National Building Controls Information Program

Product Testing Report

Duct - Mounted Relative Humidity Transmitters

April 2004

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Program Sponsors

Iowa Energy Center
NSTAR Electric and Gas Corporation
U.S. Environmental Protection Agency

Introduction

Humidity transmitters are common components in building control systems and their performance can significantly impact energy use in heating, ventilating, and air-conditioning (HVAC) systems. In particular, relative humidity transmitters are used to monitor supply and return air conditions from air handling units, monitor conditions in occupied spaces, and control humidification and dehumidification processes as well as economizer cycles. In the case of economizers, relative humidity and temperature measurements of outdoor and return air conditions are used to calculate the enthalpies of the two air streams. The air stream with the least energy content is then selected to provide building cooling. If one or both of the computed enthalpies is wrong, as can happen when humidity transmitters are not accurate, significant energy penalties can result from cooling of the incorrect air stream.

Growing concern about indoor environmental quality issues, including mold, mildew and moisture problems also emphasize the need for accurate humidity sensing devices. In many cases, humidity control is the primary means of system control in laboratories, humidity sensitive spaces, museums, and computer rooms. The consequences of poor humidity transmitter performance in these applications can outweigh energy concerns and result in costly damage.

Because of their impact on energy use and the quality of the indoor environment, the National Building Controls Information Program (NBCIP) tested and evaluated the performance of resistive and capacitive duct-mounted relative humidity transmitters used in typical building HVAC applications. NBCIP developed an experimental procedure for testing the humidity transmitters, and used this procedure to test products from six leading manufacturers.

This NBCIP Product Testing Report provides an overview of factors to consider when purchasing a humidity transmitter, presents manufacturer data for transmitters selected for testing, describes the test procedure and test apparatus used by NBCIP to evaluate transmitter performance, and presents test results for accuracy, repeatability, linearity, and hysteresis for each humidity transmitter model tested.

Throughout this report, the humidity sensing element is referred to as the sensor. A humidity transmitter is a device that consists of a sensor as well as a transducer that converts the sensor reading into an output signal. ■

Classification of Humidity Sensors

The selection of the most appropriate humidity sensor for a particular application requires knowledge of the parameter to be measured, how the sensor works, and its operating characteristics.

How Humidity is Measured

Water vapor in air or any other gas is termed humidity, while water content in liquids and solids is usually designated as moisture. Different approaches to measuring humidity are based on quantifying different physical properties of the mixture of water vapor and air, which is referred to as moist air. Humidity can be expressed in a variety of forms with the most common forms being percent relative humidity (RH), specific humidity, absolute humidity, dew point and vapor pressure. Refer to the side bar *Measuring Humidity* for a description of each of these parameters.

Types of Sensors

The most widely used humidity transmitters in HVAC control applications measure relative humidity and utilize capacitive and resistive sensors. These low-cost transmitters consist of an integrated sensor and transducer assembly. The sensor provides a measure of the relative humidity while the transducer generates an electronic output signal representative of the sensed humidity. Both capacitive and resistive humidity transmitters range in accuracy from ±5% to ±1% for HVAC applications. The corresponding cost range is \$50 to \$1000 for the capacitive type and \$100 to \$1500 for the resistive type.

Measuring Humidity

Relative Humidity

Relative humidity is the ratio of the amount of water vapor in air to the maximum amount of water vapor that the air can hold at a given temperature and pressure. It is expressed in percentage and can be determined as follows:

$$\%RH = \frac{P_V}{P_S} \times 100$$

where: P_V: Actual partial pressure of water vapor in moist air (bar; kPa)
P_S: Saturation pressure of water vapor at the same given temperature (bar; kPa)

Air is saturated at 100% relative humidity, which means it cannot hold any more water. Raising the temperature without changing the amount of water in the air reduces the relative humidity. The relative humidity decreases because warmer air can hold more water than cold air. At 100% relative humidity, the dry bulb, wet bulb, and dew point temperatures are equal.

Specific Humidity

Specific humidity is the mass of water vapor in air per unit mass of dry air. It is usually expressed as lb (kg) of water per lb (kg) of dry air or grains of water per lb of dry air (7000 grains = 1 lb):

$$W = \frac{M_W}{M_g}$$

where: M_W: mass of water vapor (lb; kg; grains)
M_g: mass of the dry air (lb; kg)

Specific humidity is sometimes referred to as the humidity ratio.

Absolute Humidity

The absolute humidity (i.e., vapor concentration or vapor density) is the mass of water vapor per unit volume of moist air. It is represented as follows:

$$AB = \frac{M_W}{V}$$

where: AB: Absolute humidity (grains/ft^3; grams/m^3)
M_W: Mass of water vapor (grains; grams)
V: Volume of moist air (ft^3; m^3)

Dew Point

Dew point is the temperature at which water begins to condense out of the air when cooled at constant pressure. When air is cooled to its dew point, it reaches 100% relative humidity and the water vapor is in a state of saturation. Additional cooling of air causes some of the water vapor in the air to change to the liquid phase. →

This NBCIP Product Testing Report addresses the performance of resistive and capacitive transmitters only. Information on other humidity sensing technologies can be found in the ASHRAE Handbook of Fundamentals (ASHRAE 2001).

Capacitive Humidity Sensors

The main components of a capacitive humidity sensor are shown in Figure 1. A capacitor is formed by depositing a polymer or metal oxide film between a conductive material (lower electrode) and a porous conductive material (upper electrode) onto a glass, ceramic, or silicon substrate. The polymer layer adsorbs water molecules as they permeate through the porous upper electrode. The dielectric constant of the polymer layer changes as it adsorbs moisture, causing the capacitance of the two electrodes to increase. The change in capacitance is directly proportional to the relative humidity.

(Continued from page 2)
Liquid water molecules accumulate, droplets form, and water condenses out of the air. At this new condition, the air contains less water vapor, has a lower specific humidity and a lower dew point temperature; however, it is still at 100% relative humidity.

Vapor Pressure

The partial pressure of water vapor is that part of the total pressure contributed by water vapor, and is also the pressure exerted by free water molecules at the surface of a solid or liquid. For most HVAC processes, the vapor pressure of interest is that of water in contact with itself, which is the saturation pressure normally found in the thermodynamic tables. However, water in contact with other substances (e.g., wood, paper, salt) also has a vapor pressure, which may be different from the vapor pressure of water in contact with itself. ■

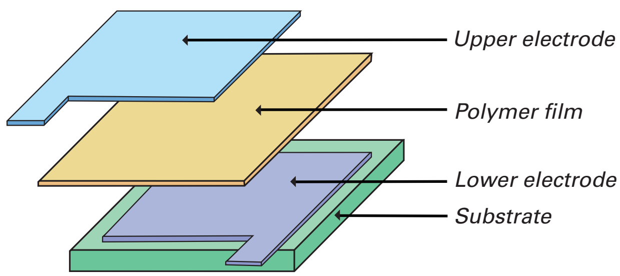

Figure 1.
Schematic of a capacitive-type humidity sensor.
(Adapted from Yamatake)

Capacitive humidity sensors are generally considered to be accurate at low humidity (less than 15% RH) and high ambient temperatures. High quality capacitive sensors have fast response times at low humidity, on the order of seconds. The main limitation of capacitive sensors is the small change in capacitance compared to the capacitance of the cable connecting the sensor. This requires signal conditioning to occur close to the sensor, usually at distances within 10 feet. Also, capacitive humidity sensors are sensitive to contaminants and chemicals, are generally considered to be inaccurate at high humidity (over 85% RH) due to saturation of the sensing material, and require periodic recalibration.

Resistive Humidity Sensors

The main components of a resistive humidity sensor are shown in Figure 2. Resistive humidity sensors are composed of interlocked metal electrodes that are deposited on a substrate. The substrate is then coated with a moisture-sensitive material, such as a conductive polymer or a salt. As the polymer coating adsorbs moisture, ions are released causing the electrical resistance to change. The resistance decreases as humidity increases. This change in electrical resistance of the polymer is measured by the sensor.

