MĀPAN-Journal of Metrology Society of India (September 2015) 30(3):211–219
DOI 10.1007/s12647-015-0142-4

ORIGINAL PAPER

A Sensor Network to Monitor Process Parameters of Fermentation and Drying in Black Tea Production

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Received: 26 November 2014 / Accepted: 04 June 2015 / Published online: 25 June 2015

Abstract: Fermentation and drying process in tea production are two important processes which play a crucial role in producing good quality tea. Tea colour and flavour are formed in the fermentation and enzyme reactions are terminated and moisture contents are reduced from the leaf particles in the drying process. Ambient temperature and relative humidity (RH) are two major factors for the fermentation process. Firing temperature of dryer is also responsible for the final quality of tea. This paper presents an instrument comprising of sensor network to monitor temperature and RH for the fermentation process and firing temperature of the dryer. For dryer temperature monitoring a thermocouple based measuring system is developed. For fermentation an RH to voltage converter and temperature to voltage converter type sensor is used to develop the RH and temperature monitoring sensor node. The sensor nodes for different stages are connected in RS 485 network. Data are logged into the hard drive of a personal computer using the developed data acquisition software. The instrument will be helpful for recording these parameters and so that their influence can be determined and final quality can be improved.

Keywords: Tea production; Temperature; Relative humidity; RS 485; Thermocouple

1. Introduction

Tea is the most widely consumed beverage throughout the world and grown widely in countries of Asia, Africa and the Near East. Among these, Assam (India) is very rich in tea production and it is an important agricultural and export item. It plays an important role to the economic growth of India in general and Assam in particular. In Assam, tea is grown both in the Brahmaputra and Barak plains. Tinsukia, Dibrugarh, Sibsagar, Jorhat, Golaghat, Nagaon and Sonitpur are the districts where tea gardens are mostly situated. Almost 2500 numbers of tea gardens (including the small tea growers) are there in Assam producing almost 51 % of the tea produced in India and about 1/6th of the tea produced in the world [1, 2].

Assam is the single largest tea-growing region in the world. The reason behind this is- the low altitude, rich loamy soil conditions, ample rainfall and a unique climate. Because of the special and unique environmental condition, the tea production is satisfactory in this reason [1].However, in the factory, different process parameters like temperature, RH, moisture content are monitored and controlled by manual means and sometimes even by guesswork [3].

Tea is produced from the plant *Camellia sinensis*. There are different varieties of tea—green tea (unfermented), black tea (fully fermented), Oolong tea (partially fermented) etc. and out of these, black tea is the most common beverage. After tea leaves are plucked from the tea plants, a number of processing stages, viz., withering, preconditioning, cut–tear–curl operation (CTC), fermentation and drying, etc. are involved in producing finished black tea as shown in the Fig. 1 [4, 5].

Fermentation is one of the important processes which is responsible for the quality of tea. In this process, tea leaves change colour and smell after proper withering and CTC. Generally fermentation takes place in fermentation floor, trough or conveyor. The residence time of tea leaf in the fermentation process is also an important issue and it plays a pivotal role in deciding final quality of the finished black tea [6]. It is a complex chain of biochemical reactions that take place during the fermentation process and once such changes reach their optimum point, the process should be

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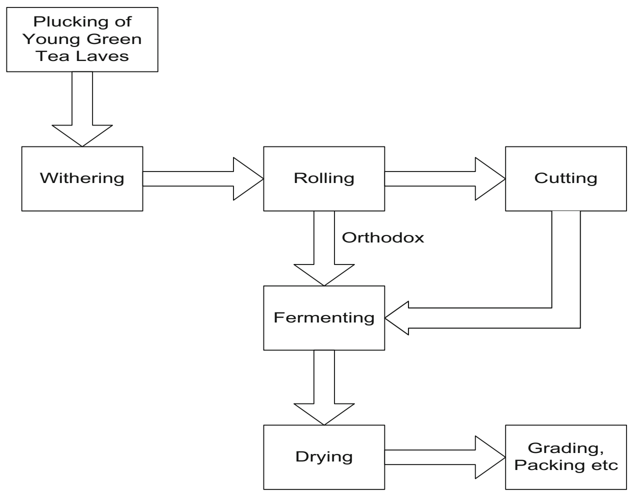

Fig. 1 Block diagram of the tea processing stages

stopped [7]. The Physical Parameters that affect the fermentation process are (i) RH, (ii) temperature, and (iii) aeration. Thus, control of these physical parameters as well as catechin composition and enzyme activity of the leaf source will be very useful for manipulation of fermentation to have desired quality of tea [5, 8]. Some pioneering work had been done by Bhattacharya et al. [9] where electronic nose based technique is used to monitor the fermentation process of black tea and correlated these data with the results of colorimetric tests and human expert evaluation. In another study of Bhattacharya et al. [5], it is reported that the optimum fermentation time can be detected by electronic nose based technique where electronic nose readings accurately matched with the colorimetric as well as human panel data.

