2005

Performance evaluation of duct-mounted relative humidity sensors used in building HVAC applications

Shailesh Narayan Joshi
Iowa State University

Performance evaluation of duct-mounted relative humidity sensors used in building HVAC applications

by

Shailesh Narayan Joshi

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Mechanical Engineering

Program of Study Committee:
Michael B. Pate, Co-major Professor
Ron Nelson, Co-major Professor
Greg Maxwell
Steve Hoff
Eugene Takle

Iowa State University

Ames, Iowa

2005

UMI Number: 3172224

Graduate College
Iowa State University

This is to certify that the doctoral dissertation of

Shailesh Narayan Joshi

has met the dissertation requirements of Iowa State University

Signature was redacted for privacy.

Co- major Professor

Signature was redacted for privacy.

Co-major Professor

Signature was redacted for privacy.

For the Major Program

ACKNOWLEDGEMENTS

I would like to thank Dr. Michael Pate and Dr. Ron Nelson for their advice and support in the research and writing of this thesis. I would also like to thank Dr. John House for his invaluable help during the course of this research project. Additionally, I also appreciate the assistance of Curt Klaassen and Maria Corsi during the project. I would like to thank the members of my committee, Dr. Greg Maxwell, Dr. Steven Hoff and Dr. Eugene Takle. I extend my thanks to the Iowa Energy Center for supporting this research project. Finally, I need to thank my wife, Kalpana, whose love and support inspired me to persevere.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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. A study was undertaken to test and evaluate the most commonly used relative humidity sensors in building HVAC systems, namely the capacitive and resistive types. Sensor models from six different manufacturers were used for testing. Three sensors of each model for a total of 18 sensors were tested, nine of them were capacitive-type sensors and nine were resistive-type sensors. The performance of these sensors was determined by subjecting the sensors to a series of tests that included accuracy, linearity, repeatability, hysteresis, ageing, response time and stress. For each test, a detailed method of test was developed and peer reviewed.

The accuracy test results showed that two of the six humidity sensor models were within manufacturer specified accuracy, while a third sensor model did not met the manufactured specified accuracy at any humidity level tested, and finally, the remaining three sensor models, met the manufacturer specified accuracy for only part of the humidity range. Further, the repeatability of all sensors models at 50% RH and 15, 25, and 35°C was within 1.5% RH. The maximum hysteresis for all sensors was less than 3.2% for all humidities and temperatures. And finally, at 25°C, Model-B sensor had the largest nonlinearity of -3.8% while Model-C sensor had the least nonlinearity of 0.0%.

The accuracy results after the ageing test showed that only one sensor out of twelve sensors was unaffected both before and after the ageing test, while four sensors out of the remaining eleven sensors were unaffected after the ageing test.

The response time test results showed that the average response times of relative humidity sensors ranged between 7 sec and 96 sec.

The accuracy test results after the stress test showed that two out of six sensors remain unaffected at all relative humidities, while two out of the remaining four sensor models were affected at any relative humidities evaluated. The remaining two sensor models failed after the stress test.

CHAPTER 1. INTRODUCTION

Background

Relative humidity measurements are increasingly important in the industrialized world because of the recognition that humidity has a significant affect on the quality of life (i.e., comfort, safety, and health) and on the cost and quality of industrial products and manufacturing processes. As shown in Table 1.1, relative humidity sensors are widely used in numerous applications, including such diverse areas as transportation, manufacturing, air-conditioning, refrigeration, electronics, chemical, agriculture, weather forecasting, food and medicine. Depending upon the specific applications, humidity sensors are designed to operate over a wide range of temperatures and humidities (also shown in Table 1.1), including harsh and extreme environments, such as high temperatures/humidities or low temperatures/humidities.

Table 1.1: Sample applications of relative humidity sensors (ASHRAE, 2003)

Industry	Application	Operating temperature (°C)	Relative humidity range (%)
Domestic electric appliance	Refrigeration	-10-10	30-70
	Microwave oven	5-100	2-100
Automobile	Exhaust emissions	20-80	50-100
Medical	Medical apparatus	10-30	80-100
	Incubator	10-30	50-100
Building air-conditioning	Residential	21-24	30-50
Manufacturing	Textile mill	10-30	50-100
	ESD control	22	30-70
	Clean room	21	35
	Motor assembly line	17-25	40-55

The performance characteristics of relative humidity sensors can significantly impact human comfort and energy use in building heating, ventilating, and air-conditioning (HVAC) systems. Examples of these performance characteristics are accuracy, linearity, repeatability, hysteresis, drift, response time, and robustness.

Accuracy of relative humidity sensors is an important parameter that not only impacts on comfort in occupied spaces but also impacts energy use in HVAC systems. For example, relative humidity and temperature measurements of outdoor and return air conditions are used to calculate the enthalpies of these two air streams, which feed the building air handling system. The air stream with the least energy content, as determined by enthalpy calculations based on the temperature and relative humidity measurements is used for space cooling to minimize mechanical cooling. If one or both of the computed enthalpies is in error, as can happen when humidity sensors are inaccurate, significant energy penalties can result from selection of the wrong air stream.

The relative humidity sensors must also have proper linearity, repeatability and hysteresis characteristics in order for an HVAC control system to operate effectively. Linearity is especially important because many control systems in HVAC applications assume a linear input/output behavior. Also, if a system is controlling humidity at a fixed set point and the instrument has hysteresis, then depending upon whether the humidity is increasing or decreasing, there could be errors in the actual value of the humidity reading. Finally, repeatability also contributes to inaccuracies in the sensor.

Knowledge of ageing effects of relative humidity sensors is important to determine changes in the accuracy with time when sensors are exposed to actual building HVAC conditions. In a typical building HVAC application, the ageing of sensors may occur due to various factors that might possibly alter the properties of the sensor element, such as continuous exposure to varying humidities/temperatures or contamination.

The response time of relative humidity sensors is important for active control of a humidification process. For instance, steam-injection humidifiers introduce a large amount of moisture into the air in a short period of time. They are typically controlled by sensing the relative humidity in the air stream and comparing this measurement to a set point or desired relative humidity. If the measured relative humidity is less than the desired value, the steam valve is opened. If it is greater than the desired value, then the steam valve is closed. If the relative humidity sensor is sluggish in responding to the increasing relative humidity, the sensed relative humidity will be lower than the actual value and the controller will send a signal to the steam valve to open further (or remain open). In this case, the actual relative humidity will likely overshoot the desired value. The degree of the overshoot will depend in part on the response time of the sensor. The same phenomenon occurs in the reverse direction (i.e. undershoot).

In a typical building HVAC application, relative humidity sensors are often subjected to extreme humidities and temperatures. Continuous exposure to these extreme conditions might affect the properties of the sensor element, thus resulting in either sensor inaccuracies or sensor failure. In addition, structural changes in the sensor element, such as swelling, may affect both the accuracy and functioning of the sensor.

Description of HVAC Relative Humidity Sensors

The most widely used relative humidity sensors in building HVAC applications are the capacitive and resistive types, which have a lower cost compared to other sensors such as the chilled mirror sensor. These capacitive and resistive 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. Descriptions of the capacitive and resistive type sensors are presented below.

Capacitive-type relative humidity sensors

Capacitive-type sensors are 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 as shown in Figure1.1. The polymer layer absorbs water molecules as the water molecules 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.

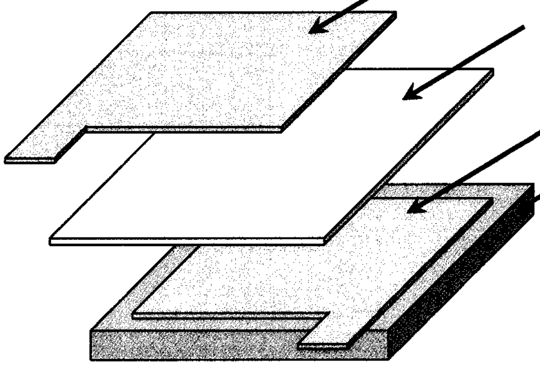


Figure 1.1: Schematic of a capacitive-type humidity sensor

The advantages of capacitive-type sensors include being generally accurate (i.e., the sensor meets the manufacturer specified accuracy) at low relative humidities (<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 relative humidity sensors

Resistive-type sensors are composed of interlocked metal electrodes that are deposited on a substrate as shown in Figure 1.2. The substrate is then coated with a moisture-sensitive material, such as a conductive polymer. 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.

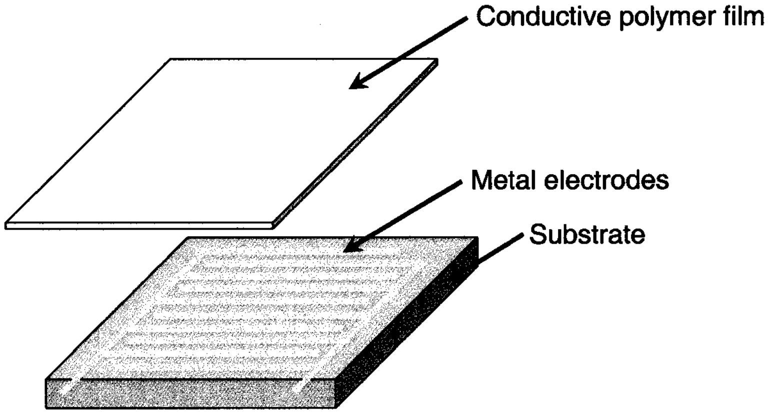


Figure 1.2: Schematic of a resistive-type relative humidity sensor

The advantages of resistive type sensors include being generally accurate (i.e., the sensor meets the manufacturer specified accuracy) in high relative humidities (>95% RH). The disadvantages of resistive-type humidity sensors include reduced accuracy at low humidity (typically less than 15% RH) and sensitivity to contaminants and chemicals along with the need for periodic recalibration of the sensor.

CHAPTER 2. LITERATURE REVIEW

To date, several past studies have reported procedures to test and evaluate relative humidity sensors in various HVAC environments, such as agriculture and ship-board environments, however, there has been no study to date that reports a detailed experimental procedure to evaluate sensor performance characteristics (e.g., accuracy, hysteresis, repeatability, linearity, response time, ageing, and extreme conditions) 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.

Past Studies

Kitano et al. (1984)

The authors evaluated response times of humidity sensors used in a manufacturing plant environment. The response time tests were performed by exposing the sensors to both rising (i.e. from 30% to 80% RH) and falling (i.e. from 80% to 30% RH) step changes to the relative humidity levels at constant air temperatures and air velocities. The response time of a sensor was then analyzed by using a "delay time" that was defined as the time for the measured humidity to reach 50% of the step change. Differences were observed in delay time between rising and falling processes, and this difference was distinct for their test sensor whose rising and falling delay times were 4.6 and 7.2sec, respectively. The authors did not report the results of accuracy, linearity, hysteresis, repeatability, ageing, and extreme conditions studies.

Erdebil and Leonard (1992)

The authors evaluated both the accuracy and hysteresis of two capacitive-type sensors and an aluminum-oxide sensor in an unspecified animal environment. The authors used an environmental chamber to test the sensors, however they did not described the procedures that were used to either set or measure the actual humidity in the environmental chamber. The results indicate that none of the sensors met the manufacturer specified accuracy. For example, the manufacturer of the two capacitive-type sensors claimed an accuracy of $\pm 2\%$ RH, whereas the measured accuracy of these sensors was around $\pm 7\%$ RH. Further, they report that the average hysteresis of two capacitive sensors and an aluminum-oxide sensor ranged from 4.4% to 6.9% RH. However, the authors did not report the results of the repeatability, linearity, response time, ageing, and extreme condition studies.

Ross and Daley (1990)

The authors evaluated both the accuracy and linearity of four different types of capacitive-type relative humidity sensors. The sensors were tested for accuracy by comparing their measured RH readings to actual RH values set by five different salt solutions (i.e. RH standards). The manufacturer stated accuracy of sensors 1, 2, and 3 were ± 3, ± 2.5 and $\pm 1.5\%$, respectively. The authors report that sensors 1 and 2 met the manufacturer accuracy claim of $\pm 2.5\%$ over the entire humidity range of 10.0%-97.6%. Sensor 3 met the manufacturer accuracy claim of $\pm 1.5\%$ over the

43.2%-97.6% humidity range while at 10.0% the humidity reading was 6.1%, which did not meet the manufacturer stated accuracy. Further, they report that the sensor with the most linear response had an R^2 (i.e., goodness of fit parameter) value of 0.99 while the sensor with least linear response had an R^2 value of 0.98 over the range of humidities of 10.0%-97.6%. However, the authors did not report the results of the repeatability, hysteresis, response time, ageing, and extreme condition studies.

Thomas (1992)

The author evaluated the accuracy of three different humidity sensors with one sensor measuring dew-point and the two others measuring relative humidity by using the resistive and capacitive approaches. The author report that the dew-point sensors meet the manufacturer specified accuracy of 4.2% RH while the capacitive and resistive type relative humidity sensors did not meet the manufacturer specified accuracy of 4.4% RH and 2.8% RH, respectively, over the entire humidity range. For example, the percentage errors in the relative humidity readings of resistive and capacitive sensors were 11.5% RH and 27.8% RH, respectively while the dew-point sensor was 2.3% RH. However, the author did not report the results of the linearity, repeatability, hysteresis, response time, ageing, and extreme conditions studies.

Visscher and Kornet (1994)

The authors evaluated the long-term (i.e. one-year) accuracy of eighteen capacitive type relative humidity sensors (±3% RH accurate) in a building environment. The testing of the sensor was performed in an air-duct (0.45 m x

0.70m X 0.40m) of a one-story building. The results of the accuracy tests were evaluated by comparing the relative humidity readings from the sensors with the reference psychrometer, which had an accuracy of ±1.5% RH. The results showed that all of the sensors met the manufacturer specified accuracy before the long term testing. After the long term testing, only one sensor did not meet the manufacturer specified accuracy. The authors did not report the results of the linearity, repeatability, hysteresis, response time, and extreme conditions studies.

Lemay et al. (2001)

The authors evaluated the performance of two types of polymer sensors (sensors 1 and 2) in a typical livestock housing conditions. The authors did not identify the types of polymer sensors used in their investigation. The manufacturer stated accuracy of the sensors was ±5% for an operating range of 5-95% relative humidity. The laboratory tests, which were performed in a humidity chamber, evaluated sensor accuracy, linearity and hysteresis. The humidity chamber was operated by introducing air into the chamber, and then splitting the air stream, with one stream passing through a desiccant drier while the other stream was bubbled through three water vials in series. This system was able to provide relative humidities between 15 and 85% for ambient temperatures varying from 20 to 25°C. A chilled mirror dew-point hygrometer was used as a reference hygrometer.

The authors report that the average mean error in relative humidity readings of both coated and uncoated sensors were within or close to the manufacturer stated accuracy of ±5%. Further, the authors report that the non-linearity of the sensors over the entire relative humidity range ranged from 3.9% to 7.3% RH while the maximum hysteresis for all sensors ranged from 0.7% to 1.6%. Furthermore, the authors report that the forward-step response time ranged from 2.4 to18.6 sec while the reverse-step response time ranged from 6.5 to 18.3 sec. Finally, the long term testing of the polymer sensors showed that the errors in relative humidity readings for most of the sensors increased rapidly during the initial stages compared to the later stages of the long term testing. The authors did not report the test conditions to which the sensors were exposed during the long-term testing. In addition, the authors did not report the results of repeatability and extreme conditions studies.

Summary

In summary, most of the past work has focused on testing humidity sensors in building HVAC system associated with the agriculture industry, with only one study (Visscher and Kornet) being done in human-occupied building. Only one study (Ross and Daley) reports the test procedures to set and measure actual relative humidity for the purpose of evaluating relative humidity sensors. Further, only two out of the above four studies (Erdebil and Leonard; Thomas) report the results of accuracy for capacitive type sensors, while only one study (Thomas) report the accuracy evaluation of resistive type sensors. Furthermore, only one study (Lemay et al.) reports the results of both the linearity and hysteresis study. Only two studies (Lemay et al.; Visscher and Kornet) report the effects of long-term testing on accuracy of relative humidity sensors. In addition, only two studies (Kitano et al.; Lemay et al.) report the results of the response time test, and finally, there are no studies done in the past that report the results of repeatability and extreme conditions.

CHAPTER 3. MEHTOD OF TEST FOR EVALUATING THE PERFORMANCE CHARACTERISTICS

Overview

A Method of Test (MOT) was developed prior to evaluating the performance (in terms of accuracy, repeatability, hysteresis and linearity) characteristics of duct-mounted relative humidity sensors. The objective of the MOT is to provide the users a systematic way to evaluate the performance of duct-mounted relative humidity sensors for HVAC applications. The MOT consisted of several different sections, such as procurement procedures, sensor quality control, test hardware, experimental test sequence, and experimental test procedures. A detailed description of each section of the MOT is provided below. The results of the performance characteristics are provided in Chapter 4.

Sensor Procurement Procedure

Relative humidity sensors were procured from six different humidity sensor manufacturers. These six manufacturers occupy a major market share in commercial production and distribution of HVAC grade duct-mounted humidity sensors, and were selected on this basis. The project time-line and scope precluded the selection of additional manufacturers.

A sensor procurement procedure was important to increase the likelihood that the sensors were taken from different manufacturing lots, thereby providing a random sample of humidity sensors from a particular manufacturer. 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, the first batch of relative humidity sensors was ordered. After two weeks, the second 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.

Half the sensors ordered were of resistive type, and the other half were of capacitive type, resulting in the procurement of 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 testing in this study provided an output voltage of 0-10 V.

Table 3.1: Manufacturer specified accuracy and relative humidity range

Manufacturer	Sensor type	Manufacturer specified humidity range	Manufacturer specified accuracy
Model-A	Capacitive	20 to 80%	± 3% at 25°C
Model-B	Capacitive	10 to 90%	± 3%[a]
Model-C	Capacitive	10 to 90%	± 3% at 20°C
Model-D	Resistive	20 to 95%	± 3%[a]
Model-E	Resistive	15 to 95%	± 3%[a]
Model-F	Resistive	20 to 95%	± 3% at 25°C

[a]manufacturer does not state a temperature

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.), which 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.
    a. 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.
    b. The voltage output signal from the sensor (0-10 V) was checked using a multimeter.
    c. Upon passing the above tests, the sensor was returned to the storage box and saved for further testing.
4. A continuous record of the date and the activity of each sensor was maintained on a log sheet. Appendix E contains the sample log sheet.

5. Manufacturers' written instructions regarding installation and operation of the sensor were followed at all times.

Test Hardware

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 for relative humidity calibration. Specifically, the humidity sensor experiments performed in this study used a humidity generator (TS 2500) consisting of a self-contained apparatus capable of producing known humidity values using the fundamental principle of the "Two-Pressure" generator developed by NIST. This system, which was purchased from Thunder Scientific, 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 3.1, 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 3.2.

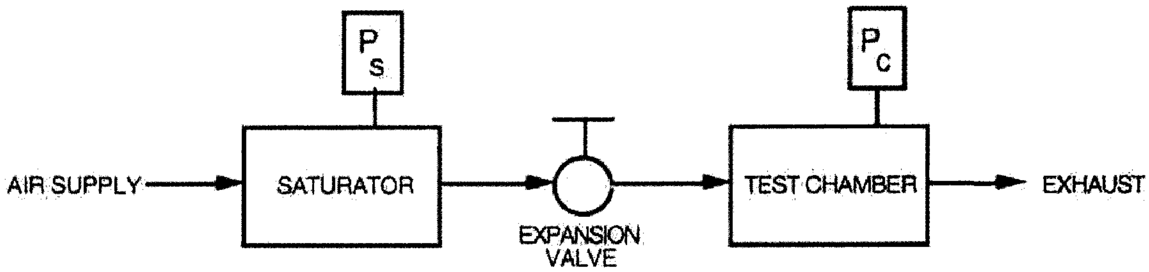


Figure 3.1: Two-Pressure humidity generator principle (Thunder Scientific, 2000)

Table 3.2: Technical specifications of the humidity generator (Thunder Scientific, 2000)

Specification description	Value or Type
Relative Humidity Operating Range	10 - 98% RH
Resolution	0.02% RH
Accuracy	± 0.5% RH
Chamber Temperature Range	0 – 70°C
Chamber Temperature Resolution	± 0.02°C
Chamber Temperature Uniformity	± 0.1°C
Chamber Temperature Accuracy	± 0.06°C
Chamber Pressure Range	Ambient (psia)
Gas Flow Rate	5 - 20(slpm)
Gas Type	Air
Calibration Standard	NIST (Two Pressure Humidity Generator)

Note- slpm: specific liter per minute

A 24 VDC power supply was used to operate the sensors. In conjunction with the power supply, a digital DC voltmeter was employed to set and measure the voltage accurately. The stability of the power supply is better than $\pm 0.1\%$ over the full range. The 0-10 V output of each sensor was sampled, recorded and stored at five-minute intervals continuously using the LabView data acquisition (DAQ) software.

Three sensors were tested at a time 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, which promoted uniform temperatures. Sensors were placed in slots 1, 2 and 3 of the manifold as shown in Figure 3.2. The conditioned air from the humidity generator entered the manifold through an inlet port and passed over the sensing element of the humidity sensors before exiting the manifold. A temperature probe located at the center of the manifold measured the temperature of the conditioned air flowing through the manifold.

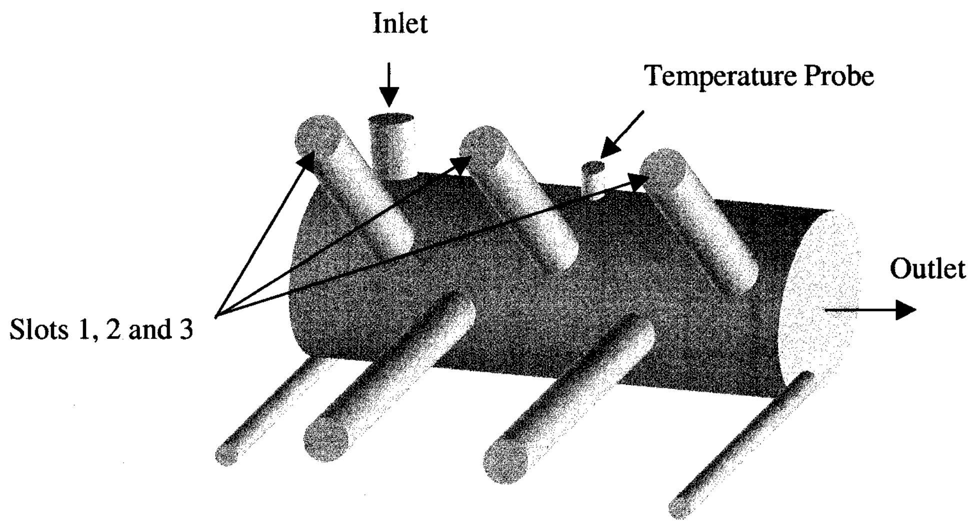


Figure 3.2: Schematic of the humidity sensor manifold

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 decrements. 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. The experimental test sequence used in this study for sensor accuracy was developed so that additional sensor characteristics, such as linearity, hysteresis and repeatability, could also be analyzed in a single test run.

A test run for a given sensor at a specified temperature produced 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 produced 10 data points at a given temperature, or 30 data points overall.

Experimental Test Procedure

During the tests, three sensors at a time were placed inside the manifold slots located inside the humidity generator. Preliminary tests were performed to evaluate any effects on relative humidity that might result from the relative position of each sensor installed in the manifold slots. These tests resulted in an error of less than 0.1% RH being observed due to the positioning of sensors, signifying that position effects are negligible.

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 3.3 and 3.4. The steady-state accuracy criteria in Table 3.3 required that the relative humidity and temperature were within ±0.5% RH and ±1.0°C of their respective set points for a 10-minute period. To satisfy the steady-state conditions in Table 3.4, the relative humidity and temperature of the humidity generator were not allowed to vary by more than ±0.5% and ±0.1°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 3.3. A detailed plot of typical relative humidities in the generator beginning 15 minutes after the step change is shown in Figure 3.4. Similarly, a detailed plot of temperatures beginning 15 minutes after the step change in RH is shown in Figure 3.5. 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.

Table 3.3: Steady-state accuracy criteria for relative humidity and temperature of the humidity generator

Parameter	Steady-state accuracy criteria
Actual Relative Humidity	Within $\pm$0.5% RH of set point for 10 minutes
Actual Manifold Temperature	Within $\pm$1.0°C of set point for 10 minutes

Table 3.4: Steady-state conditions for relative humidity and temperature of the humidity generator

Parameter	Steady-state conditions
Actual Relative humidity	Change of less than $\pm$0.5% RH for 10 minutes
Actual Manifold Temperature	Change of less than $\pm$0.1°C for 10 minutes

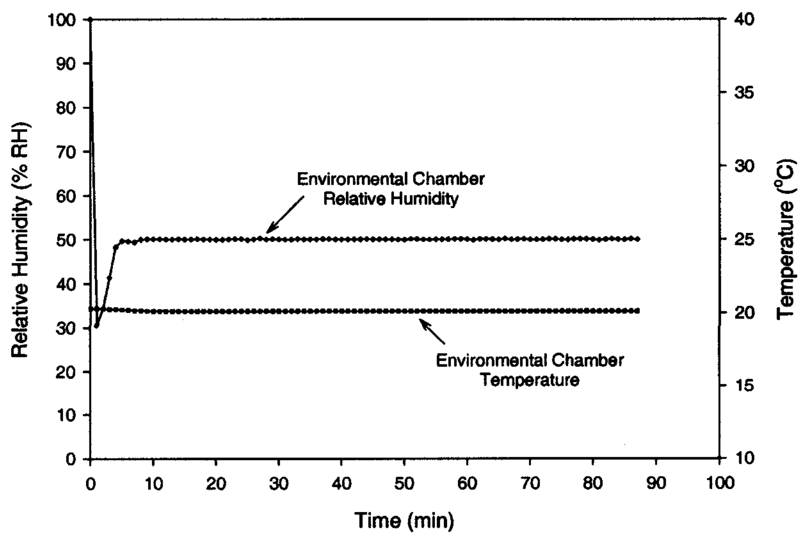


Figure 3.3: Plot of step change in relative humidity (from 30 to 50% RH) and temperature (20°C) versus time

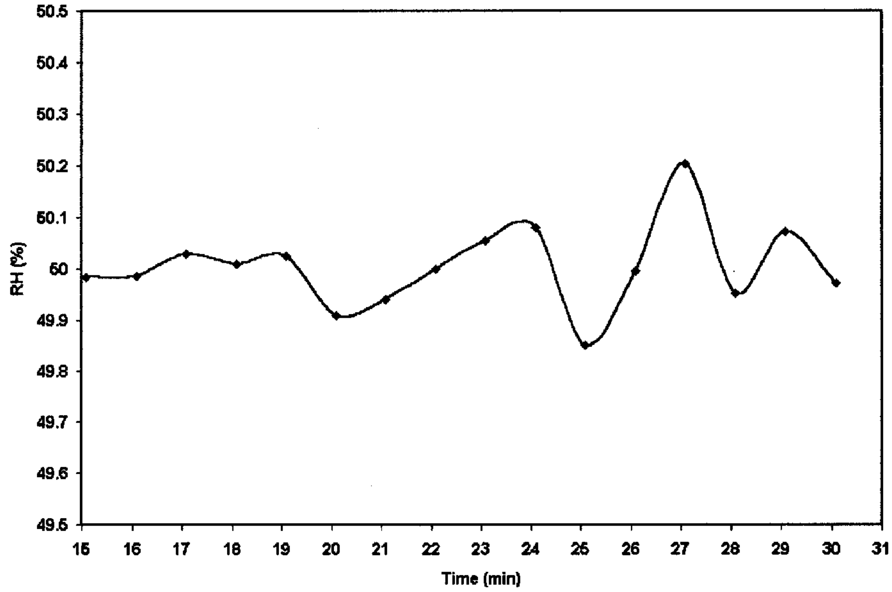


Figure 3.4: Variation of chamber relative humidity starting 15-minutes after a 20% RH step change in relative humidity

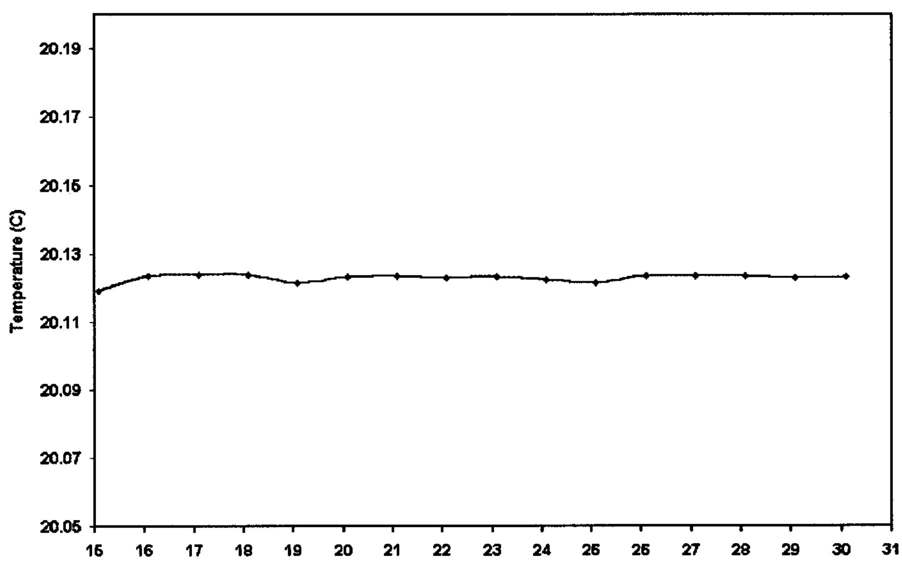


Figure 3.5: Variation of manifold temperature starting 15-minutes after a 20% RH step change in relative humidity

The sensor output was sampled at a frequency of 1 kHz, and 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 then used for further analysis.

Analysis of Performance Characteristics

Analysis of accuracy

The results of the accuracy analysis are presented in terms of the deviation of the pooled measured value from the actual value (e.g., deviation = $RH_{measured} - RH_{actual}$). The deviation of the pooled measured value represents the average deviation for all three sensors of a specific manufacturer at a given relative humidity and temperature. The data plots were used to investigate and analyze the accuracy of the humidity sensors. For example, a plot that compared pooled mean deviation and actual relative humidity from a single manufacturer at temperatures of 15°C, 25°C and 35°C were created.

Analysis of hysteresis

The test conditions used to evaluate hysteresis included measurements at 30%, 50% and 70%, with the humidity condition at specific temperatures being approached from both lower (i.e., forward measurements) and from higher humidities (i.e., reverse measurements). These measurements were then used to evaluate the hysteresis of a particular sensor model, and they are referred to as $RH_{30,1f}$, $RH_{30,1r}$, $RH_{50,1f}$, $RH_{50,1r}$, $RH_{70,1f}$, and $RH_{70,1r}$, corresponding to the first forward (subscript f) and reverse (subscript r) measurements obtained from a sensor model at a specific temperature. In particular, the pooled deviations of a sensor model at each of the three forward relative humidity conditions (i.e., $RH_{30,1f}$ $RH_{50,1f}$ and $RH_{70,1f}$) were determined at a specific temperature while similar pooled deviations were determined for the reverse relative humidity conditions (i.e., $RH_{30,1r}$ $RH_{50,1r}$ and $RH_{70,1r}$). The hysteresis for a sensor model at each specific temperature was then quantified as the differences of the pooled deviations obtained for the reverse and forward measurements at 30%, 50%, and 70% RH.

Analysis of repeatability

The test conditions used to evaluate repeatability include two measurements at 50% RH, with both measurements being taken as the relative humidity was increased (i.e., forward measurements). Specifically, these measurements were identified as $RH_{50,1f}$ and $RH_{50,2f}$, corresponding to the first and second forward measurements obtained from a particular sensor at a particular temperature.

Analysis of linearity

The linearity of each sensor was evaluated by determining the extent to which the pooled-mean values of relative humidity departed from the best-fit line through the origin. Specifically, a best-fit line through the origin was determined by using these pooled mean values. The nonlinearity of a sensor model was then quantified as the deviation of the pooled mean values from the best-fit straight line.

CHAPTER 4: RESULTS OF PERFORMANCE CHARACTERISTICS

Overview

Sensor performance can be characterized by the sensor accuracy, linearity, hysteresis and repeatability. *Accuracy* represents the deviation of the measured relative humidity value from the actual relative humidity. *Repeatability* represents the measure of the agreement between successive measurements when returning to the same conditions of measurement. *Hysteresis* of the sensor is a measure of the difference between sensor readings at the same relative humidity level when that condition is approached from a higher and a lower relative humidity. *Linearity* is defined as the departure of the measured relative humidity from the best-fit line through the origin. The test results described herein were obtained by performing experiments as described in Chapter 3.

Accuracy

The results of the accuracy analysis are presented in terms of the deviation of the pooled measured value from the actual value (e.g., deviation = $RH_{measured}$ – RH_{actual}). The deviation of the pooled measured value represents the average deviation for all three sensors of a specific manufacturer at a given relative humidity and temperature.

Analysis of deviations for each model

The analysis of deviations for each model is presented in this section. In particular, discussions on the effect of relative humidity on deviation, performance accuracy and effect of temperature on deviation for each model are presented below. It should be noted that the performance accuracy of the sensors reported herein is compared with the manufacturer specified accuracy at 25°C. The reason for selecting this temperature is that most manufacturers report the sensor accuracy at 25°C (see Table 3.1), however, discussions of the performance accuracy at 15°C and 35°C are also presented.

Model-A (capacitive type)

The deviations of the measured relative humidity from the actual relative humidity for the three Model-A sensors at 25°C are presented graphically in Figure 4.1. In addition, pooled deviations corresponding to Model-A are presented in Figure 4.2 at 15°C, 25°C and 35°C.

Effect of relative humidity on deviation. The sensitivity of the deviation to relative humidity is evident in both Figures 4.1 and 4.2. The deviation shifts upwards when the actual relative humidity is increased from 10% to 30% while the deviation shifts downwards when the actual relative humidity is increased from 30% to 90% for the three sensors at each of the three different temperatures. For example, the deviation for the forward measurement of sensor 1 at 25°C increases from -0.2% to 1.3% when the actual humidity is increased from 10% to 30% (see Figure 4.1) while the deviation decreases from 1.3% to -2.1% when the humidity is increased from 30% to 90%. This same trend is seen at all temperatures in Figure 4.2.

Performance accuracy. The manufacturer stated accuracy for the Model-A sensor is ±3% at 25°C for a relative humidity range of 20%-80%. The accuracy is not stated at 15°C and 35°C.

The performance of Model-A can be evaluated by considering the pooled deviations in Figure 4.2. At 25°C, the pooled deviations are within the manufacturer stated range of ±3% at relative humidities of 50% and 70%. The pooled deviation is 4.1% at a relative humidity of 30%, which does not meet the manufacturer stated accuracy.

At 35°C, the pooled deviations are within ±3% over a relative humidity range of 10%-70% while the deviation is -3.6% at a relative humidity of 90%. At 15°C, the deviations are within ±3% for relative humidities of 70% and 90% while the deviations are 5.1%, 6.6% and 4.7% at relative humidities of 10%, 30% and 50%, respectively.

Effect of temperature on deviation. The dependence of the pooled deviations on temperature is evident from Figure 4.2. At all relative humidity conditions, the data points corresponding to 15°C are located above the data points for 25°C, which in turn are located above the data points for 35°C. This indicates that for a given actual relative humidity the average measurement of the relative humidity decreases with increasing temperature. For example, at 10% relative humidity, the average deviations are 5.1%, 2.7% and 1.1% corresponding to 15°C, 25°C and 35°C, respectively.

Model-B (capacitive type)

Deviations of all three Model-B sensors at 25°C are shown in Figure 4.3 while pooled deviations at 15°C, 25°C and 35°C are shown in Figure 4.4.

Effect of relative humidity on deviation. The sensitivity of the deviation to relative humidity is evident in both Figures 4.3 and 4.4. The deviation generally shifts upwards when the actual humidity is increased from 10% to 50% while the deviation shifts downwards when the actual humidity is increased from 50% to 90% for the three sensors at each of the three different temperatures. For example, the deviation of the forward measurement for sensor 1 at 25°C increases from -4.1% to 3.0% when the actual humidity is increased from 10% to 50% (see Figure 4.3) while the deviation in humidity decreases from 3.0% to -2.1% when the humidity is increased from 50% to 90%. This same trend is seen at all temperatures in Figure 4.4.

Performance accuracy. The specification of accuracy provided by Model-B sensor is ±3% for a relative humidity range of 10%-90%. The accuracy is not stated at a particular temperature.

The performance of Model-B can be evaluated by considering the pooled deviations in Figure 4.4. At 25°C, the deviations are within the specified accuracy of ±3% for relative humidities of 30% and 70% while the deviations are -3.9%, 3.3% and -4.5% at relative humidities of 10%, 50% and 90%, respectively.

At 35°C, the deviations are within ±3% for a relative humidity range of 30%-70% while the deviations are -5.5% and -6.4% at relative humidities of 10% and 90%, respectively. At 15°C, the deviations are within ±3% for relative humidities of

10% and 90% while the deviations are 5.9%, 6.1% and 3.3% at relative humidities of 30%, 50% and 70%, respectively.

Effect of temperature on deviation. The dependence of the pooled deviations on temperature is evident from Figure 4.4. At all relative humidity conditions, the data points corresponding to 15°C are located above the data points for 25°C, which in turn are located above the data points for 35°C. This indicates that for a given actual relative humidity, the average measurement of the relative humidity decreases with increasing temperature. For example, at 10% relative humidity, the deviations are -1.7%, -3.9% and –5.5% corresponding to temperatures of 15°C, 25°C and 35°C, respectively.

Model-C (capacitive-type)

Deviations of all three Model-C sensors at 25°C are shown in Figure 4.5 while pooled deviations at 15°C, 25°C and 35°C are shown in Figure 4.6.

Effect of relative humidity on deviation. The sensitivity of the deviation to relative humidity is evident in both Figures 4.5 and 4.6. The deviation generally shifts downwards when the actual humidity is changed from 10% to 30%, then the deviation is almost constant for a 30% to 70% humidity range and, finally, it shifts downwards when the humidity is increased from 70% to 90% for the three sensors at each of the three different temperatures. For example, the deviation for the forward measurement of sensor 1 at 25°C decreases from 0.6% to -0.7% when the actual humidity is increased from 10% to 30% and then the deviation changes by only 0.1% when the actual humidity is increased from 30% and 70% and, finally, the deviation decreases from -1.8% to -3.0% (see Figure 4.5) when the actual humidity increases from 70% to 90%. This same trend is seen at all temperatures in Figure 4.6.

Performance accuracy. The specification of accuracy provided by Model-C sensor is $\pm 3\%$ for a relative humidity range of 10%-90%. The accuracy is not stated at 15°C and 35°C.

The performance of Model-C can be evaluated by considering the pooled deviations in Figure 4.6. At 25°C, the deviations are within the manufacturer specification of $\pm 3\%$ for a relative humidity range of 10%-70% while the deviation is -4.1% at a relative humidity of 90%, which does not meet the manufacturer specified accuracy.

At 35°C, the deviations are within $\pm 3\%$ for a relative humidity range of 10%-50% while the deviations are -3.3% and -4.6% at relative humidities of 70% and 90%, respectively. At 15°C, the deviations are within $\pm 3\%$ for a relative humidity range of 10%- 70% and the deviation is -3.3% at a relative humidity of 90%.

Effect of temperature on deviation. The dependence of the pooled deviations on temperature is evident from Figure 4.6. At all relative humidity conditions, the data points corresponding to 15°C are located above the data points for 25°C, which in turn are located above the data points for 35°C. This indicates that for a given actual relative humidity, the average measurement of the relative humidity decreases with increasing temperature. For example, at 10% relative humidity, the deviations are 0.3%, 0.1% and -0.1% corresponding to 15°C, 25°C and 35°C, respectively.

Model-D (resistive-type)

Deviations of all three Model-D sensors at 25°C are shown in Figure 4.7 while pooled deviations at 15°C, 25°C and 35°C are shown in Figure 4.8.

Effect of relative humidity on deviation. The sensitivity of the deviation to relative humidity is evident in both Figures 7 and 8. The deviation generally shifts upwards when the actual humidity is increased from 10% to 70% and the deviation shifts downwards when the actual humidity is increased from 70% to 90% for the three sensors at each of the three different temperatures. For example, the deviation for the forward measurement of sensor 1 at 25°C increases from -0.7% to 1.4% when the actual humidity is increased from 10% to 70% (see Figure 4.7) and the deviation decreases from 1.4% to 0.7% when the actual humidity increases from 70% to 90%.

Performance accuracy. The specification of accuracy provided by Model-D sensor is $\pm 3\%$ for a relative humidity range of 20%-95%. The accuracy is not stated at a particular temperature.

The performance of Model-D can be evaluated by considering the pooled deviations in Figure 4.8. At 25°C, the deviations are within the specified accuracy of $\pm 3\%$ for a relative humidity range of 10%-90%.

At 35°C, the deviations are within the $\pm 3\%$ for a relative humidity range of 10-90%. At 15°C, the deviations are within $\pm 3\%$ for a relative humidity range 30%-90% and the deviation is 4.8% at a relative humidity of 10%.

Effect of temperature on deviation. The dependence of the pooled deviations on temperature is shown in Figure 4.8. A downward shift in deviation occurs for the three sensors at 10% relative humidity as the temperature increases from 15°C to 35°C. For example, at 10% relative humidity, the deviations are 4.9%, 1.2% and -1.1% corresponding to 15°C, 25°C and 35°C, respectively. There is no obvious effect of temperature on deviation in the 30% to 90% humidity range as seen from Figure 4.8.

Model-E (resistive-type)

Deviations of all three Model-E sensors at 25°C are shown in Figure 4.9 while pooled deviations at 15°C, 25°C and 35°C are shown in Figure 4.10.

Effect of relative humidity on deviation. The sensitivity of the deviation to relative humidity is evident in both Figures 4.9 and 4.10. The deviation generally shifts downwards when the actual humidity is increased from 10% to 70% while the deviation shifts upwards when the actual relative humidity is increased from 70% to 90% for the three sensors at each of the three different temperatures. For example, the deviation for the forward measurement of sensor 1 at 25°C decreases from -1.5% to -10.1% at 25°C when the actual humidity is increased from 10 to 70% (see Figure 4.9) while the deviation in humidity increases from -10.1% to -6.7% when the humidity is increased from 70% to 90%.

Performance accuracy. The specification of accuracy provided by Model-E sensor is ±3% at 25°C for a relative humidity range of 15%-95%. The accuracy is not stated at a particular temperature.

The performance of Model-E can be evaluated by considering the pooled deviations in Figure 4.10. At 25°C, the deviations are outside the specified accuracy of $\pm 3\%$ and are -5.5%, -7.9%, -9.3% and -8.6% at relative humidities of 30%, 50%, 70% and 90%, respectively.

At 35°C, the deviations are -3.6%, -6.6%, -9.2%, -10.0% and -10.7% at relative humidities of 10%, 30%, 50%, 70% and 90%, respectively. At 15°C, the deviations are -3.2%, -5.7%, -8.1%, -8.9% and -7.7% at relative humidities of 10%, 30%, 50%, 70% and 90%, respectively.

Effect of temperature on deviation. The dependence of the pooled deviations on temperature is shown in Figure 4.10. For a 10% to 70% relative humidity range, the data points corresponding to 25°C are located above the data points for 15°C, which in turn are located above the data points for 35°C while for the relative humidity changing from 70% to 90%, the data points corresponding to 15°C are located above the data points for 25°C, which in turn are located above the data points for 35°C. Hence, there is no obvious effect of temperature on deviation in the 30% to 70% humidity range as seen from Figure 4.10.

Model-F (resistive-type)

Deviations of all three Model-F sensors at 25°C are shown in Figure 4.11 while pooled deviations at 15°C, 25°C and 35°C are shown in Figure 4.12.

