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Uncertainty evaluation of humidity sensors calibrated by saturated salt solutions

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Abstract

This study evaluates the sources of uncertainty for two types of humidity sensors. The standard humidity environment was made by several saturated salt solutions. These uncertainty sources include predicted values of calibration equation, reference humidity source, temperature variation effect, nonlinear and repeatability, and resolution source. The study also dealt with the effect of calibration methods and calibration equations on the uncertainty. The polynomial calibration equation had better predictive performance than the linear equation for two types of humidity sensors.

The uncertainty analysis shows that the predicted uncertainty is the main source for combined uncertainty. No significant difference of the uncertainty for resistive sensor was found between classical method and inverse method. However, the predicted uncertainty of inverse method is significantly lower than that of classical method for capacitive humidity sensor.

Keywords: Humidity sensor; Uncertainty; Calibration

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1. Introduction

Humidity is an important factor that affects the quality of foodstuffs, the growth of microorganisms, and the package process of microelectric [1]. The accuracy and precision of the humidity measurement have been considered for various industries. Two types of electrical humidity sensors: capacitive and resistive type, are widely used in commercial, industrial, and weather stations. The uncertainty of these humidity sensors is a concerned of users.

They are four-types humidity standard generator systems: two-pressure humidity generator [1], two-temperature humidity generator [2], divided-flow humidity generator [3,4], and fixed-point humidity systems [5]. Except for the fixed-point humidity systems, others can provide more accurate standard environment [1]. However, they are expensive and complicated. Sometimes, an experimental factory needs to be established to install these systems.

The fixed relative humidity point certified with saturated salt solutions is easy to be made [5]. A number of fixed relative humidity points could serve as the secondary standards for the calibration of humidity sensors. This fixed points method is inexpensive, convenient, and easy to be reproduced in

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a research laboratory. It is often used for the checking points for humidity sensors. However, the fixed values of humidity environment limit the applicable range of sensors. As the humidity sensor was checked at two fixed points, the accuracy and uncertainty of the measuring points between two checking points cannot be determined directly.

Recently, uncertainty evaluation had been widely adopted for sensors [6–8]. The accuracy uncertainty analysis is very useful. In this study, two types of electrical humidity sensors are calibrated by several saturated salt solutions. The adequate calibration equations are evaluated. The build of calibration equation is analyzed. According to ISO GUM [9], the uncertainty of two humidity sensors was evaluated by all sources of uncertainty.

2. Equipment and methods

2.1. Humidity sensors

Two types of humidity sensors were adopted in this study. They are resistive humidity sensor and capacitive humidity sensor. The specifications of these sensors are listed in Table 1.

2.2. Saturated salts solutions

The fixed humidity environments produced by 10 saturated salt solutions were used to calibrate two types of humidity sensors. These saturated salt solutions are listed in Table 2. The procedure for preparing a hydrostatic solution was according to the OIML R121 [10]. The purity of salt was 99.99%. The distilled water was selected as solvent. The salt was dissolved in water in such a proportion that 30–90% of the weighted sample remained as dissolved.

These salt solutions were placed in a vessel. Then these vessels were installed in a temperature controller. The ambient air temperature was set at 25 °C and the variation of air temperature was kept within 0.2 °C.

Table 2
The saturated salt solution and its standard relative humidity value for the calibration of humidity sensors at 25 °C

Salt solutions	Standard relative humidity (%)	Uncertainty (%)
LiCl	11.3	0.3
CH_3COOK	22.5	0.4
$MgCl_2 \cdot 6H_2O$	32.8	0.2
K_2CO_3	43.2	0.4
NaBr	57.6	0.4
KI	68.9	0.3
NaCl	75.3	0.2
KCl	84.3	0.3
KNO_3	93.6	0.55
K_2SO_4	97.3	0.5

Source: Greenspan [5].

At the calibrating process, each humidity sensor was placed at the headspace of the vessel with the saturated salt solutions. The calibrating period was maintained 12 h to ensure the internal air humidity would reach the equilibrate state.

2.3. Establish the calibration equation

The work of calibration equation is to establish the relationship between the reading values of sensor and the standard values of humidity. In this study, the standard humidity environments, the known x_i values, were maintained by saturated salt solutions. The reading values, the response y_i, were taken from humidity sensor. There are two mathematical ways to build the calibration equations.

