A procedure to evaluate humidity sensor performance under livestock housing conditions

S.P. Lemay[1], H. Guo[1], E.M. Barber[2] and L. Zyla[1]

[1]*Prairie Swine Centre Inc., P.O. Box 21057, 2105 8th Street East, Saskatoon, Saskatchewan, Canada S7H 5N9; and* [2]*College of Agriculture, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 5A5.*

Lemay, S.P., Guo, H., Barber, E.M. and Zyla, L. 2001. **A procedure to evaluate humidity sensor performance under livestock housing conditions**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada. **43**: 5.13 - 5.21. Humidity sensors are affected by the air quality in livestock buildings. New sensor models should be tested under existing barn conditions to assess their long-term integrity. An experimental procedure was developed to meet this requirement. After initial static and dynamic calibrations in a specially designed humidity chamber in the laboratory, the test sensors were installed in a livestock building for one year. The sensors were temporarily removed from the barn several times during the year and taken back to the laboratory for calibration against a reference hygrometer and determination of static and dynamic properties including accuracy, hysteresis, linearity, and time response. A bank of 72 humidity sensors with two different coatings and six different filters were evaluated with this procedure in a grower/finisher room. Treatment 6 had a significantly lower accuracy drift than nine of the other treatments ($P<0.05$). It had the lowest nonlinearity increase of 8.0% and sensors in treatment 6 responded significantly faster than eight of the other treatments ($P<0.05$) at the year-end tests. The results confirmed the value and practicality of the test procedure, and led to recommendations for the appropriate length of the in-barn evaluation period (minimum one year), calibration frequency (every two weeks at the beginning; every two or three months at the end of the evaluation), and required replication (minimum of three sensors of any one type).

La qualité de l'air dans les bâtiments d'élevage affecte la precision des sondes d'humidité relative. Avant d'utiliser ces sondes pour contrôler les équipements de chauffage et de ventilation, leur précision doit être évaluée dans des conditions réelles d'opération. Une procédure expérimentale a été développée pour mesurer l'évolution de la précision des sondes d'humidité relative lorsqu'elles sont exposées à la qualité de l'air d'un bâtiment d'élevage. Après avoir mesurer la précision et le temps de réponse des sondes en laboratoire, celles-ci étaient installées dans un bâtiment agricole pour une année. Les sondes étaient ensuite démontées et ramenées au laboratoire sur une base régulière pour vérifier leur précision par rapport à un appareil de référence qui lui était maintenu dans le laboratoire. La linéarité, l'hystérésis et le temps de réponse des sondes étaient également mesurés. Un ensemble de 72 sondes d'humidité relative pourvues de deux types de recouvrement et de six types de filtre ont été testées en utilisant cette procédure dans une porcherie en croissance-finition. Après une année d'exposition, les sondes correspondant au traitement 6 ont eu une dérive de leur précision significativement inférieure a neuf autres combinaisons de traitement ($P<0.05$). Ces sondes ont connu la plus faible augmentation de non-linéarité (8%) et leur temps de réponse était significativement plus rapide que huit autres combinaisons de traitement ($P<0.05$). Les résultats de cette étude ont démontré l'efficacité de cette procédure expérimentale pour tester des sondes d'humidité relative et ont conduit à certaines recommandations concernant la durée de l'évaluation (une année minimum), la fréquence de calibrage (à tous les deux semaines en début d'évaluation; à tous les deux ou trois mois en fin d'évaluation) et le nombre de sonde requis (trois sondes du même type minimum).

INTRODUCTION

Humidity monitoring and control have long been recognised as an important approach to improve barn environment. However, due to the corrosive and dusty environment of livestock buildings, continuous humidity monitoring has been limited by the availability of sensors that are reliable, economical, durable, and stable. New sensors entering the market need to be evaluated under real barn conditions before relying on them as part of a monitoring and control system.

Several approaches have been reported for evaluation of humidity sensor performance under laboratory conditions. Ross and Daley (1990) tested four thin-film capacitive relative humidity (RH) sensors in the laboratory over salt solutions that gave calibration humidities ranging from 10.0 to 97.6%. They evaluated the accuracy, repeatability, linearity, and the influence of air velocity, variations in temperature, and condensing conditions on the sensors. Chen et al. (1991) evaluated the accuracy, precision, and stability of five electronic RH sensors in the laboratory and also used saturated salt solutions to create reference relative humidities for calibration. Chen and Tsao (1992) developed a calibration device for electronic RH sensors in which two nitrogen gas streams (one pure dry and one saturated with water) were mixed to obtain the full range of RH values. These in-laboratory methods provide a convenient way to calibrate new sensors but do not predict the sensor performance during operation.

Erdebil and Leonard (1989, 1992) developed an apparatus to simulate an animal environment in laboratory tests of RH sensors. Their laboratory chamber was able to simulate constant, increasing, and decreasing humidity levels as well as controlled concentrations of ammonia and dust similar to what would be experienced in an animal building. Three humidity sensors were tested for accuracy and time response. The major limitation of their approach was that only short duration evaluation was performed.

Several authors have reported in-barn tests of humidity sensors. Vosper and Bundy (1979) kept a lithium-chloride dew-point sensor in a swine nursery for a three-month period and periodically tested its accuracy against a sling psychrometer. Ross et al. (1988) tested several thin film capacitance sensors as part of a monitoring and control system for a broiler house over a six-month period. They calibrated the sensors against humidity measurements derived using a sling psychrometer and saturated salt solutions. The frequency of calibration checks was not reported. White and Allison (1987) reported that two lithium-chloride dew-point sensors performed well over an eight-week period in a broiler barn. A filter was placed around the dewprobes to filter out contaminants and the bobbins were retreated weekly to ensure they did not become contaminated. Calibration results were not reported.