Effect of relative humidity on deviation. The sensitivity of the deviation to relative humidity is evident in both Figures 4.11 and 4.12. The deviation generally shifts upwards when the actual humidity is increased from 10% to 30% while the deviation shifts downwards when the actual humidity is increased from 30% to 90% for the three sensors at each of the three different temperatures. At 15°C, the deviation shifts downward for the entire relative humidity range. For example, the deviation for the forward measurement of sensor 1 at 25°C increases from -4.0% to 1.2% when the actual humidity is increased from 10% to 30% (see Figure 4.11) while the deviation in humidity decreases from 1.2% to -2.0% when the humidity is increased from 30% to 90%.

Performance accuracy. The specification of accuracy provided by Model-F sensor is $\pm 3\%$ at 25°C for a relative humidity range of 15%-95%. The accuracy is not stated at 15°C and 35°C.

The performance of Model-F can be evaluated by considering the pooled deviations in Figure 4.12. At 25°C, the deviations are within the manufacturer specification of $\pm 3\%$ for a relative humidity range of 30%-90%.

At 35°C, the deviations are within $\pm 3\%$ for a relative humidity range of 30%-70% and the deviations are -8.1% and -3.7% at relative humidities of 10% and 90%, respectively. At 15°C, the deviations are within $\pm 3\%$ for a relative humidity range of 50%-90%, and 5.7% and 4.2% at relative humidities of 10% and 30%, respectively.

Effect of temperature on deviation. The dependence of the pooled deviations on temperature is evident from Figure 4.12. At all relative humidity conditions, the data points corresponding to 15°C are located above the data points for 25°C, which in turn are located above the data points for 35°C. This indicates that for a given actual relative humidity, the average measurement of the relative humidity decreases with increasing temperature. For example, at 10% relative humidity, the deviations are 5.7%, -0.1% and -8.0% corresponding to 15°C, 25°C and 35°C, respectively.

Summary of results

Performance accuracy

In summary, at 25°C, two of the six humidity sensors, namely Model-D (i.e., resistive type) and Model-F (i.e., resistive types) sensors, are within specified accuracy of $\pm 3\%$ for the entire 10% to 90% humidity range. For each of the other sensors, the specified accuracy was satisfied for only part of the humidity range. For example, at 25°C, Model-C (i.e., capacitive type) sensors are within $\pm 3\%$ accuracy for a 10%-70% humidity range, however they are outside of the specified accuracy range at 90% humidity. Furthermore, for Model-E (i.e., resistive type) sensors, the specified accuracy is $\pm 3\%$ for a 15%-95% humidity range, however measured deviations are outside of the specified accuracy for the full humidity range. Model-A (i.e., capacitive type) sensors are within $\pm 3\%$ for a 20%-80% humidity range while the deviations are outside of the specified accuracy range at 30% relative humidity. Model-B (i.e., capacitive type) sensors are within the $\pm 3\%$ accuracy at 30% and 70% humidity, however they are outside of the specified accuracy range at 10%, 50%, and 90%.

Effect of relative humidity

In summary, it was observed that the deviations showed sensitivity to values in actual relative humidity over the entire range. Further, the deviations from the three sensors for each manufacturer's model follow similar patterns over the entire range of humidities. However, no obvious trends in deviations are observed among the sensor models of different manufacturers. For example, the deviation of the

Model-A sensor shifts upwards when the actual relative humidity is increased from 10% to 30% while the deviation shifts downwards when the actual relative humidity is increased from 30% to 90%. In contrast, for Model-C sensor, the deviation generally shifts downwards when the actual humidity is changed from 10% to 30%, then the deviation is almost constant for a 30% to 70% humidity range, and finally it shifts downwards when the humidity is increased from 70% to 90%.

Effect of temperature

In summary, the accuracy testing also revealed a significant and consistent temperature dependency for Model-A, B, C and F. For example, at all relative humidity conditions, the measured values for Model-A corresponding to 15°C are higher than those for 25°C, which in turn are higher than those for 35°C. The same is true for Model-B, C and F. Sensitivity to temperature is generally not addressed by manufacturer literature and, as evidenced by the results of this study, temperature can have an impact on sensor accuracy.

Comparison of resistive and capacitive sensors

As previously mentioned, the most commonly used humidity sensors in building HVAC systems are the capacitive and the resistive type relative humidity sensors. One of the advantages of capacitive-type sensors includes being accurate in the low RH (<15%) range while the advantages of resistive-type sensors includes being accurate in the high RH (>90%) range (Wiederhold, 1997). Similar trends were found in the study reported herein in that it was observed that at 25°C, capacitive sensors meet the manufacturer specified accuracy in the low RH (i.e., at 10% RH) range while the resistive sensors meet the manufacturer specified accuracy in the high RH (i.e., at 90% RH) range. For example, two of the three capacitive sensor models, namely models A and C, meets the manufacturer specified accuracy at low humidity (see Figures 4.2 and 4.6) and two of the three resistive sensor models, namely models D and F, meets the manufacturer specified accuracy at high humidity (see Figures 4.8 and 4.12).

In addition, the accuracy of both the capacitive sensors (i.e., models A, B and C) and the resistive sensors (i.e., models D, E and F) show sensitivity to values in relative humidity. However, no common pattern in variation is observed between the capacitive and resistive sensors. For example, at 25°C, the deviation for Model-A sensor shifts upwards when the actual relative humidity is increased from 10% to 30% while the deviation shifts downwards when the actual relative humidity is increased from 30% to 90%. In contrast, for Model-E sensor, the deviation shifts downwards when the actual humidity is increased from 10% to 70% while the deviation shifts upwards when the actual humidity is increased from 70% to 90%.

Furthermore, the deviations of both the capacitive sensors (i.e., models A, B and C) and the resistive sensors (i.e., models D, E and F) show sensitivity to values in temperatures. For example, the average measurement of the relative humidity for Model-C sensor decreases with increasing temperature for a given actual relative humidity while there is no obvious effect of temperature on deviation seen for Model-E sensor over a 30-70% humidity range.

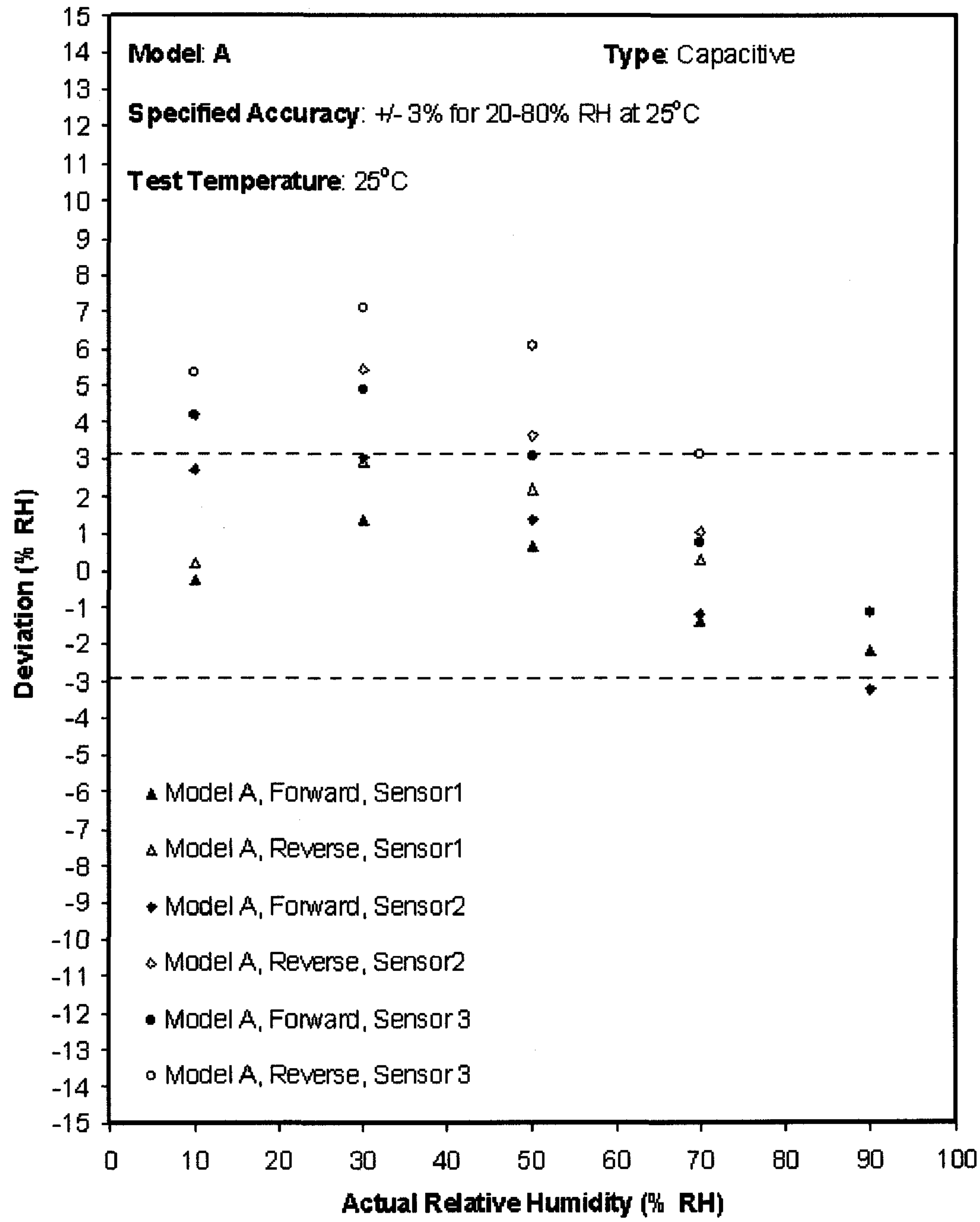


Figure 4.1: Comparison of deviation from actual relative humidity for three Model-A sensors at 25°C

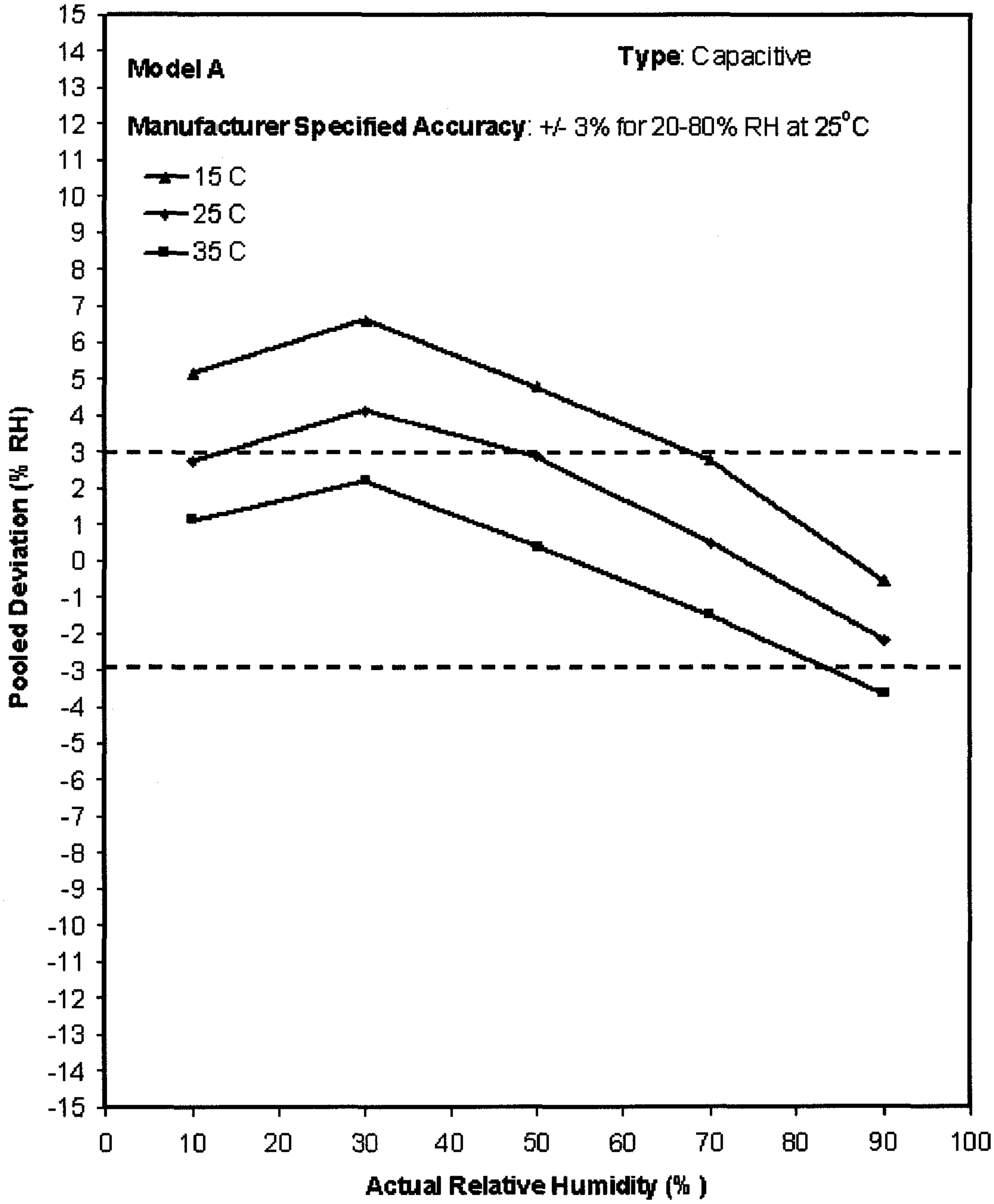


Figure 4.2: Comparison of pooled deviation from actual relative humidity for Model-A sensors

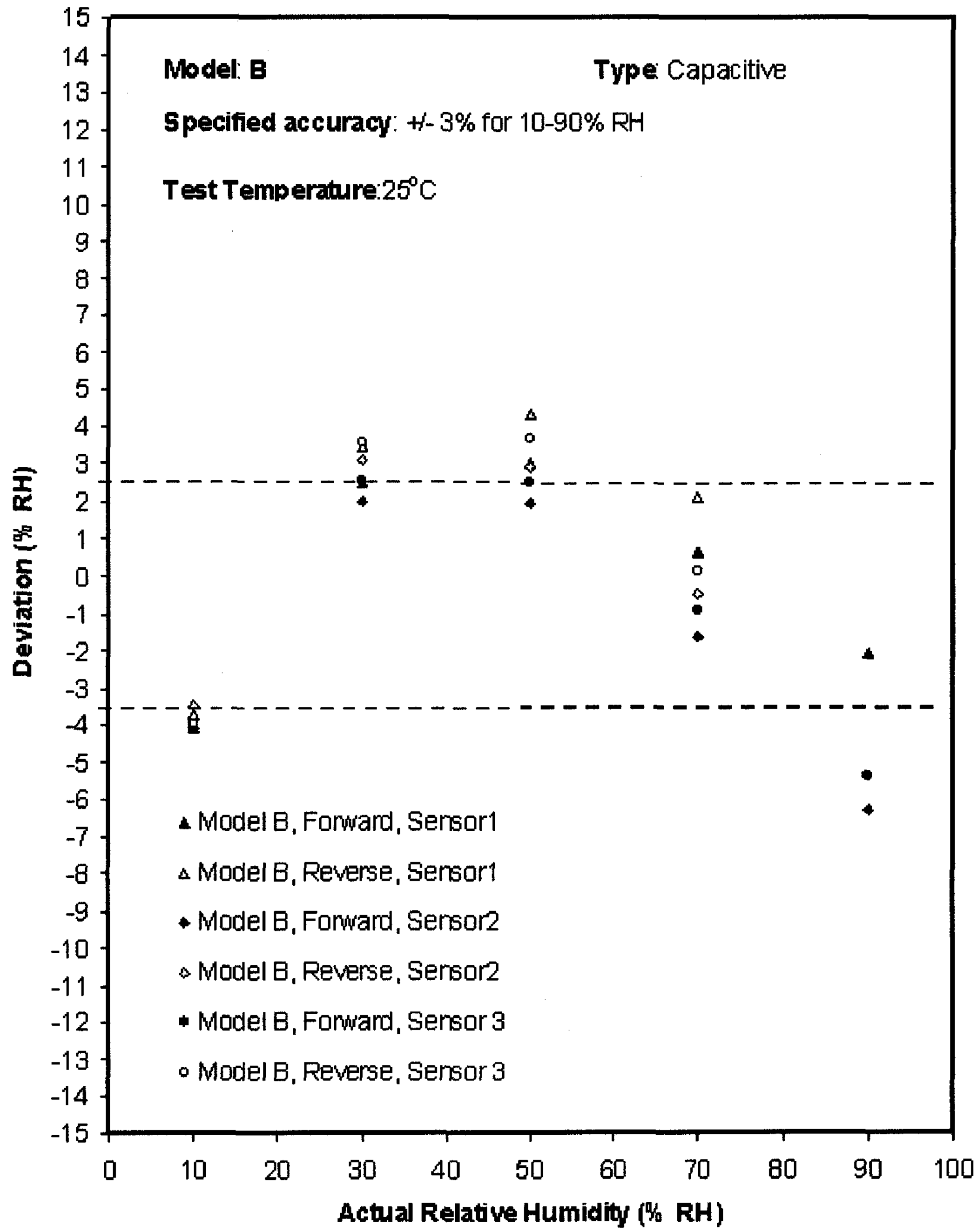


Figure 4.3: Comparison of deviation from actual relative humidity for three Model-B sensors at 25°C

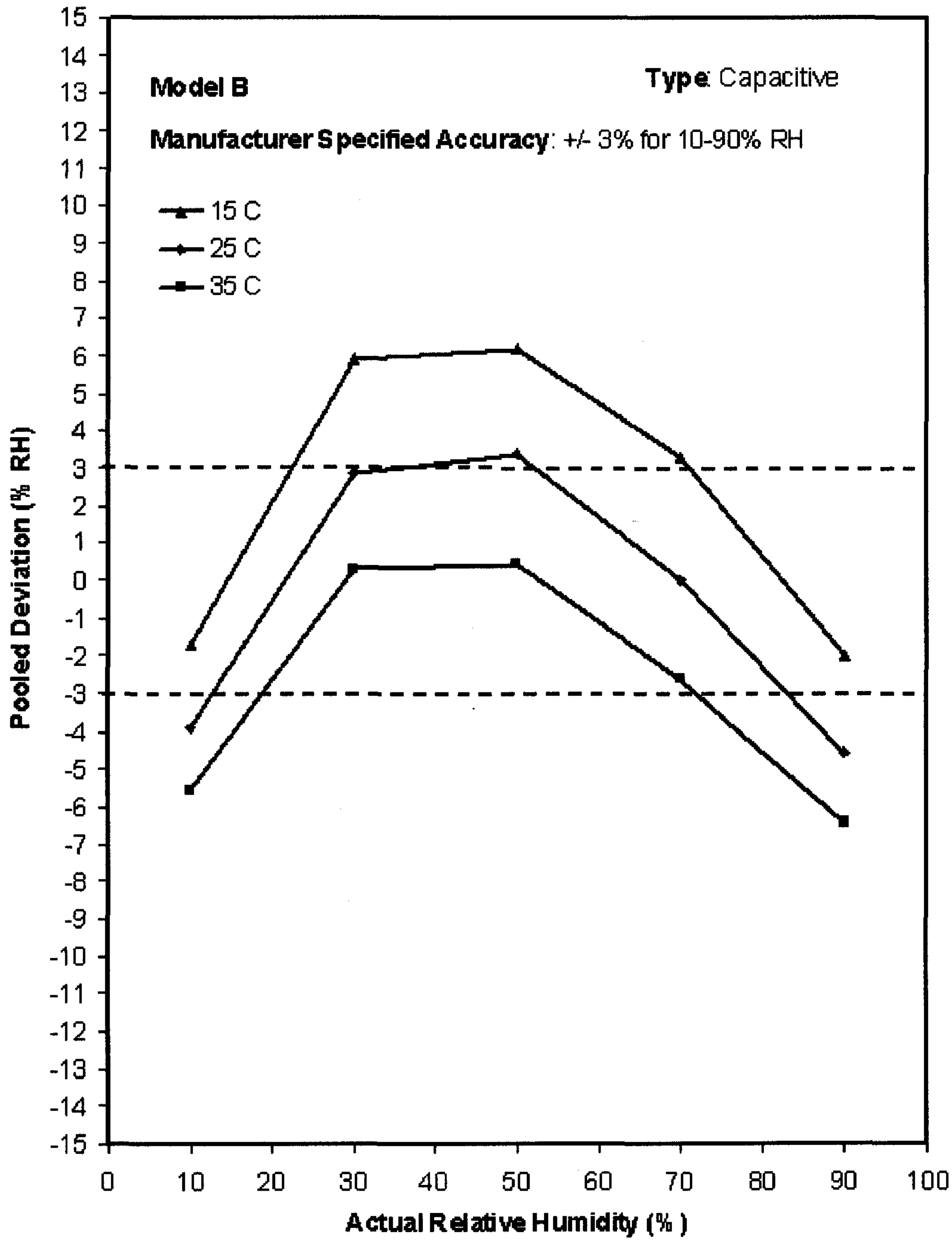


Figure 4.4: Comparison of pooled deviation from actual relative humidity for three Model-B sensors

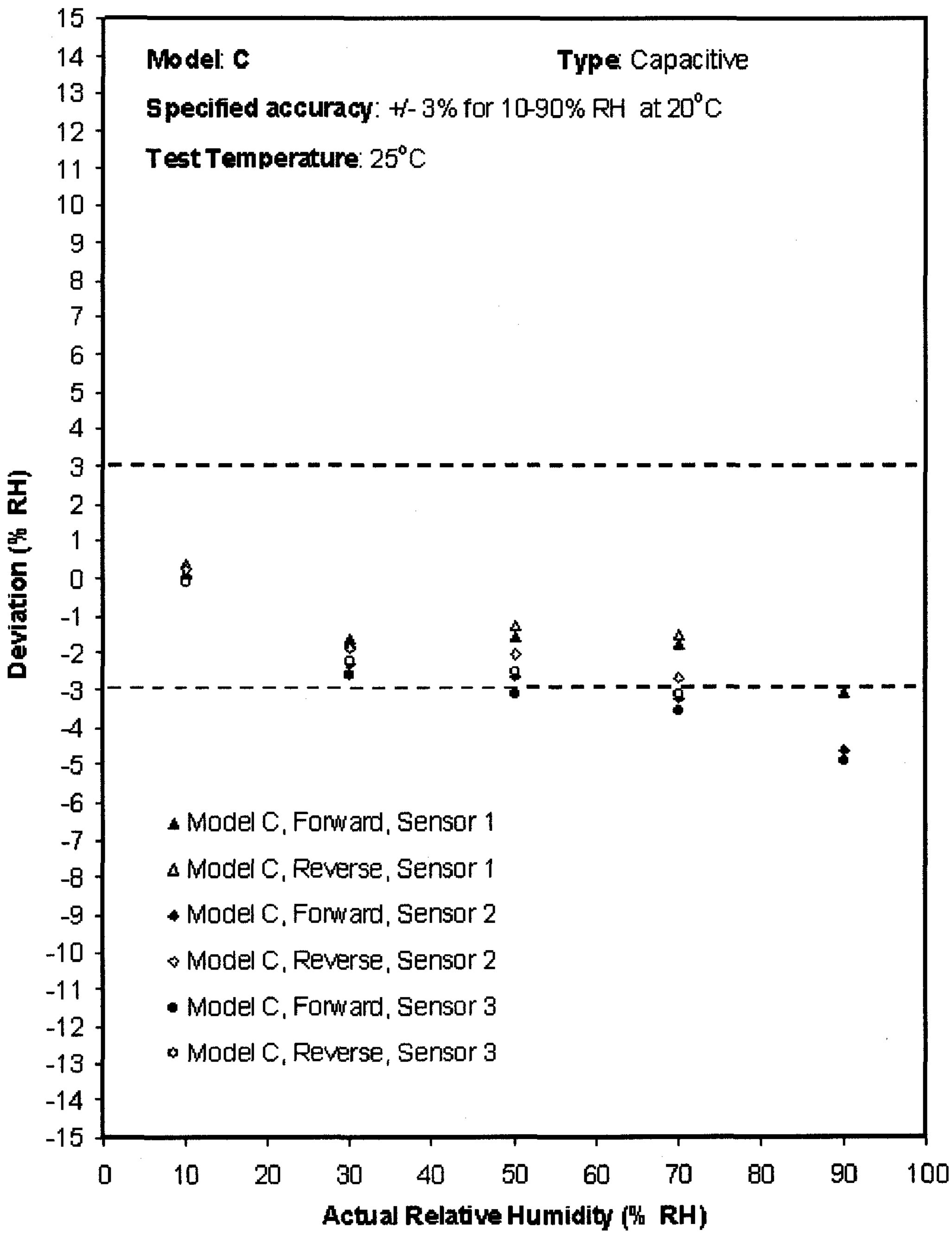


Figure 4.5: Comparison of deviation from actual relative humidity for three Model-C sensors at 25°C

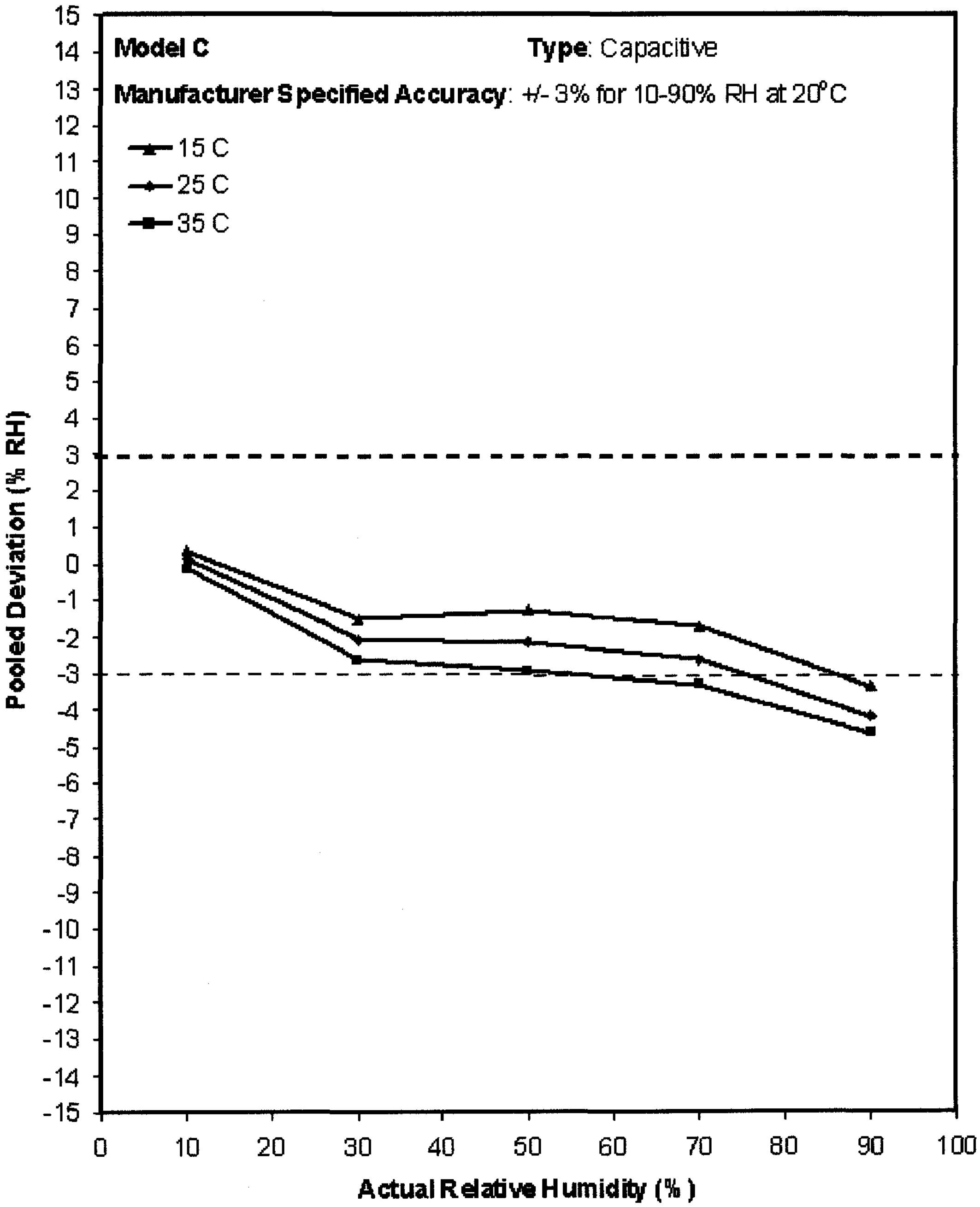


Figure 4.6: Comparison of pooled deviation from actual relative humidity for three Model-C sensors

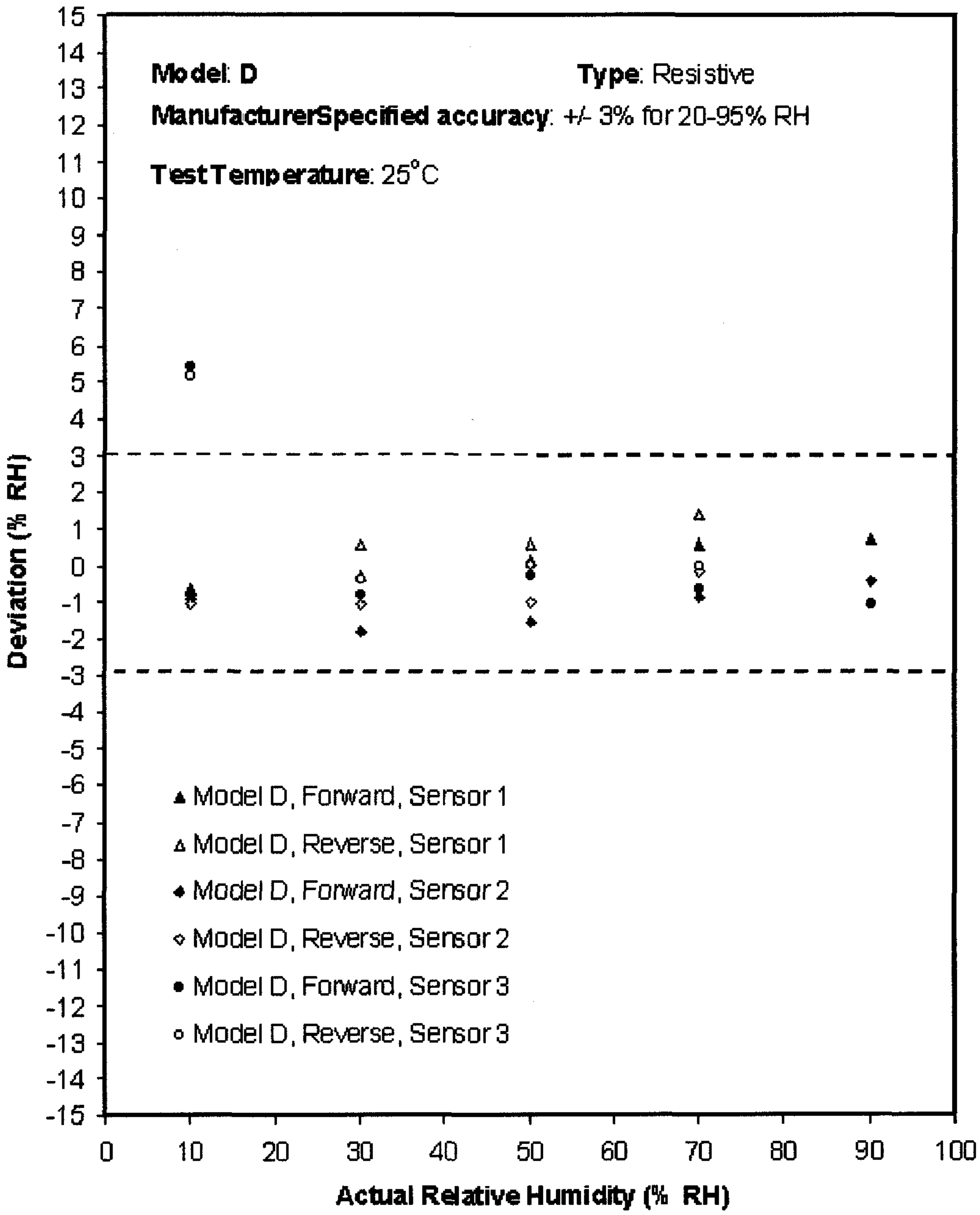


Figure 4.7: Comparison of deviation from actual relative humidity for three Model-D sensors at 25°C

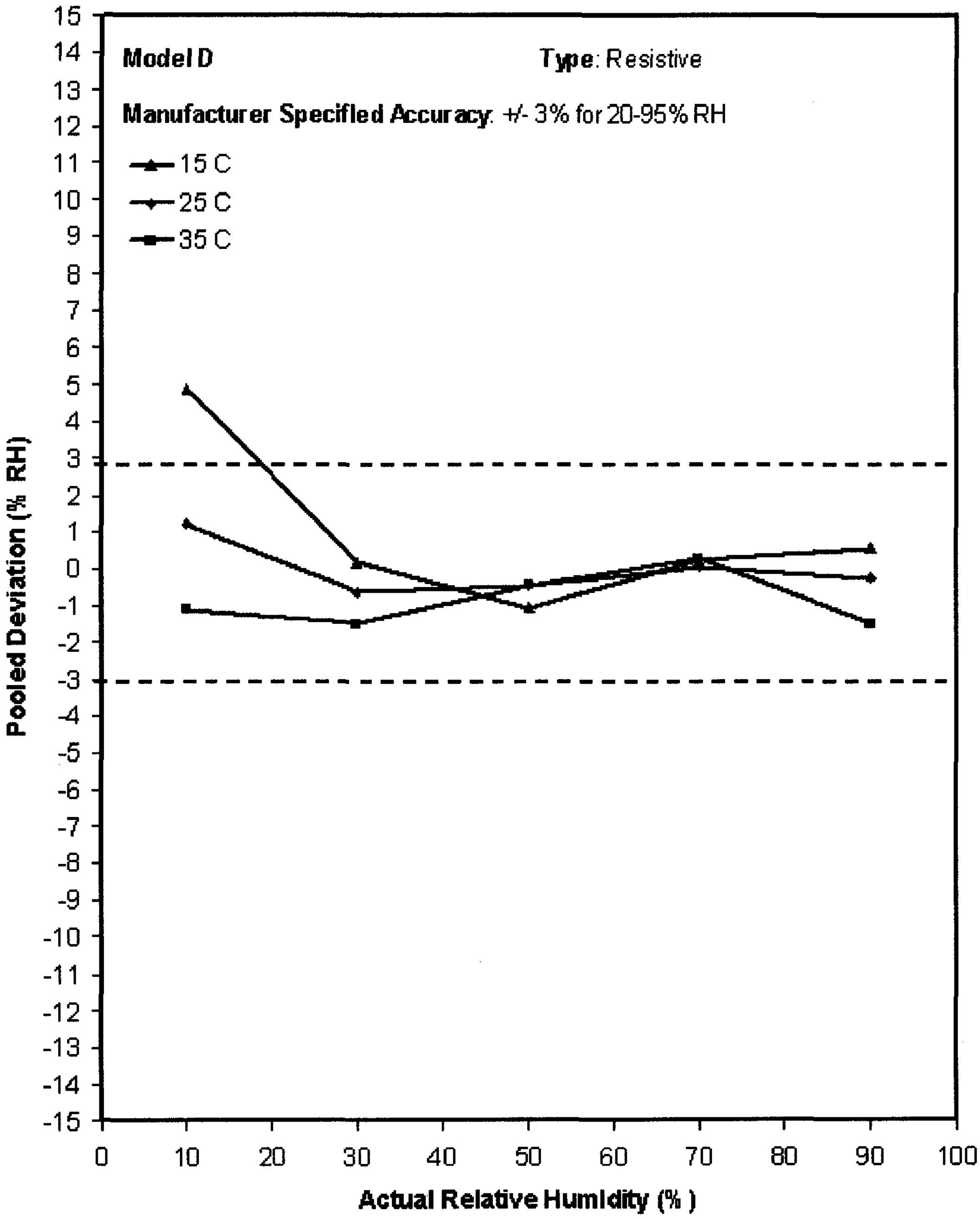


Figure 4.8: Comparison of pooled deviation from actual relative humidity for three Model-D sensors

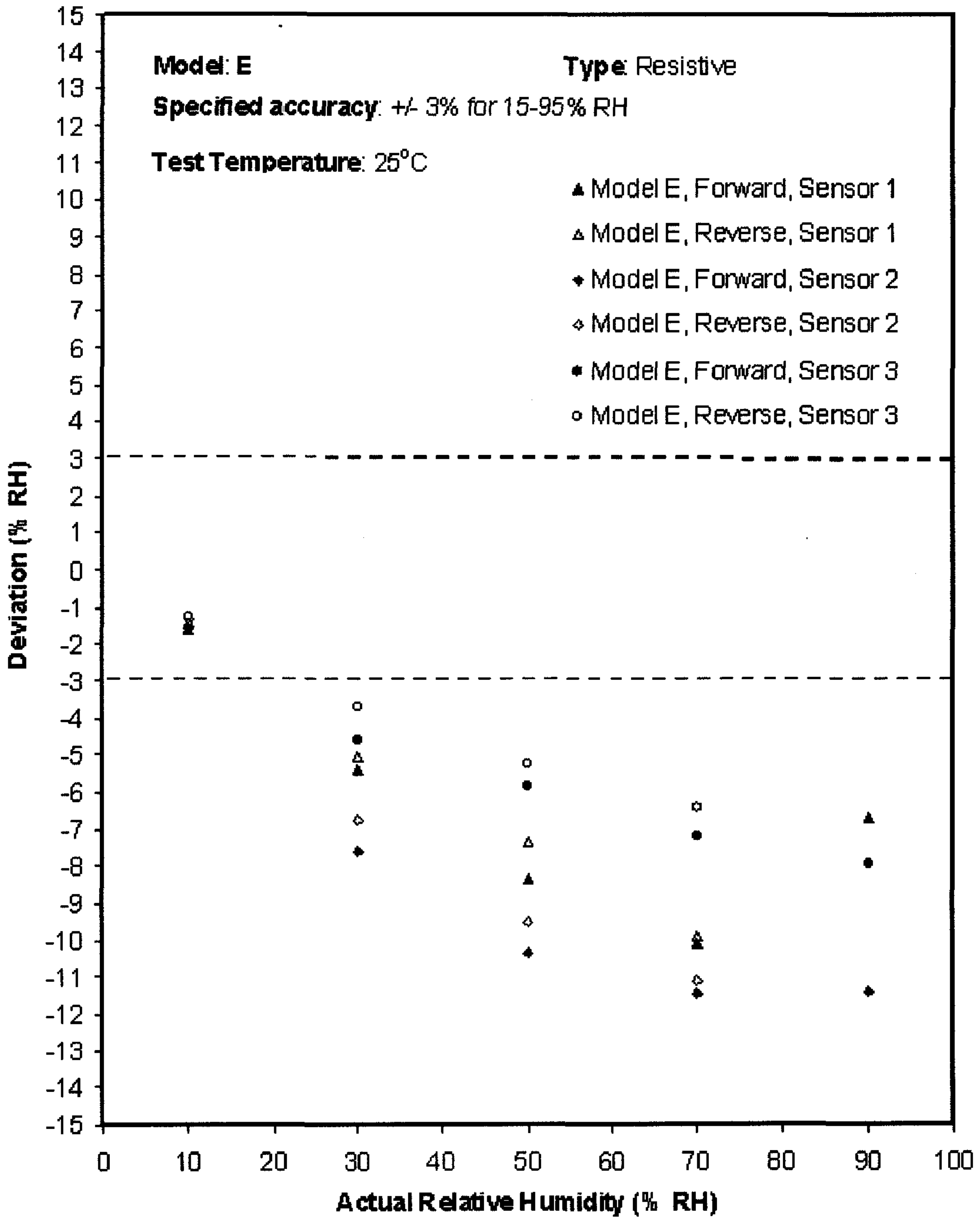


Figure 4.9: Comparison of deviation from actual relative humidity for three Model-E sensors at 25°C

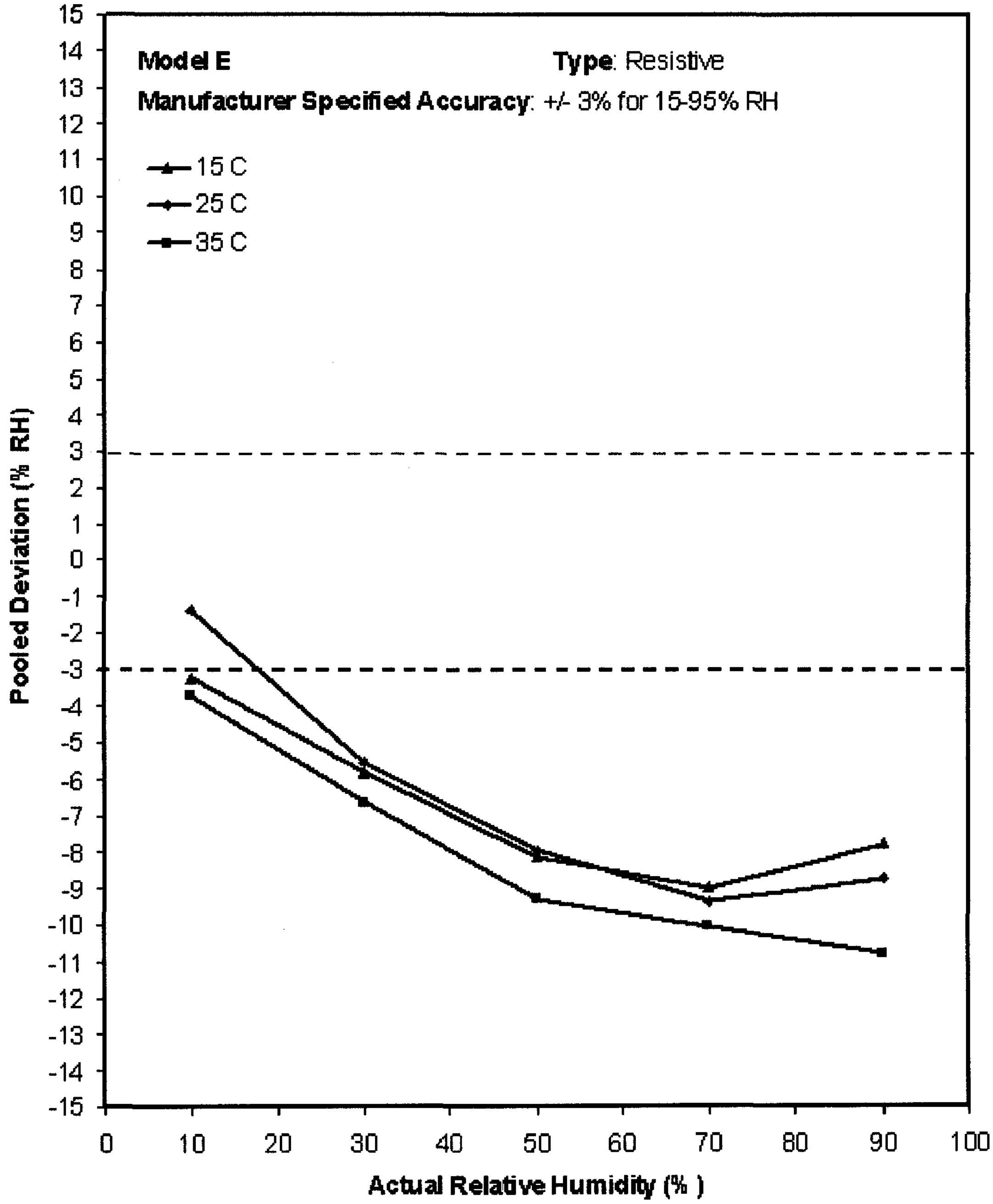


Figure 4.10: Comparison of pooled deviation from actual relative humidity for three Model-E sensors