(A) The classical method

The response y_i was the function of standard x_i values:

$$y = f(x_i) \tag{1}$$

If y_i and x_i was a linear relationship, then

$$y = b_0 + b_1 x \tag{2}$$

As the new response, x_0, was measured, the "true" value is estimated as

Table 1
Specifications of the humidity sensors

	Resistive humidity sensor	Capacitive humidity sensor
Sensing element	Macro-molecule resistive element	Capacitive-type
Measuring range	0–99% RH	0–100% RH
Nonlinearity and repeatability	±0.25% RH	±0.1% RH
Resolution	0.1% RH	0.2% RH
Temperature shift	Not available	0.005%/°C (deviated with 20 °C)

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$$\hat{x} = \frac{\hat{y} - b_0}{b_1} \tag{3}$$

This procedure is known as the classical method to calibration. If the relationship between y_i and x_i was nonlinear or polynomial function, the true values ($\hat{x}$) of measured values ($\hat{y}$) then be calculated as an algebra equation or computed by numeric analysis technique. The calibration equation was built by ordinary least square regression or nonlinear regression technique.

(B) The inverse method

In this case, the x_i is selected as dependent variable and y_i is viewed as independent variable, the calibration equation is:

$$x = g(y) \tag{4}$$

As y_i and x_i had the linear relationship:

$$x = c_0 + c_1 y_i \tag{5}$$

The true value $\hat{x}$ then can be calculated directly by Eq. (5).

The $g(y)$ can be a polynomial function or nonlinear equation, such as:

$$x = c_0 + c_1 y + c_2 y^2 \tag{6}$$

or

$$x = c_0 Exp(c_1 y + c_2 y^2) \tag{7}$$

This approach is called the inverse method.

Many textbooks of regression analysis only mentioned the classical method. Krutchkoff first reported the inverse method [11]. The author mentioned that inverse method had the smaller mean squared error b than that of classical method. After comparing the accuracy of predictions from classical and inverse method, Krutchkoff [11] concluded that the inverse method was better than classical method for prediction. Centner et al. [12] verified this statement by Monte Carlo simulations and two practical cases, their conclusion showed that the classical method gave more reliable predictions than classical method. Tellinghuisen [13] had the similar results when comparing two approach calibration methods with small data sets. Grientschnig [14] confirmed that inverse method had the better predict ability than classical method regardless of the size of the data sets.

2.4. Criteria for model evaluation

The relationships between reading values of sensor and standard humidity values are calculated by Sigma plot version 6.0. The standard error of the estimated value, s, was selected as the quantitative criteria:

$$s = \sqrt{\frac{(y - \hat{y})^2}{n - 1}} \tag{8}$$

where y is the dependent variable, $\hat{y}$ is the predicted value of model, and n is the number of data.

The relationship between residuals of model and the predicted values are plot as residual plots. For an adequate model, data distribution of residual plots should tend to be in a horizontal band centered on zero. If the residual plots indicated a clear pattern, the model could not be accepted.

3. Sources of the uncertainty for humidity sensors

According to the ISO GUM [9], the uncertainty of measurement is evaluated by a 'Type A' or 'Type B' method. The Type A evaluation of standard uncertainty is the method of evaluation by the statistical analysis of observations. The Type B evaluation of standard uncertainty is the method of evaluation by other information about the measurement.

There are several uncertainty source items. The uncertainties were calculated as follows.

3.1. The calibration equation

The standard uncertainty due to calibration equation is a Type A uncertainty. In this study, two calibration methods are considered.

(A) The classical method

(a) Linear equation

The form of linear regression equation is:

$$y = b_0 + b_1 x \tag{9}$$

where y is the reading values of humidity sensor and x is the standard value. The predicted value (x_{pred}) that calculated from the observed response (y_{obs}) has been discussed in detail [15–17]:

$$x_{\text{pred}} = \frac{y_{\text{obs}} - b_0}{b_1} \tag{10}$$

The variance of x_{pred} is given:

$$\text{Var}(x_{\text{pred}}) = \frac{s^2}{b_1^2}\left[\frac{1}{p} + \frac{1}{n} + \left[\sqrt{\left[\frac{(x_{\text{pred}} - \bar{x})^2}{\sum(x_i^2) - (\sum x_i)^2/n}\right]}\right]\right] \tag{11}$$

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where s is the standard deviation of calibration equation, p is the numbers of measurement for prediction, n is total number of measurement for calibration equation.

