Methods of Automatic Control Applied to a Resistive Furnace for Thermal Treatments

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Abstract - **The paper deals with the study of two methods used for the automatic control of the temperature of the parts from inside a resistive furnace for thermal treatment. The furnace was previously projected and simulated, as presented in other papers. After that it was created a smaller furnace in the laboratory in order to validate the results obtained through simulation. Together with the furnace it was also created the automaton system, which was connected through a microcontroller to the computer. The automation system uses an Arduino ATMega microcontroller, which communicates with the computer through a serial port. Inside the computer, using Matlab, we have created different programs, in order to receive the information from the sensors, to establish the command coefficients, based on different calculation methods, and to send these coefficients back to the automation system. We have used PID control and predictive control methods, in order to maintain the temperature of the parts to be heated on a technological curve imposed by the manufacturer. We control thus, the power of the heaters and of the ventilators of the furnace. The furnace is equipped with three resistors inside of it, and a ventilator and an exhauster. In the end is made a comparison between the command coefficients used in the two cases. This comparison is based first on the calculation of the mean square error, between the imposed temperature and the temperature of the parts, and secondly, on the evolution of the control indices.**

Keywords - ***resistive oven, thermal treatment, PID control, predictive control***

I. INTRODUCTION

The main purpose in designing the automation of an electric furnace with resistors is to realize the automatic adjustment of the temperature. In this way one can correlate the electrical power consumed, by the heating elements, with the necessary technological regime. This leads to a reduction of the specific consumption of electricity on electro-thermal processes and technological processes.

For a better work precision and for the automatic adjustment of the temperature are used all the methods of control: continuous, semi-continuous and discontinuous.

Continuous adjustment methods (PID and predictive algorithms) are, compared with the semi-continuous and the discontinuous ones, more complex and more expensive, but they provide a better accuracy of the preset temperature.

In this paper it is presented a comparison between two methods of controlling the automation system of an electrical furnace with resistors, created in the laboratory. The idea of building the furnace started from the simulated oven presented in [1], [2]. The oven build has the walls formed of three layers, a steel layer inside and a steel layer on the outside, among them being placed an insulation layer.

Two resistors are placed on the side walls, and one resistor is placed on the vault.

The heated parts represent an assembly of 4 bars, put one over the other, forming a plate and the steel rack that supports them.

This oven had been previously simulated, as presented in [3], together with its automated control system.

For the physical oven, the automation system was designed so that it can work with any furnace for heat treatment (with some adjustments in terms of circuits interfacing, achieved its technological facility).

It can actually control the furnace without being necessary to make special settings depending on the constructive characteristics of the furnace and of the load which is subjected to heat treatment.

II. SOFTWARE STRUCTURE OF THE SYSTEM OF MONITORING AND CONTROL OF ENVIRONMENTAL CONDITIONS IN THE FURNACE

Using a new work plant requires knowledge of the possibilities that it has. First we must determine the maximum speed at which parts can be heated or cooled.

The maximum heating rate is determined on one hand by the type and quantity of parts that are subjected to heat treatment and, on the other side by the resistive elements of which the plant is equipped.

The maximum speed of cooling is dependent on the diameter of the two holes through which fresh air is introduced, and that the heated air is discharged. It also depends on the maximum flow that can be provided by the fan and blower.

After some measurements, imposing a step cycle at 250°C, we have decided to realize a technological cycle of almost 10 hours, as presented in Fig. 1.

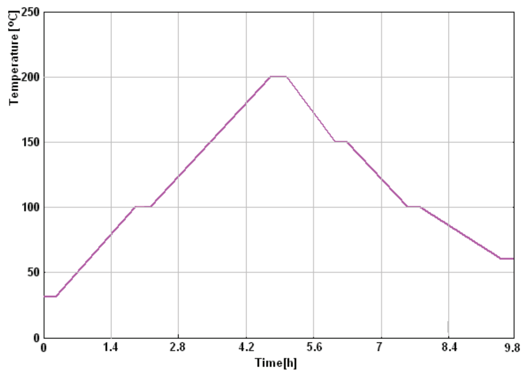

Fig. 1. Technological cycle imposed for validation

In the structure of the technological cycle is observed that there are six levels at different temperatures, two ramps with different slopes and three periods of cooling at different speeds.

