ACCURACY OF GRAIN MOISTURE CONTENT PREDICTION USING TEMPERATURE AND RELATIVE HUMIDITY SENSORS

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ABSTRACT. *Grain temperature and moisture content (MC) are considered to be principal factors for safe storage of grain. Continuous monitoring of temperatures within grain masses is relatively easy using thermocouples, but monitoring of MC is limited by availability of sensors. However, temperature and relative humidity (RH) can be used to predict grain MC based on equilibrium moisture content (EMC) equations such as the Modified Henderson, Chung-Pfost, or Oswin. These models are limited to quasi-static thermodynamic conditions but do provide a method to predict MC with commercial sensors. Error analysis was performed using EMC relationships for wheat to determine the error in grain MC prediction due to sensor error. EMC prediction errors were found to be ±0.25% to ±0.65% MC_{db} between the RH ranges of 20% to 70% RH. At higher RH levels, prediction error increased substantially. Sensor error was set to ±2% RH and ±0.4°C, for the error analysis. The sensor error was adopted from a commercial sensor that could be potentially used for a cabled monitoring system. At higher levels of sensor error (±3% RH, ±0.4°C and ±4% RH, ±0.4°C), prediction error increased from ±0.38% to ±0.96% MC_{db} and from ±0.65% to ±1.29% MC_{db}, respectively, for the same RH range. Prediction error due to sensor error was found to be of the same magnitude as the standard errors of regression models developed for wheat. Measurements of sensor accuracy were also performed and accuracy was found to be within or better than rated manufacturer specifications for RH but temperature accuracy was less than rated accuracy.*

Keywords. Equilibrium moisture content, Grain, Relative humidity, Sensors.

Grain moisture content (MC) and temperature were considered by Converse et al. (1973) to be the most critical factors for maintaining grain quality during storage. Grain deterioration caused by insects and storage molds is dependent on the grain environmental conditions of interstitial air relative humidity, or equilibrium relative humidity (ERH), and grain temperature (Navarro et al., 2002). Grain moisture is the primary source of water, which can change relative humidity (RH) and is thus critical to control. Limits on MC for delivered grain ensure good storage and thus becomes a marketing factor. High moisture grain is often discounted at receiving while over-dry grain has no added value and thus, maintaining grain at optimum MC levels is highly desirable. While perfect control over grain MC cannot always be achieved, temperature control with aeration is an effective method to lower grain temperatures to levels that provide acceptable storage conditions. Temperature control, however, cannot always be achieved as most aeration methods rely on seasonal ambient air conditions to cool grain. The ability to measure in-bin moisture content with multiple sensors would be desirable from both a storage and marketing management perspective. The use of RH and temperature sensors and equilibrium moisture content (EMC) relationships, provides a method to do this.

Published data and equations that describe EMC relationships are available through *ASAE Standards* (2002). Henderson (1952) presented early work on the basic concepts of EMC and developed an equation describing EMC as a function of relative humidity and temperature for several biological materials. Chung and Pfost (1967a) described the potential cause of adsorption of cereal grains was molecular interaction caused by van der Waals forces. They developed an EMC model (Chung and Pfost, 1967b) based on the assumptions that the free energy of the adsorbent decreased exponentially with increasing thickness of the adsorbed layer. Young and Nelson (1967a, b) hypothesized three mechanisms by which water was held by the material; they were a unimolecular layer, multimolecular layer, and moisture within the cells. Diffusional forces caused the transfer of the moisture into the cell when a layer of molecules formed on the surface. The use of the various developed EMC equations has been somewhat impeded by the variance of EMC behavior by grain type, variety and agronomic conditions as well as adsorption and desorption differences. Sensor accuracy and reliability has also been an issue when measuring RH.