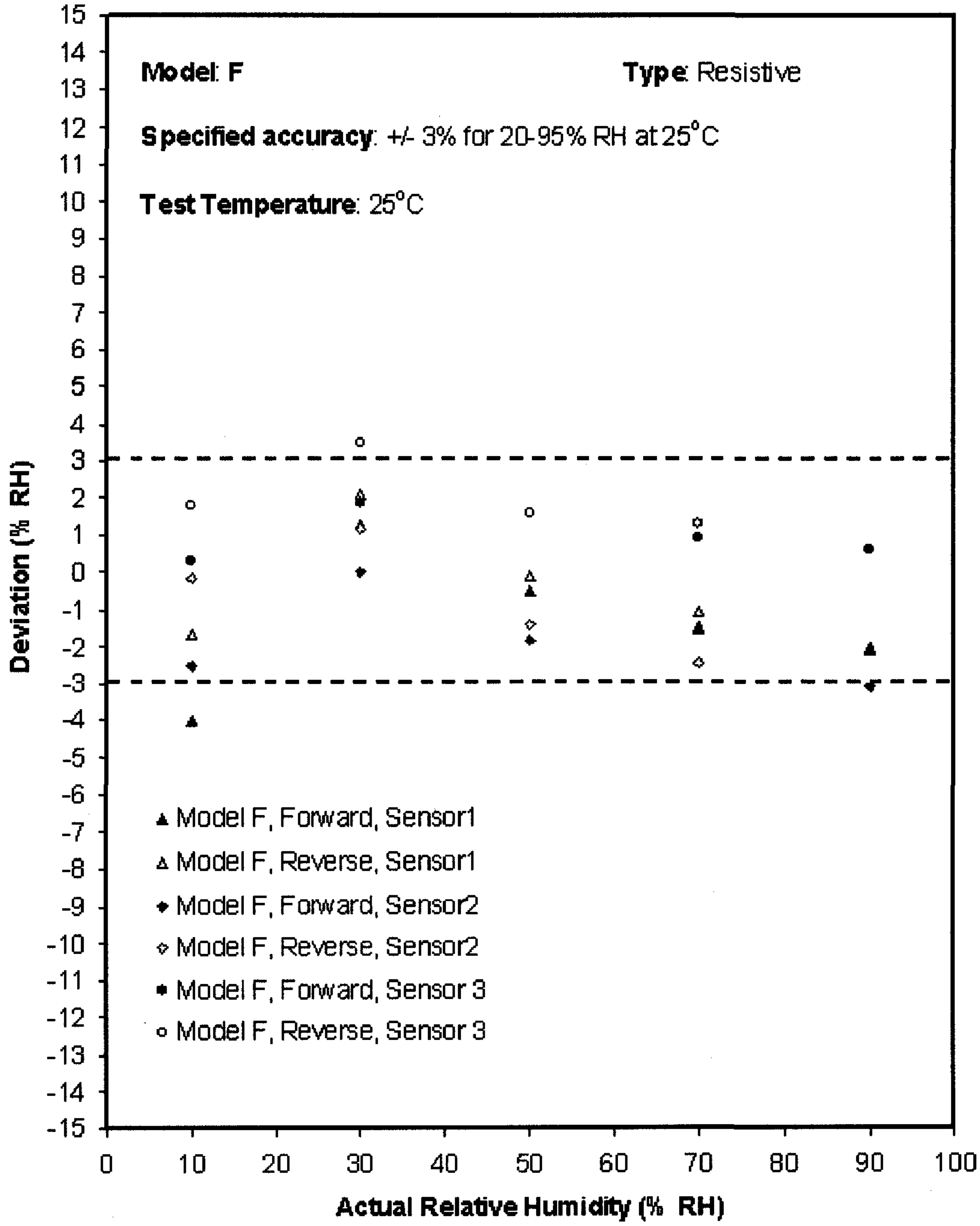


Figure 4.11: Comparison of deviation from actual relative humidity for three Model-F sensors at 25°C

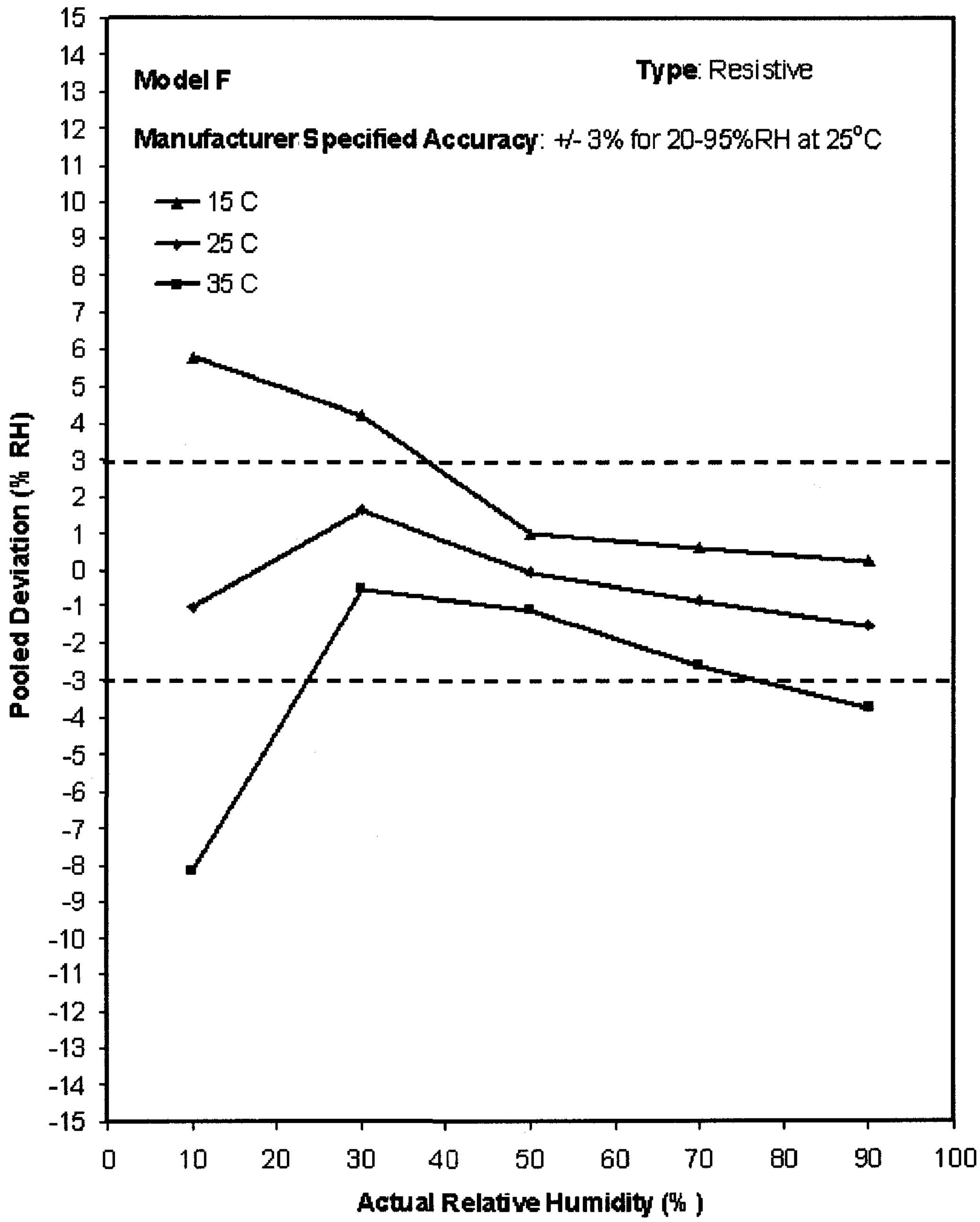


Figure 4.12: Comparison of pooled deviation from actual relative humidity for three Model-F sensors

Repeatability

The repeatability of each sensor is evaluated using two relative humidity measurements at 50% RH at each of three temperatures, namely, 15°C, 25°C and 35°C. The evaluation procedure is described in Chapter 3. The results of the repeatability study are discussed below.

Repeatability of each sensor model from a manufacturer

The repeatability of a sensor was evaluated by comparing two relative humidity measurements at the same relative humidity and temperature conditions. Specifically, the repeatability of each sensor model from a manufacturer is defined as the difference between the first forward and the second forward measurements at a relative humidity of 50% RH.

Model-A

The repeatability results of three sensor units from Model-A manufacturer at relative humidity of 50% RH and at temperatures of 15°C, 25°C and 35°C are shown in Table 4.1. In Table 4.1 'Diff.' represents the magnitude of difference between the first forward and second forward readings.

As shown in Table 4.1, the errors in repeatability at 15°C varied between 0.1% RH to 0.5% RH with the error being least for sensor unit I (0.1% RH) and most (0.5% RH) for sensor unit III.

Further, the error in repeatability at 25°C remained the same (i.e., 0.4% RH) for sensor units II and III. In addition, the error in repeatability is greater for sensor unit I compared to sensor units II and III, 2.9% RH.

Finally, the errors in repeatability at 35°C are almost same for sensor units I, II and III with the errors being 0.2% RH, 0.3% RH and 0.1% RH, respectively.

Table 4.1: Repeatability of Model-A relative humidity sensors at 50% RH and at temperatures of 15°C, 25°C and 35°C

Sensor Units	15 (°C)			25 (°C)			35 (°C)		
	1st Fwd. (% RH)	2nd Fwd. (% RH)	Diff.	1st Fwd. (% RH)	2nd Fwd. (% RH)	Diff.	1st Fwd (% RH)	2nd Fwd. (% RH)	Diff.
I	53.7	53.6	0.1	50.7	53.6	2.9	48.0	47.8	0.2
II	53.5	53.8	0.3	51.4	51.8	0.4	49.0	49.3	0.3
III	53.8	54.3	0.5	53.1	53.5	0.4	52.1	52.2	0.1

Diff.: 1st Forward – 2nd Forward

Model-B

The repeatability results of three sensor units from Model-B manufacturer at relative humidity of 50% RH and at temperatures of 15°C, 25°C and 35°C are shown in Table 4.2. In Table 4.2 'Diff.' represents the magnitude of difference between the first forward and second forward readings.

The error in repeatability at 15°C remained the same (i.e., 0.5% RH) for sensor units II and III while the error is smaller by 0.3% RH for sensor unit I.

Further, the errors in repeatability at 25°C are almost the same for sensor units II and III with the error being 0.3% RH for sensor unit II and 0.4% RH for sensor unit III. In addition, the error in repeatability is greater for sensor unit I compared to sensor units II and III, 3.8% RH.

Finally, the errors in repeatability at 35°C remained the same for sensor units I and II with the error being 0.3% RH. The error in repeatability is greater for sensor unit III compared to sensor units I and II, 2.8% RH.

Table 4.2: Repeatability of Model-B relative humidity sensors at 50% RH and at temperatures of 15°C, 25°C and 35°C

Sensor units	15 (°C)			25 (°C)			35 (°C)		
	1st Fwd. (% RH)	2nd Fwd. (% RH)	Diff.	1st Fwd. (% RH)	2nd Fwd. (% RH)	Diff.	1st Fwd (% RH)	2nd Fwd. (% RH)	Diff.
I	57.0	56.8	0.2	53.0	56.8	3.8	49.5	49.8	0.3
II	54.7	55.2	0.5	51.9	52.2	0.3	49.3	49.6	0.3
III	55.0	55.5	0.5	52.5	52.9	0.4	50.1	52.9	2.8

Diff.: 1st Forward – 2nd Forward

Model-C

The repeatability results of three sensor units from Model-C manufacturer at relative humidity of 50% RH and at temperatures of 15°C, 25°C and 35°C are shown in Table 4.3. In Table 4.3 'Diff.' represents the magnitude of difference between the first forward and second forward readings.

The error in repeatability at 15°C remained the same (i.e., 0.1% RH) for sensor units II and III while the error is greater by 0.2% RH for sensor unit I.

Further, the errors in repeatability at 25°C are almost the same for sensor units II and III with the errors of 0.4% RH and 0.5% RH, respectively. Additionally, the error is smaller by about 0.3% RH for sensor unit I as shown in Table 4.3.

Finally, the errors in repeatability at 35°C varied between 0.3% RH to 0.8% RH with the error being least for sensor unit II (0.3% RH) and most (0.8% RH) for sensor unit I.

Table 4.3: Repeatability of Model-C relative humidity sensors at 50% RH and at temperatures of 15°C, 25°C and 35°C

Sensor units	15 (°C)			25 (°C)			35 (°C)		
	1st Fwd. (% RH)	2nd Fwd. (% RH)	Diff.	1st Fwd. (% RH)	2nd Fwd. (% RH)	Diff.	1st Fwd (% RH)	2nd Fwd. (% RH)	Diff.
I	47.9	48.2	0.3	48.4	48.6	0.2	46.2	47.0	0.8
II	48.9	49.0	0.1	47.4	47.8	0.4	46.8	47.1	0.3
III	48.8	48.9	0.1	46.9	47.4	0.5	47.1	47.5	0.4

Diff.: 1st Forward – 2nd Forward

Model-D

The repeatability results of three sensor units from Model-D manufacturer at relative humidity of 50% RH and at temperatures of 15°C, 25°C and 35°C are shown in Table 4.4. In Table 4.4 'Diff.' represents the magnitude of difference between the first forward and second forward readings.

The errors in repeatability at 15°C varied between 0.1% RH to 1.2% RH with the error being least for sensor unit I (0.1% RH) and most (1.2% RH) for sensor unit III.

Further, the error in repeatability at 25°C remained the same (i.e., 0.1% RH) for sensor units II and III while the error is greater by 0.3% RH for sensor unit I.

Finally, the errors in repeatability at 35°C are almost the same for sensor units I and II with the errors of 0.3% RH and 0.4 %RH, respectively. The error in repeatability is 0.0% RH for sensor unit III.

Table 4.4: Repeatability of Model-D relative humidity sensors at 50% RH and at temperatures of 15°C, 25°C and 35°C

Sensor units	15 (°C)			25 (°C)			35 (°C)		
	1st Fwd. (% RH)	2nd Fwd. (% RH)	Diff.	1st Fwd. (% RH)	2nd Fwd. (% RH)	Diff.	1st Fwd (% RH)	2nd Fwd. (% RH)	Diff.
I	49.8	49.7	0.1	50.1	49.7	0.4	49.9	49.6	0.3
II	48.1	47.9	0.2	48.5	48.6	0.1	48.1	48.5	0.4
III	47.4	48.6	1.2	49.7	49.8	0.1	49.8	49.8	0

Diff.: 1st Forward – 2nd Forward

Model-E

The repeatability results of three sensor units from Model-E manufacturer at relative humidity of 50% RH are shown in Table 4.5. In Table 4.5 'Diff.' represents the magnitude of difference between the first forward and second forward readings.

The error in repeatability at 15°C remained the same (i.e., 0.2% RH) for all three sensor units as shown in Table 4.5.

Further, the error in repeatability at 25°C is 0.4% RH for both sensor units I and II while the error is 0.0% RH for sensor unit III.

Finally, the errors in repeatability at 35°C varied between 0.1% RH to 1.2% RH with the error being least for sensor unit II (0.1% RH) and most (1.2% RH) for sensor unit I.

Table 4.5: Repeatability of Model-E relative humidity sensors at 50% RH and at temperatures of 15°C, 25°C and 35°C

Sensor units	15 (°C)			25 (°C)			35 (°C)		
	1st Fwd. (% RH)	2nd Fwd. (% RH)	Diff.	1st Fwd. (% RH)	2nd Fwd. (% RH)	Diff.	1st Fwd (% RH)	2nd Fwd. (% RH)	Diff.
I	41.6	41.4	0.2	41.7	42.1	0.4	40.3	41.5	1.2
II	39.5	39.3	0.2	39.6	39.2	0.4	37.9	38.0	0.1
III	43.8	43.6	0.2	44.2	44.2	0	42.1	42.5	0.4

Diff.: 1st Forward – 2nd Forward

Model-F

The repeatability results of three sensor units from Model-E manufacturer at relative humidity of 50% RH and at temperatures of 15°C, 25°C and 35°C are shown in Table 4.6. In Table 4.6 'Diff.' represents the magnitude of difference between the first forward and second forward readings.

The error in repeatability at 15°C remained almost the same (i.e., 0.4% RH) for all three sensor units as shown in Table 4.6.

Further, the errors in repeatability at 25°C are almost the same for sensor units I and II with errors being 0.3% RH and 0.4% RH, respectively. Additionally, the error is 0.0% RH for sensor unit III.

Finally, the errors in repeatability at 35°C are none for sensor units I and III while the error is 0.1% RH for sensor unit III.

Table 4.6: Repeatability of Model-F relative humidity sensors at 50% RH and at temperatures of 15°C, 25°C and 35°C

Sensor units	15 (°C)			25 (°C)			35 (°C)		
	1st Fwd. (% RH)	2nd Fwd. (% RH)	Diff.	1st Fwd. (% RH)	2nd Fwd. (% RH)	Diff.	1st Fwd (% RH)	2nd Fwd. (% RH)	Diff.
I	50.7	51.1	0.4	49.5	49.8	0.3	48.3	48.3	0
II	49.7	50.2	0.5	48.2	48.6	0.4	46.6	46.7	0.1
III	51.2	51.6	0.4	51.6	51.6	0	51.6	51.6	0

Diff.: 1st Forward – 2nd Forward

Comparison of capacitive and resistive type sensors

The comparison of capacitive and resistive sensors can be performed by adopting the following two approaches for determining the repeatability of sensors:

Approach-1

Represents the pooled mean relative humidity value at 50%, when measurements are taken sequentially at 10%, 30%, 50%, 70% and 90% relative humidity.

Approach-2

Represents the pooled mean relative humidity value at 50% RH, when a measurement is taken at 10% RH actual humidity and then at 50% RH.

The differences of the absolute values between Approach-2 and Approach-1 is used to quantify the repeatability since the relative humidity measurements at 50% actual relative humidity were obtained using the above two different approaches. Further, it should be noted that the average repeatability of capacitive sensors is obtained by averaging the repeatability results of three capacitive sensor models. A similar approach was adopted for resistive sensors.

Discussion of results

In general, the average errors in repeatability of capacitive sensor models at temperatures of 15°C, 25°C and 35°C are greater compared to resistive sensor models. This conclusion is based on comparing the average errors in repeatability of capacitive and resistive sensors. For example, the average error in repeatability of capacitive sensors is 0.4% RH higher than resistive type sensors. In addition, as shown in Tables 4.7, 4.8 and 4.9 the maximum errors in repeatability of sensors (both resistive and capacitive) at temperatures of 15°C, 25°C and 35°C are 0.4%, 1.5% and 1.1% RH, respectively.

Table 4.7: Repeatability of humidity sensors from each of the six manufacturers at 50% relative humidity and 15°C

Sensor manufacturer	Sensor type	Repeatability at 50% RH and 15°C		
		Approach-1 (% RH)	Approach-2 (% RH)	Difference (% RH)
Model-A	Capacitive	53.6	53.9	0.3
Model-B	Capacitive	55.6	55.9	0.3
Model-C	Capacitive	48.5	48.7	0.2
Model-D	Resistive	48.8	48.8	0.0
Model-E	Resistive	41.6	41.4	0.2
Model-F	Resistive	50.6	51.0	0.4

Table 4.8: Repeatability of humidity sensors from each of the six manufacturers at 50% relative humidity and 25°C

Sensor manufacturer	Sensor type	Repeatability at 50% RH and 25°C		
		Approach-1 (% RH)	Approach-2 (% RH)	Difference (% RH)
Model-A	Capacitive	51.7	53.0	1.3
Model-B	Capacitive	52.4	53.9	1.5
Model-C	Capacitive	47.6	47.9	0.3
Model-D	Resistive	49.4	49.3	0.1
Model-E	Resistive	41.8	41.8	0.0
Model-F	Resistive	49.8	50.0	0.2

Table 4.9: Repeatability of humidity sensors from each of the six manufacturers at 50% relative humidity and 35°C

Sensor manufacturer	Sensor type	Repeatability at 50% RH and 35°C		
		Approach-1 (% RH)	Approach-2 (% RH)	Difference (% RH)
Model-A	Capacitive	49.6	49.7	0.1
Model-B	Capacitive	49.6	50.7	1.1
Model-C	Capacitive	46.7	47.2	0.5
Model-D	Resistive	49.2	49.3	0.1
Model-E	Resistive	40.1	40.7	0.6
Model-F	Resistive	48.8	48.8	0.0

Hysteresis

The hysteresis of each sensor was evaluated by comparing humidity measurements taken at 30%, 50% and 70% RH when the humidity condition was approached from both a lower (i.e., forward measurements) and a higher humidity (i.e., reverse measurements) for all three temperatures of 15ºC, 25ºC and 35ºC. The evaluation procedure is described in Chapter 3. The results of this study are discussed below.

The discussions of results presented herein are based on the average hysteresis value obtained by averaging the hysteresis measurements of 30%, 50% and 70% RH at a particular temperature. Therefore, a positive value in hysteresis means that when the actual humidity is decreased then the measured humidity reading is greater.

Hysteresis results of each sensor model

Model-A

It can be observed in Figure 4.13 that at 35°C the average hysteresis for the Model-A sensors is lower compared to the hysteresis at 15°C and 25°C. For example, the average hysteresis at 35°C is about 1.9% while at 15°C and 25°C the average hysteresis is about 2.9% and 2.1%, respectively.

Model-B

It can be observed in Figure 4.14 that at 35°C the average hysteresis for the Model-B sensors is lower compared to the hysteresis at 15°C and 25°C. For example, the average hysteresis at 35°C is about 1.0% while at 15°C and 25°C the average hysteresis is about 1.4% and 1.1%, respectively.

Model-C

It can be observed in Figure 4.15 that at 15°C the average hysteresis for the Model-C sensors is lower compared to the hysteresis at 25°C and 35°C. For example, the average hysteresis at 15°C is about 0.3% while at 25°C and 35°C the average hysteresis is about 0.4% and 0.6%, respectively.

Model-D

It can be observed in Figure 4.16 that at 15°C the average hysteresis for the Model-D sensors is lower compared to the hysteresis at 25°C and 35°C. For example, the average hysteresis at 15°C is about 0.4% while at 25°C and 35°C the average hysteresis is about 0.6%.

Model-E

It can be observed in Figure 4.17 that at 25°C the average hysteresis for the Model-E sensors is lower compared to the hysteresis at 15°C and 35°C. For example, the average hysteresis at 25°C is about 0.6% while at 15°C and 35°C the average hysteresis is about 0.9%.

Model-F

It can be observed in Figure 4.18 that at 35°C the average hysteresis for the Model-F sensors is lower compared to the hysteresis at 15°C and 25°C. For example, the average hysteresis at 35°C is about 0.1% while at 15°C and 25°C the average hysteresis is about 1.3% and 0.6%, respectively.

The average hysteresis values presented above are summarized in Table 4.10.

Table 4.10: Average hysteresis (% RH) of all sensor models at different temperatures

Manufacturer	Sensor type	Temperature (°C)		
		15	25	35
Model-A	Capacitive	2.9	2.1	1.9
Model-B	Capacitive	1.4	1.1	1.0
Model-C	Capacitive	0.3	0.4	0.6
Model-D	Resistive	0.4	0.6	0.6
Model-E	Resistive	0.9	0.6	0.9
Model-F	Resistive	1.3	0.6	0.1

In general, sensor models A, B and F had lower average hysteresis at the high temperature of 35°C than at 15°C and 25°C over the entire humidity range. The maximum hysteresis of all sensors is less than 3.2% for all humidities and temperatures while the minimum hysteresis for the Model-F sensors is 0.0% at 30% RH and 35°C.

It should be noted that for all the sensors tested the average hysteresis reading was positive. Additionally, for all sensor models and for all temperatures, it can be observed that the deviation in relative humidity when going in the reverse direction is always higher than the deviation when going in the forward direction. For example, the deviation of sensor Model-F at 25°C when approaching 50% RH from the forward direction is 0.6% while the deviation is 1.5% when approached from the reverse direction. This phenomenon can be explained based on the diffusion of moisture inside the humidity sensor polymer material during the adsorption (i.e., increasing RH) and desorption (i.e., decreasing RH) process. During the adsorption process, the water molecules from the humid air are adsorbed on the surface of the sensing polymer while during the desorption process these adsorbed water molecules are evaporated from the sensing polymer. As the humidity is being decreased, water molecules are evaporated from the surface of the sensing polymer so that the water vapor concentration at the surface is greater than the air, thus the sensor reading is higher than the actual value. Therefore, higher relative humidity readings are obtained when relative humidities are being decreased.

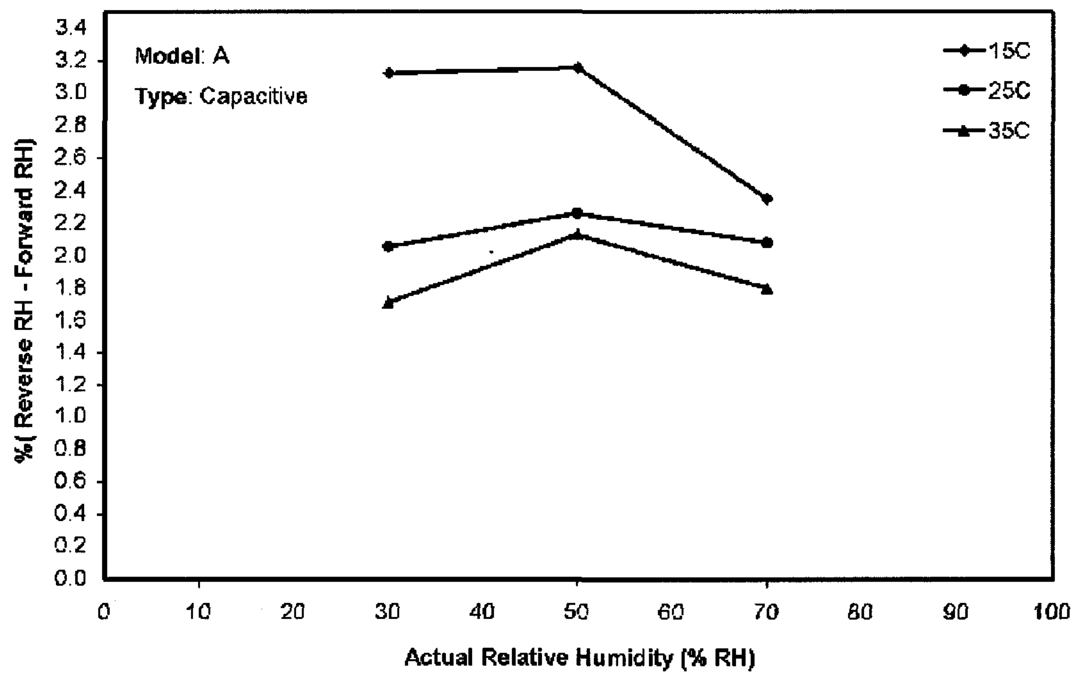


Figure 4.13: Comparison of hysteresis effects based on pooled RH readings for Model A sensors at three temperatures

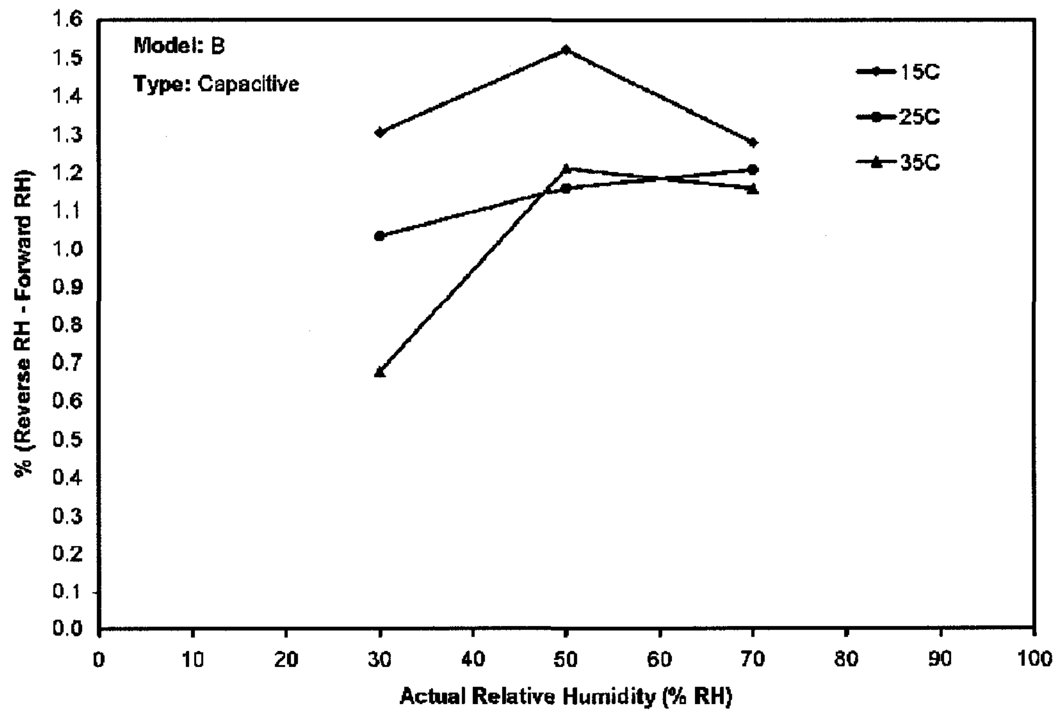


Figure 4.14: Comparison of hysteresis effects based on pooled RH readings for Model B sensors at three temperatures

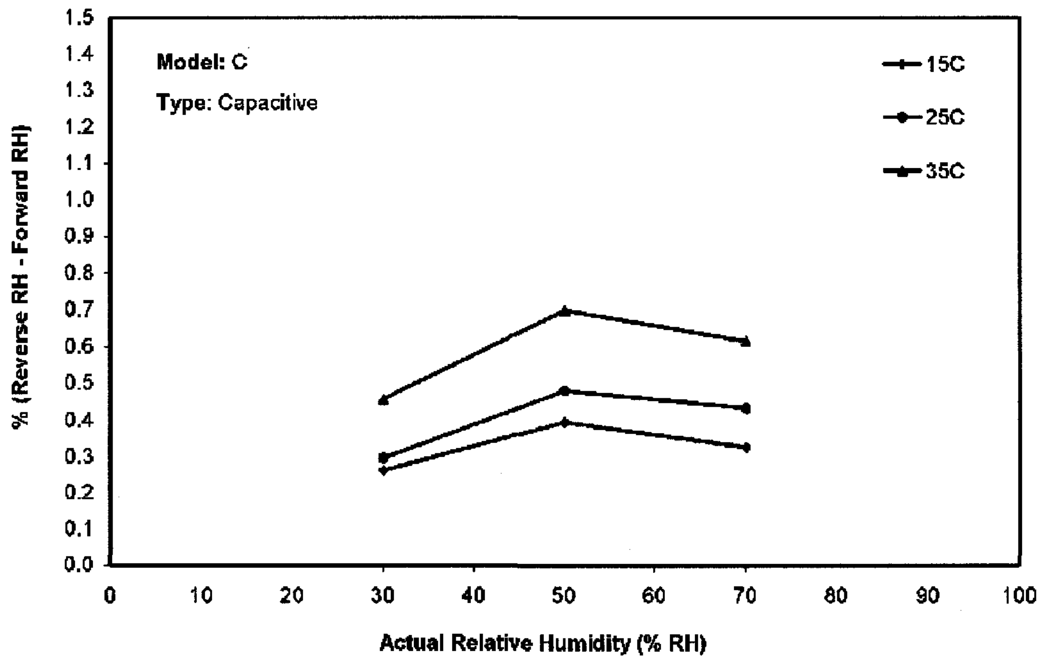


Figure 4.15: Comparison of hysteresis effects based on pooled RH readings for Model C sensors at three temperatures

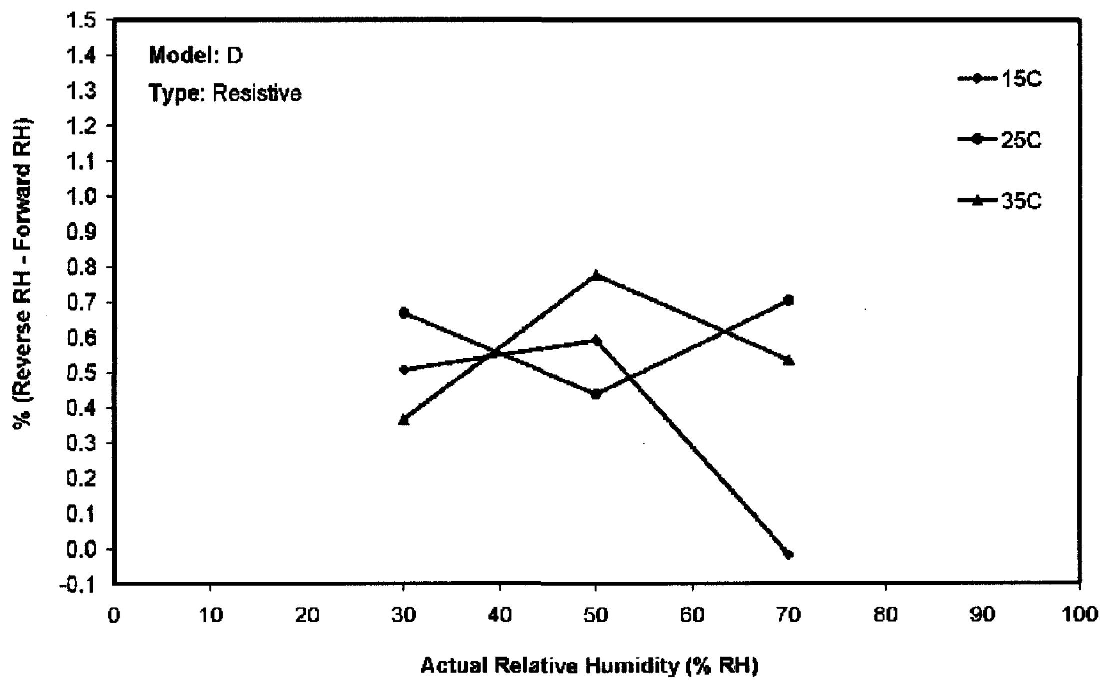


Figure 4.16: Comparison of hysteresis effects based on pooled RH readings for Model D sensors at three temperatures

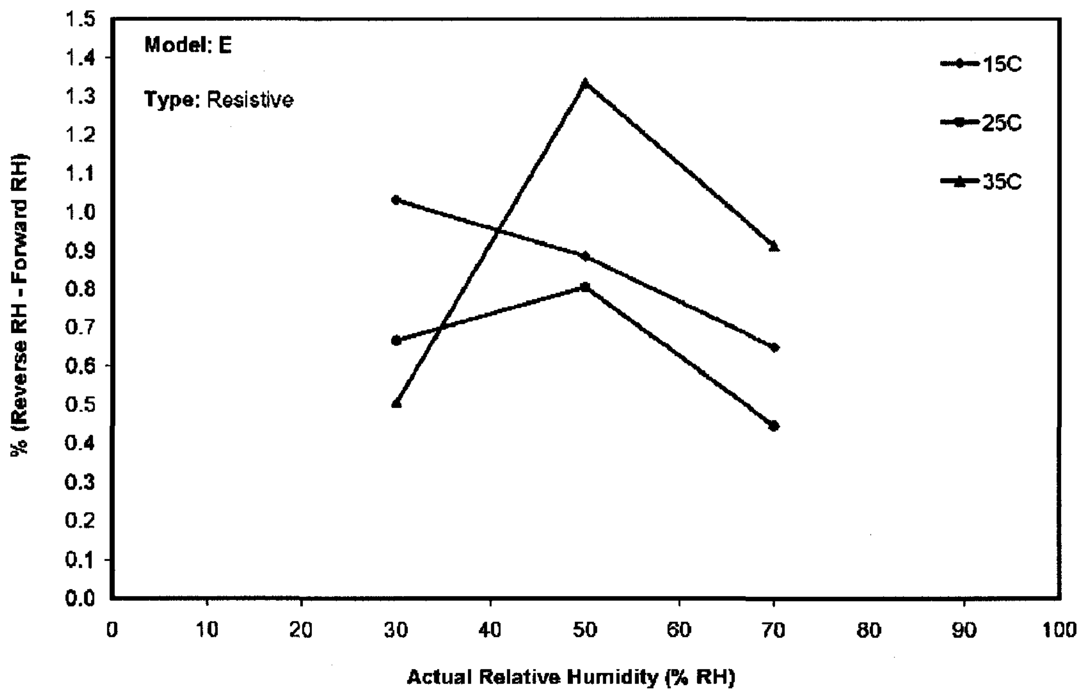


Figure 4.17: Comparison of hysteresis effects based on pooled RH readings for Model E sensors at three temperatures

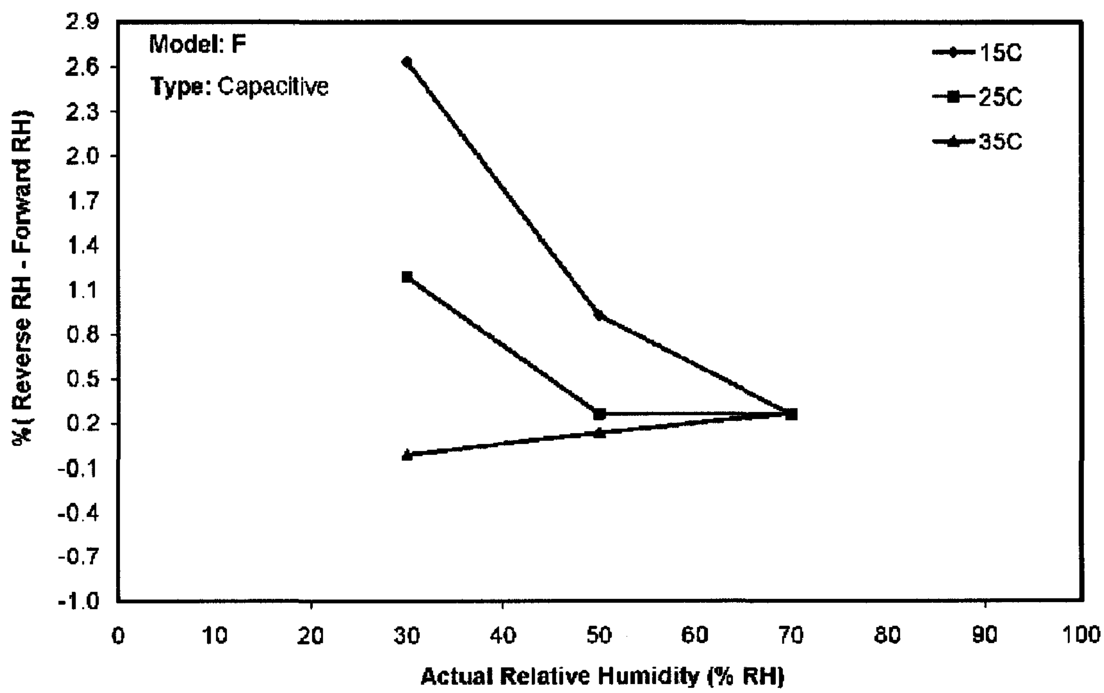


Figure 4.18: Comparison of hysteresis effects based on pooled RH readings for Model F sensors at three temperatures

Linearity

The linearity of each sensor was evaluated by determining the extent to which measured relative humidity readings depart from a best-fit straight line plotted through the origin. The evaluation procedure is described in Chapter 3. The results of this study are discussed below.

The linearity trends observed for temperatures of 15°C and 35°C are similar to the trends at 25°C. Hence, the discussion on linearity presented herein will focus at 25°C. Furthermore, the plots presented herein show only the sensor models with the least and the largest nonlinearity in the relative humidity reading, however, linearity trends for all sensors are discussed.

The sensor model with the largest nonlinearity among all the sensor models is Model-B at 25°C, which is shown in Figure 4.19. The nonlinearity shown by Model-B at 10%, 30%, 50%, 70% and 90% RH is -3.8%, 3.3%, 3.7%, 0.9% and -3.4%, respectively. Sensor Model-C at 25°C shows the least nonlinearity among all the sensor models over the entire humidity range as shown in Figure 4.20. At 50% RH the nonlinearity shown by Model-C is 0.0% RH.

The maximum nonlinearity of models D and E is 1.3% and 2.3% RH, respectively. The nonlinearity of models A and F varied considerably with RH. For example, the nonlinearity for sensor Model-F for humidity readings of 10%, 30%, 50%, 70% and 90% was -1.0%, 5.8%, 0.0%, -0.7%, -1.3% RH, respectively.

Among all sensor models at 25°C Model-B sensor has the largest nonlinearity of -3.8% while Model-C sensor has the least nonlinearity of 0.0%. The nonlinearity of other sensor models varied between 0.0% and -3.8% RH.

