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THE INFLUENCE OF RADIATION MODEL ON THE DISTRIBUTION OF HEAT FLUX IN THE PUSHER FURNACE

WPŁYW MODELU PROMIENIOWANIA NA ROZKŁAD GĘSTOŚCI STRUMIENIA CIEPŁA W PIECU PRZEPYCHOWYM

A three dimensional numerical model of the heat exchange during a charge heating process in a pusher furnace, using the finite element method, was used in this study. The radiative heat exchange in the furnace chamber was carried out based on two methods: the zone method and the method of basing on the average configuration ratio. In the zone method the flux of radiation energy reaching the surface of the heated charge was determined by performing calculations of brightness in a multi-surface closed system which is the pusher furnace chamber filled with an emitting-absorbing medium. In the second case an average configuration ratio was used by setting the radiation energy flux through linking the walls temperature with the furnace atmosphere temperature.

Keywords: radiation heat transfer, pusher furnace, charge heating

W pracy wykorzystano trójwymiarowy model numeryczny wymiany ciepła w czasie nagrzewania wsadu w piecu przepychowym przy zastosowaniu metody elementów skończonych. Radiacyjną wymianę ciepła w komorze pieca realizowano w oparciu o dwie metody: metodę strefową oraz w oparciu o średni współczynnik konfiguracji. W metodzie strefowej strumień energii radiacyjnej docierającej do powierzchni nagrzewanego wsadu wyznaczano prowadząc obliczenia jasności w wielo-powierzchniowym układzie zamkniętym jakim jest komora pieca przepychowego wypełnionego ośrodkiem emitująco-pochłaniającym. W drugim przypadku wykorzystano średni współczynnik konfiguracji wyznaczając strumień energii radiacyjnej poprzez powiązanie temperatury ścian z temperaturą atmosfery pieca.

1. Introduction

The heat furnaces used for heating the charge are characterized by relatively high energy consumption, and in the case of heating with gas, they simultaneously emit pollutants deriving from the combustion process. In the general economic balance of the steelmaking process those are the items that constitute a relatively heavy load. Creating a procedure allowing conducting a full analysis of this type devices operation has been the subject of interest of many researchers in recent years [1, 2]. The analysis to be carried out using conventional techniques, basing on the experience is very difficult due to, e.g., its high costs. Useful in this case are the computer technologies, which in many fields of science and technology are of inestimable help ad they allow a parallel study of the effects of various factors on a given process, so that the result is usually achieved more quickly, plus at a much lower cost.

Numerical modelling of the heat exchange in the heating furnaces' chamber, used to heat the steel charge, causes a lot of difficulties, especially in the case of continuous furnaces of an uninterrupted operation. The value of the heat flux reaching the surface of the heated charge depends, i.a., on the type and geometry of the furnace, and type and arrangement of burners, type of fuel or thermo-physical properties of the heated material. Almost 90% of the value of this flux is dominated by a radiative heat transfer [3], the remainder being convection and conduction mechanisms and the heat conductivity from the furnace heart side.

The numerical models that are available in the bibliography can be classified in two groups. The first of them includes solutions that base on simultaneous solving of Navier-Stokes equations describing the motion of combustion gases and equations based on the principle of preservation of energy used to describe the heat exchange in the furnace chamber [4-8]. This approach

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theoretically allows creating very accurate models; however, they are characterized by a significant computation time and high sensitivity to the input data set, due to its wide range. The second group solutions are focused on the radiation heat exchange in the operating chamber of the furnace and the heat conductivity in the heated charge [9-15]. With this approach a significant reduction in computation time is achieved without any significant impact on the quality of the end result.

Most difficulties in the mathematical description of radiative heat exchange are caused by determining of the radiation energy fluxes [16]. Those fluxes are derived from all the objects that are present in the system, and then due to a direct irradiation or after previous reflections or weakness in the absorbing media, they are absorbed by the analyzed component. Method of clarity and configuration ratios is frequently used, due to its simplicity and quick time of calculations needed to determine the radiation energy fluxes in industrial furnaces. It involves the use of surface component brightness, defined as a sum of the component emission, reflected radiation, and dimensionless parameter called ratio of configuration against modelling of a radiative energy flux that leaves the surface component. The equally effective method of determining the radiation energy flux is the approach taken from the study [17] consisting in linking the temperature of the wall with the furnace atmosphere temperature.

Calculation of the influence of the used model of radiation on the distribution of the heat flux density over the length of a pusher furnace was based on two methods: the zone method and the method based on an average configuration ratio. In the zone method the flux of radiation energy reaching the surface of the heated charge was determined by performing calculations of brightness in a multi-surface closed system which is the pusher furnace chamber filled with an emitting-absorbing medium. In the second case an average configuration ratio was used by setting the radiation energy flux through linking the walls temperature with the furnace atmosphere temperature. To create a numerical model the finite components method was used.

