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On-off control algorithms for temperature control of steel cylinder with moving inductors

Abstract. *In the article, the method of realization and results of on-off temperature control of the surface of rotating steel cylinder, heated with mobile inductors have been shown. Ensuring the uniformity of the temperature distribution along the generatrix of the cylinder during heating the object to the given temperature value was of the major importance for proposed control method.*

Streszczenie*. W artykule przedstawiono metodę realizacji oraz wyniki dwustawnej regulacji temperatury powierzchni obracającego się walca stalowego, nagrzewanego ruchomymi wzbudnikami. Istotne znaczenie dla zaproponowanej metody sterowania ma zapewnienie równomierności rozkładu temperatury wzdłuż tworzącej walca podczas nagrzewania obiektu do zadanej wartości temperatury. (****Algorytmy dwustawnej regulacji temperatury walca stalowego z zastosowaniem ruchomych wzbudników****).*

Keywords: on-off control algorithms, induction heating, moving inductors.
Słowa kluczowe: algorytmy regulacji dwustawnej, nagrzewanie indukcyjne, ruchome wzbudniki.

Introduction

In many of nowadays' technological processes heating equipment, which are objects with many inputs and outputs, are used [1,2,3]. An example of such a device may be an inductively heated, rotating steel cylinder, used in many branches of industry, such as paper, textile or rubber industry. Such a type of heating has many advantages, among which high velocity and efficiency are especially worth mentioning. In order to attain high uniformity of temperature distribution on the surface of the heated object, a group of stationary inductors is usually used. As an alternative which gives a possibility to reduce the number of inductors, and enables achieving higher uniformity of temperature distribution on the surface of the heated object, use of mobile inductors is possible. The block diagram of laboratory set-up, in which the last solution has been used, is shown in Fig. 1.

Steel cylinder of 1.2 meter length is heated by six mobile inductors which are powered by six high-frequency generators. The temperature of the surface of the heated object is measured with the use of an infrared camera [4]. With the aim of making temperature measurement of exactly precise areas of the cylinder possible, a synchronization signal is provided to the camera from an encoder, located on the axis of the cylinder. A group of six servo-drives, controlled by a PC1 computer, is responsible for the movement of inductors. Apart from that, the PC1 is also in charge of control of the heating power [5] provided to the heated cylinder and acquisition of the measurement data from the infrared camera.

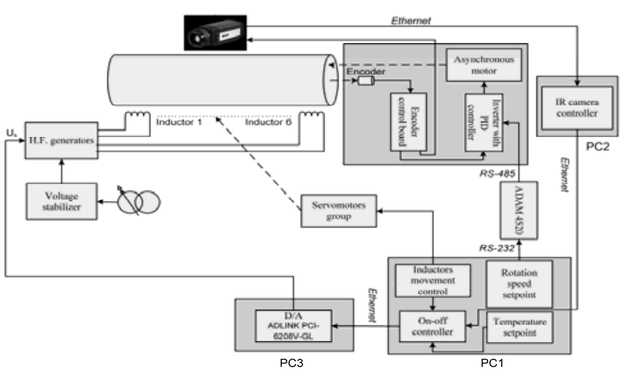


Fig. 1. Block diagram of experimental set-up

One of the simplest and most frequently used methods of temperature control is on-off control method. In the article, a possibility of its use in inductive heating of a rotating steel cylinder with the use of mobile inductors has been shown.

On-off temperature control using a single moving inductor

In order to apply on-off control to inductive heating of a rotating steel cylinder, it has been decided to divide the area of heated surface into 10 zones of equal length. It has been assumed that the moving inductor heats the zone above which its greater part is located. The algorithm of control is shown in Fig. 2.

