DIGITAL CONTROL TEMPERATURE OF A HEATING DEVICE-CONSTRUCTION OF A KIT DIDACTIC OF LOW COST FOR THE TEACHING OF DIGITAL CONTROL IN COURSES OF MECHANICAL ENGINEERING

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Abstract. *The heating devices are of great applicability in industrial processes such as chemical and metallurgical types and also in systems for thermal treatment of metal and ceramic materials. In these processes the accurate control of periodic temperature patterns is crucial. Nowadays there are several techniques of control, among them the digital control. Digital controllers are used in several applications in order to maximize performance, or minimizing energy consumption. When they are implemented by computer, great versatility and flexibility are shown as their parameters can be adjusted according to the changes in the processes. The main goal of this work is the design of a digital system to control the temperature of a heating device that follows temperature references of step or ramp type. The constructive aspects of the heating device prototype, developed specifically for this study, the modeling of the system, the electronic system for monitoring temperature and the power circuit, to supply the heating device, are shown. The experimental results are compared with numerical simulations.*

Keywords*: Digital control, Automation and control, Heating systems*

1. INTRODUCTION

Aiming to reduce costs, increase production and higher reliability in industrial processes, several studies in the field of automation and control have been developed. Such studies require interdisciplinary knowledge coming from areas like automation, electrical, electronics, mechanics and computing.

With the lower cost of digital processing equipment, the use of digital controllers in industrial processes has predominated. According to Ogata (2003), digital controllers are used to achieve optimum performance in order to achieve maximum productivity and minimum energy consumption.

The digital control implemented by computer makes possible even greater versatility and flexibility to adapt to changes in processes. According to Barczak (1995), the digital control of a dynamic system, performed in software, can incorporate compensating, implementing proportional-integral-derivative as well as other forms of linear control. Their potential to incorporate into a control program, however, is beyond the universe of traditional controllers because it allows using other methods, such as the fuzzy logic controllers which are based on rules, neural networks, expert systems and other forms of artificial intelligence.

They also highlight the importance of ensuring greater reliability and precision in control systems, and allow the collection of tables and graphs more easily, which enables an efficient comparison between the desired and the parameters achieved by the process controller and the availability of such data in a computer network for remote access. Not so long ago, when you did not want high accuracy, analog controllers were used, but today with the advent of mass marketing and micro-controllers, the cost of implementing a digital controller decreased considerably and has justified its use in most industrial processes.

These controllers can be used in cases involving several variables that need to be monitored in real time, such as temperature, pressure, humidity and density. What changes in each of these cases is the type of sensor being used, which normally turns the magnitude of the physical variable measured in a voltage or current signal.

In many industrial processes it is necessary to submit mechanical parts with different temperature cycles, such as in the manufacturing or in the hardening of tools. Very often, the commercial equipment is extremely expensive, which exclude their use with low budget or small mechanical projects. On the other hand, modest equipment can prevent the same project by the lack of control of cycles of operation. Nevertheless, the latter has ceased to be a problem, considering the evolution of micro computer which is a developing equipment with better performance, at prices more competitive, which makes real the possibility of projects that require more robustness and efficiency in the results.

Physical properties such as melting point, boiling point, specific heat, coefficient of thermal expansion and thermal conductivity, are examples of physical properties of materials that are directly affected by the change in temperature. In general, the materials submitted to a temperature change suffer internal structural changes, from an atomic arrangement to another, corresponding to the transition between different structural arrangements of molecules in the material, and consequently changes in their physical properties. In this context, it is concluded that temperature, particularly its control, is a leading role in the behavior of materials, and it is now emphasized the importance of monitoring the thermal behavior of these when subjected to changes in temperature (Gonçalves, 2000).

In response to this need, industrial furnaces equipped with digital temperature controllers are available on the market, which have in general two functions to control temperature cycles of operation, following the temperature references in a way of type step and ramps. The disadvantage of these furnaces is the relatively high cost and the operation as true black boxes with respect to the technology of control, i.e., their methodology and theoretical basis of control are not available to users, which can provide technical limitations and operational versatility limited.

In our process, which consists of control of heat transfer, a response time greater than for the case of other physical variables can be naturally found. This suggests the possibility to use computers or micro-controllers with minimum performance settings, enabling the application of digital controllers in processes for temperature control without the need for large investments.