The standard deviation $s(y_c)$ for a value of y calculated from the fitted line for new value of x:

$$s(y_c) = s\sqrt{\frac{1}{p} + \frac{1}{n} + \left[\frac{(x_{\text{pred}} - \bar{x})^2}{\sum(x_i^2) - (\sum x_i)^2/n}\right]} \tag{12}$$

Combining Eqs. (11) and (12):

$$\text{Var}(x_{\text{pred}}) = \left[\frac{s(y_c)}{b_1}\right]^2 \tag{13}$$

then

$$u(x_{\text{pred}}) = \frac{s(y_c)}{b_1} \tag{14}$$

The uncertainty of predicted values obtained by inverse method of the linear calibration equation could be computed by Eq. (14).

(b) Polynomial equation

The form of polynomial equation is:

$$y = c_0 + c_1 x + c_2 x^2 \tag{15}$$

The predicted value (x_{pred}) calculated from the observed response (y_{obs}) is calculated as:

$$x_{\text{pred}} = \frac{-c_1}{2c_2} + \sqrt{\frac{c_1^2}{4c_2^2} - \frac{c_0}{c_2} + \frac{y_{\text{obs}}}{c_2}} \tag{16}$$

From the definition of uncertainty:

$$u(x_{\text{pred}}) = \frac{\delta x}{\delta y} u(y_i) \tag{17}$$

$$u(x_{\text{pred}}) = \frac{1}{2c_2} \frac{u(y_{\text{obs}})}{\sqrt{\frac{c_1^2}{4c_2^2} - \frac{c_0}{c_2} + \frac{y_{\text{obs}}}{c_2}}} \tag{18}$$

$u(y_{\text{obs}})$ can be calculated by Eq. (12).

(B) The inverse method

(a) Linear equation

The form of linear regression model is:

$$x = d_0 + d_1 y. \tag{19}$$

(b) Polynomial equation

The form of polynomial equation is:

$$x = e_0 + e_1 y + e_2 y^2 \tag{20}$$

The uncertainty of x_{pred} is easy to be calculated by the following equation:

$$u(x) = s(x_c) = s\sqrt{\frac{1}{p} + \frac{1}{n} + \frac{(y - \bar{y})^2}{\sum(y_i^2) - (\sum y_i)^2/n}}. \tag{21}$$

3.2. Uncertainty of the reference standard

The reference standard of humidity is made by saturated salt solutions. The scale and the uncertainty of these reference standards is provided by the Organization Internationale De Metrologie Legale (OIML) R121 [10] and Greenspan [5]. The distribution of uncertainty at two temperatures is shown in Fig. 1. No distribution pattern could by found. An approximate estimate of uncertainty for the reference standard is to consider the average value of uncertainty:

$$u_{\text{ref}} = \pm\frac{\sum U_{\text{ref}}}{N_2} \tag{22}$$

where U_{ref} is the uncertainty of humidity made by saturated salt solutions and N_2 is the number of saturated salt solutions for calibration.

3.3. Uncertainty due to temperature variation

The calibration of humidity sensors is performed in standard laboratory environment. Where the temperature is maintained within 25 ± 0.2 °C. The variation response from the temperature variation is assumed a rectangular distribution:

$$u_{\text{temp}} = \pm\frac{K_{\text{temp}}\Delta t}{\sqrt{3}} \tag{23}$$

where K_{temp} is the temperature coefficient of sensitivity per 1 °C. This numeric value is specified in the manufacturer's manual. Δt is half of the ex-

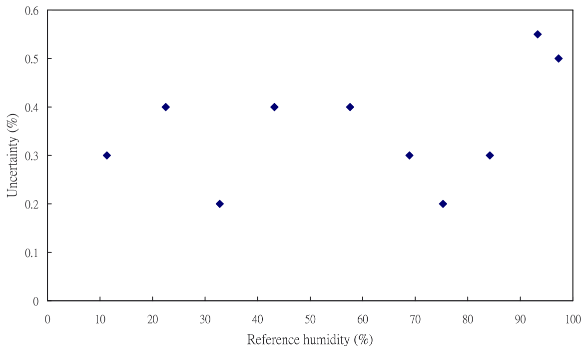

Fig. 1. The uncertainty vs. reference humidity made by saturated salt solutions at 2 °C.