Barber and Gu (1989) monitored the performance of four hygrometers over eight weeks in a dairy barn and seven weeks in a broiler barn. The instruments were left in the barns continuously after the experiments started. Measurements were recorded approximately once a week and compared to the data obtained simultaneously by a reference laboratory-model aspirated psychrometer. Barber et al. (1989) also constructed and tested four models of aspirated psychrometers for accuracy, reliability, and maintenance requirements over a 13-week period in a swine barn and over a 26-week period in a poultry barn. Before the barn tests, the accuracy of the psychrometers was tested in the laboratory against a laboratory-model aspirated psychrometer. Tested psychrometers were operated continuously in the barn and measurements were compared once every 2 to 7 days against a clean reference psychrometer.

Hao and Leonard (1994) tested the performance of two models of thin-film humidity sensors, one unit of each model, in turkey, broiler, and swine buildings over periods of 6 to 7 weeks in each barn. The sensors were left in the barn continuously once the test started but measurements from the sensors were recorded only for one or two days each week. The reference relative humidity was measured continuously with a chilled-mirror dew-point hygrometer which received filtered air from the barns. In these three field experiments, the sensors' accuracy drift over time was evaluated.

Four different RH sensors were exposed to the environment in a laying hen building for a twelve month period (Joncas and Noreau 1997). All RH sensors had an accuracy drift but because the reference hygrometer was exposed to the same conditions, it was also affected by air contaminants and no conclusions could be drawn on sensor accuracy over the year.

It is apparent from the literature that there is no standard procedure for calibrating or assessing the performance of RH sensors for use in livestock buildings. In this project, a procedure was developed which could form the basis for a standardised test protocol. The purpose of this paper is to describe the procedure and the equipment used and to review the results of using the procedure for testing electronic sensors from one manufacturer.

EXPERIMENTAL PROCEDURE

The following criteria were identified as being of importance in the testing of electronic humidity sensors:

1. Assessment of sensors should include static characteristics (e.g., accuracy, linearity, temperature dependence, and hysteresis) and dynamic characteristics (e.g., time response to changing inputs).
2. Testing should be performed to assess variability among multiple units of the same sensor model.
3. Sensor characteristics should be assessed with clean sensors and after use in the barn for varying periods of time.
4. The in-barn tests should be of long enough duration to predict the "long-term" performance of the sensors, their durability and reliability, and to assess the failure mode, whether sudden failure or a drift in accuracy.
5. Ideally the protocol should involve periodic removal of the sensors from the barn for testing rather than having to set up laboratory-type testing within the barn. However, the sensors and the accumulated fouling should not be disturbed by the test procedure.
6. Air quality parameters should be monitored within the barn to assess the conditions under which the testing is done.
7. Continuous recordings of the sensor output should be collected.

The test system described in this paper attempted to meet these design criteria. The following sections describe the laboratory apparatus, the laboratory tests that were performed, and the in-barn setting and data acquisition system. The test apparatus was sized and designed for the specific application of testing a bank of 72 electronic sensors from one manufacturer but subsequent users of the protocol will be able to adjust their laboratory apparatus to suit particular needs.

Sensors

Seventy two electronic humidity sensors (TDK Corporation of America, Mount Prospect, IL) were evaluated at Prairie Swine Centre Inc. (PSCI), Saskatoon, Saskatchewan from October 1996 to November 1997. Initial static and dynamic calibrations of the sensors were completed prior to the installation of the sensors in the barn, while final calibrations were conducted after the one year in-barn evaluation. The sensors were installed in a commercial grower/finisher pig room. During this period, sensors were taken back to the laboratory to conduct intermediate static calibrations on a monthly basis. A total of 12 static calibrations and 2 dynamic calibrations were completed.

Sensor treatments

Two types of sensors were used in the study: CHS-UGS and CHS-GSS sensors. Both types are polymer sensors with tandem-type electrodes. The sensors incorporate three basic signal processing circuits with the containing driver, the linearizer, and the temperature compensator fully enclosed in one package. The stated accuracy is ±5% RH, and the guaranteed operating range is 5 to 95% RH for CHS-UGS sensors and 5 to 90% RH for CHS-GSS sensors.

The experiment involved uncoated sensors compared to coated sensors and a comparison of six different filtration treatments, all intended to protect the sensors from the barn environment. The coating treatment involved a pure silicone conformal coating on the electronic portion of the sensors and a spray coating of silicone to the pin and socket connections after the sensors were installed. The unfiltered treatment consisted of the standard packing material. Filters 2 to 6 were proprietary compositions developed by the manufacturer of the sensors.

The factorial experimental design included two sensor types, two coatings (coated and uncoated), and six filter treatments for a total of 24 treatments. Three replicates were involved for a total of 72 test sensors. Treatments 1 to 6 refer to CHS-UGS

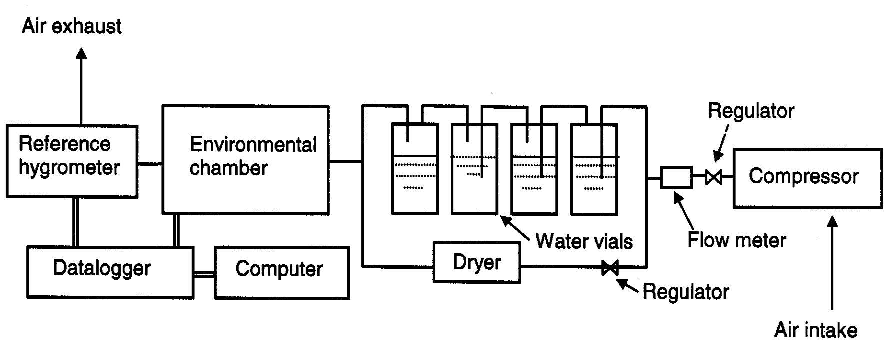

Fig. 1. Schematic diagram of the calibration equipment.

