ABSTRACT

This research paper examines issues of selecting energy-saving conditions of strip heating in strand-type tower furnaces in view of the expected fuel costs and the share of the substandard products. The preservation of the strip standard speed of movement through the furnace depending on the sizes range is aimed at. Some of the existing concepts of the energy-saving control refer to shorter periods of keeping the metal at a higher temperature level. However, a significant part of the energy cost is associated with the compensation of the external heat losses of the furnace lining which depend on the maintained temperature. Thus, a complex of mathematical heat-engineering models of the furnace and the heated metal conditions is advanced in a search for energy-saving modes. Data on a connection between the external heat losses of the furnace and the furnace cavity temperature is obtained in the course of the models adaptation to the conditions of Magnitogorsk Iron and Steel Works. It is demonstrated that the level of the fuel economy achieved is related to the share of the substandard products. The parameters of this relationship are defined on the basis of information concerning the steel strip temperature at the furnace outlet. The limits of variation of the level of the fuel economy achieved are established on the ground of the indeterminacy of the parameter identification results referring to the thermal interaction between the furnace cavity zones.

Keywords: heating model, steel strip, galvanization, adaptation, defective products.

INTRODUCTION

Strand-type furnaces are widely used to resolve steel strip thermal processing tasks prior to galvanization. The galvanized strip has a wide range of applications. For example, the products of the Continuous Hot-dip Galvanizing Units (CHDGU) of Magnitogorsk Iron and Steel Works (MISW) are in demand in construction and automotive industries. The purpose of the thermal processing is to perform recrystallization annealing of the metal strip in accordance with the required temperature conditions. The failure to comply with the required temperature conditions increases the chance of compromising the galvanized strip. The analysis of the process information of CHDGU No. 1 of MISW [1, 2] shows that, as a whole, a temporary decrease of the strip temperature below 700°C occurs at the heating section outlet for 49% of the defective coils and 23% of the non-defective coils.

CHDGU No. 1 of MISW uses a strand-type tower furnace for the thermal processing. The temperature of the strip surface is regulated at the furnace outlet by an optical pyrometer. The furnace cavity is divided into seven zones. The geometrical positioning of the zones in the furnace cavity is rather complex. The strip repeatedly enters the same zones while moving through the heating section (Fig. 1). The strip heating control system maintains the required temperature in each zone. Fig. 2 shows the average (one-year) temperatures in the zones and the average scheme of the fuel distribution among the zones for a standard range of strip sizes (a thickness of 0.00046 m; a width of 1.27 m) with a strip movement speed of 180 m/min. The strip average temperature at the furnace outlet amounts to 718.7°C, while the total average fuel consumption per furnace equals 1,068.93 m³/h.
One of the ways of increasing the unit operating efficiency refers to bringing the fuel consumption to minimum values while keeping constant the predicted share of the defective products.

A significant number of articles is dedicated to the metal heating control in through-type and strand-type furnaces [3 - 8]. Two significantly different trends may be distinguished after their examination.

The first trend is outlined in refs. [3 - 7]. It refers to the application of a furnace temperature control to provide
minimum metal heating strictly at the moment of the metal release from the furnace. The authors underline that the implementation of this measure can result in 7% - 8% fuel economy. It should be noted that the metal temperature control directly in the cavity of the heating furnaces [9, 10] is not widespread. The process planners set time buffers for guaranteed heating, decreasing thus the production efficiency. The production efficiency can be kept if a balance between the fuel economy and the probability of strip defect occurrence is maintained.

The second trend is related to finding rational schemes for a fuel load distribution among the unit zones to minimize the external heat losses. Ref. [8] shows the presence of non-linearly increasing dependences of the external heat losses on the temperature in the cavity of a continuous furnace. An unequal distribution of the external heat losses is identified over the unit length and width at similar cavity temperatures during the analysis of block 5000 of MISW heating furnaces. This suggests the presence of rational schemes of a fuel load distribution defined by the ratio between the maintained temperatures in the different zones of the furnace. The results obtained [8] show that, upon decrease of the heating furnaces production efficiency to 50% of the design capacity (which is a common production situation), the heat balance sheet connected with the furnace external heat losses determined by the lining used represents the defining characteristic and significantly exceeds the heat inputs required for the metal heating. As shown in ref. [8], the application of efficient heating conditions may decrease the external heat losses by 2% - 3%.