Resistive humidity sensors are generally considered economical to manufacture, have long-term stability, are operational over a broad humidity range (15 to 90% RH), perform well at high humidity, and are resistant to surface contaminants. However, resistive sensors are considered to be less accurate at low humidity (less than 15% RH), have slow response times (on the order of tens of seconds to minutes) because the moisture must fully permeate the conductive polymer layer before the resistance reading is affected, and are sensitive to chemicals that are similar to the polymer material (Brownawell 1989). Furthermore, polymer based sensors have a strong temperature dependence, requiring units

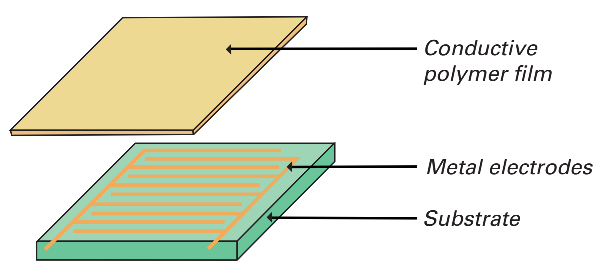

Figure 2.
Schematic of a resistive-type relative humidity sensor.
(Adapted from Yamatake)

to be temperature compensated. The use of a water-soluble coating causes resistive sensors to be less accurate if condensation occurs. Recent advances in sensor technology address condensation issues by using a ceramic substrate coated with a polymer/ceramic mixture. ■

Choosing the Right Humidity Transmitter

Specifying or selecting a humidity transmitter is dictated by the requirements of its intended application. Transmitter selection requires careful consideration of several factors and how important they are to the application. These factors include:

- Accuracy, including repeatability, linearity, and hysteresis
- Environmental conditions to which the transmitter will be exposed
- Response time
- Resistance to contaminants
- Transducer performance
- Maintenance and calibration requirements
- Long-term stability
- Transmitter cost

Accuracy

Accuracy is an important parameter in the selection of humidity transmitters; however, there is usually a direct relationship between accuracy and cost. It is important to note that a particular application may not necessarily require the most accurate and thus the most expensive humidity transmitter. In applications that require strict humidity control, such as humidity-sensitive spaces, museums, and laboratories, a humidity transmitter with ±1 or ±2% RH accuracy may be appropriate. Otherwise, a ±5% RH accuracy level may be sufficient for most HVAC applications that are non-energy critical, depending on the mounting configuration of the transmitter. For example, space or wall-mounted humidity transmitters that are used simply to monitor relative humidity conditions in enclosed spaces may be specified at ±5% RH accuracy. However, if the RH measurements are used for HVAC control, such as in a chilled water reset strategy, then an accuracy of ±3% RH is recommended. Duct-mounted humidity transmitters are exposed to high airflow conditions, associated with high energy content, justifying sensor accuracy of ±3% RH.

Selecting a humidity transmitter based solely on manufacturer stated accuracy provides only a partial view of transmitter performance. Transmitters that are calibrated at laboratory controlled temperature and humidity conditions may not reflect actual field conditions to which the transmitter will be subjected. It is therefore important to know the calibration standard that was used, the temperature and humidity condition(s) at which the transmitter was calibrated, how transmitter performance is affected by varying temperature and humidity, and how ageing of the sensor will affect its performance.

Most manufacturers calibrate and report transmitter accuracy at or around 77°F (25°C). All humidity transmitters are temperature dependent, and transmitter performance can be affected when subjected to extremes in temperature. Temperature compensation can be specified when the application requires a higher degree of accuracy or operation at high or low temperatures. Two temperature compensation options are possible: electronic compensation or control of sensor temperature.

Extreme humidity conditions can also affect transmitter performance. At high humidity levels (e.g., greater than 90% RH) even a small temperature change can result in condensation on the sensor's surface. Exposure to high humidity conditions could degrade sensor accuracy. Manufacturers suggest several methods to prevent condensation, including minimizing temperature variations by ensuring good air mixing, warming the sensor so that the probe temperature remains above the dew point temperature, or utilizing a protective coating that prevents condensation from occurring on the sensor. Furthermore, advances in sensor materials make it possible to select humidity sensors that are specifically designed to operate in extreme humidity environments.

The term accuracy also encompasses other measures of performance such as hysteresis, linearity and repeatability. In some cases, the accuracy stated in manufacturer product literature includes some or all of these performance measures, while some manufacturers report these parameters separately. Consideration of all these parameters will provide a clearer understanding of humidity transmitter behavior and will aid in selecting the most appropriate transmitter for a given application.

Response Time

Many industrial processes require humidity sensors with fast response times, on the order of seconds. In contrast, most building air-conditioning processes have response times on the order of minutes, and therefore, slower humidity sensor response times can be acceptable. In general, resistive RH sensors are considered to have slower response times than capacitive sensors, particularly at low humidity levels. The response time of resistive sensors can range from less than two minutes to as much as 15 minutes under conditions of low humidity and low air flow. This is because water vapor must fully permeate the conductive polymer layer before the resistance reading is affected. In contrast, capacitive humidity sensors are considered to have fast response times, on the order of seconds, because the porous electrode layer quickly adsorbs water vapor. However, lower quality capacitive sensors, in which the porous electrode is less uniform or contains fewer pores, may have slow response times, on the order of minutes.

Resistance to Contaminants

The accuracy, response time, and life expectancy of a humidity sensor can be adversely affected by contaminants. Contaminants include dust, particulates, chemicals, and chemical vapors. Sensor accuracy can degrade as contaminants permeate the sensor. A high level of contaminants may permanently damage the sensor while at lower levels the sensors can usually be cleaned or reactivated. Bulk polymer resistive humidity sensors are considered to be inherently resistant to surface contaminants. However, while sensor accuracy may remain unaffected, the response time may increase. Filters can be used to keep humidity sensors free from dust; however, sensor accuracy may be affected. Manufacturer's contaminant compatibility charts should be consulted if the sensor will be applied in a harsh environment.

Transducer Performance

The relative humidity transmitters of the type tested by NBCIP have two primary components: 1) a sensing element; and 2) a transducer. The transducer converts the sensed resistance or capacitance to an output voltage and may also amplify and filter the signal. In the case of humidity transmitters with a current output, the sensed resistance or capacitance is converted to a current. It is not uncommon for manufacturers to purchase the sensing element, design and fabricate the transducer, and package these components as a relative humidity transmitter. It is important to recognize that the transducer plays a critical role in determining the accuracy, noise levels and other performance characteristics of relative humidity transmitters.

Maintenance and Calibration

Maintenance requirements depend on the type of technology used in the sensor, environmental conditions and exposure to contaminants. Capacitive and resistive humidity transmitters require calibration checks and occasional cleaning. In general, manufacturers recommend that transmitters be checked and calibrated once a year. High accuracy transmitters, as well as transmitters that are subjected to high temperature and/or humidity conditions or harsh environments should be checked and recalibrated at a frequency of every six months or as recommended by the manufacturer.

Humidity transmitters that operate over a narrow temperature and humidity range can usually be checked and recalibrated at a single condition (single point calibration). In contrast, transmitters that operate over a broad range of conditions need to be checked and recalibrated at several temperature and humidity conditions (multipoint calibration).

Calibration methods vary, as do their cost and the resulting accuracy of calibration. The most accurate, and most expensive, method involves calibrating the transmitter against a known national standard in an approved laboratory. ASHRAE Standard 41.6, Method for Measurement of Moist Air Properties, identifies three calibration standards: primary, secondary, and working standards. Primary standards are based on fundamental principles and produce known humidity conditions using base units. One application of primary standards is to calibrate other instruments, including secondary devices. In the U.S., the national primary standard is the gravimetric hygrometer developed by the National Institute of Standards and Technology (NIST). This device was selected as the national primary standard because it is extremely precise in its measurements; however, it is difficult, expensive, and labor-intensive to use. NIST therefore developed the two-pressure humidity generator, which is used as a surrogate for the primary standard. Secondary standards are also based on fundamental principles; however, the accuracy of their results depends heavily on proper use. Working standards refer to devices that are widely used in commercial and industrial applications. These include, among others, resistive and capacitive humidity transmitters. Since the operation of working devices is not based on fundamental principles, they must be periodically calibrated against a primary or secondary standard.

In the U.S., devices whose calibration can be traced back to a primary standard are said to be NIST-traceable. Factory or laboratory calibrated transmitters are supplied with a calibration certificate that reports the unit's accuracy at the time of manufacture or shipment. A transmitter that has been calibrated long before it is put in use may be less accurate due to possible ageing.

Calibration can also be carried out on site using portable devices such as a portable meter, saturated bath solutions, or a portable humidity generator. Portable devices also require periodic calibration in an approved laboratory. Depending on the standard or technology used, portable calibration devices may prove to be less accurate than laboratory devices. However, they can be useful in performing spot-checks of transmitter performance on site.

Long-term Stability

Long-term stability refers to how transmitter accuracy drifts over time and determines the frequency of calibration. A stable humidity transmitter would require fewer calibrations. Most of the secondary humidity transmitters, such as resistive and capacitance types, require frequent calibration (e.g., every six months to one year), depending on the use of the humidity transmitter.

Humidity Transmitter Cost

First costs will vary depending on transmitter accuracy and the type of application. In addition to initial cost, the long-term costs, including sensor replacement and maintenance, must be considered. ■

NBCIP Testing

Manufacturer Information

NBCIP consulted trade magazines and HVAC specifiers' guides to identify manufacturers of duct-mounted relative humidity transmitters. NBCIP reviewed manufacturers' product literature and selected only duct-mounted relative humidity transmitters having an accuracy of ±3% RH and 0-10V output signal for testing.

NBCIP purchased three humidity transmitters of the same model from six leading manufacturers for a total of 18 transmitters, of which half were resistive type sensors and half were capacitive type sensors. Technical information for the transmitters, obtained from manufacturer product literature, is reported in Table 1. A sample of the humidity transmitter models that were purchased are shown in Figure 3. Transmitters were purchased anonymously from the manufacturer or authorized distributor in three separate batches over a period of several weeks to increase the possibility that they originated from different manufacturing lots. The transmitters were purchased over a period ranging from March to June 2002. At the time of purchase, manufacturers had not been informed about NBCIP's intentions to perform independent tests on the humidity transmitters. Manufacturers were contacted at the time of writing this report and were asked to verify the correctness of product information presented in Table 1. Manufacturers were not given an opportunity to view the test results prior to public release of this report.

