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Application of temperature fuzzy controller in an indirect resistance furnace

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Abstract

The paper presents the application results of a fuzzy controller of temperature and its rate of change in indirect resistance chamber furnaces. The method of an initial controller tuning based on the computer simulations is described, where the modelling of the furnace appears as a special problem. Further controller tuning was done based on tests performed on the real furnace. The quality of the finally-adopted controller on the real furnace is assessed by its tracking of the desired response, regulation robustness with respect to the presence of load in the furnace, as well as by a comparison with the ideal implementation of the Dahlin algorithm for classic PID control. The experimental part of the work is made using a 5 kW indirect resistance chamber furnace.

Keywords: Fuzzy control; Temperature control; Chamber furnace; Non-linear control

1. Introduction

A variety of industrial processes requires precise control of the temperature versus time profile. Classic hysteresis and PID controllers often cannot meet these needs. It is shown [1] that hysteresis controller application may result in large temperature overshoots, especially at low values of the set-point temperature. The problems with PID controller

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applications originate from the object non-linearity, resulting in mismatches of the real responses and the projected ones [1]. This non-linearity is a consequence of well-known laws of convection and radiation heat-transfer [2]. Apart from non-linearity, there is a problem of furnace characteristics alteration with the change of the type and the amount of load on it. The feasible solution is an application of gain-scheduling methods [3], used in the manner that the parameters are determined from the set of previously performed measurements [4] or measurements during the real-time regulated process [5]. This second technique of permanent process identification generally implies the usage of specific power profiles, used as the excitation signal of the system whose parameters should be evaluated. This paper presents the results reached by the authors using the fuzzy logic for stand-alone temperature-control in a resistance furnace. The regulation task was to keep the reference rate of temperature change (temperature slope) and to attain the temperature reference without overshoot. The paper presents a basic structure of the temperature fuzzy controller, the results of design-time simulations and the results of controller application on the real furnace.

2. The furnace characteristics

The analysis of the recorded temperature rise (with respect to the ambient temperature) at different constant heating-powers (P) showed that these could be represented by the expression

$$\theta(t) = \left(\theta_1\left(1 - e^{-\frac{t}{T_1}}\right) + \theta_2\left(1 - e^{-\frac{t}{T_2}}\right)\right)h(t - T_\mathrm{M}) \tag{1}$$

where θ_1 and θ_2 are partial temperature rises, T_1 and T_2 are time constants and T_M is transport delay. Application of direct z-transform to the temperature function and Heaviside power function results in the following transfer function:

$$G(z) = \frac{\theta(z)}{P(z)} = \frac{g(z - \mathrm{z}_z)}{\left(z - z_{p1}\right)\left(z - z_{p2}\right)} \tag{2}$$

(the values g, z_z, z_{p1}, z_{p2} are calculated from values T_1, T_2, T_M, θ_1/P and θ_2/P). If the thermal parameters of the furnace were constant, the values of T_1, T_2 and T_M, θ_1/P and θ_2/P would also be constant. Due to the heat transfer non-linearity, these values strongly depend on the heating power. Analysis of experimental results of heating from the cold state (initial temperature in the furnace being equal to the ambient temperature) brings out the parameters in Table 1. There is a good match between temperature rise delivered by expression (1) and experimental ones for all the corresponding (but constant) heating powers.

An improvement of the modelling with transfer function (2) can be made using variable parameters. These can be adapted according to the current value of heating power, using the data from Table 1. It turned out that even such modelling does not always yield accurate results. That is illustrated by the results of the experiment with the heating power amounting 15% of the rated power (P_r) during the first 4 h and 45%

Table 1
Characteristics of the empty indirect resistance chamber furnace

	Power (% of P_r)								
	15%	23%	30%	37.5%	45%	52.5%	60%	80%	100%
g ($\times 10^{-4}$)	8.9119	8.4435	9.3962	9.714	8.9365	13.249	11.017	11.481	11.95
z_{p1}	0.99398	0.9933	0.99259	0.99157	0.99259	0.9868	0.98909	0.98797	0.98621
z_{p2}	0.99947	0.99935	0.99931	0.99927	0.99924	0.99918	0.99912	0.99902	0.99902
z_z	0.99739	0.99689	0.99701	0.99661	0.99703	0.99618	0.99644	0.99619	0.99614
T_M (min)	2	2.25	2	2.5	2	1.5	1.75	1.5	1.5

P_r during the next 4 h. Fig. 1 presents the measured temperature (solid line), along with a simulation result (dashed line) obtained using the described model with variable parameters.

A significant discord after switching to another power value appears. The reason is that the parameter set derived from 45% P_r constant power heating experiment, started at the cold state, cannot be used for process modelling during the power increase from 15 to 45%, due to an initial in-furnace temperature higher than in the parameter estimation experiment. It should be noticed that the furnace is acting in a more dynamic fashion than was expected based on the simulation.

It is possible that the use of excitation signals different from Heaviside's would lead to a better and more practically applicable identification. Another approach would be to use the thermal circuit based on the physical process of non-linear heat transfer; an example of such an approach can be found in one author's previous paper [6].

