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PID TEMPERATURE CONTROL ALGORITHM DESIGN, IMPLEMENTATION AND TEST FOR COFFEE DRYERS WITH AIR FLOW MIXING AUTOMATION SYSTEM

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Abstract. *According to studies, the coffee drying process is the most crucial stage to determine the quality of the final product. The drying air temperature is the most important parameter to be analyzed in this context, because if not controlled, it can lead to several alterations in grain structure. When subjected to high temperatures, green grains acquire astringent characteristics that result in poor quality of the drink and, therefore, reduction in the market price. To avoid overheating of the drying air, the present study aims to design, install and test a laboratory prototype automation system for the most common existing coffee dryer category (based on wood furnace), utilizing low cost controllers and actuators, being able to control the air temperature by regulating the flow of unheated air, by mixing it to the hot air coming from the indirect wood combustion furnace, avoiding green grain overlay oxidation. For this purpose, a PID controller will be designed to optimize the drying air's temperature by manipulating the opening of two metal hatches connected to the ventilation duct. The algorithm design, laboratory equipment and tests performed are further detailed in this work. Results revealed nice applicability for the simulation prototype system and it was able to accomplish the main objective of avoiding drying air overheating while wasting lower levels of thermal energy.*

Keywords: *coffee drying process, quality of grains, coffee dryer, PID controller*

1. INTRODUCTION

Coffee is one of the most valuable primary products in the world, being overcome only by petroleum (Sindicafé-mg, 2015). In this context, there are several studies focusing on aspects to enhance its quality, such as cultivation techniques, chemical products, harvest technologies and post-harvest processing (Chalfoun and Carvalho, 1997; Moraes, 2006). Among those, the post-harvest processing is considered the one that affects the product quality the most. It consists of all the stages necessary to turn the coffee fruits into packed coffee beans, ready to be exported or sold to the roasting industry.

The drying process must be slow and uniform to ensure the maintenance of specific quality parameters. For the special category, it is usually made in suspended yards, excluding the utilization of drying machines that could overheat the grains, limiting to small production amounts. On the other hand, most of the producers own wide areas and have the potential to provide large volumes of production. Therefore, solutions for drying technologies, which are able to keep quality characteristics without damages, may have a great impact on the standard scores and, consequently, on its final price.

One of main problems is due to grain heterogeneous maturation process. As can be seen on Fig. 1, in a same coffee batch it can be found totally green or very mature grains. The harvesting machine does not choose what to harvest, vibrating the coffee plant as a whole and, consequently, feeding the drying machine with grains of completely different maturation stages.

Figure 1. Grains Different Maturation Stages in a same plant

A variety of studies indicates a proper drying temperature of the grains of 40°C, not exceeding 45°C (Chalfoun and Carvalho, 1997; Oliveira et al, 2010; Guida, 1994). In order to keep this parameters, and also, to reduce grains damaging, it is recommended to keep the air's temperature at about 70°C, not exceeding 80°C (Vieira and Vilela, 1995).

What physically happens during the drying process is that the fast heating of green grains causes its film oxidation, and, furthermore, astringent characteristics are highlighted resulting in poor quality of the drink and reducing its market price. If green grains are subjected to 50ºC inside the drying machine, more than half of them (51,2%) will be damaged and classified as overheated black grains (Rena, 1986). This type of defect is shown in Fig. 2.

Figure 2. Black Grains due to high drying temperature

In this point of view, the present work aims to perform the algorithm design, implementation and test for an innovation laboratory prototype of an automated system to control the drying air temperature evenly for large scale coffee dryers, able to process up to 15.000 liters of the fruit in less than three days. It consists of PID controllers and actuators applied to the hatches connected to the ventilation duct that are able to mix unheated air to the hot flow coming from the furnace. The PID optimization algorithm should accomplish a good cost-benefit relationship between processing time and quality. Therefore, the hatches opening must reduce only the minimal amount as possible of drying air temperature that would be enough to preserve the fruit flavor characteristics. In this way, the system would be able to ensure the good quality of the final product, while wasting the minimal amount of energy as possible.

2. EXPERIMENTAL PROCEDURE

The proposed solution to control the coffee's drying temperature is the partial cooling of the air that enters the cylinder, which comes from a furnace. It can be made by modulating the opening of two metal hatches connected to the ventilation duct, allowing some room temperature air to be mixed with this heated air. The hatches are located in point 2, shown in Fig. 3.