Figure 3.
Sample of duct-mounted humidity transmitters selected from six manufacturers for NBCIP testing; from left to right: MAMAC Systems Inc., Building Automation Products Inc., Johnson Controls Inc., Vaisala, General Eastern Inc., Automation Components Inc.

Table 1. Technical information for duct-mounted relative humidity transmitters tested by NBCIP, as reported in manufacturer product literature.

Manufacturer	**Automation Components Inc. (ACI)**	**Building Automation Products Inc. (BAPI)**	**General Eastern Inc. (GEA)**	**Johnson Controls Inc. (JCI)**	**MAMAC Systems Inc. (MAMAC)**	**Vaisala (Vaisala)**
Model Number	A/RH3-D	BA/H310-D	MRH-3-D	HT-6703-0N00P	HU-224-3-VDC	HMD50U
Sensing Element	Resistive	Impedance type	Bulk polymer Resistive	All-polymer Capactive	Bulk polymer Capacitive	Thin film polymer Capacitive
Price Paid by NBCIP ($US)[1]	$125	$150	$194	$248	$275	$180
Accuracy	±3% RH 20% to 95% RH *at 77°F (25°C)* [4]	±3% RH 15% to 95% RH	±3% RH at 77°F (25°C) 20% to 95% RH	±3% RH at 77°F (25°C) 20% to 80% RH ± 5% RH at 77°F (25°C) 10% to 20% and 80% to 90% RH	±3% RH 10% to 90% RH	Better than±3% RH at 68°F (20°C) 10% to 90% RH
Operating Range	-10°F to 160°F (-23.3°C to 71°C) 0% to 100% RH	*-20°F to 160°F (-28° to 70°C)* [6] 0% to 100%RH	-20°F to 140°F (-29°C to 60°C) 0% to 95% RH	32°F to 122°F (0°C to 50°C) 0% to 100% RH	-30°F to 130°F (-35°C to 55°C) 10% to 90% RH	14°F to 140°F (-10°C to 60°C) 0% to 100% RH
Linearity	NA	±0.1% of span	Included in accuracy	NA	Included in accuracy	*Included in accuracy* [4]
Hysteresis	< 0.4% RH	< 0.4% RH	<1% RH Included in accuracy	NA	±1% RH	*Included in accuracy* [4]
Repeatablity	0.5% RH	NA	0.5% RH Included in accuracy	NA	Included in accuracy	*Included in accuracy* [4]
Long Term Stability	<2% RH drift over 5 years	*<2% RH drift over 5 years* [6]	<1% RH drift per year	NA	NA	± 2% RH over 2 years
Response Time	30 sec. for 63% step	*30 sec. for 63% step* [6]	NA	Within 5% RH in 15 min. for 10-30%,30-90%,40-90% RH	NA	*< 20 sec. at 68° F (20° C) in still air* [4]
Sensitivity	0.1% RH	NA	0.1% RH	NA	NA	NA
Supply Voltage[2]	15- 36 VDC for 250 Ohm load, 18-36 VDC for 500 Ohm load[5], or 24 VAC	24 VDC 24 VAC	12-36 VDC	14-30 VDC for 0-10 VDC output, 20-30 VAC for 0-10 VDC output, 16-30 VDC for 4-20mA output	12-40 VDC 12-35 VAC	12-35 VDC/12-24 VAC for 0-1 VDC output, 15-35 VDC/15-24 VAC for 0-10 VDC output
Output[3]	0-5 VDC, 0-10 VDC, 4-20mA Jumper select	0- 10 VDC	0-5 VDC, 0-10 VDC, 4-20mA Jumper select	0-10 VDC, 4-20mA Jumper select	0-5 VDC, 0-10 VDC Jumper select	0-1 VDC, 0-10 VDC Selectable voltage 3-wire output
Storage Temperature	*-10° F to 160°F (-23.3°C to 71°C) 0% to 100% RH* [4]	*-20° F to 160° F (-28°C to 70°C)* [6]	-85° F to 158° F (-65°C to 70°C)	-40°F to 176° F (-40°C to 80°C)	*-30°F to 130°F (-35°C to 55°C)* [4]	-40° F to 140°F (-40°C to 60°C)
Warranty	2 years	NA	2 years	*3 years* [4]	2 years	*1 year* [4]

Notes:

NA indicates that the information was not available in the manufacturer's product literature.

1. Price shown in the table represents actual invoice cost to NBCIP. Your actual cost may differ depending on volume purchased, reseller, trade discounts and other pricing structures.
2. NBCIP tested the duct-mounted humidity transmitters using a supply voltage of 24 VDC.
3. NBCIP tested the duct-mounted humidity transmitters using an output voltage of 0-10 VDC. Other voltage outputs are available as indicated in the table.
4. Information in italics font was not available in manufacturer's product literature. Information in italics font was reported directly by the manufacturer.
5. The manufacturer's literature indicates a supply voltage of 17-36 VDC for 500 Ohm load. A supply voltage of 18-36 VDC was reported directly by the manufacturer.
6. Manufacturer reported that product literature is in the process of being updated. Information in italics font was reported directly by the manufacturer.

Prior to performance testing, NBCIP subjected all transmitters to the manufacturer stated voltage input to ensure they were in full working order. The voltage output signal from each transmitter was also verified. One transmitter from Building Automation Products Inc. (BAPI) failed this initial test and was replaced by a newly purchased transmitter.

Testing Methods

Performance testing of the relative humidity transmitters was performed at the Center for Building Energy Research, Iowa State University, under NBCIP's direction. Testing was performed from July to August 2002.

NBCIP tested the humidity transmitters for accuracy, repeatability, linearity, and hysteresis using a Thunder Scientific Model 2500 Humidity Generator (Thunder Scientific, 2000) that employs an operating principle traceable to the National Institute of Standards and Technology (NIST). Refer to the sidebar, *Two-Pressure Humidity Generator*, for more information.

NBCIP tested three relative humidity transmitters at a time inside the humidity generator. The transmitters were placed inside a custom made manifold that directs the conditioned air over the sensing element of the humidity transmitters. The manifold is made out of copper to achieve a uniform temperature rapidly. Transmitters were placed in Slots 1, 2 and 3 of the manifold as shown in Figure 6. The manifold was placed inside the chamber of the humidity generator. The conditioned air from the saturator of the humidity generator enters the manifold through the inlet port and passes over the sensing element of the humidity transmitters before exiting the manifold. A temperature probe is located at the center of the manifold to measure the manifold temperature.

The humidity transmitters were powered by a 24 VDC input from a Hewlett Packard (HP) Model 6253A DC power supply. The stability of the power supply is better than ±0.1% over its full range. An HP Model 3455-A digital DC voltmeter was used to measure the output of the power supply to ensure that the appropriate voltage was supplied to the transmitters.

The relative humidity transmitters tested provide a 0-10 VDC output. The voltage output leads from a transmitter were terminated at a National Instruments SCB-68 shielded input/output connector block, which was interfaced to

Two-Pressure Humidity Generator

The Thunder Scientific 2500 Humidity Generator, shown in Figure 4, can supply accurate and known humidity values based on the fundamental principle of the "Two-Pressure" generator developed by NIST. The device has an accuracy of ±0.5% RH over a humidity range of 10%RH to 98% RH and a temperature range of 32°F to 158°F (0°C to 70°C). This device can be used for instrument calibration, evaluation and verification on a continuous basis. A copy of the statement of accuracy and traceability to NIST for the Thunder Scientific 2500 Humidity Generator is included in Appendix A.

Figure 4.
Thunder Scientific 2500 Humidity Generator

The two-pressure method is shown in Figure 5. Air, or some other gas such as nitrogen, is saturated (in a saturator) with water vapor at a given pressure and temperature. The saturated gas then flows through an expansion valve where it is reduced at constant temperature to chamber pressure. If the temperature of the gas is held constant during pressure reduction, the humidity at the chamber pressure may be approximated as the ratio of the two absolute pressures, as shown below:

$$\%\ RH \approx \frac{P_C}{P_S} \times 100$$

Relative humidity produced in the test chamber does not depend on measuring the amount of water vapor in the test chamber; rather it is dependent upon the measurement of fundamental base units of pressure and temperature only. The operation of the two-pressure humidity generator is based on fundamental principles and produces known humidity conditions using base units. ■

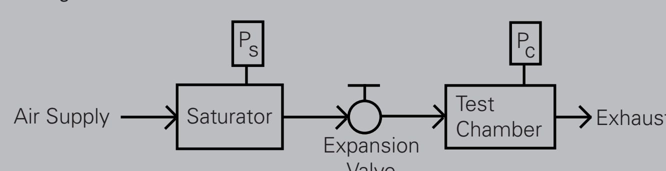

Figure 5.
Principle of the two-pressure humidity generator (Thunder Scientific, 2000).

a data acquisition card via a shielded cable. The shielded connector block and cable provide low-noise signal termination. Twisted-pair shielded wire (American Wire Gauge 22) was used for making connections between the power supply, humidity transmitters, and connector block to help reduce interference from other instruments. The National Instruments PCI-6035E data acquisition card used to measure the output of the relative humidity transmitters has 16-bit resolution on analog inputs and is calibrated traceable to NIST.