The monitoring and control system of the furnace is based on the work in tandem between the microcontroller and Matlab programming environment.

In Fig. 2 is shown a schematic diagram of the effective communication between the temperature transducers, micro-controller and computer (Matlab programming environment), which happens during a cycle of 16s.

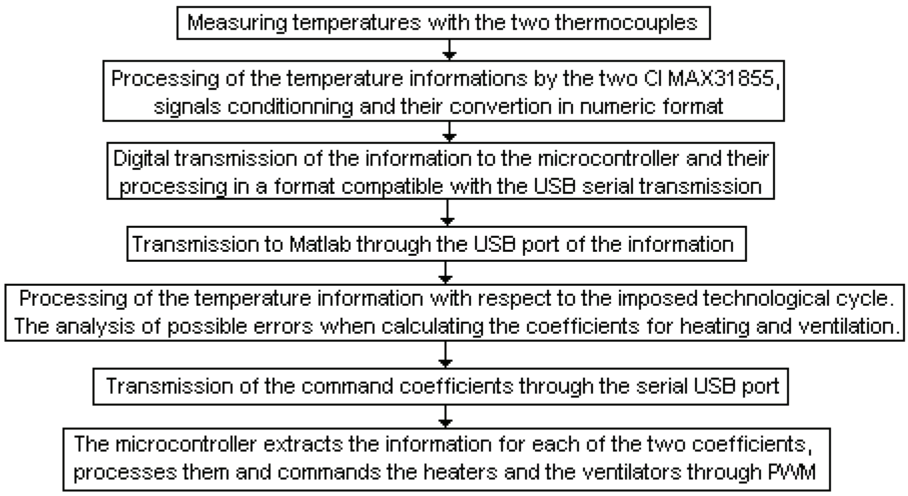

Fig. 2. Schematic diagram of communication

A. The control system using PID controllers

For the experimental validations we have tested two types of PID regulators.

First is based on the equation:

$$\Delta u(t) = K_p\left[\left(\varepsilon(t)-\varepsilon(t-1)\right)+\frac{T_s}{T_i}\cdot\varepsilon(t)+\frac{T_d}{T_s}\left(\varepsilon(t)-2\varepsilon(t-1)+\varepsilon(t-2)\right)\right] \tag{1}$$

In the program we have calculated the incrementing value of the control size of the PID regulator. This value is added with the control value provided by the regulator at the previous step:

$$u(t) = \Delta u(t) + u(t-1) \tag{2}$$

Tests made for the technological cycle shown in Fig. 1 showed a fairly good behavior, the maximum error arising between the imposed temperature and tracking temperature was of 4°C.

The values of the PID controllers for heating and ventilation were determined using Ziegler-Nichols method for tuning presented in [4], [5]. For determining these values we have used the maximum curves of the laboratory plant.

There have been made several attempts in order to provide the optimal coefficients of the two controllers, similar to the methods described in [6], [7]. The results obtained for the different versions have proved the effectiveness of tuning operations by improving the way in which the temperature curve of the parts follows the required temperature curve.

The best results obtained are shown in Fig. 3 and are based on the following sets of parameters:

- PID for heating: $k_p = 0.818$; $k_i = 1.86e^{-3}$; $k_d = 90$;
- PID for ventilation: $k_p = 0.59$; $k_i = 8.67e^{-4}$; $k_d = 78$;

The second type of PID regulator is based on the following equation, in which the start value is considered null.

$$u(t) = K_p\varepsilon(t) + \frac{K_p}{T_i}\cdot T_s\cdot\sum\varepsilon(t) + \frac{K_pT_d\left(\varepsilon(t)-\varepsilon(t-1)\right)}{T_s} \tag{3}$$

The analysis of Fig. 3 shows that the monitoring and control system proposed in this paper provides a good tracking of the prescribed temperature by the temperature of the parts to be heated.

It can be observed that momentary differences between the two temperatures are below 1,75°C throughout the entire range of the test. These values are very good, given the literature requirements that specify, for allowable, the differences of metal in heat treatment, between ± 5÷10°C.

