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UTILIZATION MATHEMATICAL AND PHYSICAL MODELS DERIVED THEREFROM REAL-TIME MODELS FOR THE OPTIMIZATION OF HEATING PROCESSES

WYKORZYSTANIE MATEMATYCZNYCH I FIZYCZNYCH MODELI NIEDZIAŁAJĄCYCH W CZASIE RZECZYWISTYM DO OPTYMALIZACJI PROCESU NAGRZEWANIA

Heating of materials is energy and costly operations. On those reasons optimization is highly desirable. One of the possible solutions to optimize heating in real time is to use a large number of fast simulations on the basis of them the optimization algorithms have chosen the most appropriate option of the heating control. This solution implies the use of extremely fast but sufficiently accurate simplified mathematical models of heating, the structure and parameters of them are defined based on accurate modelling using computationally intensive but slower classical mathematical-physical models. Based on the operating data of the reheating furnace was build an accurate model of heating. Using the simplified model simulation of heating was done with different heating conditions with downtime during heating. Proposed algorithms including the simulations show that the proposed strategy leads to verifiable savings during heating.

Keywords: heating process, mathematical and physical model, real time control, optimal control

Nagrzewanie materiałów jest procesem energochłonnym i kosztowny. Dlatego optymalizacja tych procesów jest bardzo pożądana. Jednym z rozwiązań umożliwiających optymalizację nagrzewania w czasie rzeczywistym jest przeprowadzenie dużej liczby szybkich symulacji, na podstawie których algorytmy optymalizacji wybierały najodpowiedniejszą wersję sterowania nagrzewaniem. Rozwiązanie takie zakłada stosowanie niezwykle szybkich ale wystarczająco dokładnych uproszczonych matematycznych modeli nagrzewania, których struktura i parametry określane są na podstawie dokładnych, ale wolno działających klasycznych modeli matematyczno-fizycznych. Na podstawie danych eksploatacyjnych pieca grzewczego zbudowano model dokładny, a następnie korzystając z jego wersji uproszczonych przeprowadzono symulację dla różnych warunków nagrzewania uwzględniając przestoje w trakcie nagrzewania. Zaproponowane algorytmy wraz z wynikami symulacji pokazują, że proponowane podejście prowadzi do znaczących oszczędności w trakcie nagrzewania.

1. Introduction

Optimization of heating the material in continuous reheating furnaces, given the energy and material efficiency of technologies lead to significant financial savings. Optimization algorithms may use mathematical models for their own function, but they must produce results in real-time. The exact mathematical and physical models are usually implemented off-line exploring special software and intensive calculations take too much time [1]. Therefore There are not to appropriate to the real-time optimize. However, they may well serve as a source of parameters usable in fast simplified models that can be used to predict the parameters of the final product when pulling out of the furnace and subsequent optimization of the heating process by corrections of set points of controlled variables of control loops of each zone of heating furnaces [2], [3]. The aim of optimization should be to stabilization of the characteristics of the final product while minimizing energy and material demands of heating.

2. Continuous walking beam reheating furnace

Continuous walking beam reheating furnaces are the upstream technology for the hot forming technology. Therefore, the quality of heating in these furnaces largely affects the quality of the final product of the forming process.

When loading the material into the furnace the entire contents of the furnace is moved one position in one step (defined by a length increment or an angle of the rotation) to the output of the furnace.

These downtime concerns each row of the charge of the charged furnace. Individual rows are at different positions in the furnace, and therefore there are in various stages of heating.

An application of simulations was shown in [4] that the influence of downtime on the final parameters of the heated material is so higher, so the heated material is located closer to the outlet of the furnace. It is possible to do a correction of the negative impact of the downtime with the suitable change of the temperature at each zone of the furnace only. Just the

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last four zones of furnaces are usually heated, and thus the direct control of the temperature in the furnace can be done only within these zones so the first zone is not equipped with burners.

3. The accurate and simplified models of heating

Algorithms for correcting temperatures in each zone of a furnace are intended to stabilize the parameters of the heating charge while material and energy losses are minimized during heating process. Irregular downtime of charging requires real-time interventions to the control strategy of the heating. This requires to use algorithms that apply simplified, fast working models of heating. Based on the rapid multiple simulations they select the optimal variant of the conduct to the heating appropriate for the specific situation then.

