MĀPAN-Journal of Metrology Society of India (June 2014) 29(2):77–85
DOI 10.1007/s12647-013-0069-6

ORIGINAL PAPER

Design and Characterisation of a Temperature Compensated Relative Humidity Measurement System with On Line Data Logging Feature

U. Sarma* and P. K. Boruah

Department of Instrumentation and USIC, Gauhati University, Guwahati 781014, India

Received: 29 March 2013 / Accepted: 26 August 2013 / Published online: 12 October 2013

Abstract: A method of relative humidity (RH) measurement with on line temperature correction and data logging feature is described here. The RH sensor is a thermoset polymer capacitive type with on chip conditioning. Output voltage of RH to voltage converter is digitised using a 12-bit A/D converter and it is interfaced with an 8-bit microcontroller. Temperature correction of RH in real time is done using a temperature to digital converter interfaced with the microcontroller. The corrected data is displayed in a liquid crystal display and transmitted for on line monitoring and logging via RS232C. Calibration of the system is performed using standard saturated binary salt solutions. Accuracy and precision are found out. Hysteresis and ageing effect is discussed. The system performance is also compared with a dry/wet bulb psychrometer at different ambient conditions. The performance of the system in an industrial environment is presented.

Keywords: Relative humidity; Temperature to digital converter; Data logging; RS232 communication; Psychrometer

1. Introduction

The influence of humidity is of paramount importance in wide range of application areas, such as moisture sensitive manufactured goods, textile, food processing, meteorology, clinical instrumentation, integrated chips production, study of the growth of micro organism in living environment [1–3]. Accurate relative humidity (RH) measurement system is an emerging demand for these fields. Refrigeration, heating, ventillation and air conditioning (HVAC) equipment, medical equipment and atmospheric study are also few members of the domain of RH measurement [3–5]. The predicted mean vote, a well recognised human thermal comfort index depends on RH, air temperature, mean air speed, mean radiant temperature, clothing insulation and activity level [6]. The effect of RH on the biocontaminant microenvironment, which may have a spatial scale of the order of few millimeter, has been reported by Baker et al. [2]. In this measurement the RH sensor is a thermoset polymer based capacitive RH sensor with integrated signal conditioning. The ambient temperature is measured by a Pt-100. A standard 6.5 digit resolution data acquisition system is used for the whole measurement.

Accurate measurement and control of RH is a growing demand. From the point of view of data processing and readout system electrical RH sensors are most convenient. Widely used electrical humidity sensors are either capacitive or resistive type [3, 7, 8]. They require stable ac excitation with zero dc bias to prevent polarization [7]. Conditioning hardware with the functionalities like rectification, filtering, and linearization are required for these sensors. This extra hardware introduces error due to the component tolerances and noises from RF and EM interferences. The temperature drift of the conditioning circuit is a major concern over accuracy and precision [9, 10]. Voltage output and 4–20 mA current output humidity sensors reduce these problems to a large extent. Voltage output humidity sensors are basically capacitive or resistive humidity sensor with on chip signal conditioning. It is best suited for industrial application as it comes with factory calibration and on chip signal conditioning. Temperature compensation is one of the crucial steps for online RH measurement. It can be done either by adding temperature sensor and analog computation or by using digital temperature sensor and embedded processor.

An RH measurement system based on wavelength-encoded optical psychrometer has been reported by Montanini [1]. In this system temperatures are measured by means of two fiber Bragg grating sensors used as dry-bulb and wet-bulb thermometers. For the calculation of RH the

*Corresponding author, E-mail: utpalsarma@gauhati.ac.in

measurement of atmospheric pressure has also been measured simultaneously. Thus these three parameters, dry-bulb temperature, wet-bulb temperature and atmospheric pressure determine the RH. So in this method it is necessary to measure the atmospheric pressure separately.

There are several methods of calibration of humidity sensors like two pressure humidity generator, divided flow humidity generator and fixed point humidity system [3, 11–14]. For calibration of top-end dew point and humidity sensors the design and its result of a single pressure dew point generator is presented by Hudoklin et al. [5]. Some of the fundamental standards for humidity calibration are Chilled mirror hygrometer, Electrolytic hygrometer, low cost dry/wet bulb psychrometer [1, 11, 15]. The most convenient and low cost calibration can be achieved by using saturated binary salt solution.

An online RH measurement and datalogging system is presented here. The analog output voltage of RH sensor is digitised using a 12-bit A/D converter and it is interfaced with an 8-bit microcontroller. Temperature compensation for the RH sensor in real time is achieved with the help of a temperature to digital converter (TDC) interfaced with the microcontroller. Pressure correction is not required for this method. The corrected value of RH and ambient temperature is displayed in a liquid crystal display (LCD) and also transmitted for on line monitoring and logging via RS232C to a PC. Calibration of the system using saturated binary salt solution is also presented.The performance of the system is also presented in terms of accuracy, precision, hysteresis, ageing effect, and step response. The performance of the system is compared with a dry/wet bulb psychrometer at different ambient conditions. The performance of the system in an industrial environment is presented.

2. System Architecture

The block diagram of the RH measurement system is shown in Fig. 1. The analog signal from the humidity sensor is fed to a 12-bit serial A/D converter, the reference voltage of which is 4.095 V. The A/D converter is interfaced with a microcontroller in serial synchronous interface (SSI) mode. The digital ambient temperature sensor is interfaced with the same microcontroller in SPI mode. The data conversion, ambient temperature correction is performed by the firmware embedded in the microcontroller. Finally the corrected RH and ambient temperature data is sent to the PC via RS232 interface.