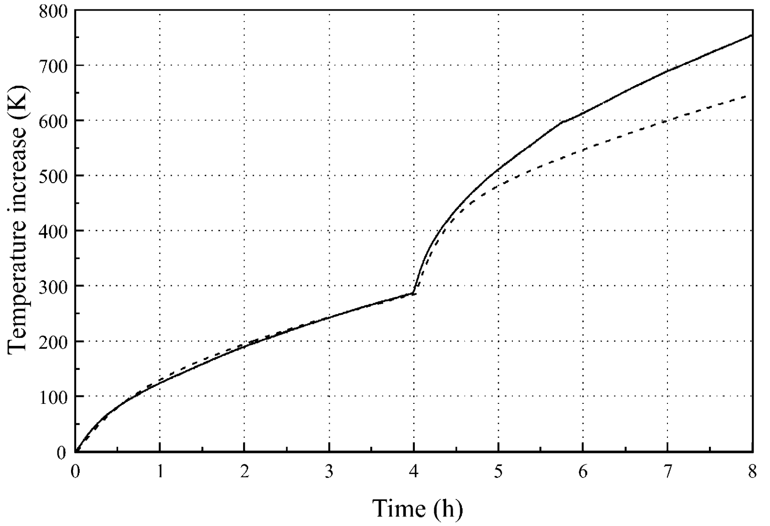

Fig. 1. Verification of the furnace thermal model.

3. The basic structure of the controller

The basic functional structure of the control loops is shown in Fig. 2.

In the domain far from the commanded temperature, the control task is to maintain the temperature slope (maximum or commanded). In the domain close to the commanded temperature, the slope must not be tracked in order to avoid temperature overshoot, i.e. it is primary to obtain a convenient approach to the commanded temperature. As a consequence of separated scopes of duty, control can be implemented via two separate fuzzy controllers.

When making the decoupled regulation system, there is an issue of the boundary value of temperature error where a switch is being made from the temperature slope regulation to the temperature regulation, which will be considered through the experiment results (Section 5.3).

Implementation of the controllers is completed using a low-end microcontroller [7]. For that purpose, two matrices containing the appropriate output values for input pairs are assembled from the fuzzy inference structures (*FIS*), developed in *Matlab* [8]. In [7], the basic structure of the laboratory equipment setup is shown.

4. Temperature fuzzy controller

4.1. Basic concepts of the controller

The fuzzy controller was set up in *Matlab* [8] as a two-input, one-output structure. The input variables are temperature error T_e (K) and the rate of temperature change T_c (K). The output variable is the increment of power P_i (% of P_r). The initial set-up of membership functions is presented in Fig. 3. The assembled fuzzy system is of Mamdani type and the centroid defuzzification method [9] is used.

The initial set of fuzzy rules, tuned on the numerical simulations, has been compiled by the compromise between fast attaining of the desired temperature and avoiding its overshoot. The initial fuzzy rules are shown in Table 2. A description of the notation for the rules is given in the caption of Fig. 3.

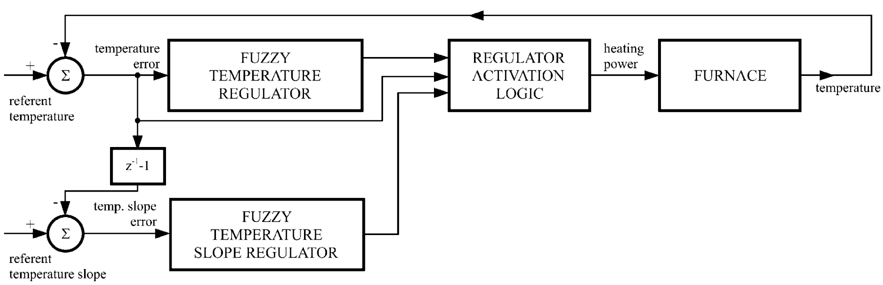

Fig. 2. Controller basic structure.