It is noted that in the first ramp and in the second plateau of the graph there are more pronounced differences. This is mainly due to the thermal inertia of the heating resistors in tube. Although the heating command is applied, when the temperature of the parts is lower than the pre-scribed temperature, the warming effect is felt after about 2 cycles of 16s. In these periods the temperature differences increase, but they do not exceed 1,75°C.

In addition, it may present some difficulties in following the prescribed temperature curve during the ventilation range, at high temperatures. This is due to the fact that at high temperatures the ventilation and exhaust efficiency is much higher than at lower temperatures.

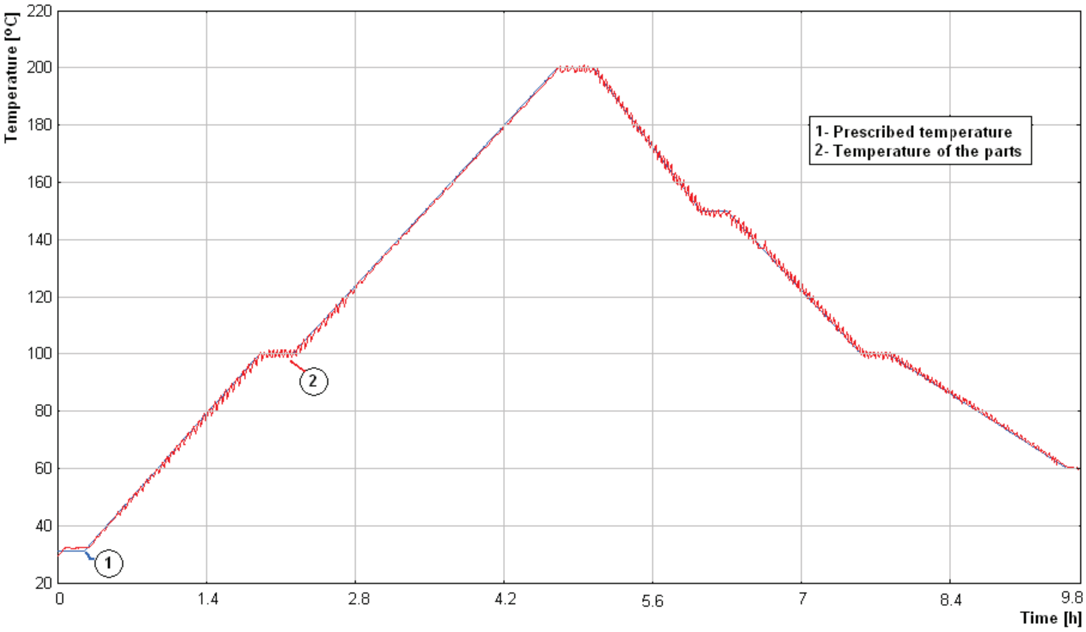

Fig. 3. Prescribed temperature and the temperature of the parts measured at experimental furnace

B. The control system using Smith predictor

In a later stage of the experimental measurements, in order to validate the method for monitoring and controlling the temperature of the parts from the furnace for heat treatment, proposed in this paper, it was developed a predictive control system based on Smith predictor.

This system assumes that some of the inertia that arise during the temperature control can be removed when the command is made, depending on the difference between the current temperature of the pieces and the temperature determined in a predictive way, as in [8] , [9].

These inertia appear both because of the use of the resistors in tube, and because of the fact that the serial transmission requires an intermediate step in which the transmitted data is stored in the input or output buffer.

In order to determine the specific parameters of the Smith predictor (to identify the model), it was performed a simulation of the heating at full power for long term (50h), for a more precise estimation of the maximum temperature of the parts (Fig. 4).