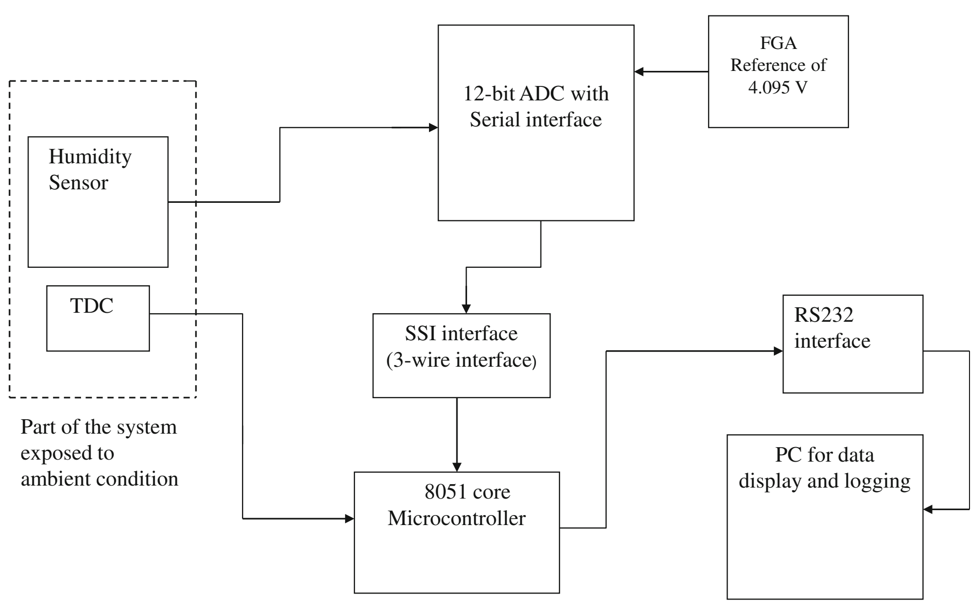
2.1. Sensors

For humidity sensing low power (200 μA) RH to voltage converter is used [16]. It is basically a laser trimmed, thermoset polymer capacitive type sensing element with on chip integrated signal conditioning [2]. The sensing element is resistant to most application hazards such as wetting, dust, dirt, oils and common environmental chemicals due to its multilayer construction. Using straight line fitting the accuracy of the sensor is ±3.5 % of RH. The repeatability and hysteresis of the sensor is ±0.5 and 3.0 % of RH respectively. It requires 4.5–9 V dc (V_{SUPPLY}) supply [2, 6]. The output is ratio metric with the supply voltage. The output voltage (V_{OUT}) and RH can be expressed typically at 25 °C [16] as:

$$\mathrm{RH} = \left(\frac{V_{OUT}}{V_{SUPPLY}} - 0.16\right) \times 161.29\ \%. \tag{1}$$

The temperature compensated RH, $(\mathrm{RH})_{TC}$, is calculated using the following equation [16]:

Fig. 1 Block diagram of the RH measurement system



$$(\mathrm{RH})_{\mathrm{TC}} = \frac{\mathrm{RH}}{(1.0546 - 0.00216\Theta)}\,\% \tag{2}$$

where Θ is the ambient temperature in degree Celsius.

For ambient temperature measurement a TDC TMP121 (Texas Instruments) is taken [17]. This SPI compatible temperature sensor requires no external component for conditioning. Digital data corresponding to the temperature can be read directly [18].

The RH sensor and TDC are assembled close to each other to minimize the temperature gradient between them and exposed to ambient environment.

2.2. Digital Interface

The circuit schematic for the digital interface is shown in Fig. 2. To read the analog voltage output of the RH sensor a 12-bit A/D converter (ADS1286) (U1) (Texas Instruments, USA) with serial interface is selected [19]. This serial A/D converter operates with no missing code, consumes less power (typically 250 μA) and occupies less board space (8 pin PDIP). The reference voltage is applied from a highly stable reference FGA™ (Floating Gate Analog Technology) (X60003B)(U4)(FGA™ is a trademark of Intersil). It features very low temperature co-efficient (10 ppm/°C), excellent long term stability (10 ppm/1000 h), low noise and excellent line and load regulations. It works from input voltage 4.5–9 V [20]. The functioning of the A/D converter is controlled by an 8051 core microcontroller (89S52) (U2), (Atmel). The A/D converter is interfaced with the microcontroller using SSI. The TDC is directly interfaced with the microcontroller in SPI mode to read the ambient temperature. The firmware for calculating RH using Eq. 1 and temperature correction using Eq. 2 is embedded in the flash ROM of the microcontroller. True RH is displayed in the 16 × 2 line character LCD and also sent to a PC via RS232C (U3) for data display and data logging. Port 2 of the microcontroller generates the required control for the LCD. Port 0 is used for data to the LCD.