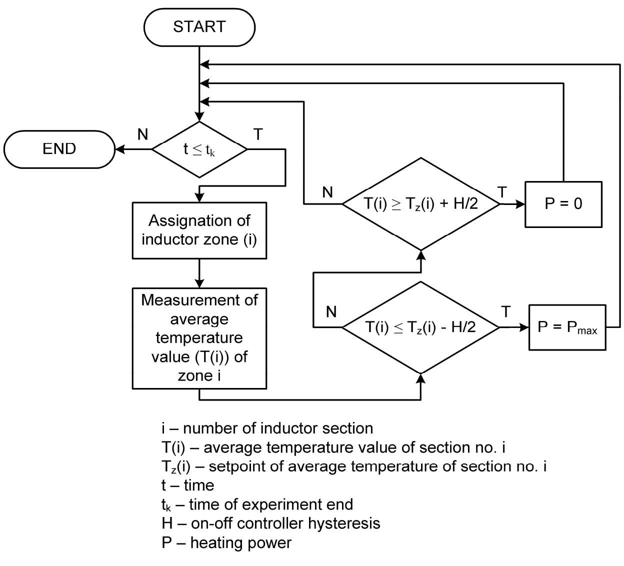


Fig. 2. On-off control algorithm for single moving inductor

The usability of algorithm shown in Fig. 2 has been verified in experiments involving 45-minutes control of constant-value temperature to the level of 40 °C, then a 30-minutes attempt to attain a linear distribution along the generatrix of the cylinder from the interval 35-45 °C. The results are shown in Fig. 3a.

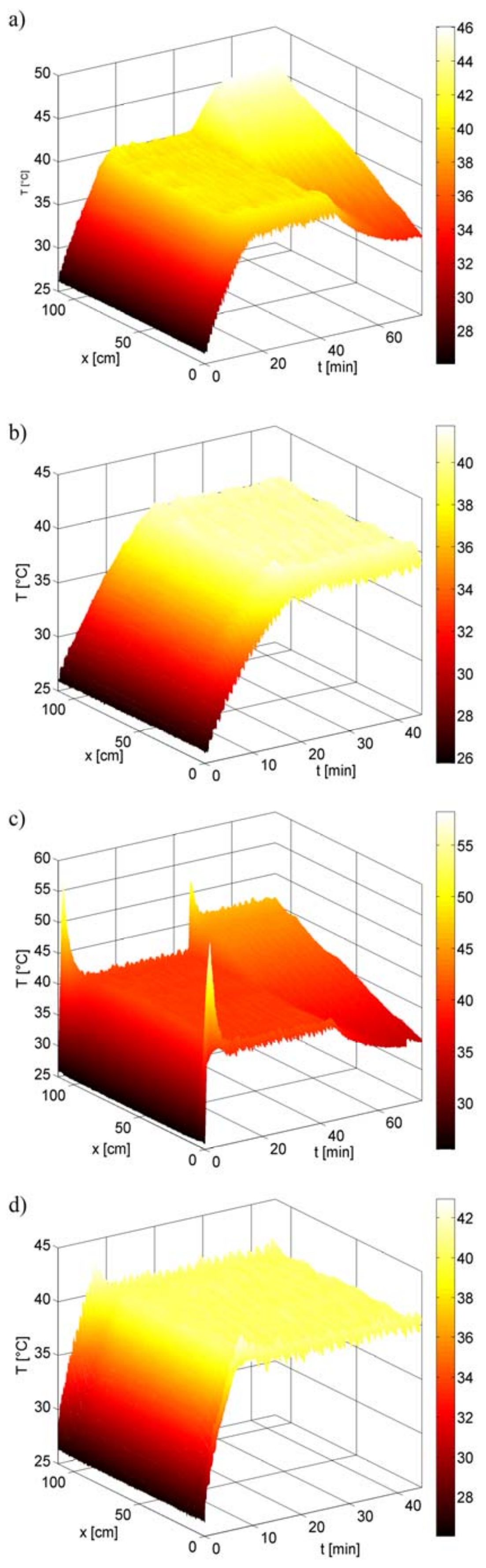


Fig. 3. Temperature control results: a) single moving inductor, b) single inductor and algorithm from Fig. 5, c) three moving inductors, d) three inductors and the algorithm from Fig. 5

With the aim to assess the quality of control, a coefficient R has been defined by the following relationship:

(1) $$R(t) = \max(T(t)) - \min(T(t))$$

The course of this coefficient in time and temperature distribution for time instants, in which R has the maximum (from the duration of the experiment of constant-value control) and minimum value (after reaching quasi-constant state) are shown in Fig. 4.