Air flow to the chamber was provided by an air compressor. The air stream was split, one portion passed through a desiccant drier and the other portion bubbled through three water vials in series. A manual valve was used to regulate the ratio of air passing through each branch. It was possible with this system to achieve a steady flow of air at a constant relative humidity between 5 and 85% for an ambient temperature varying between 20 to 25°C.

sensors with coating and filters 1 to 6, while treatments 7 to 12 used uncoated CHS-UGS sensors with filters 1 to 6, respectively. Treatments 13 to 18 used CHS-GSS sensors with coating and filters 1 to 6, and treatments 19 to 24 used uncoated CHS-GSS sensors with filters 1 to 6, respectively. A complete randomized experimental model and SAS procedures (SAS Institute., Cary, NC) were used to analyze for differences among different treatments in terms of sensor accuracy and time response.

Laboratory apparatus

The main components of the laboratory test system for determining static sensor characteristics are shown in Fig. 1. The system was designed to incorporate the best features of the system used by Erdebil and Leonard (1989, 1992).

A bank of 72 electronic humidity sensors was mounted on a horizontal board (180 mm × 260 mm). Outputs from the sensors were directed to three 25-pin cable connectors which were coupled to two networked Datataker DT 100 data loggers (Data Electronics (Aust.) Pty. Ltd., Rowville, Australia). Therefore, the sensors could be connected and disconnected easily from the data logger and moved back and forth between the laboratory chamber and the barn without disturbing the sensors. The environmental chamber into which the sensor board was placed was a shallow plastic container (110 mm × 260 mm × 360 mm) with a removable lid (Fig. 2).

Fig. 2. Sensor arrangement on the electronic board.

The reference hygrometer was a chilled mirror dew-point hygrometer (Model Dew-10 chilled mirror hygrometer, General Eastern Instruments, Watertown, MA) with a stated accuracy of ±0.5°C. A Guildline 9540 digital platinum resistance thermometer (Guildline Instruments Ltd., Smith Falls, ON) with a stated accuracy of ±0.01°C was used to obtain the dry-bulb temperature. By calibrating its output in an ice bath, the thermometer was found to be within the stated accuracy. The accuracy of the reference hygrometer was ±3% in the relative humidity range of 11 to 90%. Its accuracy was checked against standard air samples over saturated salt solutions: lithium chloride (11.3%RH), potassium acetate (23.1%RH), magnesium chloride (33.1%RH), sodium chloride (75.4%RH) and barium chloride (90.0%RH).

The sensors were calibrated as a set rather than one at a time. For static calibrations, the chamber lid was firmly attached and air was introduced to the chamber at the rate of 8.9 L/min. Calibration trials began with air at a relative humidity of 15%. Data were collected for 10% RH increments up to a high relative humidity of 85%. To check for hysteresis effects, the relative humidity levels were then lowered in 10% increments from 85% back to 15%. By this procedure, a total of 15 relative humidity setpoints were included in each calibration. After each adjustment in RH, an interval of 30 min was allowed to achieve stable steady-state conditions within the chamber.

Technical information from the manufacturer of the test sensors indicated that the time for sensors to stabilize after a change in relative humidity would not exceed 20 min. The sensor outputs were recorded every 15 s for 1 min and the average of these readings was plotted against the relative humidity as measured by the reference hygrometer.

Evaluation of the temperature characteristics of the sensors was not incorporated into this experiment. The manufacturer's technical data indicated that the sensors are insensitive to temperature over a range of 5 to 45°C which includes typical barn environments. Temperature was kept between 20 to 25°C in the laboratory.

The same apparatus as described above was used, with modifications, to determine the sensor response time (Fig. 3). For transient response tests, it was not possible to simulate an immediate step change in air relative humidity within the large environmental chamber because of the residence time of air in the chamber. A small syringe tube (18 mm in diameter and 80 mm high) was substituted for the larger chamber and was placed over each individual sensor without removing the sensors

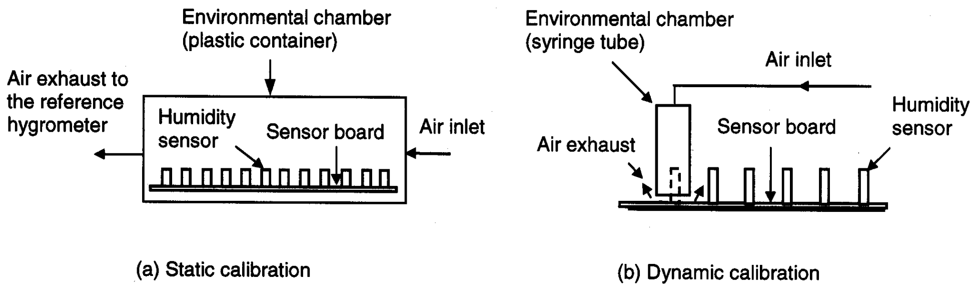

Fig. 3. Sectional sketch of environmental chambers for static and dynamic calibrations.

from the mounting board. The ability to test the sensors without disconnecting them from the mount was judged to be very important in not disturbing accumulations of contaminants after the sensors had been used in the barn.

The chamber size and airflow rate used were a compromise that allowed a near step response of the air relative humidity over the sensor but yet kept air speed over the sensors low enough so as not to disturb the accumulated fouling of the sensors. Air of two different relative humidity levels (low and high levels) was generated by installing and removing pinch clamps located on wet and dry supply lines. The conditioned air entered the top of the chamber via a tube and left the chamber at the bottom. Technical information from the manufacturer indicated that the standard response time for the sensors to provide a 90% response to a change from 30 to 85% RH was 1 min. In these tests, the sensor was first stabilised with dry air for 2 min, then the pinch clamps were adjusted to let the moist air enter the chamber. The sensor output was recorded at 1 s intervals for 2 min or until the sensor stabilised at the new output. The pinch clamps were then adjusted again to introduce dry air back into the chamber and the monitoring continued until a new equilibrium was reached. This procedure was repeated three times for each sensor.

In-barn evaluation of sensors and environmental monitoring

After initial tests in the laboratory, the sensors on the mounting board and within the base of the plastic laboratory chamber, were installed in a grower/finisher room (14.4 m ×11.2 m, 144 pigs) at 1.5 m above the floor in one corner of the room (Fig. 4). Since the sensors were not being used for control purpose, the location within the room was not critical. The location was chosen to minimise effects due to unusual air flow such as from air inlets, heaters, or fans.

