Performance of five commercial electronic humidity sensors in a swine building

H. Guo[1], S.P. Lemay[2], E.M. Barber[3] and L. Zyla[2]

[1]*Department of Agricultural and Bioresource Engineering, 57 Campus Drive, Saskatoon, Saskatchewan, Canada S7H 5A9;* [2]*Prairie Swine Centre Inc., P.O. Box 21057, 2105 8th Street East, Saskatoon, Saskatchewan, Canada S7H 5N9; and* [3]*College of Agriculture, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7H 5A5*

Guo, H., Lemay, S.P., Barber, E.M. and Zyla, L. 2004. **Performance of five commercial electronic humidity sensors in a swine building**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **46**: 5.1-5.9. Five commercial electronic relative humidity (RH) sensors (A to E), each with three replicates, were evaluated in a swine barn for one year. The sensors were calibrated in a laboratory before the in-barn trial and were brought back to the laboratory periodically for four intermediate and final calibrations. All of the sensors were affected by the corrosive barn environment. None of the sensors could maintain their stated accuracy after one year. Two sensors, A and C, each had one failed replicate. Sensor A also showed a malfunction at 15% RH. After one year, the sensor errors varied from 6.3% RH (sensor B) to 17.3% RH (sensor A) over the 15 to 85% RH range. Sensor B was significantly more accurate than sensors A and E ($P<0.05$). However, over the 55 to 85% RH range, sensor A had the lowest error of 2.8% RH while sensor B had the largest error of 8.9% RH. Sensor A was significantly better in accuracy than sensors B, D, and E ($P<0.05$) over this reduced range. The linearity of all sensors was impaired while sensor static sensitivity and hysteresis were relatively stable. One year appears to be the minimum period for evaluating RH sensors for use in barns; a shorter period would fail to determine sensor malfunction or failure. The sensor should be calibrated periodically after one month in-barn and once every three to four months thereafter. Because variations existed among individual sensor units of the same sensor type, three replicates are suggested to get reliable evaluation results. Because sensor accuracy varied widely at different humidity levels, a humidity sensor used for control purposes should be chosen according to its accuracy over the whole measuring range (15 to 85% RH) as well as the control range (55 to 85% RH).

Trois exemplaires de cinq modèles commerciaux différents de senseurs électroniques (A à E) d'humidité relative (HR) ont été évalués dans une porcherie durant une période d'un an. Les senseurs ont été calibrés en laboratoire avant le début des essais en porcherie. Ils ont également été ramenés au laboratoire périodiquement à des fins de calibration intermédiaire (à quatre reprises) et finale. Tous les senseurs ont été affectés par l'environnement corrosif de la porcherie. Aucun senseur n'a pu maintenir le niveau de précision prévu par le manufacturier après une année. Pour chacun des modèles de senseurs A et C, un des trois exemplaires n'a pu terminer l'essai en état de marche. De plus le senseur A ne fonctionnait pas adéquatement à 15% HR. Après un an, l'erreur des senseurs variait de 6,3% HR (senseur B) à 17,3% HR (senseur A) sur la plage de 15 à 85% HR. Le senseur B s'est avéré plus précis que les senseurs A et E ($p<0,05$). Cependant, sur la plage de 55 à 85% HR, le senseur A a présenté l'erreur la plus faible(2,8% HR) tandis que le senseur B avait l'erreur la plus grande de 8,9% HR. Le senseur A avait une précision supérieure comparativement aux senseurs B, D et E ($p<0,05$) sur cette plage réduite de HR. La linéarité de tous les senseurs a été affectée alors que la sensibilité statique et l'hystérèse étaient relativement stables. Un an semble être la période minimale pour l'évaluation de senseurs HR utilisés dans les porcheries, une période plus courte ne permettrait pas de déterminer le mauvais fonctionnement ou le bris des senseurs. Les senseurs devraient être calibrés périodiquement, après un mois dans la porcherie et une fois tous les trois ou quatre mois par la suite. En raison des variations observées entre des exemplaires différents d'un même type de senseur, au moins trois répétitions sont suggérées pour obtenir une évaluation fiable de la performance des senseurs HR électroniques. De plus, puisque la précision des senseurs varie grandement à différents niveaux d'humidité, un senseur d'humidité utilisé pour le contrôle d'équipement doit être choisi selon sa précision sur toute la plage de mesure (15 à 85% HR) et aussi sur la plage de contrôle (55 à 85%HR).

INTRODUCTION

Relative humidity (RH) is an important indicator of air quality in livestock buildings. Extremely low or high humidity levels can cause discomfort to animals and workers and can reduce building longevity. Humidity control also dictates building energy consumption during heating seasons. Therefore, RH monitoring and control is very important for livestock buildings, especially in cold regions such as the Canadian Prairies. However, due to the corrosive environment in livestock barns, RH sensors are liable to be affected. Continuous RH monitoring and control is limited by the availability of sensors that are reliable, economical, low maintenance, and with long-term integrity. Incorporation of RH data into environmental controllers has not been widely accomplished in livestock buildings. As new RH sensor models become available, it is essential to evaluate the sensor performance under real barn conditions before relying on the sensors as part of the monitoring and control systems.