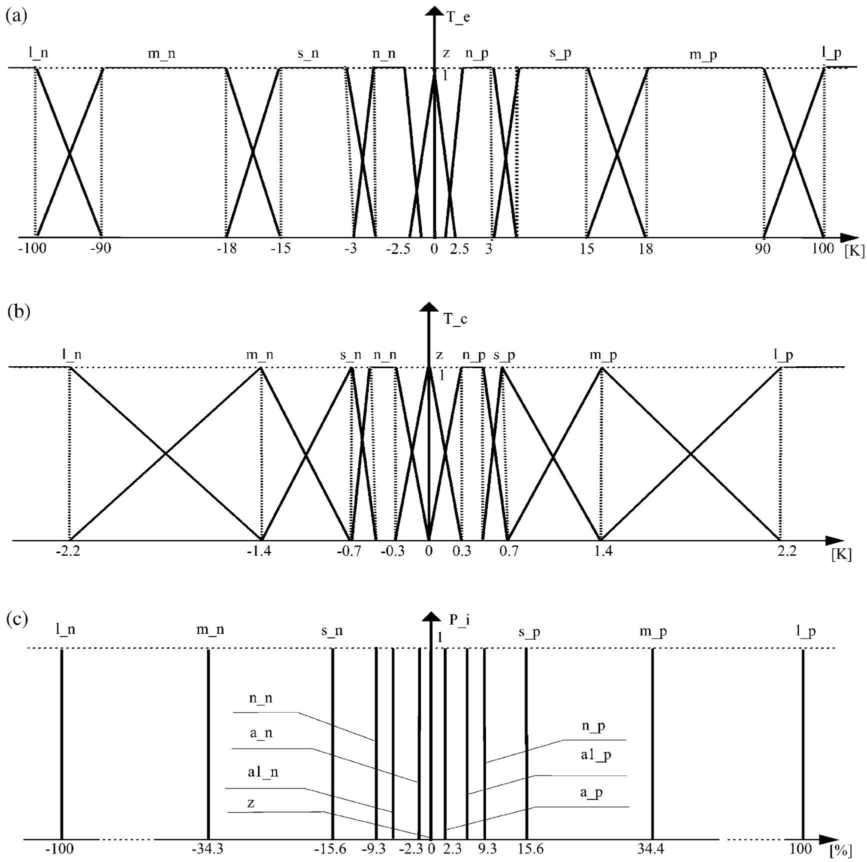

Fig. 3. Membership functions (l_n/l_p—large negative/positive, m_n/m_p—medium, s_n/s_p—small, n_n/n_p—near zero, a_n/a_p—around zero, z—zero).

Table 2
The initial-temperature fuzzy controller rules

		T_e								
		l_n	m_n	s_n	n_n	z	n_p	s_p	m_p	l_p
T_c	l_n	l_p	l_p	l_p	m_p	m_p	l_p	l_p	l_p	l_n
	m_n	l_p	l_p	m_p	s_p	s_p	m_p	l_p	s_p	l_n
	s_n	l_p	l_p	s_p	n_p	n_p	s_p	m_p	s_p	l_n
	n_n	l_p	l_p	s_p	n_p	n_p	n_p	s_p	n_p	l_n
	z	l_p	m_p	n_p	a_p	z	a_n	n_n	m_n	l_n
	n_p	l_p	n_n	s_n	n_n	n_n	n_n	s_n	l_n	l_n
	s_p	l_p	s_n	m_n	l_n	s_n	n_n	s_n	l_n	l_n
	m_p	l_p	s_n	l_n	l_n	m_n	s_n	m_n	l_n	l_n
	l_p	l_p	l_n	l_n	l_n	l_n	m_n	l_n	l_n	l_n
Rule no. (ascending downwards)		1	2–10	11–19	20–28	29–37	38–46	47–55	56–64	65

4.2. Results of the temperature fuzzy controller application

The exposed set of fuzzy rules [8] yielded simulation results shown in Fig. 4. Modelling of the furnace was performed in the simplest way, using the furnace parameters derived from the experiment of heating with constant 45% P_r power. Temperature approaches the commanded value in a suitable manner (the curve is smooth and the slope decreases in the proximity of the commanded temperature). Small temperature overshoots occur—the greatest appears at the commanded temperature-to-ambient difference of 800 K, when it reaches 5.9 K, while at 300 K reference, the overshoot is approximately 4.4 K.

The results of applying the designed controller on the real furnace are presented in Fig. 5 (initial fuzzy controller). Two inflection points can be noticed, which are explained as a consequence of a more dynamic response of the real system than the response of the model used in the simulations. Furthermore, unlike the simulation, the temperature overshoot is very small—less than 1 K. Further experiments yielded similar results; the controller behaves equally when approaching the commanded value from above and from below.

It would be convenient to speed this controller up and make a smoother approach in the vicinity of the commanded value. In order to achieve this, a series of corrections to the FIS rules is completed, decreasing the abrupt power changes as shown in Table 3. Additionally, membership functions for the temperature error are modified—transition between large and medium error moves from −90 K to −60 K, as well as symmetrically from 90 K to 60 K (applied in all cases).

Two transitional experimental results (designated as the 1st and the 2nd modification), obtained during the controller correction process are shown in Fig. 5.

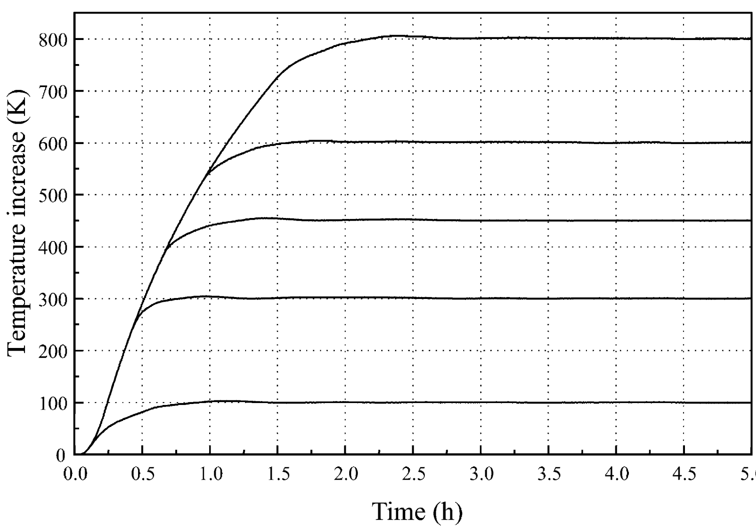

Fig. 4. Simulation result of the initial temperature fuzzy controller application.