2. The radiation heat transfer

Adoption of the zone model requires a division into zones and each zone should be additionally divided into isothermal surfaces. The division of the furnace into zones is schematically shown in Figure 1. Calculations of brightness in a multi-surface closed system which is the pusher furnace operating chamber filled with an emitting-absorbing medium gas, was performed for the gas mass treated as a not-grey body. Therefore, the equation for the brightness balance of each surface , is as follows:

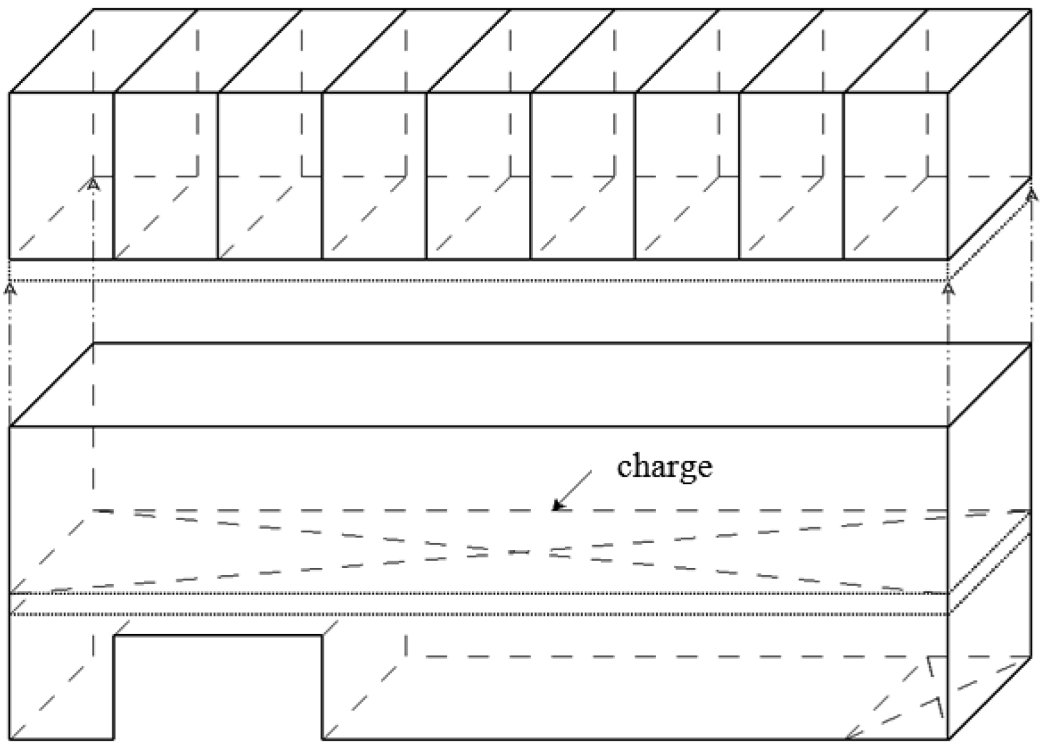

Fig. 1. Schematic for the furnace and the division of the top into isothermal surfaces

$$\dot{h}_i = \dot{e}_i + r_i\left(\dot{e}_{i,g} + \sum_{j=0}^{n}\dot{h}_j\phi_{ij}\tau_{ij}\right) \qquad (1)$$

$\dot{e}$ – radiation density, [W/m^2],
$\dot{h}$ – brightness density, [W/m^2],
r – reflectivity,
τ – transmissivity,
ϕ – configuration ratio,
g – refers to combustion gases,
i – refers to i-th isothermal surface (i = 1,. . . , N),
j – refers to j-th isothermal surface (j = 1,. . . , N).

Therefore, density of the heat flux $\dot{q}_i$ for the individual surfaces, may be determined by the following equation:

$$\dot{q}_i = \frac{\varepsilon_i}{r_i}\left(\dot{h} - \frac{\dot{e}_i}{\varepsilon_i}\right), \qquad (2)$$

The concept of determining the flux of radiation heat exchange, based on an average ratio of such a configuration, is shown, i.a., in the study [17]. Adopting the not-grey gas model, the ratio of heat absorption α_{gw} was determined based on the following formula:

$$\alpha_{gw} = \frac{5,67\varepsilon_{gw}}{t_g - t_w}\left[\frac{\varepsilon_g}{A_g}\left(\frac{t_g + 273}{100}\right)^4 - \left(\frac{t_w + 273}{100}\right)^4\right] \qquad (3)$$

where:
A_g – combustion gases absorbing capacity,
$\varepsilon_{gw} = \frac{1}{1/A_g + 1/\varepsilon_w - 1}$ – cross-emissivity of the combustion gases-charge configuration,
t_g, t_w – combustion gases and charge temperature, °C;
ε_w, ε_g – emissivity of charge and combustion gases.

