Research on temperature control with numerical regulators in electric resistance furnaces with indirect heating

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Abstract. The paper is an analysis of two-positions (hysteresis) regulators, self-tuned PID controller and PID controller for temperature control used for indirect heat resistance furnaces. For PID controller was used three methods of tuning: Ziegler-Nichols step response model, Cohen-Coon tuning rules and Ziegler-Nichols tuning rules. In experiments it used an electric furnace with indirect heating with active power of resistance of 1 kW/230V AC and a numerical temperature regulator AT-503 type (ANLY). It got a much better temperature control when using the Cohen-Coon tuning rules method than those of Ziegler-Nichols step response method and Ziegler-Nichols tuning rules method.

1. Introduction

Industrial heating processes aimed at raising the temperature of a body for various purposes, such as changing the shape parts (by casting, rolling, forging), heat treatment (normalizing, annealing, stress relief annealing, tempering, reheating, steel, treatment surfaces), melting, brazing, welding; these applications are carried out at different temperatures: 100-1200 °C.

Temperature control is an important requirement common to all industrial processes [1-4].

Making heating objects or parts can be made by various methods. Electric furnaces convert electrical energy into heat and are divided into: resistance furnaces, induction, electric arc, plasma, or microwave; may be mentioned and capacitive heating, electron beam, or laser.

If indirect heat resistance, heat is obtained from the heating elements (electric resistance power) electric furnace and then transmits the processed material by convection and radiation (Figure 1) [4-6], which will be subjected during heating or after, the physical or chemical transformation.

An electric resistance furnace contains in addition to the heating (heat source) and a walled enclosure of thermally insulating.

Electric furnaces are classified according strength obtained indoor temperature as follows: low temperature furnaces (up to 400 °C), medium temperature (400-800 °C) and high temperature (800-1400 °C) [7].

Electric furnaces are safe resistant, flexible operation (can change the temperature and the heating medium), are effective and do not pollute the environment (no dangerous gas, no sound). Their main applications are in the treatment of metals, ceramics, electronics and glass industry [8].
Measuring, monitoring and temperature control are topical in industry and domestic use. Sensors and thermocouples are a wide range of sizes, and typically stainless steel sheath to protect the transducer. For RTD temperature range that can be measured is \(-200 \div +600\) °C and thermocouple \(-40\) °C \(+1200\) °C. At these sensors output size dependence on the temperature measured is approximately linear [7].

In the case of indirect heating electric furnaces, the processed material is heated at a temperature lower than the melting temperature. The temperature-time characteristic of furnaces for heating of indirect heating is exponential, characterized by three distinct areas (Figure 2): in the low temperature characteristic is approximately linearly increasing with steep growth; in the average temperatures in the temperature is strongly nonlinear evolution; in the high temperature characteristic is saturated with small slope of growth. Theoretically, the electric resistance furnace is a second-order delay element. Its nonlinearity is due, in large part, by convection and radiation heat transmission [9-12].

Some industrial processes require precise temperature control. Getting a temperature as constant as possible in a short time is an important objective of temperature control with indirect heating furnace [6]. Basically, temperature control in closed systems can be implemented with analogue or numerical (digital) controllers [13].

It was found experimentally that determine the parameters electric furnaces with indirect heating (slow process) takes a long time and is done with large errors. Sometimes these parameters must be determined on-line (by using adaptive filters) [1], [12].
The vast majority of applications using temperature control have feedback control systems. The role of the reaction is to work on the system output is adjusted according to the temperature difference between the desired value and the measured value. The most used are type two-positions controllers (on-off controller, with hysteresis, dead band) or PID controllers [1]. In general, PID controllers are used to control processes that have good performance: high reliability, stable performance, simple algorithm implementation. Setting the PID parameters is quite difficult (being more delivery methods) and time.

2. The control algorithms recommended and experimental methods for tuning regulators

Difficulties in identifying precisely the slow processes have led to a limited application of analytical methods and the imposition of practical methods for tuning based on experience gained in exploiting the automatic control systems. Practical methods applied on systems in operation, with reference parameters and disturbance variables held constant.

By changing the tuning parameters of the regulator is reached stability, the regime is determined oscillation and frequency maintained amplitude of the output values. Using these characteristic values, determine the optimal values of tuning parameters controller [14-16].