Various RH sensors have been tested using different approaches in livestock buildings. Sensors tested varied from aspirated psychrometers to electronic sensors such as saturated-salt dew point sensors, thin film polymer sensors, aluminum oxide sensors, etc. (Vosper and Bundy 1979; White and Allison 1987; Ross et al. 1988; Ross and Daley 1990; Erdebil and Leonard 1989, 1992; Chen et al. 1991; Chen and Tsao 1992; Hao and Leonard 1994; Barber and Gu 1989; and Barber et al. 1989). Recently, Eigenberg et al. (2002) tested six units of a commercial thermistor RH sensor in a cattle barn for seven months. The sensor performance was acceptable but additional complicated construction, calibration, and temperature measurement were needed to convert the voltage

Table 1. Technical information about the tested RH sensors.

Characteristics	Tested RH sensors				
	A[#]	B	C	D	E
Technology	Polymer capacitive	Thin film capacitive	Bulk polymer capacitance	Plastfoil polymer capacitance	Polymer capacitance
Operating range (%RH)	10 - 90	0 - 100	0 - 100	12 - 90	10 - 95
Accuracy (%RH)	±3 (25°C)	<±3 (10 - 90%)	<±3	±2	±2 (20 -95%)
Linearity (%RH)	-	-	<±3	-	<±2
Hysteresis	-	-	±1	-	<3%[†]
Response time (90% of final value)	-	-	-	-	<15 s (0 - 95%)
Stability (%RH/year)	-	±1	-	-	-
Operating temperature (°C)	-	-10 - 60	-35 - 55	-15 - 50	0 - 70
Approximate price (Can$/each)	78	225	200	265	195

[#] Requires an interface ($567) to operate
- Not available or manufacturer did not choose to give related information
[†] Allow 30 min for stabilization (10 to 80% RH)

output to relative humidity. These studies tested a limited number of RH sensors ranging from one to four. Most sensors had only one replicate. Testing methods varied greatly from testing in a laboratory only to operating the sensors in barns and readings were compared periodically with a reference RH instrument. Field testing periods varied from six weeks to one year. Hence, the sensor performance in real barns over a relatively long period of service life could not be predicted by these experimental results.

Lemay et al. (2001) developed a procedure to evaluate RH sensors in real livestock building conditions. This procedure combined laboratory testing and in-barn evaluation. The tested RH sensors operated continuously in a swine building but were periodically brought to the laboratory for calibration of the various static and dynamic properties. Two polymer electrode impedance RH sensors, with 12 different coating and filtering treatments and with three replicates of each treatment, were evaluated. The test results of Lemay et al. (2001) 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).

The objective of the current study was to evaluate five promising commercial electronic RH sensors in a swine barn using the procedure developed by Lemay et al. (2001).

MATERIALS and METHODOLOGIES

Five commercial RH sensors, A to E (Sensor models are not given due to confidentiality agreement between PSCI and the manufacturers) from different manufacturers were evaluated in a swine barn at Prairie Swine Centre, Inc. (PSCI), Saskatoon, Saskatchewan. The evaluation followed the RH sensor evaluation procedure developed by Lemay et al. (2001) but dynamic calibration was excluded.

Tested RH sensors

With three replicates for each of the five sensors, 15 sensor units were evaluated. Table 1 summarizes the sensor manufacturers' specifications.

According to the information provided by the manufacturer, sensor A had been tested for swine and poultry environments. A special dip was used to protect the electronic components and a filter was provided to protect the sensor. However, the manufacturer stated that when sensor A is exposed to ammonia or other corrosive agents, the sensor might degrade and become less accurate. The electronic circuit of sensor B was contained inside a hermetically sealed enclosure and the sensor was protected from contamination with a 0.5 μm membrane filter. The manufacturer of sensor C claimed that this sensor was designed for working in a harsh environment and was not affected by condensation, fog, high humidity, or contaminants. According to the manufacturer, sensor D was a capacitive sensor and was designed for use in livestock buildings. Special protections were provided to the sensor element, which is plastfoil coated on the sides by a thin layer of gold, as well as to the electronic components. The manufacturer of sensor E also claimed good resistance of the sensor to pollutants.

Laboratory calibrations

Periodic static calibrations for the sensors were performed in the PSCI laboratory during the one year, in-barn evaluation. Also, initial and final calibrations were completed before and after the in-barn trials. During the experimental period, sensors were taken back and forth from the barn to the laboratory for four intermediate calibrations.

The laboratory environmental chamber calibrating system was the same as used by Lemay et al. (2001). It was capable of achieving a steady flow of air at a constant RH between 5 and 85% with ambient temperature from 20 to 25°C. Sensors A to E were randomly divided into three groups of five sensors, one from each kind from A to E, so as to accommodate the limited space in the chamber. All the sensors in one group were calibrated simultaneously.

A reference chilled mirror dew-point hygrometer (Model Dew-10, General Eastern Instruments, Watertown, MA) with an accuracy of ±0.5°C, was used to measure the reference RH to which the sensor readings were compared. This hygrometer was calibrated against five saturated salt solutions: lithium chloride (11.3% RH), potassium acetate (23.1% RH), magnesium

Table 2. Environmental conditions in the swine room.

	Relative humidity (%)	Air temperature (°C)	CO_2 (ppm)	NH_3 (ppm)	DMC[1] (mg/m^3)	DD[2] (mg/wk per m^3)	RDC[3] (count/mL)	TDC[4] (count/mL)
Mean	60	18.6	1124	N/A	1.36	9119	53	63
Minimum	12	11.2	300	5	0.19	1100	13	13
Maximum	99	26.3	2500	28	2.92	38,300	138	143

[1]Dust mass concentration; [2]Dust deposition rate; [3]Respirable dust count (<5 µm); [4]Total dust count

chloride (33.1% RH), sodium chloride (75.4% RH), and barium chloride (90.0% RH). A digital platinum resistance thermometer (Guildline 9540, Guildline Instruments Ltd., Smith Falls, ON) with an accuracy of ±0.1°C, was used to measure the dry bulb temperature.