The parameters of simplified models are obtained by the application of accurate mathematical models, but their complexity is not able to deliver results in the time required for real-time control of the heating process [4], [5].

The accurate models of heating

The exact mathematical models of heating works on physical laws related to the heating of materials and the overall operation of the furnace. They describe mathematically formulate all physical principles from the fuel consumption through the combustion conditions, the temperature in each zone of furnaces to heat transfer to the heated material, heat transfer inside the heated material and heat loss to the surroundings.

The exact mathematical models have to respect the shape of real geometric dimensions of the heated material. The models describing heating of the material in the shape of a cylinder will used.

The Short cylinder we mean as the intersection of an infinite plate of thickness L and an infinite cylinder of radius R.

We mark variables related to the length (height) coordinate of the cylinder with indexes L and R variables dependent on the radial coordinate of the cylinder. Then: Bi_{L} is the Biot criterion relative to the height of the block [1], Bi_{R} the Biot criterion relative to the radius of the block [1], α_{Σ} is the overall heat transfer coefficient $[\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{K}^{-1}]$, τ_{r} is the time constant of the point inside the cylindrical body [s], τ_{R} is the time constant of the point inside the cylindrical body [s], τ^{R} is the characteristic time constant of the cylinder [s], τ_{l} is ime constant of the point inside the plate element [s], $\tau_{\mathrm{L}}$is the time constant of the point on the surface of the plate element [s], τ^{L} is the characteristic time constant of the plate element [s], μ_i^{L} is the ith root of the characteristic equation plates, μ_i^{R} is the ith root of the characteristic equation plates, a is the coefficient of thermal conductivity $[\mathrm{m}^2\cdot\mathrm{s}^{-1}]$, λ is the Coefficient of thermal conductivity $[\mathrm{W}\cdot\mathrm{m}^{-1}\cdot\mathrm{K}^{-1}]$.

The transfer function system the furnace – the point inside the cylinder with boundary conditions of the third kind can be described by the equation [9], [10], [11]:

$$F(x,r,p) = 1 - \sum_{i=1}^{\infty}\sum_{j=1}^{\infty} \frac{D_i^{\mathrm{L}} D_j^{\mathrm{R}} \frac{p}{b_i^{\mathrm{L}}+b_j^{\mathrm{R}}}}{\frac{p}{b_i^{\mathrm{L}}+b_j^{\mathrm{R}}}+1}, \tag{1}$$

where

$$b_i^{\mathrm{L}} = \frac{\left(\mu_i^{\mathrm{L}}\right)^2}{\tau^{\mathrm{L}}}[s^{-1}], \tag{2}$$

$$b_i^{\mathrm{R}} = \frac{\left(\mu_i^{\mathrm{R}}\right)^2}{\tau^{\mathrm{R}}}[s^{-1}]. \tag{3}$$

The characteristic time constants of the plate and of the cylinder are:

$$\tau^L = \frac{L^2}{a}[s] \tag{4}$$

and

$$\tau^{\mathrm{R}} = \frac{R^2}{a}[s] \tag{5}$$

The roots of the characteristic equations are expressed by equations:

$$\mu_i^{\mathrm{L}} = Bi_{\mathrm{L}} \cot g\mu_i^{\mathrm{L}}, \tag{6}$$

$$\frac{\mu_j^{\mathrm{R}}\cdot J_1(\mu_j^{\mathrm{R}})}{J_0(\mu_j^{\mathrm{R}})} = Bi_{\mathrm{R}}. \tag{7}$$

The gain $D_i^{\mathrm{L}}$and D_i^{R} are expressed from relations:

$$D_i^L(x) = \frac{2\cdot\sin\mu_i}{\mu_i+\sin\mu_i\cdot\cos\mu_i}\cdot\cos(\mu_i\cdot\frac{x}{L}), \tag{8}$$

$$D_i^R(x) = \frac{2J_1(\mu_i)J_0(\mu_i\cdot\frac{r}{R})}{\mu_i\cdot[J_0^2(\mu_i)+J_1^2(\mu_i)]}. \tag{9}$$

In the transfer function (1) is considered only the first term of its expansion.

