
Shailesh N. Joshi
Student Member ASHRAE

Michael B. Pate, PhD
Member ASHRAE

John M. House, PhD
Member ASHRAE

Ron M. Nelson, PhD, PE
Member ASHRAE

Curtis J. Klaassen, PE
Member ASHRAE

ABSTRACT

Relative humidity sensors are common components in building heating, ventilating, and air-conditioning (HVAC) systems, and their performance can significantly impact energy use in these systems. Therefore, a study was undertaken to test and evaluate the most commonly used relative humidity sensors in HVAC systems, namely, the capacitive and resistive types. The procedures presented here provide a methodology to test and evaluate duct-mounted relative humidity sensors for accuracy, linearity, hysteresis, and repeatability.

The test and evaluation procedures presented in this paper are all inclusive in that they range from procuring the humidity sensors to comparing the accuracy of humidity sensors. Specifically, a procedure is presented to both procure humidity sensors from the manufacturers and to maintain quality control by controlling the storage, handling, and movement of the sensor while documenting time and date at each step. Further, it describes the apparatus and instrumentation, along with test conditions, used to perform experiments on humidity sensors. Additionally, it outlines a detailed experimental procedure to evaluate the accuracy of humidity sensors. Finally, a discussion is presented on analyzing and comparing the accuracy of humidity sensors by using test data. The results of the accuracy test and evaluation of the humidity sensors and the results of the linearity, repeatability, and hysteresis evaluation will be presented later.

INTRODUCTION

Relative humidity sensors are commonly used in building HVAC systems to monitor supply and return air conditions in air-handling units, to monitor conditions in occupied spaces, and to control humidification and dehumidification processes as well as economizer cycles. The performance of these sensors can significantly impact comfort in occupied spaces and energy use in HVAC systems. In the latter case, relative humidity and temperature measurements of outdoor and return air conditions are used to compute the enthalpies of the two airstreams, with the result that the optimum amount of outdoor air entering the building can be determined. If one or both of the computed enthalpies is erroneous, extreme energy penalties can result from the introduction of excess outdoor air.

Because of their impact on comfort and energy use, a study was undertaken to test and evaluate duct-mounted relative humidity sensors used in typical building HVAC applications. Prior to conducting this performance study, an experimental procedure for testing and evaluating duct-mounted relative humidity sensors was developed and is presented here. This procedure provides a detailed description of the methodology to evaluate the performance of duct-mounted relative humidity sensors for accuracy, linearity, hysteresis, and repeatability.

This paper presents an overview of the procedures available in the open literature to evaluate relative humidity sensors used in HVAC environments. Further, the paper describes the commonly used relative humidity sensor types and methods for procuring humidity sensors from representative manufacturers and for administering quality control, such as documenting storage and handling conditions. Furthermore, a description of the experimental test apparatus (i.e., humidity generator) and instrumentation requirements (i.e., data acquisition system) is presented here. Additionally, steady-state criteria for recording data from the humidity generator and sensors are also discussed. Finally, a detailed description of data generation and an analysis for evaluating and comparing sensors are provided.

Shailesh Joshi is a research assistant and Michael Pate and Ron Nelson are professors at Iowa State University, Ames, Iowa. John House is a research engineer and Curtis Klaassen is manager of the Energy Resource Station at the Iowa Energy Center, Ankeny, Iowa.

©2005 ASHRAE.
PREVIOUS STUDIES

This section presents a review of previous research with an emphasize on describing methods and procedures used by past researchers to generate and measure relative humidities. These studies include procedures to test and evaluate relative humidity sensors in various HVAC environments, such as agriculture and shipboard environments; however, there has been no study to date that reports a detailed experimental procedure to evaluate accuracy, hysteresis, linearity, and repeatability of duct-mounted relative humidity sensors in building HVAC environments, where the emphasis is on human comfort and energy conservation. A brief review of the past studies is presented below.

Kitano et al. (1984) evaluated both linearity and hysteresis of four different types of relative humidity sensors in a manufacturing plant environment. The authors use an environmental chamber to test the sensors, but they do not describe the procedures that were used to either set or measure the actual humidity in the environmental chamber.