The calibration started at 15% RH and increased to 85% RH in steps of 10% RH increments. To check for hysteresis characteristics, the humidity level was then dropped back to 15% RH in steps of 10% RH increments. Thus, fifteen RH set points were included for each calibration. For each humidity level adjustment, thirty minutes were given to allow the sensor output to stabilize. Then, sensor readings were collected every 15 s for 1 min with a datalogger (Datataker DT 100, Data Electronics (Aust.) Pty. LTD., Rowville, Australia). The average of the four readings was plotted against that of the reference hygrometer.

The first intermediate calibration was completed 39 days after the in-barn trial and then once every two to three months (except one missing calibration between 115 to 249 days). A randomized complete block model was adopted and the SAS GLM (SAS Institute, Cary, NC) procedure was used to analyze mean differences among the five sensors for each calibration.

Sensor in-barn evaluations and environmental monitoring

The in-barn sensor trial was conducted in a grower/finisher room at the PSCI. All the sensors were randomly mounted on a board in the southeast corner of the room at 1.8 m above the floor. Outputs from the sensors were collected by Datataker DT 100 dataloggers. The RH data was sampled every 15 min with hourly means stored. Sensors were removed from the room temporarily whenever the room was cleaned by high pressure water. Before each calibration, the dust on the sensor filters was removed by compressed air and the wires were cleaned. Once a sensor failed, it was removed and not replaced.

Air quality in the room was monitored near the sensor board. The RH was measured by the tested sensors and the readings were corrected by the most recent calibrations. Air temperature was measured by a Type T thermocouple. It was sampled every 15 min with the daily mean recorded by the datalogger. Dust mass concentration was sampled continuously and recorded three times a week. An air sampler (AirCon-2, Gilian Instrument Corp., West Caldwell, NJ) was used to draw the air through filters held by open-face air collection cups (Type A/E glass fiber filter, pore size 1 mm, Gelman Sciences, Ann Arbor, MI) with a flow rate of 10 L/min. Dust deposition rate was measured continuously and recorded weekly by using a modified Gelman Sciences collection cup. Air was sampled by a peristaltic pump (Cole-Parmer Instrument Corp., Niles, IL) into a 20-L air sampling bag every week. Then weekly means of ammonia, carbon dioxide, and hydrogen sulfide concentrations were measured by colorimetric tubes (Kitagawa, Matheson Gas Products, Secaucus, NJ). Dust count was measured once a week with a Laser Particle Counter (Met One Model 237, Met One Inc., Grants Pass, OR).

Sensor characteristics analysis

Sensor static characteristics were evaluated based on the calibration results. The mean and maximum errors (absolute difference of the sensor reading from the reference hygrometer) from 15 to 85% RH (the whole calibration range) and 55 to 85% RH (the normal control range in livestock buildings) were used to evaluate the sensor accuracy.

Other static characteristics such as non-linearity, static sensitivity, and hysteresis of sensors were also evaluated. The static sensitivity of the sensors is defined as the slope of the calibration curves. The non-linearity of the RH sensors is the maximum deviation of the calibration curve from the reference, expressed as a percentage of the full-scale output. Since the operation ranges of the five sensors were not the same (Table 1), 15 to 85% RH was taken as the operation scale to calculate and compare the nonlinearity of the sensors. Sensor hysteresis was calculated from the difference between the sensor readings at the same RH level during the increasing and decreasing processes in a calibration, and was expressed as a percentage over the whole measuring scale.

RESULTS

Environmental conditions in the barn

According to the calibration results over one year, replicate 3 of sensor B (mean error ≤0.7%) had the lowest error among all sensors. Therefore, the readings of this sensor, with the recent calibration correction, were used to give the actual RH in the experimental room.

The environment monitoring results are given in Table 2. The results indicated that the sensors were submitted to a harsh environment. All the observed gas and dust values were high in winter and low in summer. These conditions were quite similar to those observed by Lemay et al. (2001) and are typical for commercial swine barns but constituted a challenge for RH sensors.

Sensor accuracy analysis Table 3 gives the average mean and maximum errors of three (or two when one failed) replicates of the five sensors from 15 to 85% RH for four calibrations. It was observed that sensor accuracy varied at various RH levels. To analyze sensor errors over the general RH range encountered in

Table 3. Mean and maximum error of the RH sensors over the 15 to 85% RH range.

Calibration (Time in barn)	Error (% RH)	Sensor				
		A	B	C	D	E
1 (0 day)	Mean*	6.9 a	3.2 c	4.3 bc	4.9 b	8.1 a
	(SD)	(2.5)	(2.0)	(4.1)	(3.1)	(4.7)
	Maximum	13.2	7.7	16.1	11.1	16.8
2 (39 days)	Mean	9.6 a	6.7 a	9.9 a	6.7 a	8.4 a
	(SD)	(12.3)	(4.1)	(20.3)	(2.9)	(4.9)
	Maximum	86.6	15.5	87.2	11.7	16.8
4 (249 days)	Mean	5.2** b	7.2 b	4.9** b	6.8 b	10.2 a
	(SD)	(3.2)	(4.0)	(2.4)	(3.0)	(6.2)
	Maximum	12.2	14.6	9.0	12.6	20.0
6 (365 days)	Mean	17.3** a	6.3 c	7.6** c	8.7 bc	11.5 b
	(SD)	(28.3)	(3.2)	(3.4)	(4.3)	(6.8)
	Maximum	88.7	11.6	13.0	20.3	21.1

* Mean errors within a line followed by the same letters are not significantly different (P>0.05).
** Data of two replicates because one replicate failed.

livestock buildings, Table 4 gives the average mean and maximum errors of each sensor from 55 to 85% RH for the same calibrations.

