Study of thermal regimes of an electric resistance furnace using AT-503 controller

A Iaşăr¹, G N Popa¹ and C M Diniş²

¹Politehnica University of Timisoara, Department of Electrical Engineering and Industrial Informatics, 5 Revolution Street, 331128 Hunedoara, Romania

E-mail: angela.iagar@fih.upt.ro

Abstract. In this paper were studied some thermal regimes of a low-temperature electric resistance furnace, with indirect heating. To determine the heat losses was used a thermal imager, which achieved a global image of the thermal field inside the furnace and upon the carcass. Thermal images of the furnace carcass revealed the following areas of heat losses greater than admissible in steady-state: furnace door, temperature measuring point and bonding areas of furnace metal carcass. To determine dead time and time constants were analyzed heating and cooling of the furnace until reaching the steady-state. In the experiments has been used AT-503 temperature controller, equipped with a K type thermocouple. Were analyzed following control methods of furnace temperature: on/off with hysteresis of 5°C and autotuning.

1. Introduction
Electric resistance furnaces (ERF) translate electric energy into the thermal energy. These furnaces are widely used in metallurgy, machinery, building materials and semiconductor industries. Some applications include: age hardening, temper hardening, annealing, heating before forging, stretching, pressing, glazing and baking of ceramics [1], [2].

The heating process is very complicated, and depends on the type of furnace, the materials used in its construction, its geometry, being a mixture of several nonlinear characteristics. In the case of ERF a problem of slow dynamics may occur, which represents a great disadvantage [3]. An important characteristic of ERF is the possibility of adjusting the working temperature very accurate, an essential condition for obtaining quality pieces [1-10].

The analyzed furnace has a rectangular chamber with external volume of 58.464 dm³. The masonry is made of firebrick, with thickness of 45 mm; the carcass that consolidates chamber is made of steel, with thickness of 5 mm.

Two heating elements (resistors) made of Cr20-Ni80 alloy, placed near the furnace hearth (bottom), in parallel connection, are used to supply heat to the furnace chamber. Resistors are coiled on ceramic tube and their terminals are electrically insulated by ceramic beads. Active power generated by heating elements is 1kW/230Vc.a.

2. Heat losses computation in steady-state
The correct construction of the masonry and its careful execution at mounting will influence: heat losses, power consumption, heating time, quality of thermal processing, operation time, weight, overall size and cost of ERF.

Total power dissipated by heating elements is transferred to the processed material (charge) and toward the furnace masonry (Figure 1.a).
The power received by the charge is the output power ($P_u$, corresponding to useful heat flow rate $\Phi_u$), and the heat losses of ERF ($P_p$, corresponding to losses heat flow rate $\Phi_p$) include:
- heat losses accumulated in the masonry of furnace and other auxiliary materials $Q_a$;
- heat losses transmitted through the walls of the furnace (by conduction) $Q_z$;
- radiation losses through the furnace door, measuring points, etc. $Q_r$.

In order to achieve a better efficiency of electric furnace is necessary to minimize the heat losses. Masonry of electric furnace must be designed in such a way the following condition will be satisfied [2]:

$$\frac{Q_a}{t_r} + \Phi_p = \text{minimum},$$  \hspace{1cm} (1)

where: $Q_a$ is the heat stored in the furnace masonry until steady-state; $\Phi_p$ are the heat losses through the walls of the furnace to environment, in steady-state; $t_r$ is the time of furnace operation.

Dimensioning of electric furnace masonry (thicknesses of layers, number of layers and their characteristics) is satisfactory if allows to obtain a temperature on the exterior surface $\theta_e = 40...80^\circ\text{C}$ (if the temperature inside the furnace, $\theta_i$, is less than 1000°C), or $\theta_e = 150...400^\circ\text{C}$ (if $\theta_i \geq 1000^\circ\text{C}$), for heat losses at most 750 W/m$^2$ [1].

Figure 2 shows the thermal images of the furnace carcass in steady-state, obtained by thermal imager [11]. The temperature on the exterior surface, in steady-state, is below 80°C, except furnace door, measuring point of temperature in the center of furnace chamber, and bonding areas of metal carcass. So in these areas heat losses are higher than admissible.

The maximum temperature on the furnace door is 124.8°C because it is not thermally insulated. The maximum temperature at the measuring point of temperature inside furnace is 78.8°C, and the maximum temperature in bonding areas of metal carcass is 86.6°C.
Thermic balance of an ERF with indirect heating is done for steady-state, when the absorbed energy from the network is entirely transferred to environment as heat losses.

Heat losses through the masonry of low-temperature electric furnaces are mainly due to conduction and convection.