Erdebel and Leonard (1992) report a test procedure to evaluate both accuracy and hysteresis of two capacitive-type sensors and an aluminum-oxide sensor in an unspecified animal environment. In their study, the exact relative humidity values, which ranged from 33% to 85% RH at a temperature of 20°C, were produced using an environmental chamber. This environmental chamber had a continuous influx and exhaust of moist or dry air in order to generate an atmosphere that simulated an animal environment. In the calibration/accuracy tests, the sensors were stabilized and then the air inlet to the chamber was switched to use air flowing over a saturated salt solution. In this way, air of a different humidity was drawn into and then mixed with the air in the chamber. The details on experimental procedures for setting and measuring the actual relative humidity are not provided.

Slayzak and Ryan (2000) present a test procedure to evaluate and compare dew point and relative humidity sensors, such as the capacitive type. In their study, the test procedure consisted of maintaining a constant humidity ratio of 17.4 J/kg and then increasing the dry-bulb temperature to vary relative humidity. The authors, however, did not describe the method used to measure actual relative humidity for the purposes of comparing dew point and relative humidity sensors.

In summary, the past studies report on procedures to evaluate the performance of relative humidity sensors in HVAC environments, such as in manufacturing, shipboard, and animal environments; however, none of the studies provides a complete description of the test procedures used to generate and measure exact relative humidity values.

HVAC RELATIVE HUMIDITY SENSORS

The most widely used humidity sensors in HVAC applications are the capacitive and resistive types. These relative humidity sensors consist of an integrated sensor and transmitter assembly. The sensor provides a measure of the relative humidity, while the transmitter generates an electronic output signal that is representative of the sensed relative humidity.

Capacitive-Type 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 absorbs water molecules as they permeate through the porous upper electrode. The dielectric constant of the polymer layer changes as it absorbs moisture, causing the capacitance of the two electrodes to increase. The change in capacitance is directly proportional to the relative humidity.

Capacitive-type humidity sensors are typically used in home appliances, the paper manufacturing industry, combustion and heat-treating environments, high-temperature drying equipment, and HVAC climate control. The advantages of capacitive-type humidity sensors include accuracy (i.e., the sensor meets the manufacturer-specified accuracy) in both the low relative humidity range (<15% RH) and high ambient temperatures. The disadvantages of capacitive humidity sensors include sensitivity to contaminants and chemicals, inaccuracy above 95% RH, and the need for periodic recalibration.

Resistive-Type 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 absorbs moisture, ions are released, causing the electrical resistance of the polymer to change. The resistance, which is measured by the sensor, decreases as the humidity increases.

Resistive-type humidity sensors are typically used in home appliances, HVAC climate control, refrigerators, and microwave ovens. The advantages of resistive-type humidity sensors...
include being accurate (i.e., the sensor meets the manufacturer-specified accuracy) in the high relative humidity range (>95% RH). The disadvantages of resistive-type humidity sensors include reduced accuracy at low humidity (typically less than 15% RH), sensitivity to contaminants and chemicals, and the need for periodic recalibration of the sensor.

**SENSOR PROCUREMENT AND QUALITY CONTROL**

Relative humidity sensors were procured from six different humidity sensor manufacturers. Out of the many sensor manufacturers, only sensors from six manufacturers were selected for testing based on the following two reasons:

1. These manufacturers occupy a major market share in commercial production and distribution of HVAC-grade duct-mounted humidity sensors.
2. The project timeline allocated to complete the testing of humidity sensors was limited.

A sensor procurement procedure was important to increase the likelihood that the sensors would be taken from different manufacturing lots, thereby providing a random sample of humidity sensors from a particular manufacturer. In addition, quality control procedures were important to ensure that all humidity sensors were exposed to similar environmental conditions throughout the study. The procedures for sensor procurement and quality control are discussed below.

**Sensor Procurement**

The first step in procuring the humidity sensors was to identify major manufacturers of both resistive and capacitive humidity sensors for HVAC applications. The sensors were ordered in three separate batches over a period of several weeks. Initially, one humidity sensor unit from each of the manufacturers was ordered. After two weeks, the next batch of sensor units was procured in a similar fashion. The final batch of sensor units was ordered two weeks after receiving the second batch of sensors. All of the above test sensors were ordered from either the sensor manufacturer or an authorized distributor. As noted before, half the sensors ordered were of the resistive type and the other half were of the capacitive type; the total purchase was 18 sensors. Sensors with manufacturer-stated accuracies of ±3% RH were tested because they are commonly used in HVAC applications. For consistency, all of the sensors selected for test provided an output voltage of 0-10 V.