Initial sensor calibration For the initial calibration as shown in Table 3, the mean errors over the range of 15 to 85% RH varied from 3.2% RH (sensor B) to 8.1% RH (sensor E).

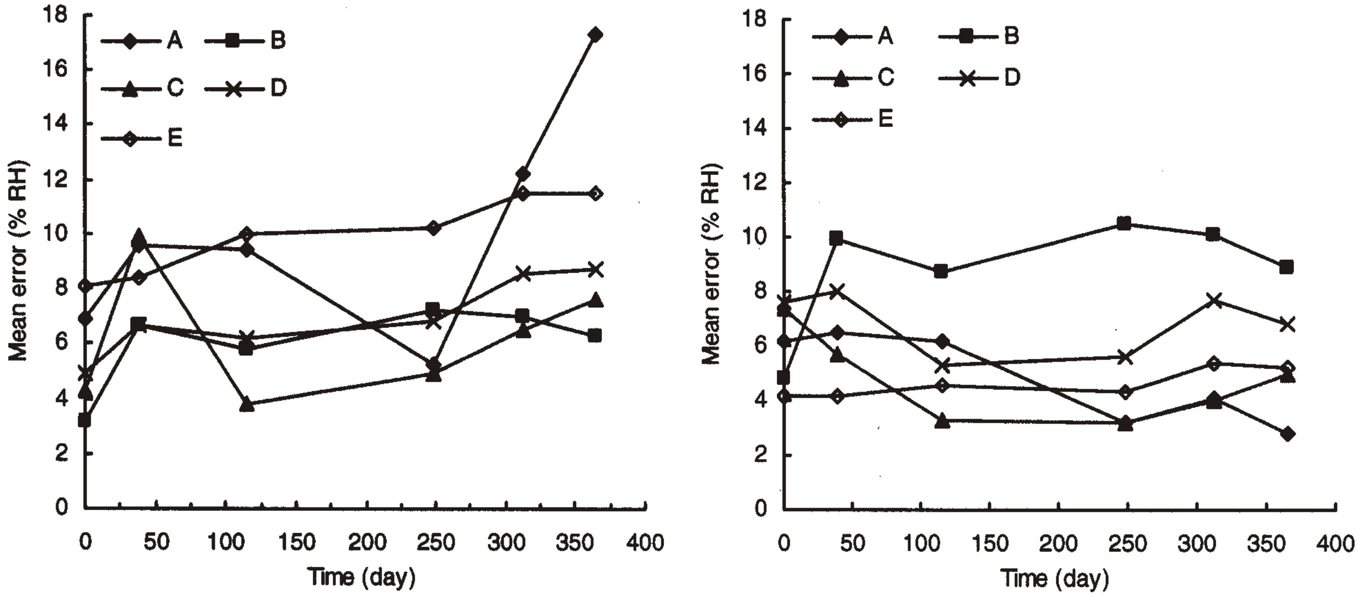
Most sensors were outside the range of their stated accuracy of ±2 to 3% RH. Sensors A and E had errors greater than ±5% RH. Sensor B had the lowest error and was significantly more accurate than sensors A, D, and E (P<0.05). The maximum errors of all sensors were between 7.7% RH (sensor B) and 16.8% RH (sensor E). The sensor error over the range of 55 to 85% RH, as shown in Table 4, varied from 4.2% RH (sensor E) to 7.6% RH (sensor D). Sensor E had the lowest error and was significantly more accurate than sensors C and D (P<0.05). The maximum errors ranged from 7.1% RH (sensor B) to 15.4% RH (sensor C).

Sensor accuracy drift All sensors were affected by the barn environment, although sensors B, D, and E had no failed replicates. Replicate 3 of sensor A malfunctioned at 15% RH at calibrations 2 and 3 by giving readings of 100% RH but read well at higher RH levels. It was not removed from the study because RH as low as 15% may never occur in livestock buildings and it still worked for higher RH levels of 25% and above. It failed completely soon after calibration 3 (115 days in barn) and was removed from the sensor board. High RH occurred in the barn before this failure. The sensor was sent back to the manufacturer to be checked for the reason of failure

Table 4. Mean and maximum errors of the RH sensors over the 55 to 85% RH range.