Mathematical formulae used to compute the thermal resistances in the processes of conduction in masonry and convection on the inner and outer surfaces of furnace chamber are expressed by equations (2-5).

\[ R_s = \frac{g_s}{\lambda_s \cdot A_{med1}}, \ [^{\circ}/W] \]  
\[ R_c = \frac{g_c}{\lambda_c \cdot A_{med2}}, \ [^{\circ}/W] \]  
\[ R_{ei} = \frac{1}{\alpha_i \cdot A_i}, \ [^{\circ}/W] \]  
\[ R_{ei} = \frac{1}{\alpha_e \cdot A_e}, \ [^{\circ}/W] \]  

In the previous relations: \( R_s \) represents the thermal resistance in the process of conduction in firebrick layer; \( g_s \) is the thickness of firebrick; \( \lambda_s [W/(m\cdot^{\circ}C)] \) is the thermal conductivity of

**Figure 2.** Thermal images of furnace carcass in steady-state
firebrick; $A_{med1}$ is the average area of firebrick layer; $R_c$ represents the thermal resistance in the process of conduction in steel carcass; $g_c$ is the thickness of carcass; $\lambda_s$ [W/(m·°C)] is the thermal conductivity of steel; $A_{med2}$ is the average area of steel carcass; $R_{ai}$ and $R_{ae}$ represent the thermal resistances in the process of convection on the inner and outer surfaces of furnace chamber; $\alpha_i$ [W/(m$^2$·°C)] and $\alpha_e$ [W/(m$^2$·°C)] are the heat transfer coefficient of air inside and outside furnace, and $A_i$ and $A_e$ are the areas inside and outside of furnace chamber.

**Figure 3.** Equivalent electric diagram corresponding to heat transfer through the masonry

The inner surface of the chamber of furnace is $A_i = 69.26$ dm$^2$, surface between firebrick and metal carcass is $A_c = 87.105$ dm$^2$, and the outer surface of the chamber of furnace is $A_e = 91.26$ dm$^2$. Furnace door has area $A_u = 1.82$ dm$^2$.

The air temperature in the vicinity of the inner wall of the furnace is $\theta_i = 247$ °C, so $\alpha_i = 23.5$ W/(m$^2$·°C), and the air temperature in the vicinity of the metal carcass is $\theta_e = 40$ °C, and $\alpha_e = 10.5$ W/(m$^2$·°C).

From the relations (4) and (5) were determined thermal resistances in the process of convection on the inner and outer surfaces of furnace chamber: $R_{ai} = 61.439779 \times 10^{-3}$ °C/W, $R_{ae} = 104.359 \times 10^{-3}$ °C/W.

Were calculated the average areas: $A_{med1} = 77.2725$ dm$^2$ (for firebrick layer) and $A_{med2} = 90.0925$ dm$^2$ (for steel carcass).

The thickness of firebrick and carcass are $g_s = 45$ mm, respectively $g_c = 5$ mm, and the thermal conductivity of steel carcass is $\lambda_c = 50.93$ W/(m·°C). Was calculated the thermal resistance in the process of conduction in metal carcass, $R_c = 0.11 \times 10^{-3}$ °C/W, using equation (3).

To calculate the thermal resistance in the process of conduction in the firebricks was considered a linear variation with temperature of firebrick thermal conductivity:

$$\lambda_s = 0.093 + 0.16 \times 10^{-3} \cdot \theta_{smed} \text{ W/(m·°C)}$$

where $\theta_{smed} = 188$ °C represents the average temperature of the chamotte layer (according to the thermal images from Figure 4).

Thermal resistance in the process of conduction in the layer of firebrick was determined by relation (2): $R_s = 473.1513276 \times 10^{-3}$ °C/W.

Heat flow rate can be computed taking into account the equivalent electric diagram corresponding to the thermal transfer through the resistance furnace masonry (from Figure 3) with the relation:

$$\Phi = \frac{\theta_i - \theta_e}{R_{ai} + R_s + R_c + R_{ae}} = 323.913 \text{ W}$$

Heat losses through the masonry represent 32.39% from the installed power of analyzed furnace, according to relation (7).

The temperature field in the furnace chamber is not uniform in steady-state (from Figures 4 and 5). The temperature in the front part (near the door) is lower than that in the back; also, the temperature in the top of chamber is lower than that in the bottom one.
Figure 4. Details regarding furnace thermal field in steady-state
3. Determination of dead time and time constants of the furnace

It is very important to determine the optimal settings of temperature controller to achieve good control accuracy. This requires a good knowledge of the furnace parameters.

To determine dead time and time constants were analyzed heating and cooling of the furnace until reaching the steady-state (Figures 6 and 7).

The heating time constant of electric resistance furnace are experimentally determined from the heating equation:

$$\theta = \theta_{\text{max}} \left(1 - e^{-\frac{t}{\tau}}\right) + \theta_a \cdot e^{-\frac{t}{\tau}} \quad (8)$$

where: $\theta_{\text{max}}$ [°C] is the maximum temperature of the furnace corresponding steady-state; $\theta_a$ [°C] is the ambient temperature; $T_i = m \cdot c / (\alpha \cdot A)$, [s] is heating time constant; $m$ - the batch weight [kg]; $c$ - specific heat of processed material, [J/(kg·°C)]; $\alpha$ - heat transfer coefficient, [W/(m²·°C)]; $A$ - heat exchange surface furnace-environment, [m²].
Knowing the maximum temperature of furnace $\theta_{\text{max}} = 321^\circ\text{C}$, ambient temperature $\theta_a = 26^\circ\text{C}$, heating time $t_i = 1600$ s and the final temperature $\theta_i = 216^\circ\text{C}$, was determined the heating time constant of the furnace:

$$T_i = \frac{t_i}{\ln(\theta_{\text{max}} - \theta_a) - \ln(\theta_{\text{max}} - \theta_i)} = 1549 \text{ s}$$  \hspace{1cm} (9)