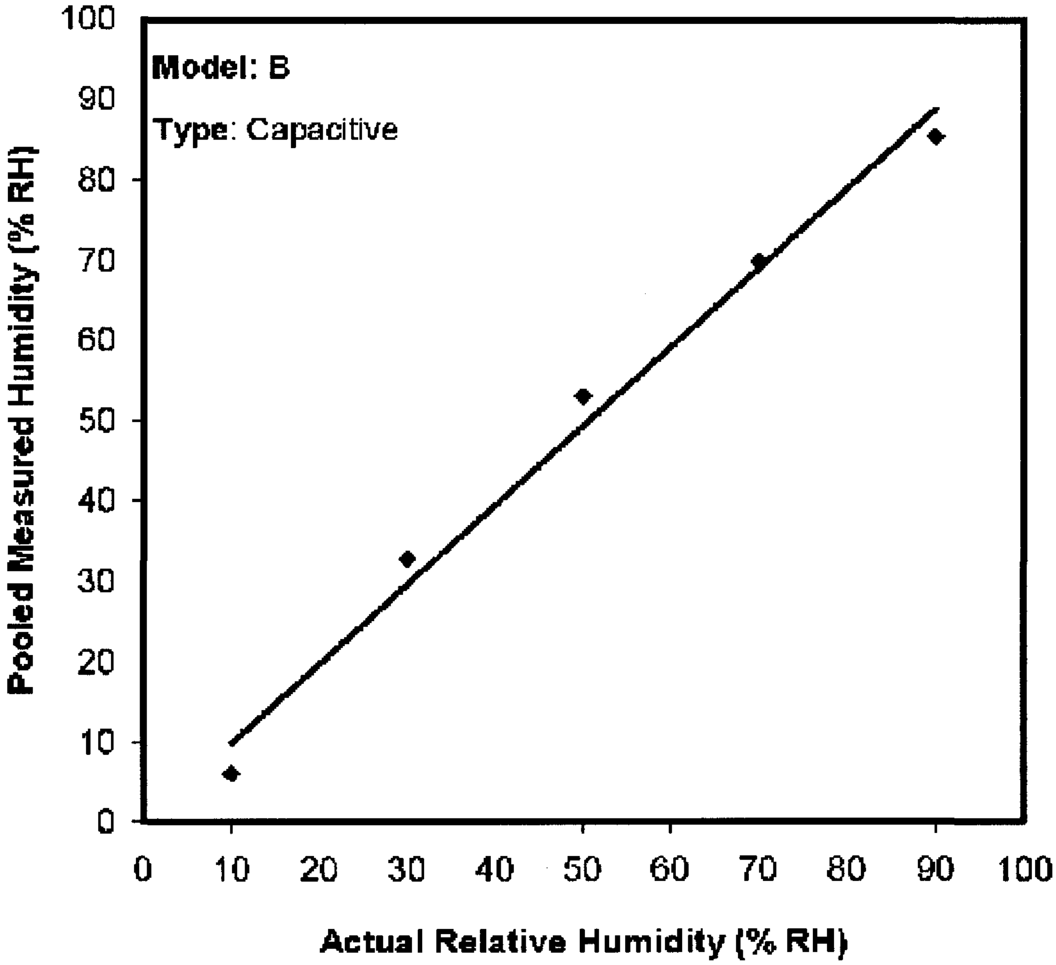


Figure 4.19: Linearity plot of Model-B humidity sensor at 25°C

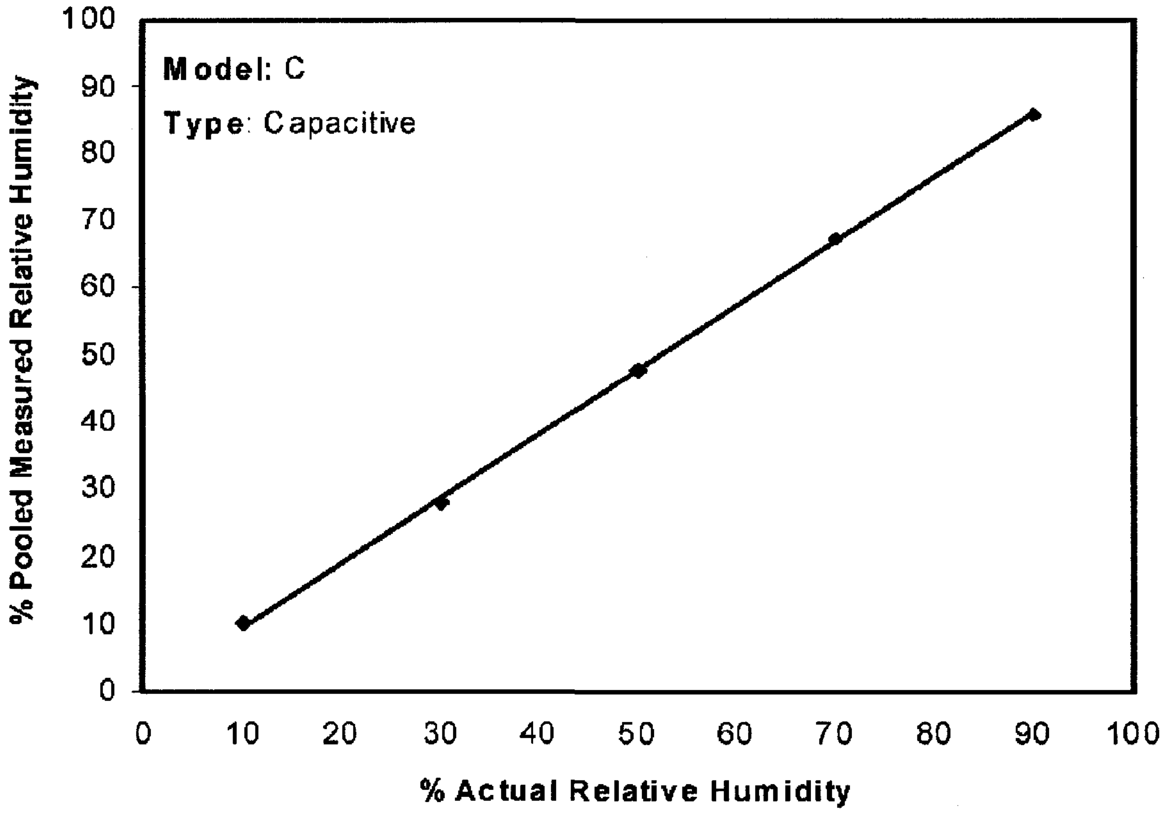


Figure 4.20: Linearity plot of Model-C humidity sensor at 25°C

Comparison of Performance Characteristics

A comparison of the magnitude of repeatability, hysteresis and linearity for all sensor models at 25°C and 50% RH is shown in Table 4.11. As shown in Table 4.11, the repeatability error of the sensor is small compared to both the hysteresis error and linearity error. Further, the repeatability, hysteresis and linearity values are least for models C, D and F being less than 0.5% RH while they are largest for the Model-A sensor being 1.3%, 2.3% and 2.4%. In addition, the hysteresis values for models C, D, E and F are less than 1% RH while for models A and B they are 2.3% and 1.2% RH, respectively. Furthermore, models C and F had 0.0% linearity. Finally, the Model-B sensor has the largest nonlinearity compared to all other sensors with a value of 3.7% RH.

Table 4.11: Comparison of magnitudes of repeatability, hysteresis and linearity for all sensor models at 25°C and 50% RH

Manufacturer	Sensor type	Repeatability (% RH)	Hysteresis[a] (% RH)	Linearity (% RH)
Model-A	Capacitive	1.3	2.3	2.4
Model-B	Capacitive	1.5	1.2	3.7
Model-C	Capacitive	0.3	0.5	0.0
Model-D	Resistive	0.1	0.4	0.2
Model-E	Resistive	0.0	0.8	1.7
Model-F	Resistive	0.2	0.5	0.0

a The hysteresis of a particular sensor model was quantified as the difference of the pooled deviation obtained for the reverse and forward measurements at 50% RH

CHAPTER 5. AGEING TEST

Overview

The ageing test investigated changes in sensor accuracy that occur over time as sensors were exposed to actual building HVAC environmental conditions. In a typical building HVAC application, the ageing of sensors may occur due to various factors, such as contamination of the sensor element and continuous exposure to varying humidities/temperatures. Since ageing affects the accuracy of the sensors, many manufacturers recommend calibrating their sensors every year. Therefore, the ageing test reported herein was performed over a one-year time period.

As described in Chapter 4, the performance (i.e., accuracy, linearity, repeatability and hysteresis) of three duct-mounted relative humidity sensors from each of six manufacturers was determined. From the three sensors tested for each manufacturer, the most accurate and least accurate sensors were selected (producing a total of 12 sensors) for the ageing test described in this chapter.

Method of Test

Prior to evaluating the effects of ageing on sensors, a Method of Test (MOT) was created and is reported in this section.

Quality control

The quality control of the sensors was conducted according to the procedures described in Chapter 3. The test hardware and the test procedure are described below.

Test hardware

The testing of the sensors was performed in the outdoor air duct of an air-handling unit (AHU) at the Energy Resource Station, which is part of the Iowa Energy Center. The test sensors were installed according to the manufacturer's written installation instructions. Two power supplies with a regulated output voltage of 24 VDC ± 1.2 V were used to power the sensors under test. One power supply was used to power six test sensors, while the second power supply was used to power the other six test sensors along with the reference relative humidity sensor. The 0-10 V output of each sensor was sampled, recorded and stored at five-minute intervals continuously using the data acquisition (DAQ) system.

In addition, the relative humidity, temperature, and average air velocity in the proximity of the test sensors was monitored by using the instruments described below.

- A reference relative humidity sensor was installed near the location of the test relative humidity sensors and served as the in-situ reference relative humidity sensor for the ageing test. This sensor has a rated accuracy of ±1% RH for the 0-90% RH range and ±2% RH for the 90-100% RH.

- The temperature near the location of the relative humidity sensors under test was measured using four 1000 Ω Platinum RTD immersion probe temperature sensors that were wired in a series-parallel arrangement to produce an average temperature. These sensors have a rated accuracy of ±0.15ºC at 0ºC and ±0.35ºC at 100ºC.
- The average air-stream velocity was measured using airflow sensors, specifically manufactured to measure air velocities inside ducts. The velocity measurements have an accuracy of ± 2% of the reading for velocities greater than or equal to 2.54 m/s and ± 0.051 m/s for velocities less than 2.54 m/s.

The relative humidity, temperature and average air velocity measurements were sampled, recorded and stored continuously at five-minute intervals using the DAQ system described previously.

Test procedure

The test sensors were installed inside the HAVC duct more than three inches away from the wall so that the sensors were exposed to uniform relative humidity, temperature, and velocity conditions. The procedure used to ensure a uniform velocity profile inside the duct along with a description of the sensor location is presented below.

Uniform velocity profile

ASHRAE Standard 111 (ASHRAE, 1988) was used to ensure that a uniform velocity profile was obtained inside the duct. A uniform velocity profile inside the duct ensured that all sensors were exposed to similar velocity conditions. The ASHRAE requirement for flow uniformity in a given velocity profile is that 75 percent or more of the velocity measurements are greater than 1/10th of the maximum velocity of that profile. Past measurements had indicated that the velocity distribution at this location satisfied the ASHRAE Standard 111 requirement.

Sensor location

The locations of the test humidity sensors are shown schematically in Figure 5.1. As shown in Figure 5.1, the sensors were installed such that the tips of the sensor probes are maintained a minimum of three inches from the nearest duct wall.

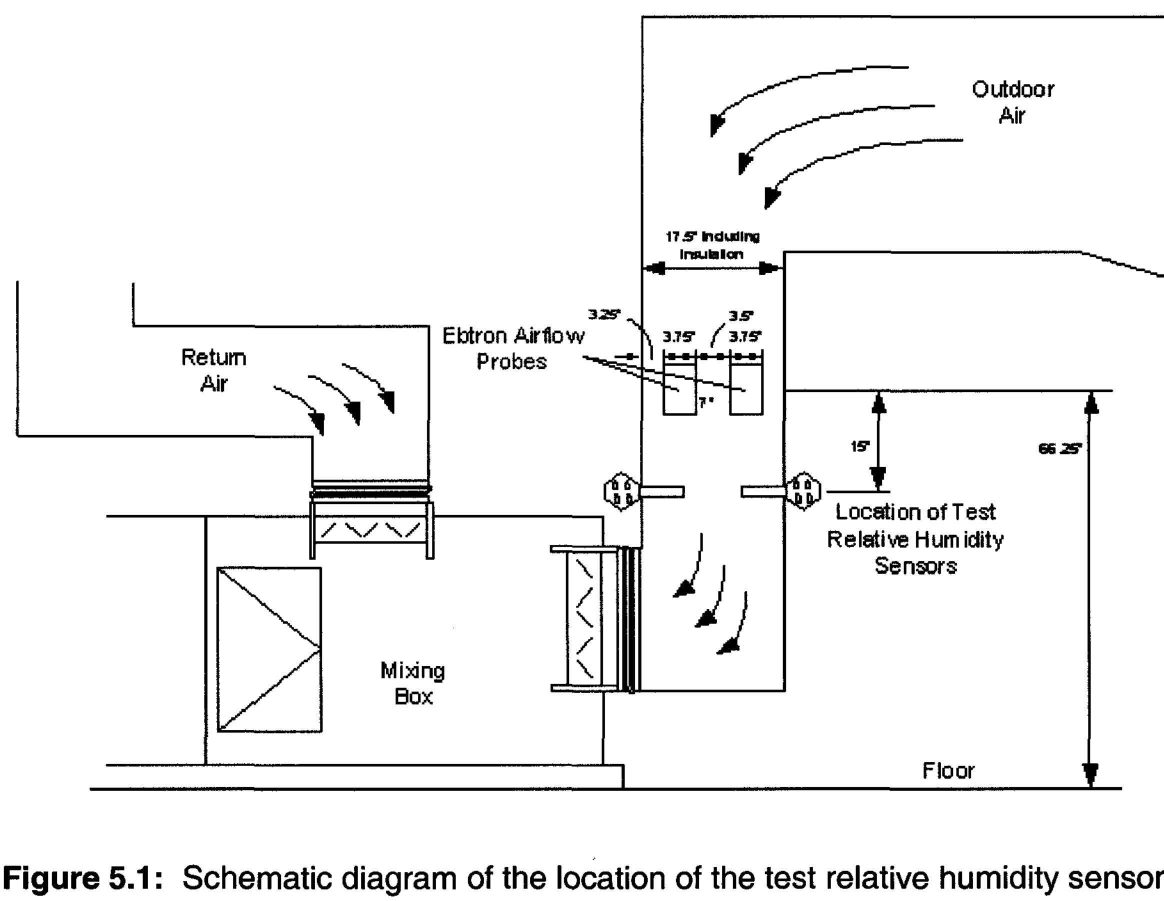


Figure 5.1: Schematic diagram of the location of the test relative humidity sensors

Further, the position of each sensor in the duct, as shown in Figure 5.2, was changed every four months to ensure that each sensor spent an equal amount of time in each of the three areas (i.e., Area 1, Area 2, and Area 3). The time period spent by each sensor in each of the three positions is listed in Table 5.1. As noted earlier, ageing tests utilized the most and least accurate sensors as identified in the accuracy study. In this light, the most accurate sensors are models I-A to VI-A while the least accurate sensors are models I-B to VI-B as shown in Table 5.1.

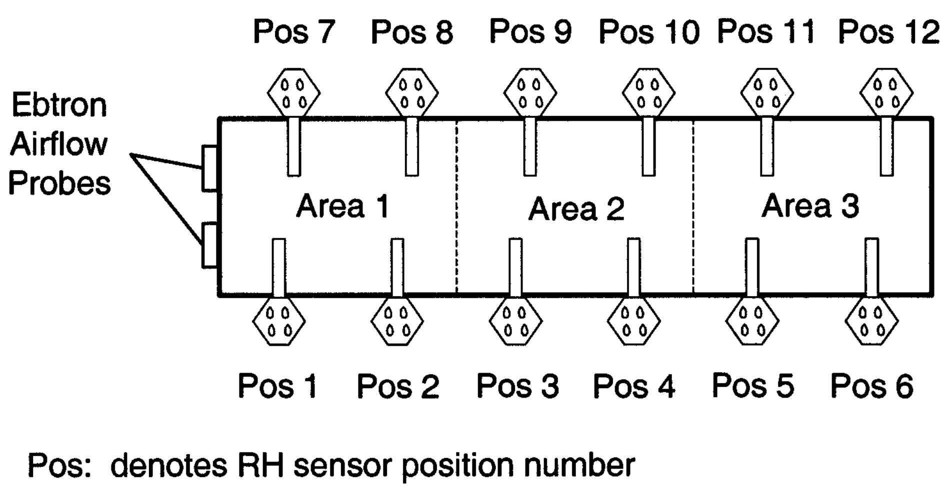


Figure 5.2: Schematic diagram of the outdoor air duct cross-section divided into three equal areas

Table 5.1: Installed positions of the test relative humidity sensors over the course of the 1-year ageing test

Humidity sensor [1]	Sensor type	Position number [2]		
		Months 1-4	Months 5-8	Months 9-12
Model A-[illegible]	Capacitive	[illegible]	[illegible]	[illegible]
Model B-[illegible]	Capacitive	[illegible]	[illegible]	[illegible]
Model C-[illegible]	Capacitive	[illegible]	[illegible]	[illegible]
Model D-[illegible]	Resistive	[illegible]	[illegible]	[illegible]
Model E-[illegible]	Resistive	[illegible]	[illegible]	[illegible]
Model F-[illegible]	Resistive	[illegible]	[illegible]	[illegible]
Model A-III	Capacitive	7	9	11
Model B-III	Capacitive	8	10	12
Model C-III	Capacitive	9	11	7
Model D-III	Resistive	10	12	8
Model E-III	Resistive	11	7	9
Model F-III	Resistive	12	8	10

1. Grey colored cells represent the most accurate sensors while the remaining sensors are the least accurate sensors. I, II and III represent sensor units from a manufacturer.
2. See Figure 5.2 for the position number in the duct cross-section.

Accuracy testing

Every four months, the test sensors were temporarily removed from the duct and then tested for accuracy at relative humidities of 10%, 30%, 50%, 70% and 90%, using the test hardware and procedures described in Chapter 3.

Results and Discussions

The ageing effects were analyzed at four months after the test sensors were exposed to a range of outdoor airflow, outdoor air temperatures and outdoor air relative humidity inside the air-duct of a building AHU. To perform the analysis, the sensors were removed every four-months and tested for accuracy inside a humidity generator. All sensors were tested inside the humidity generator at a single temperature of 25°C and relative humidities of 10%, 30%, 50%, 70%, and 90% RH and then the results were compared with the manufacturer specifications. The results for the analysis are presented in terms of the deviation of the measured value from the actual value (e.g., deviation = $RH_{measured} - RH_{actual}$).

The environmental conditions experienced by the test sensors while installed in the building HVAC and the accuracy results after the ageing periods are presented below.

Environmental conditions

The environmental conditions, such as outdoor airflow, outdoor air temperatures and outdoor air relative humidities experienced by the test sensors (both least and most accurate) during each of the three different four month periods (defined as 1st, 2nd and 3rd four months) are discussed below. It should be noted that the relative humidity readings shown in Figures 5.3 to 5.11 were produced by using the reference relative humidity sensor described previously. In addition, the 'Frequency' titles on the abscissa of histograms represent the number of times that any particular value occurs over the four-month period.

1st four months

The air flow, relative humidity and temperature conditions experienced by the test sensors of testing are shown in Figures 5.3, 5.4 and 5.5, respectively during the 1st four months.

Outdoor airflow. As shown in Figure 5.3, the test sensors were exposed to air flow rates that ranged between 0-6000 CFM, with most of the outdoor airflow rates ranging between 200-600 CFM.

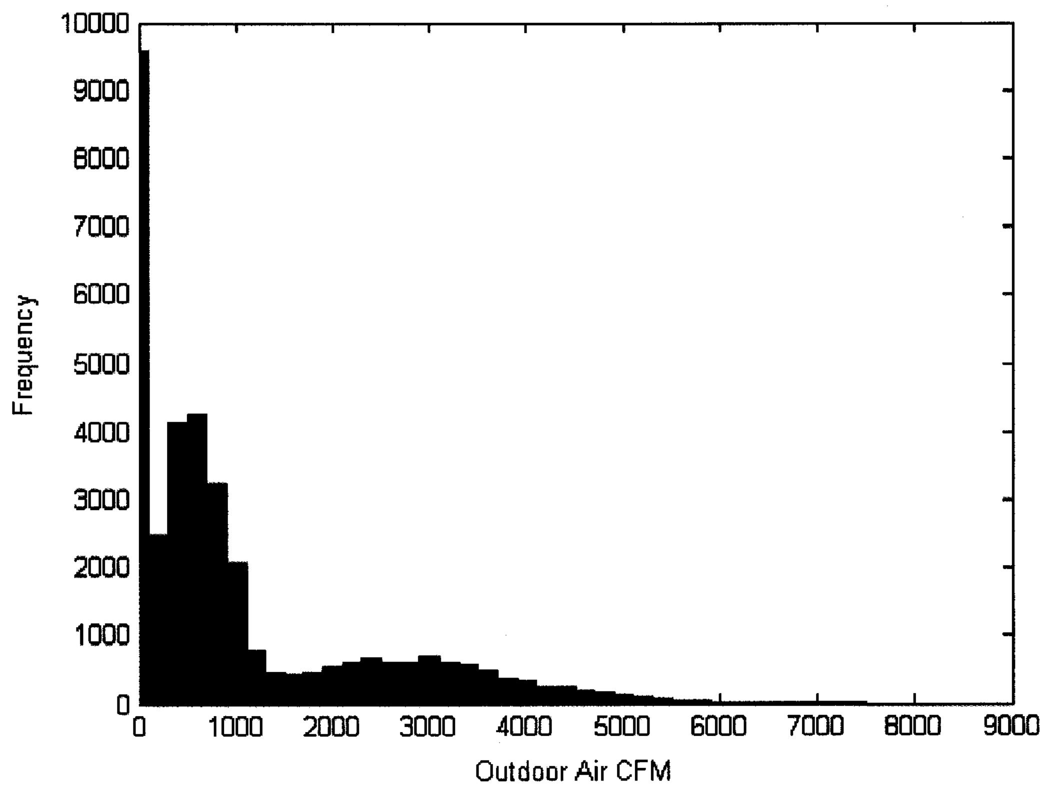


Figure 5.3: Histogram of outdoor air CFM for the 1st four months

Outdoor air temperature. As shown in Figure 5.4, the test sensors were exposed to outdoor air temperatures that ranged between 45-95°F, with most of the temperatures ranging between 65-85°F.

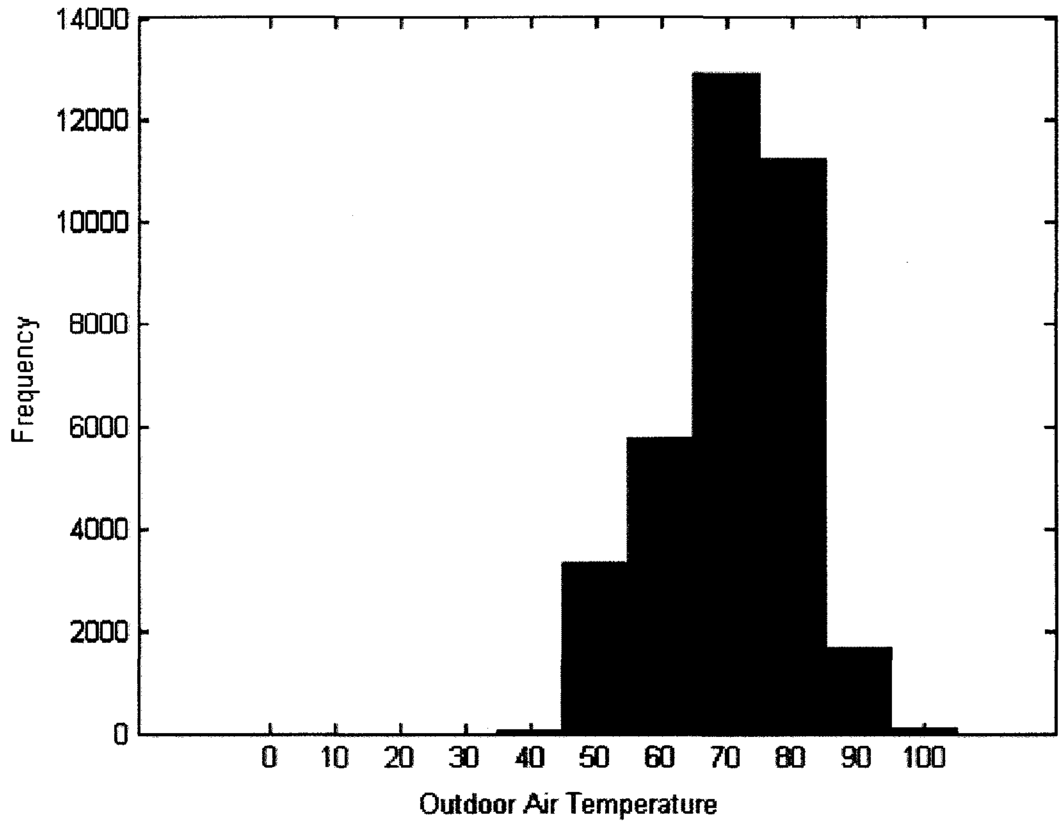


Figure 5.4: Histogram of outdoor air temperature (°F) for the 1st four months

Outdoor air relative humidity. As shown in Figure 5.5, the test sensors were exposed to outdoor air relative humidity values that ranged between 15-95% RH, with most of the values ranging between 45-75% RH.

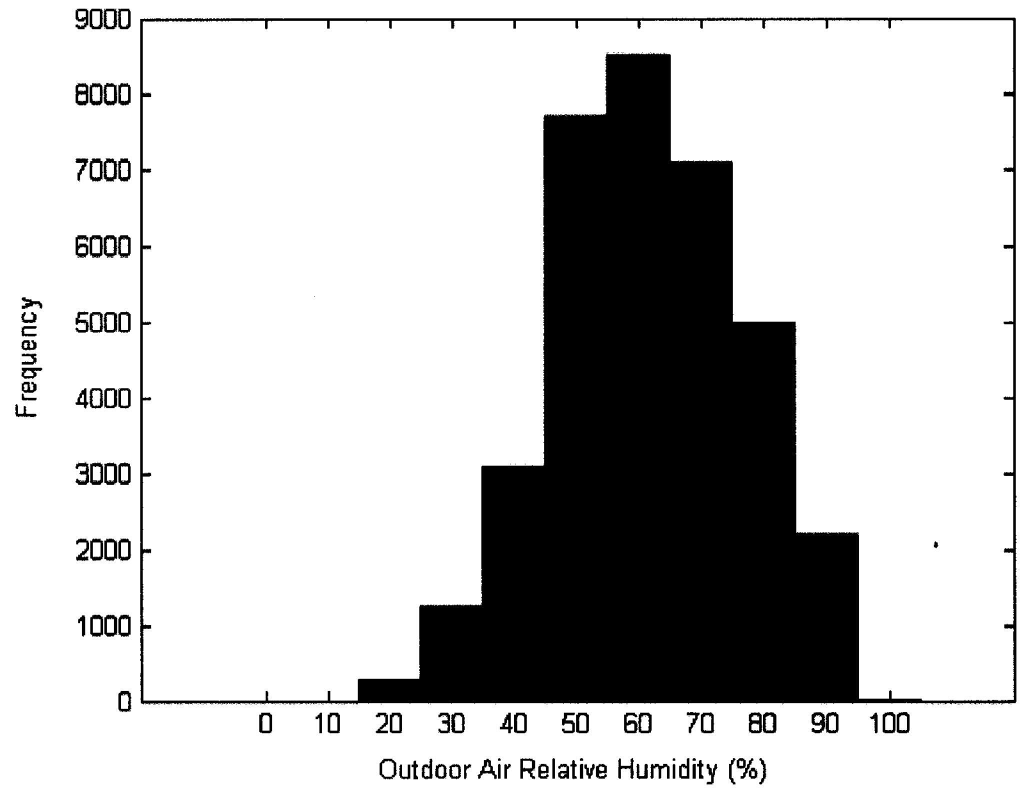


Figure 5.5: Histogram of outdoor air relative humidity for the 1st four months

In summary, during the first four months of ageing tests, the test sensors were mostly exposed to outdoor airflow, outdoor air temperature and outdoor air relative humidities that ranged between 200-600 CFM, 65-85°F and 45-75% RH, respectively.

2nd four months

The air flow, relative humidity and temperature conditions experienced by the test sensors of testing are shown in Figures 5.6, 5.7 and 5.8, respectively during the 2nd four months.

Outdoor airflow. As shown in Figure 5.6, the test sensors were exposed to air flow rates that ranged between 0-8000 CFM, with most of the outdoor airflow rates ranging between 0-600 CFM.

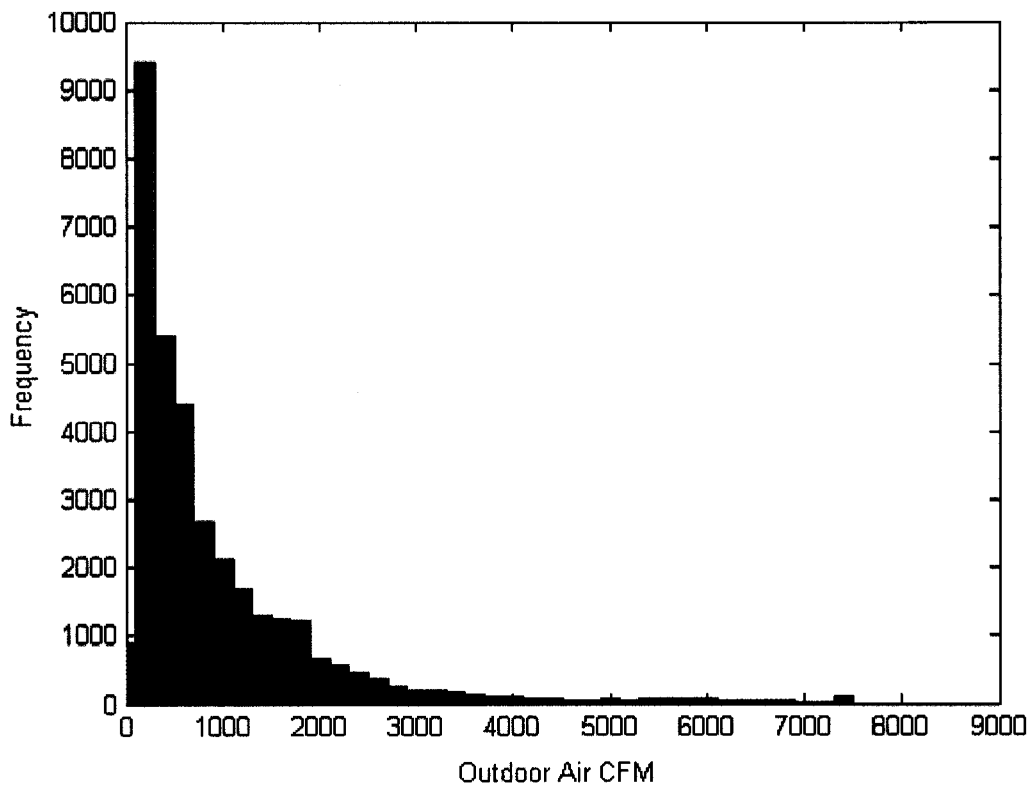


Figure 5.6: Histogram of outdoor air CFM for the 2nd four months

Outdoor air temperature. As shown in Figure 5.7, the test sensors were exposed to outdoor air temperatures that ranged between 5-95°F, with most of the temperatures ranging between 35-55°F.

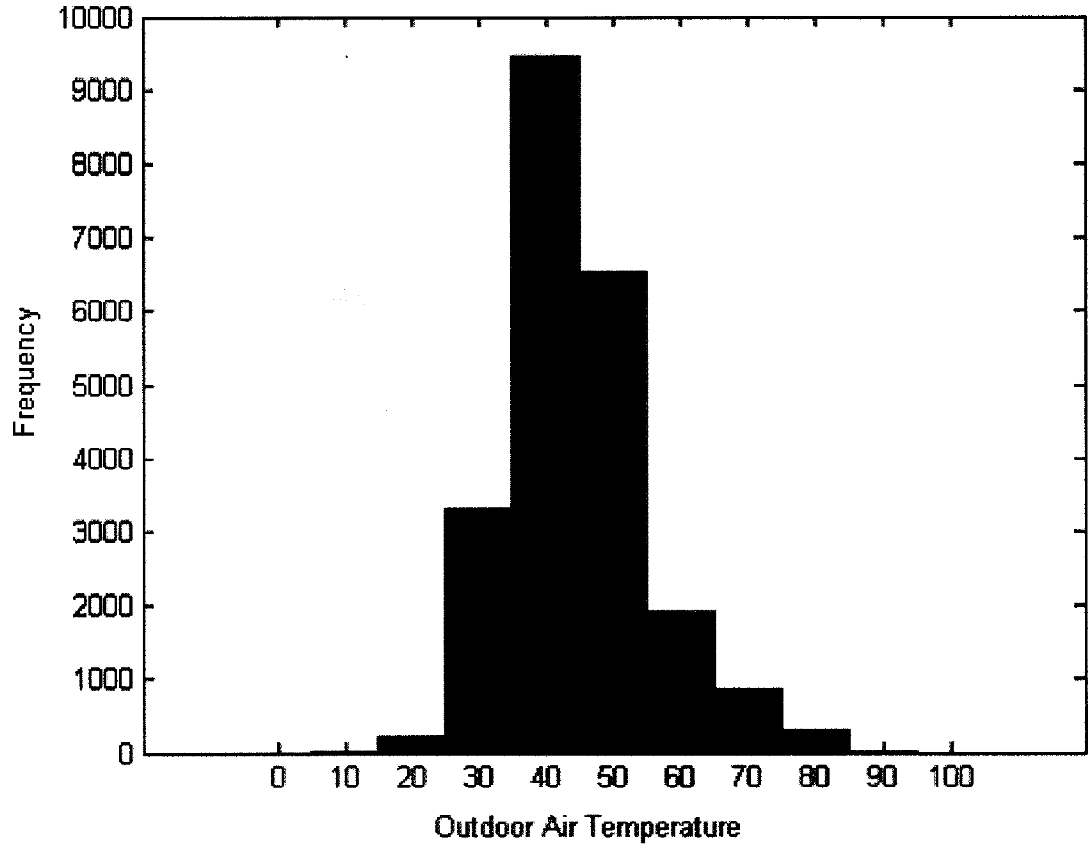


Figure 5.7: Histogram of outdoor air temperature (^{o}F) for the 2nd four months

Outdoor air relative humidity. As shown in Figure 5.8, the test sensors were exposed to outdoor air relative humidity values that ranged between 15-95% RH, with most of the values ranging between 45-65% RH.

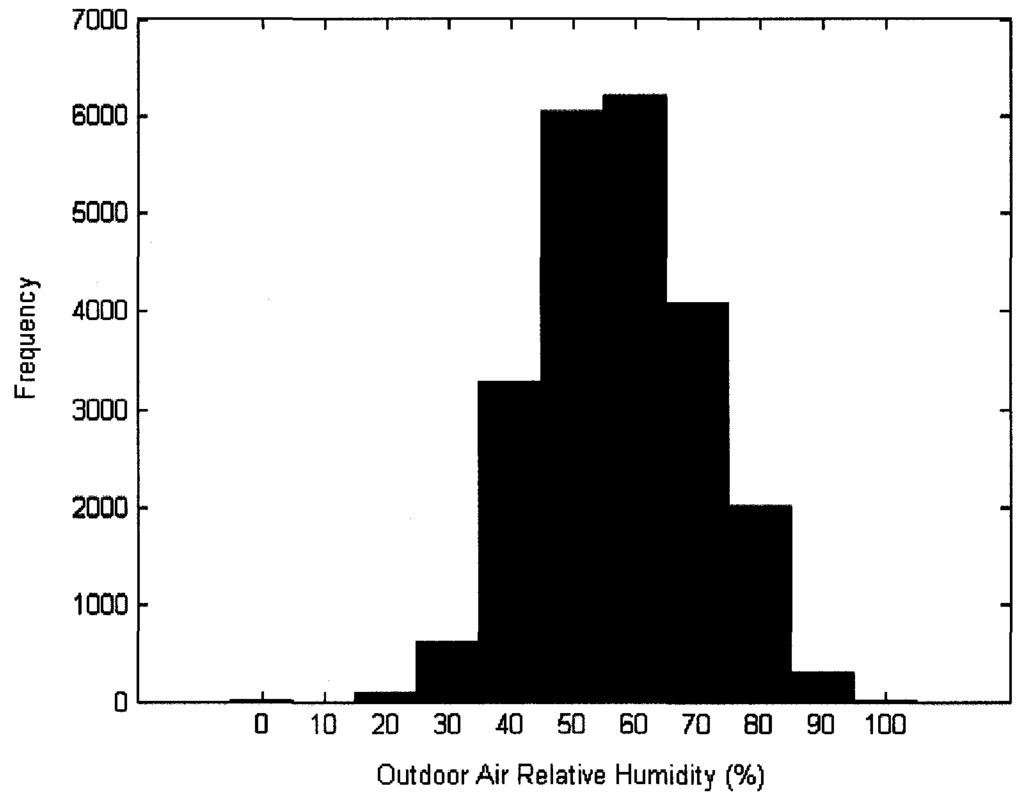


Figure 5.8: Histogram of outdoor air relative humidity for the 2nd four months

In summary, during the second four months of ageing tests, the test sensors were mostly exposed to outdoor airflow, outdoor air temperature and outdoor air relative humidities that ranged between 0-600 CFM, 35-55°F and 45-65% RH, respectively.

Last four months

The air flow, relative humidity and temperature conditions experienced by the test sensors of testing are shown in Figures 5.9, 5.10 and 5.11, respectively during the last four months.

Outdoor airflow. As shown in Figure 5.9, the test sensors were exposed to air flow rates that ranged between 0-7000 CFM, with most of the outdoor airflow rates ranging between 200-1000 CFM.

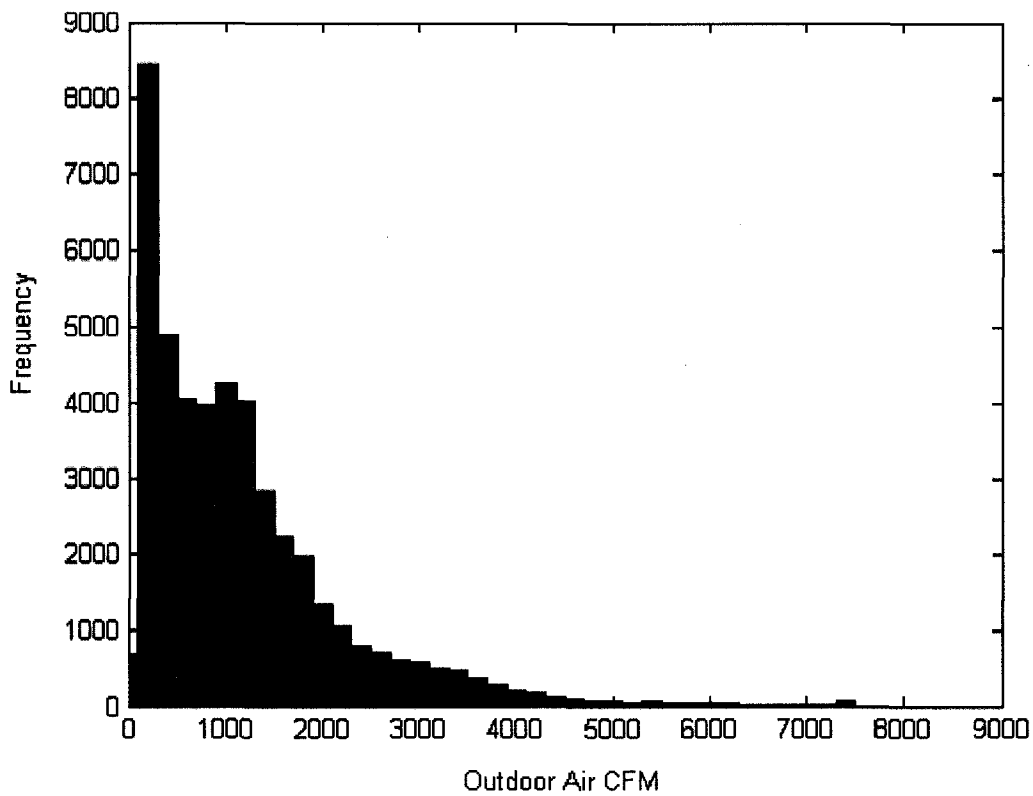


Figure 5.9: Histogram of outdoor air CFM after twelve months

Outdoor air temperature. As shown in Figure 5.10, the test sensors were exposed to outdoor air temperatures that ranged between 10-70°F, with most of the temperatures ranging between 30-50°F.

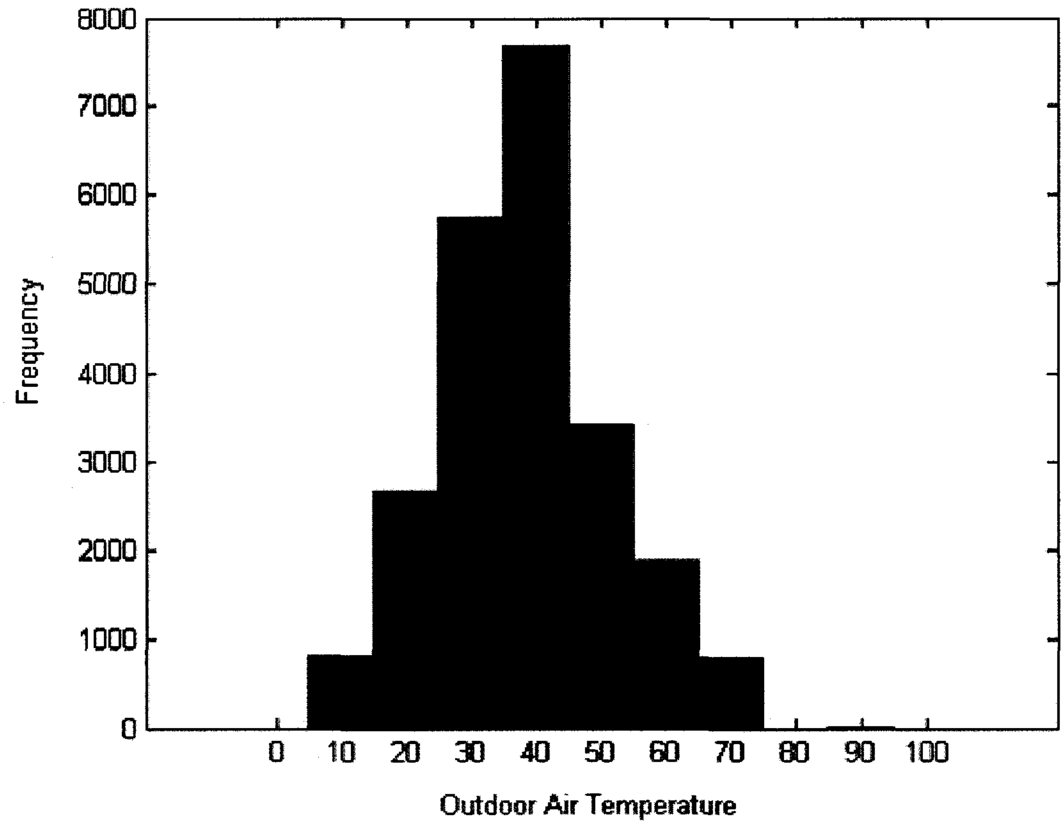


Figure 5.10: Histogram of outdoor air temperature (°F) after twelve months

Outdoor air relative humidity. As shown in Figure 5.11, the test sensors were exposed to outdoor air relative humidity values that ranged between 20-90% RH, with most of the values ranging between 40-70% RH.

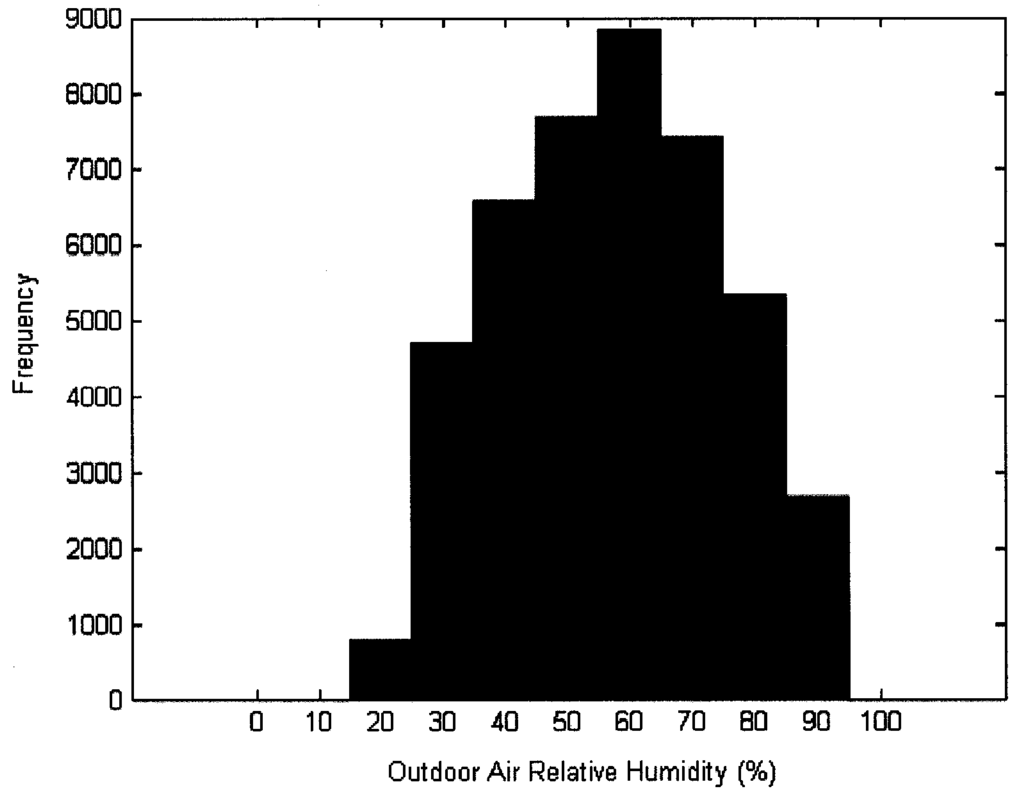


Figure 5.11: Histogram of outdoor air relative humidity after twelve months

In summary, during the last four months of ageing tests, the test sensors were mostly exposed to outdoor airflow, outdoor air temperature and outdoor air relative humidities that ranged between 200-1000 CFM, 30-50°F and 40-70% RH, respectively.