Calibration (Time in barn)	Error (% RH)	Sensor				
		A	B	C	D	E
1 (0 day)	Mean*	6.2 ab	4.8 b	7.4 a	7.6 a	4.2 b
	(SD)	(1.2)	(1.1)	(3.5)	(1.4)	(2.7)
	Maximum	8.7	7.1	15.4	10.8	11.1
2 (39 days)	Mean	6.5 abc	9.9 a	5.7 bc	8.0 ab	4.2 c
	(SD)	(2.0)	(1.8)	(3.2)	(0.9)	(2.5)
	Maximum	12.5	15.0	13.5	11.4	11.4
4 (249 days)	Mean	3.2** c	10.5 a	3.2** c	5.6 b	4.3 bc
	(SD)	(2.0)	(2.0)	(2.1)	(2.3)	(2.8)
	Maximum	6.7	14.4	7.5	11.3	10.5
6 (365 days)	Mean	2.8** c	8.9 a	5.0** bc	6.8 b	5.2 b
	(SD)	(2.1)	(1.2)	(2.7)	(2.6)	(3.2)
	Maximum	7.8	11.6	9.4	15.0	11.4

* Mean errors within a line followed by the same letters are not significantly different (P>0.05).
** Data of two replicates because one replicate failed.



(a) Mean error over the 15 to 85% RH range **(b) Mean error over the 55 to 85% RH range**

Fig. 1. Accuracy drift of the RH sensors over the experimental year.

but the manufacturer did not give the reason. The other two replicates also malfunctioned at 15% RH by giving readings of 100% RH at the last two calibrations but worked at higher RH levels, therefore, were kept in the study. Replicate 1 of sensor C started giving false readings of 99% RH constantly after 12 days of barn exposure, but it recovered after being brought to the laboratory for calibrations 2 and 3. It failed completely after eight months before calibration 4. The manufacturer checked and found that it had an electronic circuit failure but the sensing element had no problem.

As shown in Fig. 1, the errors of all sensors increased gradually as time went on in the barn. The calibration results after 39 days indicated that the error of all sensors exceeded ±5% RH over both the 15 to 85% RH and the 55 to 85% RH ranges, except that sensor E had an error of 4.2% RH over the 55 to 85% RH range.

As shown in Table 3, after the first in-barn calibration (calibration 2), sensor E still showed decreasing accuracy while other sensors were relatively stable. At the final calibration, sensor mean errors ranged from 6.3% RH (sensor B) to 17.3% RH (sensor A) over the 15 to 85% RH range. Sensor B had the lowest error and was significantly more accurate than sensors A and E ($P<0.05$). The maximum errors varied from 11.6 (sensor B) to 88.7% (sensor A). The maximum error of sensor A was caused by its malfunction at 15% RH. This replicate of sensor A was kept in this comparison because once the RH was above 15%, it started to work and kept similar accuracy as the other two replicates of sensor A.

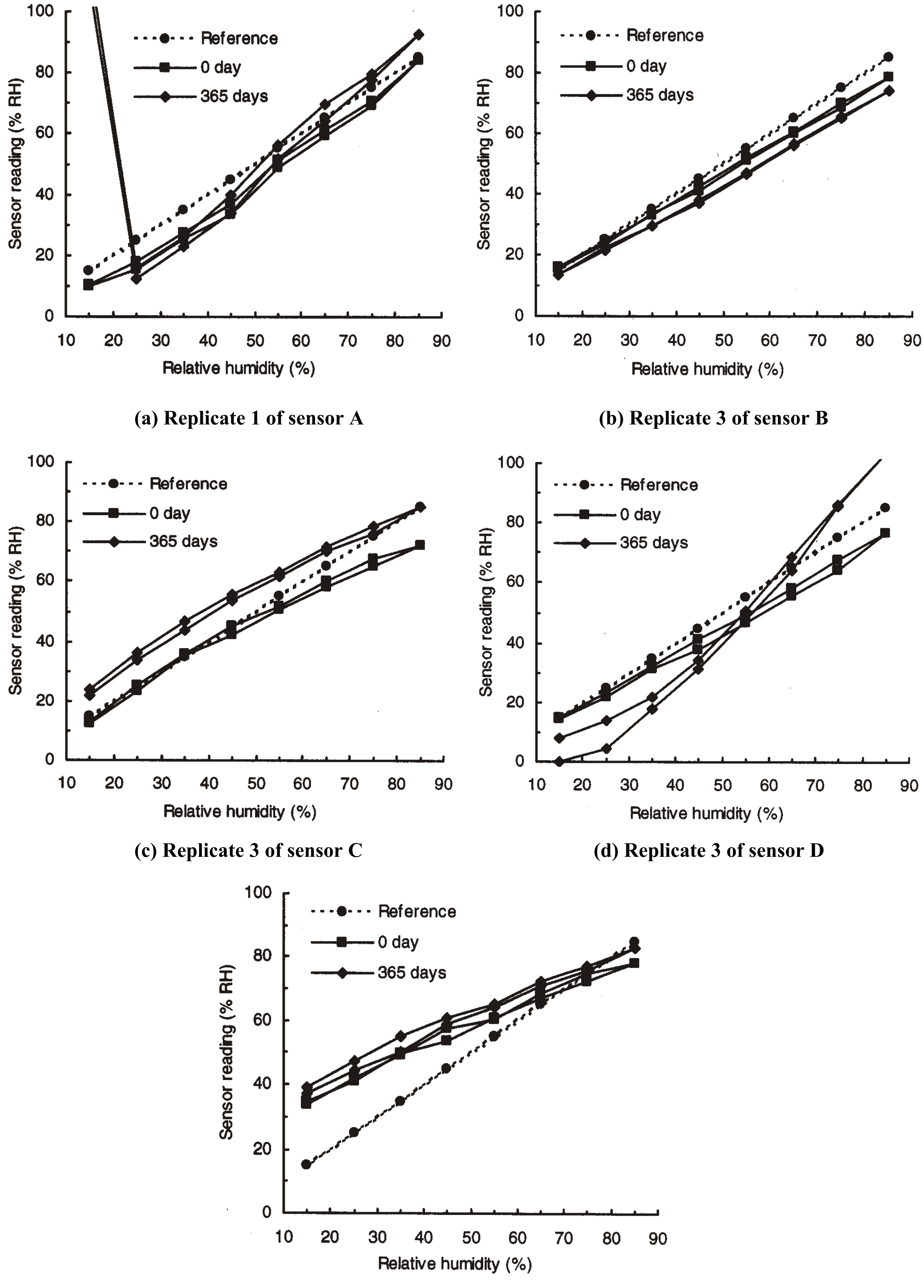
In the 55 to 85% RH range, sensor errors varied from 2.8 (sensor A) to 8.9% (sensor B) as given in Table 4. Sensor A was significantly more accurate than sensors B, D, and E ($P<0.05$). The maximum error ranged from 7.8% RH (sensor A) to 15.0% RH (sensor D).