The ratio of the heat absorption through the radiation from the furnace walls α_{gs} was determined by the following equation:

$$\alpha_{gs} = \frac{5,67\varepsilon_g}{t_g - t_s}\left[\left(\frac{t_g + 273}{100}\right)^4 - \left(\frac{t_s + 273}{100}\right)^4\right] \qquad (4)$$

where:
$t_s = t_g - 5,67\frac{1-\varphi_{12}}{\alpha_{gs}}\frac{\varepsilon_s\varepsilon_w}{\varepsilon_s + \varphi_{12}\varepsilon_w(1-\varepsilon_s)}\left[\left(\frac{t_s+273}{100}\right)^4 - \left(\frac{t_w+273}{100}\right)^4\right]$ – furnace walls surface temperature, °C;
$\varphi_{12} = \frac{F_w}{F_s}$ – average rate of configuration,
F_w, F_s – charge and furnace walls surface, m^2.

Density of the heat flux being transferred to the surface of the charge is determined by the following equation:

$$q_i = \left(\alpha_{gw} + \alpha_{gs}\right) \bullet \left(t_g - t_w\right)$$

The method of determining the emissivity, reflectance, absorbing capacity and transmittance in the analyzed models was adopted in accordance with the equations contained in the study [18].

3. Numerical calculations

The numerical simulations were performed for heating of both sides of a flat charge with the following dimensions 220×1500×2880 mm, made of S355J2G3 steel in a 30-meter long pusher furnace. The initial charge temperature was 20°C. The charge presence time in the furnace was equal to 254 minutes. Thermal characteristics of the material of which the charge was made, were taken from [17].

In order to determine the impact of the adopted model of radiating properties of the combustion gases on the distribution of the density of heat flux reaching the surface of the charge, the calculations were performed taking as a comparative criterion the temperature distribution at a point located in the middle of the width of the charge at a depth of about 12 cm from the upper surface. In addition, for verification of the calculations obtained, the obtained temperature distribution was compared to the results of measurements regarding the real object. Figure No. 2 shows an example of comparison of the simulation calculations to the measurements results in the case of a model based on an average configuration ratio. According to the assumptions, the second variant is of a similar nature. In the analyzed computational variants some calculation difficulties are caused by an unusual performing of the heating process on a real object, what is indicated by the measurement curve inflection. During this period, technological problems resulted in a significant prolongation of the time between the successive transfers of the charge. For the presented variant a selected temperature field in the cross-section of the heated charge in each zone of the furnace is shown in Figure No. 3.