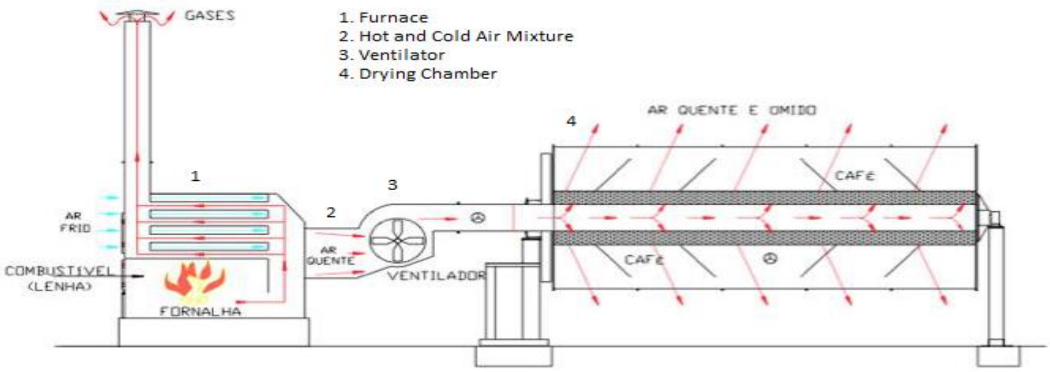


Figure 3. Drying Machine sketch. (Adapted from Isquerdo, 2011)

In order to develop the algorithm and test it, a laboratory prototype was designed, being used as a simulation approximation of the real system and enabling the PID tuning to be done as well. The prototype was constructed utilizing a wooden box to simulate a coffee dryer hatch, taking into account all the real scale dimensions measured on a coffee processing plant in Minas Gerais, according to the model that was designed utilizing SolidWorks software, as can be seen in Fig. 4.

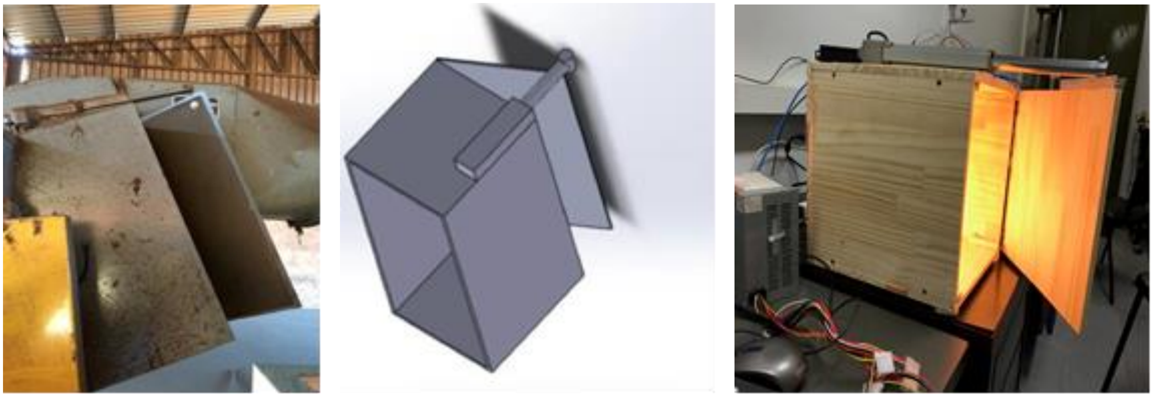


Figure 4. Construction stages. Real hatch, modeled project and laboratory prototype

To simulate the furnace (point 1 at Fig. 3), two lamps were used as heating sources. A cooler played the role of the ventilator to generate ambient air flux into the interior of the hatch. An electrical piston type actuator (Duff Norton LT100-2-150) connected to a 24V source was the responsible for the hatch opening and closing, controlled by an h-bridge L298 which modifies the direction of the engine changing the piston course. Finally, a low cost k-type thermocouple (MAX6675 digital converter module) was used to measure the air temperature. For data acquisition and control, it was used an Arduino UNO R3 microcontroller unit, according to Fig. 5.