**Sensor Quality Control**

After receiving a batch of sensors, a continuous record of location and ambient conditions was maintained to ensure that all the sensors were subjected to similar environmental conditions. For each sensor, information was recorded and appropriate precautions administered as follows:

1. All the humidity sensors were labeled for easy identification.
2. The sensors were stored in a uniform environment similar to that existing in a laboratory, classroom, or office building. To prevent damage, the sensors were kept in their shipping boxes or in an equivalent storage box. Care was taken to ensure that no extraneous matter (e.g., dirt, chemicals, etc.) that might influence the sensor operation and accuracy was in the vicinity of the humidity sensors.
3. A preliminary check of the sensors was performed to ensure that they were working properly in order to prevent testing delays that might occur if a particular sensor was found to be malfunctioning later. The following steps, which did not involve actual testing of the sensor, were taken to ensure that each sensor was working properly:
   - Each sensor was subjected to the manufacturer-stated voltage input, and then a multimeter was used to check if the sensor read the applied voltage correctly.
   - The voltage output signal from the sensor (0-10 V) was checked using a multimeter.
   - Upon passing the above tests, the sensor was returned to the storage box and saved for further testing.
4. A continuous record of the location, time, and date of each sensor was maintained on a log sheet, including the transfer from and to storage for testing.
5. Manufacturers’ written instructions regarding installation and operation of the sensor were followed at all times.

**EXPERIMENTAL APPARATUS**

The humidity sensors were tested in this study by using a known standard that was traceable to the National Institute of Standards and Technology (NIST). A NIST-traceable humidity instrument produces known values of humidity accurately by using NIST principles developed for humidity calibration. Specifically, the humidity sensor experiments performed in this study used a humidity generator consisting of a self-
Table 1. Technical Specifications of the Humidity Generator (TS 2000)

<table>
<thead>
<tr>
<th>Specification Description</th>
<th>Value or Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative humidity operating range (% RH)</td>
<td>10 - 98</td>
</tr>
<tr>
<td>Resolution (% RH)</td>
<td>0.02</td>
</tr>
<tr>
<td>Accuracy (% RH)</td>
<td>± 0.5</td>
</tr>
<tr>
<td>Chamber temperature range (°C)</td>
<td>0 - 70</td>
</tr>
<tr>
<td>Chamber temperature resolution (°C)</td>
<td>± 0.02</td>
</tr>
<tr>
<td>Chamber temperature uniformity (°C)</td>
<td>± 0.1</td>
</tr>
<tr>
<td>Chamber temperature accuracy (°C)</td>
<td>± 0.06</td>
</tr>
<tr>
<td>Chamber pressure range (psia)</td>
<td>Ambient</td>
</tr>
<tr>
<td>Gas flow rate (slpm)*</td>
<td>5 - 20</td>
</tr>
<tr>
<td>Gas type</td>
<td>Air</td>
</tr>
<tr>
<td>Calibration standard</td>
<td>NIST (two-pressure humidity generator)</td>
</tr>
</tbody>
</table>

* Note: slpm—specific liter per minute

Figure 3 Two-pressure humidity generator principle (Thunder Scientific 2000).

Figure 4 Schematic of the humidity sensor manifold.

contained apparatus capable of producing known humidity values using the fundamental principle of the “two-pressure” generator developed by NIST. This system, which was acquired from a commercial vendor, has the capability of supplying accurate and known humidity values on a continuous basis for instrument calibration, evaluation, and verification.

The two-pressure method, shown in Figure 3, involves saturating air with water vapor at a given pressure and temperature. The saturated gas then flows through an expansion valve, where it is isothermally reduced to the chamber pressure. If the temperature of the gas is held constant during the pressure reduction, then the humidity at the chamber pressure can be calculated as the ratio of the two absolute pressures.

The technical specifications of the humidity generator are presented in Table 1.