Using EMC relationships to measure MC in bulk grain, Pixton and Henderson (1981) found small varietal differences between EMC/ERH (equilibrium relative humidity) relationships for five Canadian wheats. Differences were only significant at low MC. They concluded that errors

arising from the practical problems of measuring MC with meters, variation due to sampling errors, and variation of MC in different parts of a bulk were greater than those caused by EMC relationships. Chen (2000) conducted a step-by-step ERH-determining technique to measure desorption and adsorption properties of six agricultural products dried at different temperatures. There was good agreement among ERH/EMC data from his work and from other sources for rough rice, brown rice, corncobs, and red beans. Hysteresis was observed for adsorption and desorption of moisture and relationships were affected by variety, growth location, and drying history. Chen (2001) also evaluated the accuracy of using temperature and RH sensors to determine grain MC using EMC equations (Modified-Henderson, Chung-Pfost, and Modified-Oswin) for medium rough rice and dent type corn. Calibration of the humidity sensor, using saturated salt solutions, was used to improve RH accuracy. Accuracy of the ERH prediction was within 1.0% MC compared to oven drying methods and shows the concept of using RH sensors to measure MC may be feasible.

Current RH and temperature monitoring is often employed for aeration to determine when ambient air conditions are suitable for aeration to occur. Yearsley et al. (1986) designed a feedback control system for aeration control based on temperature and RH measurement. They mentioned that limitations of humidity sensors were due to problems of dust contamination and signal integrity but added that these limitations, when overcome, would provide better system control and economics than current commercial systems without feedback. Bin humidity sensors used by Qui et al. (1987) for aeration control also showed this type of system performed better than conventional storage aeration. Sensor problems experienced by Plummer et al. (1989) in monitoring the aeration of a grain bed were sensor module failure and drift. More recent work by Eigenberg et al. (2001) checked the accuracy of six RH sensors using saturated salt solutions (NaCl and LiCl at 25°C) after monitoring meat storage for seven months. Standard deviation of the humidity readings was 0.93% RH. While the sensors used in the work above are suitable for general ambient monitoring they are bulky and expensive and thus not suitable for cabled bin monitoring.

Use of EMC relationships has good potential for grain bulk monitoring despite the experiences with earlier sensors. Two areas that need to be addressed are 1) development of suitable sensors for RH grain monitoring that have acceptable accuracy and long term stability and 2) development of EMC equations that can be broadly used across grain varieties or quickly adjusted to particular grain characteristics. This research addresses the first aspect, in part, by examining error induced in EMC prediction by sensor error.

OBJECTIVES

The primary objective of this study was to determine the effect of RH and temperature sensor error in predicting grain MC using common EMC equations. This work reports only the EMC prediction error induced by the sensor and not the error from EMC regression. The secondary objective was to examine a recently developed and commercially available RH sensor that may be suitable for a cabled grain monitoring system. Sensor characteristics of accuracy and time response were measured. Sensor accuracy was measured to determine compliance with reported manufacturer specifications and to provide a reference for future research related to sensor stability over extended periods.

MATERIALS AND METHODS

RELATIVE HUMIDITY (RH) SENSORS

This research used an integrated RH and temperature sensor, SHT75 (Sensirion AG, Zurich, Switzerland). Selection of this particular sensor was based on several factors: 1) accuracy is claimed to be as good or better than most commercial RH sensors; 2) it incorporates a temperature sensor; 3) a digital interface is used to retrieve data and thus eliminates some of the noise problems associated with other RH sensors; 4) its small size makes it suitable for a cabled monitoring system; 5) individual sensors are factory calibrated with calibration coefficients stored within the sensor; and 6) cost (estimated $15 USD in bulk) and interchangeability make it replaceable. Each sensor consisted of a capacitive polymer-sensing element for RH and a bandgap PTAT (proportional to absolute temperature) temperature sensor. RH and temperature outputs were internally coupled to a 14-bit analog to digital converter and a serial interface circuit on a singular chip. Rated absolute accuracy of the sensor was ±2.0% RH and ±0.4°C for most ambient conditions. Because sensors may be susceptible to grain dust and free moisture, individual sensors were enclosed in a porous plastic tube (Porex Corp., Fairbunn, Calif.) and sealed at each end with heat-shrink tubing and plastic electrical tape (fig. 1). Tube dimensions were 12.7-mm outside and 6.35-mm inside diameter. Pore size was 20 μm.