**Figure 6.** Time-variation of the temperature inside the furnace during the heating regime

**Figure 7.** Time-variation of the temperature inside the furnace during the cooling regime

The time constant for cooling process was experimentally determined using the cooling equation. For this purpose has been made the cooling of furnace starting from $\theta_{\text{max}}$ to the final temperature $\theta_f = 27^\circ\text{C}$, within the time period $t_r = 12000$ s.
From furnace cooling equation:

\[ \theta = (\theta_{\text{max}} - \theta_a) e^{-\frac{r}{T_r}} + \theta_a, \quad (10) \]

result:

\[ T_r = \frac{t_r}{\ln(\theta_{\text{max}} - \theta_a) - \ln(\theta_a - \theta_2)} = 2110 \text{ s.} \quad (11) \]

It is noted that the cooling time constant of ERF is higher than the heating time constant. Thus, the dynamic characteristics of furnace in the heating process differ from its dynamic characteristics in the cooling process.

From the heating curve (Figure 6) was graphically determined the dead time of electric furnace, L=37.24 s. These parameters will be used later to determine the optimal settings of AT-503 temperature controller in the control methods P, PI and PID, to achieve good control accuracy.

4. Study of ERF temperature control using AT-503 controller

Experiments were performed using AT-503 temperature controller [12]. This controller can have as inputs the following types of temperature sensors: thermocouples (K, J, T, R, E, S, B, N type), or RTD (Pt100 or JPt100). To measure the temperature at the center of the furnace chamber was used a K type thermocouple. Output controls of AT-503 include relay, SSR, linear voltage, linear current and signal retransmission.

Figure 8 shows the schematic diagram of experimental installation. The command for connecting/disconnecting the furnace resistors was done through an electromechanical contactor (Un = 230V AC, In = 10 A) using the relay output of temperature controller. Link to the computer was achieved by RS-232 communication module.

Control methods that can be implemented with AT-503 controller are: PID, PI, P, on/off and dead band. Further are presented experimental results in the case of autotuning and on/off control with hysteresis of 5°C. The set value (SV) of temperature was 100°C.
Figure 9. Time-variation of temperature inside the electric furnace in the case of autotuning.

Rise time (time necessary for the temperature to rise beyond 90% of the set value SV for the first time) is about 5 min. It is noted an overshoot of 10°C, which occurs after 7 minutes from the heating start. Temperature in the center of furnace chamber is stabilized after 24 minutes from the beginning of heating; this is settling time. The difference between set value of temperature and measured temperature at the end of recording is 1°C (steady-state error).

Figure 10. Time-variation of temperature inside the electric furnace at on/off control with hysteresis of 5°C.

Figure 9 shows the time-variation of the temperature inside the electric furnace at autotuning. Rise time (time necessary for the temperature to rise beyond 90% of the set value SV for the first time) is about 5 min.

It is noted an overshoot of 10°C, which occurs after 7 minutes from the heating start. Temperature in the center of furnace chamber is stabilized after 24 minutes from the beginning of heating; this is settling time. The difference between set value of temperature and measured temperature at the end of recording is 1°C (steady-state error).

Figure 10 shows the time-variation of the temperature inside the electric furnace in the case of on/off control with hysteresis of 5°C. This is the simplest and cheapest of all temperature control.
methods. Using electromechanical contactor, by alternative connecting and disconnecting of heating elements from the network, the active power is modified in two steps: rated power $P_n$ and 0 in this case. However control on/off may be oscillatory and leads to uneven distribution of the furnace temperature.

The dead band is of 10°C in the case of on/off control with hysteresis of 5°C. Dead band is around the set value (desired temperature) in this case, but may be outside.

5. Conclusions
The main advantages of chamber-type furnaces consist of simple construction and the possibility of achieving of various thermal regimes.

Experiments indicate that analyzed ERF is a non-linear element, with a high inertia and hysteresis and time-varying parameters.

Non-linearity of ERF is mainly due to heat transfer by convection and radiation. Heat transfer coefficient of the air is not constant, but increases with temperature. For this reason heating dynamics are faster than cooling dynamics, the cooling time constant of the furnace being greater than heating time constant.

In steady-state, thermal images of the furnace carcass, obtained with a thermal imager, revealed the following areas of heat losses greater than admissible: furnace door, temperature measuring point and bonding areas of furnace carcass. Heat losses through the masonry represent 32.39% from the installed power of analyzed furnace.

To improve the efficiency of ERF heat losses must be minimized, by insulating the door, and PI or PID fine control must be used. These control methods can reduce the overshoot and settling time, and eliminate the steady-state error.

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