3. Implementation of Control Algorithm

The control algorithm of the system is implemented in 8051 core microcontroller as discussed in the previous section. The purpose of the algorithm is as follows:

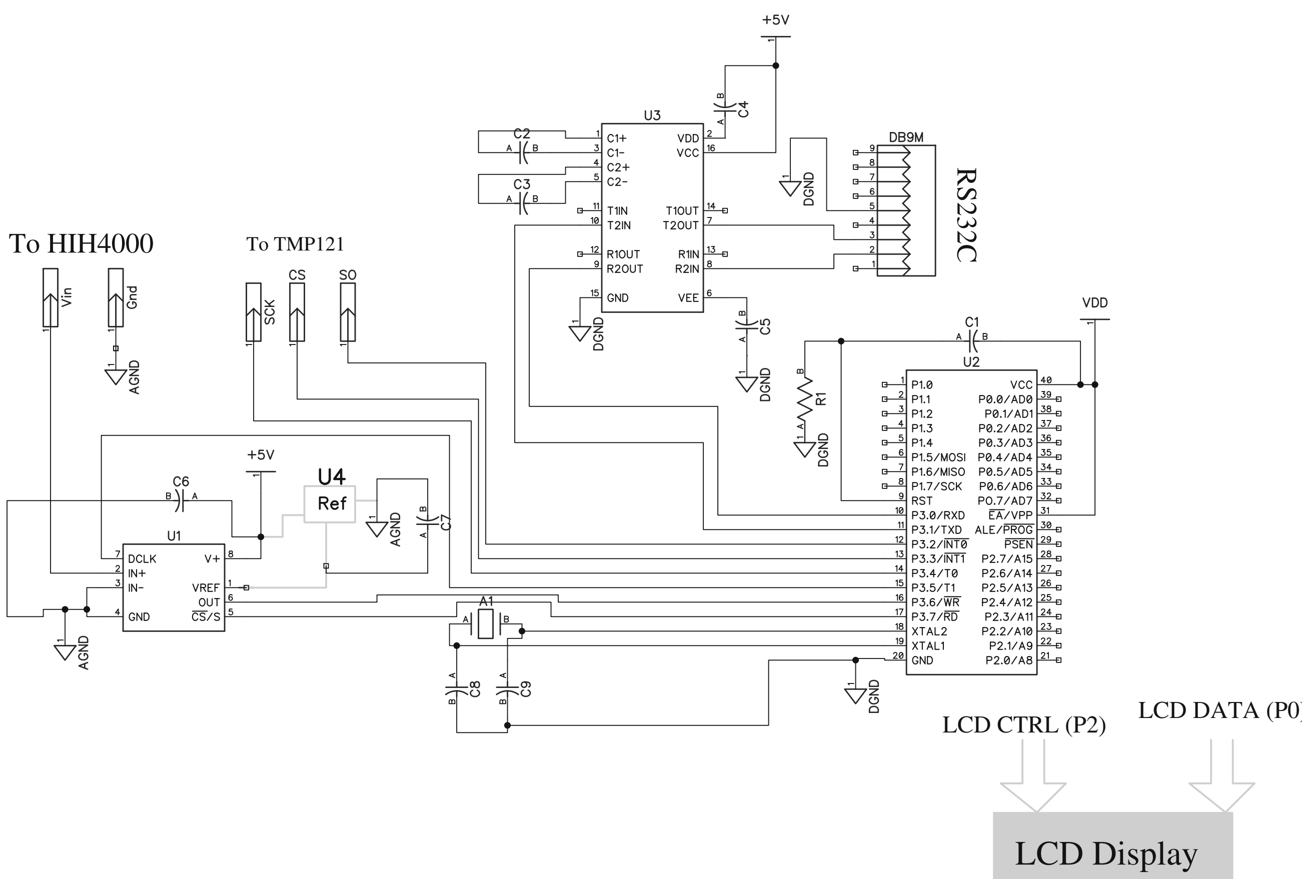


Fig. 2 Circuit schematic of RH measurement system

i) Initialize A/D converter, LCD, UART (Universal Asynchronous Receiver Transmitter) of the microcontroller.
ii) Read A/D converter and TDC.
iii) Calculate RH using Eq. 1.
iv) Calculate True RH using Eq. 2.
v) Send the result to LCD and to PC via RS232.

The program is developed with the help of PK51 from KEIL [21] using 8051 C. The corresponding binary code is flashed to the flash ROM of the microcontroller using an ISP (In System Programming) header.

The calculated time required for conversion of TDC data to corresponding temperature (in °C) using simulation is 0.787 ms for AT89S52 processor running at 11.0592 MHz. In the same condition the time for conversion of the digital data corresponding to the RH sensor output to RH in % is found to be 3.25 ms. As this time is very small in comparison to the rate of variation of the quantities (i.e. ambient temperature and RH) this method of online conversion of data using microcontroller is suitable for such application.

The corrected RH and temperature value is sent to LCD as well as to the PC in ASCII format. RS-232 standard is implemented for sending data from the system to the PC. Data is sent at 9600 baud rate with one start and stop bit with no parity bit.

To receive the data serial COM port of the PC is taken. The terminal program is developed using visual basic (Microsoft). It receives the ASCII data from the system and displays a time plot and a bar graph. Data storing to hard disc option in .txt format is also incorporated.

4. Performance Test of the System

In this section the calibration method and results, hysteresis effect, temperature variation study, determination of precision and dynamic test results of the system are discussed.

4.1. Calibration

The system is calibrated at six points using standard saturated binary salt solution at 25 °C. The selected binary salts are shown in Table 1 [11]. The solutions are prepared according to OIML R121 document [22]. Distilled water is used as solvent. The volume of the salt solution is 40 ml.