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pected temperature variations ranged during calibration period.

3.4. Uncertainty due to nonlinearity and repeatability

The deviation U_{non} due to nonlinearity and repeatability is specified by manufacturers. The variation response for this error is assumed a rectangular distribution. The uncertainty due to nonlinear and repeatability is calculated as:

$$u_{\text{non}} = \pm \frac{U_{\text{non}}}{2\sqrt{3}}. \tag{24}$$

3.5. Uncertainty due to resolution

The uncertainty measurement due to resolution is assumed a rectangular distribution. It is considered as ±1/2 of the scale value of the display. The uncertainty value due to resolution (U_{res}) is estimated as the follows:

$$u_{\text{res}} = \pm \frac{U_{\text{res}}}{2\sqrt{3}} \tag{25}$$

where U_{res} is the uncertainty due to the resolution effect.

3.6. Uncertainty due to hysteresis

The uncertainty measurement due to hysteresis did not be mentioned by manufacturers. Stevens et al. [18] compared the performance of several relative humidity meters, the effect of hysteresis was insignificant. In this study, the uncertainty measurement due to hysteresis did not be considered.

The uncertainty due to the reference standard, temperature variation, nonlinear and repeatability, and resolution are classified as Type B uncertainty.

4. Calculation of the uncertainty of humidity sensor

4.1. Resistive humidity sensor

The relationship between reading values of resistive humidity sensor and the standard humidity environment made by saturated salt solutions are presented in Fig. 2. The calibration equations with different methods are introduced as follows.

(A) Classical method

In this equation, the standard humidity values serve the independent variables (x), and the reading values of resistive humidity sensors are the dependent variables (y). The calibration equation is calculated by regression analysis.

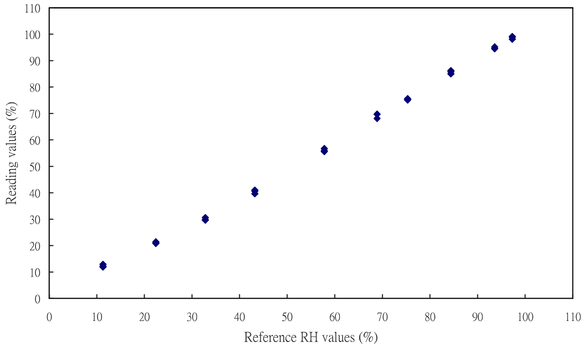

Fig. 2. Relationship between reading values and standard relative humidity values made by saturated salt solutions for resistive humidity sensor.

(a) Linear equation

$$y = -0.572 + 1.00583x$$
$$R^2 = 0.9967, \quad s = 1.836 \tag{26}$$

For the x_{pred}:

$$x_{\text{pred}} = (y_{\text{obs}} + 0.572)/1.00583 \tag{27}$$
$$u(x_{\text{pred}}) = s(y_c)/1.00583 \tag{28}$$

As new observed variable of y is 30% RH, the predicted value of x is 30.395%, $s(y_c) = 1.8795\%$, so the $u(x_{\text{pred}}) = 1.8686$. The values of x_{pred} and $u(x_{\text{pred}})$ for observation of 60% RH and 90% RH can be calculated by Eqs. (27) and (28).

The residual plot of this linear equation is shown in Fig. 3. A systematic pattern is found. In spite of the high R^2 value, the results of the residual plots indicated that the linear calibration equation could not be recognized as an adequate model.

(b) Polynomial equation

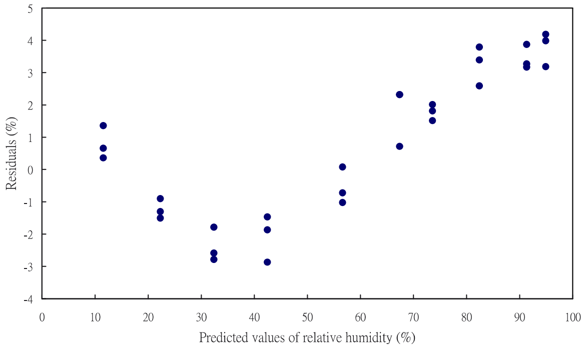

Fig. 3. Residuals plots for classical linear equation for resistive humidity sensor.

