J} + U_2 + \frac{V_2^2}{2gJ} \quad (2)$$

Assuming system elevation does not change and using the property of fluid enthalpy, h, namely

$$h = U + \frac{Pv}{J} \quad (3)$$

the steady-flow energy equation can be restated as follows:

$$\frac{W_{1\text{-}2}}{J} + Q_{1\text{-}2} + h_1 + \frac{V_1^2}{2gJ} = h_2 + \frac{V_2^2}{2gJ} \quad (4)$$

It should be noted that the steady-flow energy equation contains no specific term for friction loss. This is because fluid friction transforms the kinetic energy of eddies into thermal energy and, therefore, is represented by changes in the other terms of the equation.

In basic thermodynamics, the concept of throttling process is introduced. Flowing fluids suffer an abrupt loss of pressure when passing through restricted openings, such as valves, or similar obstacles in a flow path. A more gradual loss of pressure is experienced by fluids flowing in constant-area ducts that are straight or gradually change direction. The flow through a restricted opening is, by definition, a throttling process. However, because duct-wall friction and turbulence produce pressure loss by a similar effect, flow in a duct may be treated as a throttling process.

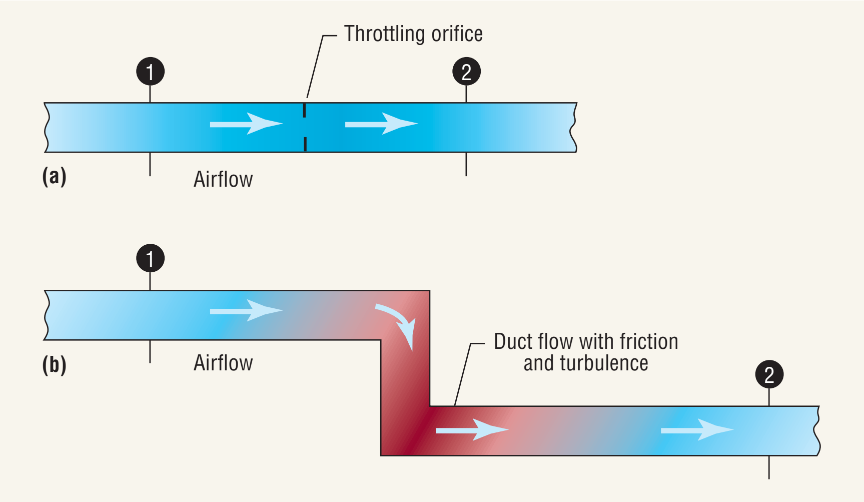


FIGURE 3. Throttling processes.

Figure 3(a) illustrates a classic throttling process: an air stream passing a restriction in a duct. Figure 3(b) shows flow in a long section of duct with a frictional pressure drop. Application of the steady-flow energy equation (Equation 4) to Figure 3(a), with no external heat transfer ($Q_{1\text{-}2} = 0$) and no shaft work ($W_{1\text{-}2} \div J = 0$), equates to:

$$h_1 + \frac{V_1^2}{2gJ} = h_2 + \frac{V_2^2}{2gJ} \quad (5)$$

If the velocities at stations 1 and 2 in Figure 3 are equal, the enthalpies in and out of the process will be equal.

Frictional effects and resulting pressure drops do not raise the temperature of air streams. In constant-area duct systems, they actually lower it slightly.

With enthalpy change for a perfect gas given by the equation

$$\Delta h = C_p \Delta T \quad (6)$$

it follows that temperature for a constant-enthalpy process remains constant. For flow with friction in a throttling process, enthalpy remains constant, as does the temperature of air as frictional effects occur.

For the duct system shown in Figure 3, the constant-enthalpy assumption is not quite correct, as system pressure drop causes a change in the specific volume of the air. With the density of the air reduced at lower pressure, downstream velocity increases slightly. Referring to Equation 5 and Figure 3(b), with a 0.5-psi drop in pressure in the duct run (13.9-in.-wg ΔP), the temperature of the air stream drops slightly. Temperature drop is calculated with the following equation:

$$h_1 - h_2 = \frac{1}{2gJ}\left(V_2^2 - V_1^2\right) \quad (7)$$

Substituting from Equation 6:

$$C_p\left(T_1 - T_2\right) = \frac{1}{2gJ}\left(V_2^2 - V_1^2\right) \quad (8)$$

Therefore:

$$T_2 = T_1 - \frac{1}{2gJC_p}\left(V_2^2 - V_1^2\right) \quad (9)$$

This temperature drop, attributed to a 0.5-psi pressure drop (very large for a conventional HVAC air system), is less than 0.02 F. Even this more rigorous examination supports temperature remaining constant or even decreasing slightly in an air duct flowing with friction.