ACCURACY AND TIME RESPONSE OF RH SENSORS

Manufacturer rated absolute accuracy for the SHT75 is shown in figures 2 and 3. Calibration procedures used by Sensirion AG for these sensors were in accordance with ISO/IEC 17025 standards. For purposes of determining sensor accuracy for this research, it was assumed that readings from multiple sensors would form a Gaussian distribution about the mean value, which was considered the true value. This provided a relatively simple way to compare rated accuracy with measured accuracy for this research and for future planned research on long-term sensor stability. Accuracy tests were completed using 15 sensors placed in a sealed plastic bucket inside a temperature-controlled environment chamber. Grain at different moisture contents was used as a desiccant to create different humidity ranges. Individual sensor readings were monitored at a rate of about four readings/minute with a custom program controlling a digital data acquisition board in a PC. The environment
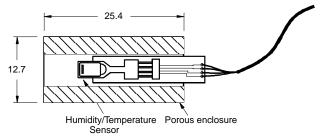

Figure 1. SHT75 RH/Temperature sensor mounted in porous tubing. Ends of enclosure sealed with heat-shrink tubing are not shown. Dimensions are in millimeters.
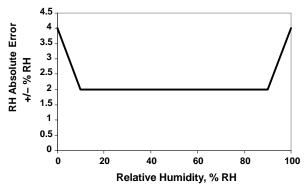
Figure 2. Absolute error of the SHT75 relative humidity sensor as specified by Sensirion AG, Zurich, Switzerland.
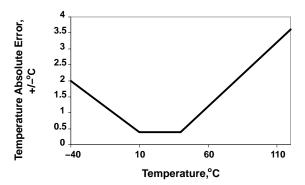

Figure 3. Absolute error of the SHT75 temperature sensor as specified by Sensirion AG, Zurich, Switzerland.

chamber was set to the desired temperature, and the sensors were monitored. When the environment temperature was within ±0.5°C of the set temperature, the environmental control was turned off to eliminate its cyclic nature and measurements were recorded after an environmental stabilization period, described later, was established .

One problem using this method was to determine criteria that defined a stable environment. The criteria used required the standard deviation for individual sensors to be at or below 0.1% RH and 0.05°C, and the standard deviation for all sensors was to be at or below 0.66% RH. Standard deviations were determined from 10 readings from each sensor over a 2.5-min period. It had been intended to use the additional criteria of using the combined sensor temperature standard deviation of 0.13°C but this could not be met in preliminary tests and was eliminated. Standard deviation values of 0.66% RH and 0.13°C were derived from the manufactured rated accuracy, which is expressed as three times the sensor standard deviation derived from sensor calibration. Figure 4 illustrates the criteria used to determine a stable environment for RH. Approximately 1 h of stabilization was required to reach these conditions. Sensor accuracy was determined at six levels of relative humidity ranging from 17.6% RH to 95.7% RH and seven levels of temperature spanning -21.8°C to 37.8°C.

Response time of the RH sensors with the porous plastic enclosure was determined using medium and high-humidity saturated salt solutions. The solutions used were magnesium-chloride ($MgCl_2$) - 50% RH and sodium chloride (NaCl) - 75% RH. Three sensors were placed in the medium-humidity RH solution until readings were stabilized and then transferred immediately to the 75% RH solution. Response
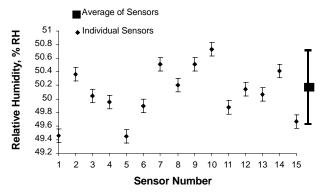

Figure 4. Criteria used to determine a stable reference environment for relative humidity. Standard deviation bars for individual sensors are shown at 0.1% RH. Standard deviation bar for all sensors are shown at 0.66% RH. Data in this figure is simulated.