Drying is the process by which enzyme reactions during the fermentation process are terminated and moisture content is reduced to about 3 %. To do this, fermented tea is passed through hot air dryer. For conventional dryer, an inlet temperature between 82 and 99 °C and the exhaust temperature between 49 and 54 °C have been found to be satisfactory [10]. The study of Temple et al. reveals that for fluidized bed dryer, [11] the exposure to at least 80 °C is necessary to quality development and maximum 120 °C can be tolerated for 1 min without effecting the quality, but, temperatures 110 °C and above may be considered as reducing quality. Precise measurement of hot air temperature at the inlet of a dryer is a crucial factor for tea quality [3].

Various analytical techniques were compared with sensory methods with emphasis on tea polyphenols which are described by Sujith Kumar et al. [12]. They concluded that application of biosensor would be effective for the evaluation of market value of tea. They used some conventional analytical techniques such as spectrophotometry, high performance liquid chromatography (HPLC) and commission international de I'Eclairage (CIE) system for the study. Samanta et al. [13] presented the importance of fermentation time and temperature for manufacturing of quality black tea. They evaluated the biochemical changes with fermentation temperatures and durations. As the RH in fermentation room is maintained at some constant range so the impact of the RH on final quality is not reported in this study. They maintained the temperature and RH with an environment control chamber in their laboratory environment at the time of the experiment. So a system is needed in the factory environment without interrupting their normal production procedure which can be useful for quality assessment as well as process monitoring.

Sarma et al. developed such system for monitoring RH and temperature of fermentation room [14, 15] and dryer temperature [16, 17]. Moghavvemi et al. [18] also developed an RH and temperature measurement instrument with built-in sensing circuitry. But networking capability is not incorporated with these systems and they need individual monitoring and data logging. These parameters are distributed in the tea factory, so network based system is useful for monitoring these parameters simultaneously with a central monitoring system.

This paper describes development and implementation of an RS 485 based smart sensor network for monitoring of fermentation room parameters [19] and dryer temperature of tea processing in the factory environment without interrupting the normal production. Fermentation room monitoring sensor node and dryer temperature measurement sensor node are connected in RS 485 bus and finally data from all the measurement system are recorded in the hard drive of personal computer. Data acquisition software is developed in NI LabVIEW. The reason of choosing RS 485 based network is its sufficient reliability for the stated purpose and relatively low cost over wireless sensor network. An RH to voltage converter and temperature to voltage converter type sensor is used to measure the fermentation room monitoring system. Dryer temperature is measured by K type thermocouple based measurement system. Calibration technique, error analysis and uncertainty of measurement are also described in this paper.

2. Materials and Methods

The Block diagram of the installed instrumentation system to monitor tea process parameters for CTC tea factory is given in Fig. 2. Total six sensor nodes are required to monitor the process parameters of the fermentation room, dryer and the ambient condition. Sensor node 1 is placed to record ambient temperature and RH. Sensor nodes 2–4 are