To set the parameters of the model is used the adaptive identification based on data measurements on real objects of the reheating furnace.

The model is a resource for setting parameters of simplified models designed to predictions in real-time and can be used to check the performance of simplified models.

Simplified models of heating

The aim is to create a sufficiently accurate simplified model of heating, the implementation of which can carry a large amount of computation in real time. Models can be based on many principles. One solution mentioned in the article [4].

These may be formulated by the following mathematic formulae:

$$\tau_1(t)\frac{dT_s(t)}{dt} + T_s(t) = T_f(t) \tag{10}$$

and

$$\tau_2(t)\frac{dT_c(t)}{dt} + T_c(t) = T_s(t), \tag{11}$$

where $\tau_1(t)$ is outside heat transfer time-variable time constant [min], $\tau_2(t)$ is inside heat transfer time-variable time constant [min], $T_s(t)$ is temperature of the heated material surface [°C], $T_f(t)$ is furnace temperature [°C], $T_c(t)$ is material heated material core temperature [°C].

The model is described by two time-variant linear differential equations, which affects the external and internal heat transfer. The model parameters are revised by the results of

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the exact mathematical model. The model input is the instantaneous temperature at the furnace, which is calculated from the temperature in each zone furnace [4].

The forecast

In our simulated case, we will assume that they are set and stabilized the optimum temperature in each zone of the furnace in case that particular material

If there is a disruption of the regular furnace operation the prediction of parameters of heated material with simulating adjustments the current temperature set point in each zone of the furnace will be executed repeatedly. It is a matter of the optimization algorithms to find the optimal variant of heating from all predicted ones [7], [8].

Optimization

The aim of the optimization algorithm is to stabilize the monitored parameters of heated material on the outlet of the furnace. The straightforwardness of simplified real-time models allows observing simply the value of optimality in the form [12]:

$$ML(t) = 60 * \sqrt{\frac{76233 * 2}{T_s(t) * e^{\left(\frac{17057}{T_s(t)}\right)}}}, \tag{12}$$

where $ML(t)$ is the metal loss [kg/m^2], $T_s(t)$ is the temperature of the heated material surface [°C].

The criterion allows the using optimization algorithms to minimize the costs associated with the iron lost. This additional criterion cannot directly include to optimization algorithms that utilize fast simplified models [13], [14], [15].

The general principle of optimization algorithms of the temperature correction in each furnace zone is a gradual temperature decrease in controlled zones of the furnace so that temperatures would be increasing gradually again to the standard values when standard continuous mode of charging (after downtime) starts again and in the same time it would be guaranteed for the individual rows of heated material in the furnace a minimal deviation to the technologically references of parameters of a hot material when putting off form the furnace.

The actions of temperature set points in each furnace zone must be such that they respect the technological requirements for the maximum allowable decrease and increase of temperatures in the furnace and the temperatures in each zone do not exceed the specified limits of technology simultaneously.

For own optimization it may be successfully used the methods of artificial intelligence in addition to traditional methods, such as genetic algorithms, etc. [13] [16], [17].

4. The results of the simulation of optimization of heating

Correcting the temperature in the furnace zones

As an illustrative example of the temperature correction in each zone the furnace the heating with an interval of one step in the duration of four minutes was simulated, which was suspended in 160 minutes by downtime in the duration of one hour. After this idle again followed regular progression of heated material in the furnace with a period of 4 minutes.

The simulation results can be seen in Figure 2, in which are plotted as curves of monitored values without correction of the temperature of zones in the furnace (solid line) as with the correction (dashed line).