The objective of this work is to develop a low cost teaching kit for the implementation of a digital controller in a heating device able to follow temperature cycles composed from step or ramps type functions. The work includes constructive aspects of the heating device, the experimental evaluation of the dynamic behavior of the plant (transfer function), the electronic system for monitoring temperature, the power circuit of the actuator and the design of digital temperature controller in order to meet the basic stability and performance criteria of the system.

2. METHODOLOGY

The first step to be worked with students of engineering is to establish the mathematical model of the system. The mathematical model of a dynamic system can be defined as a set of equations that accurately represents, or at least reasonably well, the dynamics of the system (Ogata, 2003).

It is important to emphasize that a mathematical model is not unique to a particular system, since this can be represented in many different ways and therefore may have different models depending on the perspective being considered. Depending on the system considered and the particular circumstances, a model may be more appropriate than others. For example, for systems with optimal control it is used the representation with space of states. Furthermore, for a single input/output linear system, the use of a Laplace transfer function may be more convenient than any other.

Another point that deserves mention in this step is the balance between the simplicity of the model and accuracy of the analysis results. To obtain a simplified mathematical model, it is often necessary to ignore certain physical properties inherent in the system. In particular, if it is desired a mathematical model of linear concentrated parameters, it is necessary to ignore certain non-linearity and the parameters that can be distributed in the physical system. If the effects of these ignored properties in the response are small, you can get good approximation between the results of the analysis of the mathematical model and the experimental results of the physical system.

Generally, in solving a new problem, it should be first build a simplified model in order to have a general perception on the solution. A more complete mathematical model can be used later in order to obtain more precise results (Ogata, 2003).

A simple heating oven was constructed using parallel refractory plates measuring 229 mm X 114 mm X 25 mm (width, height, depth). These refractory plates were supported by a structure of L type profiles measuring 1/8" x 3/4". With this setting the heating device presented the following internal measures (dimensions of the useful camera): 185 mm X 114 mm X 229 mm (width, height, depth).

It was used as heating element an electric resistance of 29 Ω at 220V commonly used in grills. With these characteristics, the resistive element can provide a maximum power to the heating device of approximately 1668.97 W.

The used temperature sensing element was an industrial type J thermocouple. This thermocouple has a blanket metal element that involves the driver between the join hot cold, promoting an electromagnetic shielding in order to reduce possible noise and interference from the outside.

A temperature transmitter was used for reducing noise and providing more robustness to the measurement system. This is a device that prepares the output signal of a transducer for use at a distance, making certain adjustments to the signal which are called patterns of transmission of signals (Thomazini, 2007). Other function of this device is the amplification of the signal from the thermocouple type J for the data acquisition system, making possible a greater distance between the computer and the heating device. The used transmitter is manufactured by TT301 Smar.

In order to make the acquisition of signals from temperature sensor it was necessary to use a data acquisition system, part of the interface with the computer to perform the digital control. This is the 6221 PCI card acquisition of National Instruments.

The Figure 1 illustrates the heating device constructed in this work.

Figure 1. Detail of the resistance set at the top of the heating device

This heating system, for simplicity, can be seen as a first order system. This system has as main characteristic a high constant-time, so that the responses of the system are slow. The Equation (1) shows the transfer function for this type of system.

$$\frac{C(s)}{R(s)} = \frac{K}{Ts+1} \tag{1}$$

The parameters of this model can be experimentally obtained applying a step input with maximum power on the system and then obtain the values of temperature inside the heating device at regular time intervals of 15 seconds. From these data it is then possible to draw a curve of response as shown in Fig. 2:

