LOW-COST ELECTRIC DRYING SYSTEM WITH TEMPERATURE CONTROL FOR PIECES MADE OF PLASTER OF PARIS

JENNY P. VIEDA D.¹, FERNANDO MARTÍNEZ S.¹ & DANTE G. STERPIN B.²

¹Technology Faculty, Universidad Distrital Francisco José de Caldas, Bogotá, Colombia

²Electronic Engineering Program, Corporación Unificada Nacional de Educación Superior, Bogotá, Colombia

ABSTRACT

The following paper shows the obtained results of the design and implementation of a low-cost electric drying system with temperature control, for the elaboration of pieces made of plaster of Paris, in the Bogotá city, Colombia. In that way, an improvement of the dry time and, thus, the product quality was achieved. The electric drying system was carried out by a halogen lamp which is the heat source in the oven which maintains stable the optimal temperature using a proportional controller, for drying the plaster pieces. Likewise, the sustainability of the project, analyzing the involved costs and the recovery time of the inversion, was detailed in Colombian pesos (COP).

KEYWORDS: Temperature Proportional Control, Pulse-Width Modulation (PWM), Plaster Pieces Drying

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1 INTRODUCTION

During the last 10 years, the ambient temperature in Bogotá has ranged from 9°C to 20°C, and the annual average of rainy days has been 214 (TuTiempo.net, 2020). Plaster of Paris, as the main material for the production of ornamental pieces, kneaded with a water ratio of 80%, and left at a constant temperature between 25°C and 45°C (Rodríguez, 2016), loses almost all of its non-combined water, that is, almost 50% of its dry weight, in less than 40 minutes. Those conditions affect the drying of pieces made of plaster because they are below the minimum required for the optimal drying, increasing production times by 75%, and causing loss of quality such as fissures in 10% of the pieces, lack of brightness in 70%, and loss of material in 3%.

In relation to this data, most of the year the temperature is below the ideal temperature to carry out the drying process, so it is essential to develop a drying system that constantly guarantees a temperature of 38°C (Cabrera, 1996 & Zambrano, 2009), because to achieve an optimal product it is necessary to improve the drying process, and reduce its production costs. In this paper, first, the design and results of a temperature control to dry the pieces made of plaster in an oven are presented and, subsequently, the costs of that development are analyzed to calculate the estimated time of recovery of the investment.

2 METHODOLOGY

The structure of the oven was built with 15mm wood sheets, because it is very stable and easy to work with, supports humidity and is economical. The oven doors are made of glass and its dimensions were obtained based on the possible maximum production capacity of a micro company, and considering the size of the largest piece to be

elaborated. The measures of the oven are shown in table 1. Three sliding and removable shelves are placed on top of the oven, to hold 20 plaster pieces on each one.

Table 1: Measures of the Oven as a Plant to Control

FEATURE	MEASURE [cm.]
Height	78.5
Width	54.5
Depth	67

2.1 Modelling the Plant

For the initial testing of the plant, the heating system was defined by a halogen lamp with an electrical power of 300 W., a nominal voltage of 120 V. and a current consumption of 2.5 A. This selection was made in order to achieve, inside the oven, similar conditions of a sunny day, to have a fast response time and maximum efficiency for the paint drying process, to improve the brightness of the pieces. The lamp was located in the lower central part of the oven in order to obtain a better temperature distribution. After that, samples of the plant's behaviour were taken in open loop, measuring the voltage by a sensor and the temperature by a thermocouple, using a multimeter, every 10 seconds. The signals are shown in the Figure 1.

Figure 1: Behaviour of Temperature and Voltage in Open Loop.

These data were imported into Matlab and using the ident tool, the least complex equation was found, with the best approach to plant behavior (Sigmon, 1992, Rairán, 2007 & MathWorks, 2018). Equation 1 details the mathematical model obtained and Fig. 2 shows the contrast between the real behavior of the plant and its model.

$$G1(s) = \frac{k}{(1+Tp1s)} = \frac{0.51048}{(1+199.41s)} \quad (1)$$

2.2 Getting the Controller

With the data obtained, the implementation of a PIC16F877A microcontroller was defined (Microchip, 2019; Chekired, F., et al. 2020). Using an algorithm in C language (Gota, D., et al 2020, Nguyen, T., et al. 2018), a proportional controller is made whose output signal will be made in a PWM module that will feed the power stage (dimmer), to control the intensity of the lamp. Figure 3 shows the flow diagram used.

Figure 2: Mathematical Modelling with 72% of Accuracy.

Figure 3: Algorithm for the Controller in the PIC.

2.2.1 Power Stage

Since the lamp's power supply is 120 VAC and its current is over 2 A, it is necessary to use a power circuit, and it was done using a dimmer-type circuit. Dimmers are electronic devices capable of regulating the intensity of electrical sources by switching. All dimmer systems operate on the basis of two techniques to limit the current flow in the lamp, which are: i). voltage variation, and ii). Time interval variation, in which the current flows during each of the alternating current cycle.