Table 1 The selected binary salts with standard RH values [11]

Sample	Standard RH at 25 °C in %
S1: Potassium hydroxide	8.23 ± 0.72
S2: Magnesium chloride	32.78 ± 0.16
S3: Magnesium nitrate	52.89 ± 0.22
S4: Sodium chloride	75.29 ± 0.12
S5: Potassium chloride	84.34 ± 0.26
S6: Potassium sulphate	97.30 ± 0.45

Table 2 Calibration data

Sample #	Standard RH at 25 °C in %	RH measured by the system in %	Error (%)	Precision index in %RH
S1	8.23 ± 0.72	8.26	0.03	0.15
S2	32.78 ± 0.16	34.37	1.59	0.16
S3	52.89 ± 0.22	53.46	0.57	0.15
S4	75.29 ± 0.12	74.92	−0.37	0.13
S5	84.34 ± 0.26	84.20	−0.14	0.20
S6	97.30 ± 0.45	97.25	−0.05	0.18

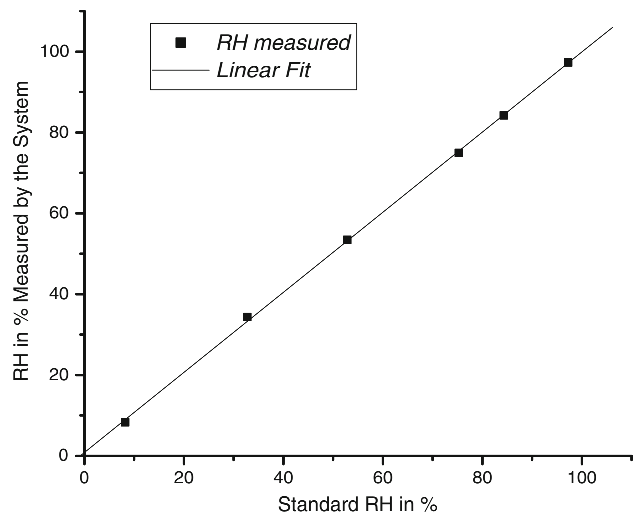


Fig. 3 Calibration curve

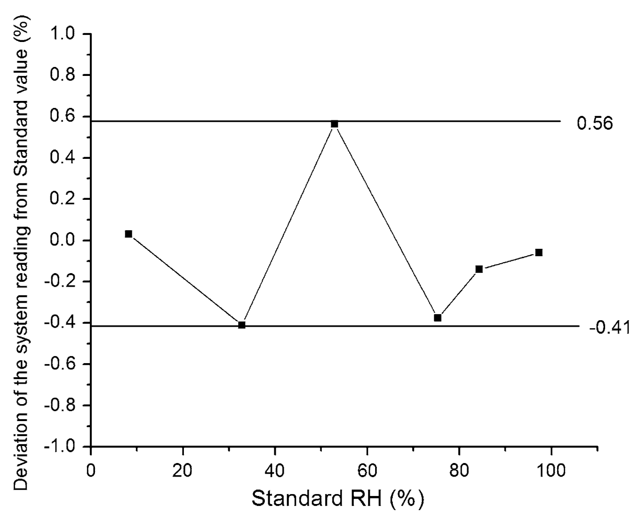


Fig. 4 Deviation from standard value

Table 3 Ambient temperature effect

Temperature in °C	Standard value in %	RH with temp. compensation in %	RH without temp. compensation in %
20	54.38 ± 0.23	54.82	55.40
25	52.89 ± 0.22	54.21	54.21
30	51.40 ± 0.24	51.48	50.96
35	49.91 ± 0.29	49.99	48.94
40	48.42 ± 0.37	48.42	46.88

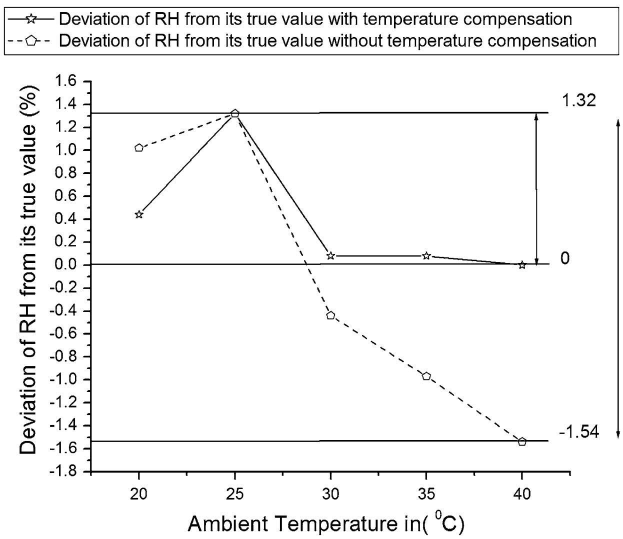


Fig. 5 Effect of temperature compensation

Table 4 Hysteresis effect

Sample #	RH in %		|a−b|
	Increasing(a)	Decreasing(b)	
S1	8.12	8.40	0.28
S2	34.20	34.54	0.34
S3	52.87	54.04	1.17
S4	73.91	75.92	2.01
S5	83.09	85.31	2.22
S6	96.55	97.93	1.38

The sensing part is inserted in the hygrostat which is a closed vessel containing the hygrostatic solution. The variation of RH is monitored on a PC. When system shows a stable value of RH for 30 min, 100 readings are recorded using on line data acquisition facility of the system. To attain this equilibrium the system is taking an average time of 1 h. The average values of the readings with accuracies and precisions are shown in Table 2. The calculated values of accuracy error and precision index are in percentage of full scale output range (FSOR).