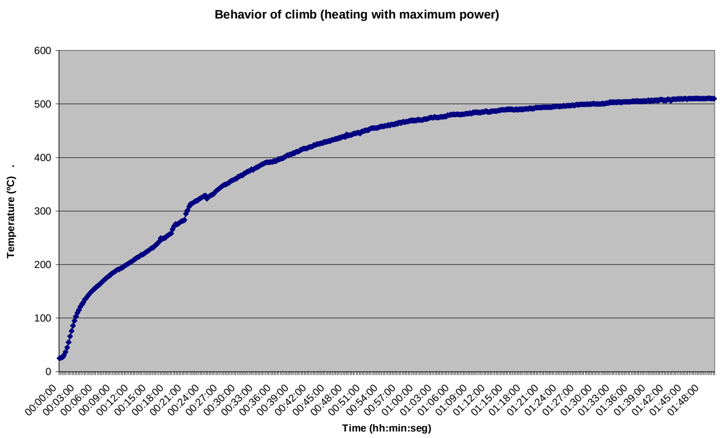

Figure 2. The step response curve of maximum power

From Fig. 2, we can observe that it took 70 minutes (3T) to the heating device to reach the temperature of 484.5 °C, or 95% of the value on a permanent basis. Thus, T = 1400s.

Found the value of the constant of time, the next step is to calculate the gain of the plant. This can be given by the relationship between the higher temperature and the maximum power generated by the resistance. Thus, we have:

$$K = \frac{\Theta_{max}}{P_{max}} \tag{2}$$

Where:

K = gain of plant.
Θ_{max} *= maximum temperature reached in the plant (^oC).*
P_{max} *= maximum power generated by electrical resistance (W).*

So, from Eq. (2) the gain of the transfer function is equal to 0,30558 and then the transfer function G(s) of the heating device is:

$$\frac{\Theta(s)}{P(s)} = \frac{0,30558}{1400s + 1} \tag{3}$$

From the experimental curve in Fig. 2 the limits of the heating device in order to reach some temperature can be observed, so that it is not possible to get a certain temperature in a time less than achieved with maximum power.

In order to obtain also the limits of cooling the heating device, because of descent ramps are also desired in this system, a curve was obtained in natural cooling. Because there is no implementation of an actuator to promote cooling of the heating device, the experiment to obtain this curve consisted on turn off the power of the electrical resistance (zero power supply to glass) and to measure at intervals of time the value of temperature. The response curve obtained is shown in Fig. 3.

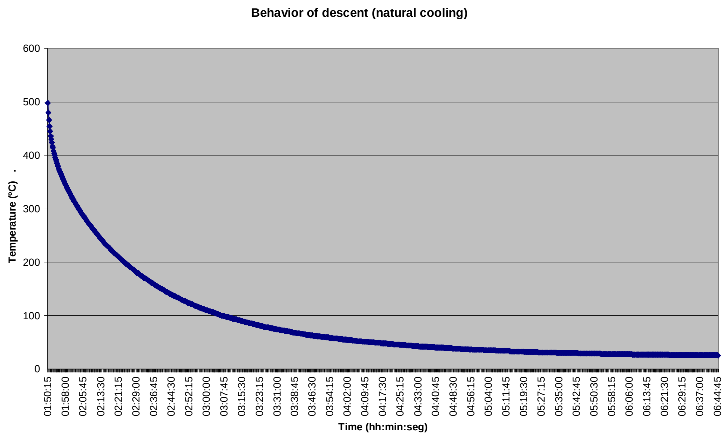

Figure 3. Natural cooling curve of the heating device

With the transfer function of the system, it is possible to design the digital controller that meets the desired characteristics for the system. This study used the technique that consists on to design an analog controller, analyzing its performance with the continuous plant, and then perform its discretization verifying its performance in the discrete domain. This last step is very important because a controller can be efficient in a continuous domain, but not meet the desired requirements when discretized. One of the factors that can lead to this problem is the choice of an inappropriate sampling frequency.

As the proportional-integral-derivative controller satisfactorily meets the system requirements in most cases, it could be used to control the temperature of the heating device. Before, however, some remarks on the control system and the transfer function of the plant should be commented.

The transfer function of the plant, Eq. (3), shows the system being controlled as a first order or zero degree. For this type of system usually a derivative action offers low contributions and is put off, so the use of a PI controller is sufficient. This is because these types of systems are generally very slow and require a response in steady state with zero error, which is obtained with the integrative action. For systems that require higher order or a control with more precise adjustment it is then recommended the use of PID controllers. It is of great importance show these considerations for students as well as proposes the design of different controllers that meet the requirements.