The air temperature was measured every 15 min by a Type T thermocouple located close to the data collection area. Only the daily mean temperature was recorded. The mass concentration of the dust in the room air was measured three times a week by sampling air continuously with an air sampler (Gilian AirCon-2, Gilian Instrument Corp., West Caldwell, NJ) through filters held by an open-face air collection cup (Type A/E glass fiber filter, pore size 1 µm, Gelman Sciences, Ann Arbor, MI) and at an air flow rate of 10 L/min. The dust deposition rate was measured continuously and recorded weekly using a modified Gelman Sciences collection cup. Dust particles count was measured once a week with a laser particle counter (Model 237, Met One Inc., Grants Pass, OR) in four ranges: 0.30 to 0.49 µm, 0.50 to 0.99 µm, 1.0 to 4.9 µm, 5.0 µm and larger. Air was sampled continuously by a peristaltic pump (Cole-Parmer Instrument Co., Niles, IL) into a 20 L Tedlar air sampling bag (Cole-Parmer Instrument Co., Niles, IL). Weekly means of ammonia, carbon dioxide and hydrogen sulfide concentrations were measured via Kitagawa colorimetric tubes (Matheson Gas Products, Secaucus, NJ).

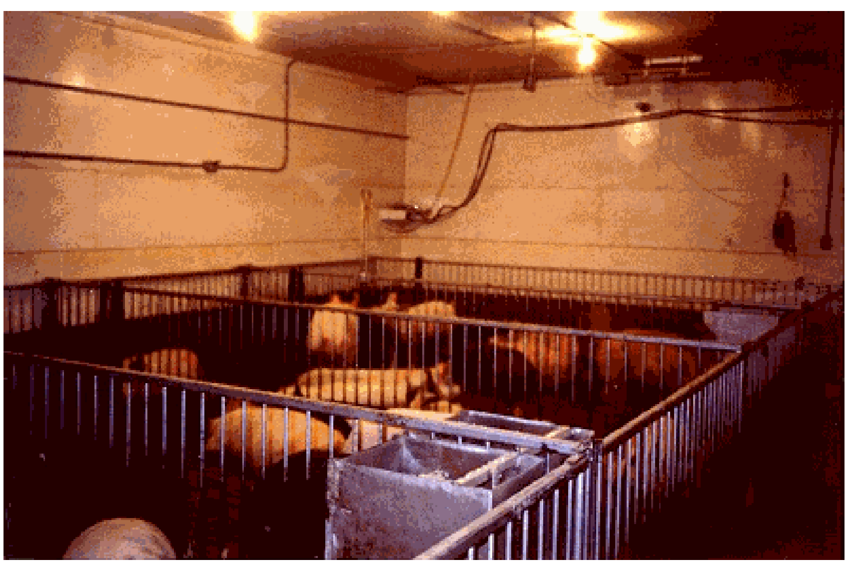

Fig. 4. In-barn sensor installation setup (center above pens).

The entire bank of sensors was removed from the barn on a monthly basis and returned to the laboratory for retesting. Because of the design of the connecting pins, disturbance or loss of accumulations of dust or other fouling from the sensors were avoided. The sensors were operated over a one year period or until failure. No maintenance was applied to the sensors during the test period.

Analysis of sensor characteristics

In this section, further details are given of the various sensor characteristics that were tested.

Accuracy The mean error is generally used to assess the accuracy of humidity sensors (Barber et al. 1989; Chen et al. 1991; Hao and Leonard 1994) even if it cannot provide the sensor accuracy at specific relative humidity levels. The maximum error, which is the largest deviation of any data point from the true value, is also frequently used in engineering practice (Doebelin 1990).

However, this parameter is quite conservative since the error of the sensor may be less than the maximum error under most conditions. In this procedure, the mean errors of sensors were determined by comparison with the reference hygrometer readings for the 15 humidity set points for each static calibration, while maximum errors were also noted for further information.

Other static characteristics Other static characteristics also evaluated from the static calibration data were static sensitivity, linearity, and hysteresis of sensors. The static sensitivity of sensors is defined as the slope of the best-fit straight line on the graph of the test sensor output versus the reference hygrometer readings. A static sensitivity of less than 1.0 indicates that the test sensors underestimate the actual relative humidity. The nonlinearity of the humidity sensors is the maximum deviation of the calibration curve from the reference and is expressed as a percentage of the full-scale output. Hysteresis of the sensor is calculated by the difference between the sensor readings at the same humidity level in the rising and falling processes in each calibration. For each sensor, one value for hysteris is calculated as the mean for all calibration humidity levels and the value is reported as a percentage over the whole measuring scale.

Time response Several characteristics have been defined to evaluate dynamic properties of humidity sensors. Kitano et al. (1984) used delay time, which was defined as the time taken for the output to reach 50% of the desired value of the humidity step input. Erdebil and Leonard (1992) developed a non-dimensional equation to describe the time response of humidity sensors. In the current procedure, the sensors were considered as a first-order instrument and the time constant was used to evaluate dynamic properties of the sensors. The time constant was the time required for a RH sensor to reach 63.21% of the input change (Doebelin 1990).

RESULTS and DISCUSSION

Although the main purpose of this paper is to describe and evaluate a procedure for testing humidity sensors, it is nevertheless instructive to consider the data obtained from testing of specific sensors. The data presented in this section illustrate the kinds of responses that might be detected by the test procedure and the kind of variability that can be expected among different sensors.