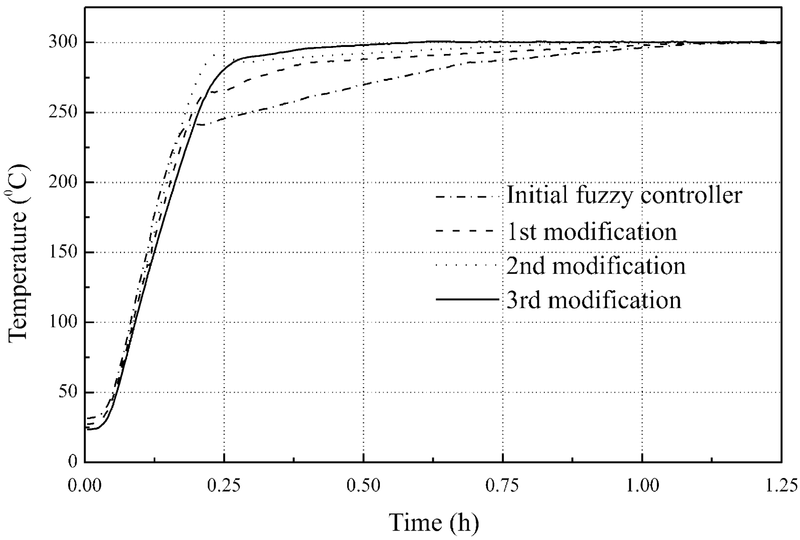

Fig. 5. Application result of the temperature fuzzy controller.

Table 3
Corrections of the temperature fuzzy controller rules

		T_e			
		1st modification	2nd modification	3rd modification	
		m_n	m_n	s_n	n_n
T_c	n_p	a_n		n_n	s_n
	s_p	n_n	al_n	s_n	m_n
	m_p		n_n	m_n	
	l_p		m_n		
Rule no.		7, 8	8, 9, 10	16, 17, 18	25, 26

Finally, a smooth response curve is obtained, without the jumpy changes of temperature and with maintained minimum overshoot quality (below 1 K)—3rd modified controller.

5. Slope and temperature fuzzy controller

Unlike the concept of forcing maximum possible temperature slope and attaining the commanded value without overshoot, used for the temperature controller, some processes do not allow the temperature slope to exceed certain values. In such cases, the initial control task becomes that of maintaining commanded temperature slope, all the way to the vicinity of the commanded temperature, when the task of control becomes one to assure the approach to the reference without overshoot. Therefore, the ideal response, for several different temperature slopes, is depicted in Fig. 6.

5.1. Feasible controller concepts

The regulation could be conceived with the previously-described temperature fuzzy controller simply by using a ramp reference, but it performed badly when tested. Modifications of membership functions and rules can ensure keeping the slope at a certain value, but the solution is inflexible since it requires a new FIS for each desired slope. It is also possible to compile a unified FIS, which would have temperature and slope errors as two inputs, and their variations as another two inputs. This four-input FIS would require a large four-dimensional matrix for microcontroller implementation, by far exceeding the on-board memory. Temperature and slope controllers have separated scopes of duty, as explained in Section 3, and the concept in Fig. 2—two-fold fuzzy controller—provides the optimal solution.

5.2. Two-fold fuzzy controller

In the FIS used for the temperature-slope regulation, the membership functions for "temperature slope error" are preserved in the same way as for variable "temperature change rate" in the FIS for temperature regulation. Due to the difficulties with identifying the variable "change of temperature slope", caused by measurement resolution and noise, only three membership functions are defined, as shown in Fig. 7.

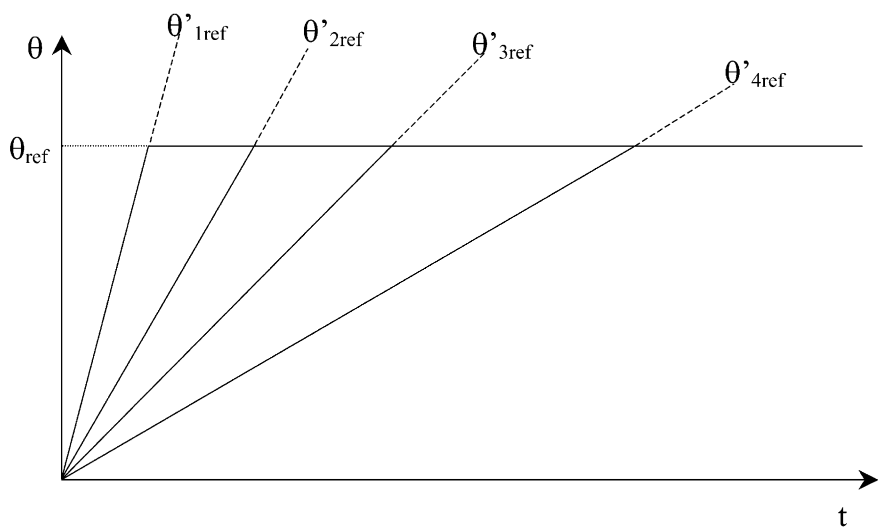

Fig. 6. Ideal temperature responses for reference slope and temperature.