Among other possibilities for implementation of controllers for this system, the transfer function of the PI controller (Proportional-Integrative) can be as in Eq. (4).

$$\frac{U(s)}{E(s)} = K\frac{(s+0{,}001)}{s} \tag{4}$$

It is suggested then use MATLAB and plot the root locus of the compensated system. It is still possible, according to the discipline and the interest, complete the route manually in accordance with techniques that maybe have been studied. Using this plot there is the location of the poles of the compensated closed loop system.

Even with the graph of the root locus can be obtained the value of the gain K to leave the system controlled with appropriate responses to the specifications of the project.

The Figure 4 shows the chart of root locus of the compensated system.

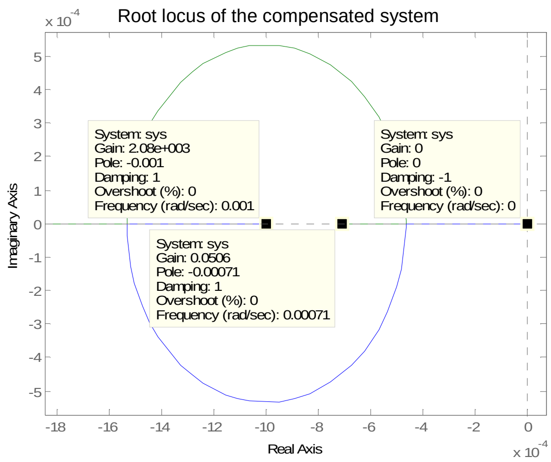

Figure 4. Root locus of the compensated system with identification of poles and zeros

Once considered the place of the roots of the compensated system, you must then evaluate the response to a step input or ramp. It is expected that this study controlled the system is able to follow the rise and fall ramps with maximum error of 10^{o}C and can achieve a level (step) temperature defined by the user with an error less than 5% of final value.

To perform simulations of the response of the entry ramps and steps you can use MATLAB. In the case of application of this work is to the use of Simulink, a tool available in the software mentioned above. Thus it is possible not only to check the response of the system defined entries, but also include limiting (in the case of this work to consider that the system has a physical limitation of action for maximum power to be delivered to the heating device) among other features. Can also be easily modified and configured with different types of input for analysis. Using this model it is possible to analyze the response of the system to a step of 100^{o}C and 400^{o}C, for example. In the Figure 5 is presented a model created in Simulink.

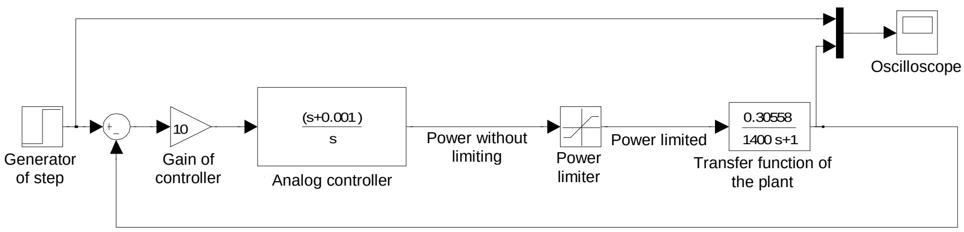

Figure 5. Model for simulation of control built in Simulink

Once designed and with results of computer simulation should be available then followed for the second phase of the project. This phase is the discretization of the controller designed and the achievement of performance tests for analysis of the response of the system using a digital controller.

To perform the discretization of continuous monitoring should be used in the methods available, such as bilinear transformation (also known as a method of Tustin), married processing, transformation or married modified bilinear transformation with frequency distortion (Barczak, 1995). In this work the method is to Tustin which is based on numerical integration. To perform the discretization of analog controller just replace the term *s* of the transfer function by the expression of Eq. (5), where *T* is the time of sampling used in the system.

$$s = \frac{2}{T} \cdot \frac{z-1}{z+1} \tag{5}$$

Making the discretization of the controller with sampling time *T* equal to 4 seconds, you get the Eq. (6).

$$\frac{U(z)}{E(z)} = K \cdot \frac{1{,}002z - 0{,}998}{z-1} \tag{6}$$

The discretization of analog controller can also be performed computationally using the MATLAB. To do this simply use the command c2dm and choose the method of Tustin or other desired method.

