Advanced characterization of a coffee fermenting tank by multi-distributed wireless sensors: spatial interpolation and phase diagrams

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Abstract. *In coffee processing the fermentation stage is considered one of the critical operations by its impact on the final quality of the product. However, the level of control of the fermentation process on each farm is often not adequate; the use of sensorics for controlling coffee fermentation is not common. The objective of this work is to characterize the fermentation temperature in a fermentation tank by applying spatial interpolation and a new methodology of data analysis based on phase space diagrams of temperature data, collected by means of multi-distributed, low cost and autonomous wireless sensors. A real coffee fermentation was supervised in the Cauca region (Colombia) with a network of 24 semi-passive TurboTag RFID temperature loggers with vacuum plastic cover, submerged directly in the fermenting mass. Temporal evolution and spatial distribution of temperature is described in terms of the phase diagram areas which characterizes the cyclic behaviour of temperature and highlights the significant heterogeneity of thermal conditions at different locations in the tank where the average temperature of the fermentation was 21.2 °C, although there were temperature ranges of 4.6°C, and average spatial standard deviation of ±1.21ºC. In the upper part of the tank we found high heterogeneity of temperatures, the higher temperatures and therefore the higher fermentation rates. While at the bottom, it has been computed an area in the phase diagram practically half of the area occupied by the sensors of the upper tank, therefore this location showed higher temperature homogeneity.*

Keywords: temperature, WIFI, attractor, control, polar coordinates.

Introduction

The fermentation of coffee is one of the critical stages of its production process. Fermentations prolonged, incomplete or poorly controlled favor the development of sensory defects in the final product (Pushpa S. Murthy and M. Madhava Naidu, 2011). According to various researches, the main control variables of this process are temperature and pH, which can be used to predict the time when fermentation is completed. Rapid advances in sensors and wireless communications give us low cost, wireless and autonomous sensors, from the point of view of power supply and recording capabilities. These allow intensive and real-time data acquisition networks that make feasible to reconstruct the time and spatial distribution of variables such as temperature from point measurements. On the other hand, the phase space (or phase diagram) is the most adequate representation where the behaviour of a dynamical system is displayed. As it was proven by several authors, we can approximately reconstruct the phase space of an unknown dynamical system through a time series obtained by measuring one of its physical variables along time (Packard et al., 1980). **The objective** of this work is to develop a new methodology of data analysis based on the reconstruction of spatial distribution and the implementation of phase space graphs of temperature, in order to analyze the two-dimensional projections of the derived phase space.

Materials and methods

A natural fermentation of coffee was monitored in a covered plastic tank, placed inside a warehouse, at Popayán (Colombia). The tank was filled with 276 kg of coffee cherries mechanically depulped immediately after harvesting. The fermentation begun at 17:00 pm (sunset at 17:44 pm in October) when outside temperatures go down and the process ended at 9:50 am (sunrise at 5:42 am). The coffee master was, who based on his experience, made the decision on which after 16.8 h the fermentation was completed properly. The multidistributed sensor network was made-up by 28 TurboTag® RFID Tags (only 24 correctly collected the data). These RFID Tags, temperature loggers with vacuum plastic cover, were fully submerged directly in the fermenting mass. The temporal resolution selected was 2 min/data and 504 valid data per sensor were recorded. The sensors were equi-spatially distributed along 8 radiuses (Figure 1). Three horizontal planes (parallels to the floor) were defined. On each plane 8 sensors were placed at end of each radius and one more at center of circle. Other tag was placed out of the fermenting tank, in order to register the ambient temperature.

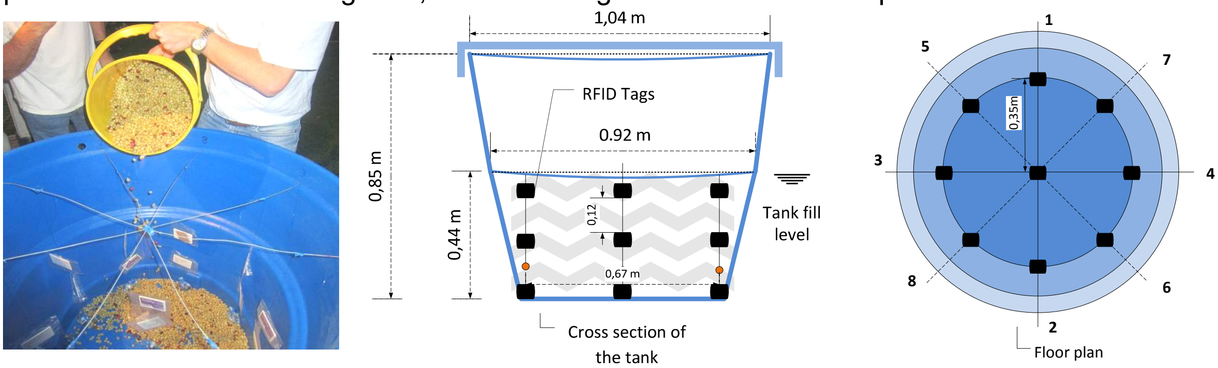

Figure 1. Image and schemes of the sensors distribution in the tank.