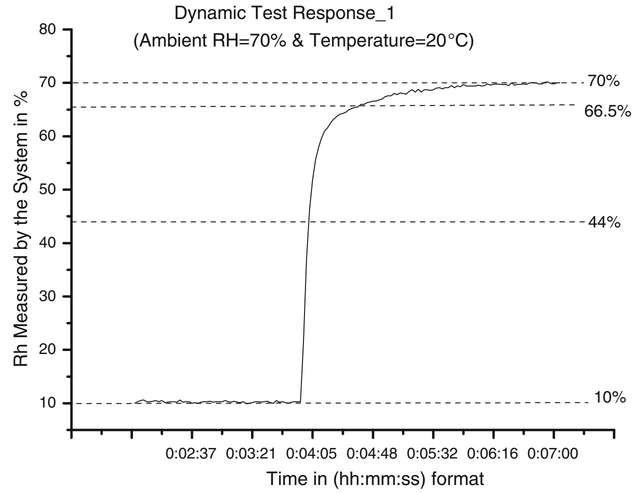


Fig. 6 Dynamic test response_1 (Ambient RH = 70 % and Temperature = 20 °C)

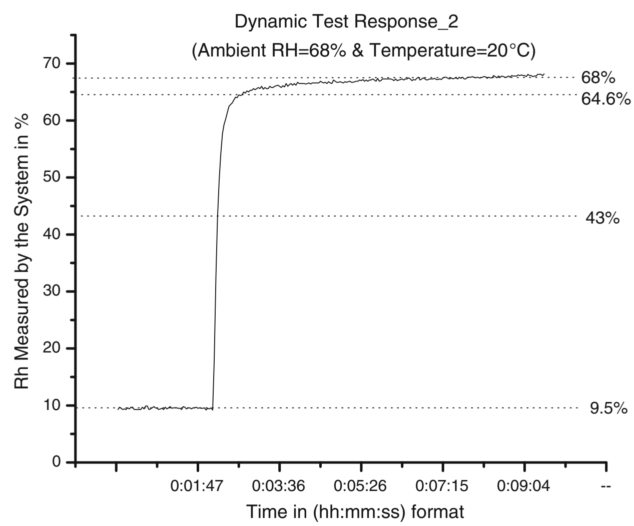


Fig. 7 Dynamic Test Response_2 (Ambient RH = 68 % and Temperature = 20 °C)

Table 5 Result of the dynamic test

Test #	Average ambient RH (%)	Time constant (in s)	Response Time (in s) (in 5 % tolerance band)
1	70	4	42
2	68	5	48

The calibration curve is shown in Fig. 3. The linear fit of the data gives a slope of 0.9899 and an intercept of 0.86229. The value of R (Goodness of Fit) is 0.99982. The deviation of the system reading from the standard value is shown in Fig. 4.

Table 6 Uncertainty budget based on UKAS requirement [24]

Source of uncertainty	Value	Probability distribution	Divisor	Sensitivity co-efficient	Standard uncertainty in %RH
V_{out}	1×10^{-3}	Rectangular	$\sqrt{3}$	40	0.023
V_{supply}	0.1	Rectangular	$\sqrt{3}$	24.6	1.420
Θ	0.0625	Rectangular	$\sqrt{3}$	0.013	4.7×10^{-4}
Combined standard uncertainty					1.420
Coverage factor for confidence level of 95 %					2
Expanded uncertainty					2.84