Based on the diagram shown above, it was obtained the model of the process as a 1st order element with dead time, having the following transfer function:

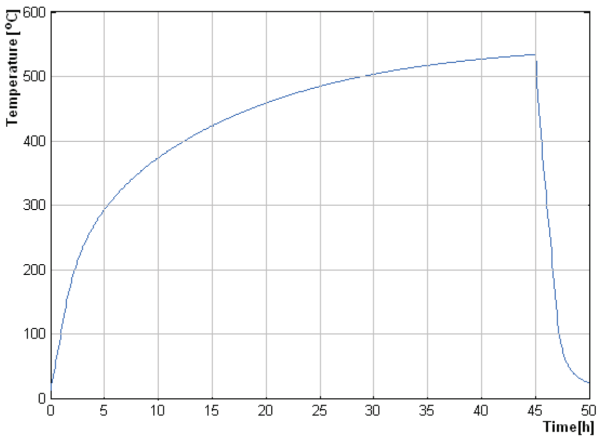

Fig. 4. The temperature of the parts – simulation of 50h

$$G(s) = \frac{K_f}{1 + s \cdot T_f} \cdot e^{-s \cdot L} = \frac{517}{1 + 25387 \cdot s} \cdot e^{-575 \cdot s} \quad (4)$$

Fig. 5 presents the results obtained by completing the program in Matlab, previously used, with the second type of PID controller based on Smith predictor, using a control system with dead time.

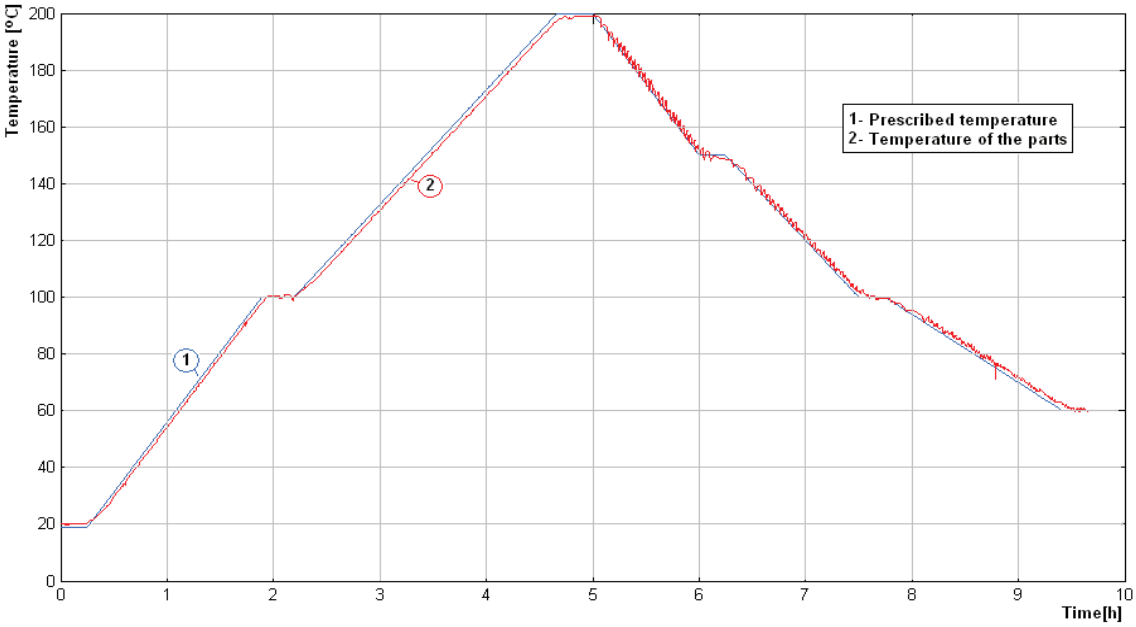

Fig. 5. Prescribed temperature and the temperature of the parts obtained using the control with Smith predictor

Comparing Fig. 3 and Fig. 5 it is clear that the fidelity with which the temperature of parts pursues the temperature required in the technological cycle, is much better in the case of the control based on a predictive control system with dead time (Smith predictor). It can be noted a gap of about 144s between the required temperature and the temperature of the pieces.

It is noted that ascendant ramps and plateaus are followed precisely due to the Smith predictor applied to the heating controller. Larger differences occurred on the slopes of ventilation corresponding to high temperatures.

III. Comparative Study between the two Control Methods

As noted above, the errors in the fidelity with which the temperature of the parts follows the temperature imposed by the technological cycle, are clearly lower in case of the predictive control.

This was proved by calculating the mean square error.