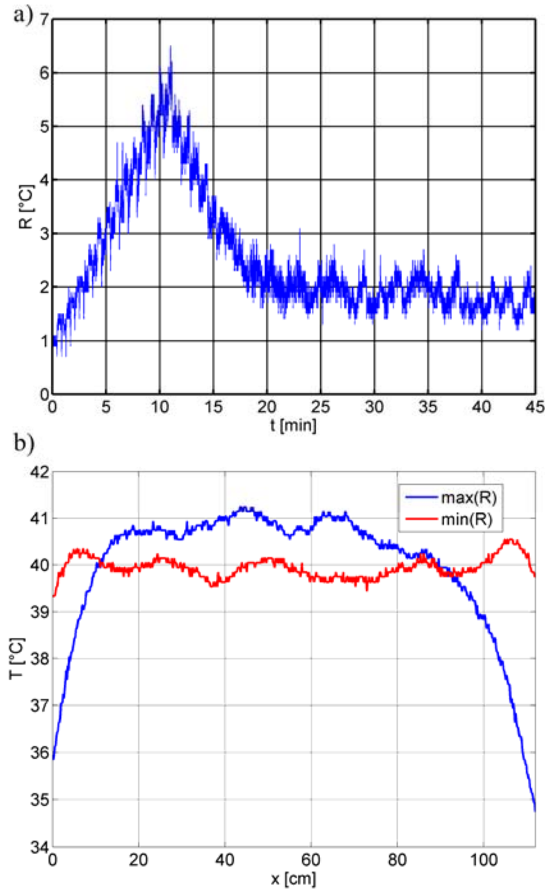


Fig. 4. Control quality index R(t) (a) and temperature distributions on cylinder surface (b)

Analyzing Fig. 4, a significant irregularity of temperature distribution during leading the surface to the given temperature is noticeable. According to that, in order to magnify the uniformity of temperature distribution it has been decided to change the algorithm shown in Fig.2. Also, to enable comparing the quality of derived temperature, it has been decided to use the maximum (from the duration of the experiment of constant-value control) and minimum value (after reaching quasi-constant state) of the coefficient R, and new coefficients of temperature quality have been defined by (2) and (3).

(2) $$I_1 = \sum_{k=1}^{n} \sum_{x=1}^{m} \left| T_{k,x} - T_z \right|$$

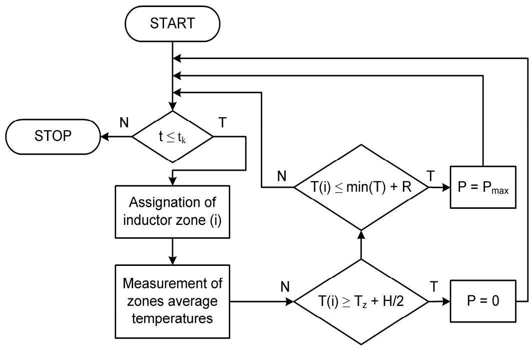
(3) $$I_2 = \sum_{k=p}^{n} \sum_{x=1}^{m} \left| T_{k,x} - mean\left(T_{p \div n, 1 \div x}\right) \right|$$

where: k – time step, n – numer of time steps, x – point coordinate, m –number of cylinder points, T_z – temperature reference value, T – surface temperature.

For the type of temperature control described in this chapter, these coefficients of temperature quality are equal: R_{min}=1.2°C, R_{max}=6.5 °C, I_1=1.709e7°C and I_2=1.029e6°C.

On-off temperature control with the use of a single mobile inductor and control algorithm magnifying the uniformity of temperature distribution

The occurring of temperature distribution on the surface of the cylinder during its heating was decided to be decreased by using the algorithm shown in Fig. 5.



i – number of inductor section
T – vector of average temperatures of zones
T_z – setpoint value of temperature
t – time
t_k – time of experiment end
H – on-off controller temperature
P – heating power
R – permitted deviation of zones temperature

Fig. 5. Modified temperature control algorithm

The correctness of the abovementioned algorithm was proved by experience of constant-value temperature control. The achieved results of measurements are shown in Fig. 3b. Similarly to previously analyzed type of temperature control, the time course of R coefficient has been determined, and values of the indices (2) and (3) have been calculated. The derived temperature distributions for time instants, in which R reaches its maximum and minimum value have been depicted in Fig. 6b. The values of analyzed quality indices of temperature control for this type are as follows: R_{min}=1.2°C, R_{max}=4.5°C, I_1=2.032e7°C and I_2=1.029e6°C.