Environmental conditions in the barn

The environment observed in the experimental room over the year was typical of swine barns. Sensor 36 (treatment 6) displayed a mean error over the test year of 2.2% after calibration correction. Readings obtained from this sensor were assumed to represent the actual relative humidity in the barn. The relative humidity varied from a low of 22% to a high of 99% with a yearly average of 63%. The temperature varied over a wide range from 11.4 to 30.0°C with a yearly average of 18.0°C (data not available from July 6 to August 6, 1997). The carbon dioxide concentration was between 500 and 4000 ppm and the yearly average was 1928 ppm. Ammonia concentration in the air ranged from 8 ppm in summer to higher than 20 ppm (maximum detectable concentration) in winter. Hydrogen sulfide was not detected for the first five months at a detection level of 0.3 ppm, so it was not measured for the remainder of the experiment. The dust mass concentration ranged from 0.35 to 2.51 mg/m^3 with a yearly average of 1.22 mg/m^3. The dust deposition rate varied from 2900 to 20,300 mg m^{-2} wk^{-1} with an average of 8896 mg m^{-2} wk^{-1}. Over the year, the respirable dust (< 5 μm) particle count ranged from 12 to 61 particles/mL with an average of 36 particles/mL while total dust particle count varied between 14 and 80 particles/mL (average: 45 particles/mL). All observed gas and dust values were highest during the winter when the ventilation rate was low and lowest during the summer when the ambient temperature and ventilation rate were highest. Whereas the air quality in the room was normal for pig buildings, the contamination level constituted challenging conditions for electronic humidity sensors. The sensors on the board were heavily polluted and covered by a thick layer of dust after the experimental period.

Sensor static characteristics

Sensor accuracy drifts The drift in sensor accuracy is one of the more important characteristics to be identified by any test procedure, and the data collected in this experiment illustrate the wide range in accuracy drift that can be expected for electronic humidity sensors. The change in mean error for all 24 treatments is shown in Fig. 5. Each data point is the mean of three replicates. As seen in the figure, several of the sensors failed before the end of the test year, and there was considerable variability in the failure frequency for different treatments.

At the initial calibration, the average mean error of the CHS-UGS sensors in each treatment ranged from 1.9 to 4.6% RH (average: 3.4% RH), while the error ranged from 2.4 to 5.3% RH (average: 3.8% RH) for CHS-GSS sensors. The sensors were within or close to their stated nominal accuracy of ±5% RH prior to installation in the barn. There was no statistical difference among all treatment combinations at this time (P>0.05).

As seen in Fig. 5, the best sensor treatment resulted in a mean error drift over one year of 6% RH, whereas most sensors had accuracy drifts exceeding 10% RH and several much higher than that. These data indicate that only a few of the sensor treatments would be acceptable for use in a ventilation control system. The error of all sensors increased gradually over time, which indicated that the barn environment had a significant influence on sensors (Fig. 5). In retrospect, it would have been interesting to place one or more sensors in a clean environment to test for non-environmentally induced sensor drift.

Since the CHS-UGS sensors (treatments 1 to 12) outperformed CHS-GSS sensors (treatments 13 to 24), and many of the CHS-GSS sensors failed completely, for the sake of brevity the following discussion relates only to the CHS-UGS sensors. Table 1 shows the mean and maximum errors for the 12 treatments involving CHS-UGS sensors at the initial, middle, and final calibrations. In the final calibration for CHS-UGS sensors, the average mean errors of each treatment varied from 8.0 (treatment 6) to 26.5% (treatment 5). There was no significant difference among coating and filter treatments. However, the factorial design analysis showed significant differences among the combined effects of coating and filtering treatments. Treatment 6 had a significantly lower error than nine of the other treatments (P<0.05).

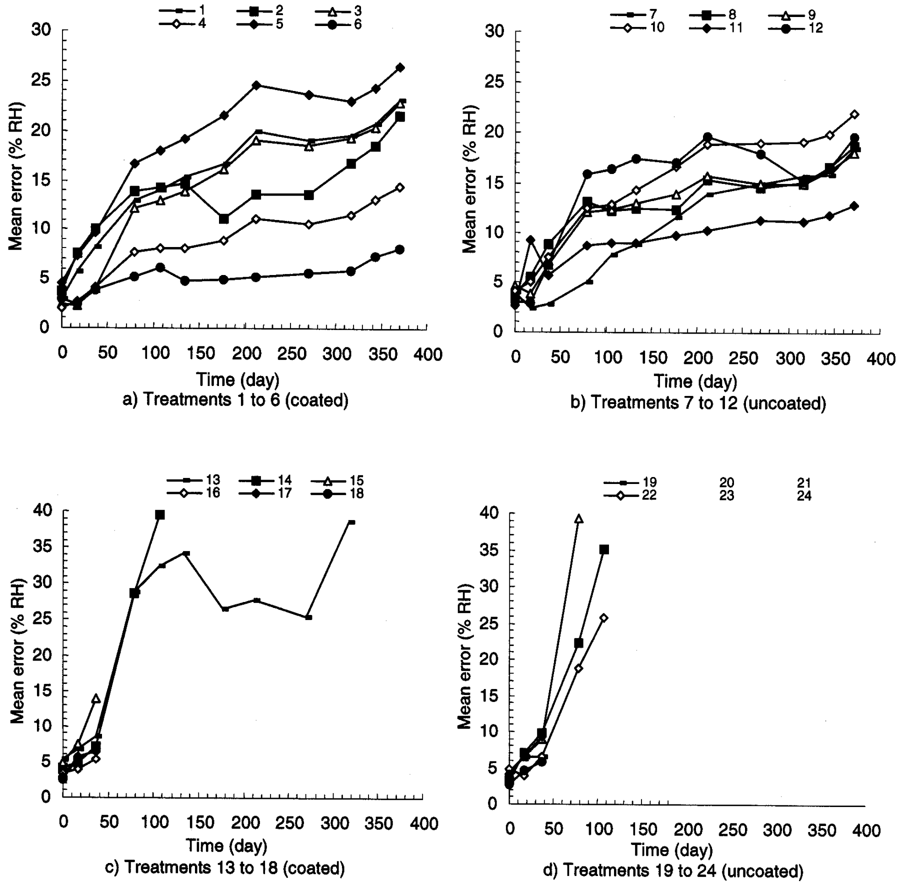

Fig. 5. Accuracy drift of CHS-UGS and CHS-GSS sensors over the year.

To better compare the drift in sensor accuracy, calibration data are shown for two sensors from the initial, middle, and final calibrations (Fig. 6). For each sensor, data are given for both the rising and the falling RH calibrations. It is clear that the test procedure was able to distinguish between the two different sensor performances and sensor treatment 6 was identified as the best treatment.