By comparing mean and maximum errors of the sensors, it is apparent that the accuracy of some sensors varied widely at different humidity levels. Figure 2 gives the outputs of one replicate from each sensor for the initial and final calibrations. Due to the accuracy variations at different RH levels, at the final calibration sensor A had the largest mean error of 17.3% RH over the 15 to 85% RH range as shown in Table 3 while it also had the lowest error of 2.8% RH over the 55 to 85% RH range as shown in Table 4. By contrast, sensor B had the lowest mean error of 6.3% RH over the 15 to 85% RH range (Table 3), but it had the largest error of 8.9% RH over the 55 to 85% RH range (Table 4). Sensor E had much lower error at high RH than at low RH as shown in Fig. 2 e). Over the year, its error was between 8.1 and 11.5% RH over the 15 to 85% RH range (Table 3), and 4.2 to 5.2% RH over the 55 to 85% RH range (Table 4). Sensor C demonstrated larger errors at high RH than low RH at the initial calibration, but the result was reversed by the end of the year (Fig. 2 c). Sensor D performed better between 45 and 65% RH than in the lower and higher ranges at the end of the test period (Fig. 2 d).

Variations existed among the individual replicates of the same sensor. Figure 3 presents the readings of all replicates of sensors A to E at the final calibration. The three replicates of sensor A performed differently and so did the replicates of sensors C and D. Sensors B and E showed little difference among three replicates. Figure 3 also indicated that the readings of sensors B and E were more consistent compared with the other sensors and their errors could be easily calibrated out.

Other static characteristics

Table 5 shows the change of static characteristics of the sensors over the experimental year. The static sensitivity was quite stable for most sensors. Sensor A had a very low static sensitivity mainly because of its malfunction at low RH levels. The nonlinearity of the sensors increased gradually with time. Sensor B had the lowest nonlinearity at the end of the test period while sensor A had the highest due to its malfunction at



(a) Replicate 1 of sensor A

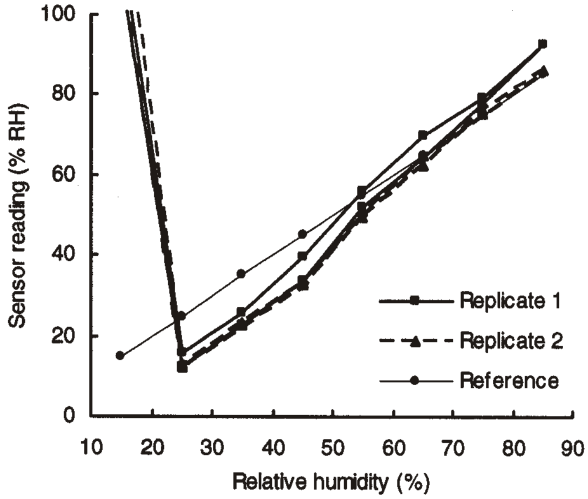
(b) Replicate 3 of sensor B

(c) Replicate 3 of sensor C

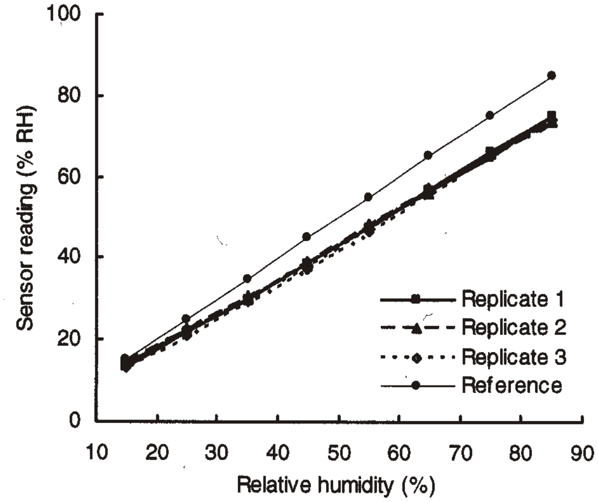
(d) Replicate 3 of sensor D

(e) Replicate 3 of sensor E

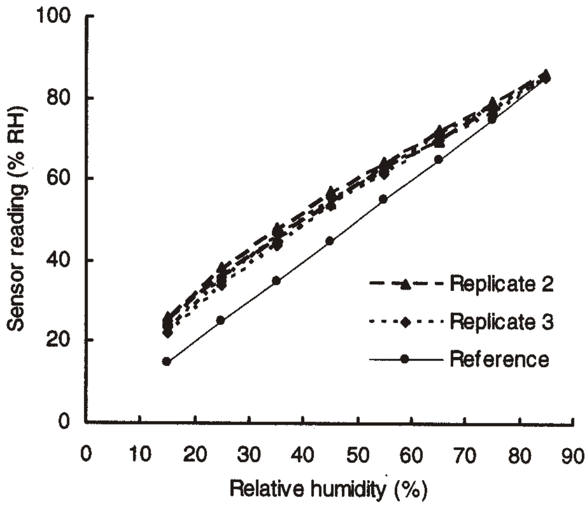
Fig. 2. The RH sensor reading changes over the experimental year.