Three sensors at a time were tested inside the humidity generator. The sensors were placed inside a custom-made manifold that directed the conditioned air over the sensing element of each humidity sensor. The manifold was made out of copper in order to promote uniform temperatures. Sensors were placed in slots 1, 2, and 3 of the manifold, as shown in Figure 4. The conditioned air from the humidity generator enters the manifold through an inlet port and passes over the sensing element of the humidity sensors before exiting the manifold. A temperature probe located at the center of the manifold measures the temperature of the conditioned air flowing through the manifold.

INSTRUMENTATION AND MEASUREMENT TECHNIQUES

Data acquisition (DAQ) software was used to record data from the sensors being tested. The 0-10 V voltage output signals from the humidity transmitters were transformed to 0-100% RH readings and stored in a spreadsheet. A 16-bit data acquisition card was used for recording reliable RH measurements over a wide range of test conditions. The card gave 16-bit performance on 16 single-ended analog inputs. To minimize noise and other extraneous interferences during data transfer, the card was enclosed in a shielded connector block. The connector block encompassed the 16 single-ended analog inputs. Shielded wire (AWG 22) was used for making connections to the power.
supply and humidity sensors in order to reduce interference from other instruments.

Humidity sensors require power input as a functional requirement; hence, a DC power supply was used for the experiments. The stability of the power supply was ±0.1% over the full range. In conjunction with the power supply, a digital DC voltmeter (±0.01%) was employed to set and measure the voltage accurately.

EXPERIMENTAL METHODOLOGY

This section describes the experimental test sequence, the experimental test procedure, and the data analysis used to test and evaluate duct-mounted relative humidity sensors. The experimental test sequence used in this study for sensor accuracy was developed so additional sensor characteristics, such as linearity, hysteresis, and repeatability, could also be analyzed in a single test run. Further, the experimental test procedure used in this study spans the range of humidity and temperature conditions encountered in a typical building HVAC operation.

Experimental Test Sequence

The range of temperatures and relative humidities used for testing humidity sensor performance reflected the conditions normally encountered in a typical building HVAC system. The humidity sensors were tested at five different levels of relative humidity (i.e., 10%, 30%, 50%, 70%, and 90% RH) and three different temperatures (i.e., 15°C, 25°C, and 35°C).

The tests were performed according to a set procedure. Specifically, the test temperature and relative humidity were initially set to 15°C and 10% RH. At 15°C, the relative humidity was increased up to 90% RH in 20% RH increments. These measurements are referred to as the forward measurements. After reaching 90% RH and while maintaining the test temperature at 15°C, the test conditions were reversed, with the relative humidity being decreased from 90% RH to 10% RH in 20% RH increments. These measurements are referred to as the reverse measurements. Once the 10% RH level was attained, the relative humidity was increased back to 50% RH, again while maintaining 15°C. The above procedure was repeated for test temperatures of 25°C and 35°C.

A test run for a given sensor at a specified temperature produces two data points at 10%, 30%, and 70% RH each, three data points at 50% RH, and one data point at 90% RH. Thus, each sensor produces 10 data points at a given temperature, or 30 data points overall.

Experimental Test Procedure

To expedite testing, three sensors at a time were placed in manifold slots, which is described in the section on experimental apparatus. Preliminary tests were performed to assess any effects on relative humidity due to the position of the sensor inside the manifold slots. These preliminary tests resulted in an error of less than 0.1% RH being observed due to the positioning of sensors, thereby resulting in a negligible error in relative humidity.

Testing of the humidity sensors was performed at steady-state conditions. Specifically, testing was initiated and data recorded while the test environment approached the specified limits for steady state defined in Tables 2 and 3. The steady-state accuracy criteria in Table 2 required that the relative humidity and temperature be within ±0.5% RH and ±1.0°C of their respective setpoints for a 10-minute period. To satisfy the steady-state conditions in Table 3, the relative humidity and temperature of the humidity generator were not allowed to vary more than ±0.5% and ±1.0°C, respectively, from their mean values for a 10-minute period.

A typical time response of the environmental chamber conditions to a step change in relative humidity from 30% to 50% RH at a fixed temperature is shown in Figure 5. A detailed plot of typical relative humidities in the generator beginning 15 minutes after the step change is shown in Figure 6. Similarly, a detailed plot of temperatures beginning 15 minutes after the step change in RH is shown in Figure 7. These figures reveal that the conditions in the environmental chamber satisfied steady-state conditions within 25 minutes after a 20% RH step change in relative humidity.