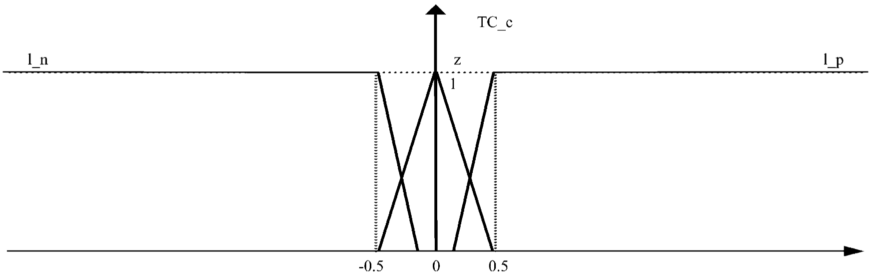

Fig. 7. Membership functions of variable "change of temperature slope".

Table 4
The initial temperature slope fuzzy controller rules

		TC_e								
		l_n	m_n	s_n	n_n	z	n_p	s_p	m_p	l_p
TC_c	l_n	l_p	m_p	m_p	m_p	s_p	m_n	l_n	l_n	l_n
	z	l_p	m_p	m_p	m_p	z	m_n	l_n	l_n	l_n
	l_p	l_p	m_p	m_p	m_p	m_n	m_n	l_n	l_n	l_n
Rule no.		1	2	6	7	4, 3, 5	8	9	10	11

This fuzzy structure contains 11 rules, shown in Table 4. These rules involve variables TC_e (temperature slope error), TC_c (change of temperature slope) and P_i (power increment—its membership functions are identical to those used with the temperature controller).

Results of test simulations of this FIS, for references 0.5, 1.5 and 2.5 K/(15 s), are shown in Fig. 8.

Exponential decay that begins after a while is a consequence of attaining the maximum power. One can notice the presence of a steady-state regulation error for all three cases. This error can be reduced by an alteration of the rules, but the realistic estimation of its value can be given only after an experiment, due to the described more dynamic behaviour of the real furnace (Fig. 1). Therefore, the response was tuned in to the simulations to be more sluggish than actually wanted.

Fig. 9 presents the experimental results of the controller performance test for the same references as for Fig. 8. The measured temperature signal is filtered. When taking into account the more dynamic behaviour of the real furnace than the simulation model, an estimation of the influence of steady-state errors was necessary. The steady-state error can be noticed only for the greatest temperature change rate of 2.5 K/(15 s).

To reduce the temperature slope overshoot, a modified structure is made. Membership functions remain unchanged, and the rules are shown in Table 5.

The practical test of this FIS provided the results shown in Fig. 10: the dashed line presents the profile of the commanded values, which was as follows: temperature 400 °C, temperature slope 1.5 K/(15 s); when 400 °C is attained, the commanded slope of −0.5 K/(15 s) is issued; this commanded temperature slope was retained

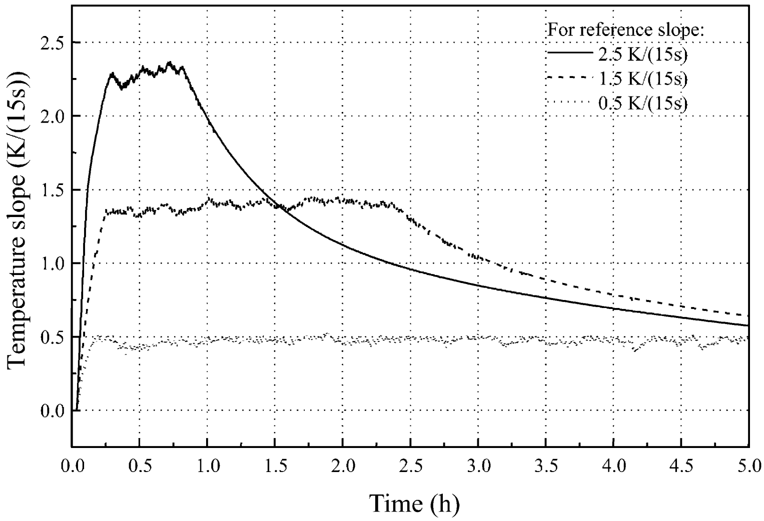

Fig. 8. Simulation results of temperature slope controller application.

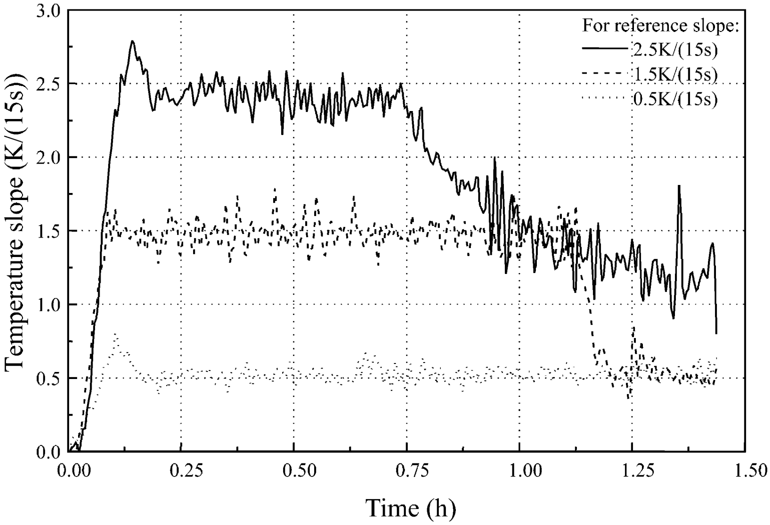

Fig. 9. Application results of the temperature slope controller.

until the power dropped to zero, and then a 3 K/(15 s) temperature slope was issued; when the power attained the maximum, a zero slope was commanded.