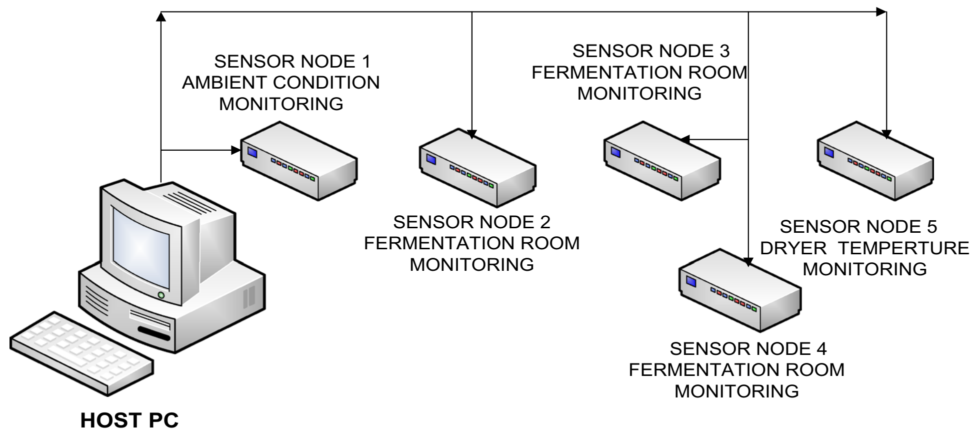

Fig. 2 Block diagram of the process parameters monitoring system of tea factory

installed in the fermentation room to monitor average temperature and RH. Sensor node 5 is installed in the dryer inlet to monitor the firing temperature of dryer.

2.1. Dryer Temperature Monitoring Sensor Node

For dryer temperature monitoring a K type thermocouple based measurement system is developed. The block diagram of the sensor node is given in Fig. 3. The signal conditioning for thermocouple is achieved by AD595 [20] which offers complete instrumentation amplifier and thermocouple cold junction compensator on a monolithic chip. It combines an ice point reference with a pre calibrated amplifier to produce a high level (10 mV/°C) output directly from a thermocouple signal. The output of the AD 595 is connected with a 10 bit built in ADC of the PIC microcontroller [21]. The application algorithm embedded in the PIC microcontroller is used for A/D conversion and communication through RS 485 network bus [22].

2.2. Analysis of Signal Conditioning Circuit

AD 595 provides complete signal conditioning circuit for K type thermocouple. The signal conditioning circuit is tested in the range of ambient temperature (34 °C on that specific day) to 130 °C as the temperature in the dryer is maintained within the range of 80–120 °C. The output voltage of the signal conditioning circuit is recorded with the help of digital multimeter (DMM) and the thermocouple output in mV is recorded by another DMM (AGILENT U1252B). The experiment is done for ten times and average thermoemf is calculated from those data. The standard temperature is calculated from the NIST data [23]. A relation between standard temperature and the signal conditioning output of the thermoemf is found by applying a least square linear fitting algorithm. The relation is given below

$$y = ax + b \quad (1)$$

where coefficients $a = 10.49$, $b = 9.425$ and 'x' and 'y' represent temperature and thermoemf respectively. The temperature is recalculated using the Eq. (1) to get the deviation of temperature from the actual one (found from NIST data) which gives the observational error pattern. It is needed here to estimate the observational error of the signal conditioning part. The variation of error with actual temperature is found from 0.7 to −0.9 °C as shown in Fig. 4.

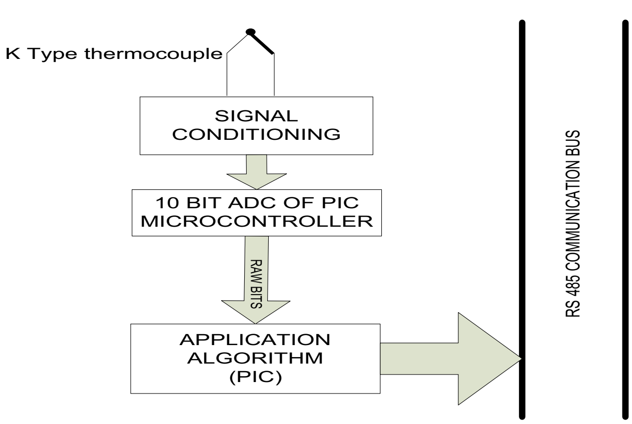

Fig. 3 Block diagram of dryer temperature monitoring system

2.3. Fermentation Room Monitoring Sensor Node

An RH to voltage converter (HIH 4000) [24] and temperature to voltage converter type sensor (LM 35) [25] are used to develop the RH and temperature monitoring sensor node. The block diagram is given in Fig. 5. The temperature is sensed by the sensor LM 35 (temperature to voltage converter) and the voltage is read by the 10 bit built in ADC of the PIC microcontroller [21]. The analog signal from the humidity sensor is fed to the same microcontroller and analog to digital conversion is done by another 10 bit built in ADC. In case of RH measurement ambient temperature effect is nullified by temperature compensation using Eq. (3) [15, 24]. The system is calibrated [15, 19, 26] and the digital data are sent to PC via RS 485 communication. All these conversion and communication is done by