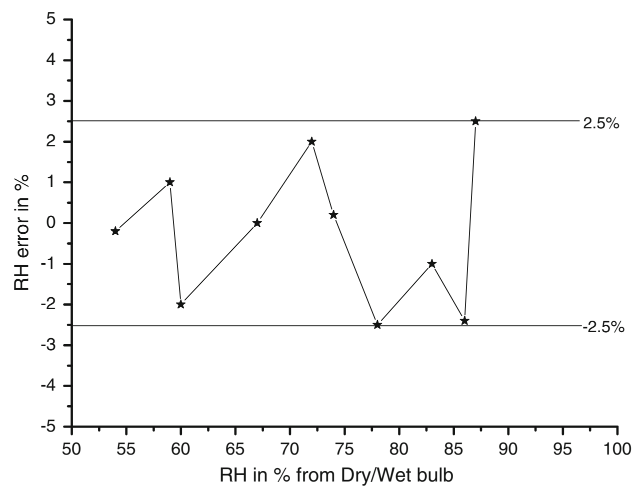


Fig. 8 Deviation of the system reading compared with psychrometer

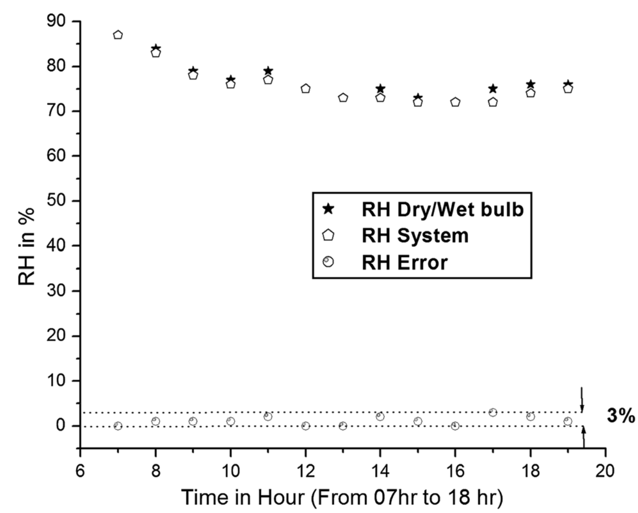


Fig. 9 Plot of data taken by the system for 12 h at 1 h interval

4.2. Effect of Ambient Temperature

To study the effect of ambient temperature on the system, salt S3 (Magnesium nitrate) is considered. From 20 to 40 °C at 5 °C interval the readings are recorded in the same way as discussed in Sect. 4.1. The average values of the recorded data with and without temperature compensation are shown in Table 3.

The data presented in the Table 2 and 3 are taken independently.

The deviation of the readings (both temperature compensated and uncompensated) from standard values at different temperatures are shown in Fig. 5.

4.3. Precision

The precision index as a percentage FSOR of the system for each sample is calculated at 25 °C and is shown in Table 2 [23].

4.4. Hysteresis Effect

The effect of hysteresis is shown in the Table 4. The RH is recorded in the same way as discussed in Sect. 4.1, the samples are considered from low RH to high RH (i.e. from S1 to S6) and then in the reverse way. These data were recorded at stable ambient temperature of 25 °C. The maximum difference |a−b| (Table 4) is found to be 2.22. As the FSOR of the sensor is 100 % hence the maximum hysteresis error as a percentage of FSOR is 2.22 %.

4.5. Ageing Effect

To test the ageing effect of the system, a set of readings is taken at 25 °C for sample S2. The average value of this set of reading is 34.20 %. After 30 days at the same condition another set of readings is taken for the same sample with a freshly prepared solution. The average value of this set of reading is 33.72 %. This variation is within the limit of maximum error. So the ageing effect within this time period is negligible.

4.6. Dynamic Test

The dynamic test of the system is performed and responses are shown in Figs. 6 and 7. For this test the sensor assembly is inserted in the hygrostat containing freshly prepared solution of sample S1 and the change is monitored. The standard RH for this sample at 20 °C is 9.32 %

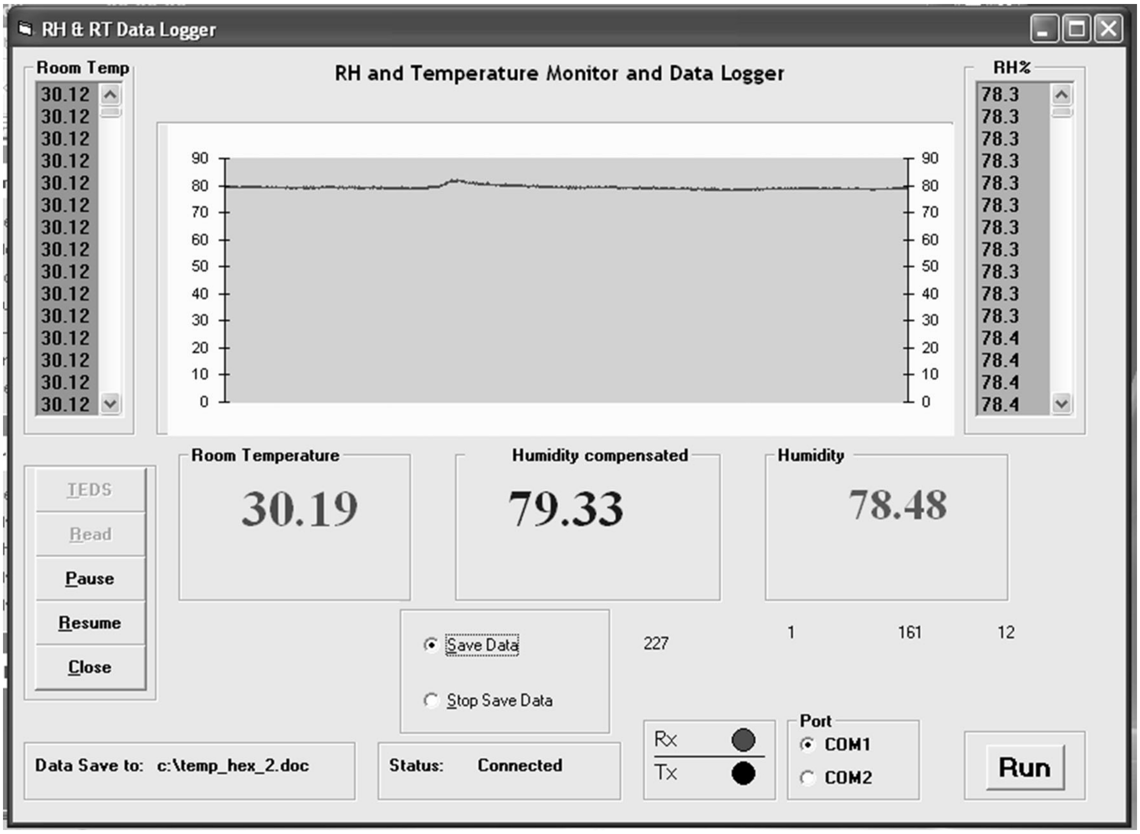


Fig. 10 Screen shot of the GUI (Time taken: 3 h)