time was calculated based on a first-order unit step function (Bentley, 1996).

$$RH(t) = RH_i + (RH_f - RH_i)(1 - e^{-t/\tau}) \qquad (1)$$

where
τ = time constant (s)
RH_i = initial relative humidity (%RH)
RH_f = final relative humidity (%RH)
t = time (s)

GENERAL FORMULA FOR ERROR PROPAGATION

EMC prediction error due to RH and temperature measurement error was analyzed using the following error analysis procedures from Bentley (1996) where the uncertainty or error of a dependent variable q is defined as:

$$\Delta q = \sqrt{\left[\frac{\partial q}{\partial x_1}\Delta x_1\right]^2 + \ldots + \left[\frac{\partial q}{\partial x_n}\Delta x_n\right]^2} \qquad (2)$$

where q is f(x_1, x_2.....x_n) and x_1, x_2.....x_n are measured with uncertainties of Δx_1, Δx_2… Δx_n.

The Modified Henderson, Chung-Pfost and Oswin equations were examined using the above method to determine the effect of sensor error on MC prediction.

Moisture content prediction using the Modified Henderson equation is:

$$MC = \left[\frac{-\ln(1-RH)}{A(T+C)}\right]^{1/B} \qquad (3)$$

where
MC = moisture content (dry basis)
RH = relative humidity of interstitial air within the grain (decimal RH)
T = temperature of the grain (°C)
A = constant
B = constant
C = constant

The partial derivatives used, with respect to temperature and relative humidity, were:

$$\frac{\partial(MC)}{\partial T} = \frac{1}{B}\left[\frac{-\ln(1-RH)}{A(T+C)}\right]^{\frac{1}{B}-1}\left[\frac{\ln(1-RH)}{A(T+C)^2}\right] \qquad (3a)$$

$$\frac{\partial(MC)}{\partial(RH)} = \frac{1}{B}\left[\frac{-\ln(1-RH)}{A(T+C)}\right]^{\frac{1}{B}-1}\left[\frac{1}{A(1-RH)(T+C)}\right] \quad (3b)$$

Similarly for the Modified Chung-Pfost equation:

$$MC = -\frac{1}{B}\ln\left[\frac{-(T+C)\ln(RH)}{A}\right] \quad (4)$$

$$\frac{\partial(MC)}{\partial T} = -\frac{1}{B(T+C)} \quad (4a)$$

$$\frac{\partial(MC)}{\partial(RH)} = -\frac{1}{B\times RH \times \ln(RH)} \quad (4b)$$

and for the Modified Oswin equation:

$$MC = \frac{A+BT}{\left(\frac{1}{RH}-1\right)^{\frac{1}{C}}} \quad (5)$$

$$\frac{\partial(MC)}{\partial T} = \frac{B}{\left(\frac{1}{RH}-1\right)^{\frac{1}{C}}} \quad (5a)$$

$$\frac{\partial(MC)}{\partial(RH)} = \frac{A+BT}{C\left(\frac{1}{RH}-1\right)^{\left(1+\frac{1}{C}\right)}RH^2} \quad (5b)$$

Total error in MC prediction was calculated by:

$$\Delta MC = \sqrt{\left[\frac{\partial(MC)}{\partial T}\Delta T\right]^2 + \left[\frac{\partial(MC)}{\partial(RH)}\Delta RH\right]^2} \quad (6)$$

where ΔT and ΔRH are the measurement errors (accuracy) of the sensor.

Equation 6 was used to determine the accuracy of predicting MC, given the sensor errors (ΔT and ΔRH) for the three EMC equations.