The determination of these conditions for strand-type tower furnaces is an interesting task. As for CHDGUI No. 1 of MISW, this process is rather difficult due to the complex geometry of the zones. A complex of mathematical models providing a comprehensive assessment of the heat distribution in each zone of the furnace is required to resolve the task.

**A complex of models referring to the furnace heat-engineering conditions**

An issue of identifying the external heat losses from the CHDGUI No. 1 lining with the use of the process data array accumulated over a significant period of time is examined in ref. [11]. It is proposed to resolve it by simulating the heating and the cooling processes in the furnace cavity during the furnace start-up and stoppage for a repair. The metal is not moved through the furnace during the periods indicated above.

Two basic parameters for each zone (a thermal capacitance and external heat losses) are determined upon identification of the heat-engineering characteristics of the furnace on the basis of the available data. The thermal capacitance is presented as constant $C_z$, individual for each zone, in view of the rather high stability of the specific thermal capacitance of the refractories within the temperature range up to 800°C ($\pm 10\%$).

The external heat losses of each zone are presented in the following form to minimize the number of unknown terms:

$$Q_{z1} = a_z \cdot t^k \cdot \Delta \tau$$  \hspace{1cm} (1)

where $t$ is the furnace cavity temperature, $\Delta \tau$ is the time interval, while $a_z$ and $k$ are the target coefficients.

Coefficients $C_z$ and $q_z$ are selected through a minimization of the deviation of the furnace cavity heating and cooling simulation results in respect to the experimental data in the course of calculating the zone temperature, $t_z$:

$$t_z (\tau) = t_z (\tau - \Delta \tau) + \frac{Q_{zg} - Q_{zfg}}{C_z}.$$  \hspace{1cm} (2)

$Q_{zg}$ and $Q_{zfg}$ refer to the heat provided by burning the natural gas supplied to the zone radiant pipes, and the heat of the flue gases after the recovery process, correspondingly, while $t_{ze}$ is the experimental data for the zone temperature.

The comparison of the simulation errors shows that the best results in respect to the simulation accuracy are achieved at $k = 2$, therefore, it is expedient to represent the dependency of heat losses on temperature in the form of a parabolic curve. Fig. 3 shows as an example some of the experimental data and the simulation results for an individual zone referring to heating and cooling periods (the data discreteness is 5 times lower for the cooling periods). It is evident that a rather high accuracy of the thermal processes description can be achieved on the ground of a rather simple model (2).

Fig. 4 shows the results referring to the determination of the thermal capacitance of the furnace zones and the temperature dependence of the external heat losses. It is clearly seen that the external heat losses of the zones
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The results obtained for $a_z$ values may be used in the course of optimization tasks execution. Upon obtaining the results, the sets corresponding to abnormal periods, where the produced model provided significant deviations, are excluded from adjusting the data in Fig. 4. The examination of the factors determining the deviations based on the thermal balances in case of standard metal products obtained shows that the level of the heat losses changes significantly within a year (Fig. 5). The peculiarities of the heat losses changes over the time are similar for zones No. 2, 4, 6, 7.