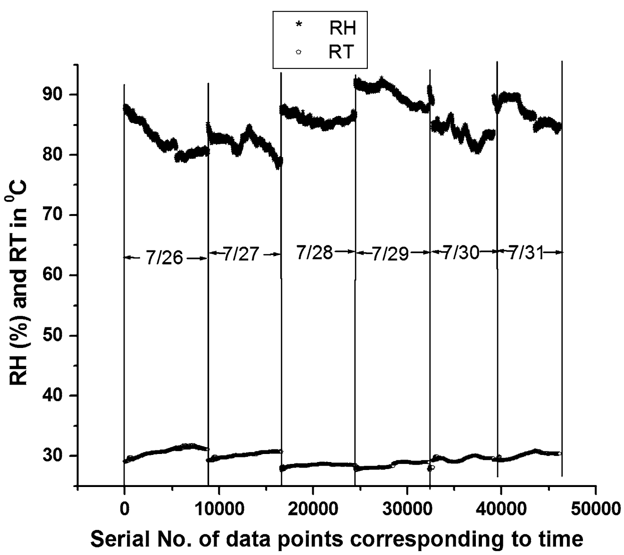


Fig. 11 Variation of RH and RT for 6 days during working hours of factory

[11]. When it attains equilibrium, the acquisition of data is initiated and the sensor is exposed to the ambient environment at 70 %RH and 20 °C temperature. The method is repeated using same sample in a different ambient condition (68 % RH and temperature 20 °C). The time constant and response time of the system from these two sets of data are shown in Table 5.

4.7. Uncertainty Analysis

An uncertainty budget of the system is presented in Table 6. The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a coverage probability of approximately 95 %. The uncertainty evaluation has been carried out in accordance with UKAS requirement [24–26].

The RH of the system is calculated by the firmware integrated to the microcontroller using Eq. 1 and 2 as discussed in Sect. 3. The main sources of uncertainty are V_{OUT}, V_{supply} and Θ. The output voltage of the sensor V_{OUT}, is measured using 12-bit ADC with reference voltage as 4.096 V which gives a resolution of 1 mV. The V_{supply} is obtained from a 5 V linear voltage regulator (LM7805A), tolerance of which is ±0.1 V. The ambient temperature is measured by temperature to digital converter (TMP121) the resolution of which is 0.0625 °C.

As shown in the table the expanded uncertainty is obtained as 2.84. This assessment is obtained at $(\mathrm{RH})_{\mathrm{TC}} = 97.3$ %, $\Theta = 25$ °C, $V_{\mathrm{supply}} = 4.9$ V, and $V_{\mathrm{OUT}} = 3.741$ V.

4.8. Testing of the System in Ambient Condition

The reading of the system is also compared with a dry/wet bulb psychrometer (Make: Zeal, England) in ambient condition [3]. Dry/Wet Bulb Psychrometer is chosen for this purpose as it is convenient to use in the ambient environment. The uncertainty of measurement by a dry/wet bulb psychrometer is around 2–5 % of RH at best [27]. The system has been tested in different ambient conditions at different time. The error compared with the RH from dry and wet bulb is shown in Fig. 8.

It is found that ±2.5 % RH error is shown by the system in the range 54–86 % RH when it is compared with a dry/wet bulb psychrometer in the open environment.

A plot of data taken by the system for 12–1 h interval is shown in the Fig. 9. A corresponding curve representing RH measured by dry/wet bulb method is also shown on the same plot. The maximum deviation shown by this curve is 3 %.

4.9. Field Trial

The system was installed for testing at Sonapur Tea Factory, Sonapur, Kamrup, Assam (India). In tea processing tea leaves are fermented after withering and cutting. The RH and room temperature of the fermentation room are key parameters that determine proper fermentation, which ultimately affects the quality of tea. The system developed was installed in the fermentation room and used to monitor and store the RH and room temperature data. The screenshot of the graphic user interface for data logging and monitoring is shown in Fig. 10. A plot of collected data for 6 days during working hours of the factory is shown in Fig. 11. The system was being run continuously during factory operation and it is found to be fully operational in the industrial environment. The ambient temperature variation in this tea factory is from 20 to 40 °C and ambient RH varies from 60 to 90 % RH during day time from June to November.

The fermentation room is situated at a distance of 30 m from the control room. So RS232C communication works properly in this environment.

5. Conclusion

A temperature compensated RH sensor with data logging feature is successfully developed. Since the sensor output is connected directly to the A/D converter, there is no need of trimming for adjustment of analog output. This, together with the stable reference reduces the error and noise, which may otherwise be large due to necessary trimming. Moreover, the system is capable of independent ambient temperature and RH measurement. As the firmware corrects the RH with temperature on line, it can be used as a temperature compensated RH measurement system provided RH sensor and TDC are installed near to each other. The system can be implemented as a smart transducer interface module (STIM) with slight modification on the network interface section hardware (as RS232 cannot be used for STIM) and firmware.