As seen in the bottom part of Fig. 10, an overshoot still exists at 1.5 K/(15 s), but disappears at −0.5 K/(15 s). Only at 3 K/(15 s) steady-state error becomes conspicuous.

The temperature slope steady-state error is not large, but it still exists. It is a consequence of the insufficient controller astatism. It can be shown, from the controlled

Table 5
Modified temperature slope fuzzy controller rules

		TC_e								
		l_n	m_n	s_n	n_n	z	n_p	s_p	m_p	l_p
TC_c	l_n	m_p	s_p	s_p	s_p	n_p	n_n	m_n	l_n	l_n
	z	m_p	s_p	s_p	s_p	z	n_n	m_n	l_n	l_n
	l_p	m_p	s_p	s_p	s_p	n_n	n_n	m_n	l_n	l_n
Rule no.		1	2	6	7	4, 3, 5	8	9	10	11

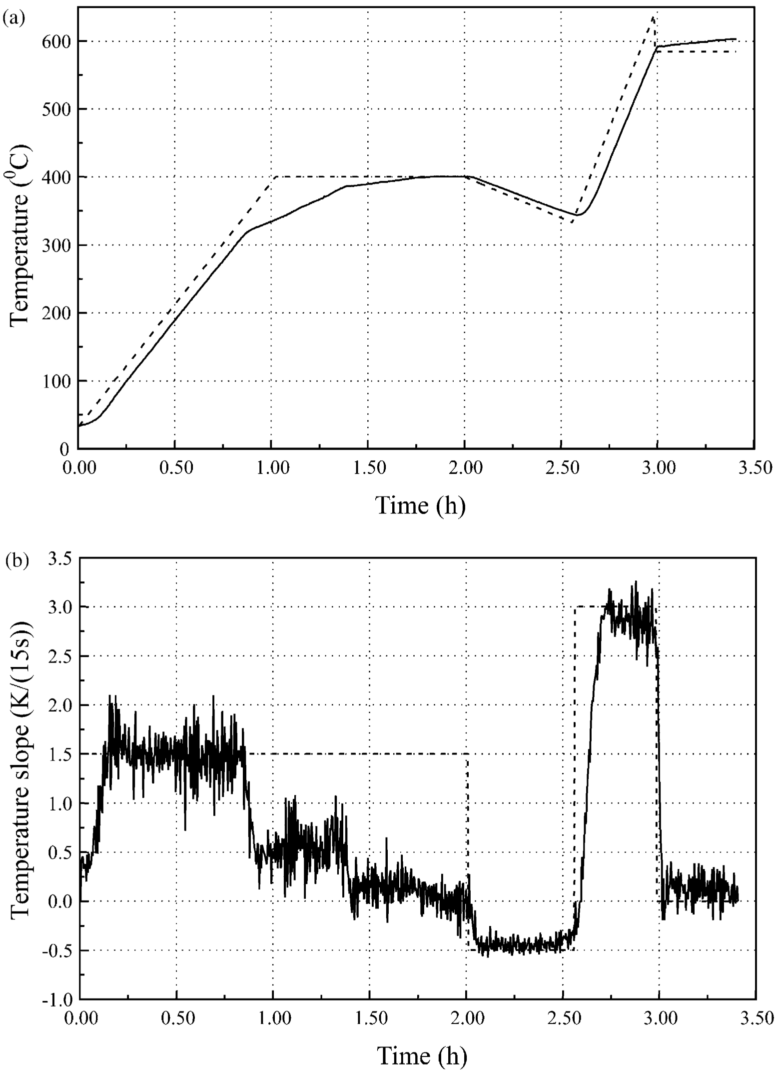

Fig. 10. Response of the modified two-fold fuzzy controller.

object's transfer function, that a steady-state constant temperature slope requires a constant power slope to be applied. Since the controller output is power increment, it outputs a certain constant increment value when it has zero for both inputs, while the correct power increment depends on the desired temperature slope and therefore is not constant. A theoretical solution would be advised by adding another integrator in series with the present one, while the fuzzy controller output would become the power increment, allowing power slope to always attain the correct value. Numerical simulations were performed using such a controller, but practically applicable results were not obtained, though the simulations proved the theoretical assumption about the steady-state error elimination.