RESULTS AND DISCUSSION

ACCURACY AND TIME RESPONSE OF RH SENSORS

RH accuracy expressed as the standard deviation of the readings is shown in table 1 at different RH levels. The standard deviation ranged from 0.502% to 0.634% RH. Rated absolute accuracy of the sensor, as stated by the manufacturer, is ±2% RH and was calculated as three times the standard deviation (3* δ) of the sensor readings and calibration reference value (Sensirion, 2004). Temperature accuracy, expressed as the standard deviation of all measurements, is shown in table 2. Rated absolute accuracy of the temperature sensor, as stated by the manufacturer, is ±0.4°C and was also calculated as three times the standard deviation of sensor readings and calibration reference value. Measured sensor accuracy for RH was generally within manufacturer-speci-

fied accuracy. Accuracy for temperature was generally found to be half the rated accuracy. RH drift of the sensor used in this study was claimed to be ±1% RH over a 1-year period. Long-term studies are needed to determine the effects of time, use, and environmental conditions on sensor stability. Adequate dust protection of the polymer-sensing element is needed and must be implemented so that it does not compromise long-term accuracy. One concern is that dust collected around any protective device may induce a microenvironment causing inaccurate EMC/ERH measurements.

Table 1. Average and standard deviation of RH readings from 15 sensors.

Average % RH	17.68	39.51	51.80	66.45	76.83	95.68
Standard deviation of sensor readings, δ	0.604	0.634	0.621	0.502	0.632	0.517
(3*δ)	1.812	1.902	1.863	1.506	1.896	1.551
Rated accuracy from fig. 2	2	2	2	2	2	3

Table 2. Average and standard deviation of temperature readings from 15 sensors.

Average temp. (°C)	-21.82[a]	1.74	10.91	16.10	19.77	24.71	38.11
Standard deviation of sensor readings, δ	0.838	0.358	0.290	0.273	0.260	0.263	0.261
(3*δ)	2.514	1.074	0.870	0.819	0.780	0.789	0.783
Rated accuracy from fig. 3	1.42	0.66	0.4	0.4	0.4	0.4	0.4

[a] Readings were taken in a freezer unit and individual readings would not stabilize to the threshold standard deviation.

The systematic error of individual sensors for RH and temperature can be seen in figures 5 and 6. The temperature-sensing element exhibited very predictable patterns in all but one case. RH measurement patterns were somewhat less predictable but still evident for individual sensors. These tests were done at different RH and temperature conditions from those shown in tables 1 and 2 but used the same criteria to determine when a stable environment was reached. Temperature conditions were 11.2, 13.4, 14.5, 16.7, 21.4, 24.6, 28.6, 31.4, 34.6, 37.2, and 39.8°C. RH conditions were 19.5, 20.8, 30.6, 38.0, 32.7, 45.1, 54.9, 60.0, 72.4, 78.0, and 83.2% RH.
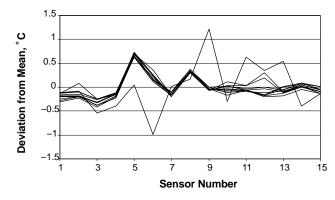

Figure 5. Individual sensor deviation from 15 sensor average at different temperature levels.
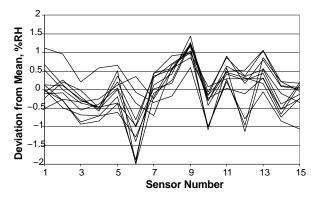
Figure 6. Individual sensor deviation from 15 sensor average at different RH levels.

Figure 7. EMC prediction error induced by sensor error across a range of relative humidity at 0°C for the Chung-Phost equation.

The time constant (τ) of three sensors with the protective porous plastic tubing ranged from 90 to 280 s in the stagnant environment. This is substantially longer than the manufacturer rating of 5 s but is acceptable for grain monitoring. Adding the protective polymer for dust apparently slows the movement of air reaching the sensing element.

EMC PREDICTION ERROR

EMC prediction error was calculated for the Modified Henderson, Chung-Pfost, and Modified Oswin equations using equation 6 and the respective EMC partial derivatives over a range of relative humidity (5%-95%) and temperatures (0-50°C). Coefficients used for the EMC equations were taken from *ASAE Standards* (2002) and from Uddin (2005; table 3). The RH and temperature range used to derive these coefficients was 11% to 93% RH and 5°C to 45°C for ASAE Standards data and 25% to 80% RH and 5°C to 45°C for data from Uddin (2005). Values of ΔT and ΔRH, the absolute measurement error, were set to those specified by the manufacturer shown in figures 2 and 3.