Discussion of accuracy results

The accuracy results of each sensor model after the ageing tests are presented in Table 5.2 and the trends in the deviations of each sensor model are presented in Table 5.3. The discussions of the results of the ageing test are presented below. It should also be noted that sensor Model B-I failed after eight months while sensor Model D-III was removed from the outdoor air duct after eight months of ageing tests and then used to perform response time and stress tests. Therefore, the accuracy results of sensors models B-I and D-III are presented and discussed only up to eight months. In addition, sensor Model F-II failed during the accuracy test after the twelve month test period, and therefore, the accuracy results after twelve months are not discussed. Instead, the accuracy results of sensor Model F-II only up to eight months are discussed herein.

As shown in Table 5.2, only one sensor out of twelve sensors met the manufacturer stated accuracy both before and after the ageing test while another sensor did not meet the stated accuracy either before or after the ageing test over any of the relative humidity range. The remaining ten sensors met the stated accuracy only at a few relative humidities.

As shown in Table 5.2, five out of twelve sensors show negligible changes in the deviations after the ageing test. For example, the deviations of Model C-III sensor at relative humidities of 10%, 30%, 50%, 70% and 90% RH increased by only 0.4% RH, 0% RH, 0.2% RH, 0.6% RH, 0.7% RH, respectively, after the ageing test. In contrast, three sensors out of the remaining seven sensors show significant changes in the deviations after the ageing test. For example, at 90% RH the deviation of Model F-II sensor increased by about 4% RH after the ageing test as shown in Table 5.2. And finally, the remaining four sensors do not show any variations in the deviations after the ageing test.

As shown in Table 5.3, the deviations of five out of the twelve sensors changed abruptly after the ageing test. For example, the deviation of Model E-III at

50% RH increased abruptly from 5.5% to 12.8% RH after the ageing test. In contrast, the deviations of two out of the remaining seven sensors changed gradually after the ageing test. For example, at 30% RH the deviation of Model A-III after the ageing test increased gradually from 2.0% to 2.5% RH after the ageing test. And finally, the variations in deviations of the remaining five sensors are negligible.

Table 5.2: Accuracy results before and after the ageing test of each sensor model at various relative humidities

Sensor model	Sensor	10 % RH		30 % RH		50 % RH		70 % RH		90 % RH	
		Before	After	Before	After	Before	After	Before	After	Before	After
A	I	-	-	OK	4.2	OK	OK	OK	OK	-	-
	III	-	-	6.0	7.3	4.6	6.0	2.0	3.4	-	-
B	I*	-3.9	OK	OK	3.5	3.7	4.5	OK	OK	OK	OK
	III	-4.0	OK	3.1	5.4	3.1	5.8	OK	OK	-5.3	6.1
C	I	OK	OK	OK	OK	OK	-3.2	OK	-4.1	OK	-5.9
	III	OK	OK	OK	OK	OK	OK	-3.3	-3.9	-4.9	-5.6
D	II	-	-	OK	-4.1	OK	-3.8	OK	OK	OK	OK
	III *	-	-	OK	OK	OK	OK	OK	OK	OK	OK
E	I	-	-	-5.2	-6.7	-7.9	-9.7	-10	-9.5	-6.7	-8.1
	III	-	-	-4.2	-9.8	-5.5	-13.0	-6.8	-12.1	-8.0	-13.3
F	II*	-	-	OK	OK	OK	OK	OK	OK	-3.1	-7.4
	III	-	-	OK	-5.6	OK	OK	OK	OK	OK	OK

Notes: -: manufacturer does not state accuracy

*: the deviation values in the table are after eight months

OK: sensor meets the manufacturer stated accuracy

I, II, III represent sensor units from a particular manufacturer

Table 5.3: Trends in the deviations of each sensor model

Sensor model	Sensor type	Sensor	Ageing trends	Change in deviations	
				Abruptly	Gradually
A	Capacitive	I	Yes	----	√
		III	No	----	----
B	Capacitive	I	No	----	----
		III	Yes	----	√
C	Capacitive	I	Yes	√	----
		III	No	----	----
D	Resistive	II	Yes	√	----
		III	No	----	----
E	Resistive	I	No	----	----
		III	Yes	√	----
F	Resistive	II	Yes	√	----
		III	Yes	√	----

Comparison of sensor models from a manufacturer

Model A

As shown in Table 5.2, capacitive sensor Model A-III is unaffected by the ageing test as evaluated by the variation in the deviations of the sensor being negligible over the entire relative humidity range. In contrast, sensor Model A-I is affected by the ageing test since the sensor does not meet the manufacturer stated accuracy at a relative humidity of 30% RH. In addition, as shown in Table 5.3 the deviations of sensor Model A-I changed gradually after the ageing test at all relative humidities evaluated.

Model B

As shown in Table 5.2, capacitive sensor Model B-I is unaffected by the ageing test as evaluated by the variations in the deviations of the sensor being negligible over the entire relative humidity range. In contrast, sensor Model B-III is affected by the ageing test since a large variation in the deviation is observed at a relative humidity of 90% RH. In addition, as shown in Table 5.3 the deviations of sensor Model B-III changed gradually rather than abruptly at all other relative humidities evaluated.

Model C

As shown in Table 5.2, capacitive sensor Model C-III is unaffected by the ageing test while sensor Model C-I is affected since the sensor did not meet the manufacturer stated accuracy at relative humidities of 50%, 70% and 90% RH. In addition, as shown in Table 5.3 the deviations of sensor Model C-I after the ageing test changed abruptly rather than gradually at all relative humidities evaluated.

Model D

As shown in Table 5.2, resistive sensor Model D-II is affected by the ageing test as evidenced by the sensor not meeting the manufacturer stated accuracy at relative humidities of 30% and 50% RH. While in contrast, sensor Model D-III is unaffected by the ageing test. In addition, as shown in Table 5.3 the deviations of sensor Model D-II after the ageing test changed abruptly rather than gradually at all relative humidities evaluated.

Model E

As shown in Table 5.2, resistive sensor Model E-III is affected by the ageing test as evidenced by the sensor showing large variations in deviations at all relative humidities evaluated. However, sensor Model E-I is unaffected by the ageing test at all relative humidities evaluated. In addition, as shown in Table 5.3 the deviations of sensor Model E-III after the ageing test changed abruptly rather than gradually at all relative humidities evaluated.

Model F

As shown in Table 5.2, resistive sensor models F-II and F-III are affected by the ageing test. For instance, sensor Model F-III does not meet the manufacturer stated accuracy at 30% RH, and sensor Model F-II shows large variation in the deviation at 90% RH. In addition, as shown in Table 5.3 the deviations of sensor models F-II and F-III after the ageing test changed abruptly rather than gradually at all relative humidities evaluated.

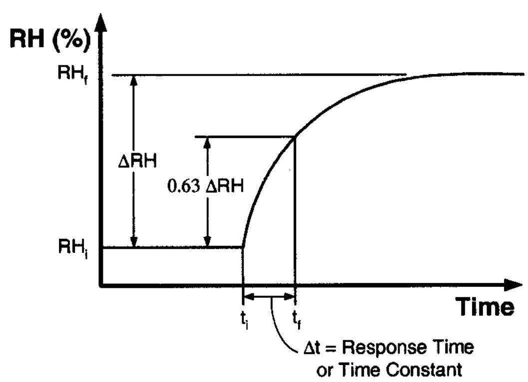
Summary

Based on the above discussions, only one sensor out of twelve sensors was unaffected both before and after the ageing tests in that the sensor met the manufacturer specified accuracy both before and after the ageing test. Further, four sensors out of the remaining eleven sensors remained unaffected after the ageing test with negligible changes in the deviations, for example, the changes in the deviations of sensor Model C-III was not more than 0.7% RH. The remaining seven sensors were affected after the ageing test as evidenced by either a large variation in deviations after the ageing test or by not meeting the manufacturer specified accuracy. For example, sensor Model C-I was affected after the ageing test since the sensor did not meet the manufacturer stated accuracy at relative humidities of 50%, 70% and 90% RH. Further, it appears that over the entire relative humidity range the ageing effects of two out of six capacitive sensors were gradual, while the ageing effects of a capacitive sensor from the remaining four sensors was abrupt rather than gradual. For example, the deviations of sensor Model A-I (Capacitive-type) changed gradually while the deviations of sensor Model C-I (Capacitive-type) changed abruptly over the entire relative humidity range. Finally, the ageing effects of four out of six resistive sensors were abrupt rather than gradual over the entire relative humidity range evaluated. For example, the deviations of resistive sensor models D-II, E-III, F-II, and F-III changed abruptly over the entire relative humidity range.

CHAPTER 6: RESPONSE TIME TEST

Overview

The response time study determined the time required for the relative humidity sensors to respond to a step change in the relative humidity. The response time (also commonly referred to as the time constant) of a relative humidity sensor is defined as the time it takes to reach 63% of its final value when subjected to a step change (either increasing or decreasing) in the relative humidity. A graphical depiction of this definition of the response time is shown in Figure 6.1. As illustrated, the response time is the amount of time it takes for the sensor output to reach 63% of its final value when subjected to a step change in the relative humidity being measured.



RH_i: Initial relative humidity value
RH_f: Final relative humidity value
ΔRH: Difference between the final and initial relative humidity value
t_f: Final time
t_i: Initial time

Figure 6.1: Graphical depiction of response time of a relative humidity sensor

As mentioned earlier in the ageing test, the most accurate and least accurate sensors were selected to undergo the ageing test while the third sensor was used for the response time test described herein. As discussed previously, for the time response tests, three sensors are of the capacitive type and the three remaining sensors are of the resistive type.

Method of Test

Prior to evaluating the response times of sensors, a Method of Test (MOT) was created and is reported in this section.

Quality control

The quality control of the sensors during the response time tests was conducted according to the procedures described earlier in Chapter 3.

Sensor installation inside the duct

The test sensors were installed in a duct whose inlet and outlet were connected to an air space in a large laboratory room. The purpose of the duct being connected to the laboratory air space was to provide a buffer against abrupt changes in the environmental conditions to which the test sensors are exposed. A 12V DC fan was used to draw air through the duct, and, thus, provide uniform velocity conditions inside the duct. The fan operated at a single speed resulting in air velocities of about 3 m/s.

Room conditions were measured by using a Vaisala model HMP 233 relative humidity sensor, which is hereafter referred to as the in-situ reference sensor. This in-situ reference sensor was installed in close proximity to the test sensors, and it has a measurement range of 0-100% RH with a manufacturer stated accuracy of ±1% RH for 0-90% RH and ±2% RH for 90-100% RH. A T-type thermocouple was used to measure the air temperature in the duct. Figure 6.2 is a schematic of the duct showing the relative locations of the test sensors, reference sensor, reference thermocouple and fan. The power supply and data acquisition equipment described previously was used to power the test and reference sensors and to measure the outputs of these sensors.

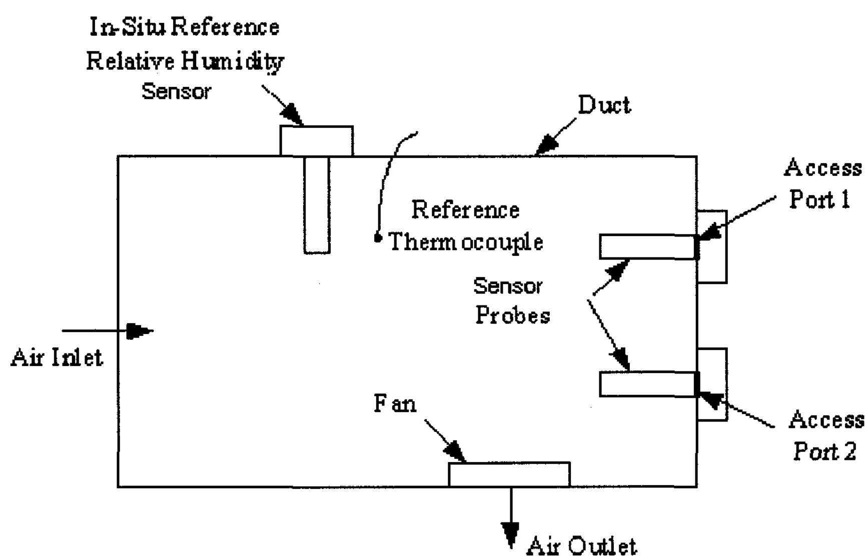


Figure 6.2: Sensor mounting layout inside the duct

Sensor installation inside the humidity generator

The test sensors were installed in the humidity generator through access ports so that the sensor electronics remained outside the humidity generator while the sensor probe was exposed to the conditioned air in the humidity generator. A 12V DC fan was used to move air across the sensor so that the velocity conditions were similar to those in the duct. A description of the humidity generator was provided earlier, and its technical specifications are listed in Table 3.2. Figure 6.3 is a schematic showing sensor probe location, sensor electronics and access ports in the humidity generator. Since the apparatus has two access ports, two relative humidity sensors were tested at the same time.

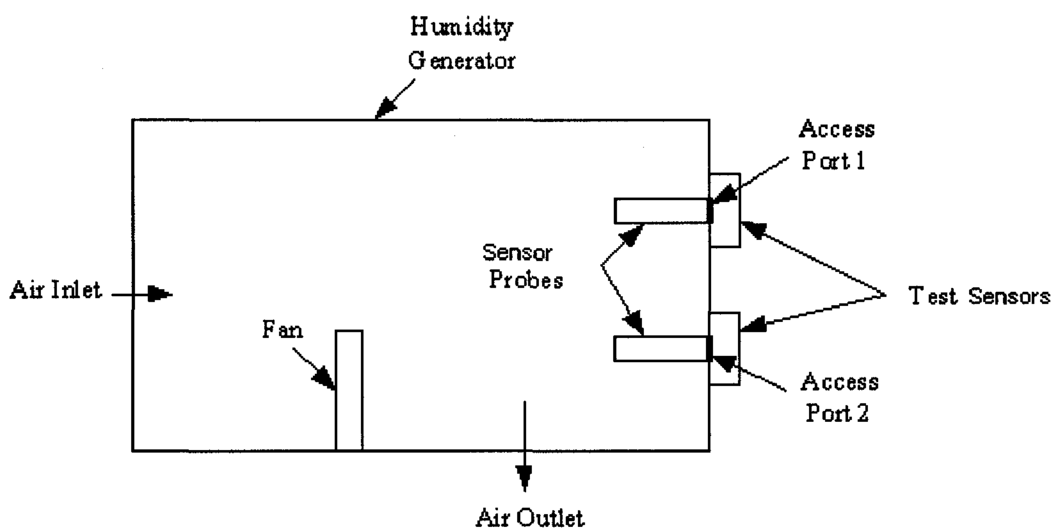


Figure 6.3: Sensor mounting layout through humidity generator access port

Test conditions

A step change in relative humidity was generated by moving the test sensors from one environmental condition to a second environmental condition. A forward step test consisted of moving the sensor from room conditions, which typically ranged from 20% to 55% RH, to humidity generator conditions, which were set at 80% RH. In contrast, a reverse step test consisted of moving the sensor from the humidity generator (set at 80% RH) to room conditions. For the forward and reverse step tests, the details about the initial and the final relative humidity test conditions, along with the steady-state criteria for the test sensors and the humidity generator are described below.

Forward step test

Initial relative humidity. The initial test condition was established by exposing the test sensors to room relative humidity and temperature conditions. The room relative humidity typically ranged from 20-55% RH and the temperature typically ranged from 20-25ºC. Testing of the sensors was performed only when the room relative humidity ranged between 20-55% RH. The test sensors were exposed to room conditions until stability was reached in the room conditions, the humidity generator conditions and measurements from the test sensor. The steady-state criteria in Table 6.1 was used to ensure that both relative humidity and temperature conditions were stable. For example, as shown in Table 6.1 the variations in the relative humidity readings from the test sensor and the humidity generator were not allowed to vary more than ±1% RH and ±0.5% RH, respectively, for a 10-minute period. In addition, the variations in the temperature readings were not allowed to vary more than ± 1°C for a 10-minute period.

Table 6.1: Steady state criteria for the test sensor, temperature sensor and humidity generator

Device	Parameter	Steady state conditions
Test Relative Humidity Sensor	Sensor Relative Humidity	Change of less than $\pm 1\%$ RH for 10 minutes based on measurements taken at one-second intervals
T-Type Reference Thermocouple	Room Temperature	Change of less than $\pm 1^{o}C$ for 10 minutes based on measurements taken at one-second intervals
Humidity Generator	Actual Relative Humidity in the humidity generator	Change of less than $\pm 0.5\%$ RH for 10 minutes

Final relative humidity. The final test condition for the forward step test was established by exposing the test sensors to the conditions in the humidity generator. The test sensors were exposed to the conditions in the humidity generator until the test sensors satisfied the steady-state criterion in Table 6.1.

Reverse step test

Initial relative humidity. The initial test condition for the reverse step test was established by exposing the test sensors to the conditions in the humidity generator. The test sensors were exposed to the conditions in the humidity generator until the room conditions, humidity generator conditions and measurements from the test sensor satisfied the steady-state criteria in Table 6.1. Testing of the sensors was carried out only when the room relative humidity was between 20-55% RH.

Final relative humidity. The second test condition for the reverse step test was established by exposing the test sensors to room relative humidity and temperature conditions. The test sensors were exposed to room conditions until the measurements from the test sensors satisfied the steady-state criterion in Table 6.1.

The test procedures for the forward and reverse step tests are provided in the following sections. The forward and reverse step tests were performed three times each to establish the response time of each test sensor. In addition, a forward-step test (performed once) with both fans switched OFF was also performed for the purpose of evaluating the effect of air flow on the response times of the sensors.

Forward step test

A forward step test consisted of moving the sensor from room conditions, which typically ranged from 20% to 55% RH, to humidity generator conditions, which were set at 80% RH. The test sensor was exposed to the room conditions for not less than 30 min and until the steady-state criteria in Table 6.1 for the test sensor, reference thermocouple, and humidity generator were satisfied. The relative humidity conditions measured by the test and reference sensors and the temperature measured by the reference thermocouple were recorded at one-second intervals. Once the criteria for steady state was satisfied by the test sensor and reference thermocouple, a one-minute average of the temperature readings from the reference thermocouple was obtained. The temperature in the humidity generator was set to match the room temperature, while the relative humidity condition in the humidity generator was then set to 80% RH. When the temperature in the humidity generator was within 1ºC of the room temperature, and the steady-state criteria in Table 6.1 were satisfied, a one-minute averages of the test sensors, the reference relative humidity sensor, and the reference thermocouple were recorded. The one-minute average relative humidity reading from the test sensor represented the initial value used for calculating the time constant of the humidity sensor. The test sensor was then moved to the humidity chamber after recording the time.

During the test period when the sensor was exposed to the generator conditions, the fan located inside the humidity generator created velocity conditions similar to those in the duct. Several velocity measurements were recorded both inside the generator and inside the duct to ensure that the sensors were exposed to similar velocity conditions. Measurements from the test sensor were recorded at one-second intervals continuously until steady state was achieved and then a one-minute average of the relative humidity reading was recorded and used as the final value for calculating the time constant of the sensor. One-minute average readings of relative humidity and temperature for the humidity generator were also recorded. A flow chart of the test procedure is provided in Figure 6.4.

Reverse step test

A reverse step test consisted of moving the sensor from the humidity generator (80% RH) to room conditions. The test sensor was exposed to the conditions in the humidity generator for not less than 30 min and until the steady-state criteria for the test sensor, reference thermocouple, and humidity generator were satisfied. The steady-state criteria are provided in Table 6.1. During the test period when the sensors were exposed to the generator conditions, the fan located inside the humidity generator created velocity conditions similar to those in the duct.

The relative humidity conditions measured by the test and reference sensors and the temperature measured by the reference thermocouple were recorded at one-second intervals. Once the criteria for steady state were satisfied by the test sensor and reference thermocouple, a one-minute average of the temperature readings from the reference thermocouple was obtained and then used to set the temperature in the humidity generator. The relative humidity condition in the humidity generator was set at 80% RH. After all the steady-state criteria in Table 6.1 were satisfied and the temperature in the humidity generator was within 1°C of the room temperature, a one-minute average of relative humidity measured by the test sensor was recorded. The one-minute average relative humidity reading from the test sensor represented the initial value used for calculating the time constant of the humidity sensor. One-minute average relative humidity and temperature readings from the humidity generator were also recorded. The test sensor was then moved to the duct and the time when the sensor is moved was recorded.

The test sensor remained in the duct (exposed to room conditions) until the test sensor satisfied its steady-state criteria in Table 6.1. Measurements from the test sensor were recorded continuously at one-second intervals. A one-minute average of the relative humidity reading recorded after achieving the steady state was then used as the final value to calculate the time constant. One-minute averages of relative humidity and temperature measured by the reference sensor and the reference thermocouple were also recorded. The flow chart for the reverse test is similar to the flow chart for the forward test shown in Figure 6.4.

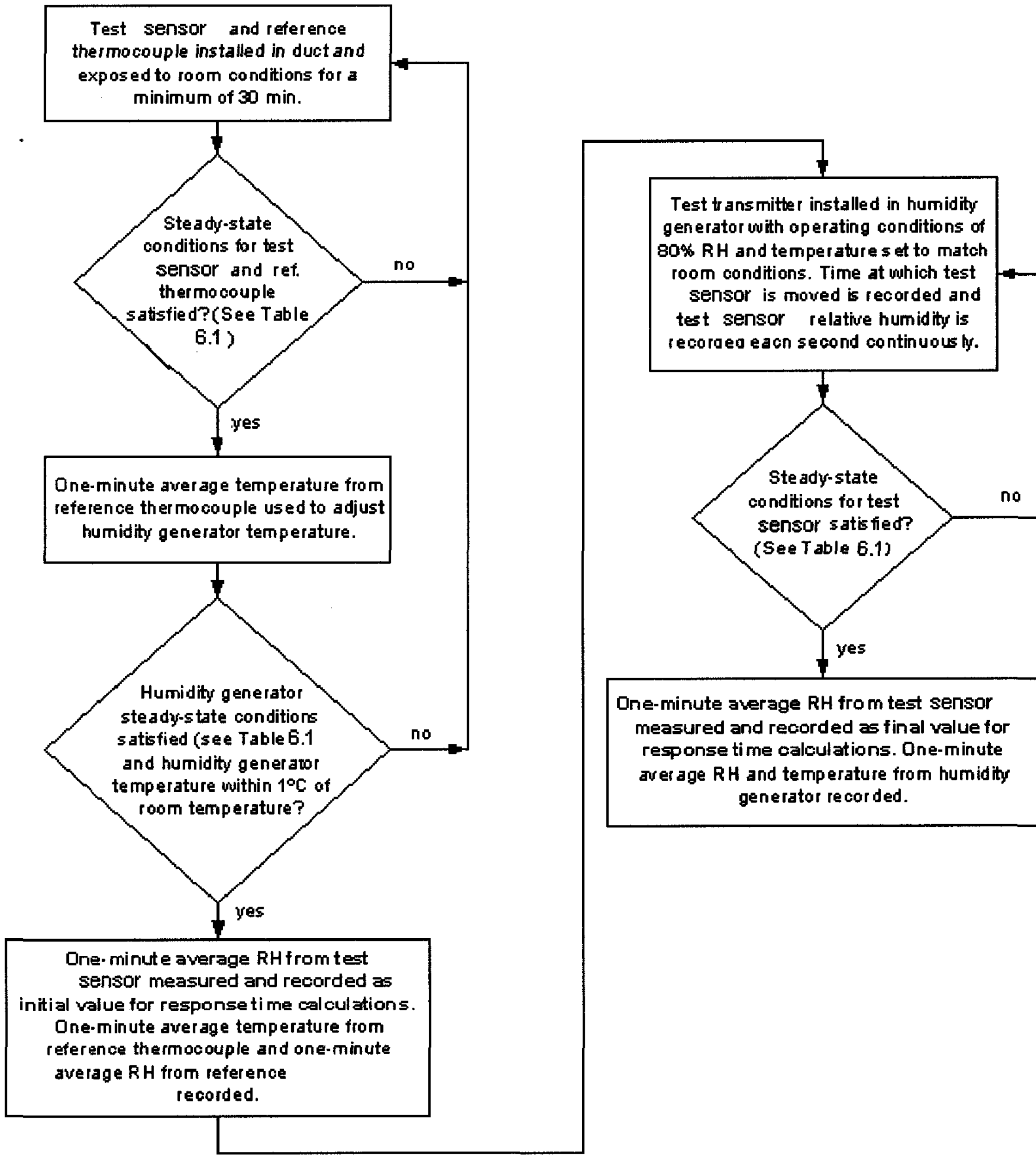


Figure 6.4: Response time testing procedure for the forward step test

Response time calculations

For the forward step tests, the initial reading obtained when the test sensor was exposed to room conditions is designated RH_i and the final relative humidity reading obtained when the test sensor was exposed to conditions in the humidity generator is designated RH_f (see Figure 6.1). The difference between the humidity values is given by, $\Delta RH=RH_f-RH_i$. The relative humidity value corresponding to a 63% change (i.e., one time constant) from the initial relative humidity reading to the final reading is given by, $RH_{0.63}=(0.63\times \Delta RH)+RH_i$. Therefore, the amount of time Δt required for the test sensor to reach the 63% change in relative humidity, $RH_{0.63}$, determined the time constant of the test sensor. Even though the above calculation procedure is for the forward step tests, it is also applicable for the reverse step tests in that the initial relative humidity reading was defined based on the humidity generator conditions, while the final relative humidity was defined based on the room conditions.

Results and Discussions

Six relative humidity sensors representing different manufacturers were tested to determine their response time, and the results are presented in this section. For each sensor, the results for three forward step and three reverse step tests are presented. In addition, each of the three readings are averaged to obtain average forward and average reverse step response times. Also, for each test run the results are presented in terms of the deviations from the average for both forward and reverse steps.

Discussion of results

The forward step and reverse step response times are presented, analyzed and discussed below for each sensor model.

Model A

The results for sensor Model-A are shown in Table 6.2 for three test runs. Sensor Model-A has slower reverse-step response times compared to forward-step response times for the three test runs. For example, the reverse-step response times of sensor Model-A are larger than the forward-step response times by 31 sec, 30 sec and 40 sec for the three test runs. Further, the average reverse-step response time is larger than the forward-step response time by 34 sec as shown in Table 6.2. Furthermore, as shown in Table 6.2 the deviation in response time from the average for the reverse-step is larger than the forward-step by 3%.

Table 6.2: Response times of three forward-step runs and three reverse step runs of Model-A sensor

Test runs	Forward-step (sec)	Fwd. step dev. from the average (%)	Reverse-step (sec)	Rev. step dev. from the average (%)	Difference (sec)
1	48	1	79	4	31
2	46	5	76	7	30
3	52	7	91	10	40
Average	**49**	**4**	**82**	**7**	**34**

Note: Difference= Reverse – Forward; Fwd.: Forward; dev.: deviation; Rev.: Reverse

Model B

The results for sensor Model-B is shown in Table 6.3 for three test runs. Sensor Model-B has slower reverse-step response times compared to forward-step response times for three test runs. For example, the reverse-step response times of sensor Model-B are larger than the forward-step response times by 30 sec, 10 sec and 17 sec for all three test runs. Further, the average reverse-step response time is larger than the forward-step response time by 19 sec as shown in Table 6.3. Furthermore, as shown in Table 6.3 the deviation in response time from the average for the reverse-step is smaller than the forward-step by 13%.

Table 6.3: Response times of three forward-step runs and three reverse step runs of Model-B sensor

Test runs	Forward-step (sec)	Fwd. step dev. from the average (%)	Reverse-step (sec)	Rev. step dev. from the average (%)	Difference (sec)
1	24	35	54	4	30
2	40	8	50	11	10
3	47	27	65	15	17
Average	**37**	**23**	**56**	**10**	**19**

Note: Difference= Reverse – Forward; Fwd.: Forward; dev.: deviation; Rev.: Reverse

Model C

The results for sensor Model-C is shown in Table 6.4 for three test runs. Sensor Model-C has faster reverse-step response times compared to forward-step response times for three test runs. For example, the reverse-step response times of sensor Model-C are smaller than the forward-step response times by 3 sec, 8 sec and 2 sec for three test runs. Further, the average reverse-step response time is smaller than the forward-step response time by 4 sec as shown in Table 6.4. Furthermore, as shown in Table 6.4 the deviation in response time from the average for the reverse-step is smaller than the forward-step by 26%.

Table 6.4: Response times of three forward-step runs and three reverse step runs of Model-C sensor

Test runs	Forward-step (sec)	Fwd. step dev. from the average (%)	Reverse-step (sec)	Rev. step dev. from the average (%)	Difference (sec)
1	8	14	5	0	3
2	13	39	5	0	8
3	7	25	5	0	2
Average	**9**	**26**	**5**	**0**	**4**

Note: Difference= Reverse – Forward; Fwd.: Forward; dev.: deviation; Rev.: Reverse

Model D

The results for sensor Model-D for three test runs is shown in Table 6.5. Sensor Model-D has faster reverse-step response time compared to the forward-step response time for test run 2, while sensor Model-D has slower reverse-step response time compared to the forward-step response time for test run 1, and the forward-step and reverse-step response times of sensor Model-D are 88 sec. Further, the average reverse-step response time is smaller than the forward-step response time by 16 sec as shown in Table 6.5. Furthermore, as shown in Table 6.5 the deviation in response time from the average for the reverse-step is smaller than the forward-step by 13%.

Table 6.5: Response times of three forward-step runs and three reverse step runs of Model-D sensor

Test runs	Forward-step (sec)	Fwd. step dev. from the average (%)	Reverse-step (sec)	Rev. step dev. from the average (%)	Difference (sec)
1	89	12	95	6	6
2	128	26	86	4	42
3	88	13	88	2	0
Average	**102**	**17**	**90**	**4**	**16**

Note: Difference= Reverse – Forward; Fwd.: Forward; dev.: deviation; Rev.: Reverse

Model E

The results for sensor Model-E is shown in Table 6.6 for three test runs. Sensor Model-E has slower reverse-step response times compared to forward-step response times for three test runs. For example, the reverse-step response times of sensor Model-E are larger than the forward-step response times by 9 sec, 24 sec and 17 sec for three test runs. Further, the average reverse-step response time is larger than the forward-step response time by 17 sec as shown in Table 6.6. Furthermore, as shown in Table 6.6 the deviation in response time from the average for the reverse-step is smaller than the forward-step by 4%.

Table 6.6: Response times of three forward-step runs and three reverse step runs of Model-E sensor

Test runs	Forward-step (sec)	Fwd. step dev. from the average (%)	Reverse-step (sec)	Rev. step dev. from the average (%)	Difference (sec)
1	90	11	99	1	9
2	78	4	102	4	24
3	76	7	93	5	17
Average	**81**	**7**	**98**	**3**	**17**

Note: Difference= Reverse – Forward; Fwd.: Forward; dev.: deviation; Rev.: Reverse

Model F

The results for sensor Model-F is shown in Table 6.7 for three test runs. Sensor Model-F has slower reverse-step response times compared to forward-step response times for three test runs. For example, the reverse-step response times of sensor Model-F are larger than the forward-step response times by 2 sec, 1 sec and 3 sec for three test runs. Further, the average reverse-step response time is larger than the forward-step response time by 2 sec as shown in Table 6.7. Furthermore, as shown in Table 6.7 the deviation in response time from the average for the reverse-step is smaller than the forward-step by 7%.

Table 6.7: Response times of three forward-step runs and three reverse step runs of Model-F sensor

Test runs	Forward-step (sec)	Fwd. step dev. from the average (%)	Reverse-step (sec)	Rev. step dev. from the average (%)	Difference (sec)
1	9	0	11	0	2
2	10	11	11	0	1
3	8	11	11	0	3
Average	**9**	7	**11**	0	**2**

Note: Difference= Reverse – Forward; Fwd.: Forward; dev.: deviation; Rev.: Reverse

Comparison of average response-time

The response-times of the six sensors are compared by focusing on the average response-time for each sensor model. The average response-time of a sensor model was determined by averaging the response times of three forward runs and three reverse step runs.

As seen in Table 6.8, sensor models C and F have the fastest average response times of 7 sec and 10 sec, respectively, while sensor models A, D and E have the slowest average response times of 66 sec, 96 sec and 90 sec, respectively. The average response time of sensor Model-B is intermediate, at 47 sec. It can be concluded that humidity sensor response times can vary considerably from manufacture to manufacture with the average response times for this study varying from 7 sec to 96 sec.

Table 6.8: Average response time of each sensor model

Sensor Model	Average response time (sec)
A	66
B	47
C	7
D	96
E	90
F	10

Comparison of average forward and reverse response-times

The average forward-step response-time for each sensor model was determined by averaging the response times of three runs while the average reverse-step response time was determined similarly.

As shown in Table 6.9, sensor models A, B, E and F have slower average reverse-step response times compared to the average forward-step response times. For example, the average reverse-step response times of sensor models A, B, E and F were larger than the forward-step response times by 33 sec, 19 sec,17 sec and 2 sec respectively.

In contrast, sensor models C and D had faster average reverse-step response times compared to average forward-step response times. For example, the average reverse-step response times of sensor models C and D are smaller than the forward-step response times by 4 sec and 12 sec, respectively.

In general, sensor models A, B and C show large percent changes (i.e., Difference*100/Forward) in the response times compared to sensor models D, E and F when going from forward-step to reverse-step as shown in Table 6.9. These sensors are capacitive sensors (i.e., models A, B and C).

Table 6.9: Average forward-step and reverse-step response times of each sensor model

Sensor model	Average forward-step response time (sec)	Average reverse-step response time (sec)	Difference (sec)*	% Change
A	49	82	33	67
B	37	56	19	51
C	9	5	4	-44
D	102	90	12	-12
E	81	98	17	21
F	9	11	2	22

*: represents the magnitude of difference between reverse-step and forward-step response times

Comparison of capacitive and resistive types

In general, the capacitive-type sensor had faster response times compared to resistive-type sensors. This conclusion is based on using several different approaches to compare the response times of the two sensor categories. For example, the average response time of all three capacitive sensors is 40 sec (i.e., average of capacitive sensors A, B and C) while the average response time of all three resistive sensor models is 65 sec (i.e., average of resistive sensors D, E and F).

Another approach for comparing response times is to compare the fastest capacitive sensors with the fastest resistive sensor and then repeat this comparison for the slowest sensors and finally the intermediate sensors. As seen in Table 6.10, the fastest capacitive-type sensor, Model-C, has an average response time of 7 sec compared to the fastest resistive-type sensor, Model-F, of 10 sec. The slowest capacitive-type sensor, Model-A, has an average response time of 66 sec compared to the slowest resistive-type sensor, Model-D, of 96 sec. The intermediate capacitive-type sensor, Model-B, has an average response time of 47 sec compared to the intermediate resistive-type sensor, Model-E, of 90 sec.

Table 6.10: Comparison of average response times for capacitive and resistive type sensors

Sensor model	Sensor type	Average forward-step response time (sec)	Average reverse-step response time (sec)	Average response time (sec)
A	Capacitive	49	82	66
B	Capacitive	37	56	47
C	Capacitive	9	5	7
D	Resistive	102	90	96
E	Resistive	81	98	90
F	Resistive	9	11	10

Comparison of response times for fan ON and fan OFF conditions

The results of the forward-step response time test presented above, which were performed with both fans switched ON, were compared to time response tests with both fans switched OFF. This comparison was performed only for forward-step response times, and it is based on averaging the response times of three forward-step runs.

As shown in Table 6.11, the response times of sensor models A, B, C, E and F got larger when the fan was switched OFF. For example, the response times of sensor models A, B, C, E and F with the fan switched OFF increased by 17 sec, 11 sec, 3 sec, 9 sec, and 9 sec, respectively. In contrast, the response time of sensor Model-D got smaller when the fan was switched OFF. For example, the response time of sensor Model-D when the fan was switched OFF decreased by 12 sec compared to the response time when the fan was switched ON.

Table 6.11: Forward-step response times of each sensor model with both fans switched ON and switched OFF

Sensor model	Forward-step response time (sec), Fan ON	Forward-step response time (sec), Fan OFF	Difference (sec)
A	49	66	17
B	37	48	11
C	9	12	3
D	102	90	-12
E	81	90	9
F	9	18	9

Summary

In summary, five out of six sensor models had slower reverse-step response times compared to the forward-step response times for the three test runs. However, the remaining one sensor did not show any obvious trend in the response times for the three test runs. Further, the average reverse-step response times of four out of six sensor models were slower compared to the average forward-step response times. In contrast, the remaining two sensor models had faster average reverse-step response times compared to the average forward-step. Furthermore, the analysis indicated that the average response times of relative humidity sensors varied considerably from manufacturer to manufacturer with the fastest average response time being 7 sec and slowest average response time being 96 sec. Among the capacitive and resistive types, capacitive-type sensor had faster response times compared to resistive-type sensors with the average response time of all three capacitive sensors being 40 sec while that of all three resistive sensor models being 65 sec. Finally, with the fan switched OFF the response times of five out of six models got larger with the magnitude of increase between 3 to17 sec, while the response time of the remaining sensor got smaller by 12 sec.

CHAPTER 7. STRESS TESTS

Overview

The stress tests are the final set of tests that were performed on the relative humidity sensors, and they were designed to subject the sensors to extreme conditions. The same set of sensors that were used in the response-time test described earlier were used for stress testing.

Stress testing of humidity sensors consists of three types of tests: cycling, desiccation-saturation and submergence. The cycling test subjected the sensors to cyclic variations in relative humidity conditions, the desiccation-saturation test exposed the test sensors to extreme relative humidity conditions of 0% and 100%, and the submergence test immersed the sensing element of the test sensor in water. Following each phase of the stress test, the accuracy of the sensors was measured at several relative humidity conditions to evaluate the extent to which the sensors were affected by each test.

Method of Test

Prior to evaluating the effects of stress tests, a Method of Test (MOT) was created and is reported in this section.

Cycling test

In the cycling test, the sensors were repeatedly exposed to extreme relative humidity conditions of 10% and 95% RH at fixed temperatures of 5°C and 35°C. The test conditions along with the test procedure used in the cycling test are described below.

Test conditions

The sensors were subjected to an environment in which the relative humidity was cycled between 10% and 95% RH while the temperature was held constant either at 5°C or 35°C. These conditions were generated with the humidity generator. These relative humidity conditions represent the extreme range of conditions that a sensor would likely be exposed to in an actual application, and in addition, these conditions represent the limits of the humidity generator.

Test procedure

Three sensors were tested simultaneously inside the humidity generator using the custom-made manifold described earlier in Chapter 3. Humidity generator conditions were set at 5°C and 10% RH and then allowed to stabilize for 30-minutes. Next, the relative humidity of the generator was changed to 95%, and the conditions were again allowed to stabilize for 30-minutes before the humidity was changed back to 10% RH. The above change in conditions constituted one complete cycle. The sensors underwent 50 consecutive cycles while the temperature inside the humidity generator was maintained at 5°C. After completing the 50 cycles at 5°C, the sensors underwent 50 consecutive cycles at 35°C.

During the cycling test, readings from the sensors were collected and stored at 5-minute intervals. Following the cycling test, the accuracy of the sensors was measured at a temperature of 25°C and at relative humidities of 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH.

Desiccation-Saturation test

The desiccation-saturation test consisted of exposing the test sensors to 0% and 100% RH environments at room temperature. This was followed by accuracy testing at a temperature of 25°C and at relative humidities of 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH. The test conditions and procedure are described below.

Test conditions

The dry environment (0% RH) was produced by sealing a container that was partially filled with desiccant, which is hereafter referred to as the desiccant bath. After a 24 hour period, the air in the space above the desiccant was assumed to have reached equilibrium condition of 0% RH. The saturated environment (100% RH) was produced by sealing a container that was partially filled with water, which is hereafter referred to as the water bath. After a 24 hour period, the air in the space above the desiccant was assumed to have reached equilibrium condition of 100% RH. A reference sensor, namely, Vaisala model HMP 233 relative humidity/temperature sensor, was used to ensure that the environments in both the containers were at or near the desired 0% and 100% RH conditions. This reference sensor has a measurement range of 0-100% RH and a rated accuracy of ±1% RH for 0-90% RH and ±2% RH for 90-100% RH.

A schematic of the test setup is shown in Figure 7.1. The test sensors were installed so that the sensor element protruded into the container while the sensor electronics remained outside the container. The container had dimensions of 36 × 15 × 12 inches and had six openings in the lid to accommodate the test sensors. After installing the sensors in their respective openings, the openings were then sealed so that there was no ingress/egress of air, thus maintaining the moisture content inside the container constant. In addition, care was taken to ensure that the tips were a uniform distance above the surface of the desiccant/water bath.

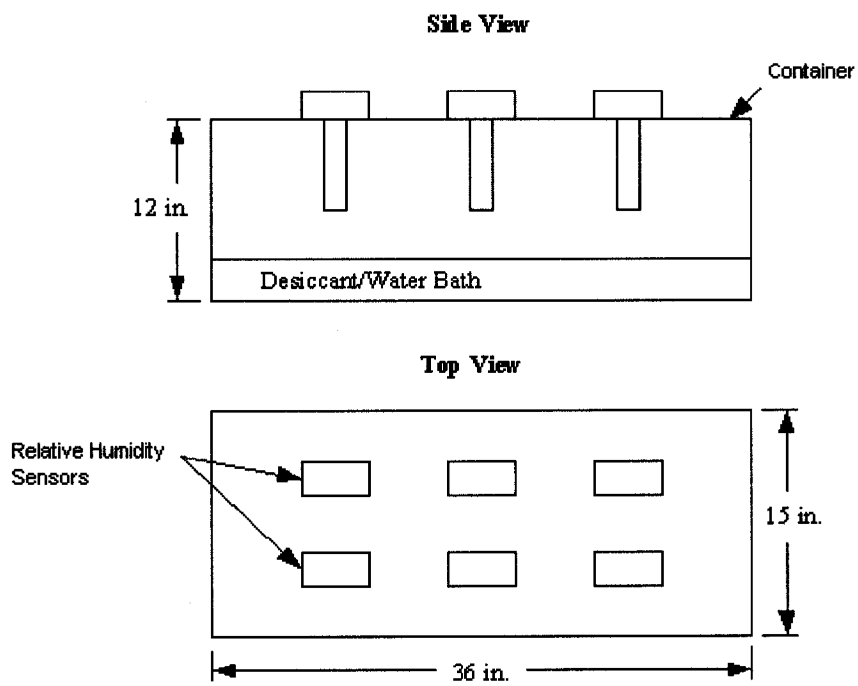


Figure 7.1: Schematic of the container used for the desiccation-saturation test

Test procedure

The first step in the desiccation-saturation test procedure was to generate the dry and saturated environments in the two separate containers. Once these environments were established, the test sensors were divided into two sets, with three sensors per set, and the test procedure described below was implemented. During the time periods when the test sensors were installed in the dry and saturated environments, readings from the sensors were collected and stored at 5-minute intervals. The accuracy measurements identified in this test procedure were made in the humidity generator in accordance with the procedures described earlier. The test schedule is shown in Table 7.1 and described below.

Day-1. The first set of three sensors was installed in the dry environment and remained there for two days. The second set of sensors was placed in storage.

Day-2. The second set of three sensors was installed in the dry environment and remained there for two days.

Day-3. The first set of sensors was removed from the dry environment and the accuracy of this set of sensors was measured at 25°C and 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH.

Day-4. The second set of sensors was removed from the dry environment and the accuracy of this set of sensors was measured at 25°C and 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH. The first set of sensors was transferred to the saturated environment and remained there for two days.

Day-5. The second set of sensors was installed in the saturated environment and remained there for two days.

Day-6. The first set of sensors was removed from the saturated environment and the accuracy of this set of sensors was measured at 25°C and 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH.

Day-7. The second set of sensors was removed from the saturated environment and the accuracy of this set of sensors was measured at 25°C and 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH. The first set of sensors was placed in storage.