Other static characteristics Table 2 shows the results of sensor static sensitivity, linearity, and hysteresis over the experimental year for the treatments involving coated CHS-UGS sensors. For most sensors, the static sensitivity gradually decreased with time. This result indicates that the test sensors generally underestimated the actual relative humidity and the extent of the underestimation increased with time. Designers of control systems using these sensors would need to be aware of this sensor characteristic and perhaps compensate through adjustments to RH setpoint. Treatment 6 sensors had the highest sensitivity.

The nonlinearity of the sensors increased with time. In the initial calibration, nonlinearity was in the range of 3.9 to 7.3% over the entire RH range. After a year, the nonlinearity had increased into the range from 13.4 to 44.2%. Treatment 6 sensors had the lowest nonlinearity increase of 8.0%.

The maximum hysteresis for all CHS-UGS sensors ranged from 0.7 to 1.6% at the first calibration and from 6.9 to 16.1% at the last calibration. Treatment 2 sensors had the lowest hysteresis value.

Table 1. Mean and maximum errors for TDK CHS-UGS sensors.

Time (day)	Error (%RH)	Treatment											
		1	2	3	4	5	6	7	8	9	10	11	12
0	Mean	2.9	3.7	2.4	1.9	4.4	2.9	4.0	3.7	4.6	4.1	2.7	3.0
	(SD)	(1.1)	(2.0)	(1.2)	(1.0)	(1.7)	(1.4)	(1.6)	(1.8)	(1.8)	(1.6)	(0.9)	(1.4)
	Max.	4.4	6.5	4.3	3.5	6.6	4.9	5.7	6.1	6.8	6.3	3.9	4.9
177	Mean	16.6	11.1[1]	16.1	8.8	21.5	4.9	11.5	12.4	13.9	16.7	9.7	17.0[1]
	(SD)	(6.5)	(3.5)	(6.0)	(3.3)	(7.4)	(1.6)	(4.4)	(5.0)	(5.8)	(6.0)	(3.7)	(7.5)
	Max.	22.8	15.2	21.8	12.5	28.7	7.4	15.6	18.0	21.0	22.2	13.9	24.2
371	Mean	23.1	21.5	22.8	14.5	26.5	8.0	18.5	18.7	18.1	22.0	12.8	19.6[2]
	S.A.[3]	ab	abc	abc	bcd	a	d	abc	abc	abc	abc	d	abc
	(SD)	(11.0)	(7.7)	(9.6)	(5.2)	(11.6)	(3.0)	(9.1)	(6.8)	(8.7)	(10.4)	(6.1)	(10.3)
	Max.	35.2	29.0	34.1	20.7	39.8	12.1	29.1	26.0	28.0	33.8	20.2	31.7
	S.A.[3]	ab	abc	abc	bcd	a	d	abc	abcd	abc	abc	cd	abc
Average		14.8	13.3	13.7	8.5	18.2	5.2	10.7	12.4	12.2	14.3	9.2	15.3

[1]The data from this calibration are average errors of two sensors since one sensor failed.
[2]The data from this calibration are errors of the only sensor left; the other two sensors had failed.
[3]S.A.: statistical analysis. Means or maximums within a line characterized by the same letter are not significantly different ($P > 0.05$).

Table 2. Static characteristics of CHS-UGS sensors.

Characteristics	Time (day)	Treatment					
		1	2	3	4	5	6
Static sensitivity (unitless)	0	0.95	0.96	1.00	0.98	0.98	0.98
	177	0.82	0.97	0.89	0.99	0.77	1.15
	371	0.62	0.76	0.72	0.86	0.63	0.98
Nonlinearity (%)	0	4.9	7.2[1]	4.8	3.9	7.3	5.4
	177	25.3	16.9	24.2	13.9	31.9	8.2
	371	39.1	32.2	37.9	23.0	44.2	13.4
Maximum hysteresis (%)	0	0.7	1.6	1.0	1.4	1.0	0.8
	177	4.8	5.1	5.9	7.5	5.2	11.7
	371	11.0	6.9	14.0	9.2	16.1	9.1

[1]The data from this calibration are average values of two sensors since one sensor failed.

Sensor time response properties

Figure 7 shows a typical dynamic response of the sensors (sensor 36 in treatment 6). Data are given as sensor output of the same sensor at the beginning of the experiment and after the one-year period in the barn.

At the initial calibration, all sensors (including CHS-GSS sensors) achieved a stable output within 2 min for a rising humidity step process and within 32 s for a falling step process. However, at the final calibration, the time response for the rising process became much slower as the sensors became fouled and all sensors could not reach a stable output value within 2 min. On the other hand, the sensor reading could still reach the final value within 32 s in a falling step process. To simplify the analysis, for rising processes of both initial and final calibrations, the sensor reading at 2 min was chosen as the approximate final value to calculate the time constant. For the falling humidity step input, the final sensor reading at 60 s was chosen as the final relative humidity value in determining the time constant. Therefore, the time constant was the time required to reach 63.21% of the 2 min sensor output for a rising process or 60 s sensor output for a falling process.

Tables 3 and 4 provide a summary of the initial and final time response results for coated CHS-UGS sensors. The time response of the sensors for a falling humidity change was quite stable throughout the year in the barn considering time constants of 1.9 to 4.8 s at the beginning and 2.6 to 6.8 s at the end. At the final calibration, no significant difference existed among the sensors ($P>0.05$). For the rising process, the time constant increased from a range of 2.2 to 4.0 s at the beginning to 6.9 to 25.6 s at the end. Sensors in treatment 6 responded significantly faster than eight of the other treatments ($P<0.05$) at the year-end tests.

For CHS-GSS sensors in the falling process of the initial calibration, most of the sensors reached 95% of their final value in 6 to 34 s, but five sensors did not reach a stable final reading within 2 min. The time constant varied in the range of 2.4 to 18.6 s for the falling process and 6.5 to 18.3 s for the rising process.