The sensor output was sampled at a frequency of 1 kHz. The 1000 samples collected each second were then averaged to produce a single recorded value for each one-second time period. The humidity readings were recorded in the spreadsheet file each second during the 45-minute period after the generator had satisfied the steady-state criteria. The humidity value obtained after 45 minutes was used for further analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Steady-State Accuracy Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual relative humidity</td>
<td>Within ±0.5% RH of setpoint for 10 minutes</td>
</tr>
<tr>
<td>Actual manifold temperature</td>
<td>Within ±1.0°C of setpoint for 10 minutes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Steady-State Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual relative humidity</td>
<td>Change of less than ±0.5% RH for 10 minutes</td>
</tr>
<tr>
<td>Actual manifold temperature</td>
<td>Change of less than ±0.1°C for 10 minutes</td>
</tr>
</tbody>
</table>

ASHRAE Transactions: Research 173
DATA ANALYSIS

The results are presented in terms of the deviation of the measured value from the actual value (i.e., deviation = RH_{measured} - RH_{actual}). The pooled mean of the deviation at each test condition was used for the analysis. The pooled mean of the deviation represents the average deviation considering all three sensors at a given condition.

The data plots were used to investigate and analyze the accuracy of the humidity sensors. Specifically, a plot that compares pooled mean deviation and actual relative humidity from a single manufacturer at 15°C, 25°C, and 35°C was created. In addition, these plots were used to quantify any dependence of the pooled deviations on temperature. Separate figures were created for each sensor manufacturer (i.e., one figure per manufacturer). A sample plot that compares the pooled mean deviation and actual relative humidity for a single manufacturer is shown in Figure 8.

Another tool for evaluating sensor accuracy is to create plots that compare the measured RH deviation (i.e., measured sensor accuracy) and actual relative humidity for three sensors from a single manufacturer at a particular temperature. In addition, these plots were used to compare the manufacturer-specified accuracy with the measured sensor accuracy. Separate figures were created for each sensor manufacturer and for temperatures of 15°C, 25°C, and 35°C. A sample plot that shows the deviation of measured relative humidity values from actual relative humidity values for three sensors from a single manufacturer is shown in Figure 9.
CONCLUSION

This paper presents systematic procedures to test and evaluate the accuracy of typical duct-mounted relative humidity sensors used in HVAC applications, such as capacitive and resistive sensors. Further, an experimental procedure is presented to both procure humidity sensors from the manufacturers and to maintain quality control by controlling the storage, handling, and movement of the sensor while documenting time and date at each step. Furthermore, it describes the experimental test apparatus (i.e., humidity generator and instrumentation techniques (i.e., data acquisition system) that are needed to perform the experimental performance evaluations. Additionally, steady-state criteria for recording data from the humidity generator and humidity sensors are also presented. Furthermore, the paper outlines a detailed experimental procedure for evaluating the accuracy of humidity sensors. Finally, a discussion on data analysis and plotting that is necessary for evaluating and comparing sensors is provided.

ACKNOWLEDGMENT

This work was performed for the National Building Controls Information Program, which is funded by the United States Environmental Protection Agency (under Cooperative Agreement No. X-829347010), NSTAR Electric and Gas Corporation, and the Iowa Energy Center.

BIBLIOGRAPHY


LabView, National Instruments Corporation, 11500 N Mopac Expwy, Austin, TX 78759-3504.

National Institute of Standards and Technology (NIST), 100 Bureau Drive, Stop 3460, Gaithersburg, MD 20899-3460.


Personal Communications. 2001a. Mid-West Control Products, 180 Weidman Road, Suite 103 Manchester, MO, USA, 63021-5724.

Personal Communications. 2001b. Rotronic Instrument Corporation, 160 E. Main Street, Huntington, NY, USA.

Personal Communications. 2001c. Building Automation Products, PO Box 207, Cross Plains, WI, 53528, USA.

Personal Communications. 2001d. Automation Components Incorporated, 2305 Evergreen Road, Middleton, WI, 53562, USA.

Personal Communications. 2001. MAMAC Systems, 7400 Flying Cloud Drive Minneapolis, Minnesota, 55444-3720 USA.