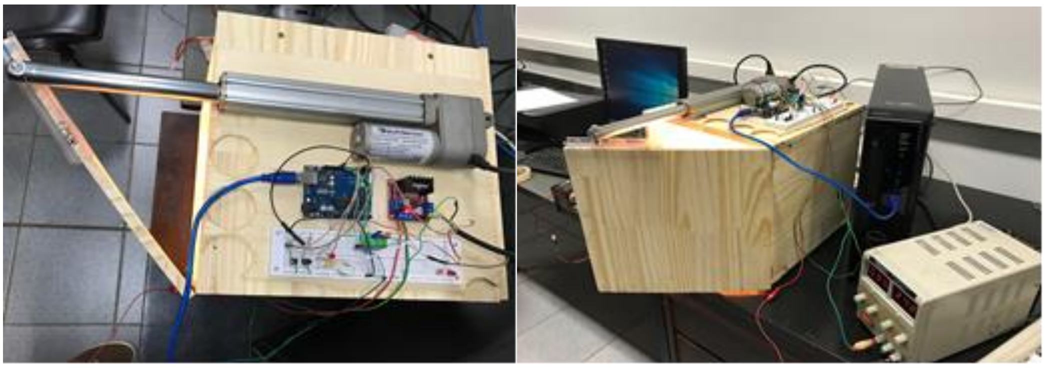


Figure 5. Components installed on the laboratory system simulation prototype

The first step was to identify the system parameters. Starting from the ambient temperature and with the hatch totally closed, the data acquisition was initiated by the microcontroller. After the temperature stabilization, as shown by Fig. 6, a step test was performed, consisting of a maximum hatch opening, according to the maximum actuator length. Thus, the plant is defined by the negative slope curve, representing the temperature decay over time, for a totally opened hatch. Considering the plant as a first order system, the obtained transfer function is given by

$$G(s) = \frac{-17.25}{286s + 1} e^{-5s} \tag{1}$$

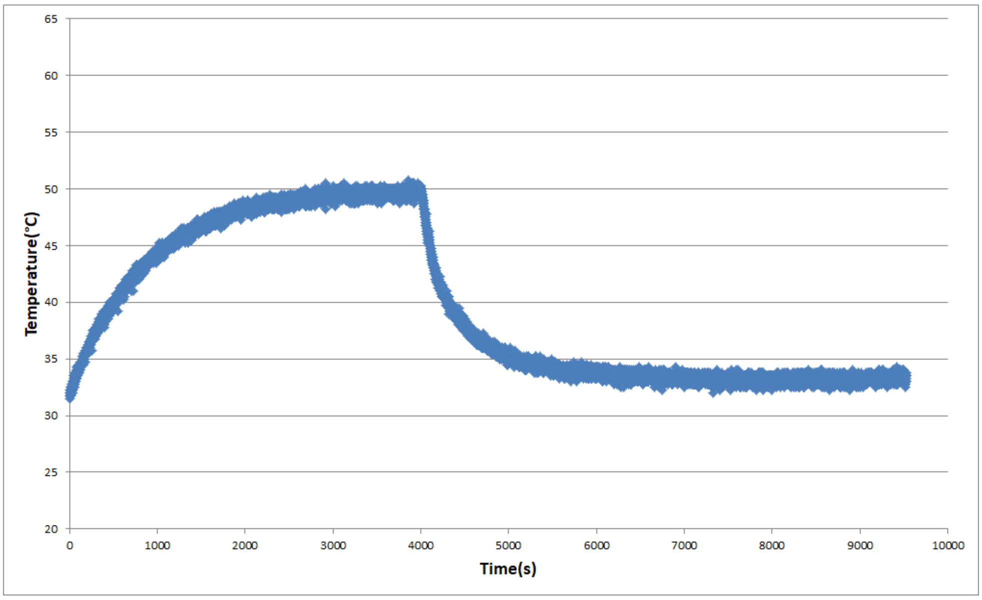
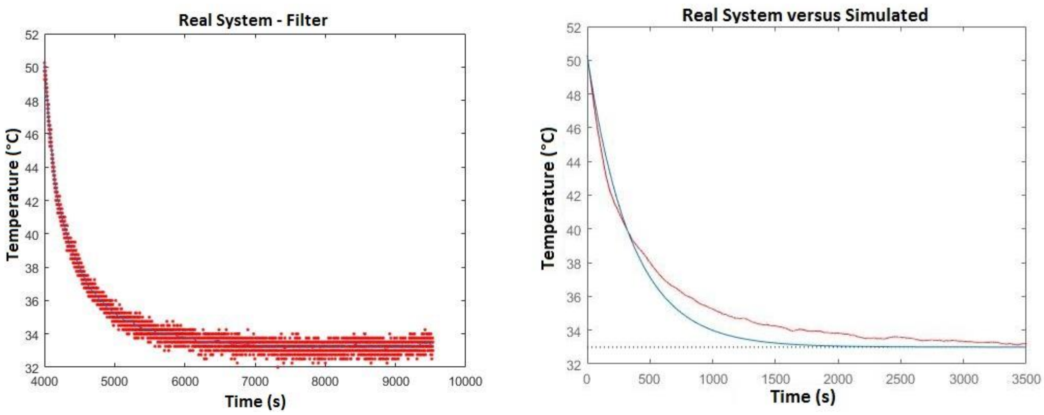