The data acquisition card was interfaced to LabVIEW software, which provided a convenient graphical interface for controlling and monitoring data collection. LabVIEW was used to scale the digital representation of the 0-10 V output from the relative humidity transmitters into the measured relative humidity ranging from 0-100%.

NBCIP tested the humidity transmitters at five levels of relative humidity, 10%, 30%, 50%, 70% and 90% RH, for each of three different temperatures, 59°F, 77°F, and 95°F (15°C, 25°C and 35°C, respectively), to reflect the conditions encountered in a typical building HVAC system. The following procedure was used:

- The test temperature and relative humidity were initially set to 59°F (15°C) and 10% RH. At 59°F (15°C), the relative humidity was increased up to 90% RH in 20% RH increments. These measurements are referred to as the **first forward measurements**.
- After reaching 90% RH, the tests were reversed, with the relative humidity being decreased from 90% RH to 10% RH in 20% RH increments while maintaining the test temperature at 59°F (15°C). These measurements are referred to as the **reverse measurements**.
- Once the 10% RH level was attained, the relative humidity was increased again to 50% RH at 59°F (15°C). This measurement is referred to as the **second forward measurement**.
- The above procedure was repeated once for 77°F (25°C) and 95°F (35°C) test temperatures.

This procedure resulted in 10 data points at each temperature for each transmitter tested.

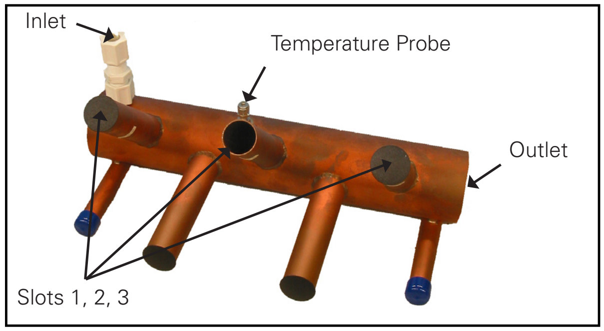

Figure 6.
Schematic of the humidity transmitter manifold developed by Thunder Scientific.

Figure 7 illustrates an example data set and the numbering scheme used to identify the data points.

The humidity transmitters were tested at steady-state conditions inside the humidity generator. The transmitter output was sampled at a frequency of 1 kHz. The 1000 samples collected each second were averaged to produce a single recorded value for each second. NBCIP recorded the humidity readings each second for 45 minutes after the generator had satisfied the steady-state criteria. Data recorded at 45 minutes were then used for further analysis. ■

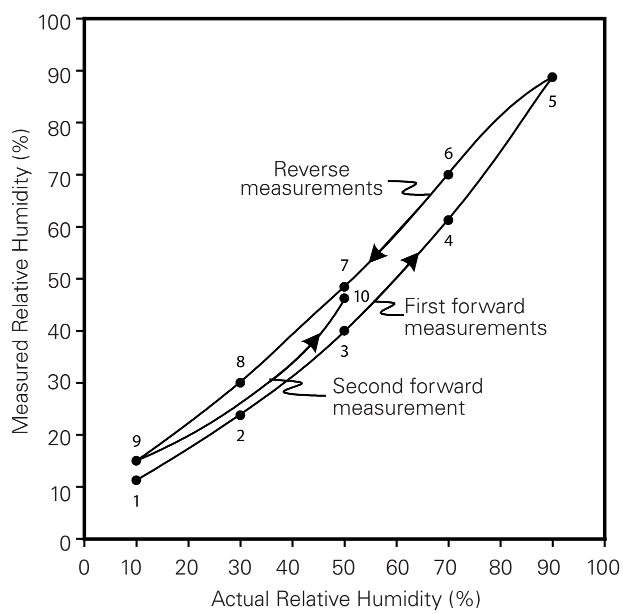

Figure 7.
Example data set to illustrate numbering scheme used to identify data points for NBCIP tests.

Test Results

Accuracy

Manufacturer stated accuracy for the humidity transmitter models tested is ±3% RH. General Eastern Inc., Johnson Controls Inc., and Automation Components Inc. report accuracy at 77°F (25°C), Vaisala at 68°F (20°C), while Building Automation Products Inc. and MAMAC Systems Inc. do not report the temperature at which the accuracy is stated (Table 1). The manufacturer stated humidity range at which the accuracy is ±3% RH varies from manufacturer to manufacturer and is indicated in Table 1.

Figures 8 to 13 show the results of NBCIP's evaluations of humidity transmitter accuracy for each manufacturer. NBCIP calculated the deviation of the measured relative humidity from the actual relative humidity for each transmitter tested and at each test condition (refer to the *Terms and Definitions* section at the end of this report for an explanation of terms related to test data). NBCIP then calculated and plotted the average deviation, referred to as the pooled deviation, which combines the forward and reverse measurements of all three transmitters from a single manufacturer at each test condition, namely 10, 30, 50, 70 and 90% RH and at 59°F, 77°F and 95°F (15°C, 25°C and 35°C). Similar figures were produced for each manufacturer. The accuracy of the humidity generator introduces a maximum uncertainty of ±0.5% RH in the calculated deviations.

The humidity transmitter model from Automation Components Inc. consistently performed within the ±3% RH accuracy rating at all three test temperature conditions and at all humidity conditions within the manufacturer stated humidity range (shown by the shaded area in Figure 8). The transmitter model from Vaisala performed within the specified accuracy over a 10% to 80% humidity range at each test temperature condition (Figure 13). The transmitter model from Building Automation Products Inc. consistently performed outside the specified accuracy of ±3% RH (Figure 9). Transmitters from General Eastern Inc. (Figure 10), Johnson Controls Inc. (Figure 11), and MAMAC Systems Inc. (Figure 12) show a strong temperature dependence. Transmitter models from Automation Components Inc. and General Eastern also showed a wide range in accuracy at the lowest level of relative humidity (10% RH).

Repeatability

Repeatability is the degree to which a humidity transmitter produces the same measurement when subjected repeatedly to the same conditions as they are approached from the same direction. The test conditions defined by NBCIP included three measurements at 50% RH, two of which were taken when the relative humidity was increasing (e.g., the forward measurements). NBCIP assessed the error in repeatability of the humidity transmitters at 50% RH and at each of the three test temperature conditions, namely, 59°F, 77°F and 95°F (15°C, 25°C and 35°C), using pooled measurements of all three transmitters for a given manufacturer. NBCIP defined the error in repeatability as the difference between the two pooled forward measurements at 50% RH, as shown in Figure 14. Referring to Figure 14, the error in repeatability is the first pooled forward measurement (data point 3) minus the second pooled forward measurement (data point 10).

The error in repeatability of the transmitters tested by NBCIP is shown in Table 2. Note that humidity transmitter manufacturers may define and report repeatability differently than NBCIP; therefore, the results in Table 2 should be used to compare transmitter performance among manufacturers, rather than comparing individual results with manufacturer reported data. The error in repeatability of transmitters from Automation Components Inc. was consistently within ±0.1% RH at all three test temperature conditions. The error in repeatability of humidity transmitters from Building Automation Products Inc., General Eastern Inc., and Vaisala is less than ±0.6% RH. Transmitters from Johnson Controls Inc. and MAMAC Systems Inc. are repeatable within ±1.5% RH, with the highest error in repeatability occurring at 77°F (25°C).

The shaded area in Figures 8 to 13 shows the range in RH for which the stated accuracy is ±3%, according to manufacturer product literature. NBCIP tested the performance of the humidity transmitters over a range of 10% to 90% RH and at three different temperatures, 59°F, 77°F and 95°F (15°C, 25°C and 35°C). Refer to Table 1 for product information reported in manufacturer literature.

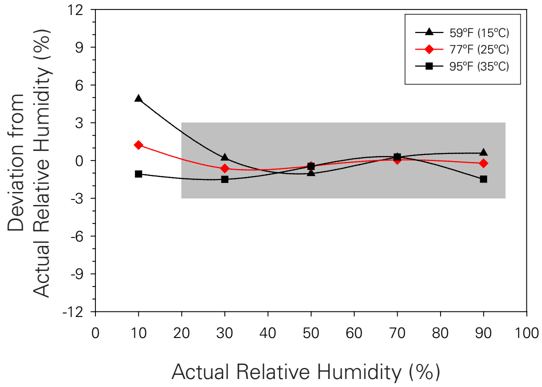

Figure 8.
NBCIP measured accuracy of Automation Components Inc. humidity transmitters, model A/RH3-D.