Day-8. The accuracy of the first set of sensors was measured at 25°C and 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH. The second set of sensors was placed in storage.

Day-9. The accuracy of the second set of sensors was measured at 25°C and 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH. The first set of sensors was placed in storage.

Testing on Day-8 and Day-9 was designed to determine if the sensor performance improved after the sensors had been removed from the extreme environments for two days.

Table 7.1: Desiccation-Saturation test schedule

Activity	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9
Temporary storage of sensors									
Continuous testing in the humiditiy generator *									
Exposure to 100% RH environment									
Continuous testing in the humiditiy generator *									
Exposure to 0% RH environment									

: First set of three sensors; : Second set of three sensors

: First set of sensors testing in the humidity generator

: Second set of sensors testing in the humidity generator

* : Testing at 25°C and 20, 30, 50, 70, 90, 70, 50, and 30% RH

Submergence test

The submergence test was performed after the completion of the cycling and desiccation-saturation tests. In the submergence test, the sensor elements were submerged in water for a fixed period of time, and then tested for accuracy to evaluate the change in performance of the sensors. The test conditions and test procedures for the submergence test are described below.

Test conditions

The test setup for the submergence test is shown in Figure 7.2. In this setup, sensor elements were submerged in water for a one-day period. The sensor electronics were kept outside the container as shown in Figure 7.2. During the submergence test, the room relative humidity conditions were recorded by a ±3% accurate Vaisala sensor, which had a measurement range of 10-90% RH.

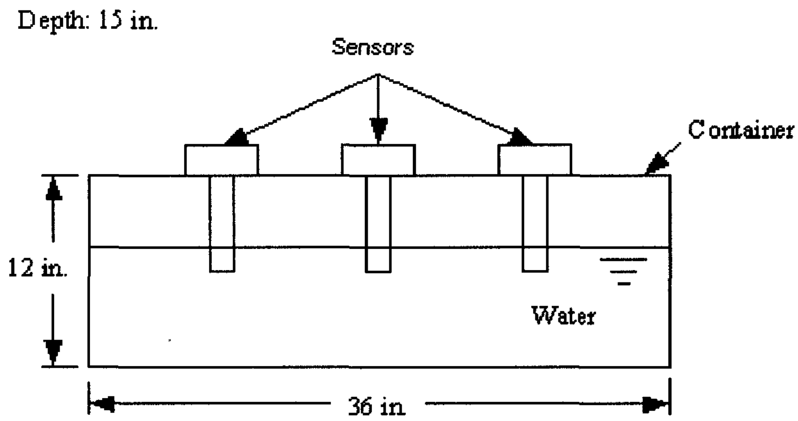


Figure 7.2: Schematic of the submergence test setup

Test procedure

The sensors were divided into two sets of three sensors, and then submerged, and tested over a period of six days following the test procedure described below. While submerged, readings from the sensors were collected and stored at 5-minute intervals. After removal from the submergence test setup, accuracy measurements were performed in the humidity generator in accordance with the procedures described earlier. The test schedule is shown in Table 7.2.

Day-1. The first set of sensors was submerged in water while the second set of sensors was placed in storage.

Day-2. The first set was removed from the container, and the accuracies were measured at 25°C and 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH. The second set was submerged in water in the container.

Day-3. The second set was removed from the container and the accuracies was measured at 25°C and 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH, while the first set of sensors was placed in storage.

Day-4. The accuracy of the first set of sensors was measured again at 25°C and 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH, while the second set of sensors was placed in storage.

Day-5. The accuracy of the second set of sensors was measured again at 25°C and 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH while the first set of sensors was placed in storage.

Testing on Day-4 and Day-5 was designed to determine if the sensor performance improved after the sensors had been given two days to recover.

Table 7.2: Submergence test schedule

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
Temporary storage of sensors	■			■	
			▒		▒
Continuous testing in the humidity generator*			■		■
		▒		▒	
Submerge sensors		■			
	▒				

■ : First set of three sensors; ▒ : Second set of three sensors

*: 25°C and 20, 30, 50, 70, 90, 70, 50, and 30% RH

Results and Discussions

Two sets of accuracy testing were performed after the desiccation, the saturation and the submergence test. In particular, the first set of accuracy testing was performed immediately after each stress test while the second set of accuracy testing was performed two days following each stress test. The accuracy of the sensors was measured at a temperature of 25°C and at relative humidities of 20%, 30%, 50%, 70%, 90%, 70%, 50% and 30% RH. This test sequence was adopted to eliminate possible errors in relative humidity measurements at 30%, 50% and 70% RH due to hysteresis. The procedures that were used for making these accuracy measurements were described earlier in Chapter 3.

When two accuracy measurements were taken at 30%, 50% and 70% RH, then the average relative humidities were obtained by averaging the forward and reverse measurements. The accuracy results are presented in terms of the deviation of the measured value from the actual value (e.g., deviation = $RH_{measured} - RH_{actual}$).

The test results of the cycling test, the desiccation-saturation test and the submergence test are discussed in the following sections.

Results of the cycling test

Humidity generator test conditions

During the cycling test, the actual relative humidity conditions generated by the humidity generator were 10% RH and 95% RH at either temperatures of 5°C or 35°C.

Accuracy tests results

As shown in Figure 7.3, sensor Model-A met the manufacturer stated accuracy before the cycling test at relative humidities of 50% and 70% RH, however, immediately after the cycling test, the sensor did not meet the accuracy at 50% RH (see Figure 7.3). For example, the deviation of Model-A sensor at 50% RH increased from 2.5% RH before the cycling test to 3.4% RH immediately afterwards. At 30% RH the sensor Model-A did not meet the manufacturer stated accuracy either before or immediately after the cycling test.

As shown in Figure 7.4, sensor Model-B met the manufacturer stated accuracy before the cycling test at relative humidities of 30%, 50% and 70% RH, however, immediately after the cycling test the sensor did not meet the accuracy at relative humidities of 30% and 50% RH. For example, the deviation of Model-B sensor at 30% RH increased from 2.6% RH before the cycling test to 3.4% RH afterwards, while at 50% RH the deviation increased from 2.6% RH to 4.4% RH.

As shown in Figures 7.5 and 7.6, sensor models C and F met the manufacturer stated accuracy both before and immediately after the cycling test at all relative humidities evaluated.

As shown in Figure 7.7, sensor Model-D met the manufacturer stated accuracy before and after the cycling test at relative humidities of 30% and 70% RH. Surprisingly, immediately after the cycling test the sensor met the accuracy at 50% RH even though it did not meet the manufacturer accuracy before the cycling test. For example, the deviation of Model-D sensor at 50% RH decreased from 3.2% RH before the cycling test to 3.0% RH immediately afterwards.

As shown in Figure 7.8, sensor Model-E met the manufacturer stated accuracy before the cycling test at all relative humidities evaluated. However, immediately after the cycling test, the sensor does not meet the accuracy at a relative humidity of 70% RH in that the deviation increased from 1.1% RH to 3.9% RH.

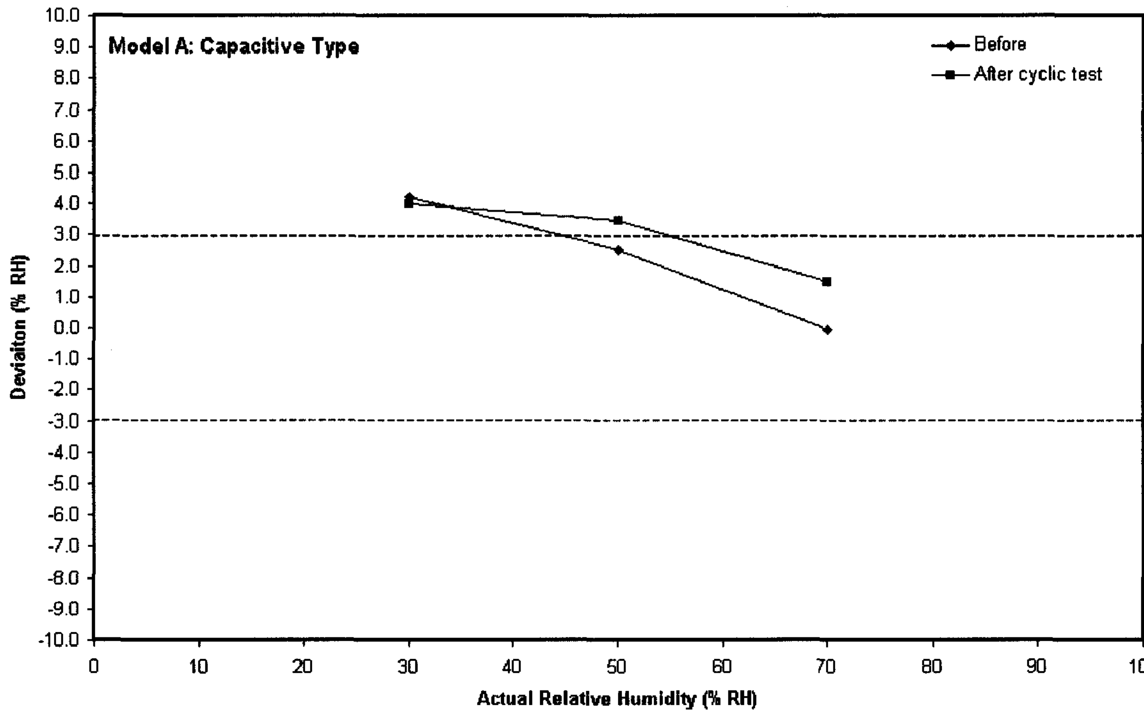


Figure 7.3: Comparison of deviations before and after the cyclic test for Model-A sensor

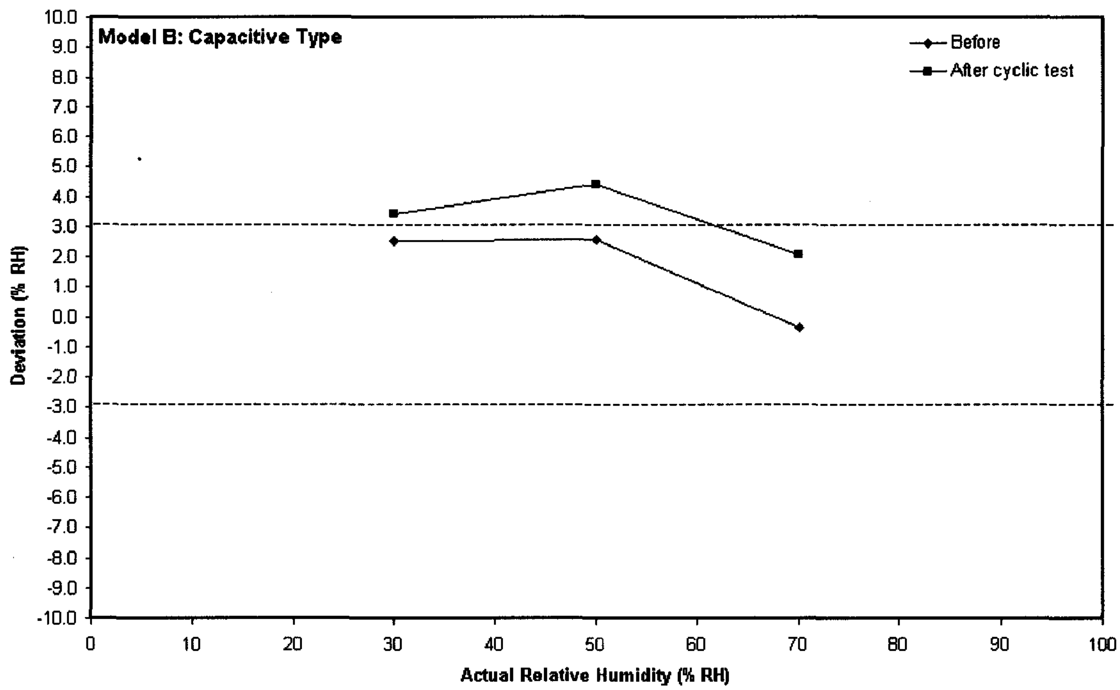


Figure 7.4: Comparison of deviations before and after the cyclic test for Model-B sensor

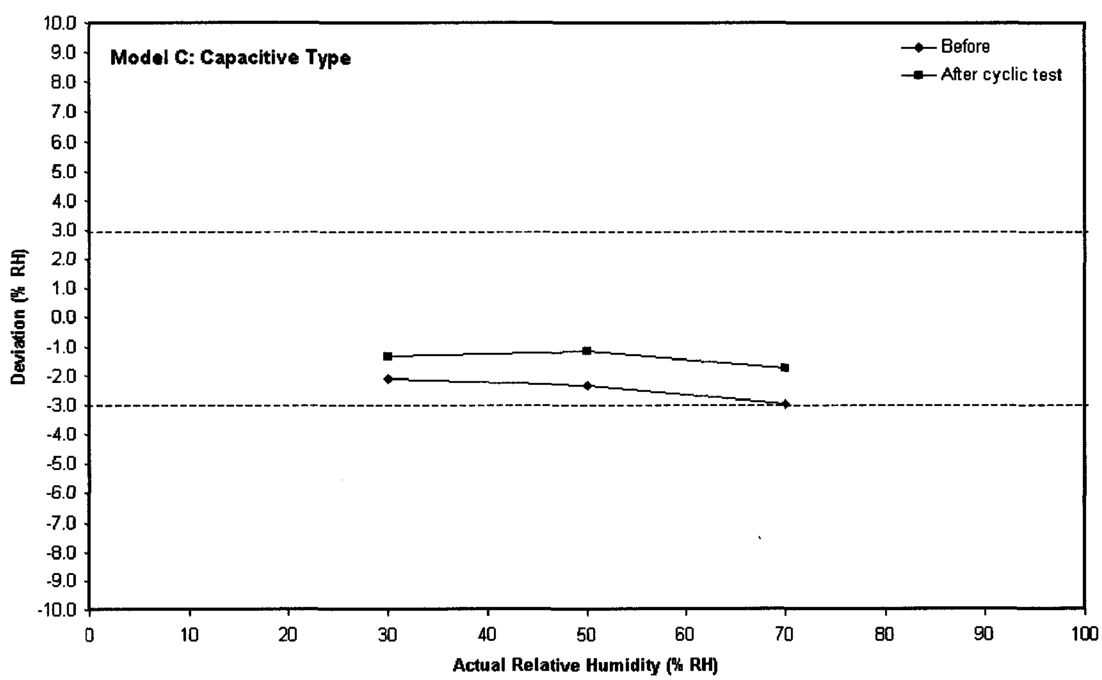


Figure 7.5: Comparison of deviations before and after the cyclic test for Model-C sensor

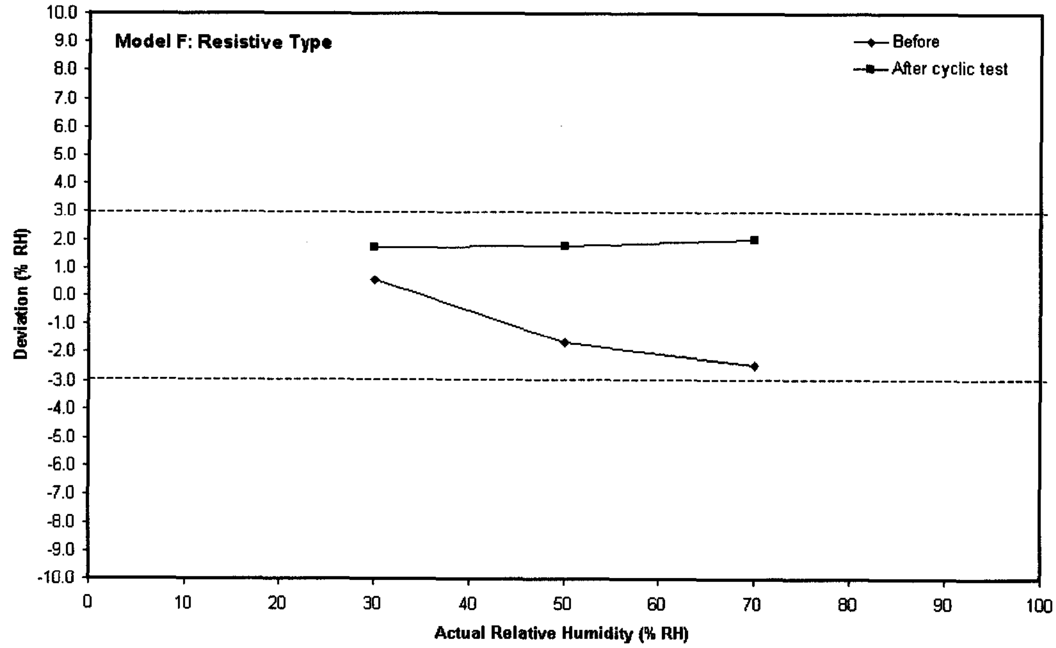


Figure 7.6: Comparison of deviations before and after the cyclic test for Model-F sensor

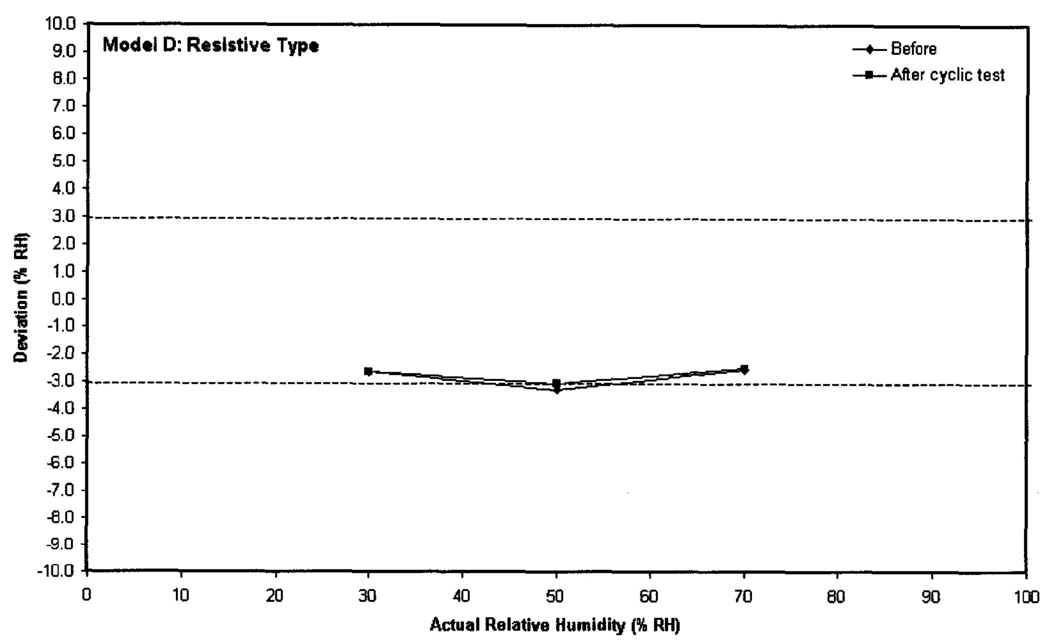


Figure 7.7: Comparison of deviations before and after the cyclic test for Model-D sensor

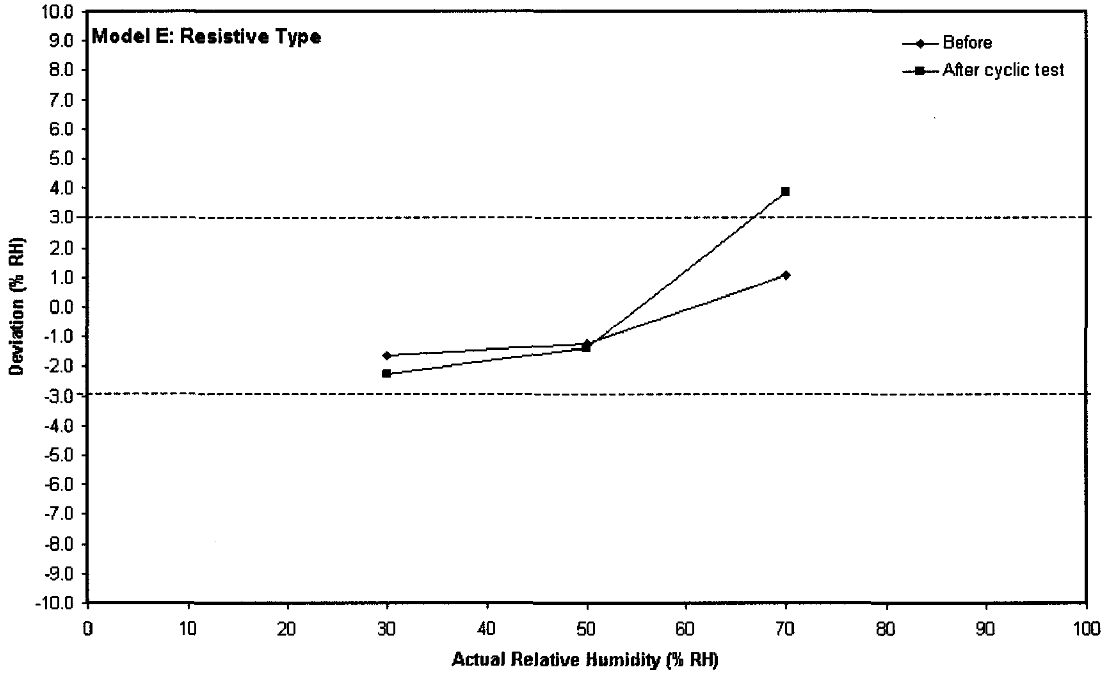


Figure 7.8: Comparison of deviations before and after the cyclic test for Model-E sensor

Results of the desiccation test

Humidity generator test conditions

During the desiccation test, the actual relative humidity of the desiccation bath was 0.0% RH as recorded by the reference relative humidity sensor.

Accuracy tests results

As shown in Figure 7.9, sensor Model-B met the manufacturer stated accuracy before the desiccation test at all relative humidities while immediately after the desiccation test the sensor did not meet the accuracy at 50% RH. For example, the deviation of Model-B sensor at 50% RH increased from 2.6% RH before the desiccation test to 3.3% RH immediately afterwards.

As shown in Figures 7.10, 7.12 and 7.13, sensor models C, E and F met the manufacturer stated accuracy at all relative humidities evaluated, both before and immediately after the desiccation test. However, as shown in Table 7.3 sensor Model-A did not meet the manufacturer stated accuracy at any relative humidities evaluated immediately after the desiccation test.

Table 7.3: Deviations of sensor Model-A before and after the desiccation test

% RH	Before (% RH)	After (% RH)
30	4.2	-8.3
50	2.5	-16.3
70	-0.1	-24.6

As shown in Figure 7.11, sensor Model-D met the manufacturer stated accuracy both before and immediately after the desiccation test at relative humidities of 30% and 70% RH. However, the sensor did not meet the accuracy at 50% RH, either before or immediately after the desiccation test.

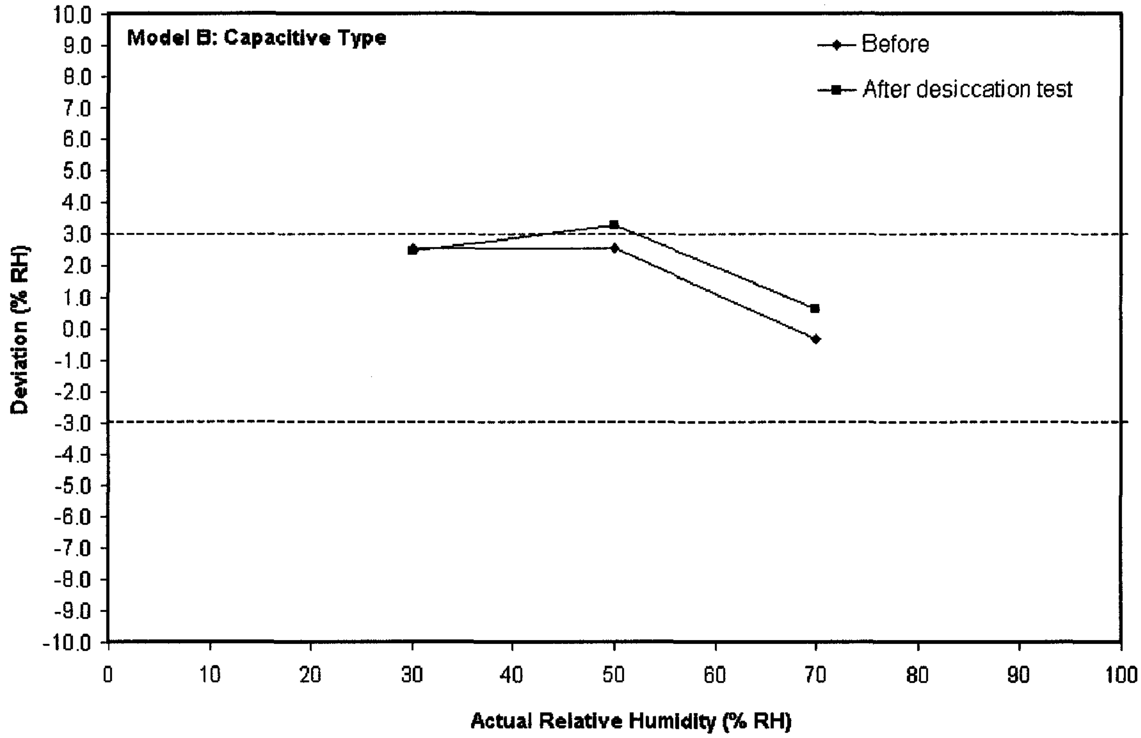


Figure 7.9: Comparison of deviations before the desiccation test and after the desiccation test for Model-B sensor

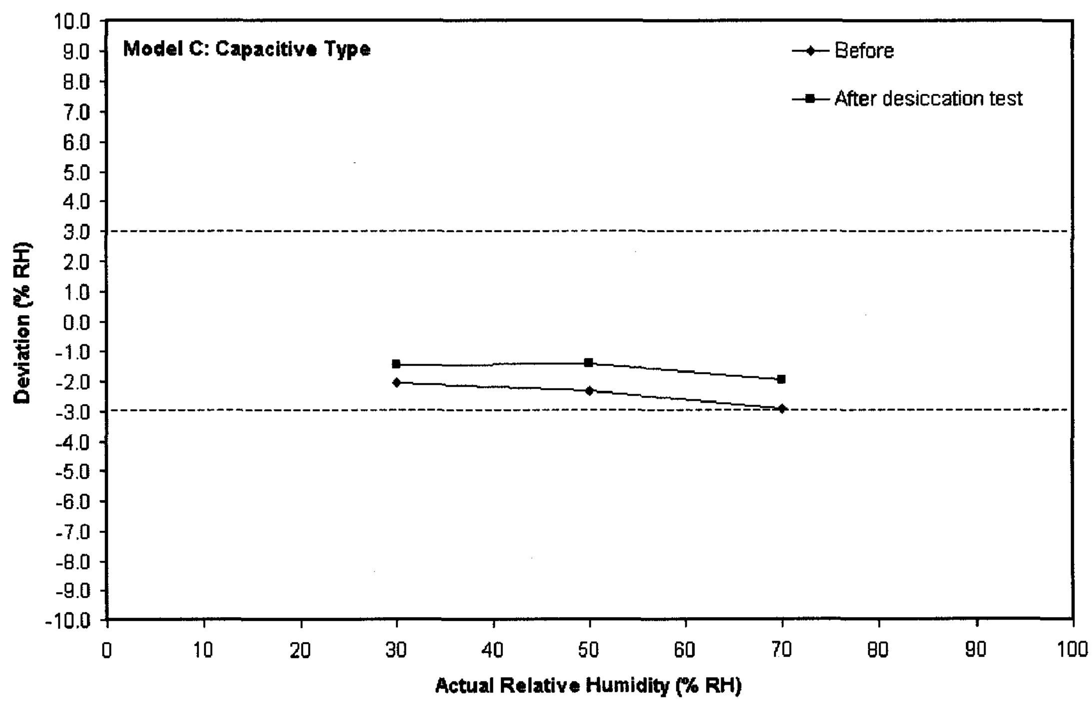


Figure 7.10: Comparison of deviations before the desiccation test and after the desiccation test for Model-C sensor

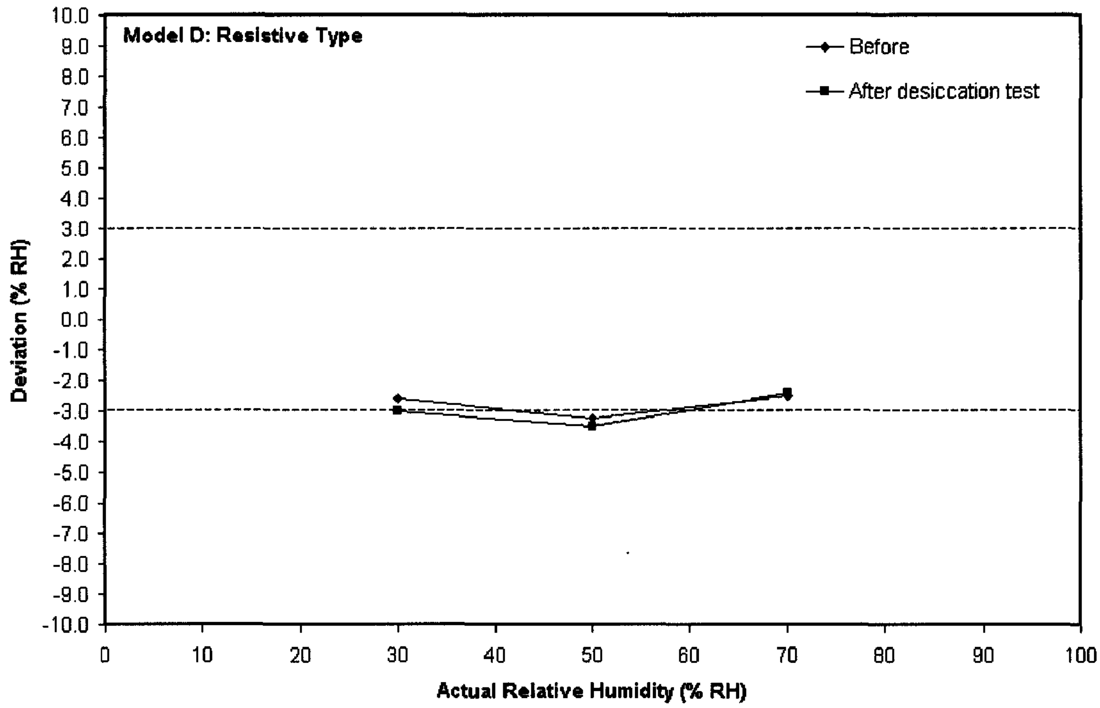


Figure 7.11: Comparison of deviations before the desiccation test and after the desiccation test for Model-D sensor

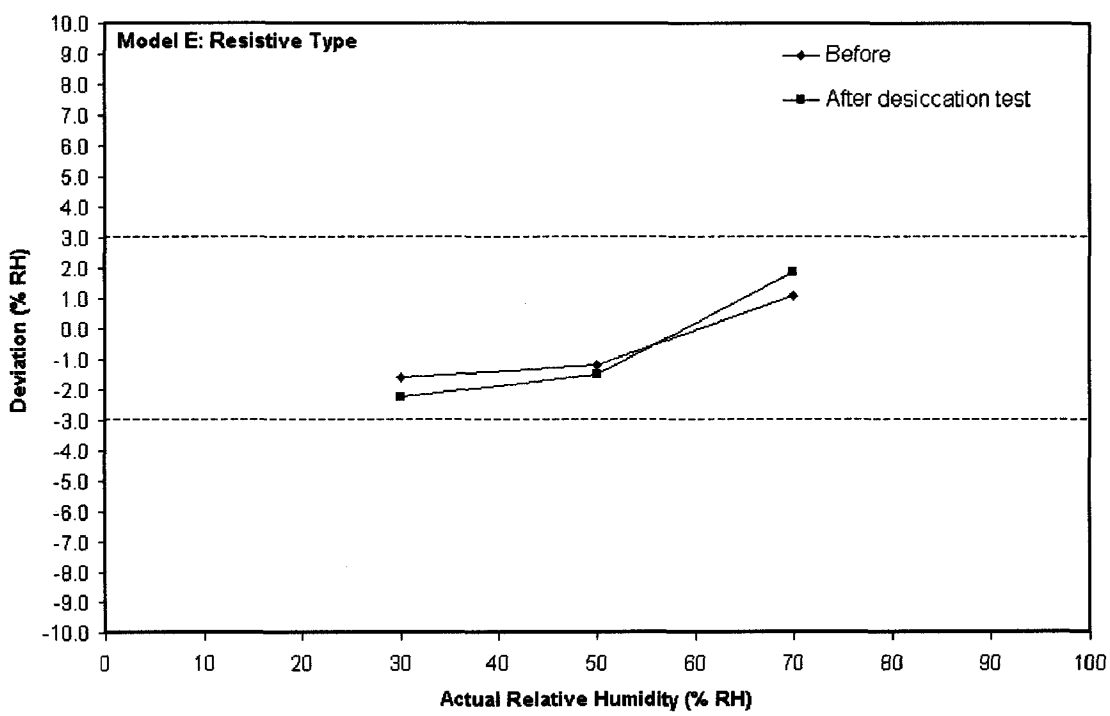


Figure 7.12: Comparison of deviations before the desiccation test and after the desiccation test for Model-E sensor

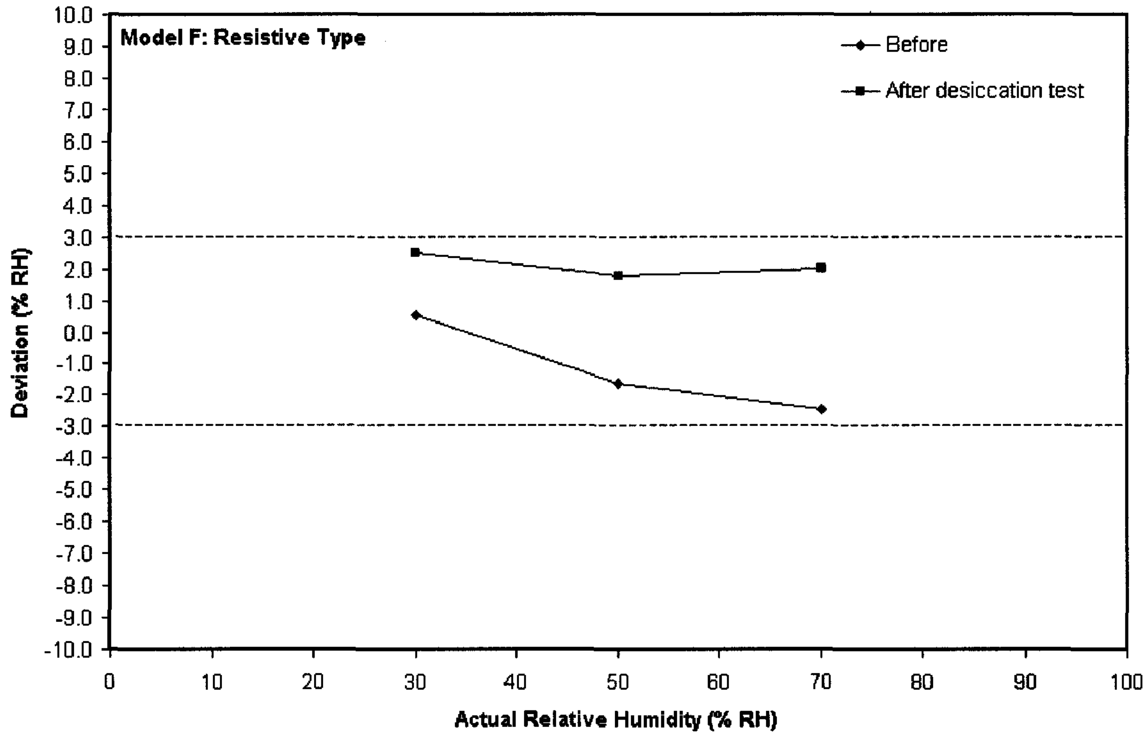


Figure 7.13: Comparison of deviations before the desiccation test and after the desiccation test for Model-F sensor

Results of the saturation test

Humidity generator test conditions

During the saturation test, the actual relative humidity of the water bath was 98.0% RH as recorded by the reference relative humidity sensor.

Accuracy tests results

As shown in Figures 7.15, 7.16 and 7.17 sensor models C, D and E met the manufacturer stated accuracy at all relative humidities evaluated both before and immediately after the saturation test. In contrast, the sensor Model-A did not met the accuracy both before and immediately after the saturation test at any relative humidities. Further, as shown in Figure 7.14 sensor Model-B did not met the accuracy immediately after the saturation test at all relative humidities evaluated.

Table 7.4: Deviations of sensor Model-A before and after the saturation test

% RH	Before (% RH)	After (% RH)
30	-8.3	-4.6
50	-16.3	-13.0
70	-24.6	-21.5

As shown in Figure 7.18, sensor Model-F met the manufacturer stated accuracy before the saturation test at all relative humidities, however, immediately after the saturation test the sensor did not meet the accuracy at relative humidities of 50% and 70% RH. For example, the deviation of Model-F sensor at 50% RH increased from 1.8% RH before the saturation test to 3.9% RH immediately afterwards while at 70% RH the deviation increased from 2.0% to 5.8% RH.

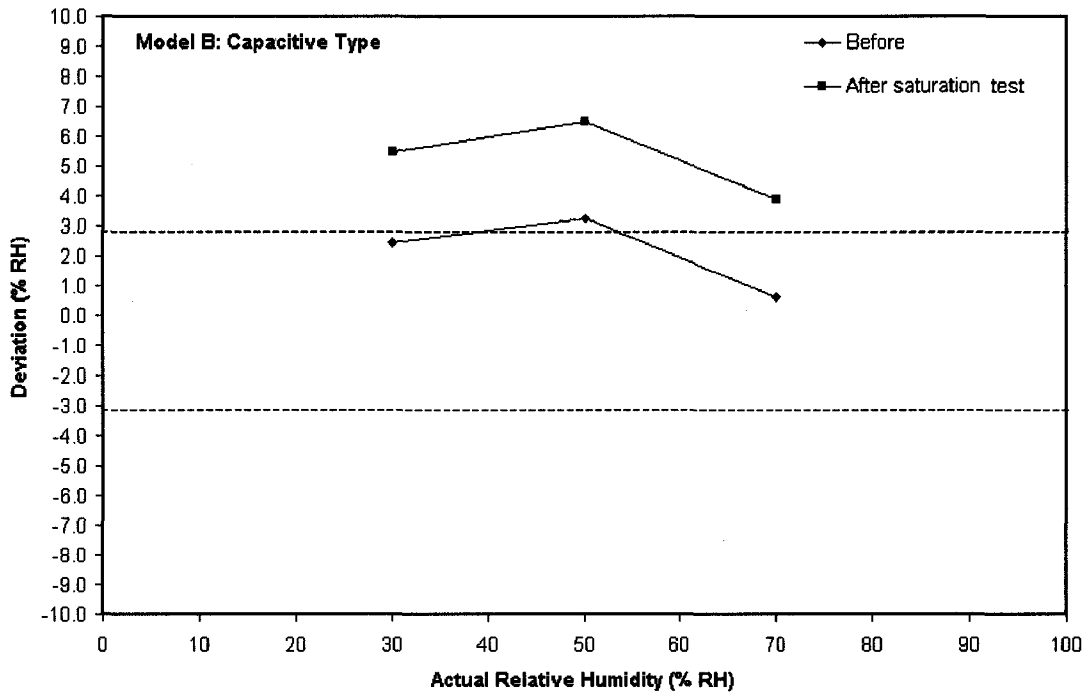


Figure 7.14: Comparison of deviations before the saturation test and after the saturation test for Model-B sensor

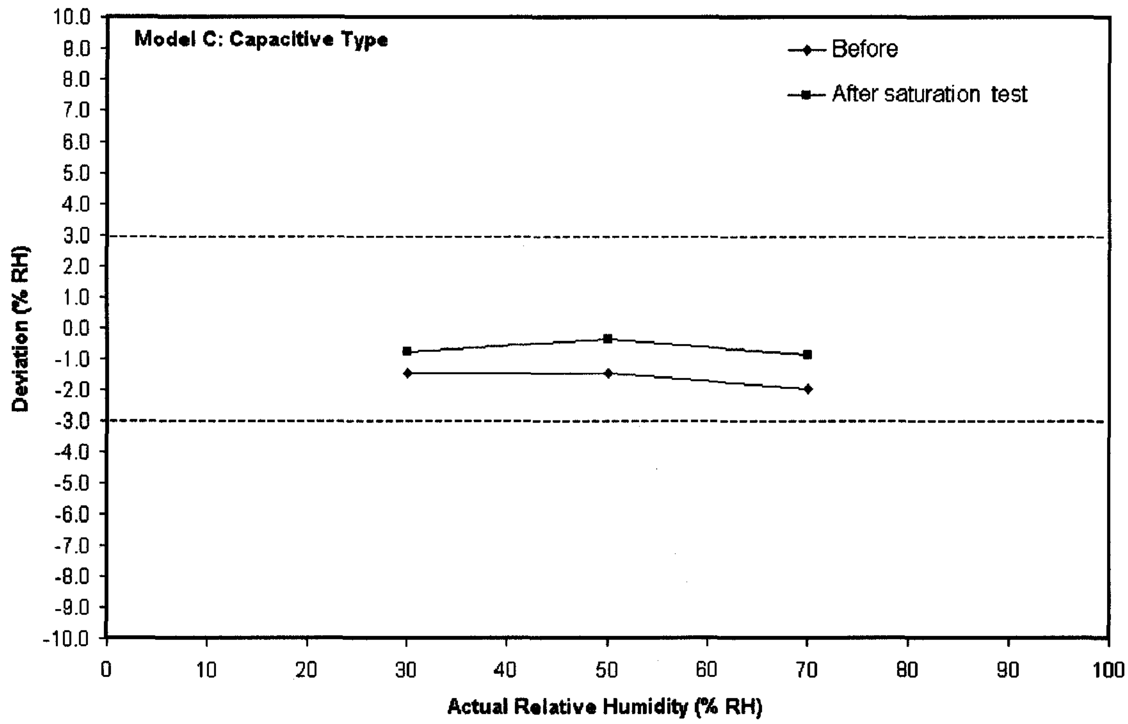


Figure 7.15: Comparison of deviations before the saturation test and after the saturation test for Model-C sensor

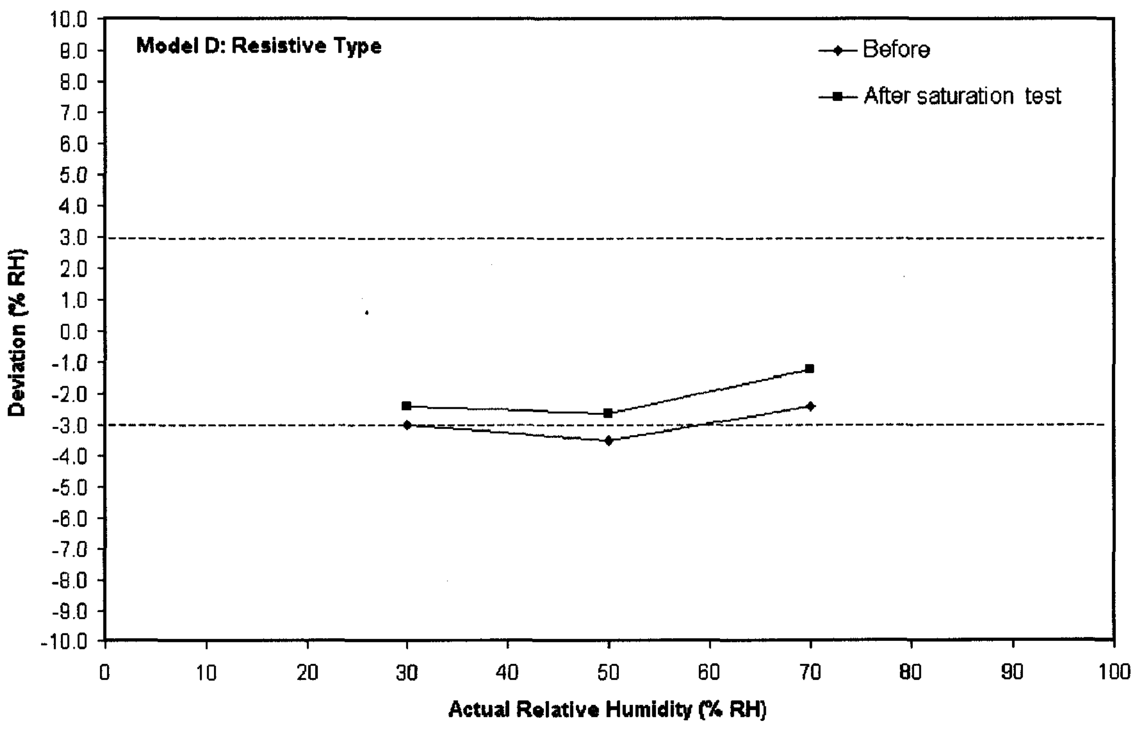


Figure 7.16: Comparison of deviations before the saturation test and after the saturation test for Model-D sensor

