Sensors Network for Temperature Measurement in a Cocoa Fermentator

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Abstract The article deals with the technical aspects of designing, implementing and operating a network of temperature sensors that operate in a finite porous media. The design follows the analytical hierarchical process to select components. The resulting system has 21 channels and is used to the measurement of cocoa bean (*Theobrama cacao*) fermentation during seven days. It reads ambient temperature and humidity as well as 19 internal temperature points and is delivered as a spreadsheet file for further processing depending on needs.

Keywords Temperature distribution · Temperature grid sensor · Porous media · Cocoa fermentation · Analytical hierarchy process

1 Introduction

Temperature measurements are taken in specific points and in a discreet way. In some cases, for example in large volumes or when there are high gradients, more than one measurement point is required. In this case, we have a small medium (1.0 m × 0.9 m × 0.8 m) with a gradient within, which according to literature is not high, is around 35 °C during the day and 25 °C at night. The process requires a minimum temperature of 42 °C at lowest, but 48 °C is recommended [1]. The substances

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formed during the cocoa beans fermentation process are biochemically transformed from their original composition; they enter the seed killing the germ, which makes it not viable for sowing [1]. Additionally, the medium contained is a mixture of solids: cocoa beans (*Theobrama cacao*) and mucilage, which contain sugar that decompose in water, CO_2 and heat during fermentation process. This conjunction of factors converts the process into a problem of heat transfer in a porous medium. Therefore, these implications have to be taken into account when one is considering such type of temperature measurement.

Yokoyama et al. [2] performed a spatial distribution of the variation of air temperature in the city of Tokyo by comparing the results with respect to grid sizes of 10 and 100 m. The smaller 10 m mesh showed hot spots that were not identified with the 100 m mesh. Schafer et al. [3] reported the time evolution of the temperature on the walls of a stainless steel cylindrical tank. The measurement was made through an 8 $\times$ 32 mesh of platinum sensors (Pt1000) mounted on the wall of the tank. Ortiz et al. [4] performed temperature measurements in a system with a high gradient within and adjusted the values to a theoretical model with the least squares algorithm.

In literature, several studies reference which types of sensors are needed to measure physical and chemical variables in a porous medium, such as cocoa. Chavanne [5] presents how a sensor measures, in addition to temperature, salinity and humidity in a porous medium. Allain et al. [6] used a Cernox model CX-1030 thermometer that has a high sensitivity to small changes in temperature to measure temperature gradients at microscale. Tinoco and Ospina [7] measured temperature of cocoa beans, but in the drying stage, comparing values with simulations by finite elements, finding good correlation.

On the other hand, some educational booklets [1] recommend the use of a digital temperature meter to maintain traceability of the fermentation process, measuring both ambient and internal temperatures. However, they lack specifics of where inside the tank to measure. Several studies [8, 9] report temperature evolution curves throughout the cocoa beans fermentation process, usually lasting week when the process is exothermic. However, they do not report details of the measurement, number or location of sensors. This work describes the process of establishing needs, selecting instruments, how to process the gathered information and how to present it.

2 Description of the Continuous Temperature Measurement System

First, the requirements need to be established, and the layout is explained to fulfill said requirements. Then, the selected instruments are presented, to follow with the data logger script.

2.1 Fermenter and Requirements

Traditionally and when needed, some cocoa producers monitor the temperature of the fermentation process by measuring at specific points. However, the purpose of this research is to know the distribution of heat within the fermentation box to determine the critical points for a subsequent control action. That is why it is proposed a network of sensors distributed in the drawer based on the following observations:

- Cocoa fermentation is an exothermic process. The mass needs to be flipped every so often to allow oxygen required to decompose sugar.
- The temperature is not homogeneous in the drawer. Both, producers and heat transfer theory say that the central point is the hottest and temperatures decrease radially toward the drawer edges.
- The distribution of heat in containers under the same boundary conditions is symmetrical as long as boundary conditions are the same around the box.
- The location of the primary measuring element or temperature sensor has as much or greater importance than the control itself. Therefore, the sensor must be installed in a place where the heat transfer coefficient is higher.

Finally, the variable to be measured is the temperature of the cocoa fermentation process along, with ambient temperature and relative humidity.