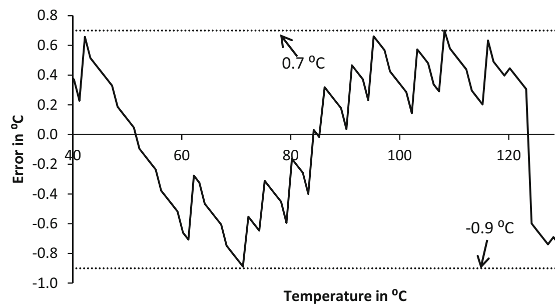

Fig. 4 Error curve for the range of ambient temperature to 130 °C with linear fitting

the application algorithm embedded in the microcontroller. The transceivers for RS 485 communication in both the cases are MAX 485 [27].

2.4. Specifications of the Sensors

(a) *Sensing the temperature*

   (i) *Thermocouple* A K-type thermocouple is used to measure the firing temperature of the dryer [17].

   (ii) *LM 35* It is an IC temperature sensor which gives 10 mV/°C output with ±1.5 °C accuracy [25].

(b) *Sensing the RH* For sensing RH, low power RH to voltage converter is used. It is basically a LASER trimmed, thermoset polymer capacitive type sensing element with on chip integrated signal conditioning. The accuracy of the sensor is ± 3.5 % at 25 °C with 5 Volt Dc supply. The output voltage (V_{OUT}) and RH can be expressed typically at 25 °C as [15, 19, 24, 26]:

$$\mathrm{RH} = \left(\frac{V_{\mathrm{OUT}}}{V_{\mathrm{SUPPLY}}} - 0.16\right) \times 161.29\,\% \qquad (2)$$

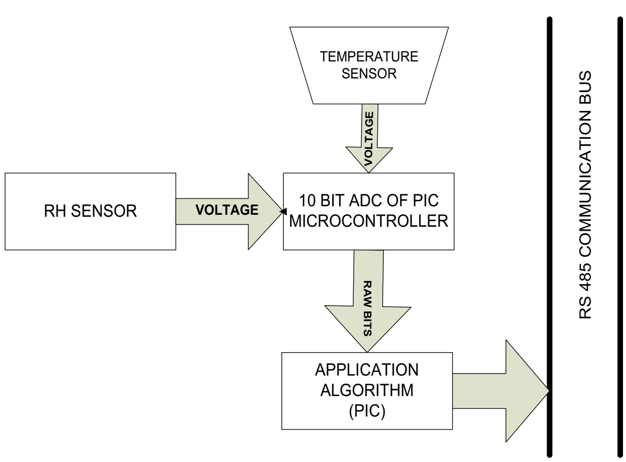

Fig. 5 Block diagram of RH and temperature monitoring system

The temperature compensated RH can be represented as

$$\mathrm{RH} = \left(\frac{\mathrm{SensorRH}}{1.0546 - (0.00216 \times T)}\right),\ T\ \mathrm{in}\ ^\circ\mathrm{C} \qquad (3)$$

2.5. Firmware Development

The firmware is developed in MPLAB IDE of Microchip Technology using PIC C language. The function of the firmware developed for PIC18F452 [21] is shown in Fig. 6.