The optimization, unlike the adaptation procedure, implies a variation of the fuel consumption in the different zones and calculation of the independent heat balance sheets using a model with no linkage to the process data. The purpose of the zones fuel consumptions calculation is to define the established temperatures in the zones. To this end, the minimization of the imbalance criterion $K_1$ is performed using the equation:

$$K_1 = \sum_{i=1}^{n} \left( Q_{rg}(i) - Q_{rg}(i) - Q_{int}(i) - Q_{str}(i) \right)^2,$$

where $n$ is the number of zones, which is equal to 7, $i$ is the zone number, $Q_{rg}(i)$ stands for the heat inputs per strip in zone $i$, while $Q_{int}(i)$ is the heat transmitted due to the inter-zone heat exchange.
The adaptation of a strip annealing model requires to calculate $Q_{\text{str}} (i)$, while $Q_{\text{zfg}} (i)$ and $Q_{\text{int}} (i)$ have to be defined to evaluate $K_1$. The static dependencies of the flue gas temperature after recovery of zone $t_{zfg} (i)$ on the furnace cavity temperature $t_z (i)$ and each zone fuel consumption $V_f (i)$ are used to calculate $Q_{\text{zfg}} (i)$.

Fig. 6 illustrates the dependence $(t_{zfg} (i)) = f (t_z (i))$. The consideration of $V_f (i)$ impact is performed by minimizing the regression remainders $(t_{zfg} (i)) = f (t_z (i))$.

A solution of the issue concerning the identification of the inter-zone heat exchange parameters is proposed in ref. [11]. Data on standard operating conditions of the furnace with manual (operator-regulated) fuel consumption control is used to identify the thermal interaction parameters between the zones. Such conditions are rare for a unit. About forty of such operation periods in case the strip parameters, the fuel and the air consumptions of all zones, except one, are stable, are found in the database of a two years period. However, one-time steep fuel consumption change in one of the zones is made by the operator. An example of such dynamics of zones fuel consumption change is given in Fig. 7 (a). It is evident that the operator changes the fuel consumption in zone 6 at a definite point of time. It leads to a temperature change in the adjacent zones 4 and 7 in relation to the predicted change dynamics. The prediction is made on the basis of a first-order inertia link.

The following simplified model describes the temperature change dynamics in an individual zone after perturbation:

$$t_z (\tau) = t_z (\tau_0) + \frac{1}{C_z} \int_{\tau_0}^{\tau} \left( q_{\text{zfg}} - q_{\text{st}} - q_{\text{str}} + q_{\text{int}} - q_{\text{sm}} \right) d\tau \quad (4)$$

where $\tau_0$ is the moment of the fuel consumption change.

It can be assumed, on the ground of Eq. (4), that $q_{\text{zfg}} = q_{\text{zfg}} - q_{\text{st}} - q_{\text{str}} - q_{\text{sm}} = \text{const}$ for zone 4 located upstream of zones 6 and 7 in the strip movement direction. Thus, one can derive that:

$$t_4 (\tau) = t_4 (\tau_0) + \frac{\lambda_{6,4}}{C_z} \int_{\tau_0}^{\tau} \left( t_6 (\tau) - t_4 (\tau) \right) d\tau + \frac{\tau - \tau_0}{C_z} q_6, \quad (5)$$

accepting that the thermal current between the zones is proportional to the temperatures fluctuations. $\lambda$ in Eq. 5 stands for the target parameter characterizing the heat exchange between the zones.

Eq. (5) contains two unknown terms: $\lambda_{6,4}$ and $q_6$. Let us consider the system of two Eqs. (5) aiming to define $\lambda_{6,4}$ for the actual and the predicted (as per perturbation data) temperature change (Fig. 7 (b)). The result obtained will be:

$$\lambda_{6,4} (\tau) = \frac{C_z \left( t_{4p} (\tau) - t_{4a} (\tau) \right)}{\int_{\tau_0}^{\tau} \left( t_{4p} (\tau) - t_{4a} (\tau) \right) d\tau - \int_{\tau_0}^{\tau} \left( t_{6a} (\tau) - t_{4a} (\tau) \right) d\tau}, \quad (6)$$

where “p” and “a” indices refer to the predicted and the
actual values, correspondingly.