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Table 3
The predicted values and uncertainty of three observations for resistive humidity sensor for two types of calibration equations

Calibration method	Regression equation	y_{obs}					
		30% RH		60% RH		90% RH	
		x_{pred}	$u(x)$	x_{pred}	$u(x)$	x_{pred}	$u(x)$
Classical	Linear	30.39	1.8686	60.22	1.8508	90.05	1.8805
	Polynomial	31.46	1.1954	61.88	1.1541	89.22	1.1511
Inverse	Linear	31.31	1.5641	60.51	1.5411	89.69	1.5644
	Polynomial	31.59	1.1843	61.77	1.1926	89.21	1.1865

The result for the polynomial calibration equation is shown as follows:

$$y = 2.7637 + 0.8047x + 1.9409 \times 10^{-3}x^2 \qquad R^2 = 0.9987, \quad s = 1.1656 \tag{29}$$

For the x_{pred}:

$$x_{\text{pred}} = \frac{-0.8047 + \sqrt{22.1037 - 7.7636y}}{3.8818} \tag{30}$$

$$u(x_{\text{pred}}) = \frac{257.6u(y_{\text{obs}})}{\sqrt{4.545 + 515.2y_{\text{obs}}}} \tag{31}$$

The x_{pred} and $u(x_{\text{pred}})$ for three observations: 30%, 60% and 90% are listed in Table 3.

The residual plot for this calibration equation is shown in Fig. 4. The uniformly distribution of the scattered points indicated the equation was adequate.

(B) Inverse method

For the inverse calibration equation, the reading values of resistive humidity sensors are the independent variable (y), and the standard humidity values are the dependent variables (x). The calibration equations were conducted.

(a) Linear equation

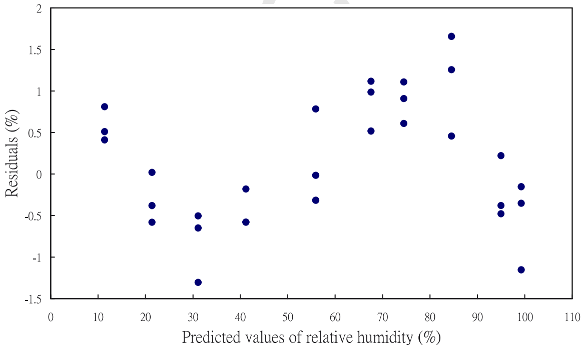

Fig. 4. Residuals plots for classical polynomial equation for resistive humidity sensor.

$$x = 2.1143 + 0.9731y \qquad R^2 = 0.9973, \quad s = 1.517 \tag{32}$$

The residual plot of this equation indicated a clear pattern.

(b) Polynomial equation

The results for the equation were:

$$x = -1.3568 + 1.1439y - 1.5294 \times 10^{-3}y^2 \qquad R^2 = 0.9985, \quad s = 1.1147 \tag{33}$$

The x_{pred} and $u(y_{\text{pred}})$ for three observations are listed in Table 3. The residual plots for this polynomial equation indicated a uniform distribution.

The Type B uncertainty analysis for resistive humidity sensor is calculated by Eqs. (22), (24) and (25). The result is listed in Table 4.

4.2. Capacitive humidity sensor

The relationship between reading values of capacitive humidity sensor and the standard humidity environment from saturated salt solutions is shown in Fig. 5.

(A) Classical method

The calibration equation is:

(a) Linear equation

$$y = -0.2521 + 0.9705x \qquad R^2 = 0.9983, \quad s = 1.1187. \tag{34}$$

Table 4
The Type B uncertainty analysis for resistive humidity sensor

Description	Estimate value (%)	Standard uncertainty $u(x)$ (%)	Probability distribution
Reference standard, U_{ref}	±0.3333	0.1924	Rectangular
Nonlinear and repeatability, U_{non}	±0.25	0.0072	Rectangular
Resolution, U_{res}	0.1	0.0029	Rectangular

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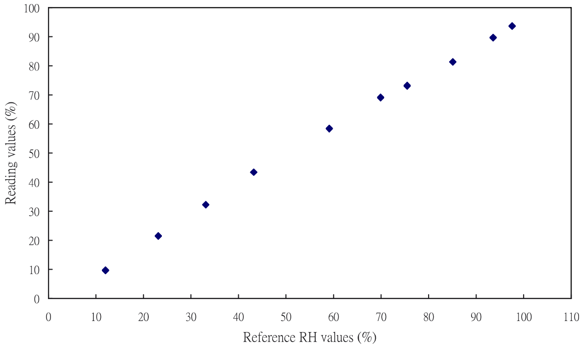

Fig. 5. Relationship between reading values and standard relative humidity values made by saturated salt solutions for capacitive humidity sensor.