Data transfer specification is given below

Baud rate: 9600
Data bits: 8
Parity: None
Stop bits: 1

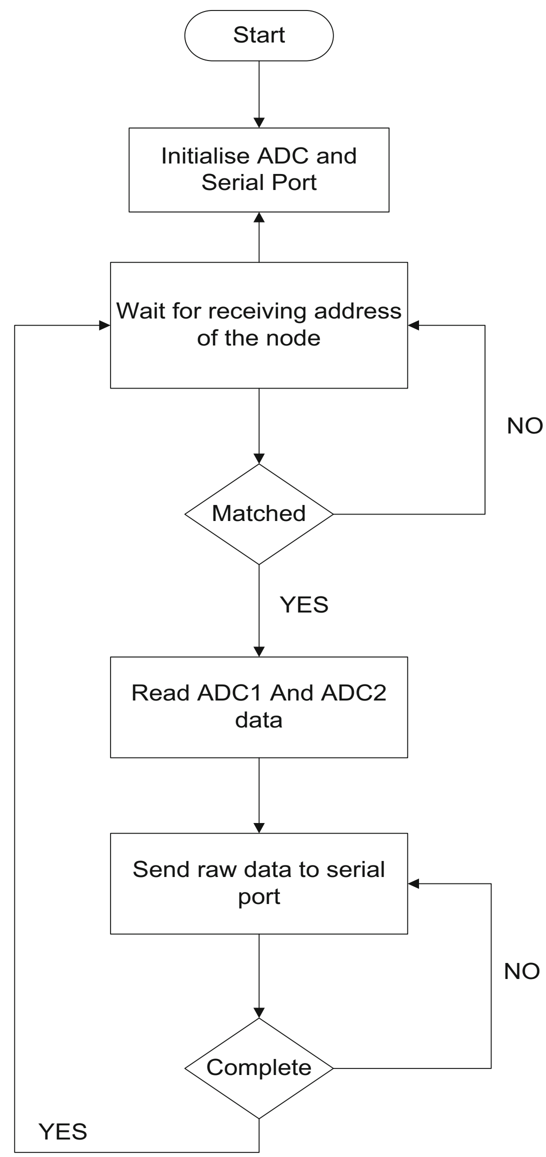

Fig. 6 Flowchart of the firmware embedded in the microcontroller

2.6. Data Acquisition Software

The software required at PC to send and receive data serially using RS 485 protocol is developed in Lab VIEW. The primary responsibility of the software as under

(i) Send the address of the sensor node through COM port.
(ii) Receive digital data from the matched node.
(iii) Separate the digital data with the help of signature attached with the data.
(iv) Convert the data to RH/temperature and online temperature compensation.
(v) Display the data.
(vi) Store the data in HDD.

The digital data is converted to temperature and RH in this software. The format of the signature sent by the PC is shown in Fig. 7 and the format of the data received by the PC is in Fig. 8a, b. In Fig. 7 the data frame comprises of the address of the sensor node with one start bit and one stop bit. In Fig. 8a, the data sent from the sensor node consisting of total seven bytes and significance of each byte is shown there. Each byte comprises of one start bit and one stop bit and eight data bits as shown in Fig. 8b.

Screenshot of the data acquisition software is given in Fig. 9.

3. Calibration of the System

3.1. Calibration of Fermentation Room Monitoring Sensor Node

The system is calibrated [15, 19, 26] using four standard saturated binary salt solutions at 30 °C using the setup as given in Fig. 10. The corresponding RH values for the selected binary salts are shown in Table 1 [28]. The system is calibrated in the range of 50–100 % as the fermentation room is maintained in the specified range. The solutions are prepared according to OIML R121 [29] standard where distilled water is selected as solvent. The sensing part is inserted in hygrostat which is a closed vessel containing the solution. The RH and temperature are recorded in a PC and after showing a stable value, 100 readings are taken for

Fig. 7 Format of the signature sent to sensor node from PC

Start Bit (1 bit)	Node Address (1 byte)	Stop bit (1 bit)

Fig. 8 **a** Format of the data sent to PC from sensor node. **b** Format of each byte shown in Fig. 8**a**

Signature of the parameter (1 byte)	Signature of the Sensor node (1 byte)	Data (5 byte)				

(a)

Start Bit (1 bit)	Data Byte	Stop bit (1 bit)

(b)