This type of error is characterized by good stability and satisfactory precision [10].

$$e = \pm\sqrt{\frac{\sum_{1}^{n}\left(\theta_{prescris} - \theta_{piesa}\right)^2}{n}} \qquad (5)$$

Applying the above formula for the errors between the prescribed temperature and the actual temperature of the parts, in the two cases studied, for the heating ramps, where it works the Smith predictor, gave the following results:

- for the normal PID controller, the mean square error is: 0.9447°C;
- for the PID controller with predictive control, for a gap of 144s, the mean square error is: 0.6362°C;

It is noted that the introduction of predictive control improved the process; the mean square error decreased with 32,65%.

Another parameter followed in the experimental determination was the evolution of the control indices of the heating elements, namely ventilation, calculated with Matlab and transmitted through the microcontroller to the actuators (Fig. 6 and Fig. 7).

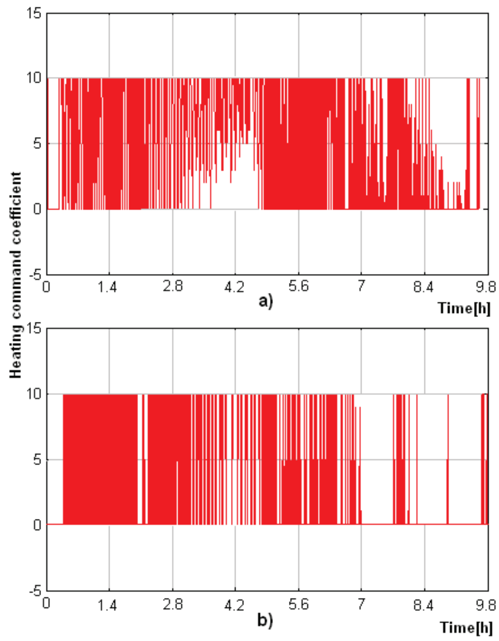

Fig. 6. Control coefficients for heating

a) normal PID b) controller with Smith predictor

The analysis of the above graphs indicates that the heat resistance does not repeat the switching during heating, in the case of predictive control. This explains the possibility of more accurate tracking of prescribed temperature.

When referring to periods of cooling, thermal inertia of the used resistances determine the temperature to drop during additional 2 cycles even though the ventilation stops and heating resistors are commanded.

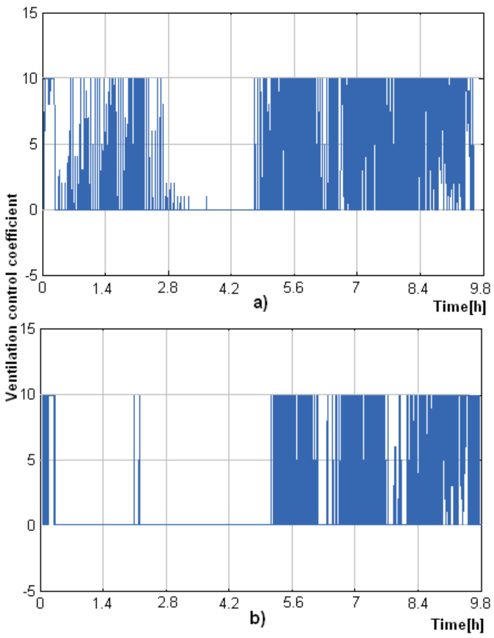

Fig. 7. Control coefficients for ventilation

a) normal PID b) controller with Smith predictor

The graphs of the ventilation control coefficients indicate a clear advantage of the predictive controller which translates into fewer switches, especially during the heating period.

Recall that, for ventilation, unlike the case of heating, the system commands simultaneously four control devices constituting the experimental plant (timer, closing valves, fan and blower).

IV. CONCLUSIONS

As noted above, the differences in the fidelity with which the temperature of the pieces follows the temperature of the imposed technological cycle, are clearly lower in case of the control using Smith predictor.

The automation system is practically controlling the heating system and the ventilation system of the furnace. The control is made through a PWM signal, with the help of an assembly comprising the computer, a microcontroller and the temperature transducers.

This paper proves that we have created an automation system which can control the temperature from inside a furnace, without depending on the technological cycle.

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