5.3. Considerations on the point of switch between the controllers

An "early" switch (far enough from the temperature reference) to the temperature fuzzy controller guarantees an approach to the reference as in the case when only a temperature controller is used. The results presented in the previous part of

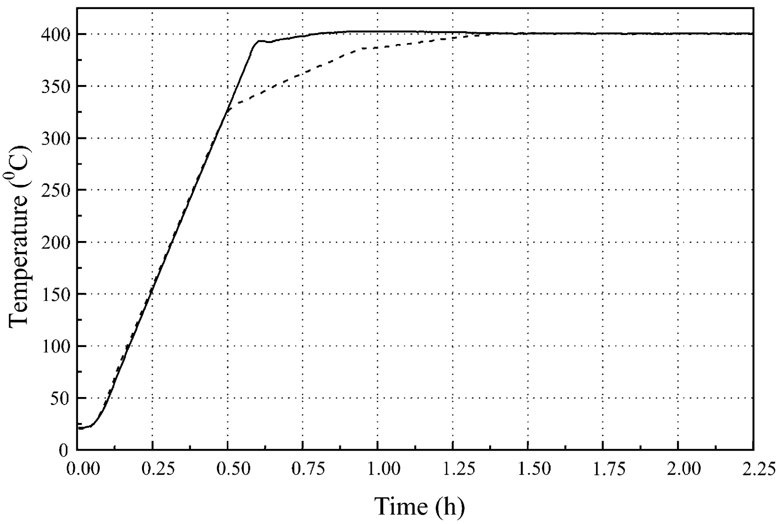

Fig. 11. Influence of switching point from slope to temperature control.

Table 6
Response of two-fold controller at different reference values

Reference temperature (°C)	Reference slope [K/(15 s)]	θ_{ref}* (°C)	Time to attain ϑ_{ref}* (min)	Temperature overshoot (K)
400	3	396.2	43	2.6
600	2	594.2	86	2.5
400	2	396.2	64	1.1
800	1.3	792.2	160	3.2
600	1.3	594.2	117	1.3
400	1.3	396.2	87	0.7

Section 5 are exactly of that type—the switch to the temperature fuzzy controller was made when the temperature error absolute value drops below 101 K. A later switch ensures faster attaining of the commanded temperature, but it involves a risk of overshooting it. Fig. 11 displays the responses for a 3 K/(15 s) temperature slope reference and 400 °C temperature reference, for switches made when the temperature error is 89 K (dashed line) and 20 K (solid line).

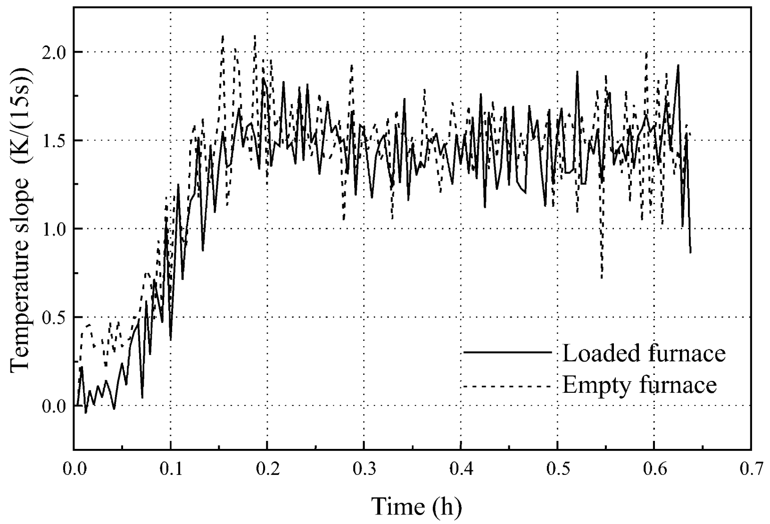

Fig. 12. Behaviour of the temperature slope controller in the empty and the loaded furnace.

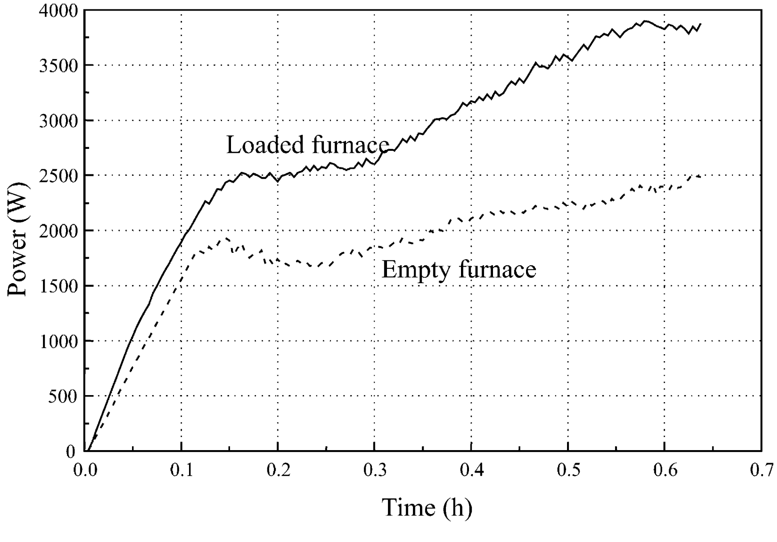

Fig. 13. Heating powers at the same temperature slope reference in the empty and the loaded furnace.

Table 6 shows overshoots of the commanded temperature and the time needed to attain 99% of the commanded temperature rise [$\vartheta_{ref}^* = 20\ ^\circ C + 0.99\ (\vartheta_{ref} - 20\ ^\circ C)$] for different commanded slopes and temperatures. As a temperature fuzzy controller, the initial fuzzy controller (Section 4.1) was used and the switching point is set at 20 K.