2.2 Sensors Layout

Figure 1 shows how proposed arrangement for sensors. At the top is the logical layout and at the bottom their physical distribution within the box. As stated in the previous section, there is symmetry in the *yz*-plane (see coordinate system in Fig. 1), so sensors were deployed in only half the volume.

For the installation of the sensors inside the fermenter, the center of the box was determined as the origin of the coordinate system, see Fig. 1. From this reference, the following distribution of the primary elements of temperature measurement (TE) was determined as shown in Eq. (1), and the TEs were located at three heights as described by Eq. (2).

$$\text{Position } (X, Y)\text{TE's} = \begin{bmatrix} (0, 35) & & (45, 35) \\ (0, 0) & (25, 0) & (45, 0) \\ (0, -35) & & (-45, -35) \end{bmatrix} (\text{cm}) \tag{1}$$

$$\text{Layer } 1_{z=20\text{ cm}} = \begin{bmatrix} \text{TE05} & & \text{TE08} \\ & \text{TE17} & \text{TE11} \\ \text{TE02} & & \text{TE14} \end{bmatrix}$$

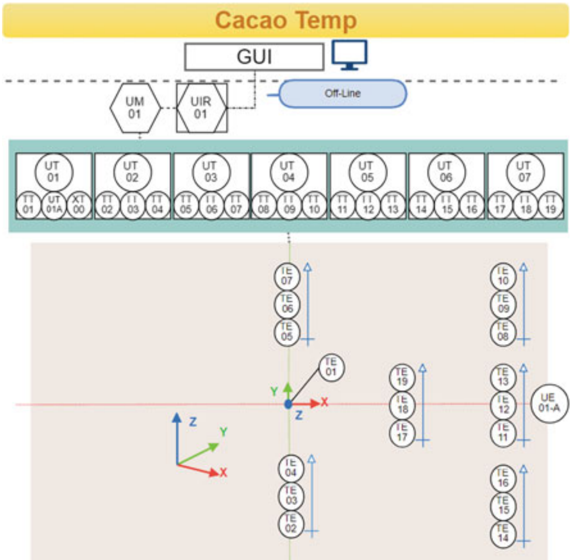


Fig. 1 Schematic diagram of instruments for the cocoa fermentation measurement system

$$\text{Layer } 2_{z=45\text{ cm}} = \begin{bmatrix} \text{TE06} & & \text{TE09} \\ & \text{TE18} & \text{TE12} \\ \text{TE03} & & \text{TE15} \end{bmatrix}$$

$$\text{Layer } 3_{z=70\text{ cm}} = \begin{bmatrix} \text{TE07} & & \text{TE10} \\ \text{TE01} & \text{TE19} & \text{TE13} \\ \text{TE04} & & \text{TE16} \end{bmatrix} \tag{2}$$

2.3 Instruments Selection

The required instruments need to comply with follow observations:

- The fermentation process handles temperature ranging from 25 to 55 °C.
- The dimensions of the box are 100 cm × 90 cm × 80 cm. Therefore, the length of the extension cables of the sensors must be at least 2 m.
- The medium is porous and wet. The sensor must have protection against it.

Static characteristics related to measurement are accuracy, resolution and sensitivity.

The analytical hierarchy process (AHP) was applied to the selection of instruments. The AHP is a multiobjective method that makes decisions combining quantitative and qualitative analysis, proposed by Saaty [10]. The levels of importance or

Table 1 AHP compliance level for systems requirements

Selection criteria	Given weight
Accuracy	(1) There is no information (3) A > 0.5 C (5) A < 0.5 C
Range	(1) There is no information (3) 0 ~ 80 C (5) −10 ~ 120 C
Output variable	(1) Analog (3) Relay digital

weighting of the factors are estimated by means of comparisons between them [11]. The weight for each criteria selection used in AHP is shown in Table 1.

Some criteria are mandatory, such as protection against water and dust and a minimum length of 2 m. Although cost and availability are of greater importance, they are not considered here. The result of applying the above weights to each instrument is presented in Table 2.

2.4 Data Logger

In stage 2, there is a mega Arduino with 54 digital input and output pins, in which 33 pins are used to connect the sensors. For the connection of each power board, five pins are necessary, and just one pin is used for the DTH (temperature–humidity sensor) connection.