Figure 6. Final temperature of the step test

Figure 7(a) shows the step test plots using MATLAB software and a filter was established in order to reduce the error caused by the thermocouple measurements. A comparison between the filtered system and the transfer function is shown in Fig. 7(b), revealing minimal discrepancies that could be related to the sensor variability that led to errors on the definition of stabilization points, time constant calculation and even at the gain. Even though, the general proximity of the curves confirms good correlation for the model.



(a) (b)

Figure 7. Test plots for the system (a) identification and filtering; and (b) transfer function validation

In order to validate the laboratory prototype behavior, an evaluation of the drying air temperature curve variation caused by the hatch opening from a real processing coffee plant in Minas Gerais was performed. For this, a K type thermocouple (PT100 model) was installed in the duct before the drying cylinder in order to register the entering air temperature. The same electric piston was used to regulate the hatches opening and a PLC (programmable logic controller) performed the data acquisition and system control. The installation procedure and utilized equipment can be better understood by Fig. 8 observation.

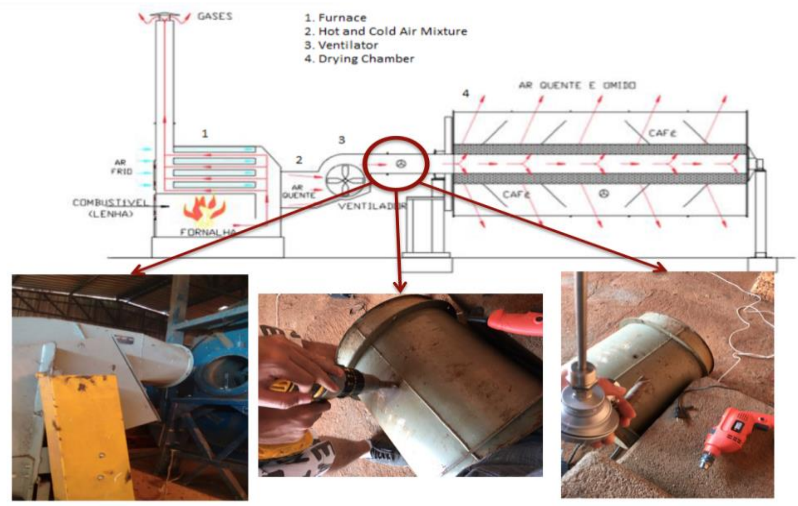


Figure 8. Real coffee mechanical dryer and drying air behavior data acquisition

The furnace was fully loaded to generate an overheating condition and the step input was performed by completely opening the hatch. Figure 9 shows the practical situation for the test under real scale plant conditions of a mechanical coffee dryer, after an installation of a PLC, shown in Fig. 10.