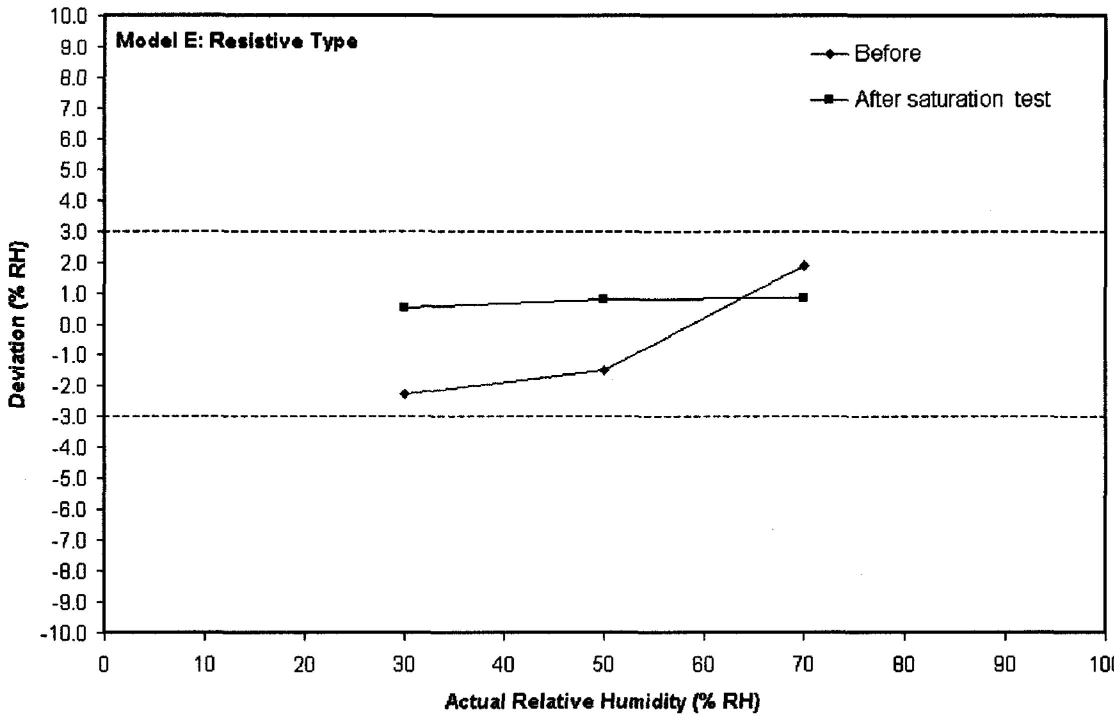


Figure 7.17: Comparison of deviations before the saturation test and after the saturation test for Model-E sensor

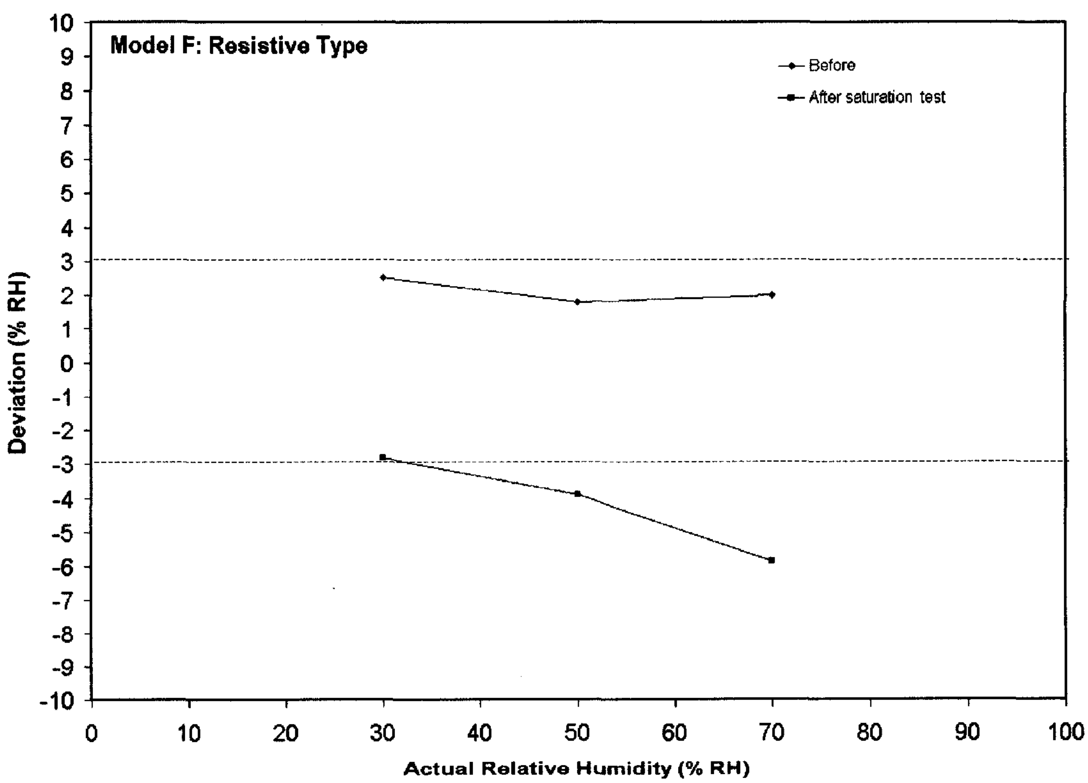


Figure 7.18: Comparison of deviations before the saturation test and after the saturation test for Model-F sensor

Results after two days of storage

Accuracy testing of sensors at relative humidities of 30%, 50% and 70% was designed to determine if the sensor performance improved after the sensors had been removed from the dry and saturated environments for two days.

As shown in Figure 7.19, sensor Model-B did not met the manufacturer stated accuracy before two days at all relative humidities evaluated, however, after two days the sensor met the accuracy at relative humidity of 70% RH.

As shown in Figures 7.20, 7.21 and 7.22, sensor models C, D and E met the manufacturer stated accuracy both before and after two days at all relative humidities evaluated. In contrast, as shown in Table 7.5 sensor Model-A did not meet the manufacturer stated accuracy both before and after two days at all relative humidities evaluated.

Table 7.5: Deviations of sensor Model-A before and after two days (Desiccation-Saturation test)

% RH	Before (% RH)	After (% RH)
30	-4.6	-5.9
50	-13.0	-14.4
70	-21.5	-23.4

As shown in Figure 7.23, sensor Model-F met the manufacturer stated accuracy both before and after two days at a relative humidity of 30% RH. However, the sensor did not meet the accuracy at relative humidities of 50% and 70% RH, either before or after two days.

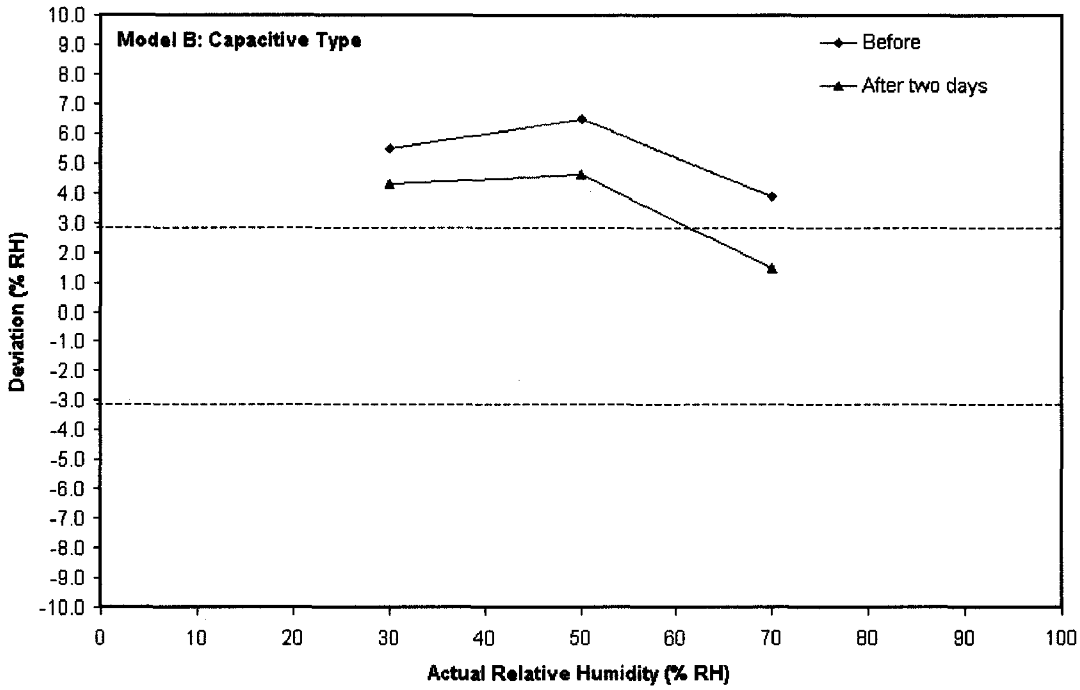


Figure 7.19: Comparison of deviations before and after two days for Model-B sensor (Desiccation-Saturation Test)

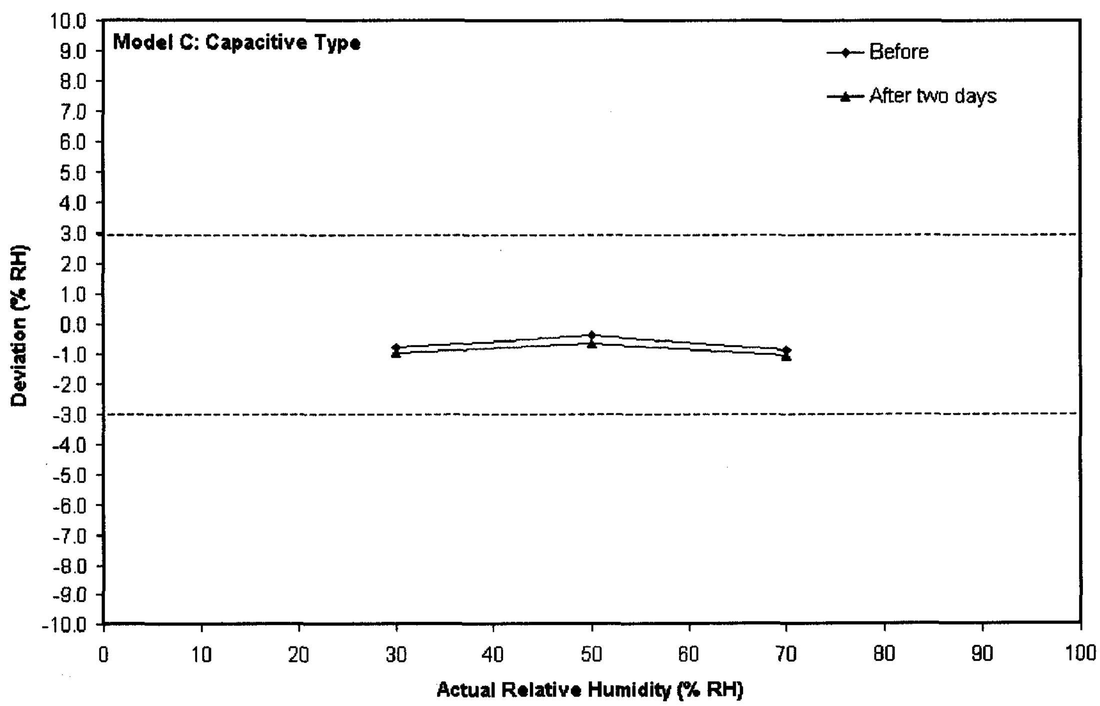


Figure 7.20: Comparison of deviations before and after two days for Model-C sensor (Desiccation-Saturation Test)

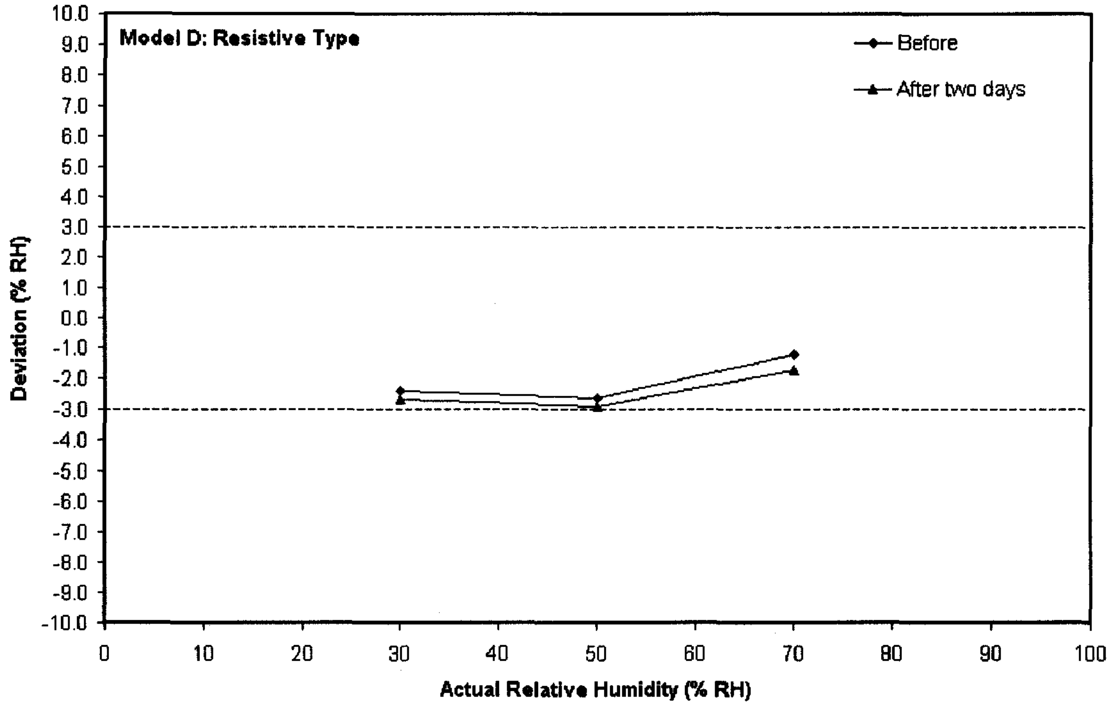


Figure 7.21: Comparison of deviations before and after two days for Model-D sensor (Desiccation-Saturation Test)

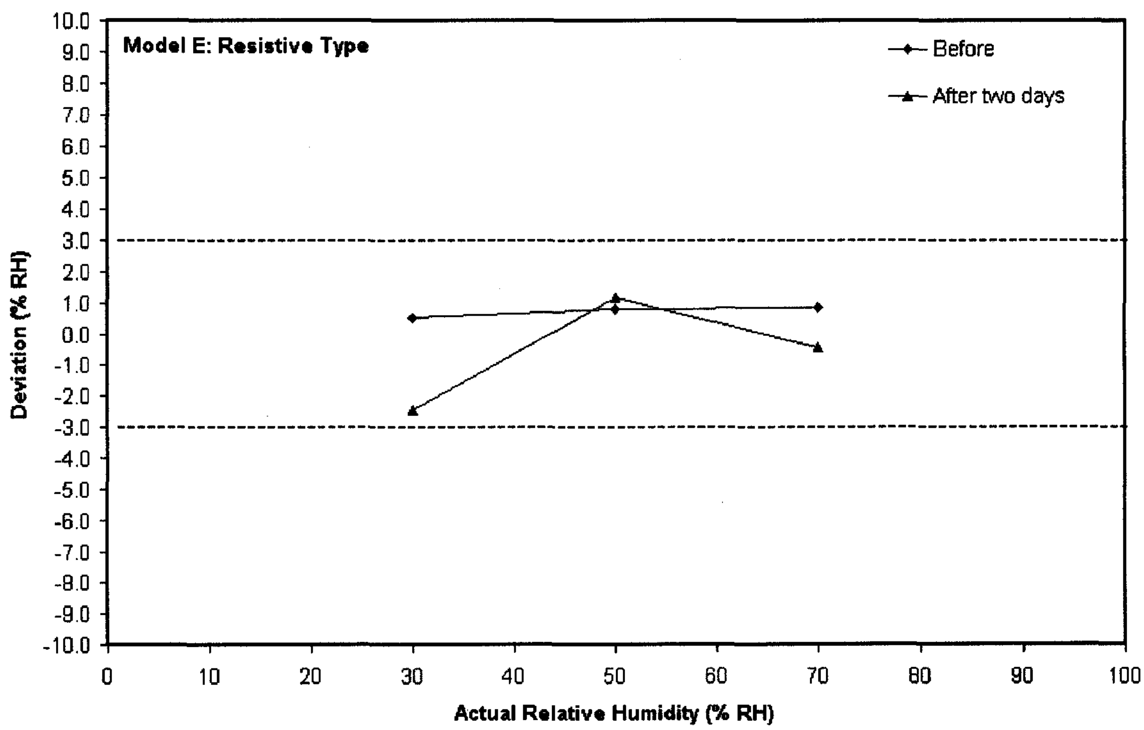


Figure 7.22: Comparison of deviations before and after two days for Model-E sensor (Desiccation-Saturation Test)

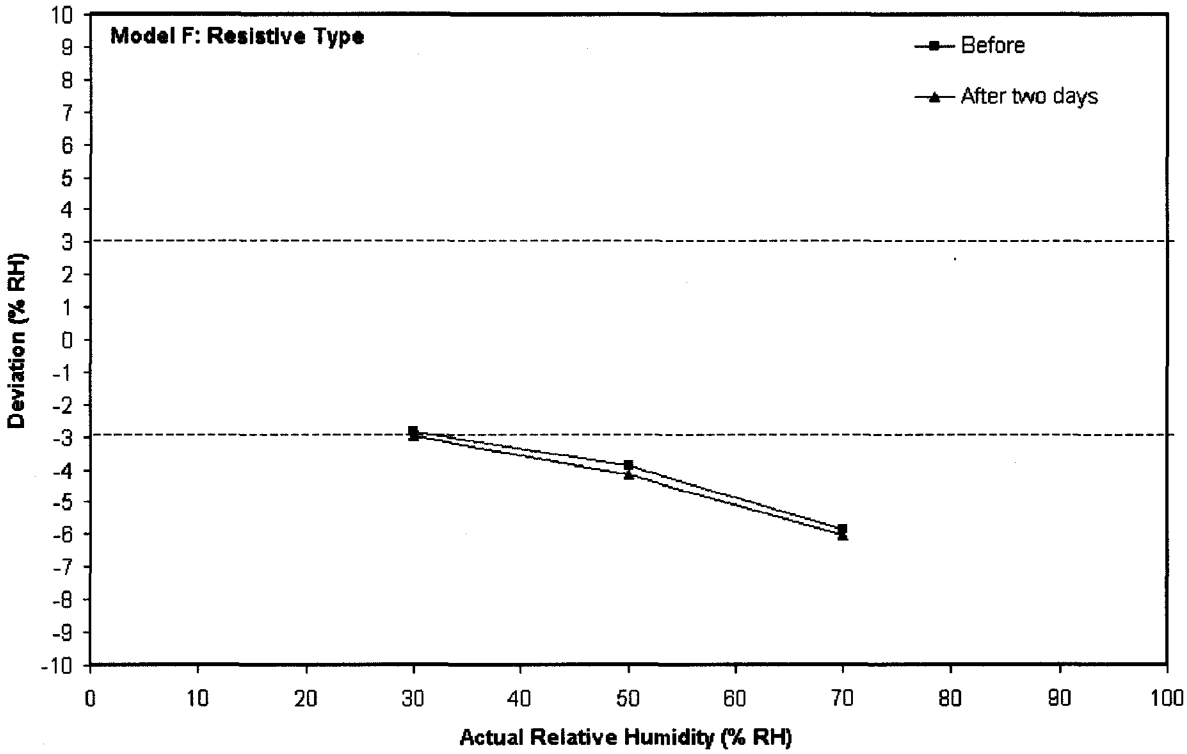


Figure 7.23: Comparison of deviations before and after two days for Model-F sensor (Desiccation-Saturation Test)

Results of the submergence test

Room relative humidity conditions

During the submergence test, the room relative humidity conditions ranged between 30% RH to 35% RH as recorded by the ±3% RH accurate Vaisala sensor.

Accuracy tests results

The sensor Model-C met the manufacturer stated accuracy both before and after the submergence test at all relative humidities evaluated. In contrast, as shown in Table 7.6 sensor models A, B and E did not meet the manufacturer stated accuracy immediately after the submergence test at any relative humidities evaluated. Further, sensor Model-F did not meet the manufacturer stated accuracy after the submergence test at relative humidities of 50% and 70% RH. For example, the deviations of Model-F sensor after the submergence test are -4.2% and -6.3% RH at relative humidities of 50% and 70% RH, respectively. The sensor Model-D failed immediately after submerging in water.

Table 7.6: Deviations of sensor models A, B and E before and after the submergence test

Sensor Model	Before (% RH)			After (% RH)		
	30	50	70	30	50	70
A	-5.9	-14.4	-23.4	56.9	36.9	16.9
B	4.3	4.6	1.5	68.9	48.9	28.9
E	-2.4	1.2	-0.4	10.7	-12.1	-45.5

Results after two days of storage

As mentioned earlier in the desiccation-saturation test, accuracy testing of the sensors was performed after two days to record any improvements in the accuracy.

The accuracy test results show that sensor Model-C met the manufacturer stated accuracy both before and after two days at all relative humidities evaluated. In contrast, as shown in Table 7.5 sensor models A and B did not meet the manufacturer stated accuracy either before or after two days at all relative humidities evaluated. Further, as shown in Figure 7.24 the sensor Model-F did not meet the manufacturer specified accuracy before two days at relative humidities of 50% and 70% RH, while the sensor met the accuracy at all relative humidities after two days. As mentioned above, sensor Model-D failed immediately after submerging in water. Finally, after two days the sensor Model-E failed during the accuracy test.

Table 7.5: Deviations of sensor models A and B before and after two days (Submergence test)

Sensor Model	Before (% RH)			After (% RH)		
	30	50	70	30	50	70.0
A	56.9	36.9	16.9	35	37	17.0
B	68.9	48.9	28.9	59	49	29.0

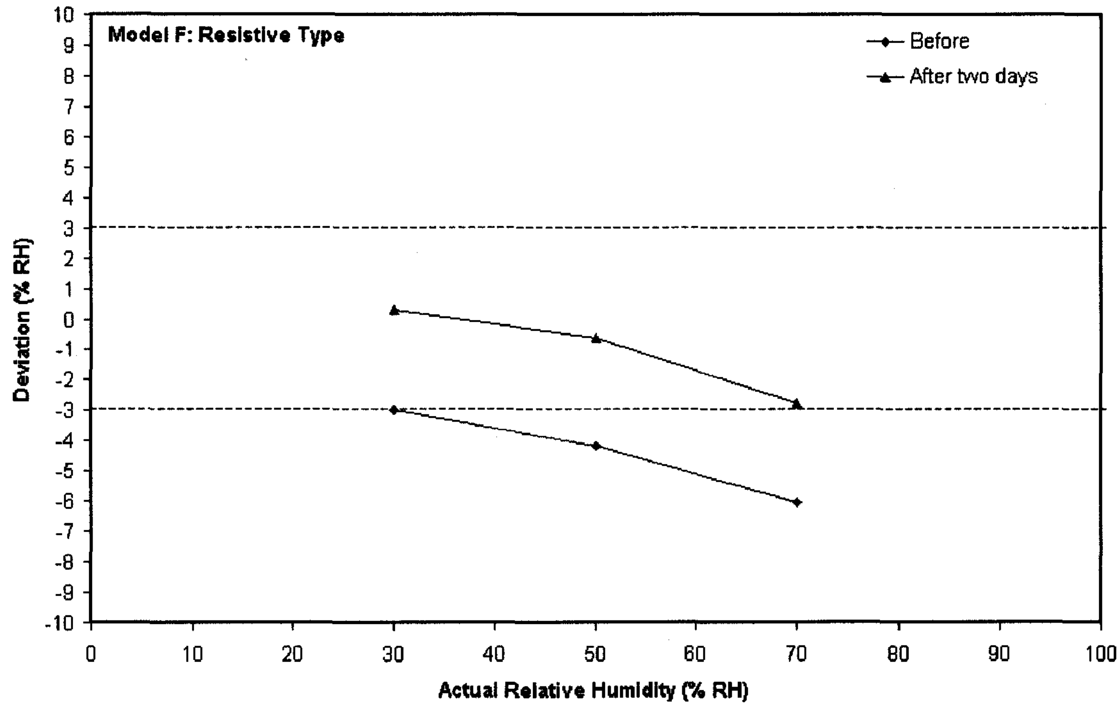


Figure 7.24: Comparison of deviations before and after two days for Model-F sensor (Submergence Test)

Summary

Out of the six sensor models only one sensor model, namely, Model-C met the manufacturer specified accuracy both before and after the stress tests. The sensor models A and B did not meet the manufacturer specified accuracy at all relative humidities after the stress tests. Finally, the sensor Model-F met the manufacturer specified accuracy at 30% RH. The remaining sensor models D and E failed during the stress tests.

CHAPTER 8. CONCLUSION

The study reported herein was undertaken to test and evaluate the most commonly used relative humidity sensors in HVAC systems, namely the capacitive and resistive types. A total of 18 sensors were tested, nine of them were capacitive-type sensors and nine were resistive-type sensors. The sensors were tested to evaluate the sensor accuracy and to provide a comparison with manufacturer specified accuracy. In addition, linearity, repeatability, and hysteresis studies were performed. Other studies performed included the ageing, response-time and stress tests. For all the tests (i.e., accuracy, repeatability, linearity, hysteresis, ageing, response time and stress), a Method of Test (MOT) was developed and peer reviewed for the purpose of providing a detailed methodology for evaluating the performance of duct-mounted relative humidity sensors. The main conclusions of each test are presented below.

Accuracy Test

Based upon the accuracy testing, it was observed that two of the six humidity sensor models, namely, Model-C (i.e., capacitive type) and Model-D (i.e., resistive type) were within manufacturer specified accuracy of $\pm 3\%$ for the entire 10% to 90% humidity range. A third sensor model, namely, Model-E (i.e., resistive type) did not meet the manufacturer specified accuracy of $\pm 3\%$ at any humidity level tested while the remaining three sensor models, namely, Model-A (i.e., capacitive type), Model-B (i.e., capacitive type) and Model-F (i.e., resistive type) met the manufacturer specified accuracy of $\pm 3\%$ for only part of the humidity range. Further, two of the three capacitive sensors were accurate in the low RH (i.e., at 10%) range while two of the three resistive sensors were accurate in the high RH (i.e., at 90%) range. All sensor models showed relative humidity dependence for the entire humidity range. In addition, all sensor models except Model-D sensor showed temperature dependence for the entire humidity range.

Repeatability, Hysteresis and Linearity

In general, the average error in repeatability of capacitive sensor models is 0.4% RH higher than resistive type sensors. In addition, the maximum errors in repeatability of sensors (both resistive and capacitive) at temperatures of 15°C, 25°C and 35°C are 0.4%, 1.5% and 1.1% RH, respectively. The hysteresis for all sensor models was positive in that the measured humidities when going in the reverse-step direction were higher. Further, at 35°C the hysteresis for models A, B and F is lower than the hysteresis at 15 and 25°C. The maximum hysteresis for all sensors was less than 3.2% for all humidities and temperatures. At 25°C, Model-B sensor has the largest nonlinearity of -3.8% while Model-C sensor has the least nonlinearity of 0.0%. In general, the magnitude of errors for the repeatability study for all sensor models was least when compared to the magnitude of errors for both the hysteresis and linearity study.

Ageing Test

The accuracy results after the ageing test demonstrated that only one sensor out of twelve sensors was unaffected both before and after the ageing test in that the sensor met the manufacturer specified accuracy both before and after the ageing test. Further, four sensors out of the remaining eleven sensors remained unaffected after the ageing test with negligible changes in the deviations. The remaining seven sensors were affected after the ageing test that was evidenced by either a large variation in accuracy or by not meeting the manufacturer specified accuracy. Further, over the entire relative humidity range, the ageing effects of two out of six capacitive sensors were gradual, while the ageing effects of a capacitive sensor from the remaining four sensors was abrupt. Finally, the ageing effects of four out of six resistive sensors were abrupt rather than gradual over the entire relative humidity range evaluated.

Response Time Test

The response time results indicated that five out of six sensor models had slower reverse-step response times compared to the forward-step response times for the three test runs. However, the remaining one sensor did not show any obvious trend in the response times for the three test runs. The average reverse-step response times of four out of six sensor models were slower compared to the average forward-step response times. In contrast, the remaining two sensor models had faster average reverse-step response times compared to the average forward-step. Further, the average response times of relative humidity sensors varied considerably from manufacturer to manufacturer with the fastest being 7 sec and slowest being 96 sec. Furthermore, the average response time of capacitive-type sensors (i.e., average of three capacitive sensors) was 25 sec faster than the average response time of resistive-type sensors (i.e., average of three resistive sensors). Finally, with the no air flow over the sensor, the response times of five out of six models got larger with the magnitude of increase was between 3 to17 sec, while the response time of the remaining sensor got smaller by 12 sec.

Stress Tests (Cycling, Desiccation-Saturation and Submergence)

The accuracy results after the cycling test showed that two out of six sensor models were unaffected after the cycling test for all relative humidities evaluated. For example, sensor models C and F met the manufacturer specified accuracy both before and immediately after the cycling test. The remaining four sensors were affected by the cycling test at few relative humidities.

The accuracy results after the desiccation test show that three out of six sensors (i.e., models C, E and F) were unaffected after the desiccation test for all relative humidities evaluated. The remaining three sensor models, namely, A, B and D were affected after the desiccation test at a few relative humidities. Further, the accuracy results after the saturation test indicated that three sensors, namely, models C, D and E were unaffected after the saturation test for all relative humidities evaluated. The accuracy of sensor Model-B was affected after the saturation test in that the sensor met the accuracy before the saturation test, while the sensor did not meet the accuracy immediately after the saturation test at all relative humidities evaluated. The remaining two sensor models, namely, A and F were affected at a few relative humidities after the saturation test. In addition, the accuracy tests performed two days after the desiccation-saturation test showed that models C, D, and E were unaffected after two days for all relative humidities evaluated. While the remaining three sensor models, namely, A, B and F were affected at a few relative humidities after two days.

The accuracy results after the submergence test showed that sensor models C and F were unaffected immediately after the submergence test, in contrast, sensor models A, B and E were affected after the submergence test. The remaining sensor Model-D failed immediately after submerging in water. Finally, the accuracy tests performed two days after the submergence test showed that sensors models C and F remained unaffected after two days, while sensors models A and B were affected after two days at any relative humidities evaluated. The remaining sensor Model-E failed during the accuracy test.

CHAPTER 9. RECOMMENDATIONS

Several important areas for future research emerged during this project, which consisted of extensive evaluations of the performance of duct-mounted relative humidity sensors in HVAC systems. However, a few studies remain unaddressed.

- In this study, the results of the accuracy, repeatability, linearity, hysteresis, and response time tests were primarily based on the experimental evaluations. However, in addition to experimental evaluations, theoretical modeling of the capacitive and resistive sensors would be beneficial to predict the performance of these sensors under different operating conditions. These predictions can be of significant importance, especially to improve the performance of the sensors.
- In the response time study, it was observed that the response times of sensors with both fans switched OFF varied compared to that with both fans switched ON. This conclusion suggests that the response time of the sensors is dependent upon the velocity of the air moving across the sensor element. Therefore, a detailed study focused on investigating the effects of velocity on the response time of sensors is needed.
- Another study that investigates the effect of contaminants/dust on the performance of capacitive and resistive sensors could prove beneficial for engineers. For example, a study of sensor accuracy degradation when

exposed to building environment contaminants would provide useful information.

- The ageing test results indicated that the deviations of some sensors changed abruptly after the first four months. To provide an explanation for the abrupt change in the deviations, additional accuracy tests after every one or two weeks during the first four months would be required.

REFERENCES

1. ASHRAE. 2003. ASHRAE Handbook-HVAC Applications. American Society of Heating, Refrigerating, and Air-conditioning Engineers, Atlanta.

2. Background of Capacitive and Resistive Sensors, Retrieved on March 30, 2004, from http://ibdcom.yamatake.co.jp/products/fp3/background.html

3. Erdebil, I., and J. J. Leonard. 1992. Laboratory Testing of Humidity Sensors for Use in Animal Environments, Canadian Agricultural Engineering, 34 (3): 267-271.

4. House, J. 2003. Personal Communications, Energy Resource Station, 2006 S. Ankeny Blvd., Ankeny, IA 50021.

5. Kitano, M. H., Eguchi, and T. Matsui. 1984. Analysis of Static and Dynamic Characteristics of Humidity Sensors, Biotronics, 13: 11-28.

6. Lemay, S. P., H. Guo, E. M. Barber, L. Zyla. 2001. A Procedure to Evaluate Humidity Sensors Performance Under Livestock Housing Conditions, Canadian Biosystems Engineering, 43: 5.13-5.21.

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

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

9. Vaisala Inc., 100 Commerce Way, Woburn, MA 01801, USA.

10. Mid-West Control Products, 180 Weidman Road, Suite 103 Manchester, MO, USA, 63021-5724.

11. Rotronic Instrument Corporation, 160 E. Main Street, Huntington, NY, USA.

12. Building Automation Products, PO Box 207, Cross Plains, WI, 53528, USA.

13. Automation Components Incorporated, 2305 Evergreen Road, Middleton, WI, 53562, USA.

14. MAMAC Systems, 7400 Flying Cloud Drive Minneapolis, Minnesota, 55344-3720 USA.

15. Ross, C., and W. D. R. Daley. 1990. Capacitive Relative Humidity Sensing in Animal housing. The American Society of Agricultural Engineers Meeting, Paper No. 904022.

16. Thomas, R. M. 1992. Humidity Sensors in Heating, Ventilating and Air-Conditioning (HVAC) Systems. ASHRAE Transactions, 529-538.

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

18. Visscher, G., J., W., and J., G., Kornet. 1994. Long-Term Tests Of Capacitive Humidity Sensors, Measurement Science and Technology, 5: 1294-1302.

19. Wiederhold, P. R. 1997. Water Vapor Measurement- Methods and Instrumentation, New York: Marcel Dekker Inc.

APPENDIX A: ACCURACY, HYSTERESIS AND LINEARITY TESTS DATA

Table A.1: Accuracy, hysteresis and linearity of batch-1 sensors at 15°C

Model	Actual RH (% RH)	Fwd. RH (% RH)	Rev. RH (% RH)	Avg. RH[1] (% RH)	Dev[2] (% RH)	Hysteresis[3] (% RH)	Best-fit RH values (% RH)	Linearity[4] (% RH)
A-I	10.0	12.9	12.9	12.9	2.9	0.0	10.4	2.5
	30.0	34.3	36.0	35.2	5.2	1.7	31.2	4.0
	50.0	53.7	55.4	54.6	4.6	1.7	52.0	2.6
	70.0	72.0	73.5	72.8	2.8	1.5	72.9	-0.1
	90.0	90.7	90.7	90.7	0.7	0.0	93.7	-3.0
B-I	10.0	8.6	8.5	8.6	-1.5	-0.1	10.6	-2.0
	30.0	36.0	36.9	36.5	6.5	0.9	31.8	4.7
	50.0	57.0	58.1	57.6	7.6	1.1	53.0	4.6
	70.0	74.7	75.9	75.3	5.3	1.2	74.2	1.1
	90.0	90.6	90.6	90.6	0.6	0.0	95.4	-4.8
C-I	10.0	10.0	10.1	10.1	0.1	0.1	9.6	0.5
	30.0	27.7	28.2	28.0	-2.1	0.5	28.9	-0.9
	50.0	47.9	48.4	48.2	-1.9	0.5	48.1	0.1
	70.0	67.7	68.0	67.9	-2.2	0.3	67.3	0.6
	90.0	86.3	86.3	86.3	-3.7	0.0	86.6	-0.3
D-I	10.0	11.4	11.4	11.4	1.4	0.0	10.2	1.2
	30.0	30.6	30.9	30.8	0.8	0.3	30.5	0.3
	50.0	49.8	50.9	50.4	0.3	1.1	50.9	-0.5
	70.0	70.8	71.3	71.1	1.1	0.5	71.3	-0.2
	90.0	91.8	91.8	91.8	1.8	0.0	91.6	0.2
E-I	10.0	5.8	6.4	6.1	-3.9	0.6	8.9	-2.8
	30.0	23.5	24.3	23.9	-6.1	0.8	26.8	-2.9
	50.0	41.6	42.6	42.1	-7.9	1.0	44.6	-2.5
	70.0	61.1	61.7	61.4	-8.6	0.6	62.5	-1.1
	90.0	83.8	83.8	83.8	-6.2	0.0	80.3	3.5
F-I	10.0	14.3	16.6	15.5	5.5	2.3	10.2	5.3
	30.0	32.9	35.6	34.3	4.3	2.7	30.5	3.8
	50.0	50.7	51.9	51.3	1.3	1.2	50.8	0.5
	70.0	70.2	71.0	70.6	0.6	0.8	71.1	-0.5
	90.0	89.6	89.6	89.6	-0.4	0.0	91.4	-1.8

1: Average relative humidity represents the average of forward and reverse measurements
2: Deviation: Average RH – Actual RH
3: Hysteresis: Reverse RH – Forward RH
4: Linearity: Average RH – Best fit RH values

Table A.2: Accuracy, hysteresis and linearity of batch-1 sensors at 25°C

Model	Actual RH (% RH)	Fwd. RH (% RH)	Rev. RH (% RH)	Avg. RH[1] (% RH)	Dev[2] (% RH)	Hysteresis[3] (% RH)	Best-fit RH values (% RH)	Linearity[4] (% RH)
A-I	10.0	9.8	10.2	10.0	0.0	0.4	10.0	0.0
	30.0	31.4	32.9	32.2	2.2	1.5	29.9	2.4
	50.0	50.7	52.2	51.5	1.5	1.5	49.8	1.8
	70.0	68.7	70.3	69.5	-0.5	1.6	69.7	-0.2
	90.0	87.9	87.9	87.9	-2.1	0.0	89.6	-1.6
B-I	10.0	5.9	6.2	6.1	-4.0	0.3	10.1	-4.0
	30.0	32.5	33.5	33.0	3.0	1.0	30.3	2.7
	50.0	53.0	54.3	53.7	3.7	1.3	50.4	3.3
	70.0	70.6	72.1	71.4	1.3	1.5	70.6	0.8
	90.0	87.9	87.9	87.9	-2.1	0.0	90.8	-2.9
C-I	10.0	10.2	10.4	10.3	0.3	0.2	9.7	0.6
	30.0	28.3	28.4	28.4	-1.7	0.1	29.1	-0.7
	50.0	48.4	48.7	48.6	-1.5	0.3	48.5	0.1
	70.0	68.2	68.5	68.4	-1.7	0.3	67.9	0.5
	90.0	87.0	87.0	87.0	-3.0	0.0	87.3	-0.3
D-I	10.0	9.3	9.3	9.3	-0.7	0.0	10.1	-0.8
	30.0	29.7	30.6	30.2	0.1	0.9	30.3	-0.1
	50.0	50.1	50.6	50.4	0.4	0.5	50.5	-0.1
	70.0	70.6	71.4	71.0	1.0	0.8	70.6	0.4
	90.0	90.7	90.7	90.7	0.7	0.0	90.8	-0.1
E-I	10.0	8.4	8.6	8.5	-1.5	0.2	8.9	-0.4
	30.0	24.6	24.9	24.8	-5.3	0.3	26.6	-1.8
	50.0	41.7	42.6	42.2	-7.8	0.9	44.4	-2.2
	70.0	59.9	60.1	60.0	-10.0	0.2	62.1	-2.1
	90.0	83.3	83.3	83.3	-6.7	0.0	79.8	3.5
F-I	10.0	6.0	8.4	7.2	-2.8	2.4	9.8	-2.6
	30.0	31.3	32.1	31.7	1.7	0.8	29.5	2.2
	50.0	49.5	49.9	49.7	-0.3	0.4	49.2	0.5
	70.0	68.5	68.9	68.7	-1.3	0.4	68.9	-0.2
	90.0	88.0	88.0	88.0	-2.0	0.0	88.6	-0.6

1: Average relative humidity represents the average of forward and reverse measurements
2: Deviation: Average RH – Actual RH
3: Hysteresis: Reverse RH – Forward RH
4: Linearity= Average RH – Best fit RH values

Table A.3: Accuracy, hysteresis and linearity of batch-1 sensors at 35°C

Model	Actual RH (% RH)	Fwd. RH (% RH)	Rev. RH (% RH)	Avg. RH[1] (% RH)	Dev[2] (% RH)	Hysteresis[3] (% RH)	Best-fit RH values (% RH)	Linearity[4] (% RH)
A-I	10.0	8.4	8.2	8.3	-1.7	-0.2	9.6	0.0
	30.0	29.3	30.5	29.9	-0.1	1.2	28.8	1.1
	50.0	48.0	49.5	48.8	-1.3	1.5	48.0	0.8
	70.0	66.4	67.7	67.1	-2.9	1.3	67.2	-0.1
	90.0	85.7	85.7	85.7	-4.3	0.0	86.3	-0.6
B-I	10.0	4.5	4.1	4.3	-5.7	-0.4	9.7	-5.4
	30.0	29.8	30.4	30.1	0.1	0.6	29.0	1.1
	50.0	49.5	50.9	50.2	0.2	1.4	48.4	1.8
	70.0	67.5	68.9	68.2	-1.8	1.4	67.7	0.5
	90.0	85.9	85.9	85.9	-4.1	0.0	87.1	-1.2
C-I	10.0	9.7	9.9	9.8	-0.2	0.2	9.4	0.4
	30.0	26.7	27.4	27.1	-3.0	0.7	28.3	-1.2
	50.0	46.2	47.1	46.7	-3.3	0.9	47.2	-0.5
	70.0	65.9	66.9	66.4	-3.6	1.0	66.1	0.3
	90.0	85.3	85.3	85.3	-4.7	0.0	84.9	0.4
D-I	10.0	8.9	8.8	8.9	-1.2	-0.1	10.0	-1.1
	30.0	29.1	29.7	29.4	-0.6	0.6	30.1	-0.7
	50.0	49.9	50.8	50.4	0.3	0.9	50.1	0.3
	70.0	71.1	71.4	71.3	1.3	0.3	70.2	1.1
	90.0	89.6	89.6	89.6	-0.4	0.0	90.3	-0.7
E-I	10.0	7.2	5.8	6.5	-3.5	-1.4	8.6	-2.1
	30.0	22.2	23.0	22.6	-7.4	0.8	25.7	-3.1
	50.0	40.3	41.8	41.1	-9.0	1.5	42.9	-1.8
	70.0	58.3	60.1	59.2	-10.8	1.8	60.0	-0.8
	90.0	80.0	80.0	80.0	-10.0	0.0	77.1	2.9
F-I	10.0	1.2	1.2	1.2	-8.8	0.0	9.5	-8.3
	30.0	29.3	29.3	29.3	-0.7	0.0	28.4	0.9
	50.0	48.3	48.3	48.3	-1.7	0.0	47.3	1.0
	70.0	66.1	66.5	66.3	-3.7	0.4	66.2	0.1
	90.0	85.2	85.2	85.2	-4.8	0.0	85.2	0.0