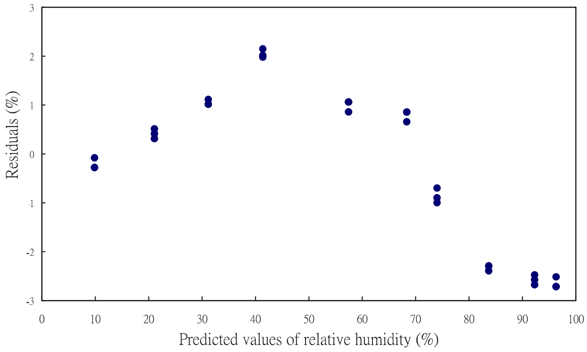

Fig. 6. Residuals plots for classical linear equation for capacitive humidity sensor.

The residual plot is presented in Fig. 6. The clear pattern indicated the linear equation could not be recognized as an adequate model:

$$x_{\mathrm{pred}} = (y_{\mathrm{obs}} + 0.2521)/0.9705 \tag{35}$$

$$u(x_{\mathrm{pred}}) = s(y_{\mathrm{c}})/b_1 \tag{36}$$

The predicted values and uncertainty is listed in Table 5.

(b) Polynomial equation

$$\begin{aligned} y &= -3.877 + 1.1471x - 1.5791 \times 10^{-3}x^2 \\ R^2 &= 0.9997, \quad s = 0.5311 \end{aligned} \tag{37}$$

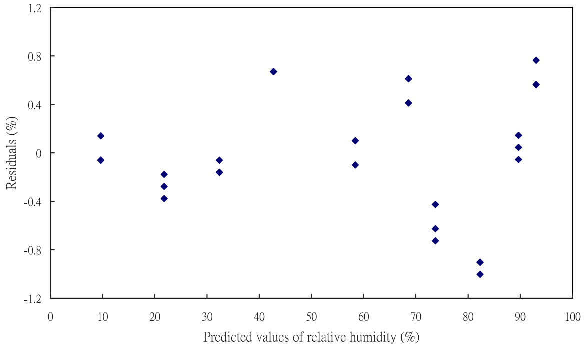

Fig. 7. Residual plots for classical polynomial equation for capacitive humidity sensor of classic polynomial equation.

The residual plots (Fig. 7) showed a systematic pattern and indication the fitting-agreement of this model:

$$u(x) = \frac{316.64u(y_{\mathrm{obs}})}{\sqrt{15654 + 633.3y}} \tag{38}$$

The predicted values and uncertainty is listed in Table 5.

(B) Inverse method

(a) Linear equation

$$\begin{aligned} x &= 0.36025 + 1.0286y \\ R^2 &= 0.9983, \quad s = 1.222. \end{aligned} \tag{39}$$

(b) Polynomial equation

$$\begin{aligned} x &= 3.7345 + 0.8498y + 1.6942 \times 10^{-3}y^2 \\ R^2 &= 0.9997, \quad s = 0.552 \end{aligned} \tag{40}$$

The predicted values and uncertainty is listed in Table 5.

The Type B uncertainty analysis for capacitive humidity sensor is calculated by Eqs. (22)–(25). This result is listed in Table 6.