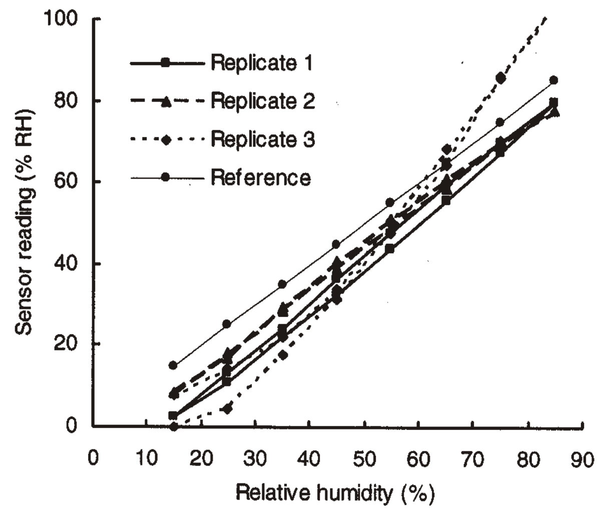
(a) Sensor A



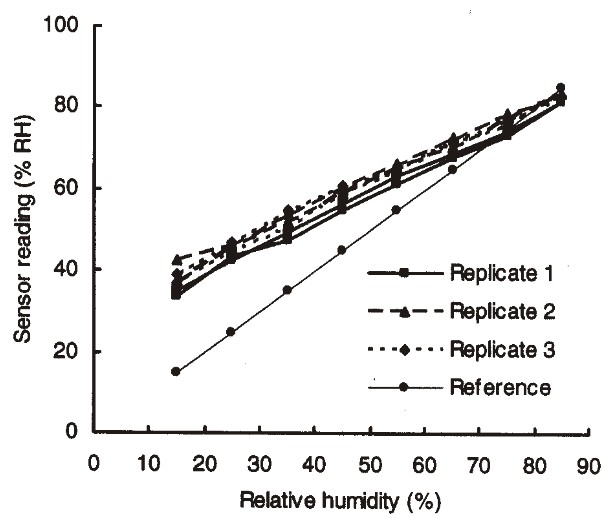
(b) Sensor B



(c) Sensor C



(d) Sensor D



(e) Sensor E

Fig. 3. Readings of sensors at the final calibration.

Table 5. Static characteristics of the RH sensors over the 15 to 85% RH range.

Characteristics	Timein-barn (days)	Sensor					
		A	B	C	D	E	A#
Static sensitivity (unitless)	0	1.00	0.91	0.85	0.87	0.70	
	39	0.88	0.81	0.58	0.93	0.66	1.01
	249	1.14*	0.83	0.84*	1.06	0.67	
	365	0.36*	0.86	0.89*	1.17	0.69	1.16*
Nonlinearity (%)	0	14.3	8.6	18.3	12.1	17.5	
	39	47.8	16.2	44.5	12.4	18.9	17.6
	249	13.4*	17.3	10.5*	13.6	22.4	
	365	110.0*	13.8	15.0*	17.4	24.5	15.9*
Maximum hysteresis (%)	0	3.2	1.7	4.3	3.4	4.4	
	39	47.5	8.1	50.0	5.5	7.8	6.0
	249	6.7*	3.2	4.8*	6.0	3.4	
	365	16.7*	1.6	3.7*	6.6	4.7	5.2*

*Data of two replicates because one replicate failed.

#Calculated by taking the reading at 15% RH as 9 to 10% RH, the value the sensor gave in the first 10 min. After 10 min, sensors gave reading of 100% RH when the true relative humidity was approximately 15% RH.

low RH levels. The maximum hysteresis of the sensors B, C, D, and E did not change much. At the last calibration, sensor A had the largest hysteresis while sensor B had the lowest.

DISCUSSIONS

The present study confirmed some conclusions obtained by Lemay et al. (2001). Since the harsh barn environment affected all sensors to varying degrees, it is essential to evaluate RH sensors in both laboratory and barn. The RH sensor evaluation procedure was proved effective and the sensor accuracy drift over time was monitored satisfactorily.

The accuracy of all sensors over the 15 to 85% RH range gradually reduced over the time in-barn, so no sensor could maintain the manufacturer's stated accuracy for the experimental year (Table 3). The lowest error after 249 days in-barn, i.e. 4.9% RH, was given by sensor C but it had one failed replicate (Table 3). However, in the RH range of 55 to 85%, some sensors showed high stability in accuracy. Sensor E had a yearly accuracy drift of 1.0% RH from 4.2 to 5.2% RH (Table 4). Although one replicate of both sensors A and C failed, the other two replicates of these two sensors showed no decrease in accuracy. Especially, sensor A had an accuracy of 2.8% RH at the end of the year (Table 4). Sensors B showed increasing errors over the time in-barn (Table 4).