Discussion of the experimental procedure

The experience gained in this project demonstrated the necessity for testing new models of humidity sensors under both laboratory and barn conditions. The initial laboratory calibration results for all 72 sensors were satisfactory and the CHS-GSS sensors did not show any difference compared to CHS-UGS sensors. However, after their barn exposure, all sensors demonstrated increased errors and the two types of sensors demonstrated markedly different performances. Testing only in the laboratory would fail to distinguish among alternative sensors with quite different in-barn performances.

Because of the poor air quality in livestock barns, the reference hygrometer needs to be kept in clean conditions. Whereas it may be possible to protect the reference hygrometer in some enclosure and to clean the air before it reaches the hygrometer sensor, the current procedures demonstrate a practical alternative. By keeping the reference hygrometer in the laboratory, it is well protected from any contamination and its accuracy can be maintained over time. With careful design of the mounting boards, it is possible to remove sensors from the in-barn test environment without disturbing the accumulation of dust and other contaminants from the test sensors. Some concern may arise over the biosecurity risks of repeated re-entry of experimental apparatus into a swine barn and this risk needs to be assessed and dealt with on an individual case basis. In this experiment, the sensor board was kept within the base of the plastic environmental chamber and the cover was replaced during transport between the barn and

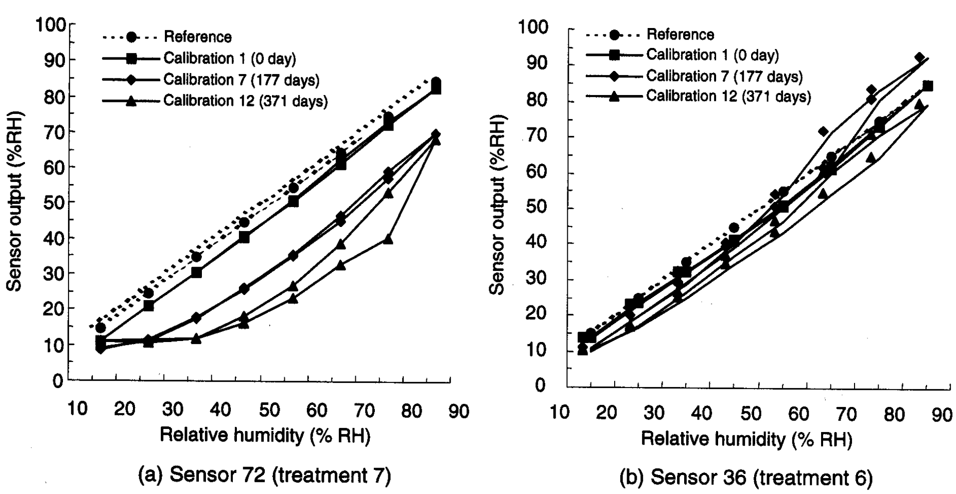

Fig. 6. Accuracy drift of a treated and an untreated sensor over the year.

Table 3. Initial time response calibration for TDK CHS-UGS sensors.

Treatment No.	Sensor output (%RH)				Time constant (s)		
	Rising[1]		Falling[1]				
	Initial[2]	Final[2]	Initial	Final	Rising	Falling	Average
1	8	87	88	7	3.6	4.8	4.2
2	6	66	67	6	4.0	3.3	3.7
3	6	76	76	6	2.6	2.1	2.4
4	6	73	73	6	3.4	3.3	3.3
5	6	69	69	7	3.0	2.0	2.5
6	6	73	73	6	2.2	1.9	2.0

[1]Rising or falling process.
[2]Initial or final value.

Table 4. Final time response calibration for TDK CHS-UGS sensors.

Treatment No.	Sensor output (%RH)				Time constant (s)		
	Rising[1]		Falling[1]				
	Initial[2]	Final[2]	Initial	Final	Rising[4]	Falling[4]	Average[4]
1	10	46	50	10	25.6 a	4.8 a	15.2 a
2[3]	7	49	53	8	23.7 a	6.8 a	15.2 a
3	8	52	54	8	20.1 a	5.7 a	12.9 ab
4	8	55	56	8	8.4 b	5.3 a	6.9 bc
5	8	31	32	8	25.0 a	2.6 a	13.8 a
6	8	72	75	7	6.9 b	4.9 a	5.9 c

[1] Rising or falling process.
[2] Initial or final value.
[3] Two sensors left and one sensor failed.
[4] Values within this column followed by the same letter are not significantly different ($P > 0.05$).

the laboratory. The outside of the plastic case was thoroughly disinfected before each re-entry to the barn.

The procedures used in this project provided accurate and reliable observations regarding various static and dynamic characteristics of the electronic humidity sensors when submitted to a real barn environment. It was possible to select one treatment (treatment 6, coated and filter 6) from among 24 treatments that would provide suitable performance for use in a control system.

The laboratory calibration set-up and procedures were practical and adequate to evaluate various static and dynamic RH sensor characteristics. Although the time response calibration method may not provide a true humidity step change, it provided enough data to describe the sensor time constant and settling time with sufficient sensibility to quantify the impact of barn exposure on sensor response. Therefore, the results can be used to compare time response properties of sensors with different treatments.

In terms of the in-barn evaluation time, one year appears to be the minimum suitable period to evaluate humidity sensor accuracy. A four-month in-barn exposure was enough to identify sensors that were particularly sensitive to the barn environment and that failed due to excessive errors or complete sensor failure. However, some sensors performed well for up to 9 months and then demonstrated unacceptable accuracy drift. The data in Fig. 5 suggest that the error for some of the sensors was still increasing; hence, one year is recommended as a minimum evaluation period.

In this experiment, the sensors were recalibrated every month. The accuracy drift of the 72 electronic humidity sensors was successfully monitored with this calibration frequency. For many sensors, the increase in error was rapid during the early stage of the in-barn exposure but, for most sensors, further drift was very gradual for the later stages. A more economical procedure may be to conduct the first two in-barn calibrations every two weeks, then once a month until six-months, then every two or three months thereafter.