Method Ziegler-Nichols applies to slow processes that load disturbances are determined and have great times. For an automatic control system with conventional structure provided with a PID controller having transfer function of the form:

\[ H_R(s) = K_R \left( \frac{1}{T_i s} + T_d s \right) \]

with inter-influence factor \( q=0 \), the tuning is as follows:
- \( T_i \) is fixed parameter at the maximum value \( (T_i \rightarrow \infty) \), \( T_d \) parameter to the minimum \( (T_d = 0) \), resulting a \( P \)-type controller. It changes the amplification factor \( K_R \) up to \( K_{R0} \) value at which the system reach the stability limit, the output value of the system enters into unamortized oscillation regime with \( T_0 \) period. Offreins method is recommended for \( PI \) regulators to ensure an optimal response to disturbance, namely:

\[ K_{R opt} = 0,5 \cdot K_{R0}; T_{i opt} = 0,3 \cdot T_{i0} \]

where \( T_{i0} \) is the limit value of \( T_i \) where the stability limit is exceeded.

Other practical methods for determining the optimal parameters were agreed based on the \( \tau / T_f \), characteristic of a process dead time \( \tau \) and time constant \( T_f \):

\[ H_f(s) = \frac{K_f}{T_f s + 1} \cdot e^{-\tau s} \]

Kopelovici relations establish the optimum tuning parameters which provides a minimum duration aperiodic transient response, respectively a response with 20% overshoot maximum.

Chien-Hrones-Reswick relation determining optimal tuning parameters for an optimal behavior when at the input is step signal, ensuring a minimum duration aperiodic response and 20% overshoot.

Adoption of one tuning relation (Ziegler-Nichols, Oppelt, Kopelovici, Chien-Hrones-Reswick, etc.) depends on the specific conditions under automatic control system works. Diversity of practical criteria emphasizes that the tuning of controller for slow processes is very complex and depends on the knowledge of the process and the experience gained in choosing and giving regulators.

To highlight the type of regulator influence the behaviour automatic control systems, responses were plotted in Figure 3 while the output size of an automation control system \( y(t) \) to a step change in the input, \( y_{ref}(t) = 1 \), while the used controllers \( P, PI, PD \) and \( PID \) [15], [16].

Comparing the response curves can be made the following remarks:

- \( P \) controller reduce appreciably overshoot, leading to a short transitional time \( t_s \), but introduces a
large stationary error $\varepsilon_s$;
- by introducing of component $I$, PI regulator canceled the stationary error for input step signal, but leads to an overshoot higher than the $P$ controller, and a large amount of response time $t_r$;
- by introducing of of component $D$, the PD controller improves the dynamic behavior (the overshoot $\sigma$ and the transitional time $t$ are small), but maintains a large stationary error;
- PID controller, combining the effects of $P$, $I$ and $D$, provides superior performance, both steady and transient state.

![Figure 3. Step responses of an automatic control system for various continuous and linear regulators](image)

Table 1. Recommended control algorithms, depending on the nature of the setting parameter

| Regulator type/ Adjust parameter | P     | PI     | PID    |
|---------------------------------|-------|--------|--------|
| Temperature                     | YES   | YES    | YES    |
| Pressure                        | YES, if there is no too much dead times | YES    | In special cases |
| Flow rate                       | NO    | YES    | NO     |
| Level                           | YES, if there is no too much dead times | YES    | YES     |

Until now, not been determined so far an accurate method to tuning PID controllers. There are known temperature control with controllers $P$, $PI$ and $PID$. The $P$ controller set size is proportional to the error. With this controller obtains a continuous steady error, which can be removed using $PI$ controllers by introducing integration effect. A further improvement can be made by the controller derivative action which aims to forecast the error. The $PID$ controller can be used to control the temperature, if is right tuned [1].

The tuning of controller represents parameter adjustment for process requirements. If this adjustment takes into account the behavior of the process according to certain criteria (eg. minimum duration transient process, minimal influence of disturbances, etc.), the tuning is called optimal.
### Table 2. Recommended control algorithms for different transfer functions of control process

| Control type/Transfer function | P | PI | PD | PID |
|-------------------------------|---|----|----|-----|
| $\frac{k_f}{T_f s + I}$      | YES | YES, if requirements are imposed on $\varepsilon_{st}$ | YES, if $T_f$ is precisely determined | NO |
| $\frac{k_f}{(T_{f1} s + I)(T_{f2} s + I)}$ | YES, with low performance | YES, with restrictions on gain | Rarely used, with restrictions on amplification | YES |
| $\frac{k_f}{\prod_{i} T_f s + I}$ | Rarely used, with low performance | YES | Rarely used | YES |
| $\frac{k_f}{T_f s + I} e^{-\tau s}$ | YES, when $\tau T_f < 0.1$, $\varepsilon_{st}$ is in acceptable limits | YES | Very rarely used | Inconvenient when $\tau$ is produced during transport and there is noise |
| $k_f e^{-\tau s}$ | NO | NO | NO | NO |
| $\frac{k_f}{(T_{f1} s + I)(T_{f2} s + I)} e^{-\tau s}$ | NO | YES | NO | Rarely used, depending on the $\tau$ and the effect of component $D$ |