All thyristor-based dimmer circuits require that the device be triggered at some specific point after the zero crossing of the sine signal. This is done by controlling the driving time of the thyristor, to regulate the current delivered to a load, in order to control the power consumed (Couëdic, 1999). Figure 4 shows the circuit diagram of the power stage used in this work.

Figure 4: Circuit of the Power Stage.

2.2.2 Control Stage

In the control stage, a proportional controller (Paraskevopoulos, 2017). is used, in which a temperature sampling interval is set every 500 ms, because the sampling frequency is too low and the stability of the system may be degraded, and information may be lost because the signals used change too quickly, and the data present would not be used. Indeed, by defining this sampling time, the amount of information increases and the controller manages to operate quickly and correctly (UPM, 2007).

The output signal is made by a pulse width modulation (PWM) to control the power delivered to the heat source of the temperature control system. The PWM is known as a technique that modifies the duty cycle of a periodic signal (Maloney, 2004). It was determined that using the signal from the temperature sensor, a temperature of 38°C was maintained, because the ideal temperature for drying the pieces was established in a range of 35°C to 40°C. An algorithm in C language was used, and Figure 5 shows the control stage circuit used in this work.

Figure 5: Circuit of the Control Stage.

2.2.3 Transfer Function

The implementation of a trigger circuit in the control system implies a disturbance in the transfer function of the plant, so it is necessary to perform the analysis of the behavior and influence of that. The following is the analysis of the response to a 0-10 V ramp stimulus. First the gain behavior of the LM35 sensor is analyzed (Texas Instruments, 1999). When that sensor receives the signal it has a consumption value that is reflected in the transfer function because it is the one that feeds back the signal to the system. Therefore we will call it H and its gain value is 0.01. For the direct phase control system is implemented equation 2 that models the firing angle circuits in control systems (Rashid, 2003).

$$V_{rms} = V_{max} \sqrt{\frac{\pi - \alpha}{2\pi} + \frac{\sin(2\alpha)}{4\pi}} \quad (2)$$

Equation 2 relates the RMS voltage and the firing angle, under ideal conditions, ignoring the voltage drop at the power element and neglecting possible voltage amplitude variations in the power grid. As a result of the implementation of equation 2 we obtain the graph of Figure 6 for the firing angle. From this graph, the linearization area is taken into account

to obtain the gain value of the trigger angle transfer function that controls the dimmer, and the resulting value is 14.568. With this data, in Figure 7 G1 is the model of the plant, G2 is the gain obtained by the dimmer trigger circuit, and H is the gain of the sensor.

Figure 6: RMS Voltage Applied to the Lamp vs. Firing Angle.

Figure 7: Block diagram with G1, G2 y H.

Solving the block diagram in Figure 7 the transfer function that models the system is obtained, and it is detailed in Figure 8.

Figure 8: Block diagram Analysed in Matlab.

2.2.4 Root Locus

To determine the parameters of the compensator applied to the plant, the compensation by the place of the roots (Dòria-Cerezo, A., & Bodson, M. 2016; Iqbal, K., 2020) is used, using the matlab's sisotool (MathWorks, 2018). The data of the transfer function (G), the sensor gain (H) and the position of the poles are loaded as it is shown in Figure 8. In consequence, Figure 9 shows the location of the poles and Fig. 10 shows the change of the plant response. The tool optimizes the response of the plant by reducing its stabilization time, and as a result the gain of the compensator ($C=4$) is obtained, as finally detailed in Figure 11.

Figure 9: Root Locus Plot.

Figure 10: Response of the Plant with Compensation.

Figure 11: Implemented block diagram.

2.3 Electric Testing of the System

With the controller ready, we proceed to perform tests and take measurements in order to know the behavior of the plant when the controller is used. Those measurements were taken with a power quality analyzer DM-III Multitest (Amprobe, 2001), and the obtained results of voltage, current and power, without and with controller are shown in the Figure 12 to 14.

Figure 12: Behaviour of Voltage, without and with Controller.

Figure 13: Behaviour of Current, without and with Controller.

Figure 14: Behaviour of Power, without and with Controller.

Observing the voltage, current and power behaviors, Table 2 details the difference between the plant's consumption without and with a controller. There, we can see that, when using the control system, energy consumption is reduced by 54.8%. Figure 15 shows that when using the oven without temperature control, the temperature increases above 50° C, which causes compaction problems and the appearance of fissures in the plaster pieces. On the other hand, when using the oven with control, the temperature is stabilized at 38°C, and under this condition an optimal product is obtained and the drying time is considerably reduced.

Table 2: Averages of the Electrical Measurements

Test Condition	Voltage [V]	Current [A]	Power[W]	Energy[Kw-H]
Without controller	123.12	2.37	291.82	0.27
With controller	126.40	0.84	93.75	0.08

Figure 15: Behaviour of Temperature, without and with Controller.