A reliable evaluation of humidity sensors requires that a minimum of 3 sensors of one type be tested. This project demonstrated that there is sufficient variability among sensors of the same type to cast doubt on the reliability of results from the testing of only one sensor. One sensor in treatment 11 showed a large error after only 17 days in the barn, whereas the other two sensors of the same type worked very well with mean errors of 6.1 and 6.5% at the

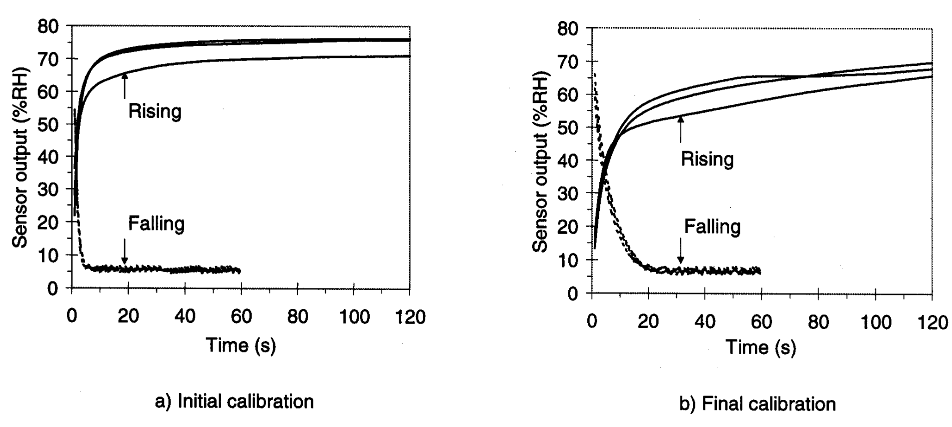

Fig. 7. Output of sensor 36 for the initial and final time response calibration.

end of the year. In treatments 2 and 12, some sensors failed after 6 to 9 months while other sensors in the same treatment still worked after one year.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. The RH sensor evaluation procedure combining sensor laboratory calibration and in-barn exposure proved to be effective and practical for assessment of RH sensor performance in livestock buildings. This procedure is applicable for selecting RH sensors for long term relative humidity monitoring and control in livestock buildings.
2. With this procedure, 72 TDK RH sensors with different coating and filtering treatments were successfully evaluated in a swine building. The results confirmed that a silicone coating combined with a TDK experimental filter effectively protected the RH sensor from the barn environment such that accuracy was maintained over a year with no sensor maintenance or cleaning.
3. Testing sensor characteristics only in the laboratory will not provide accurate predictions about in-barn performance. The in-barn evaluation period should be appropriately planned according to the expected service life of the sensors, but a period of one year seems to be minimal.
4. The reference hygrometer should be kept within the laboratory to maintain its accuracy. The frequency of removal of sensors for laboratory calibration can be varied from every two weeks at the beginning of the barn evaluation to every 2 or 3 months at the end of the barn evaluation period.
5. Sensors of the same type were shown to vary in terms of accuracy drift under barn conditions. Therefore, it is recommended that a minimum of three sensors of any one type should be tested.

ACKNOWLEDGMENTS

The authors acknowledge the funding provided for this project by the Natural Sciences and Engineering Research Council of Canada, Agriculture and Agri-Food Canada, and TDK Corporation of America. The project was initiated by Drs. Y. Zhang and A. Tanaka and their foresight in starting the project and obtaining funding is appreciated.

REFERENCES

Barber, E.M. and D. Gu. 1989. Performance of an aspirated psychrometer and three hygrometers in livestock barns. *Applied Engineering in Agriculture* 5(4):595-599.

Barber, E.M., D. Gu and H.L. Classen. 1989. Development and testing of low-maintenance aspirated psychrometers for continuous use in livestock barns. *Applied Engineering in Agriculture* 5(4):601-610.

Chen, C.C., C.T. Tsao and C.C. Lai. 1991. The evaluation of the performance on the electronic relative humidity sensor. *Journal of Agricultural Research of China* 40(1):71-89.

Chen, C.C. and C.T. Tsao. 1992. Development and test of a standard calibration device for relative humidity sensors. *Journal of Agricultural Research of China* 41(4):371-381.

Doebelin, E.O. 1990. *Measurement Systems: Application and Design*, 4th edition. New York, NY: McGraw-Hill Publishing Company.

Erdebil, I. and J.J. Leonard. 1989. Apparatus for testing of humidity sensors for animal environments. ASAE Paper No. 89-4073. St. Joseph, MI: ASAE.

Erdebil, I. and J.J. Leonard. 1992. Laboratory testing of humidity sensors for use in animal environments. *Canadian Agricultural Engineering* 34(3):267-271.

Hao, H. and J.J. Leonard. 1994. Performance of thin-film humidity sensors in poultry and swine environments. *Canadian Agricultural Engineering* 36(4):273-277.

Joncas, R. and J. Noreau. 1997. Évaluation de sondes d'humidité pour contrôler l'ambiance dans les poulaillers. Rapport final du projet no.: R-1105-94-091. Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec.

Kitano, M., H. Eguchi and T. Matsui. 1984. Analysis of static and dynamic characteristics of humidity sensors. *Biotronics* 13: 11-28.

Ross, C.C. and W.D.R. Daley. 1990. Capacitive relative humidity sensing in animal housing. ASAE Paper No. 90-4022. St. Joseph, MI: ASAE.

Ross, C.C., W.D.R. Daley and M.S. Smith. 1988. Sensor performance in monitoring and control system for animal housing. In *Livestock Environment III*, 224-231. Publication No. 01-88. St. Joseph, MI: ASAE.

Vosper, F.C. and D.S. Bundy. 1979. Dew-point sensing for humidity measurement in confinement housing. ASAE Paper No. 79-4011. St. Joseph, MI: ASAE.

White, J.M. and J.M. Allison. 1987. Microcomputer control of the environment of a production broiler. ASAE Paper No. 87-3008. St. Joseph. MI: ASAE.