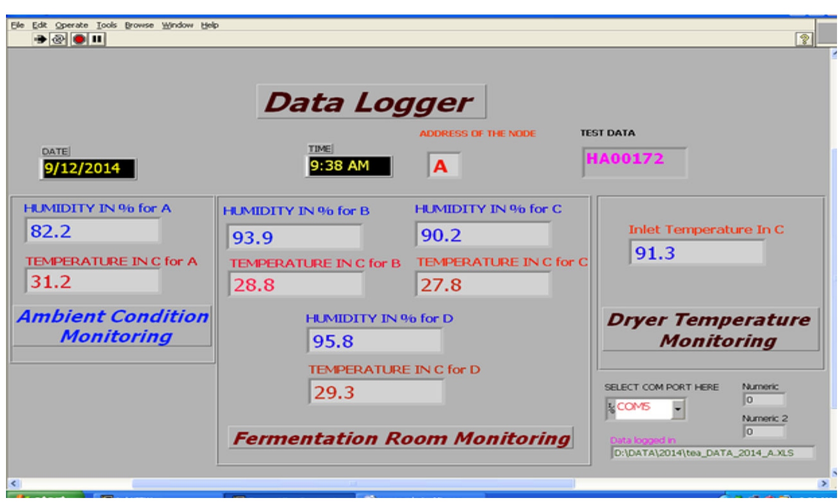

Fig. 9 Screenshot of the data acquisition software

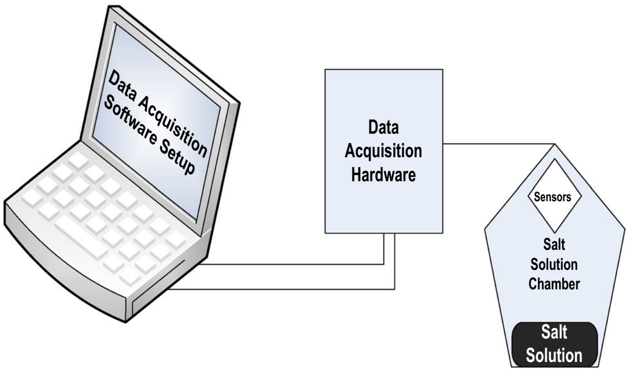

Fig. 10 Calibration setup of the temperature and RH measurement system

Table 1 The selected binary salts with standard RH values

Sample	Standard RH (%) at 30 °C
S1: magnesium nitrate	51.40 ± 0.24
S2: sodium chloride	75.09 ± 0.11
S3: potassium chloride	83.62 ± 0.25
S4: potassium sulphate	97.00 ± 0.40

calculation. Uncertainty of measurement is also calculated from the recorded data using Type A uncertainty evaluation method [26, 30–35]. In type A evaluation, uncertainty of measurement is calculated using the standard deviation of the independent observations. Here it is calculated using the following equation

$$u = \frac{s}{\sqrt{n}} \tag{4}$$

where u is the uncertainty of measurement, s is the standard deviation of the observation, and n is the number of observations.

This method reflects the precision of the measurement. Calibration data of RH and temperature measurement system with uncertainty of measurement is shown in Table 2. Calibration curve is shown in Fig. 11. The deviation of system reading from the standard value is shown in Fig. 12.

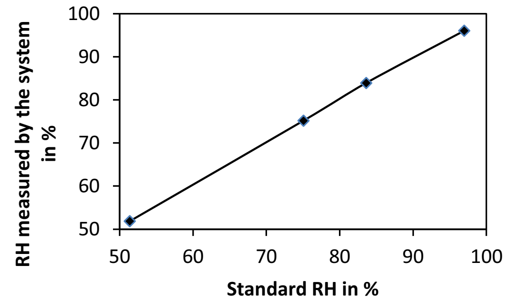

Fig. 11 Calibration curve of RH

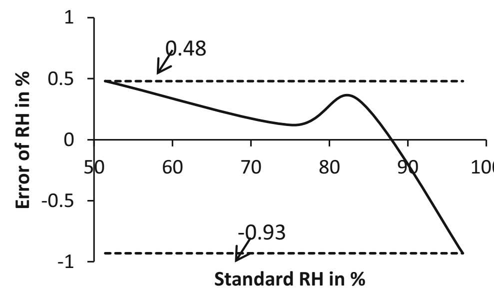

Fig. 12 Deviation from standard value

3.2. Calibration of Dryer Temperature Measurement Sensor Node

The system is calibrated using the setup [17] as shown in the Fig. 13. The thermocouple is inserted in the heating chamber where a variac is adjusted to maintain a stable temperature. The change in thermoemf and the corresponding temperature change of the chamber are measured simultaneously. The change in thermoemf of the thermocouple due to the temperature change is measured by DMM (AGILENT U1252B) with 1 µV resolution. The corresponding temperature from NIST data [23] for K type thermocouple is taken. The calibration curve as well as error curve is shown in Figs. 14 and 15.

Uncertainty of measurement is also estimated for the dryer temperature measurement sensor node by type A evaluation method [26, 30–35]. The temperature is kept

Table 2 Calibration data of RH and temperature measurement system with uncertainty of measurement

Sample	Standard %RH at 30 °C	Mean RH (%) measured by the system	Mean temperature at °C	Standard Deviation		Uncertainty of measurement (±) for	
				RH (%)	Temperature (°C)	RH (%)	Temperature (°C)
S1	51.40 ± 0.24	51.88	30	0.58	0.39	0.058	0.039
S2	75.09 ± 0.11	75.21	30	0.66	0.57	0.066	0.057
S3	83.62 ± 0.25	83.95	30	0.32	0.42	0.032	0.042
S4	97.00 ± 0.40	96.07	30	0.37	0.50	0.037	0.050