Although enthalpy may not change as air passes through a duct system, friction certainly can change the outcome of a process. If a 0.5-psi pressure drop were to occur in an adiabatic reversible (frictionless) process, the final temperature at Station 2 in Figure 3(b) could be calculated with the polytropic-process equation[5]:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \quad (10)$$

Assuming an initial air temperature of 75 F, atmospheric pressure at Station 2, and a ratio of specific heat capacities of 1.4 for air:

$$T_2 = \left(460 + 75\right)\left(\frac{14.7}{15.2}\right)^{\frac{1.4-1}{1.4}} = 530\ R = 70\ F$$

Restated, if a process with 0.5-psi pressure loss occurred reversibly (without friction) in the duct section of Figure 3(b), air-stream temperature would drop 5 F. When a test was performed, however, air-stream temperature remained the same. This was a result of the thermodynamic property of entropy, a measure of the unavailable energy in a closed thermodynamic system. The mechanical energy lost because of friction within the duct was converted to heat, which was absorbed by the gas in the process. The gas, then, lost mechanical energy, but received an equivalent amount of thermal energy or heat. This represents what usually is termed the Second Law of Thermodynamics: In essence, an increase in entropy in a duct air stream provides the heat necessary to offset the drop in temperature of a gas.[6]

Figure 4 is a temperature-entropy diagram showing ideal and actual flow processes. Changes in entropy vary with changes in the ratio of increment of heat taken in during a process to absolute temperature at which heat is absorbed. When a real fluid passes through a pipe or duct, internal entropy increases. The mechanical energy lost because of friction is converted to heat and added to the internal energy of the gas. Figure 4 (Point 1 to Point 2) depicts the throttling process for an air-duct system flowing with friction for a pressure drop from P_1 to P_2. This constant-enthalpy process occurs at a constant temperature ($T_1 = T_2$), but with an increase in entropy:

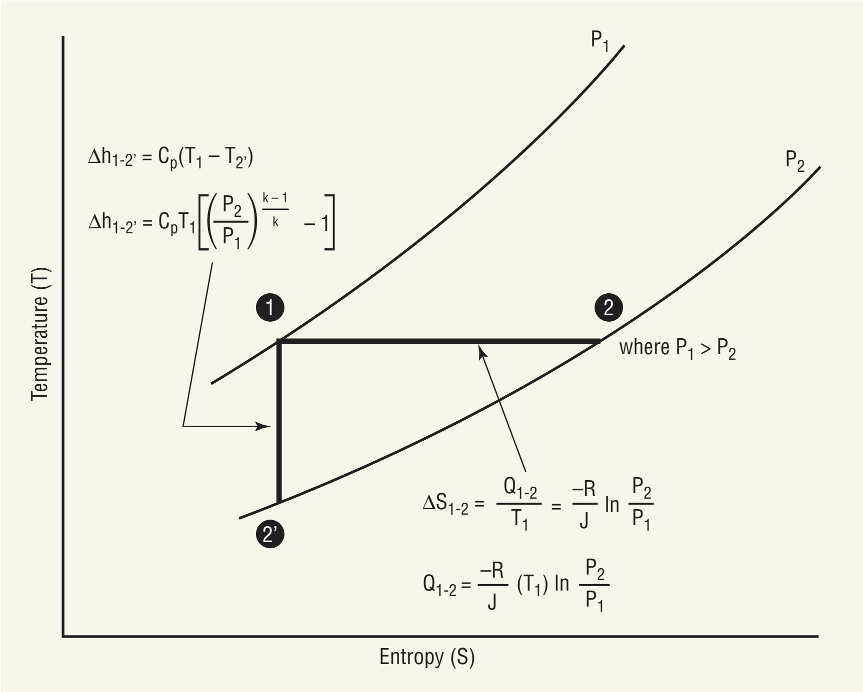


FIGURE 4. Temperature-entropy diagram showing ideal and actual flow processes.

$$\Delta S_{1-2} = \frac{Q_{1-2}}{T_1} = -\frac{R}{J} ln \frac{P_2}{P_1} \quad (11)$$

Therefore:

$$Q_{1-2} = -\frac{RT_1}{J} ln \frac{P_2}{P_1} \quad (12)$$

This addition of heat occurs internally as a result of frictional dissipation of mechanical energy. The process could be compared to the following fictitious cycle: First, air undergoes an adiabatic, reversible change, dropping in pressure and temperature (Point 1 to Point 2'). During this process, enthalpy also drops. Next, the mechanical energy lost to friction is converted to heat at the lower pressure and added to the internal energy of the gas, causing a return to the initial temperature and a rise in enthalpy equal to, but of the opposite sign of, the change in heat content of the first process (Point 2' to Point 2). Thus, the constant-enthalpy, constant-temperature process of air flowing in a duct with friction can be characterized as an adiabatic, reversible pressure drop followed by the addition of frictional heat for a return to the original temperature and enthalpy condition. This can be demonstrated by verifying that for the range of temperatures and pressures encountered in HVAC-system design, the enthalpy loss for adiabatic, reversible expansion (based on pressures utilizing the polytropic-gas equation),

$$\Delta h_{1-2'} = C_p T_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right] \quad (13)$$

is roughly equal to the heat rise attributed to the increase in entropy from the frictional process (Equation 12).

SUMMARY

Frictional effects and resulting pressure drops—whether they occur because of duct lining, duct elbows, turning vanes, or dirty filters—do not raise the temperature of air streams. In constant-area duct systems, they actually lower it slightly. Further, total pressure decreases at every location along the airflow path in a duct system except that of the fan. The fan is where total pressure increases. Next month, Part 2 of this article will discuss the thermodynamic characteristics of the fan, where actual energy input occurs, and where air-temperature rise is experienced. Lastly, it will examine pump heat and discuss both its significance and that of fan heat in HVAC-system design.

Total pressure decreases at every location along the airflow path in a duct system except that of the fan. The fan is where total pressure increases.

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