3 RESULTS

With the plant working at a stable temperature of 38°C a batch of the product is taken for testing. The tests in the oven were carried out with half of the batch, i.e. 60 pieces were worked at a constant temperature of 38°C inside the oven, while the other half of the pieces were worked at ambient temperature which was ranging from 12°C to 20°C.

During the molding stage of the pieces, those that were worked inside the oven had a drying time of approximately 15 minutes, while in the open air the drying time was 40 minutes. During the casting stage, the drying time inside the oven was 20 hours, with an excellent finish, while for the pieces in the open air, the drying time was 48 hours, with an excellent finish. During the neutralizer drying stage, it was observed that inside the oven it takes 2 minutes, while in the open air it takes 20 minutes. Finally, during the drying of the paint, the time inside the oven was 5 minutes, for each layer of paint, with an excellent finish, while for the pieces in the open air the time was 20 minutes, for each layer of paint, with an approximate temperature of about 16°C, obtaining a good quality finish but with loss of gloss and a rough surface. These data are consolidated in Table 3.

Table 3: Comparison of Drying Times

Dry Process		Dry at Open Air [Min.]	Dry in the Oven [Min.]
Casting	Molding	40	15
	Finishing	2880	720
Neutralizer		10	2
Paint (3 layers)		20	5
Total		2950 [2.05 days]	742 [0.52 days]

3.1 Costs Analysis and Viability

With the results obtained, we proceed to calculate the production that can be achieved based on the capacity of the microenterprise, for which we take as statistical data the production in the last three months, that is an average of 180 pieces per week, that is 8640 pieces per year. As the estimated time of production of a piece in the oven is reduced by 75%, the operating capacity of the micro-company was observed and it was noted that the maximum production capacity is 300 pieces per week, which is restrictive because the capacity of the oven is close to 720 pieces, therefore, in table 4 the analysis was made based on a production of 300 pieces per week or 14400 pieces per year.

To determine the value of the profit per piece, the values associated with the production of the piece were studied. Table 5 shows that the cost is \$3,900, and since the piece is sold at about \$4,700, the resulting profit value per piece is \$800. So, for a production without using the oven, the annual profit is \$6,912,000. Using the oven, the production costs increase by \$113,493, according to Table 4, due to the price of the energy consumed annually by the oven. This implies a decrease in the profit per piece of \$8, but as the production increases to 14400 pieces per year, the final profit is \$11,406,507 per year.

Table 4: Relation between Production and Profit

Realization	Amount of Production			Profit	
	WEEKLY [Unit]	MONTHLY [Unit]	ANNUALY [Unit]	PER UNIT [COP]	ANNUAL [COP]
Without oven	180	720	8640	\$800	\$6,912,000
With oven	300	1200	14400	\$792	\$11,406,507

Table 5: Production Costs of Each Plaster Piece

Item	Without Oven	With Oven
Material	\$2,100	\$2,100
Workforce	\$1,800	\$1,800
Energy	\$0	\$8
Total cost	\$3,900	\$3,908
Selling price	\$4,700	\$4,700
Profit	\$800	\$792

3.2 Return on Investment

In order to carry out the return on investment (ROI) study (Duermyer, 2020), the value of the total annual profit obtained from the use of the oven is taken, and it is \$11,406,507. So, the increase in the additional annual profit is calculated, given that the profit is caused by the benefit of using the oven, and it is \$4,548,215. With this value, the additional daily profit obtained from the use of the oven is \$18,951, in order to know in how many days the invested in the oven will be recovered, which is \$3,858,635, the total time required to obtain the ROI is 204 days, as the Table 6 shows. So, the ROI will happen from 9 to 10 months of real working time in the microenterprise.

Table 6: Return on Investment (ROI)

Profit Increment	Worked Days	Daily Profit	Cost of the Oven	Roi [Days]
\$4,548,215	240	\$18,951	\$3,858,635	204

4 CONCLUSIONS

In this work a temperature control for a low-cost oven was designed and tested, to improve the quality of pieces made of plaster of Paris, and to increase its profit. So, the drying time of the figures was reduced by 75%. The production of figures was increased by 167%. The return on investment is at most 10 months, and it is expected that the profits in the second year will be \$4'548.216. If a control system is not implemented in the oven, the energy consumed will increase by 54.8%. So, the improvement obtained in the quality of the pieces is notorious since it reduces the waste of material and the time of elaboration of the pieces, achieving a better quality in the product. This project is viable, since it generates a better profitability in terms of production, quality and profits, improving the quality of life of the worker, and guaranteeing the timely delivery of the production.

The oven responds adequately in the need to maintain its temperature stable, however the implementation of materials that isolate the internal temperature from the external will improve the ratio of on and off the oven, reducing the cost of operation by energy expenditure. As future work, the efficiency of the oven can be improved by using insulating materials that can maintain the temperature inside for a longer time. It can also be coated on the outside faces for use outdoors, allowing modifications that tend to use other heat sources. Other control methods can be explored to further reduce electrical energy consumption, and a humidity sensor can be added to improve the quality of the pieces, as well as a display to set drying times and visualize the temperature and humidity inside the oven.

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