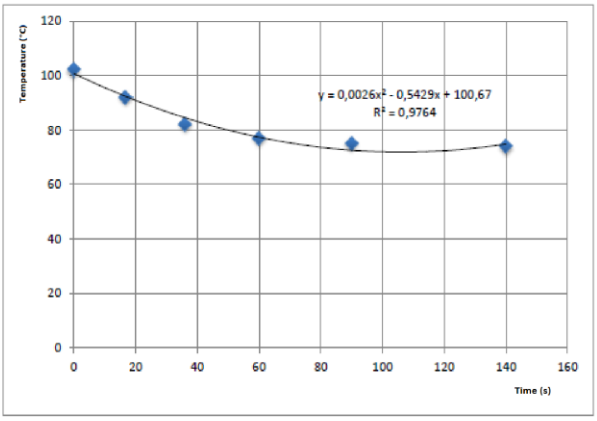


Figure 9. Drying air temperature decay with hatch totally opened

Analyzing the drying air temperature decay when a hatch opening occurs in the ventilation duct, it shows a very rapid response of the system. According to Fig. 9, with a hatch totally opened, it took about 40 seconds for a 20°C decrease in the air temperature, stabilizing in less than 3 minutes (furnace fully loaded). The settling time for the steady state condition was much faster than the laboratory prototype, probably due to the much higher suction force generated by the real turbine when compared to the cooler fan used on the laboratory experiment. However, the real world plant can also be approximated by a first order system, as well as the laboratory prototype.

Figure 10. PLC installation at real plant

The next step was to perform the PID tuning by the simulation model. Ziegler-Nichols open-loop tuning method was the first trial. Firstly, it was confirmed that the system step response curve (Fig.6) has an approximate 'S' shape, as required for this tuning method. This 'S' shape is inverted, once the System Gain is negative. Next, it was drawn a tangent to the point of the curve with the highest inclination. By crossing the X plot, this line defines the values of the L and T parameters, which respectively correspond to the delay and the time constant of the system. These values are used to tune the PID controller, as shown in Table 1.

Table 1 – Ziegler-Nichols Tuning Chart (Meshram and Kanojiya, 2012)

Controller Type	*Kp*	*Ti*	*Td*
P	*T/L*	-	-
PI	*0.9T/L*	*L/0.3*	-
PID	*1.2T/L*	*2L*	*0.5L*

A Simulink model of the system was created in order to assess the controller performance. This block diagram, shown in Fig. 11, includes a saturation parameter, in order to guarantee that the controller will not try to open or close the hatch more than physically possible.

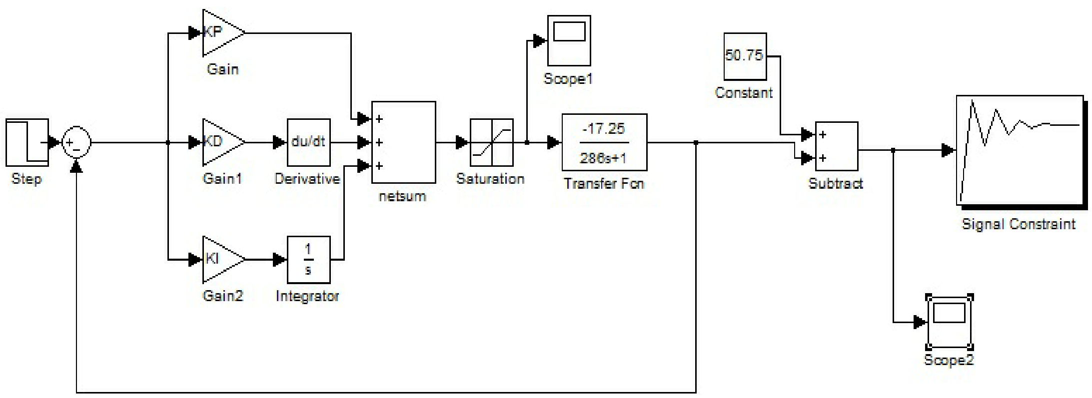


Figure 11. Simulink Model for the PID tuning Optimization

3. RESULTS AND DISCUSSION

For the Ziegler-Nichols PID tuning method, the values obtained for the gains were *Kp* =-76.80, *Ki* =-30.72 and *Kd* =-768. As the System Gain is negative, the PID gains were also set to negative. The results showed unexpected behavior for the controller and the output signal curve could never reach a steady state condition when using the gains obtained from the Ziegler-Nichols procedure. Furthermore, the analysis of the controller behavior with Simulink showed that the hatch opening was saturated in 100% or 0% most of the time. The possible explanation for this problem is that the defined values for the gain were too high and this led the system to try to stabilize the temperature condition extremely fast, what cannot be obtained on real conditions, as the system response is relatively slow. In this fast stabilization attempt, it was trying to immediately fully open the hatch, more than it can physically support, concluding that it was not compatible and very distant from real possible conditions. As well as the Ziegler-Nichols, a variety of methods presented in the literature requires a time delay. Since the input delay obtained for this case is considered to small when comparing to the system response, affecting the "S" shape, these methods may not give feasible gain values.