1: Average relative humidity represents the average of forward and reverse measurements
2: Deviation: Average RH – Actual RH
3: Hysteresis: Reverse RH – Forward RH
4: Linearity= Average RH – Best fit RH values

Table A.4: Accuracy, hysteresis and linearity of batch-2 sensors at 15°C

Model	Actual RH (% RH)	Fwd. RH (% RH)	Rev. RH (% RH)	Avg. RH[1] (% RH)	Dev[2] (% RH)	Hysteresis[3] (% RH)	Best-fit RH values (% RH)	Linearity[4] (% RH)
A-II	10.0	15.5	17.2	16.4	6.4	1.7	10.4	6.0
	30.0	35.4	39.2	37.3	7.3	3.8	31.1	6.2
	50.0	53.5	57.3	55.4	5.4	3.8	51.8	3.6
	70.0	71.2	74.0	72.6	2.6	2.8	72.5	0.1
	90.0	88.4	88.4	88.4	-1.6	0.0	93.2	-4.8
B-II	10.0	8.0	8.9	8.5	-1.6	0.9	10.1	-1.6
	30.0	34.8	36.5	35.7	5.7	1.7	30.4	5.3
	50.0	54.7	56.5	55.6	5.6	1.8	50.7	4.9
	70.0	71.3	72.8	72.1	2.1	1.5	70.9	1.2
	90.0	86.0	86.0	86.0	-4.0	0.0	91.2	-5.2
C-II	10.0	10.4	10.6	10.5	0.5	0.2	9.7	0.8
	30.0	28.9	29.0	29.0	-1.1	0.1	29.1	-0.1
	50.0	48.8	49.2	49.0	-1.0	0.4	48.6	0.4
	70.0	68.3	68.6	68.5	-1.6	0.3	68.0	0.5
	90.0	86.7	86.7	86.7	-3.3	0.0	87.4	-0.7
D-II	10.0	11.3	11.4	11.4	1.4	0.1	9.9	1.5
	30.0	28.4	28.9	28.7	-1.4	0.5	29.8	-1.1
	50.0	48.1	48.4	48.3	-1.8	0.3	49.6	-1.3
	70.0	70.1	69.0	69.6	-0.5	-1.1	69.5	0.1
	90.0	90.1	90.1	90.1	0.1	0.0	89.3	0.8
E-II	10.0	6.3	7.9	7.1	-2.9	1.6	8.5	-1.4
	30.0	22.2	23.6	22.9	-7.1	1.4	25.6	-2.7
	50.0	39.5	40.6	40.1	-10.0	1.1	42.7	-2.6
	70.0	58.5	59.3	58.9	-11.1	0.8	59.7	-0.8
	90.0	79.9	79.9	79.9	-10.1	0.0	76.8	3.1
F-II	10.0	13.4	15.8	14.6	4.6	2.4	10.1	4.5
	30.0	32.4	34.7	33.6	3.6	2.3	30.2	3.4
	50.0	49.7	50.6	50.2	0.2	0.9	50.4	-0.2
	70.0	69.9	69.9	69.9	-0.1	0.0	70.6	-0.7
	90.0	89.7	89.7	89.7	-0.3	0.0	90.7	-1.0

1: Average relative humidity represents the average of forward and reverse measurements
2: Deviation: Average RH – Actual RH
3: Hysteresis: Reverse RH – Forward RH
4: Linearity= Average RH – Best fit RH values

Table A.5: Accuracy, hysteresis and linearity of batch-2 sensors at 25°C

Model	Actual RH (% RH)	Fwd. RH (% RH)	Rev. RH (% RH)	Avg. RH[1] (% RH)	Dev[2] (% RH)	Hysteresis[3] (% RH)	Best-fit RH values (% RH)	Linearity[4] (% RH)
A-II	10.0	12.7	14.2	13.5	3.5	1.5	10.0	3.5
	30.0	33.0	35.5	34.3	4.3	2.5	30.0	4.3
	50.0	51.4	53.7	52.6	2.6	2.3	50.0	2.6
	70.0	68.8	71.1	70.0	-0.1	2.3	70.0	0.0
	90.0	86.8	86.8	86.8	-3.2	0.0	90.0	-3.2
B-II	10.0	5.9	6.5	6.2	-3.8	0.6	9.7	-3.5
	30.0	32.0	33.1	32.6	2.6	1.1	29.1	3.5
	50.0	51.9	52.9	52.4	2.4	1.0	48.6	3.8
	70.0	68.4	69.5	69.0	-1.1	1.1	68.0	1.0
	90.0	83.7	83.7	83.7	-6.3	0.0	87.4	-3.7
C-II	10.0	10.1	10.2	10.2	0.1	0.1	9.5	0.7
	30.0	27.7	28.1	27.9	-2.1	0.4	28.6	-0.7
	50.0	47.4	48.0	47.7	-2.3	0.6	47.6	0.1
	70.0	66.8	67.4	67.1	-2.9	0.6	66.5	0.5
	90.0	85.4	85.4	85.4	-4.6	0.0	85.7	-0.3
D-II	10.0	9.1	9.0	9.1	-0.9	-0.1	9.9	-0.8
	30.0	28.2	28.9	28.6	-1.5	0.7	29.7	-1.1
	50.0	48.5	49.0	48.8	-1.3	0.5	49.5	-0.7
	70.0	69.2	69.8	69.5	-0.5	0.6	69.2	0.3
	90.0	89.6	89.6	89.6	-0.4	0.0	89.0	0.6
E-II	10.0	8.5	8.7	8.6	-1.4	0.2	8.5	0.1
	30.0	22.4	23.2	22.8	-7.2	0.8	25.4	-2.6
	50.0	39.6	40.5	40.1	-10.0	0.9	42.3	-2.2
	70.0	58.5	58.9	58.7	-11.3	0.4	59.2	-0.5
	90.0	78.6	78.6	78.6	-11.4	0.0	76.1	2.5
F-II	10.0	7.5	9.8	8.7	-1.4	2.3	9.7	-1.0
	30.0	30.0	31.2	30.6	0.6	1.2	29.1	1.5
	50.0	48.2	48.6	48.4	-1.6	0.4	48.4	0.0
	70.0	67.6	67.6	67.6	-2.4	0.0	67.8	-0.2
	90.0	86.9	86.9	86.9	-3.1	0.0	87.2	-0.3

1: Average relative humidity represents the average of forward and reverse measurements
2: Deviation: Average RH – Actual RH
3: Hysteresis: Reverse RH – Forward RH
4: Linearity= Average RH – Best fit RH values

Table A.6: Accuracy, hysteresis and linearity of batch-2 sensors at 35°C

Model	Actual RH (% RH)	Fwd. RH (% RH)	Rev. RH (% RH)	Avg. RH[1] (% RH)	Dev[2] (% RH)	Hysteresis[3] (% RH)	Best-fit RH values (% RH)	Linearity[4] (% RH)
A-II	10.0	11.1	11.9	11.5	1.5	0.8	9.7	1.8
	30.0	31.1	33.0	32.1	2.1	1.9	29.0	3.1
	50.0	49.0	51.4	50.2	0.2	2.4	48.3	1.9
	70.0	66.5	68.5	67.5	-2.5	2.0	67.6	-0.1
	90.0	84.8	84.8	84.8	-5.2	0.0	87.0	-2.2
B-II	10.0	4.6	4.8	4.7	-5.3	0.2	9.4	-4.7
	30.0	29.9	30.6	30.3	0.3	0.7	28.2	2.1
	50.0	49.3	50.6	50.0	0.0	1.3	47.0	3.0
	70.0	66.0	67.2	66.6	-3.4	1.2	65.8	0.8
	90.0	82.0	82.0	82.0	-8.0	0.0	84.5	-2.5
C-II	10.0	10.1	10.0	10.1	0.1	-0.1	9.4	0.7
	30.0	27.4	27.7	27.6	-2.5	0.3	28.3	-0.7
	50.0	46.8	47.4	47.1	-2.9	0.6	47.2	-0.1
	70.0	66.3	66.8	66.6	-3.5	0.5	66.1	0.5
	90.0	84.9	84.9	84.9	-5.1	0.0	85.0	-0.1
D-II	10.0	8.1	8.1	8.1	-1.9	0.0	9.8	-1.7
	30.0	27.8	28.2	28.0	-2.0	0.4	29.4	-1.4
	50.0	48.1	49.0	48.6	-1.5	0.9	49.0	-0.4
	70.0	69.1	69.9	69.5	-0.5	0.8	68.6	0.9
	90.0	88.3	88.3	88.3	-1.7	0.0	88.2	0.1
E-II	10.0	6.3	6.4	6.4	-3.7	0.1	8.3	-1.9
	30.0	21.9	22.7	22.3	-7.7	0.8	24.9	-2.6
	50.0	37.9	39.3	38.6	-11.4	1.4	41.4	-2.8
	70.0	58.4	59.0	58.7	-11.3	0.6	58.0	0.7
	90.0	76.7	76.7	76.7	-13.3	0.0	74.6	2.1
F-II	10.0	1.2	2.0	1.6	-8.4	0.8	9.3	-7.7
	30.0	28.0	28.0	28.0	-2.0	0.0	28.0	0.0
	50.0	46.6	47.0	46.8	-3.2	0.4	46.6	0.2
	70.0	65.2	65.2	65.2	-4.8	0.0	65.2	0.0
	90.0	84.6	84.6	84.6	-5.4	0.0	83.9	0.7

1: Average relative humidity represents the average of forward and reverse measurements
2: Deviation: Average RH – Actual RH
3: Hysteresis: Reverse RH – Forward RH
4: Linearity= Average RH – Best fit RH values

Table A.7: Accuracy, hysteresis and linearity of batch-3 sensors at 15°C

Model	Actual RH (% RH)	Fwd. RH (% RH)	Rev. RH (% RH)	Avg. RH[1] (% RH)	Dev[2] (% RH)	Hysteresis[3] (% RH)	Best-fit RH values (% RH)	Linearity[4] (% RH)
A-III	10.0	15.5	17.1	16.3	6.3	1.6	10.4	5.9
	30.0	35.5	39.3	37.4	7.4	3.8	31.3	6.1
	50.0	53.8	57.6	55.7	5.7	3.8	52.1	3.6
	70.0	71.6	74.3	73.0	2.9	2.7	73.0	0.0
	90.0	89.2	89.2	89.2	-0.8	0.0	93.9	-4.7
B-III	10.0	7.4	8.4	7.9	-2.1	1.0	10.2	-2.3
	30.0	35.0	36.3	35.7	5.7	1.3	30.7	5.0
	50.0	55.0	56.6	55.8	5.8	1.6	51.2	4.6
	70.0	71.9	73.1	72.5	2.5	1.2	71.7	0.8
	90.0	87.5	87.5	87.5	-2.5	0.0	92.1	-4.6
C-III	10.0	9.9	9.8	9.9	-0.1	-0.1	9.5	0.4
	30.0	27.3	27.7	27.5	-2.5	0.4	28.6	-1.1
	50.0	47.0	47.7	47.4	-2.7	0.7	47.7	-0.3
	70.0	66.9	67.4	67.2	-2.8	0.5	66.8	0.4
	90.0	86.0	86.0	86.0	-4.0	0.0	85.8	0.2
D-III	10.0	10.0	9.7	9.9	-0.2	-0.3	9.8	0.1
	30.0	28.0	28.2	28.1	-1.9	0.2	29.5	-1.4
	50.0	49.8	50.3	50.1	0.0	0.5	49.2	0.9
	70.0	69.9	70.3	70.1	0.1	0.4	68.9	1.2
	90.0	87.6	87.6	87.6	-2.4	0.0	88.6	-1.0
E-III	10.0	6.8	5.4	6.1	-3.9	-1.4	8.8	-2.7
	30.0	25.2	25.3	25.3	-4.8	0.1	26.5	-1.2
	50.0	42.1	43.2	42.7	-7.3	1.1	44.2	-1.5
	70.0	61.8	62.2	62.0	-8.0	0.4	61.9	0.1
	90.0	81.0	81.0	81.0	-9.0	0.0	79.6	1.4
F-III	10.0	16.9	17.7	17.3	7.3	0.8	10.3	7.0
	30.0	33.4	36.2	34.8	4.8	2.8	31.0	3.8
	50.0	51.2	52.0	51.6	1.6	0.8	51.6	0.0
	70.0	71.3	71.3	71.3	1.3	0.0	72.2	-0.9
	90.0	91.5	91.5	91.5	1.5	0.0	92.9	-1.4

1: Average relative humidity represents the average of forward and reverse measurements
2: Deviation: Average RH – Actual RH
3: Hysteresis: Reverse RH – Forward RH
4: Linearity= Average RH – Best fit RH values

Table A.8: Accuracy, hysteresis and linearity of batch-3 sensors at 25°C

Model	Actual RH (% RH)	Fwd. RH (% RH)	Rev. RH (% RH)	Avg. RH[1] (% RH)	Dev[2] (% RH)	Hysteresis[3] (% RH)	Best-fit RH values (% RH)	Linearity[4] (% RH)
A-III	10.0	14.2	15.4	14.8	4.8	1.2	10.3	4.5
	30.0	34.9	37.1	36.0	6.0	2.2	30.9	5.1
	50.0	53.1	56.1	54.6	4.6	3.0	51.5	3.1
	70.0	70.8	73.2	72.0	2.0	2.4	72.1	-0.1
	90.0	88.9	88.9	88.9	-1.1	0.0	92.7	-3.8
B-III	10.0	5.9	6.1	6.0	-4.0	0.2	9.8	-3.8
	30.0	32.5	33.6	33.1	3.1	1.1	29.5	3.6
	50.0	52.5	53.7	53.1	3.1	1.2	49.1	4.0
	70.0	69.1	70.1	69.6	-0.4	1.0	68.7	0.9
	90.0	84.7	84.7	84.7	-5.3	0.0	88.4	-3.7
C-III	10.0	9.9	9.9	9.9	-0.1	0.0	9.5	0.4
	30.0	27.4	27.8	27.6	-2.4	0.4	28.4	-0.8
	50.0	46.9	47.5	47.2	-2.8	0.6	47.3	-0.1
	70.0	66.5	66.9	66.7	-3.3	0.4	66.2	0.5
	90.0	85.1	85.1	85.1	-4.9	0.0	85.2	-0.1
D-III	10.0	15.4	15.2	15.3	5.3	-0.2	10.0	5.3
	30.0	29.2	29.6	29.4	-0.6	0.4	29.9	-0.5
	50.0	49.7	50.0	49.9	-0.1	0.3	49.8	0.1
	70.0	69.3	70.0	69.7	-0.3	0.7	69.7	0.0
	90.0	89.0	89.0	89.0	-1.0	0.0	89.6	-0.6
E-III	10.0	8.7	8.7	8.7	-1.3	0.0	9.0	-0.3
	30.0	25.4	26.3	25.9	-4.2	0.9	27.1	-1.2
	50.0	44.2	44.8	44.5	-5.5	0.6	45.1	-0.6
	70.0	62.8	63.6	63.2	-6.8	0.8	63.2	0.0
	90.0	82.0	82.0	82.0	-8.0	0.0	81.2	0.8
F-III	10.0	10.3	11.8	11.1	1.1	1.5	10.2	0.9
	30.0	31.9	33.5	32.7	2.7	1.6	30.6	2.1
	50.0	51.6	51.6	51.6	1.6	0.0	50.9	0.7
	70.0	70.9	71.3	71.1	1.1	0.4	71.3	-0.2
	90.0	90.6	90.6	90.6	0.6	0.0	91.7	-1.1

1: Average relative humidity represents the average of forward and reverse measurements
2: Deviation: Average RH – Actual RH
3: Hysteresis: Reverse RH – Forward RH
4: Linearity= Average RH – Best fit RH values

Table A.9: Accuracy, hysteresis and linearity of batch-3 sensors at 35°C

Model	Actual RH (% RH)	Fwd. RH (% RH)	Rev. RH (% RH)	Avg. RH[1] (% RH)	Dev[2] (% RH)	Hysteresis[3] (% RH)	Best-fit RH values (% RH)	Linearity[4] (% RH)
A-III	10.0	13.9	13.4	13.7	3.7	-0.5	10.2	3.5
	30.0	33.7	35.7	34.7	4.7	2.0	30.5	4.2
	50.0	52.1	54.6	53.4	3.4	2.5	50.9	2.5
	70.0	69.9	72.0	71.0	1.0	2.1	71.2	-0.2
	90.0	88.5	88.5	88.5	-1.5	0.0	91.5	-3.0
B-III	10.0	4.6	4.1	4.4	-5.7	-0.5	9.5	-5.1
	30.0	30.2	31.0	30.6	0.6	0.8	28.5	2.1
	50.0	50.1	51.1	50.6	0.6	1.0	47.5	3.1
	70.0	66.9	67.8	67.4	-2.7	0.9	66.5	0.9
	90.0	82.9	82.9	82.9	-7.1	0.0	85.5	-2.6
C-III	10.0	9.9	9.8	9.9	-0.1	-0.1	9.5	0.4
	30.0	27.3	27.7	27.5	-2.5	0.4	28.6	-1.1
	50.0	47.0	47.7	47.4	-2.7	0.7	47.7	-0.3
	70.0	66.9	67.4	67.2	-2.8	0.5	66.8	0.4
	90.0	86.0	86.0	86.0	-4.0	0.0	85.8	0.2
D-III	10.0	10.0	9.7	9.9	-0.2	-0.3	9.8	0.1
	30.0	28.0	28.2	28.1	-1.9	0.2	29.5	-1.4
	50.0	49.8	50.3	50.1	0.0	0.5	49.2	0.9
	70.0	69.9	70.3	70.1	0.1	0.4	68.9	1.2
	90.0	87.6	87.6	87.6	-2.4	0.0	88.6	-1.0
E-III	10.0	6.8	5.4	6.1	-3.9	-1.4	8.8	-2.7
	30.0	25.2	25.3	25.3	-4.8	0.1	26.5	-1.2
	50.0	42.1	43.2	42.7	-7.3	1.1	44.2	-1.5
	70.0	61.8	62.2	62.0	-8.0	0.4	61.9	0.1
	90.0	81.0	81.0	81.0	-9.0	0.0	79.6	1.4
F-III	10.0	2.3	3.1	2.7	-7.3	0.8	10.0	-7.3
	30.0	31.1	31.1	31.1	1.1	0.0	30.0	1.1
	50.0	51.6	51.6	51.6	1.6	0.0	50.0	1.6
	70.0	70.5	70.9	70.7	0.7	0.4	70.0	0.7
	90.0	89.0	89.0	89.0	-1.0	0.0	90.0	-1.0

1: Average relative humidity represents the average of forward and reverse measurements
2: Deviation: Average RH – Actual RH
3: Hysteresis: Reverse RH – Forward RH
4: Linearity= Average RH – Best fit RH values

APPENDIX B: AGEING TEST DATA

Table B.1: Accuracy test data for the ageing test after four months at 25°C (most accurate sensors)

Model	Actual Relative Humidity (% RH)	Forward Relative Humidity (% RH)	Reverse Relative Humidity (% RH)	Average Relative Humidity* (% RH)	Deviation** (% RH)
A-I	10.0	10.9	10.2	10.6	0.6
	30.0	31.9	33.0	32.5	2.5
	50.0	50.5	52.2	51.4	1.4
	70.0	68.5	70.0	69.2	-0.8
	90.0	87.3	87.3	87.3	-2.7
B-I	10.0	7.5	7.5	7.5	-2.5
	30.0	33.6	34.6	34.1	4.1
	50.0	53.6	55.1	54.4	4.4
	70.0	71.2	72.6	71.9	1.9
	90.0	89.9	89.9	89.9	-0.1
C-I	10.0	10.0	10.0	10.0	0.0
	30.0	27.5	27.7	27.6	-2.4
	50.0	47.0	47.3	47.2	-2.9
	70.0	66.3	66.6	66.5	-3.6
	90.0	84.7	84.7	84.7	-5.3
D-II	10.0	8.4	8.5	8.5	-1.6
	30.0	25.9	26.7	26.3	-3.7
	50.0	46.0	46.8	46.4	-3.6
	70.0	66.2	67.0	66.6	-3.4
	90.0	87.1	87.1	87.1	-2.9
E-I	10.0	4.8	5.1	5.0	-5.1
	30.0	22.8	23.3	23.1	-7.0
	50.0	40.0	40.7	40.4	-9.7
	70.0	59.2	59.6	59.4	-10.6
	90.0	81.4	81.4	81.4	-8.6
F-II	10.0	7.3	7.7	7.5	-2.5
	30.0	28.6	28.7	28.7	-1.4
	50.0	50.8	50.8	50.8	0.8
	70.0	72.5	72.9	72.7	2.7
	90.0	97.4	97.4	97.4	7.4

* Average relative humidity represents the average of forward and reverse measurements

** Deviation: Average RH – Actual RH

Table B.2: Accuracy test data for the ageing test after four months at 25°C (least accurate sensors)

Model	Actual Relative Humidity (% RH)	Forward Relative Humidity (% RH)	Reverse Relative Humidity (% RH)	Average Relative Humidity* (% RH)	Deviation** (% RH)
A-III	10.0	14.8	14.7	14.8	4.8
	30.0	35.2	37.0	36.1	6.1
	50.0	53.6	55.1	54.4	4.4
	70.0	71.4	73.6	72.5	2.5
	90.0	90.0	90.0	90.0	0.0
B-III	10.0	7.1	7.1	7.1	-2.9
	30.0	33.8	34.8	34.3	4.3
	50.0	53.8	55.0	54.4	4.4
	70.0	70.4	71.7	71.1	1.1
	90.0	89.7	89.7	89.7	-0.3
C-III	10.0	9.9	10.0	10.0	-0.1
	30.0	27.4	27.6	27.5	-2.5
	50.0	46.7	47.1	46.9	-3.1
	70.0	65.9	66.2	66.1	-3.9
	90.0	84.2	84.2	84.2	-5.8
D-III	10.0	17.0	16.8	16.9	6.9
	30.0	27.6	27.9	27.8	-2.3
	50.0	46.8	47.5	47.2	-2.9
	70.0	67.5	68.2	67.9	-2.2
	90.0	87.0	87.0	87.0	-3.0
E-III	10.0	6.7	6.6	6.7	-3.4
	30.0	20.4	20.5	20.5	-9.6
	50.0	36.9	37.6	37.3	-12.8
	70.0	56.4	57.0	56.7	-13.3
	90.0	78.1	78.1	78.1	-11.9
F-III	10.0	8.8	8.8	8.8	-1.2
	30.0	25.0	25.4	25.2	-4.8
	50.0	49.4	49.8	49.6	-0.4
	70.0	71.9	72.3	72.1	2.1
	90.0	93.2	93.2	93.2	3.2

* Average relative humidity represents the average of forward and reverse measurements
** Deviation: Average RH – Actual RH

Table B.3: Accuracy test data for the ageing test after eight months at 25°C (most accurate sensors)

Model	Actual Relative Humidity (% RH)	Forward Relative Humidity (% RH)	Reverse Relative Humidity (% RH)	Average Relative Humidity* (% RH)	Deviation** (% RH)
	10.0	8.5	10.9	9.7	-0.3
	30.0	29.3	32.9	31.1	1.1
A-I	50.0	48.3	51.9	50.1	0.1
	70.0	66.9	69.4	68.2	-1.8
	90.0	86.0	86.0	86.0	-4.0
	10.0	6.3	7.9	7.1	-2.9
	30.0	32.2	34.8	33.5	3.5
B-I	50.0	53.2	55.7	54.5	4.5
	70.0	71.6	73.9	72.8	2.8
	90.0	91.8	91.8	91.8	1.8
	10.0	9.6	9.9	9.8	-0.3
	30.0	27.1	27.6	27.4	-2.7
C-I	50.0	46.9	47.4	47.2	-2.9
	70.0	66.4	66.8	66.6	-3.4
	90.0	85.0	85.0	85.0	-5.0
	10.0	8.5	8.2	8.4	-1.7
	30.0	26.1	26.4	26.3	-3.8
D-II	50.0	46.7	47.0	46.9	-3.2
	70.0	67.5	68.0	67.8	-2.3
	90.0	88.4	88.4	88.4	-1.6
	10.0	1.4	2.5	2.0	-8.1
	30.0	23.2	24.2	23.7	-6.3
E-I	50.0	40.2	40.5	40.4	-9.7
	70.0	50.4	50.8	50.6	-19.4
	90.0	51.0	51.0	51.0	-39.0
	10.0	6.6	7.3	7.0	-3.1
	30.0	26.2	27.8	27.0	-3.0
F-II	50.0	50.0	50.4	50.2	0.2
	70.0	71.7	72.1	71.9	1.9
	90.0	97.4	97.4	97.4	7.4

* Average relative humidity represents the average of forward and reverse measurements
** Deviation: Average RH – Actual RH

Table B.4: Accuracy test data for the ageing test after eight months at 25°C (least accurate sensors)

Model	Actual Relative Humidity (% RH)	Forward Relative Humidity (% RH)	Reverse Relative Humidity (% RH)	Average Relative Humidity* (% RH)	Deviation** (% RH)
A-III	10.0	11.8	14.4	13.1	3.1
	30.0	32.7	36.6	34.7	4.7
	50.0	51.9	55.7	53.8	3.8
	70.0	70.5	73.4	72.0	2.0
	90.0	89.8	89.8	89.8	-0.2
B-III	10.0	5.5	6.7	6.1	-3.9
	30.0	32.0	34.3	33.2	3.2
	50.0	53.0	55.0	54.0	4.0
	70.0	70.8	72.6	71.7	1.7
	90.0	94.0	94.0	94.0	4.0
C-III	10.0	9.7	9.9	9.8	-0.2
	30.0	27.1	27.6	27.4	-2.7
	50.0	46.9	47.3	47.1	-2.9
	70.0	66.3	66.6	66.5	-3.6
	90.0	84.8	84.8	84.8	-5.2
D-III	10.0	17.1	16.8	17.0	7.0
	30.0	27.5	27.8	27.7	-2.4
	50.0	46.8	47.5	47.2	-2.9
	70.0	67.7	68.1	67.9	-2.1
	90.0	87.2	87.2	87.2	-2.8
E-III	10.0	0.8	2.1	1.5	-8.6
	30.0	19.7	20.3	20.0	-10.0
	50.0	36.0	36.8	36.4	-13.6
	70.0	56.2	57.3	56.8	-13.3
	90.0	78.2	78.2	78.2	-11.8
F-III	10.0	8.9	8.5	8.7	-1.3
	30.0	23.8	24.6	24.2	-5.8
	50.0	49.4	49.8	49.6	-0.4
	70.0	72.3	72.7	72.5	2.5
	90.0	93.6	93.6	93.6	3.6

* Average relative humidity represents the average of forward and reverse measurements

** Deviation: Average RH – Actual RH

Table B.5: Accuracy test data for the ageing test after twelve months at 25°C (most accurate sensors)

Model	Actual Relative Humidity (% RH)	Forward Relative Humidity (% RH)	Reverse Relative Humidity (% RH)	Average Relative Humidity* (% RH)	Deviation** (% RH)
A-I	10.0	15.0	13.0	14.0	4.0
	30.0	33.2	35.2	34.2	4.2
	50.0	51.2	53.4	52.3	2.3
	70.0	68.4	70.3	69.3	-0.7
	90.0	86.1	86.1	86.1	-3.9
B-I	10.0	Sensor connectors came loose, therefore not tested			
	30.0				
	50.0				
	70.0				
	90.0				
C-I	10.0	9.9	9.9	9.9	-0.1
	30.0	27.3	27.5	27.4	-2.6
	50.0	46.6	47.0	46.8	-3.2
	70.0	65.8	66.0	65.9	-4.1
	90.0	84.1	84.1	84.1	-5.9
D-II	10.0	8.3	8.3	8.3	-1.7
	30.0	25.5	26.2	25.9	-4.1
	50.0	45.9	46.6	46.2	-3.8
	70.0	66.8	67.2	67.0	-3.0
	90.0	87.7	87.7	87.7	-2.3
E-I	10.0	7.9	7.1	7.5	-2.5
	30.0	23.8	22.9	23.4	-6.7
	50.0	40.4	40.3	40.4	-9.7
	70.0	59.9	61.1	60.5	-9.5
	90.0	81.9	81.9	81.9	-8.1
F-II	10.0	4.5	4.1	4.3	-5.7
	30.0	4.1	4.1	4.1	-25.9
	50.0	4.1	4.2	4.2	-45.9
	70.0	4.2	4.6	4.4	-65.6
	90.0	5.8	5.8	5.8	-84.2

* Average relative humidity represents the average of forward and reverse measurements
** Deviation: Average RH – Actual RH

Table B.6: Accuracy test data for the ageing test after twelve months at 25°C (least accurate sensors)

Model	Actual Relative Humidity (% RH)	Forward Relative Humidity (% RH)	Reverse Relative Humidity (% RH)	Average Relative Humidity* (% RH)	Deviation** (% RH)
A-III	10.0	17.0	15.5	16.3	6.3
	30.0	36.3	38.3	37.3	7.3
	50.0	54.9	57.0	56.0	6.0
	70.0	72.5	74.3	73.4	3.4
	90.0	90.4	90.4	90.4	0.4
B-III	10.0	7.9	7.7	7.8	-2.2
	30.0	35.0	35.9	35.4	5.4
	50.0	55.3	56.3	55.8	5.8
	70.0	72.2	73.2	72.7	2.7
	90.0	96.1	96.1	96.1	6.1
C-III	10.0	9.9	9.9	9.9	-0.5
	30.0	27.5	27.6	27.5	-2.5
	50.0	46.9	47.1	47.0	-3.0
	70.0	66.0	66.3	66.1	-3.9
	90.0	84.4	84.4	84.4	-5.6
D-III	10.0	Sensor was used for response time testing			
	30.0				
	50.0				
	70.0				
	90.0				
E-III	10.0	7.9	7.7	7.8	-2.2
	30.0	20.2	20.2	20.2	-9.8
	50.0	36.7	37.3	37.0	-13.0
	70.0	57.3	58.6	58.0	-12.1
	90.0	76.7	76.7	76.7	-13.3
F-III	10.0	9.2	8.9	9.1	-0.9
	30.0	24.2	24.6	24.4	-5.6
	50.0	49.0	49.4	49.2	-0.8
	70.0	71.9	72.2	72.1	2.1
	90.0	92.7	92.7	92.7	2.7

* Average relative humidity represents the average of forward and reverse measurements
** Deviation: Average RH – Actual RH

APPENDIX C: RESPONSE TIME TEST DATA

Table C.1: Response time data for Run 1

Model	Step	Initial Relative Humidity (% RH)	Final Relative Humidity (% RH)	Δ RH	Δ $RH_{63\%}$	Response Time (sec)
A	Forward	32.8	78.2	45.5	61.4	46.2
	Reverse	78	33.2	-44.9	49.8	78.6
B	Forward	51.5	79.7	28.2	69.2	24
	Reverse	80.1	51.6	-28.6	62.1	54
C	Forward	29	76.3	47.3	58.8	7.8
	Reverse	76	28.3	-47.7	46	4.8
D	Forward	45.6	78.1	32.5	66	88.8
	Reverse	78.6	43.2	-35.5	56.3	94.8
E	Forward	30.1	84.9	54.8	64.6	90
	Reverse	80.2	28.1	-52.1	47.4	99
F	Forward	30.4	79.9	49.5	61.6	9
	Reverse	79.9	32.7	-47.2	50.2	10.8

Δ RH: Difference between final and initial relative humidity readings

$RH_{0.63} = (0.63 \times \Delta RH) + RH_{initial}$

Table C.2: Response time data for Run 2

Model	Step	Initial Relative Humidity (% RH)	Final Relative Humidity (% RH)	Δ RH	Δ $RH_{63\%}$	Response Time (sec)
A	Forward	33.8	78.7	44.9	62.1	46.2
	Reverse	78.9	33.8	-45.1	50.5	76.2
B	Forward	50.8	79.5	28.8	68.9	40.2
	Reverse	79.6	50.7	-28.9	61.4	49.8
C	Forward	28.4	76.3	47.9	58.6	13.2
	Reverse	76.3	28.4	-47.9	46.1	4.8
D	Forward	42.3	77.9	35.6	64.7	127.8
	Reverse	77.3	42.3	-35	55.3	85.8
E	Forward	31.8	81.9	50.1	63.4	100.2
	Reverse	83.3	27.8	-55.6	48.3	102.2
F	Forward	33.3	80.2	47	62.9	9.6
	Reverse	80.2	33.5	-46.7	50.8	10.8

Δ RH: Difference between final and initial relative humidity readings

$RH_{0.63} = (0.63 \times \Delta RH) + RH_{initial}$

Table C.3: Response time data for Run 3

Model	Step	Initial Relative Humidity (% RH)	Final Relative Humidity (% RH)	Δ RH	$\Delta RH_{63\%}$	Response Time (sec)
A	Forward	28.9	79.2	50.3	60.6	61.6
	Reverse	79.2	31.5	-47.7	44.2	91.2
B	Forward	50.3	79.5	29.2	68.7	47.4
	Reverse	80.2	51.8	-28.4	62.3	64.8
C	Forward	28.4	76.3	47.9	58.6	7.2
	Reverse	76.3	27.9	-48.4	45.8	5.4
D	Forward	43	78.3	35.2	65.2	88.2
	Reverse	78.4	42.5	-35.9	55.8	87.6
E	Forward	28.9	79.5	50.6	60.8	76.2
	Reverse	76.5	29.8	-46.7	47.1	93
F	Forward	29.4	80.2	50.9	61.4	8.4
	Reverse	80.3	31.2	-49.1	49.3	11.4

Δ RH: Difference between final and initial relative humidity readings

$RH_{0.63} = (0.63 \times \Delta RH) + RH_{initial}$

APPENDIX D: STRESS TESTS DATA

Table D.1: Accuracy test data for the cycling test at 25°C

Model	Actual Relative Humidity (% RH)	Forward Relative Humidity (% RH)	Reverse Relative Humidity (% RH)	Average Relative Humidity* (% RH)	Deviation** (% RH)
A-II	30.0	33.8	34.3	34.0	4.0
	50.0	52.3	54.6	53.4	3.4
	70.0	70.5	72.5	71.5	1.5
B-V	30.0	32.9	34.0	33.4	3.4
	50.0	53.7	55.2	54.4	4.4
	70.0	71.5	72.7	72.1	2.1
C-II	30.0	28.7	28.7	28.7	-1.3
	50.0	48.8	49.0	48.9	-1.1
	70.0	68.2	68.4	68.3	-1.7
D-IV	30.0	27.1	27.6	27.4	-2.6
	50.0	46.6	47.4	47.0	-3.0
	70.0	67.3	67.8	67.5	-2.5
E-VII	30.0	28.2	27.3	27.7	-2.3
	50.0	48.3	49.0	48.6	-1.4
	70.0	74.0	73.7	73.9	3.9
F-I	30.0	31.6	31.9	31.8	1.8
	50.0	51.8	51.8	51.8	1.8
	70.0	72.0	72.0	72.0	2.0

* Average relative humidity represents the average of forward and reverse measurements
** Deviation: Average RH – Actual RH

Table D.2: Accuracy test data for the desiccation test at 25°C

Model	Actual Relative Humidity (% RH)	Forward Relative Humidity (% RH)	Reverse Relative Humidity (% RH)	Average Relative Humidity* (% RH)	Deviation** (% RH)
A-II	30.0	20.1	23.4	21.7	-8.3
	50.0	31.9	35.4	33.7	-16.3
	70.0	44.3	46.6	45.4	-24.6
B-V	30.0	31.4	33.5	32.4	2.4
	50.0	52.2	54.4	53.3	3.3
	70.0	69.9	71.4	70.6	0.6
C-II	30.0	28.4	28.7	28.5	-1.5
	50.0	48.4	48.8	48.6	-1.4
	70.0	67.9	68.2	68.1	-1.9
D-IV	30.0	26.7	27.3	27.0	-3.0
	50.0	46.2	46.8	46.5	-3.5
	70.0	67.3	67.9	67.6	-2.4
E-VII	30.0	27.7	27.8	27.8	-2.2
	50.0	48.0	49.0	48.5	-1.5
	70.0	73.5	70.3	71.9	1.9
F-I	30.0	31.9	33.1	32.5	2.5
	50.0	51.8	51.8	51.8	1.8
	70.0	72.0	72.0	72.0	2.0

* Average relative humidity represents the average of forward and reverse measurements

** Deviation: Average RH – Actual RH

Table D.3: Accuracy test data for the saturation test at 25°C

Model	Actual Relative Humidity (% RH)	Forward Relative Humidity (% RH)	Reverse Relative Humidity (% RH)	Average Relative Humidity* (% RH)	Deviation** (% RH)
A-II	30.0	25.3	25.6	25.4	-4.6
	50.0	36.5	37.5	37.0	-13.0
	70.0	48.1	48.9	48.5	-21.5
B-V	30.0	35.4	35.6	35.5	5.5
	50.0	56.2	56.8	56.5	6.5
	70.0	73.8	74.0	73.9	3.9
C-II	30.0	29.2	29.2	29.2	-0.8
	50.0	49.6	49.7	49.7	-0.3
	70.0	69.1	69.2	69.1	-0.9
D-IV	30.0	27.7	27.5	27.6	-2.4
	50.0	47.3	47.4	47.4	-2.6
	70.0	68.8	68.8	68.8	-1.2
E-VII	30.0	30.0	31.0	30.5	0.5
	50.0	50.3	51.3	50.8	0.8
	70.0	69.9	71.9	70.9	0.9
F-I	30.0	27.2	27.2	27.2	-2.8
	50.0	46.1	46.1	46.1	-3.9
	70.0	64.1	64.2	64.2	-5.8

* Average relative humidity represents the average of forward and reverse measurements
** Deviation: Average RH – Actual RH

Table D.4: Accuracy test data two days after desiccation-saturation test at 25C

Model	Actual Relative Humidity (% RH)	Forward Relative Humidity (% RH)	Reverse Relative Humidity (% RH)	Average Relative Humidity* (% RH)	Deviation** (% RH)
A-II	30.0	23.3	24.8	24.1	-5.9
	50.0	34.5	36.7	35.6	-14.4
	70.0	45.9	47.3	46.6	-23.4
B-V	30.0	33.9	34.7	34.3	4.3
	50.0	54.0	55.3	54.6	4.6
	70.0	71.1	71.9	71.5	1.5
C-II	30.0	29.0	29.1	29.0	-1.0
	50.0	49.2	49.5	49.4	-0.6
	70.0	68.9	69.1	69.0	-1.0
D-IV	30.0	27.3	27.4	27.4	-2.6
	50.0	47.0	47.2	47.1	-2.9
	70.0	68.1	68.5	68.3	-1.7
E-VII	30.0	27.2	27.9	27.6	-2.4
	50.0	51.2	51.2	51.2	1.2
	70.0	69.2	69.9	69.6	-0.4
F-I	30.0	27.0	27.1	27.0	-3.0
	50.0	45.7	46.0	45.8	-4.2
	70.0	63.8	64.1	64.0	-6.0

* Average relative humidity represents the average of forward and reverse measurements
** Deviation: Average RH – Actual RH

Table D.5: Accuracy test data for the submergence test at 25°C

Model	Actual Relative Humidity (% RH)	Forward Relative Humidity (% RH)	Reverse Relative Humidity (% RH)	Average Relative Humidity* (% RH)	Deviation** (% RH)
A-II	30.0	86.9	87.0	86.9	86.9
	50.0	86.9	87.0	86.9	86.9
	70.0	86.9	86.9	86.9	86.9
B-V	30.0	98.9	98.9	98.9	98.9
	50.0	98.9	98.9	98.9	98.9
	70.0	98.9	98.9	98.9	98.9
C-II	30.0	29.6	29.3	29.4	-0.6
	50.0	50.1	50.0	50.0	0.0
	70.0	69.3	69.4	69.4	-0.6
D-IV	30.0	Sensor failed during the test			
	50.0				
	70.0				
E-VII	30.0	99.2	42.2	70.7	40.7
	50.0	91.9	83.9	87.9	37.9
	70.0	92.5	96.6	94.6	24.6
F-I	30.0	30.4	30.2	30.3	0.3
	50.0	49.5	49.3	49.4	-0.6
	70.0	67.2	67.3	67.3	-2.7

* Average relative humidity represents the average of forward and reverse measurements

** Deviation: Average RH – Actual RH

Table D.6: Accuracy test data two days after the submergence test at 25°C

Model	Actual Relative Humidity (% RH)	Forward Relative Humidity (% RH)	Reverse Relative Humidity (% RH)	Average Relative Humidity* (% RH)	Deviation** (% RH)
A-II	30.0	86.8	43.1	65.0	35.0
	50.0	86.8	86.8	86.8	36.8
	70.0	86.9	86.9	86.9	16.9
B-V	30.0	98.9	78.8	88.9	58.9
	50.0	98.9	98.9	98.9	48.9
	70.0	98.9	98.9	98.9	28.9
C-II	30.0	29.0	29.2	29.4	-0.6
	50.0	49.2	49.5	50.0	0.0
	70.0	68.6	68.8	69.4	-0.6
D-IV	30.0	Sensor failed			
	50.0				
	70.0				
E-VII	30.0	Sensor failed			
	50.0				
	70.0				
F-I	30.0	27.0	27.1	30.3	0.3
	50.0	45.7	45.9	49.4	-0.6
	70.0	63.7	63.9	67.3	-2.7

* Average relative humidity represents the average of forward and reverse measurements
** Deviation: Average RH – Actual RH

APPENDIX E: SAMPLE LOG SHEET

Table E.1: Log sheet for sensor Model E

Sensor Name	**Model-E**
Date	**Action**
4/4/2002	Sensors arrived in the Lab
4/4/2002	Sensor stored in the cabinet
7/26/2002	Sensor taken out from the cabinet and testing at 25°C commences
7/26/2002	Test run finishes. Sensor placed in the cabinet
7/27/2002	Testing of sensor at 15°C commences
7/27/2002	Test run finished. Sensor placed in the cabinet
7/28/2002	Sensor testing at 35°C commences
7/28/2002	Test run finished. Sensor placed in the cabinet
11/18/2003	Sensor tested for noise at ERS
11/19/2003	Sensor failed
1/20/2004	Sensor delivered, however, found severed wire, returned
1/29/2004	Second sensor unit delivered
1/30/2004	Second sensor unit testing for accuracy
01/30/2004 - 04/21/04	Stored in the box
4/22/2004	Response time testing completed
4/22/2004-05/16/04	Sensor stored in the box
5/16/2004 - 05/17/04	Cyclic testing at 5°C
5/18/2004 - 05/19/04	Cyclic testing at 35°C
5/20/2004	Accuracy testing at 25°C
5/20/2004	Sensors stored in the box
6/18/2004	Sensor installed for desiccation test
6/19/2004	Sensor installed for desiccation test
6/20/2004	Accuracy testing of sensors in Thunder Scientific (TS)
6/21/2004	Sensor insatalled for Saturation test
6/22/2004	Sensor installed for Saturation test
6/23/2004	Accuracy testing of sensors in TS
6/24/2004	Sensor stored in the box
6/25/2004	Accuracy testing of sensor in TS
6/26/2004	Submergence test of the sensor
6/27/2004	Accuracy testing of sensors in TS
6/28/2004	Sensor stored in the box
6/29/2004	Sensor found failed, accuracy testing was abandoned, no specific reason for failure
6/30/2004	Sensor stored in the box