It is also required to consider the variability of the thermal current flowing to the strip in order to define $\lambda_{6.7}$, characterizing the heat exchange between zones 6 and 7. The adapted strip heating model proposed in ref. [1] is used to calculate this coefficient. The time dependencies $\lambda_{6.4}$ and $\lambda_{6.7}$ obtained show a rather high degree of constancy of these coefficients. The average values of $\lambda_{6.4}$ and $\lambda_{6.7}$ in the example considered amount to 36 kJ/(°C min) and 250 kJ/(°C min), respectively. However, the replication of the reviewed calculations referring to the various experimental data shows a significant variability of $\lambda$ upon change of the thermal current distribution direction. This is due to the various distances between the temperature control points and the zone borders. This peculiarity shall be considered in resolving the optimization tasks. The average parameter of the inter-seasonal interaction $\lambda$ is assumed indefinite within the variation range of 10 kJ/(°C min) – 290 kJ/(°C min).

**An optimization of the temperature conditions**

The optimization purpose is to find the minimum total fuel consumption for the heating section zones at the set parameters of the strip thickness, width, movement speed, as well as the temperature at the heating section outlet.

The methods of solution of similar tasks on the basis of mathematical models which are relative to the conditions of the continuous heating furnaces are examined in refs. [12,13]. A search of the optimal billet heating trajectory is performed in ref. [12] by the simplex method. Ref. [13] sets a task of an optimal heating control of a massive steel billet in a heating furnace of a roll mill. It demonstrates its solution using the principle of the maximum. A disadvantage of these methods is in the high degree of the obtained result dependence on the initial conditions. Therefore, an approach based on the combination of the Monte Carlo and the Newton methods is used in resolving the task. The search for the optimal solution is performed in three stages.

The first one includes a random generation of a set of thousands of values referring to the fuel consumption of the zones, $V_f(i)$, and the temperatures established there, $t_f(i)$. The generated $t_f(i)$ and $V_f(i)$ values are measured using the Newton method with a minimization of the criterion $K_{\text{opt}}$ calculated on the basis of the simulation results:

$$K_{\text{opt}} = a_1 K_1 + a_2 K_2 + a_3 K_3, \quad K_2 = (t_{\text{set}} - t_{\text{sp}})^2;$$

$$K_3 = \sum_{i=1}^n V_f(i),$$

(7)

where $a_1$, $a_2$, $a_3$ define the components contribution to the criterion value, while $t_{\text{sp}}$ is the set point.

The minimization of $K_{\text{opt}}$ implies a simultaneous
minimization in the course of finding of an imbalance of zones $K_1$ (3), a strip temperature deviation at the furnace outlet from the required value - $K_2$, as well as a minimization of the total fuel consumption per furnace - $K_3$. It is possible to influence the criterion component values obtained during the search by varying the coefficients $a_1, a_2, a_3$. A multitude of conditions for which the values of the zones fuel consumption are specified by $K_1$ minimization is obtained as a result of the first stage. The optimal conditions refer to the minimum value of $K_3$.

The rational conditions ascribed to different average values of the inter-zone interaction parameter $\lambda$ are calculated for the mentioned standard range of sizes using the method considered above. The optimal temperature schemes for $\lambda$ values of 10 kJ/(°С×min) - 100 kJ/(°С×min) are similar for the zones. Fig. 8 illustrates the optimal conditions for $\lambda = 100$ kJ/(°C×min). The total fuel consumption amounts to $1,032.68$ m$^3$/h on the ground of the process database. It provides 3.38% economy of the average value. A more uniform distribution of the fuel consumption among the zones is obtained under the optimal conditions found when compared to the existing one. The results obtained correspond to those found on the basis of the statistical neuron network models in ref. [14].

The scheme of the zone temperatures at $\lambda = 290$ kJ/(°C×min) in Fig. 8 (a) cannot be practically implemented due to the limited burners capacity and which is why the optimization effect decreases. The dependence given in Fig. 9 shows a significant effect of $\lambda$ on the fuel economy achieved but it has not been considered in many studies [4 - 7].

Studying the interconnection between the share of the substandard products and the fuel economy achieved.
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is also of interest. It is obvious that the required strip temperature at the heating section outlet accepted in the calculations exceeds the required minimum in terms of the recrystallization processes completion. This temperature decrease ensures a fuel economy but it also leads to an increase of the probability of obtaining defective products due to a possible deviation of the actual conditions in respect to the design one.