The final solution was to simulate the system by a MATLAB function named as Signal Constraints, which uses input data of *Kp, Ki* and *Kd* that will be optimized taking into account physical real initial conditions defined by the user. It was utilized low initial values for the gain to approximate the mathematical to the physical model.

The gains were initially set as:

Kp= -0.3
Ki= -0.5/100
Kd= -0.5

The optimization calculation was made and the border parameters were set. The maximum overshoot was defined as 10%, the rising time (actually the direction is downwards) as 350 seconds and the settling time as 750 seconds, since the real system present a slow reaction time behavior. The primary results are shown by Fig. 12

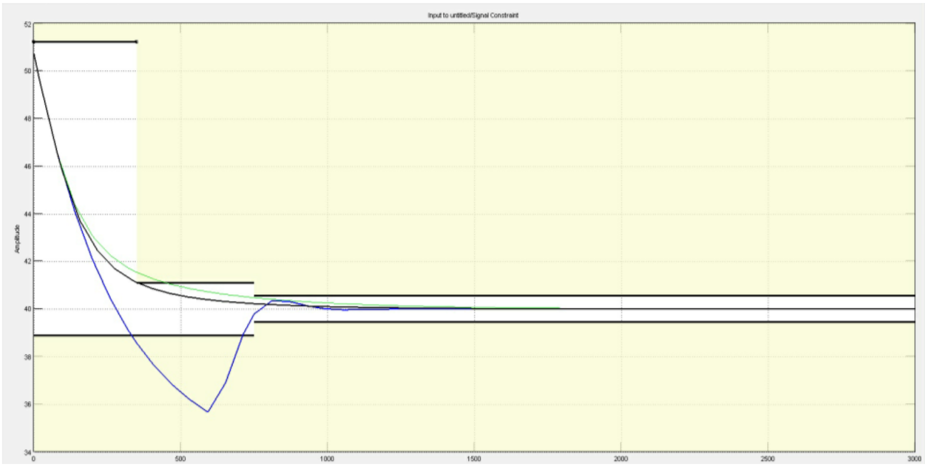


Figure 12. Signal Constraints Function for the Simulation Model

The simulation led to the optimized gains shown in Fig. 13, and were finally set to Kp =-0.0942, Ki =-3.554$x10^{-4}$ and Kd =3.9501.

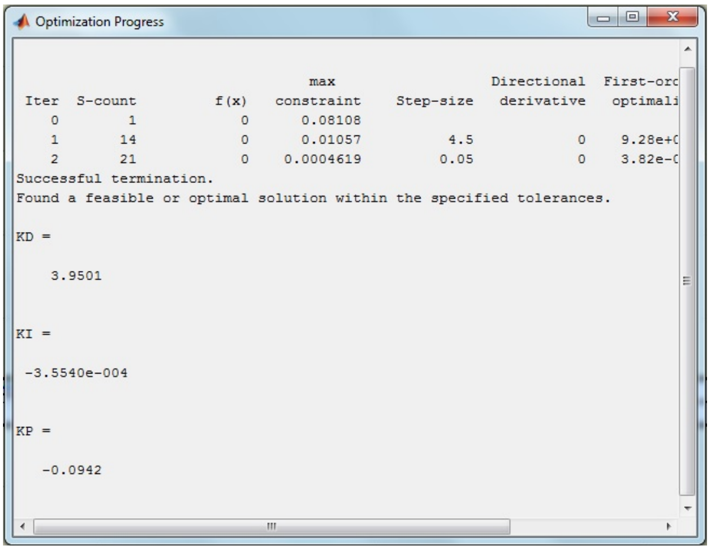


Figure 13. Model Simulation Optimized Parameters Results

For the Arduino implementation, the PID controller obtained was programmed to control the actuator motion. A temperature of 40°C was defined as a setpoint, and its error between the sensor's reading is used to calculate the corrective action as follows

$$error = Setpoint - T_{read} \tag{2}$$

$$Corrective_{action} = K_P * error + K_I * integral + K_D * Derivative \tag{3}$$

where

$$integral = integral_{prev} + error * \Delta t \tag{4}$$

$$derivative = (error - error_{prev})/\Delta t \tag{5}$$

The value obtained by equation (3) is in percentage and the result is then multiplied by the actuator total course to set a desired position. By proper activating the h-bridge, a high signal is sent to the actuator until it reaches the stablished position, driven forward or backwards, opening or closing the hatch. Since a saturation parameter was needed for the system, to provide limits for the actuator, the equation (3) was only applied within the saturation, a procedure referred as the integrator windup, to prevent the integral term to accumulate significant error outside the saturation limits.