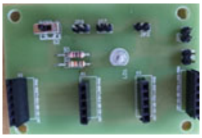
In stage 3, a Raspberry Pi 3 is used to store the information provided by the sensors obtained by means of Arduino´s serial port. An acquisition program was developed in Python, which allows storing measured data as a MS-Excel ® file and showing values in real time. From this point, stage 4 takes over, which consists of a MS-Excel ® file generated by the program in which the stored data consist of temperature and time.

3 Usage Scenario

The described system was tested at the "Villa Mónica" farm (San Vicente de Chucurí, Colombia, 6° 51′ 48.265″ N 73° 24′ 47.971″ O) which has an altitude of 880 m above sea level, a mean temperature of 25 °C during the day and 17 °C at night. The region annually produces about 7000 metric tons of cocoa beans.

The farm "Villa Mónica" has a 3 m long box divided in three equal compartments, 1 m long, 0.85 m wide and 0.70 m deep with capacity for 500 kg of fresh cocoa beans per compartment as shown in Fig. 2. The first drawer has holes one centimeter in diameter at the bottom to facilitate the drainage of the exudations produced by the

Table 2 Specification of selected instruments

Instrument	Role in the system	Specification	Image
Thermocouple *K* TE 01	Primary element	Diameter: 5 mm Length: 15 cm Extension cable length: 3 m	
DTH-22 UE 01	Temperature–humidity sensor (for ambient readings)	Range RH: 0–100% Temp range: (−40 ~ 80 °C) Precision temp: ±0.5 °C Accuracy: ±2% RH	
MAX 6675 TT 01	Transducer	SPI transmission protocol	
PCI UT 01	Transmitter		
Arduino mega 2560 UM 01	Control and sampling		
Raspberry UIR 01	Data storage		

decomposition of mucilage from the beans. A close-up of instruments during temperature measurement is seen in Fig. 3. It can be seen the wiring for each instrument entering the fermentation box.

Fig. 2 Fermenter loaded with fresh cocoa beans

Fig. 3 Details of instrumentation in situ during measurement campaign

4 Results

The database stored the values of a set of temperature sensors composed of 19 K-type thermocouples with a probe and a DTH-22 temperature and humidity sensor. This set of sensors was exposed to a cocoa fermentation process. The thermocouples were positioned within the cacao mass, while the DTH-22 sensor monitored ambient

Table 3 Example of attributes for storing readings

Day	Date	Initial hour	Hour ends
1	06-July-2018	17:04:08	19:29:18
		First flip	
2	07-July-2018	–	–
3	08-July-2018	21:37:57	22:48:04
4	09-July-2018	07:18:30	17:35:02
		Second flip	
		18:45:50	23:56:21
5	10-July-2018	00:01:22	01:16:32
		Third flip	
		18:41:39	23:59:24
6	11-July-2018	00:04:25	17:23:29
		Fourth flip	
		19:10:47	23:55:35
7	12-July-2018	00:00:35	17:54:51

temperature and humidity in the enclosure in which the fermenter was located. The sensors measured the activity of the fermentation process for 168 h, which includes stops to flip the mass. The measurement was interrupted every 24 h after the first 48 h, when the aerobic phase of the process began.

The set of readings is composed of an MS-Excel ® file where the data taken in real time are stored. Each element of the data set has a serial identifier for easy identification.

The stored data are divided into the following columns:

- ID for each data obtained from the sensors (Thermocouple)
- ID for temperature and humidity data of DTH-22
- Date: year, month, day and time:hour:minute:second.

The set of readings is made up of 743 data; to visualize the time in which the sample was taken, see column 2 in Table 3. On the MS-EXCEL ® file, these consist of 23 columns and each one has a title according to the following:

- Id: Thermocouples (TE 01 through TE 19)
- ID: The DTH-22 sensor data (humidity %, ambient)
- The temperature measurement in celsius and humidity in percentage.

5 Conclusion

A system for continuous process temperature measurement was designed, built and tested. The design process included identification of requirements, selection of components based on the AHP method. The system delivers data as spreadsheet file ready to be processed.

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