The change of the fuel economy level at \( \lambda = 100 \text{ kJ/(C min)} \) depends on the required strip temperature at the heating section outlet. It is illustrated by Fig. 9 (b).

Fig. 10 shows the density of distribution of the defective \( f_d(t_{str}) \) and non-defective \( f_n(t_{str}) \) at the minimum strip temperature (in the course of the processing) at the heating section outlet for the standard range of sizes. The data referring to \( N_d = 677 \) defective coils and \( N_n = 8,594 \) non-defective coils is studied aiming to obtain \( f_d(t_{w}) \) and \( f_n(t_{w}) \). The distributions found are close to those of the normal law.

The approximations of the density distribution functions in Fig. 10 provide the calculation of the probability of the substandard products occurrence \( P_d(t_{str}) \) for various strip temperature values at the furnace outlet:

\[
P_d(t_{str}) = \frac{f_d(t_{str}) \cdot N_d}{f_d(t_{str}) \cdot N_d + f_n(t_{str}) \cdot N_n},
\]

The function \( P_d(t_{w}) \) can be approximated using the following equation (Fig. 11):

\[
P_d(t_{w}) = \left( 1 - 0.0405 \right) \left( \frac{1}{2} \cdot \frac{1}{2} \tanh \left( \frac{t_{w}}{675.63} \cdot 0.09125 \right) \right) + 0.0405.
\]

Eq. (9) can be used in calculations for \( t_{str} > 720^\circ\text{C}, \) where the small volume of the data referring to defective coils prevents the application of Eq. (8).

Information on the unpredictable changes distribution in respect to the simulation error of the strip temperature at the furnace outlet, related to conditions changes, is required in case of using Eq. (9) for practical calculations. An example of such errors for the unit considered is given in Fig. 12 (a). Fig. 12 (b) shows the error distribution and its approximation by a normal distribution \( f_E = N(a,\sigma) \) and parameters \( a = -2 \) and \( \sigma = 8.66. \)
The results given in Fig. 11 and 12 allow assessing the interdependence between the share of the substandard products and the fuel economy. The following equation is used to calculate the share of the substandard products $\eta_d$ at a set strip temperature point $t_p$ at the furnace outlet:

$$\eta_d = \int_{-\infty}^{\infty} P_d(t_{\text{str}}) f_E(t_{\text{str}} - t_{sp}) dt_{\text{str}}.$$ \hspace{1cm} (10)

Fig. 13 shows the dependences of the share of the substandard products on the set strip temperature at the heating section outlet (a) and on the fuel economy (b): 1 - $\sigma = 8.66$; 2 - $\sigma = 4.33$.

The results indicate a significant nonlinearity of the connection between the fuel economy and the share of the substandard products, $\eta_d$. The fuel economy level achieved amounts to approximately 4% - 6% depending on the inter-zone interaction parameter, $\lambda$, in case 6%-7% share of defective products is maintained.

**CONCLUSIONS**

The results obtained are indicative of the principal possibility to resolve the control optimization task of strip heating conditions considering achievable fuel economy and a substandard products share. The paper describes a static solution of the task oriented towards the standard range of sizes, and average heat-engineering characteristics of the furnace and metal properties.

Self-adjustment systems of the furnace and metal annealing mathematical heat-engineering models are required to increase the fuel economy at the expense of reduction of $\sigma$ in the distribution $f_E = N(\sigma, \lambda)$. The issues of such systems creation are related to the fact that the efficiency evaluations, such as $A_1$ and $A_2$, are difficult to use as monitoring parameters under varying heat-exchange conditions. At the same time, the parameters that can be used for self-adjustment, for example the current deviation of the actual temperature at the furnace outlet in respect to the model calculations, are indirect in
relation to the evaluation parameters, and the adjustment on the ground of these parameters does not guarantee an achievement of extreme values by efficiency criteria.

REFERENCES