To achieve the desired simulation is still necessary discretized model of the plant. According to Ogata (1995), is often used a data hold of order zero (ZOH - zero order hold). This discretization can be performed using the MATLAB command c2dm and choosing how zoh method. The stapler of order zero is responsible for maintaining the value of the sample until the conversion is complete (Barczak, 1995). Thus, considering a sampling time equal to 4 seconds, the transfer function of the plant may be rewritten in z as in Eq. (7).

$$\frac{\Theta(z)}{P(z)} = \frac{0{,}008714}{z - 0{,}997147} \tag{7}$$

Now just set the gain of the controller through simulations of discretized system. Should be assessed the responses to steps of different values of temperature and ramps with different slopes.

In possession of the results obtained through computer simulation and validated the digital controller, you must then find the difference equations that should be implemented in software as part of the control algorithm. The difference equation to a controller with a gain equal to 15 can be expressed as in Eq. (8).

$$P(k) = 15{,}03\varepsilon(k) - 14{,}97\varepsilon(k-1) + P(k-1) \tag{8}$$

The Figure 6 illustrates the structure of the digital control system of temperature proposed in this work.

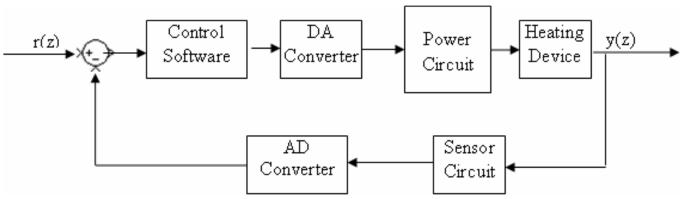

Figure 6. Structure of the digital control system of temperature

The next step is the creation of software to control where to use the difference equations found. In the system developed, the temperature inside the heating device is measured using a thermocouple type J. This provides a low voltage to a temperature transmitter which in turn performs amplification and signal processing for use with long distances. The signal provided by transmitter must then be delivered to an input analog/digital (A/D) of the PCI card. The software interprets the value of control voltage and converts a measured value of temperature.

In possession of the value of the measured temperature controller must make a comparison with the reference temperature value and calculate the error between the measured value and expected. It is from this error that the controller must decide the level of electric power to be supplied to the heating device. Set this value to control the software triggers the digital/analog converter (D/A) which in turn controls a power circuit. This is then responsible for providing power to the heating device calculated by software control. The circuit power is defined as actuator and because of its functionality in the system can be considered part of the control system.

The Figure 7 shows a picture of the complete structure of the automation system developed in this project.

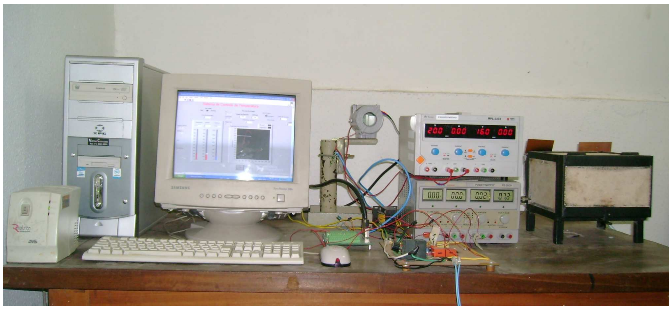

Figure 7. Picture of the complete structure of the automation system

The power circuit is a system used to control the phase angle of firing of two thyristors, devices commonly used in circuits that require high current. The thyristors then connect the load source for a period of each cycle of input voltage. For generation of firing angles in accordance with the desired amount of tension in the actuator is used TCA 785 integrated circuit, manufactured by Siemens. The layout of the electronic power circuit is provided in Fig. 8 below.