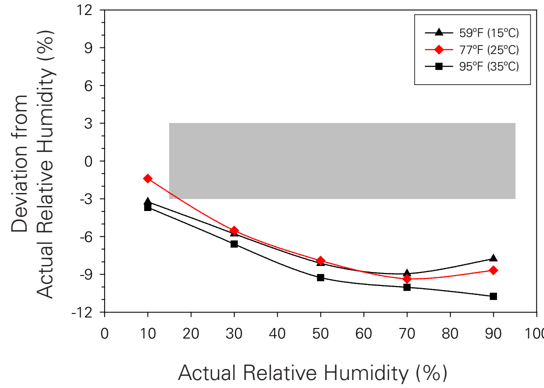

Figure 9.
NBCIP measured accuracy of Building Automation Products Inc. humidity transmitters, model BA/H310-D.

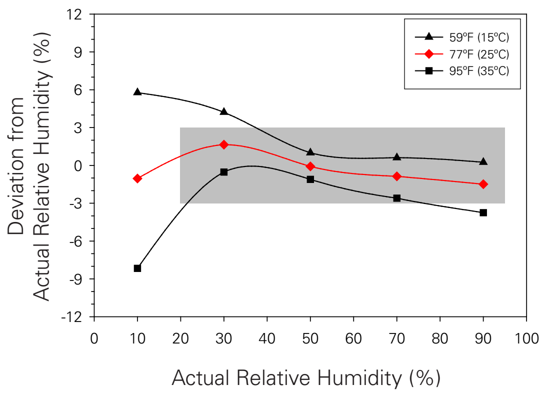

Figure 10.
NBCIP measured accuracy of General Eastern Inc. humidity transmitters, model MRH-3-D.

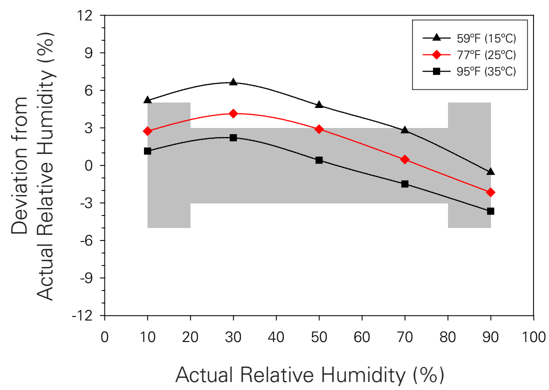

Figure 11.
NBCIP measured accuracy of Johnson Controls Inc. humidity transmitters, model HT-6703-0N00P.

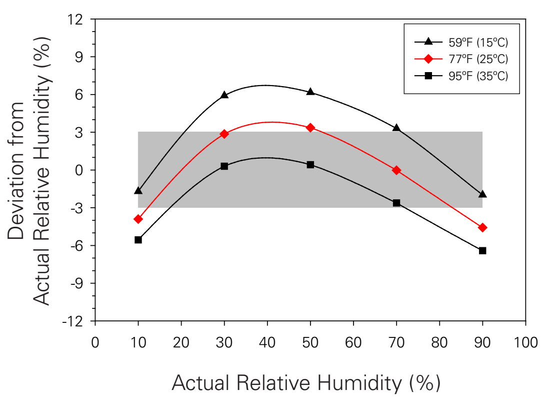

Figure 12.
NBCIP measured accuracy of MAMAC Systems Inc. humidity transmitters, model HU-224-3-VDC.

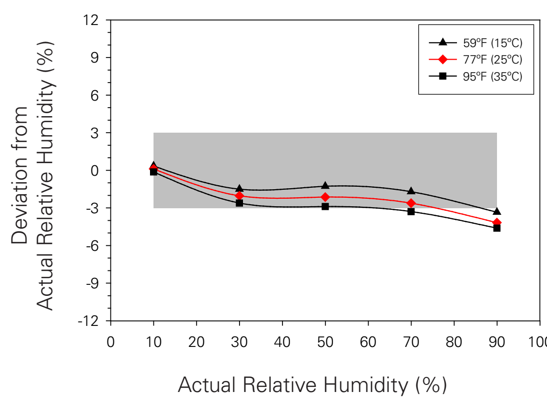

Figure 13.
NBCIP measured accuracy of Vaisala humidity transmitters, model HMD50U.

Table 2. NBCIP test results for repeatability of relative humidity transmitters at 50% RH.

Manufacturer	Model Number	Error in Repeatability at 50% RH (% RH)		
		59˚ F (15˚ C)	**77˚ F (25˚ C)**	**95˚ F (35˚ C)**
Automation Components Inc.	A/RH3-D	0.0	0.1	0.1
Building Automation Products Inc.	BA/H310-D	0.2	0.0	0.6
General Eastern Inc.	MRH-3-D	0.4	0.2	0.0
Johnson Controls Inc.	HT-6703-0N00P	0.3	1.3	0.1
MAMAC Systems Inc.	HU-224-3-VDC	0.3	1.4	1.1
Vaisala	HMD50U	0.2	0.3	0.5

Note: Only the magnitude of the error in repeatability is shown in the table; consequently, negative signs have been omitted.

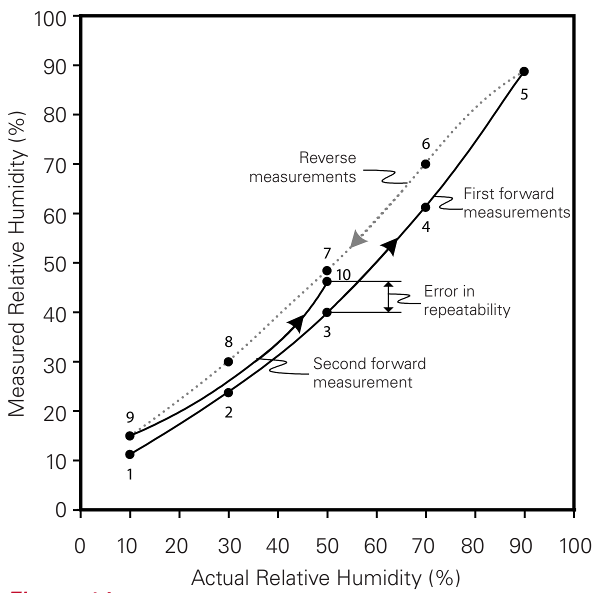

Figure 14.
Example of repeatability of a relative humidity transmitter. NBCIP evaluated repeatability at 50% RH, corresponding to the difference in value between data point 3 and data point 10.

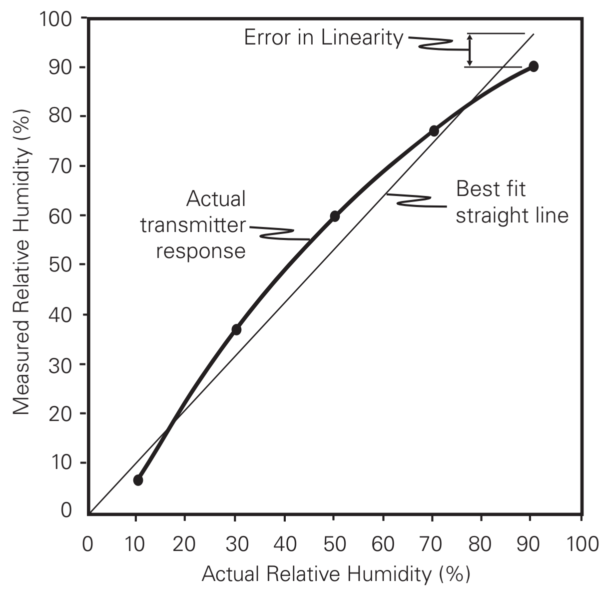

Figure 15.
Example of linearity error of a relative humidity transmitter. In this example the maximum difference between the measured realative humidity and the best fit straight line occurs at 90% RH.

Linearity

Humidity transmitters generally do not show a 1:1 linear relationship between the input (actual conditions) and output (measured value) over the working range. The term linearity denotes the extent to which the transmitter input and output can be approximated by a linear function. A highly non-linear humidity transmitter can result in poor control of HVAC processes. Knowledge of a transmitter's linearity characteristics can be embedded in a controller to best represent and compensate for the transmitter's true behavior. NBCIP assessed the error in linearity of the humidity transmitters as the maximum difference between the pooled measured relative humidity of three transmitters from a particular manufacturer and the best-fit straight line of the measured data through the origin, as illustrated in Figure 15. In this example, the maximum difference between the measured RH and the best fit straight line occurs at 90% RH.

The linearity of the transmitters tested by NBCIP at 77°F (25°C) is shown in Figures 16 to 21. Similar figures showing linearity results for tests performed at 59°F and 95°F (15°C and 35°C) are included in Appendix B. Each figure shows the equation of the best-fit straight line of the measured data as well as the R^2 parameter. Refer to the side bar, *Explanation of Linearity Figures*, for more information.

NBCIP tested the linearity of the humidity transmitters over a range of 10% to 90% RH and at three different temperatures, 59˚F, 77˚F and 95˚F (15°C, 25°C and 35°C). Linearity plots for transmitters tested at 77˚F (25°C) are shown in Figures 16 to 21. Refer to Appendix B for results at 59˚F and 95˚F (15°C and 35°C). Refer to Table 1 for product information reported in manufacturer literature.