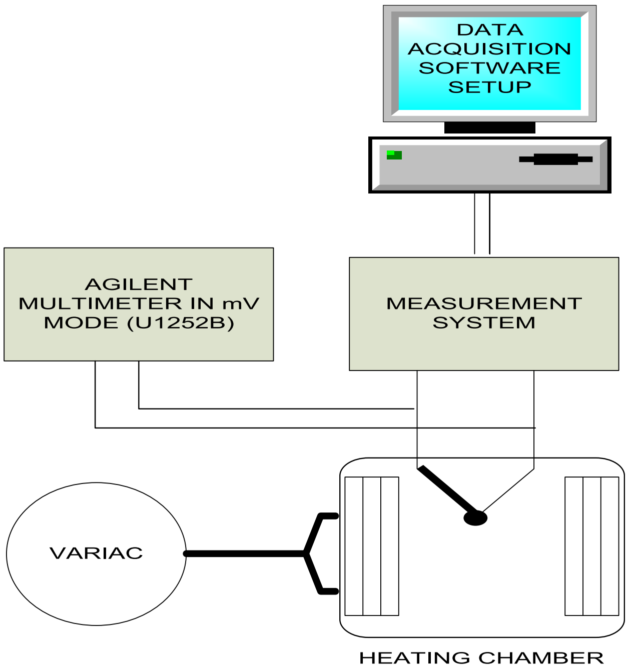

Fig. 13 Calibration setup of the dryer temperature measurement system

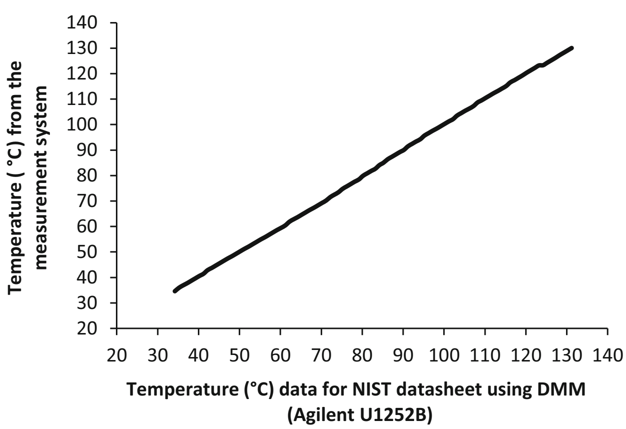

Fig. 14 Calibration curve of dryer temperature measurement sensor node

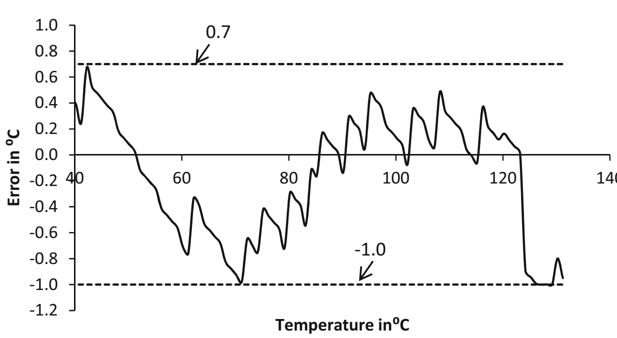

Fig. 15 Experimental error curve for dryer temperature measurement sensor node

Table 3 Uncertainty of measurement of the dryer temperature measurement sensor node

S. no.	Constant temperature (°C) measured by AGILENT U1252A (A)	Mean temperature (°C) measured by the system (B)	SD for column (B)	Uncertainty of measurement (±) for column (B)
1	33.7	34.3	0.4	0.04
2	46.9	46.6	0.3	0.03
3	56.5	56.7	0.3	0.03
4	70.3	69.7	0.2	0.02
5	81.3	80.9	0.3	0.03

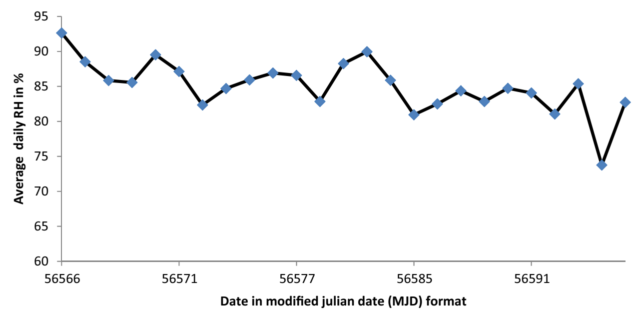

Fig. 16 Variation of daily average RH of tea fermentation room for (01/10/2013–31/10/2013)

constant for five different temperatures as shown in Table 3. Temperature is measured and calculated from NIST datasheet by measuring the thermoemf using DMM in mV mode and by the system. A set of 100 readings are taken at constant temperature of the chamber and unaltered ambient condition. Table 3 represents the uncertainty of measurement of the dryer temperature measurement sensor node using Type A method as described in Sect. 3.1 using the Eq. (4).