The calibration with standard saturated salt gives a maximum accuracy of ±1.6 %. The online temperature compensation gives deviation from 0 to 1.32 % of RH from the standard value. But the readings without temperature compensation show deviation from 1.32 to −1.54 % of RH. Thus online temperature compensation improves the performance of the system. The maximum precision index is found to be ±0.20 %RH (Table 2). The system shows a hysteresis error 2.22 % as a percentage of FSOR (Table 4).

The readings are compared with standard dry/wet bulb psychrometer and from the error curve it is found that the maximum variation of error is ±2.5 %.

The behavior of the system is studied in the industrial environment and found to be suitable for such environment.

Acknowledgement Authors gratefully acknowledge the financial support under University Grants Commission's minor research project. The support from Mr. D. Chakraborty and Ms. KunjalataKalita in design and characterization of the system is also acknowledged.

References

[1] R. Montanini, Wavelength-encoded optical psychrometer for relative humidity measurement, Rev. Sci. Instrum., **78** (2007) 025103.

[2] P.H. Baker, G.H. Galbraith, R.C. McLean and C.H. Sanders, The development of instrumentation for the measurement of relative humidity within building microenvironments, Measurement, **39**(6) (2006) 565–574.

[3] T. Lu and C. Chen, Uncertainty evaluation of humidity sensors calibrated by saturated salt solutions, Measurement, **40**(6) (2007) 591–599.

[4] K.P.J. Tangirala, A handheld programmable-logic-device-based temperature and relative-humidity sensor, processor, and display system platform for automation and control of industry processes, IEEE Trans. Ind. Appl., **46**(4) (2010).

[5] D. Hudoklin, J. Bojkovski, J. Nielsen and J. Drnovsek, Design and validation of a new primary standard for calibration of the top-end humidity sensors, Measurement, **41**(9) (2008) 950–959.

[6] W.L. Tse and W.L. Chan, Real-time measurement of thermal comfort by using an open networking technology, Measurement, **40**(6) (2007) 654–664.

[7] Choosing humidity sensor: a review of three technology, http://www.sensorsmag.com/sensors/humidity-moisture/choosing-a-humidity-sensor-a-review-three-technologies-840. Accessed 20 Nov 2010.

[8] G. Nikolov and B. Nikolava, Design, development and calibration of virtual system for relative humidity measurement, Sens. Transducers, **93**(6) (2008) 1–14.

[9] Y. Wang and Z. Zhao, A mini high-precision digital measurement system of electrical resistance temperature based on MSC1210, IEEE ICIA Conference (2004) 220–223.
[10] J.M. Dias Pereira et al., Minimizing temperature drift errors of conditioning circuit using artificial neural networks, IEEE Trans. Instrum. Measurement, **49**(5) (2000) 1122–1127.
[11] L. Greenspam, Humidity fixed points of binary saturated aqueous solutions, J. Res. Natl. Bur. Stand., **81**A (1977) 89–96.
[12] E.E. Mahmoud, Realization of relative humidity scale from 10% to 98% at 25°C, MAPAN-J. Metrol. Soc. India, **24** (2009) 241–245.
[13] B. Singh, H. Kishan and Y.P. Singh, Calibration of special relative humidity and temperature (RHT) sensors and evaluation and expression of uncertainty in the Measurement, MAPAN-J. Metrol. Soc. India, **23** (2008) 115–121.
[14] H. Kishan, B. Singh and Y.P. Singh, Mixed flow relative humidity generator, MAPAN-J. Metrol. Soc. India, **23** (2008) 21–24.
[15] P.R. Wiederholdetal, True accuracy of humidity measurement, http://sensormag.com. Accessed 1 Dec 2009.
[16] Datasheet of HIH4000 at http://sensing.honeywell.com/index.cfm/ci_id/1/document/1/re_id/0. Accessed 18 Nov 2009.
[17] Datasheet of TMP121 from Texas Instruments http://www.ti.com. Accessed 18 Nov 2009.
[18] U. Sarma and P.K. Boruah, Design and development of a high precision thermocouple based smart industrial thermometer with on line linearization and data logging feature, Measurement, **43** (2010) 1589–1594.
[19] Datasheet of ADS1286 from Texas Instruments http://www.ti.com. Accessed 18 Nov 2009.
[20] Datasheet of X60003BIG3-41T1 fromIntersil http://www.intersil.com. Accessed 18 Nov 2009.
[21] http://www.keil.com. Accessed 29 Nov 2009.
[22] OMIL, The scale of relative humidity of air certified against salt solutions, Organization Internationale De MetrologieLegale OMIL R 121, (1996).
[23] E.O. Doeblin, Measurement systems application and design, 5th ed., TMH, New Delhi (2007) pp. 40–222.
[24] UKAS M3003, The expression of uncertainty and confidence in measurement, 3rd ed., UKAS New York (2012).
[25] A.S. Tistomo, A. Achmadi and I.A. Rifai, Characterization of KIM LIPI's relative humidity standard, MAPAN-J. Metrol. Soc. India, (2013). doi:10.1007/s12647-013-0055-z.
[26] A.N. Johnson, C.J. Crowley and T.T. Yeh, Uncertainty analysis of NIST's 20 liter hydrocarbon liquid flow standard, MAPAN-J. Metrol. Soc. India, **26** (2011) 187–202.
[27] A. Dyer Stephan, Survey of instrumentation and measurement; 1st ed., Wiley-IEEE, New York (2001) pp. 668–669.