In order to analyze the data from sensor recording, two different procedures were implemented. First, polar coordinate interpolation using devoted Matlab code was used to make 2D spatial representations of temperature profiles inside the tank. Secondly, the reconstruction of the phase space from the time series, using time delays, was carried out. Two-dimensional phase spaces were performed plotting the temperature at time $t(k+\Delta)$ versus the temperature at time *t*(*k*), where Δ corresponds to different steps. Different values of Δ were tested looking for the optimal Δ in which the cyclic trajectories or attractor in the phase space showed the maximum area (for this work Δ=10 and t_d =10(step)·2(min/step) = 20 min). The area of the different polygons that include the data points corresponding to cyclic behaviour in the phase space per sensor or sensor group was computed, using the Matlab Function CONVHULLN which returns the vertexes and area in $ºC^2$ of refereed convex hull on phase spaces. This function allows to manually select a set of points on the attractor in the phase space graph, and gives the smallest convex envelope that contains these points.

Results

Taking into account all data of the 23 Tags the average fermentation temperature was 21.2ºC. The lowest temperature registered was 19.04ºC corresponding to one sensor located in the bottom of the tank, while the maximum absolute temperature was registered at the center of tank in the surface plane (23.6ºC). The average standard deviation (SD, n=23 sensors) was ±0.36ºC (TurboTag accuracy ±0.5ºC), while the average spatial SD (calculated for sensors at different locations for the same instant, n=504 time data) was more than three times that value (±1.21ºC). In order to facilitate the handling of data from the 23 RFID Tags, a sensors clustering was carried out looking for similar patterns among time temperature series recorded by sensors at different locations in the tank. Five groups were identified labeled from A to E: group A, consisting of 3 RFID Tags corresponding to the hottest locations inside the tank (in surface and medium plane at center), B, 10 RFID Tags in surface and medium plane, group C corresponded to one stable sensor at average temperature located in the medium plane, group D with 7 RFID Tags located at the bottom of the tank and finally group E with 2 sensors at the coldest location on floor plane.

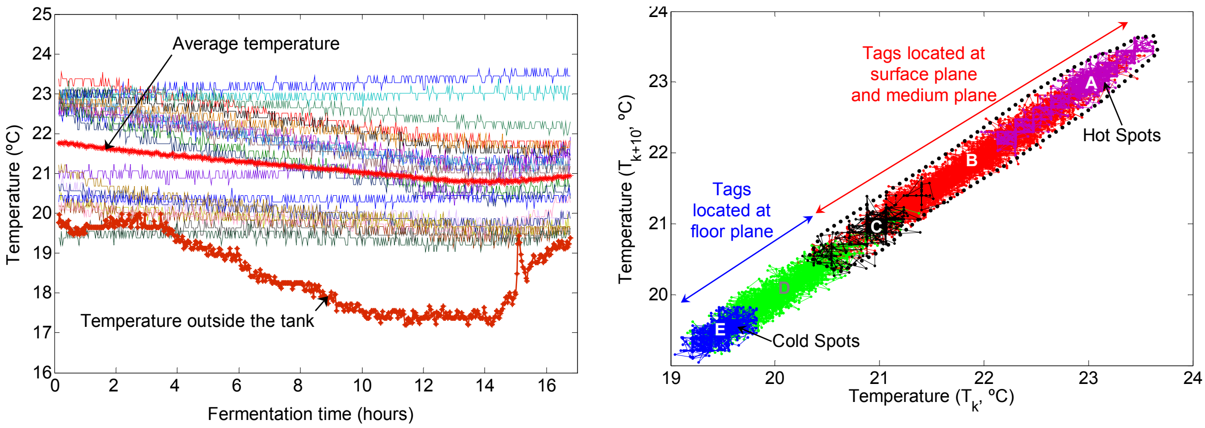

Figure 2. Dynamics of temperature inside the tank (left) and phase diagram for temperature (right) for the 5 group of sensors identified. The dotted line on A,B and C groups shows an example of the area selected and computed in $ºC^2$ using Matlab function CONVHULL.