### 3. Temperature control experiments at indirect heat resistance furnaces, using numerical regulator AT-503 type (ANLY)

Over time they developed several methods for tuning PID controllers (good gain method, Ziegler-Nichols, Cohen-Coon, Tyreus-Luyben, Oppelt, Kopelovici, etc.) involving different times of tuning [1], [9], [12], [17]. Each of these methods of tuning has not granting maximum performance (overshoot, response time, error stationary). PID controllers can be used for linear systems with known mathematical models. Temperature control in electric furnaces is nonlinear because the delay time is not constant (changes during heating).

![Figure 4](image_url) **Figure 4.** Controlling the temperature in an electric furnace with indirect heating with autotuning controller

![Figure 5](image_url) **Figure 5.** Controlling the temperature in an electric furnace with indirect heating with a two-position hysteresis controller, $\pm 3^\circ$C
Usually numerical control temperature controllers are able to use the auto-tuned PID controller that not sometimes offers high performance (Figure 4). The vast majority of digital controllers with auto-tuning do not allow the introduction of the main parameters of furnaces: time delay, time constant, only the set point temperature.

Although two-positions controllers are easier to use (no known constants of electric furnace), have low performance in terms of over-shoot (high values), the response time and error stationary. By using these controllers, controlled size (temperature) oscillates around the setting value (Figure 5). The oscillations occur due to a small change of the system over-reactions of the error. These oscillations can be reduced by using PID controllers.

This paper contains an analysis of PID controllers used to control temperature resistance furnaces with indirect heating using three methods of tuning regulators: Ziegler-Nichols step response method (ZNSRM, Figures 6, 7 and 8), Cohen-Coon tuning rules method (CCTRM, Figures 9, 10 and 11) and Ziegler-Nichols tuning rules method (ZNTRM, Figures 12, 13 and 14).

In experiments it used an electric furnace with indirect heating with active power of resistance of $1kW / 230V \text{ AC}$. The furnace enclosure is rectangular, with exterior dimensions: 320 (height)x435 (width)x420 (depth) $mm$ and the furnace is coated inside with refractory brick masonry with 45 $mm$ thickness. The casing is made of sheet metal with a 5 $mm$ thickness. The door dimensions are: 140 (height)x130 (width) $mm$. The furnace temperature was measured using a thermocouple cromel-alumel. In experiments it used a dedicated numerical temperature regulator AT-503, ANLY [18].

**Ziegler-Nichols step response method**
- Measure $A$ and $L$ from step response;
- $T_p$ expected time constant for closed-loop system.

| Controller | $K_p$ ; $BP$ | $T_i$ | $T_d$ | $T_p$ |
|------------|--------------|-------|-------|-------|
| $P$        | $K_p = 1/A = 36.9$ ; $BP = 2.7$ | -     | -     | $4 \cdot L$ |
| $PI$       | $K_p = 0.9/A = 33.3$ ; $BP = 3$ | $3 \cdot L = 112$ | -     | $5.7 \cdot L$ |
| $PID$      | $K_p = 1.2/A = 44.28$ ; $BP = 2.3$ | $2 \cdot L = 74$ | $L/2 = 19$ | $3.4 \cdot L$ |

**Figure 6.** Controlling the temperature in an electric furnace with indirect heating with a $PID$ controller using ZNSRM

**Figure 7.** Controlling the temperature in an electric furnace with indirect heating with a $PI$ controller using ZNSRM
Figure 8. Controlling the temperature in an electric furnace with indirect heating with a $P$ controller using ZNSRM.