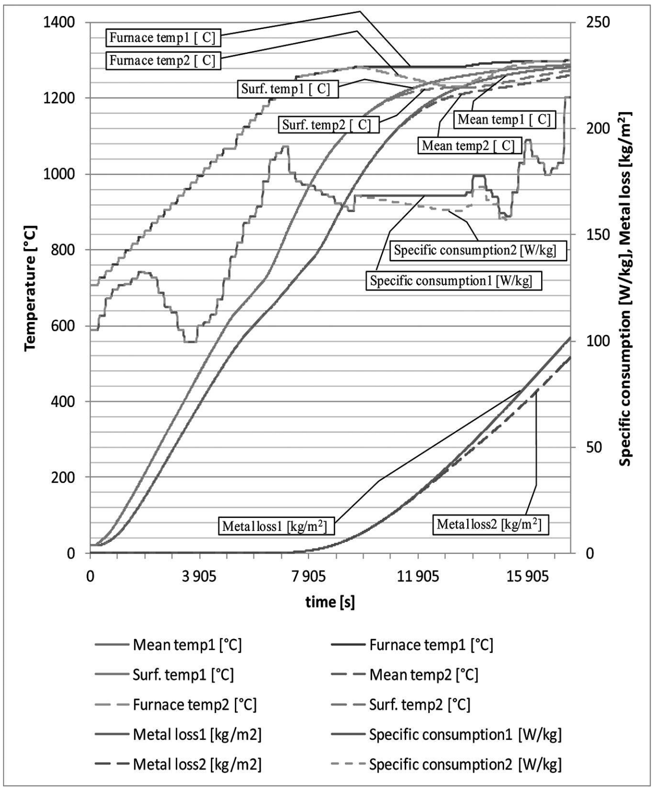

Fig. 1. The simulation results of heating – the time course of the monitored quantities

The simulation results

The simulation results without correction of the temperature in each zone furnace as with the correction of heating to optimize it can be seen in Figures 3. It is complicated to correct mean temperature and it is only possible through the adjustment of the surface temperature.

The simulation results without correction:

The surface temperature and the mean temperature of the heated material during heating since the downtime till pulling out from the furnace are too high (Mean temp = 1283°C, Surf. temp = 1289°C).

This leads to an increase in the metal loss during the heating compared to the standard heating without downtime (101.5 kg/m^2).

It leads to increasing of the energy needs associated with prolonged heating compared to the standard heating (2724.813 kWs/kg).

The simulation results with correction:

The surface temperature and the mean temperature of the heated material does not rise so sharply since the moment of downtime till pulling out of the oven already during the heating and in the time of discharging these temperatures are

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comparable to a standard heating without downtime (Mean temp = 1260°C, Surf. temp = 1273°C).

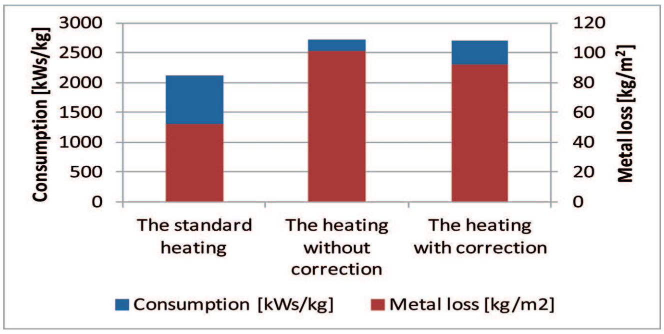

Fig. 2. The simulation results of heating – the economic indicators

This leads to a reduction metal losses during heating compared to the heating with downtime and without a correction (92.1 kg/m^2 which is about 10%) and there is slight reduction in energy needs of the heating compared to the heating with downtime and without correction (the decrease is down to 2701.488 kWs/kg, what means about 1% of energy savings).

5. Summary

The aim of the heating process optimizing using the set point corrections of control variables of control loops of each zone of the reheating furnace is to stabilize the parameters of heated material at the furnace outlet while minimizing energy and material demands of heating.

For creating fast and simple models for self-optimization artificial intelligence can also be successfully applied, such as neural networks and principles of evolutionary and genetic algorithms.

Two simulations were performed to compare this with the heating without downtime. The both simulations with downtime show an increasing of a surface and a mean temperature of the heated material when leaving the furnace. The surface temperature with the correction of heating was much closer to the case without delay. Also, the mean temperature during the correction of heating close the case without delay, but this temperature can only indirectly affect by changes in a surface temperature of the heated material.

The consumption increased and also the metal loss was higher when the downtime when correcting heating lower values have been reported compared to the case without correction. Even if there consumption and metal loss were not percentage too important for energy and material demands of production significant decreases in financial savings would be reached.

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