Hence, no matter whether the RH sensor is used for monitoring or control purpose, it should be calibrated periodically. The calibration frequency employed should be able to provide enough information on sensor performance drift. Since sensor accuracy was reduced rapidly during the early period of the in-barn trial, sensor calibration after one month in-barn is very important. In practical applications, calibration frequency thereafter should be decided according to the specific sensor used. It is recommended that the sensors be calibrated once every three or four months. When the humidity level is very low (<20% RH), sensor A should be checked frequently to observe any malfunctions, especially when used for control purposes.

Because sensor accuracy varied at different RH levels, it is essential to analyze sensor accuracy at various RH levels. RH sensors should be selected according to the purpose of the sensors. Sensors used for monitoring purposes might be chosen according to accuracy over a large RH range, e.g. 15 to 90% RH. Because most livestock buildings do not have dehumidifying systems, the control of high RH level is a general requirement. Therefore, when selecting RH sensors for RH control purposes, sensor accuracy over the 55 to 85% RH range is likely the priority.

Some sensor accuracy fluctuations were observed. For example, sensors B, D, and E had lower errors in calibration 6 than in calibration 2 (Tables 3 and 4). Over 55 to 85% RH, the mean error of replicate 2 of sensor A increased from 6.8% at calibration 1 to 11.1% at calibration 3, but its mean error reduced to 2.3% at calibration 4 and maintained 5.8 and 2.1% for calibrations 5 and 6, respectively (Table 4). The difference among the last three calibrations could have resulted from the uncertainty of the reference hygrometer and the possibly high stability of the sensor during this period. However, the great accuracy increase from calibrations 3 to 4 is inexplicable. As described above, replicate 1 of sensor C malfunctioned after 12 days in-barn but recovered after being brought back to the laboratory for calibrations. At calibration 2, it only malfunctioned from 45 to 15% RH during the RH decreasing process by giving a reading of 99% RH. At calibration 3 it did not malfunction and had mean errors of 3.5% (55 to 85% RH) and 3.7% (15 to 85% RH). There was no apparent reason for such dramatic improvement.

The evaluation results suggested that one year might be the minimum period for in-barn evaluation. A shorter period would fail to see some sensor malfunction. For example, an in-barn period of less than 12 days would have failed to see the malfunction of replicate 1 of sensor C while a trial of less than 8 months would have failed to observe the failures of two sensor replicates.

The experiment results also confirmed the variations of individual units of the same type of sensor. Testing one or two sensor replicates would not likely get reliable results. Three sensor replicates seemed to be the minimal for obtaining reliable evaluation results.

Regarding the sensing technologies, most tested RH sensors employ polymer impedance or capacitive technology (sensing technology is unknown for sensor E). According to the current study, there was no sensor significantly superior to others and sensor properties varied even within the same sensing technology. However, most sensors, e.g. sensors A, C, D, and E, showed high stability with little accuracy drift over 55 to 85% RH. This indicated that the sensing technologies and the protection technologies for sensor and electronic components are promising for use in corrosive barn environments.

CONCLUSIONS

The typical swine barn environment was rather harsh so that all RH sensors were affected. By evaluating the RH sensors in both laboratory and barn, the sensor accuracy drift over time was monitored satisfactorily. According to the experimental results, the following conclusions can be drawn:

1. The accuracy of all sensors was reduced over the time in the barn; no sensor could maintain the stated accuracy for the experimental year. Both sensors A and C had one failed replicate. The other two replicates of sensor A also showed malfunction at 15% RH. Over the 15 to 85% RH range, after one year, sensor errors ranged from 6.3% (sensor B) to 17.3% (sensor A). Sensor B was significantly better than sensors A and E ($P<0.05$). To the contrary, over the 55 to 85% RH, sensor A had the lowest error of 2.8% while sensor B had the largest error of 8.9%. Sensor A was significantly better than sensors B, D and E ($P<0.05$). However, the errors of sensors B and E could be calibrated out because their readings were more consistent.
2. The linearity of the sensors was also reduced over the time in the barn. The static sensitivity and hysteresis of the sensors were relatively stable except for sensor A, which malfunctioned at low RH.
3. Humidity sensor accuracy should be analyzed over the whole testing range as well as the control range (55 to 85% RH) because sensor accuracy varied widely at different RH levels. When selecting a sensor for control purposes, the priority should be given to its accuracy over the control range of RH.
4. One year may be the minimum period for evaluating RH sensors for use in barns. A shorter period would fail to see sensor malfunction or failure. The sensor should be calibrated periodically, especially after the first month in the barn because the sensor accuracy is likely to be affected most in the early period. Thereafter, most sensors would have relatively stable performance and could be checked once every three to four months.
5. Variations existed among individual units of the same sensor. Three sensor replicates are suggested to get reliable evaluation results.

ACKNOWLEDGMENTS

The authors acknowledge the funding provided by the Natural Sciences and Engineering Research Council (NSERC) of Canada as well as the companies that provided the humidity sensors for the project.

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. 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.

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.

Eigenberg, R.A., J.A. Nienaber, T.M. Brown-Brandl and G. L. Hahn. 2002. Development of rugged environmental monitoring units for humidity and temperature. *Applied Engineering in Agriculture* 18(4): 493 496.

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.

Lemay, S.P., H. Guo, E.M. Barber and L. Zyla. 2001. A procedure to evaluate humidity sensor performance under livestock housing conditions. *Canadian Biosystems Engineering* 43: 5.13-5.21.

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.