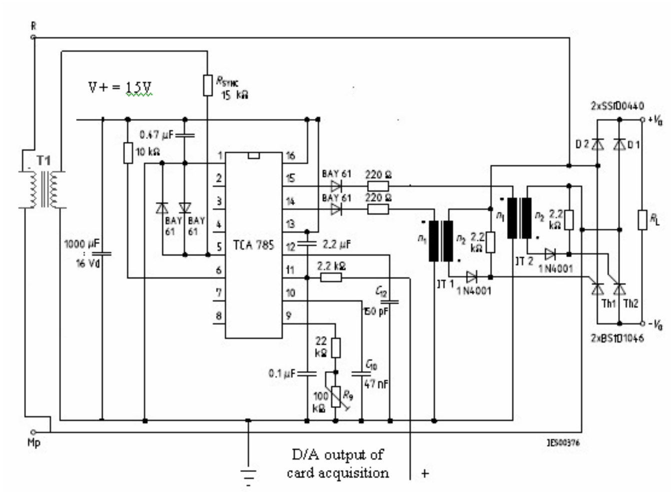

Figure 8. Schematic of electronic power circuit

The electrical resistance to be driven by the power circuit must be supplied with a voltage up to 220V, and for this reason the power circuit uses the same voltage. A 15V transformer is used to perform the function of reducing the amount of voltage to meet specifications of the operation of TCA 785 and achieve the isolation between the control and the power in the circuit. The triggering angle of thyristors to be provided to TIC 126D is generated by the TCA 785. The variation can be 0^o to 180^o and can be controlled by the voltage supplied to pin 11 of IC. The manufacturer of IC, the voltage applied on this pin must be between 0V and the value of supply voltage supplied to the operation of the same (15V in this work). In addition to electronic components used for generation of reference as required by the manufacturer two processors are used to attach the pulse driving the thyristors.

You can then to controller the value of the output voltage of the circuit from the power control signal provided on pin 11 of TCA 785. This signal is generated using the software of control and sent to digital-analog converter via channel zero of the card purchase.

The control program developed in this project used the LabView platform in version 8.2.1 and a computer with Pentium 1.8GHz, 512MB RAM and 40GB hard disk with the Windows XP operating system installed. The control program was developed in two versions: functional and educational (Afonso, 2008).

In the functional version on the screen the system presents only general parameters of interest in setting a user's application, which makes it well suited to application in industries. Already in the educational version is available other information of interest, such as the parameters of the controller used and the variables of the system. These data were only available in this version because it is information open to interpretation by professionals or students in the area of control. The Figure 9 and Figure 10 show the screens of the control system as functional and educational, respectively.

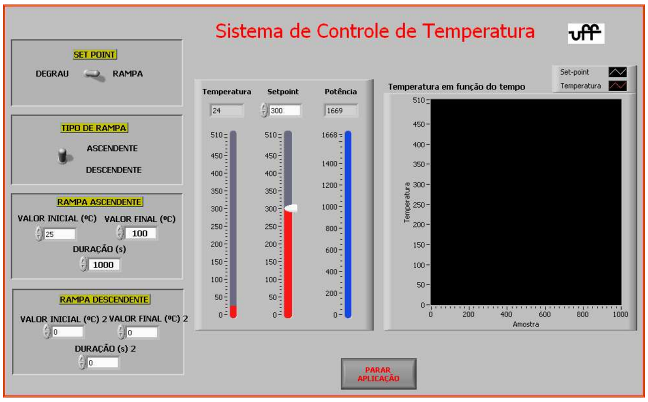

Figure 9. Screen of the software developed to control the temperature in the functional version

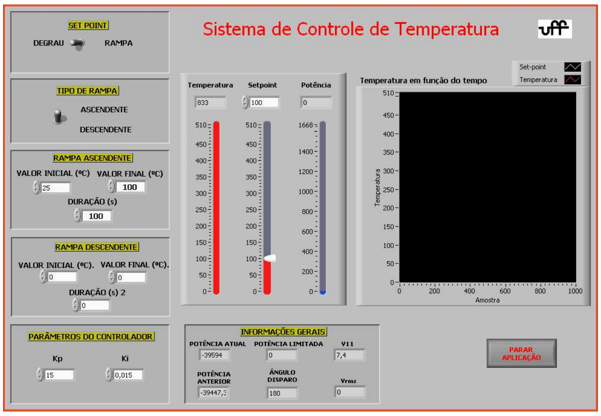

Figure 10. Screen of the software developed to control the temperature in the educational version

3. EXPERIMENTAL RESULTS

With the system built using the controller with the gain equal to 15 was possible to obtain the curves displayed in Fig. 11 and Fig. 12. Other curves with different controllers can also be tested with students for various designed controllers.