4. Field Test

The system described above has been designed, developed and successfully installed and operated in a tea factory near Mangaldoi, Assam, India after continuous testing for 3 months in the laboratory. The acquired data shows ±8 % maximum variation from the average in case of RH and ±2.5 °C maximum variation in case of temperature for a particular day of the fermentation room of the tea factory during tea production. Analysis of data for 102 days shows the average variation of RH as 83–90 % and temperature from 27 to 32 °C in the fermentation room. It also shows ±9 °C variation in firing temperature. The average firing temperature varies from 82 to 100 °C. The above analysis is for the period of 26/07/2013 (when it is installed) to 03/12/2013 (when the season ends). Figures 16, 17 and 18

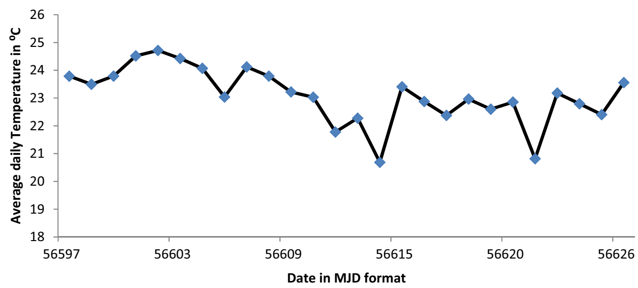

Fig. 17 Variation of daily average temperature of tea fermentation room for (01/11/2013–30/11/2013)

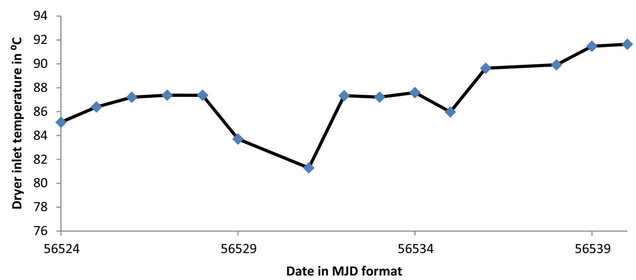

Fig. 18 Variation of daily average dryer inlet temperature of tea factory (20/08/13–05/09/13)

represents variation of daily average RH, temperature of fermentation room and dryer temperature respectively for the period as given.

5. Conclusion

The instrument to monitor tea process parameter especially for fermentation and dryer is developed and implemented in the tea factory after successful testing in the laboratory. The system is developed in such a way that the process parameters can be monitored online during production. The system is installed without disturbing the normal production of the factory near Mangaldoi, Assam, India and now it is running satisfactorily. All the sensor nodes are calibrated in the range as required in the tea factory. It is observed that temperature and RH in the fermentation room varied from time to time with a maximum variation of ±2.5 °C for temperature and 8 % for RH. Maximum firing temperature variation in the dryer is found ±9 °C from the recorded data. Data logging feature is not incorporated with the conventional system of the tea factory so this may be considered as the merits of the developed system over the conventional one. Other merits are as follows

- Low cost
- Ease of installation due to Small hardware setup

By monitoring these parameters, the optimum process condition can be found out. We propose to correlate these data with tea tasting report to evaluate its influence in tea quality.

Acknowledgement Department of Science and Technology, Government of India is acknowledged for providing INSPIRE Fellowship to one of the authors. Assam Science Technology and Environment Council (ASTEC) is also acknowledged for their financial support with sanction order ASTEC/S&T/192(198)/11-12/217/dt 26/7/12. The authors of the paper acknowledge the authority and staff of tea factory for their help and support. The authors of the paper acknowledge Dr. Banty Tiru, Asst. Professor, Department of Physics, Gauhati University, for helping in software issues. Mr. Manash Protim Goswami is also acknowledged for helping in installation of the instrument in the tea factory.

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