Based on the presented results, it can be concluded that the overshoot decreases with the slope reference decrease. Moreover, overshoot is smaller at lower temperature references. Nevertheless, it should be observed that for all the commanded slopes and

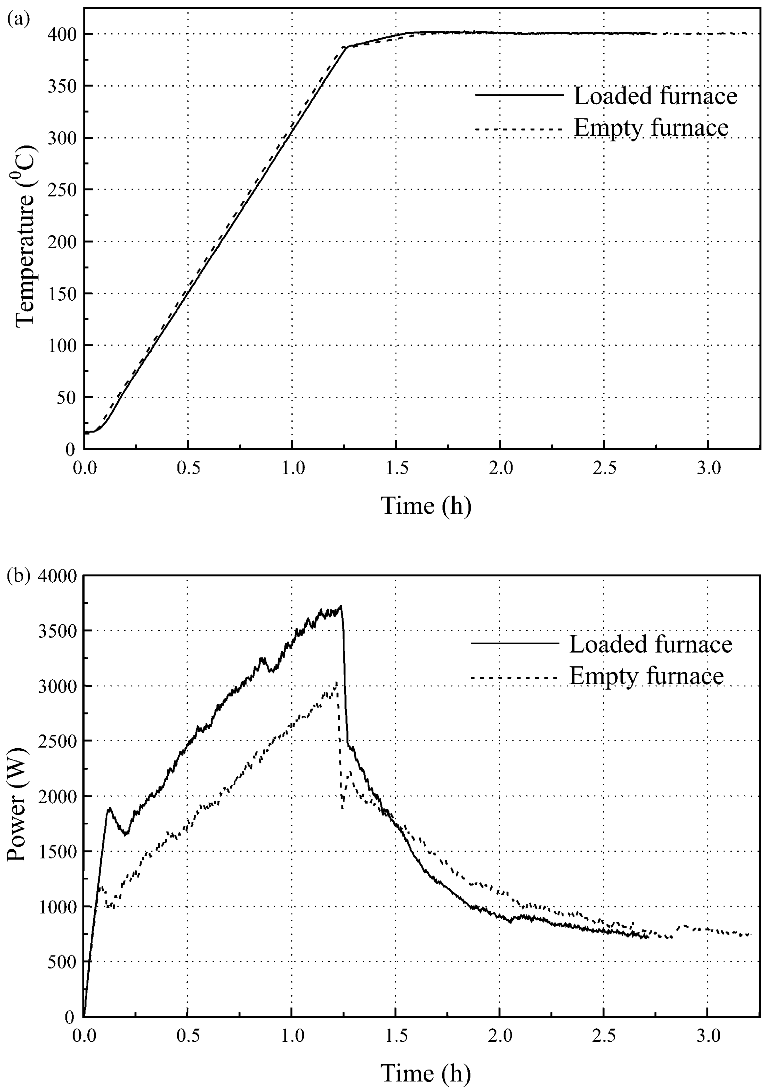

Fig. 14. Two-fold controller robustness with respect to the furnace loading.

temperatures, and switch point at 20 K, the overshoot was less than 1% of the commanded temperature-rise.

5.4. Controller robustness with respect to the presence of the load in the furnace

Loading the furnace changes its characteristics (i.e. makes it more sluggish) and it can lead to the changes of the temperature response in the closed loop with the fuzzy controller. Controller robustness was tested with 1.5 K/(15 s) slope reference, for a furnace fully loaded with approximately 10 kg of steel bars and weights. The result is shown in Fig. 12.

The two traces appear to be quite similar. The overshoot that occurred with an empty furnace at this commanded slope value is hardly conspicuous when the furnace is loaded. The reference attaining is not noticeably more sluggish than with the empty furnace. In order to verify that the furnace load leads to a change in furnace characteristics, significant, even in this relatively short experiment, heating powers (i.e. controller output) when operating with and without load are shown in Fig. 13.

Apart from the test of the controller robustness in the domain of slope regulation, the behaviour at the commanded temperature and slope is tested. The results of an experiment with a 400 °C temperature reference and 1.3 K/(15 s) slope reference, with the furnace loaded in the described fashion, are shown in Fig. 14. A temperature of 396.2 °C was attained in 87 min (in 92 min without load), and temperature overshoot was 1.8 K (1 K without load). The presented results confirm the controller's robustness.

6. Conclusion

The necessity to use the fuzzy logic temperature regulation emerged due to nonlinearity of the controlled chamber furnace and varying of its characteristics with the type and the amount of load. The fuzzy controller is implemented with separate controllers of temperature and its slope, where the switch between them is made in the vicinity of the commanded temperature. The conclusions drawn during the development and implementation on a 5 kW furnace are:

- its tuning using numerical simulations cannot be done precisely, due to the difficulties in precise modelling of the controlled object;
- with the concept of tracking a constant slope all the way until the temperature gets close to the reference, an improvement is made in the response speed compared to the classical digital PID regulation methods (e.g. the Dahlin algorithm [10]), where it is lost due to the bend of the projected exponential response curve from an approximately straight-line initial segment;
- responses to the commanded temperature and temperature slope are good with the controllers used, as illustrated by numerous experimental results;
- optimal switching point from the temperature slope regulation to temperature regulation providing maximum response speeds and overshoot absence

depends on the temperature and the slope references, but a real practical problem of the switch point choice does not exist;

- the implemented fuzzy controllers exhibited robustness with respect to the change of the amount of the load in the furnace.

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