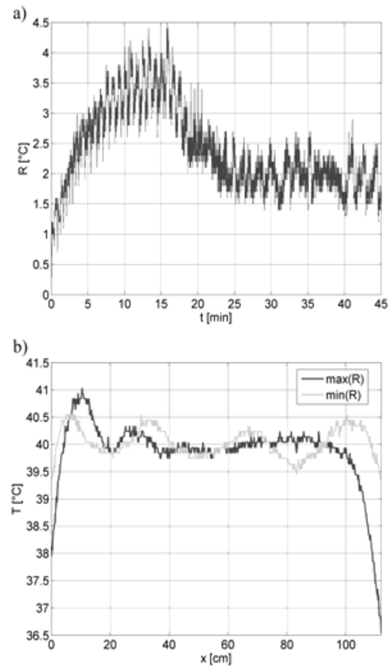


Fig. 6. Control quality index $R(t)$ (a) and temperature distribution on cylinder surface (b)

Analyzing Figure 4 and 6, a decrease in irregularity of temperature distribution on the surface of the cylinder during its heating is noticeable. The occurring irregularity may be decreased by increasing the number of zones in which the surface of the cylinder is divided. Moreover, it should be mentioned that the border zones include side areas of the cylinder, which are characterized by greater, in comparison to central areas, value of convection coefficient.

Additionally, comparing Figures 3a and 3b, it is noticeable that applying the algorithm shown in Fig. 5 increases the time of reaching the given temperature by the object. It is a result of the fact that the side areas of the cylinder require supplying more energy to reach the given value of temperature than central areas, and the applied algorithm during heating reduces the amount of energy supplied to the central areas of the cylinder not to allow too big irregularity of temperature distribution occur.

On-off temperature control with the use of a single mobile inductor and two auxiliary stationary inductors

Analysis of the abovementioned typed of temperature control implies that it appears to be reasonable to use auxiliary inductors, heating separately side areas of the cylinder. For that purpose, the variant of temperature control with the use of one mobile inductor, heating the central part of the cylinder (zones 2-9), and two stationary inductors, controlling the temperature of side areas of the cylinder has been analyzed. The attained results are shown in Fig. 3c.

Similarly to previously analyzed type of temperature control, the time course of R coefficient has been determined, and values of the indices (2) and (3) have been calculated. The derived temperature distributions for time instants, in which R reaches its maximum and minimum value have been depicted in Fig. 7b. The values of analyzed coefficients of quality of temperature control for this type are as follows: R_{min}=0.5°C, R_{max}=30.6°C, I_1=1.34e7°C oraz I_2=9.655e5°C.

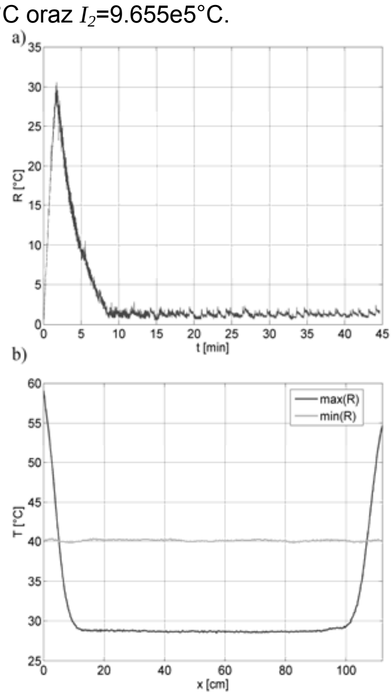


Fig. 7. Control quality index $R(t)$ (a) and temperature distributions on cylinder surface (b)

Analyzing Figures 3c and 7 as well as the values of quality indices, it may be noticed that the given value of temperature is significantly exceeded in the side areas of the cylinder. It is a result of the fact that stationary inductors lead the temperature of side areas of the cylinder to the given value at the expense of the uniformity of temperature distribution. Due to that, it has been decided to apply the algorithm depicted in Figure 5 to the system of heating with the use of three inductors.