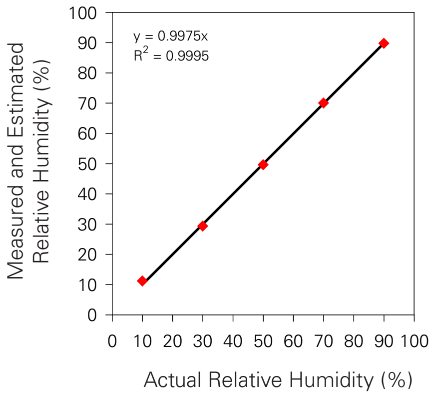

Figure 16.
NBCIP measured linearity of Automation Components Inc. humidity transmitters, model A/RH3-D tested at 77˚F (25°C).

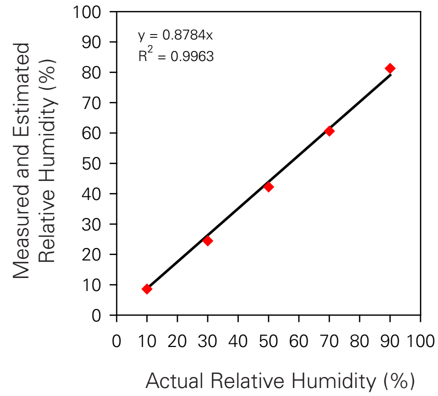

Figure 17.
NBCIP measured linearity of Building Automation Products Inc. humidity transmitters, model BA/H310-D tested at 77˚F (25°C).

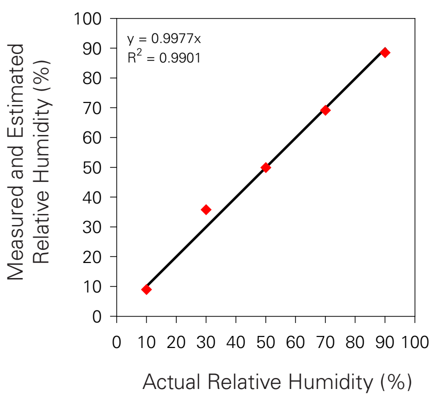

Figure 18.
NBCIP measured linearity of General Eastern Inc. humidity transmitters, model MRH-3-D tested at 77˚F (25°C).

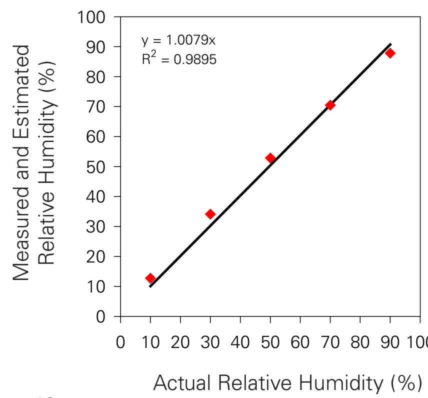

Figure 19.
NBCIP measured linearity of Johnson Controls Inc. humidity transmitters, model HT-6703-0N00P tested at 77˚F (25°C).

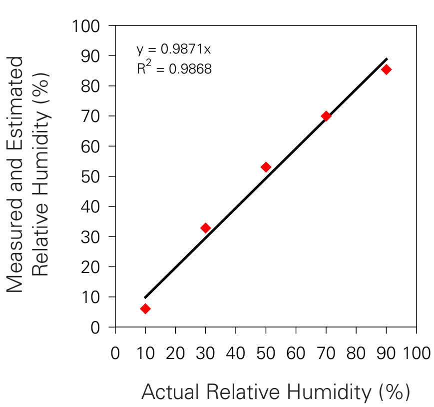

Figure 20.
NBCIP measured linearity of MAMAC Systems Inc. humidity transmitters, model HU-224-3-VDC tested at 77˚F (25°C).

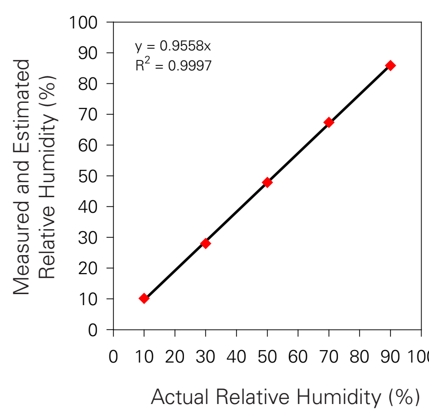

Figure 21.
NBCIP measured linearity of Vaisala humidity transmitters, model HMD50U tested at 77˚F (25˚C).

Table 3. NBCIP test results for error in linearity of relative humidity transmitters.

Manufacturer	Model Number	Error in Linearity (%RH) 59° F (15° C)	77° F (25° C)	95° F (35° C)
Automation Components Inc.	A/RH3-D	4.8	1.2	1.2
Building Automation Products Inc.	BA/H310-D	2.7	2.2	2.3
General Eastern Inc.	MRH-3-D	5.6	5.8	7.8
Johnson Controls Inc.	HT-6703-0N00P	5.4	3.9	2.8
MAMAC Systems Inc.	HU-224-3-VDC	4.9	3.8	5.1
Vaisala	HMD50U	0.6	0.7	1.0

Note: Only the magnitude of the error in linearity is shown in the table; consequently, negative signs have been omitted.

The maximum difference between the measured value and the best-fit straight line are summarized in Table 3 for each humidity transmitter model tested and at all three temperatures. Note that humidity transmitter manufacturers may define and report linearity differently than NBCIP; therefore, the results in Figures 16 to 21, figures in Appendix B, and values in Table 3 should be used to compare transmitter performance among manufacturers, rather than comparing individual results with manufacturer reported data.

Figures 16 to 21 show that all relative humidity transmitters tested at 77°F (25°C) exhibit a linear relationship between input and output. With the exception of the transmitter model from Building Automation Products Inc., the best-fit straight line for the transmitters tested is very close to an ideal 1:1 linear relationship (i.e., the slopes of the best-fit straight lines are nearly equal to one). Table 3 shows that the transmitters from Vaisala have the lowest error in linearity, while transmitters from General Eastern Inc. have the highest error in linearity across all test temperatures.

Hysteresis

Hysteresis is the error in measurement when the same humidity condition is approached from a lower and then higher humidity condition. NBCIP assessed the hysteresis of each manufacturer's humidity transmitters using the pooled forward measurements and the pooled reverse measurements, which were available at 30%, 50% and 70% at each test temperature. The hysteresis of a manufacturer's humidity transmitter at each temperature was calculated as the maximum difference of the pooled values obtained for the forward and reverse measurements, as illustrated in Figure 22. In the example shown in Figure 22, the maximum

Explanation of Linearity Figures

A best-fit straight line through the origin has the relationship y = ax, where a is the slope of the line, x is the actual relative humidity, and y is the predicted relative humidity based on the best-fit straight line. R^2 is a measure of the agreement between the measured relative humidity data from transmitters and predicted values of the relative humidity obtained from the best-fit straight line. R^2 can take a value between 0 and 1. An R^2 value close to 1 indicates a good fit of the data to the line.

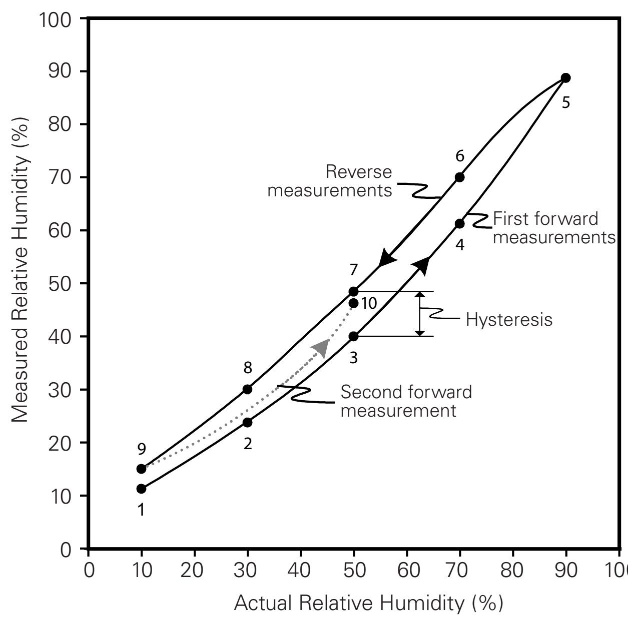

Figure 22.
Example of hysteresis of a relative humidity transmitter. NBCIP evaluated the hysteresis at 30%, 50%, and 70% RH and reported the maximum value. In this example, the maximum value of hysteresis occurs at 50% RH, corresponding to the difference in value between data point 7 and data point 3.

Table 4. NBCIP test results for maximum hysteresis of relative humidity transmitters.