Table 5
The predicted values and uncertainty of three observations for capacitive humidity sensor for two kinds of calibration equations

Calibration method	Regression equation	y_{obs}					
		30% RH		60% RH		90% RH	
		x_{pred}	$u(x)$	x_{pred}	$u(x)$	x_{pred}	$u(x)$
Classical	Linear	31.17	1.2641	62.08	1.2434	92.99	1.2664
	Polynomial	30.75	0.9354	60.82	1.1343	93.94	1.1663
Inverse	Linear	31.22	1.2611	62.08	1.2425	92.93	1.2699
	Polynomial	30.95	0.571	60.77	0.5736	93.88	0.5815

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Table 6
The Type B uncertainty analysis for the capacitive humidity sensor

Description	Estimate value (%)	Standard uncertainty $u(x)$ (%)	Probability distribution
Reference standard, U_{ref}	±0.3333	0.1924	Rectangular
Temperature, U_{temp}	±0.0075	0.0043	Rectangular
Nonlinear and repeatability, U_{non}	±0.1	0.0058	Rectangular
Resolution, U_{res}	0.2	0.0058	Rectangular

4.3. The combined standard uncertainty (u_c)

Comparing these sources of uncertainty for resistive humidity sensor with Tables 3 and 4, the main source of the uncertainty is from the predicted uncertainty. The uncertainty of polynomial equation is significantly less than that of linear equation for classical or inverse method for resistive humidity sensor. The comparison of the source of uncertainty for capacitive humidity sensor with Tables 5 and 6 also had similar results.

The combined standard uncertainty (u_c) can be estimated from the following equation:

$$u_c = \sqrt{\sum u_i^2} = \sqrt{u_{\mathrm{ref}}^2 + u_{\mathrm{temp}}^2 + u_{\mathrm{non}}^2 + u_{\mathrm{res}}^2 + u^2 X_{\mathrm{pred}}} \qquad (41)$$

The u_c value for two humidity sensors used two calibration equations at three observations are listed in Table 7.

According to Eq. (41), the values of u_c are calculated at 30%, 60% and 90% of the observed humidity. They are found to be 1.8785%, 1.8608%, and 1.8904% for resistive humidity sensor using linear classical calibration equation, respectively. For the polynomial form of calibration equation, the combining standard uncertainty evaluated at 30%, 60% and 90% of the relative humidity were 1.2108%, 1.1701% and 1.1816%, respectively. The linear equation is an inadequate equation by the display of residual plots. This result indicated that the inadequate calibration equation could increase the uncertainty significantly. A similar result also was found for the inverse method and for two calibration methods of the capacitive humidity sensor.

Comparing the combined standard uncertainty of the polynomial equations between the classical model and inverse model for observation values of 30%, 60% and 90% RH, both sets of data did not have a significant difference for resistive humidity sensor.

The values of u_c obtained at 30%, 60% and 90% of the observed humidity for the capacitive humidity sensor had different results. The u_c values of the linear equation are higher than that of polynomial equation for classical and inverse method. The combined uncertainty calculated by calibration equations of the classical method is significantly higher than that of inverse method.

The uncertainty arising from the inadequate calibration equation has been mentioned [19]. The methods of calibrating $u(x)$ due to the addition variation of inadequate equation are proposed in this study. The adding variation of inadequate equation is found as the main source of uncertainty.

The uncertainty analysis has become the basis information for sensors. No literature was found that mentioned the calculation of uncertainty analysis of electrical humidity sensors. In this study,

Table 7
The combined standard uncertainty for two humidity sensors

Humidity Sensor	Calibration method	Regression equation	Observations		
			30% RH	60% RH	90% RH
Resitive	Classical	Linear	1.8785	1.8608	1.8904
		Polynomial	1.2108	1.1701	1.1816
	Inverse	Linear	1.5759	1.5531	1.5762
		Polynomial	1.1999	1.2080	1.2020
Capacitive	Classical	Linear	1.2786	1.2582	1.2810
		Polynomial	0.9550	1.1505	1.1820
	Inverse	Linear	1.2756	1.2573	1.2844
		Polynomial	0.6026	0.6051	0.6126

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the fixed relative humidity point was made by saturated salt solutions. The novelty method of uncertainty calculation was developed. This method was easily applied in a research laboratory.

5. Conclusion

This study evaluated the sources of uncertainty for two types of humidity sensors. These sources include predicted values of calibration equation, reference source, temperature variation effect, nonlinear and repeatability, and resolution source. The study also dealt with the effect of calibration methods and calibration equations on the uncertainty.

The uncertainty analysis shows that the predicted uncertainly is the main source for combined uncertainty. No significant difference of the uncertainty for resistive sensor was found between classical method and inverse method. However, the predicted uncertainty of inverse method is significantly lower than that of classical method for capacitive humidity sensor. For both humidity sensors, the adding variation of inadequate equation is found as the main source of uncertainty.

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