On-off temperature control with the use of a single mobile and two stationary auxiliary inductors with the application of the algorithm increasing the regularity of temperature distribution

In this chapter, the variant of temperature control with the use of one mobile inductor, heating the central part of the cylinder (zones 2-9), and two stationary inductors, controlling the temperature of side areas of the cylinder has been implemented. The power control was realized using the algorithm shown in Fig. 5, for each inductor independently.

The attained results of constant-value temperature control are shown in Fig. 3d. Similarly to previously analyzed type of temperature control, the time course of R coefficient has been determined, and values of the indices (2) and (3) have been calculated. The derived temperature distributions for time instants, in which R reaches its maximum and minimum value have been depicted in Fig. 8b. The values of analyzed coefficients of quality of temperature control for this type are as follows: R_{min}=0.5°C, R_{max}=6.3°C, I_1=1.202e7°C and I_2=8.577e5°C.

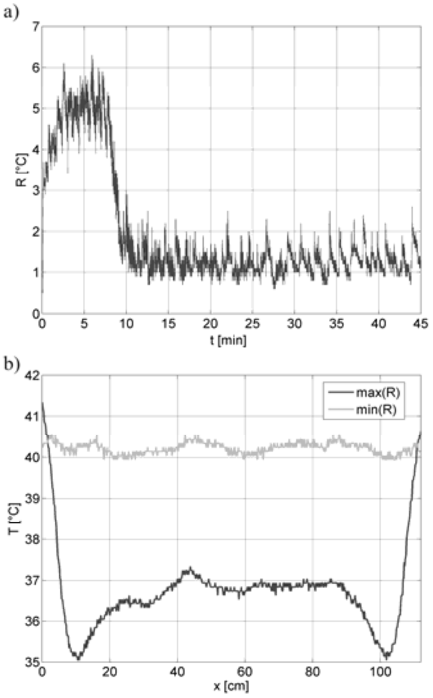


Fig. 8. Control quality index $R(t)$ (a) and temperature distributions on cylinder surface (b)

Comparison of Figures 3c and 3d shows that application of aforementioned algorithm significantly improves the uniformity of temperature distribution during heating of the object. Moreover, it should be noticed that the maximum value of R is mainly caused by the fact that the value of temperature of side zones of the cylinder is controlled, and because of the steel closure of sides, they heat faster than the center of the cylinder.

Conclusions

With the aim to compare the analyzed variants of on-off control of cylinder surface temperature the relative values of calculated control quality indices have been collected in Fig.9.

By the analysis of Fig. 9, it may be concluded that each of the presented variants has its pros and cons. The variant of control with the use of three inductors and application of the algorithm shown in Fig. 5 has minimum flaws. By increasing slightly the maximum value of dispersion in time of heating (in comparison to the variant using single inductor and the algorithm shown in Fig. 5), a significant decrease of dispersion in a quasi-constant state and improvement of remaining quality indices of temperature control may be attained.

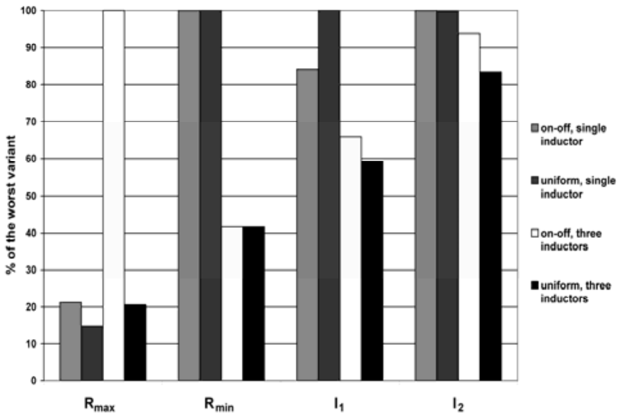


Fig. 9. Relative values of control quality indices

Acknowledgements

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