After the PID tuning implementation on the Arduino microcontroller, the results from the test running from ambient temperature until the 40ºC setpoint, proved to present an acceptable behavior control, stabilizing the steady state output temperature signal as 40ºC with a 1ºC error fluctuation and 1,75ºC overshoot. This result is shown in Fig. 14.

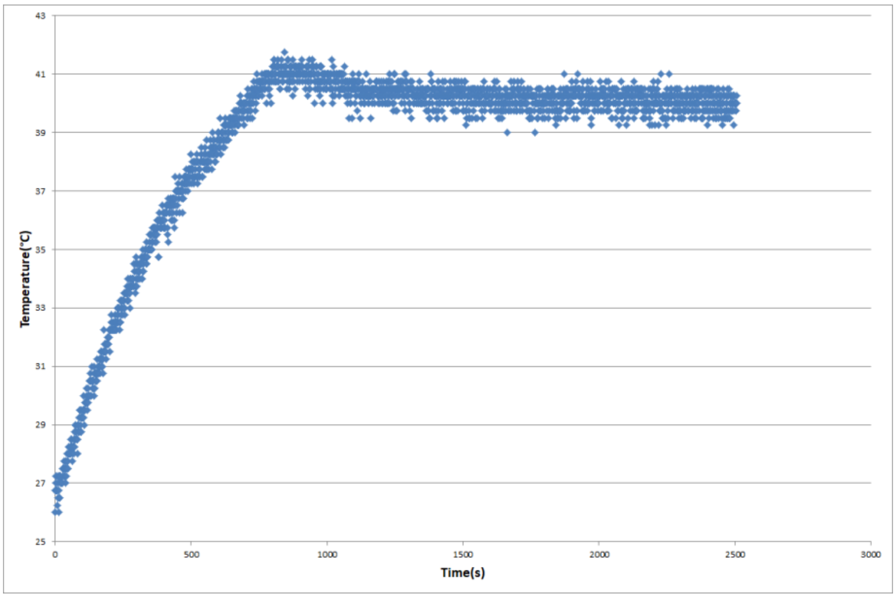


Figure 14. Laboratory Prototype PID Control Test

The cooling capacity for the real plant condition was of a maximum of 30°C when the initial temperature of 100°C, what reveals approximately a 30% of the initial temperature maximum reduction for the steady state. The laboratory prototype, due to physical construction viability, worked on lower temperatures, about half of the real operating plant but the reduction percentage was really close to what is seen. For the initial temperature of 50°C, it achieved a reduction of 17°C, what represents 34%.

4. CONCLUSION

In full capacity of the wood furnace, the hot air can reach close to 110°C, which helps for a rapid rise in the temperature of the coffee grains, causing physical and chemical damage, especially for the green ones, which frequently suffer from overlay oxidation. The fuel feeding process is manual, what commonly causes the air temperature to vary widely during the entire process.

In accordance with recent international market demand for coffee quality, the results indicate that a proper control of the hatch opening could maintain the air temperature optimized, helping the grains temperature to be kept under the desired values for a high quality coffee production, avoiding green grain overlay oxidation and even reducing wood utilization in the process, as lower temperatures are recommended. The PID algorithm could ally the overheat temperature avoidance with the minimal reduction time in the drying process as a whole. Simulation tools were effective to simulate the laboratory prototype which presented high correlation with the real scale tests performed in a coffee processing drying plant in Minas Gerais, Brazil. Therefore, the problem in the real plant can be extinguished by the PID system implementation, which showed enough potential to completely avoid overheating above the recommended temperatures for the drying air, even in the scenario of maximum capacity combustible feeding.

The PID automation system implementation showed enough potential to keep the drying air temperature among the 70-80ºC range and therefore, completely avoid overheating above the recommended temperatures for the drying air, even in the scenario of maximum capacity combustible feeding, when the hot air can reach close to 110ºC by the manual feeding with no operation control.

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