Figures 7-11 show the EMC prediction error for the different equations using prediction coefficients from table 3 at temperatures of 0°C and 50°C. Prediction error remains reasonably steady at about ±0.25% to ±0.65% MC$_{db}$ between the range of 10% to 70% RH for all cases. Above 70% RH, error begins to increase substantially Overall there are only slight variations in prediction error from the various sets of EMC equations within the 10% to 70% RH range. For the Oswin equation and HR Waldron sample, error above
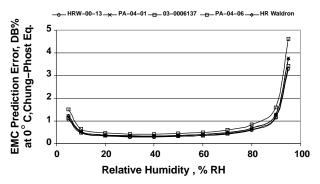
70% RH increases at about twice the rate as the Chung-Phost and Henderson equation errors (fig. 13). This indicates that the Oswin EMC equation may respond differently to sensor error in this region but only one set of coefficients were available for comparison between equations. Although the range over which the models developed by Uddin (2005) typically spanned test conditions of 20% to 80% RH, their extrapolated error behavior (>80% RH) was similar to that for the HR Waldron sample which was derived from data spanning 11% to 93% RH

EMC prediction models were evaluated similarly at increased levels of sensor error. RH error was increased by 1% and 2% RH to account for sensor drift with time, i.e. sensor error was set to ±3% RH and ±4% RH. The
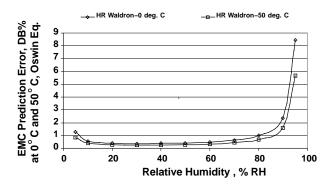

Figure 11. EMC prediction error induced by sensor error across a range of relative humidity at 0°C and 50°C for the Oswin equation.

Table 3. Model coefficients used to determine prediction error caused by sensor error.

EMC Equation	A	B	C	Stand. Error of Residuals[a]	Sample ID	Wheat Class	Source
Modified Henderson	0.000043295	2.11190	41.565	3.8 erh	HR Waldron	HRW	ASAE (2002)[b]
	0.01007678	2.15552	6420.2	0.44 emc	HRW–00–13	HRW	Uddin (2005)[c]
	0.09288120	1.88267	388.2	0.52 emc	PA–04–01	Durum	Uddin (2005)[c]
	0.08346740	2.13744	693.7	0.46 emc	03–0006137	SRW	Uddin (2005)[c]
	0.02186979	1.44465	775.6	0.25 emc	PA–04–06	Durum	Uddin (2005)[c]
Modified Chung–Phost	377.52	0.16456	35.59	2.46 erh	HR Waldron	HRW	ASAE (2002)[b]
	8437.88	18.67657	1261.3	0.39 emc	HRW–00–13	HRW	Uddin (2005)[c]
	1408.24	16.36271	270.1	0.41 emc	PA–04–01	Durum	Uddin (2005)[c]
	2726.96	17.91562	413.3	0.44 emc	03–0006137	SRW	Uddin (2005)[c]
	1463.34	13.31346	484.2	0.22 emc	PA–04–06	Durum	Uddin (2005)[c]
Modified Oswin	15.868	−0.10378	3.0842	2.15 erh	HR Waldron	HRW	ASAE (2002)[b]

[a] erh, emc Standard error of residuals with ERH or EMC as the dependent variable, respectively.

[b] Variable format is %MC$_{db}$ and decimal RH.

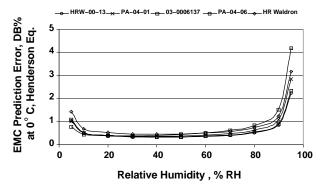[c] Variable format is decimal MC$_{db}$ and decimal RH.