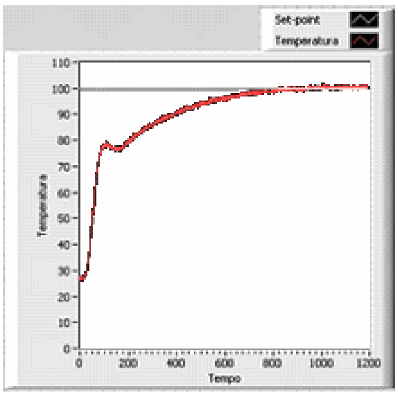

Figure 11. Experimental result in response to a step input of 100^{o}C

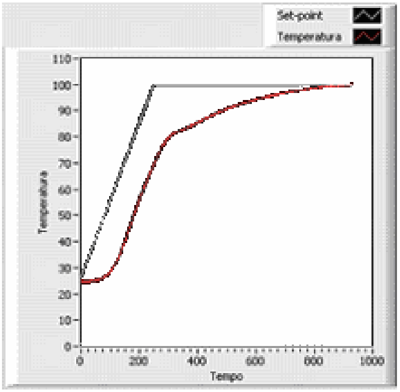

Figure 12. Experimental result of an entry in response to ramp up followed by step of 100°C

The Figure 13 shows the response of the system to the input signal from the control system when the gain of the controller is equal to 50.

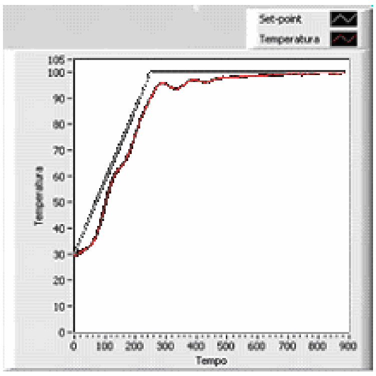

Figure 13. Experimental result of an entry in response to ramp up followed by step of 100°C - digital controller with a gain equal to 50

Analyzing the response of the system when using the digital controller with a gain equal to 50, can be seen that the offset error of the system is around 6°C and that the time for accommodation is approximately 650 seconds. The completion of this analysis with the students is very important.

The Figure 14 shows the response of the system to an entry ramp up the type of 100°C followed by a step and then a downward ramp to the temperature of 25°C (value of the temperature at the time of conducting the experiments). The PI digital controller was used with a gain equal to 50.

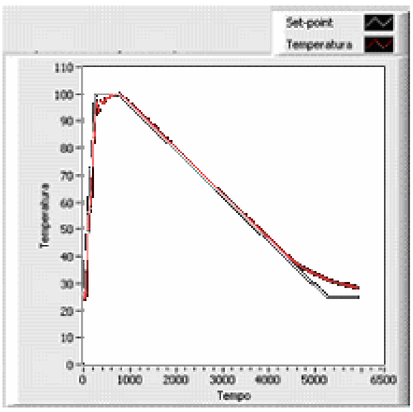

Figure 14. Experimental result of an entry in response to ramp up followed by a step of up to 100oC and descending temperature ramp - digital controller with a gain equal to 50

4. CONCLUSIONS

With the development of all the steps outlined above, it is possible to perform a complete and practical study of discrete control. It can also be explored other more type of power circuit and control techniques. From the experiment carried out using a PI controller it was possible to meet the desired requirements for the system and with an accuracy of temperature reading of around 1°C.

It was possible to observe and implement all stages of development of a digital controller, since the experimental modeling to the testing of the whole system.

Given the expected requirements, it is also important to clarify some factors that may contribute to the small differences between simulated results and experimental values obtained:

- To perform the simulation we used a mathematical model to represent the transfer function of the heating device, and more needs to be made in order to obtain a better approximation of the real model;
- Through the process of control there are some noise not considered in computer simulation, which can bring differences between the results obtained;
- The loss of heat from the heating device to the environment was neglected to ensure simplicity of the linear mathematical model but in the real case a small non-linearity at high temperatures is observed;
- Under high temperatures, the behavior of electrical resistance also has a small variation, which may influence the response of the system.

The built teaching kit is an important tool that can be used to teach digital control in courses of mechanical engineering.

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