Manufacturer	Model Number	Maximum Hysteresis (% RH) 59° F (15° C)	77° F (25° C)	95° F (35° C)
Automation Components Inc.	A/RH3-D	0.6	0.7	0.8
Building Automation Products Inc.	BA/H310-D	1.0	0.8	1.3
General Eastern Inc.	MRH-3-D	2.6	1.2	0.3
Johnson Controls Inc.	HT-6703-0N00P	3.2	2.3	2.1
MAMAC Systems Inc.	HU-224-3-VDC	1.5	1.2	1.2
Vaisala	HMD50U	0.4	0.5	0.7

Note: Only the magnitude of the maximum hysteresis is shown in the table; consequently, negative signs have been omitted.

difference in pooled measured values occurs at 50% RH, corresponding to the difference in value between data point 7 and data point 3. The maximum hysteresis of the transmitters tested by NBCIP is shown in Table 4. Note that humidity transmitter manufacturers may define and report hysteresis differently than NBCIP; therefore, the results in Table 4 should be used to compare transmitter performance among manufacturers, rather than comparing individual results with manufacturer reported data.

The hysteresis of humidity transmitters from Automation Components Inc. and Vaisala does not exceed 0.8% RH and shows very little variation with temperature. The hysteresis of humidity transmitters from Building Automation Products Inc. and MAMAC Systems Inc. does not exceed 1.5% RH. The largest value of hysteresis occurs for humidity transmitters from General Eastern Inc. and Johnson Controls Inc. (hysteresis of 2.6% RH and 3.2% RH, respectively) at a temperature of 59°F (15°C) and decreases with increasing test temperature. ■

Conclusions

The specification of a relative humidity transmitter goes beyond an examination of manufacturer stated accuracy. Manufacturers' product literature usually states accuracy and other performance criteria for a single temperature condition, which often does not reflect the conditions the transmitter is likely to be subjected to in the field. NBCIP purchased duct-mounted relative humidity transmitters with a stated accuracy of ±3% RH from six manufacturers and tested the transmitters for accuracy, repeatability, linearity and hysteresis. The results show that some humidity transmitters are sensitive to varying temperature and humidity conditions. Some of the transmitters tested did not perform within the manufacturer stated accuracy. In certain cases, the transmitter accuracy differed significantly from the stated ±3% RH accuracy at temperatures that were higher and lower than the temperature at which accuracy was reported by manufacturers. Ultimately, specifying a humidity transmitter requires careful consideration of the application in which the transmitter is expected to perform and careful analysis of product manufacturer information to determine whether a particular product will meet the needs of the application.

Next Steps

NBCIP is currently testing the long-term performance of the relative humidity transmitters discussed in this report. Two humidity transmitters from each of the six manufacturers were installed in an outdoor air duct of the Iowa Energy Center's **Energy Resource Station** (NBCIP's test facility). The transmitters will be exposed to a broad range of environmental conditions for a period of one year. The transmitters will be tested for accuracy every four months to assess sensor drift. Additional testing will also measure response time, an important characteristic for control applications, as well as the capability of the transmitters to withstand extreme conditions such as cycling between high and low relative humidity conditions and exposure to saturated conditions. Results of this phase of testing will be available to the public as a supplement to this report. ■

Terms and Definitions

Accuracy:
Accuracy is the deviation of the relative humidity measured by a humidity transmitter from the actual, or known, humidity.

Actual Relative Humidity:
The relative humidity generated by the reference standard.

Deviation:
Deviation is the difference between the measured and actual relative humidity at a given test condition, and is defined by the following equation:

$$\text{Deviation} = RH_{measured} - RH_{actual}$$

NBCIP calculated the deviation for each humidity transmitter tested at each test condition. NBCIP also calculated the **mean deviation** for a given transmitter at a given test condition by averaging the deviation of the forward measurement(s) and the deviation of the reverse measurement. Referring to Figure 7 as an example, at 10% RH, data point 1 represents the forward measurement, and data point 9 represents the reverse measurement. The deviation of the forward measurement is:

$$\text{Deviation}_1 = RH_{measured\_1} - RH_{actual\_1}.$$

Similarly, the deviation of the reverse measurement is:

$$\text{Deviation}_9 = RH_{measured\_9} - RH_{actual\_9}.$$

The mean deviation is therefore the average of Deviation $_1$ and Deviation $_9$.

Humidity Sensor:
Refers to the humidity sensing element.

Humidity Transmitter:
A device that consists of a sensor as well as a transducer that converts the sensor reading into an output signal.

Hysteresis:
Hysteresis is the error in measurement when the same humidity condition is approached from a lower and then higher humidity condition.

Linearity:
Linearity is the extent to which the humidity transmitter input and output can be approximated by a linear function through the origin.

Measured Relative Humidity:
The relative humidity reading from a humidity transmitter.

Pooled Deviation:
The pooled deviation at a given test condition is determined by averaging the mean deviation of all humidity transmitters of a specific manufacturer model at the test condition. Note that NBCIP tested three humidity transmitters of a given model per manufacturer. As an example, consider a test condition of 59°F (15°C) and 10% RH. If the three transmitters of a given manufacturer I are denoted by A, B, and C, the pooled deviation is calculated as:

$$PD_{I,10,59} = \frac{(MD_A + MD_B + MD_C)_{I,10,59}}{3}$$

where: $PD_{I,10,59}$ = pooled deviation for transmitters A, B, C from manufacturer I at 10% RH and 59°F (15°C)
MD = mean deviation of each transmitter (A, B, C) from manufacturer I

Repeatability:
Repeatability is the degree to which a humidity transmitter produces the same measurement when subjected repeatedly to the same conditions as they are approached from the same direction.

Further Reading

ASHRAE, Handbook of Fundamentals, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA, 2001.

ASHRAE, Humidity Control Design Guide For Commercial and Institutional Buildings, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc, Atlanta, GA, 2001.

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Brownawell, M., "An RH sensor review, with HVAC considerations", Sensors, March 1989, Vol. 6, No. 3, pp. 35-40.

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Thunder Scientific Technical Catalog, Thunder Scientific Corporation, 623 Wyoming S. E. Albuqerque, NM 87123, USA, 2000.

Wiederhold, P. R., "Optimizing RH transmitter performance for HVAC applications", Sensors, March 1990, Vol. 7, No. 3, pp. 69-71, 1990.

Weiderhold, P. R., "True Accuracy of Humidity Measurement", Sensors Magazine, September 1997. http://www.sensorsmag.com/articles/0997/humidity /main.shtml

Yamatake, 2004. http://ibdcom.yamatake.co.jp/products/fp3/background.html

Appendix A:
Copy of statement of accuracy and traceability to NIST for Thunder Scientific 2500 Humidity Generator.

CALIBRATED
THUNDER SCIENTIFIC CORPORATION
IDENTIFICATION NO. [redacted]
CALIBRATION DATE 1 FEB 02
CALIBRATED BY
CALIBRATION DUE 1 FEB 03

Thunder Scientific Corporation

Certificate of Calibration

Customer:	IOWA STATE UNIVERSITY
Purchase Order:	[redacted]
Item:	Model 2500 Humidity Generator
Serial Number:	[redacted]
Date Tested:	1 Feb 02
Procedure:	CL-SOP-0013
Cert Number:	2767

This certifies that the above product was calibrated in compliance with ANSI/NCSL Z540-1 using applicable Thunder Scientific procedures.

At planned intervals, Thunder Scientific measurement and generation standards are calibrated by comparison to or measurement against national standards, natural physical constants, consensus standards, or by ratio type measurements using self-calibrating techniques.

National standards are administered by the National Institute of Standards and Technology (NIST) or other recognized national standards laboratories.

On the date tested, your instrument met its published operating specifications.

The environment in which this instrument was calibrated is maintained within the operating specifications of the instrument and the standards.

Supporting documentation relative to traceability is on file and is available for examination upon request.

The recommended calibration interval for this instrument is 12 months.

Thunder Scientific Corporation

Thunder Scientific Corporation • 623 Wyoming SE • Albuquerque, NM 87123 • 505-265-8701

Appendix B:
Linearity plots for humidity transmitters tested at 59°F (15°C) and 95°F (35°C).

NBCIP tested the linearity of the humidity transmitters over a range of 10% to 90% RH and at three different temperatures, 59°F, 77°F and 95°F (15°C, 25°C and 35°C). Linearity plots for transmitters tested at 59°F (15°C) are shown in Figures 23 to 28. Linearity plots for transmitters tested at 95°F (35°C) are shown in Figures 29 to 34. Refer to Table 1 for product information reported in manufacturer literature.

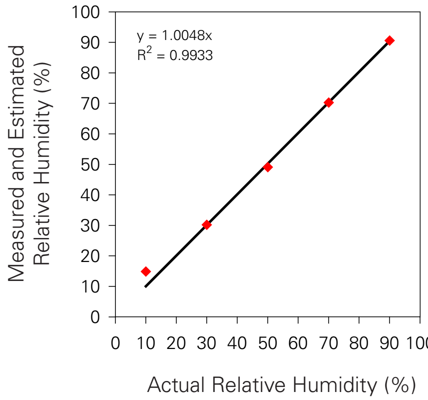

Figure 23.
NBCIP measured linearity of Automation Components Inc. humidity transmitters, model A/RH3-D tested at 59˚F (15˚C).