Cohen-Coon tuning rules method. Calculate process parameters: $t_i$, $\tau$, $\tau_{del}$, $K$, $r$ as follows

$$t_i = \frac{t_j - (ln(2))t_j}{1-ln(2)}; \quad \tau = t_i - t_j; \quad \tau_{del} = t_i - t_0; \quad K = \frac{B}{A}; \quad r = \frac{\tau_{del}}{\tau}.$$ 

Table 4. Parameters for optimal tuning Cohen-Coon rules method

| Controller | $K_c$ | $\tau_{int}$ | $\tau_{Der}$ |
|------------|------|--------------|--------------|
| $P$        | $\frac{1}{rK} \left( 1 + \frac{r}{3} \right) = 6.2$ | - | - |
| $PI$       | $\frac{1}{rK} \left( 0.9 + \frac{r}{12} \right) = 5.4$ | $\frac{30 + 3r}{9 + 20r} = 390$ | - |
| $PID$      | $\frac{1}{rK} \left( \frac{4 + r}{3} \right) = 8.2$ | $\frac{32 + 6r}{13 + 8r} = 340$ | $\frac{4 + 2r}{11 + 2r} = 52$ |

Figure 9. Controlling the temperature in an electric furnace with indirect heating with a $PID$ controller using $CCTR$.

Figure 10. Controlling the temperature in an electric furnace with indirect heating with a $PI$ controller using $CCTR$.
Ziegler-Nichols tuning rules method

\[ T = 2585.79 \text{ s}; \]
\[ L = 113.8 \text{ s} \]

**Table 5.** Parameters for optimal tuning using Ziegler-Nichols rules method

| Controller | \( K_P; \) \( BP \) | \( K_I \) | \( K_D \) |
|------------|----------------|-----------|-----------|
| \( P \)    | \( K_P = \frac{T}{L} = 22.72 \) \( BP = \frac{100}{K_P} = 4.4 \) | 0         | 0         |
| \( PI \)   | \( K_P = 0.9 \cdot \frac{T}{L} = 20.4 \) \( BP = \frac{100}{K_P} \approx 4.9 \) | 0.27 \( \left( \frac{T}{L} \right)^2 \approx 139 \) | 0         |
| \( PID \)  | \( K_P = 1.2 \cdot \frac{T}{L} = 27.2 \) \( BP = \frac{100}{K_P} \approx 3.6 \) | 0.6 \( \left( \frac{T}{L} \right)^2 \approx 309 \) | 0.6 \( T \approx 1551 \) |

Figure 11. Controlling the temperature in an electric furnace with indirect heating with a \( P \) controller using \( CCTRM \)

Figure 12. Controlling the temperature in an electric furnace with indirect heating with a \( PID \) controller using \( ZNTRM \)

Figure 13. Controlling the temperature in an electric furnace with indirect heating with a \( PI \) controller using \( ZNTRM \)
Controlling the temperature in an electric furnace with indirect heating with a $P$ controller using ZNTRM

PID controllers controlling nonlinear elements and not have outstanding performance [1], [9]. However, the heating curve for electric ovens with indirect heating depends on the operating mode (idle or under load). Determination of the electric furnace parameters is done with imprecision and PID controller parameters can’t be set correctly. Sometimes (eg. thermal treatments) temperature overshoot must be eliminated or reduced, in terms of a minimum response time.

4. Conclusions

Comparing the experimental response curves obtained from the use of optimal parameters for tuning Ziegler-Nichols step response method (Table 3), optimal parameters for Cohen-Coon tuning rules method (Table 4) and optimal parameters for Ziegler-Nichols tuning rules method (Table 5), the following observations can be made:

- overshoot response curves obtained with Cohen-Coon tuning rules method is smaller than the overshoot response curves obtained with Ziegler-Nichols step response method and Ziegler-Nichols tuning rules method;
- in curves obtained experimentally Cohen-Coon tuning rules method achieved a response time (minimum 13 min. for $PID$ controller and up to 20 min. for the $PI$) much less than the response time curves obtained from Ziegler-Nichols step response method and Ziegler-Nichols tuning rules method;
- the stationary error obtained in the response curves (Figures 9, 10 and 11) from the Cohen-Coon tuning rules method is much lower than that error obtained by Ziegler-Nichols step response method (Figures 6, 7 and 8) and Ziegler-Nichols tuning rules method (Figures 12, 13 and 14).

It found that get a temperature control with numerical controller AT-503 with indirect heating furnace much better when using the method parameters for Cohen-Coon tuning rules than those of Ziegler-Nichols step response method and Ziegler-Nichols tuning rules method.

Using fuzzy controllers will be an important alternative to temperature control in electric furnaces with indirect heating. Fuzzy controllers can be implemented to control nonlinear processes, which are difficult to determine mathematical models and the time constants changes in time. Implementing rules in fuzzy controllers will be done correctly to achieve optimum performance [2], [17], [19-21].

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