Figure 2 shows the phase diagram of temperature for the five groups of sensors. Sensors belonging to the same group appear in the same color and in the same region of the phase diagram. The areas of the polygons that include all the data points of each sensor group quantify the variability of the temperature within each zone of the tank. Consequently, groups A,B and C located at the surface and intermedium plane include the hottest points of the tank and due to its largest area on the phase space that equals 2.85 ($ºC^2$, Δ=10) can be identified as the zone subjected to the highest temperature gradients. This result is corroborated by the spatial information obtained from the spatial interpolation of temperatures in the tank. Figure 3 shows as fermentation process progressed (from time 0h to 16.8h), both the surface plane and especially the medium plane of the tank, developed a greater number of temperature level curves, which evolve radially from the center, at higher temperatures, to the periphery where lower temperatures were recorded. Groups D and E corresponding to the floor plane of the tank are located on the base of the phase diagram and join totaling an area of 1.5 (ºC^2, Δ=10). Therefore, the floor plane provides the coldest points and lower temperature gradient, as indicates the smaller number of temperature level curves in Figure 3.

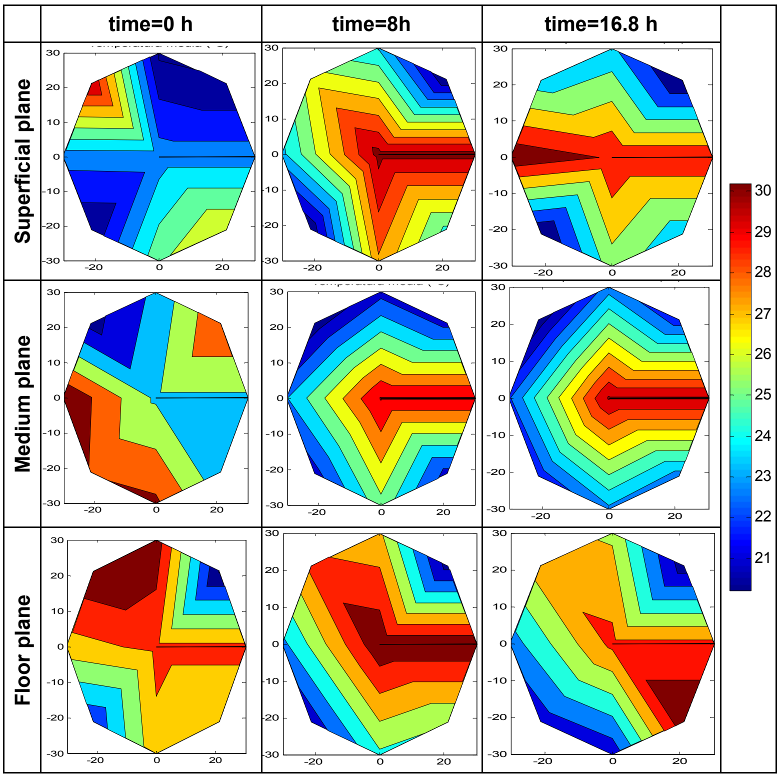

Figure 3. Polar interpolation of temperatures inside the tank along time and for the three planes defined

Conclusions

In this natural coffee fermentation the maximum range of variation registered by RFID Tags was 4.6ºC, being the maximum spatial range (same time, different location) 4.4ºC, which occurred at the end of the fermentation process. These results show the ineffectiveness of a natural fermentation process in temperature control, the current availability of low cost sensors promotes overcoming this limitation. In this work a methodology for the analysis of data series is proposed, to the authors´ knowledge, phase diagrams have never been attempted thus far to study the temperature in fermenting process. Phase graphs allow highlighting, in a confined space, the enormous differences in fermenting conditions inside the tank. In the upper part of the tank we found high heterogeneity of temperatures, the higher temperatures and therefore the higher fermentation rates and the highest risk of develop stinker beans (over fermented beans). While at the bottom, it has been computed an area in the phase diagram practically half of the area occupied by the sensors of the upper tank, therefore this location showed higher temperature homogeneity. The registration of lower temperatures results lower fermentation rates that could lead to a higher risk of the mucilage breakdown is not complete and thus of develop uncontrolled secondary fermentations. It is remarkable that phase graphs allow compressing the information, due to its cyclic shape, being independent of the timescale.

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