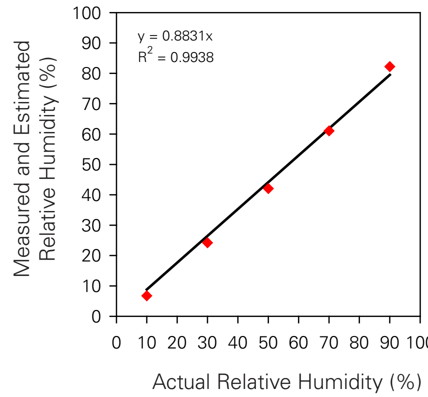

Figure 24.
NBCIP measured linearity of Building Automation Products Inc. humidity transmitters, model BA/H310-D tested at 59˚F (15˚C).

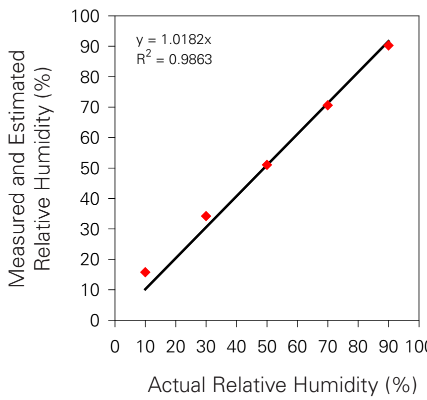

Figure 25.
NBCIP measured linearity of General Eastern Inc. humidity transmitters, model MRH-3-D tested at 59˚F (15˚C).

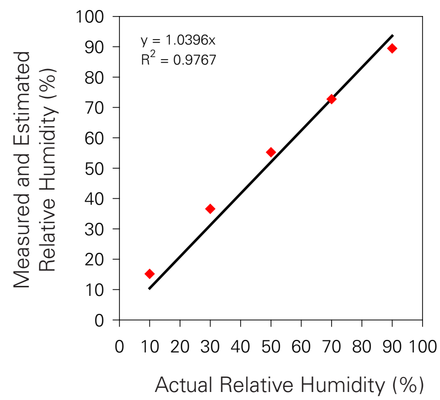

Figure 26.
NBCIP measured linearity of Johnson Controls Inc. humidity transmitters, model HT-6703-0N00P tested at 59˚F (15˚C).

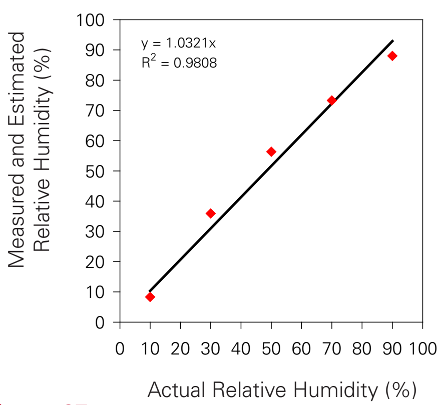

Figure 27.
NBCIP measured linearity of MAMAC Systems Inc. humidity transmitters, model HU-224-3-VDC tested at 59˚F (15˚C).

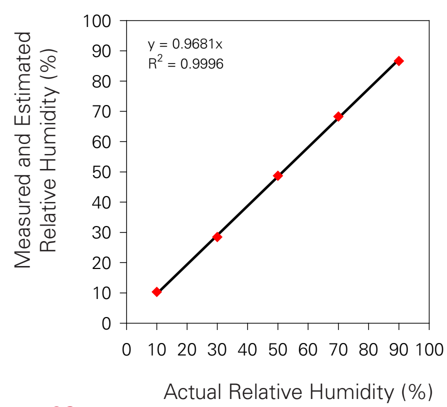

Figure 28.
NBCIP measured linearity of Vaisala humidity transmitters, model HMD50U tested at 59˚F (15˚C).

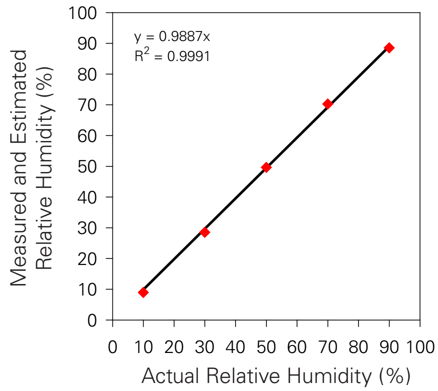

Figure 29.

NBCIP measured linearity of Automation Components Inc. humidity transmitters, model A/RH3-D tested at 95˚F (35˚C).

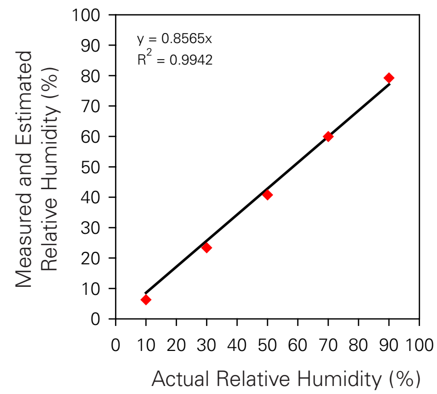

Figure 30.

NBCIP measured linearity of Building Automation Products Inc. humidity transmitters, model BA/H310-D tested at 95˚F (35˚C).

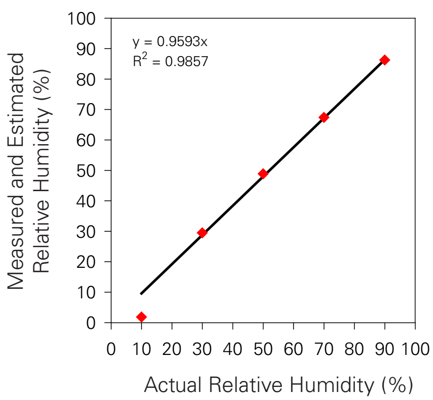

Figure 31.

NBCIP measured linearity of General Eastern Inc. humidity transmitters, model MRH-3-D tested at 95˚F (35˚C).

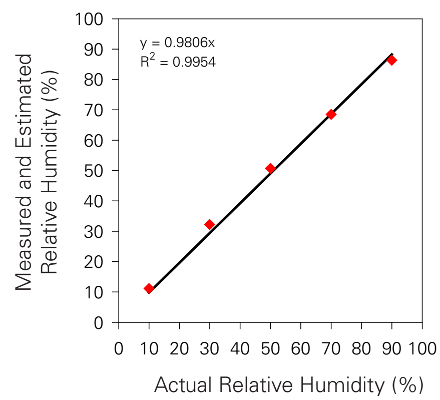

Figure 32.

NBCIP measured linearity of Johnson Controls Inc. humidity transmitters, model HT-6703-0N00P tested at 95˚F (35˚C).

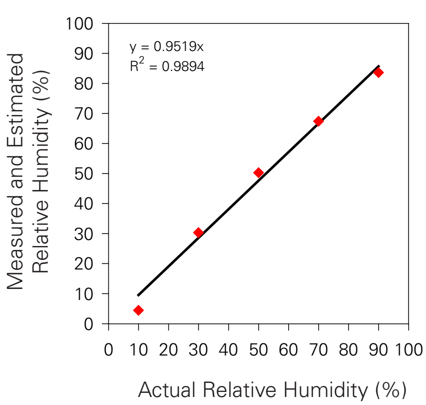

Figure 33.

NBCIP measured linearity of MAMAC Systems Inc. humidity transmitters, model HU-224-3-VDC tested at 95˚F (35˚C).

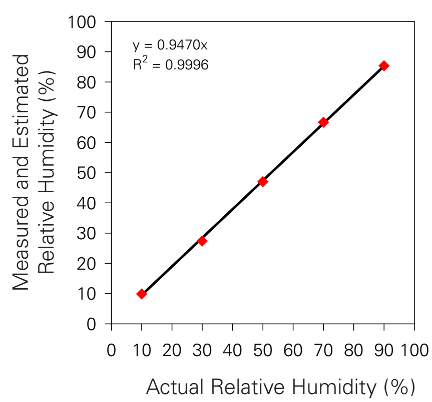

Figure 34.

NBCIP measured linearity of Vaisala humidity transmitters, model HMD50U tested at 95˚F (35˚C).

Product Testing Report
Duct-Mounted Relative Humidity Transmitters

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The National Building Controls Information Program

The National Building Controls Information Program (NBCIP) was established by the Iowa Energy Center in 2001 with support from the U.S. Environmental Protection Agency to facilitate the adoption of energy efficient building control products and strategies through testing, demonstration, education and dissemination of product information. The Iowa Energy Center has launched this national initiative based on our investment in the Energy Resource Station, a unique facility that serves as NBCIP's testing laboratory, and the expertise our researchers have acquired in building controls.

NBCIP recognizes that improving the operation of control systems is a major energy saving opportunity. NBCIP research is aimed at understanding the cause of problems with building controls, evaluating the performance of control systems and strategies, and developing best-practice recommendations for implementing energy-efficient control strategies.

NBCIP provides unbiased, accurate, reliable, manufacturer-specific information on building control systems to guide and improve the selection, installation, operation and maintenance of control products and strategies for building applications.

NBCIP establishes building control product performance in a consistent manner. The NBCIP label signifies that testing was performed using an established process that includes peer review of the method of test and the test results. To ensure objectivity, NBCIP does not accept funding from control product manufacturers.

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