Figure 8. EMC prediction error induced by sensor error across a range of relative humidity at 0°C for the Henderson equation.
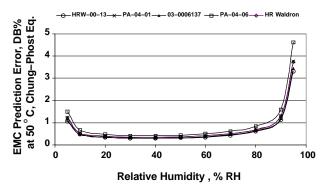

Figure 9. EMC prediction error induced by sensor error across a range of relative humidity at 50°C for the Chung-Phost equation.
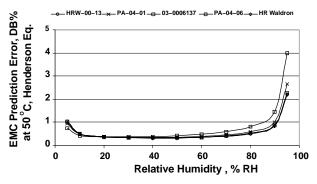

Figure 10. EMC prediction error induced by sensor error across a range of relative humidity at 50°C for the Henderson equation.

calculated EMC prediction error for each of these cases was $\pm0.38\%$ to $\pm0.96\%$ MC_{db} and $\pm0.65\%$ to $\pm1.29\%$ MC_{db} respectively over the 10% to 70% RH range. Graphical data, not shown, were similar to that in figures 7-11 but at the increased levels of error. Temperature error was also examined at $\pm0.8°C$, which is half the rated accuracy of $0.4°C$. This additional sensor error resulted in a maximum increase of EMC prediction error of only 0.05% MC_{db} for any particular temperature and RH.

These results indicate the amount of error due to sensor error when predicting the MC of wheat and assumes a perfect EMC equation (i.e., prediction is perfect if there is no sensor error). EMC regression models developed by Uddin (2005) for 47 wheat varieties and classes had standard errors of residuals ranging from 0.31% to 0.63% MCd_{db} which shows

prediction error due to the sensor is of the same magnitude and can be significant.

Prediction error is very sensitive to the slope of the EMC prediction equation. Larger slopes for EMC equations occur at higher RH levels (>80% RH) and will show increasing prediction error due to measurement error. An additional factor detrimental to accurate EMC prediction at high RH is that sensor error increases in this range.

From a practical perspective, accurate RH and temperature measurement is required between 20% and 80% RH and 0 to 50°C for wheat varieties and many storage situations for corn. Within this range, these grain types have moisture contents ranging from 6% MC_{db} to approximately 20% MC_{db}, which is where grain moisture management is most critical. This study indicates that for storage monitoring, the error in MC prediction could be kept reasonably low provided other factors could be accounted for such as adsorption and desorption characteristics, and varietal, agronomic and physical differences.

Although there are many challenges to overcome for accurate EMC prediction, RH storage monitoring by itself can be a good tool by providing additional environmental information on storage conditions. Conditions which suppress the specific microflora during storage are fairly well understood and are primarily a function of temperature and RH. The sensor used in this study could potentially be used as a sensor for storage monitoring as it appears suitable for a cabled system. Additional studies are required though to implement protection from grain dust and to determine long-term accuracy.

CONCLUSIONS

The contribution of sensor error to EMC prediction was found to be between approximately $\pm0.25\%$ to $\pm0.65\%$ MC_{db} for ERH conditions between 20% to 70% regardless of which equations (Modified Henderson, Modified Chung-Pfost, Modified Oswin) were used to predict moisture. Sensor error in this RH range was $\pm2.0\%$ RH and $\pm0.4°C$. Increasing sensor error by 1% and 2% RH to simulate long-term sensor drift, increases the EMC prediction error by $\pm0.38\%$ to $\pm0.96\%$ MC_{db} and $\pm0.65\%$ to $\pm1.29\%$ MC_{db} respectively, for the same RH range. EMC prediction error at RH levels above 70% RH increases substantially for all equations with the Modified Oswin having the most error ($\pm8.5\%$ MC_{db} at 95% RH and 50°C). Temperature error has negligible effect on EMC prediction compared to RH error.

The accuracy of the sensor used in this study was determined to be within or better than the rated RH accuracy as specified by the manufacturer. Temperature accuracy was determined to be about half the specified accuracy.

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