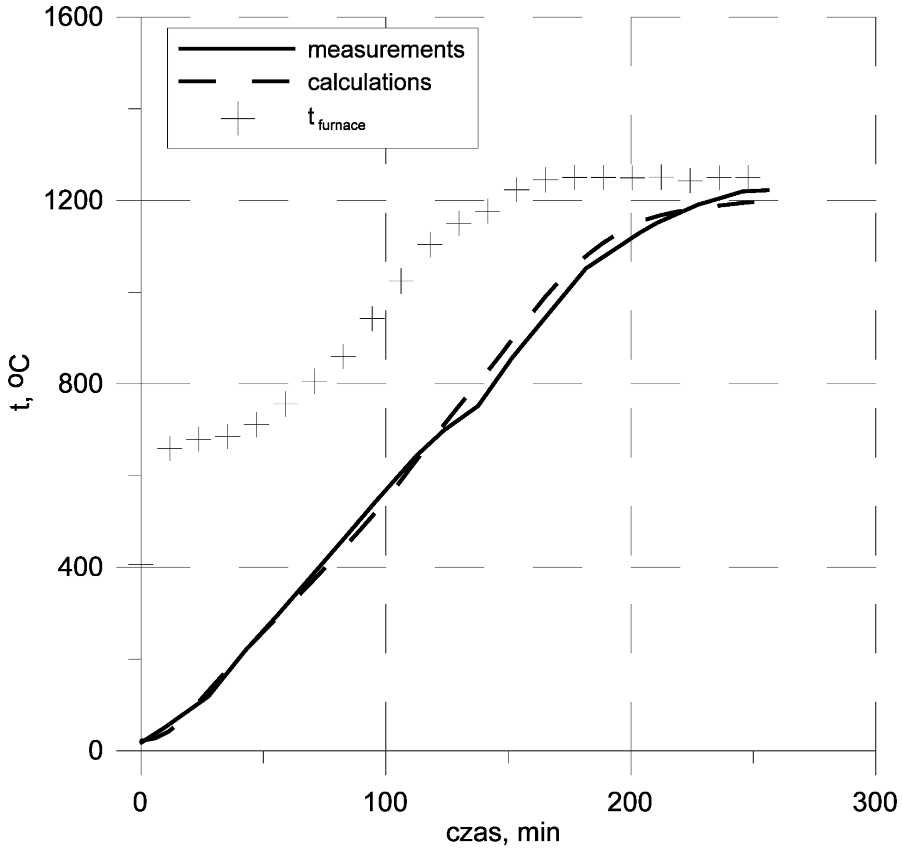

Fig. 2. Verification of the heat transfer model based on data from measurements – the method based on the average view factor

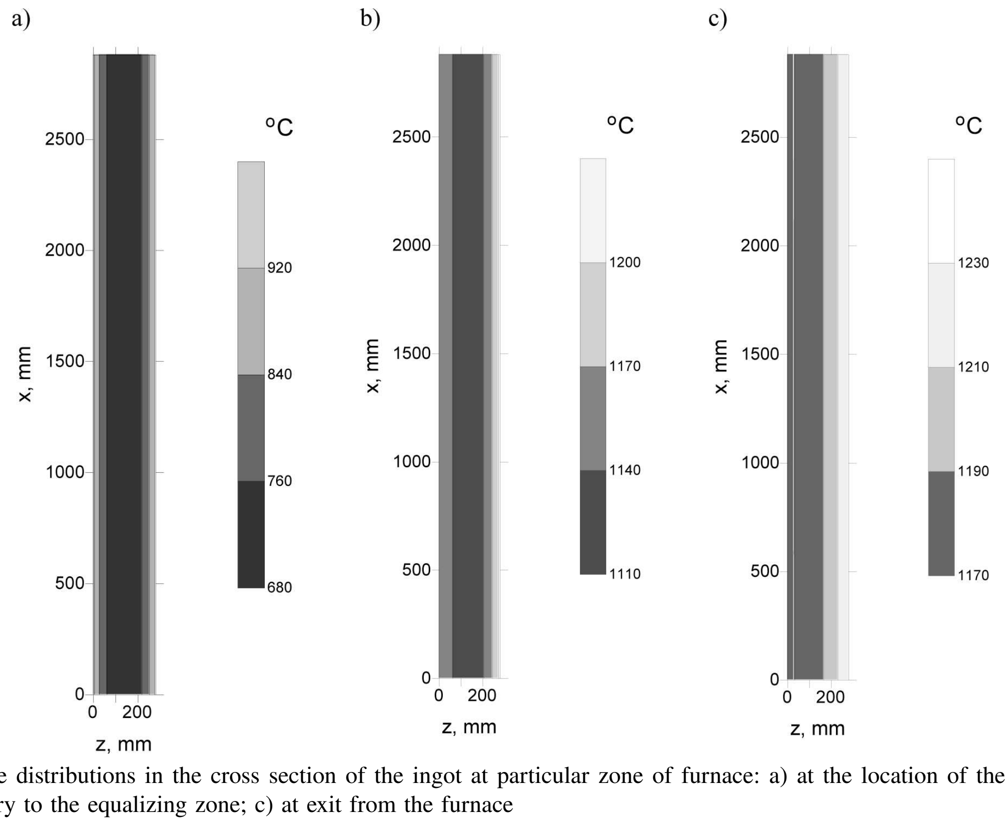

Fig. 3. Temperature distributions in the cross section of the ingot at particular zone of furnace: a) at the location of the maximum of the heat flux; b) at entry to the equalizing zone; c) at exit from the furnace

In the case of a charge absorbing the maximum values of the heat flux from the lower and upper surface the temperature difference in the cross section of a constant ingot reaches 300K (Fig. 3a). The lowest temperature occurs in the axis of the charge (approx. 680°C), the highest one is on the bottom and the upper side of the charge (about 940°C). The dominant temperature range in the cross-section of the charge is equal to 680÷760°C. The temperature difference in the charge fed to the fixed furnace heart is above 90K (Fig. 3b). The highest temperature in this case occurs in the upper surface and the lowest in the axis of the charge. They were respectively equal to 1208 and 1119°C. The dominant temperature range in the cross-section of the heated charge is equal to 1110÷1140°C. At the output of the furnace, the temperature difference in the charge cross-section is approx. 60K (Fig. 3c). This is a value slightly in excess of the limit values of temperature differences for the hot working process. So large difference in temperature in the charge cross-section may result from the heating technology performed in an unusual way during the test. Not very desirable feature is also the occurring asymmetry of the temperature distribution. In the lower surface it was equal to 1170°C, in the charge axis it was equal to 1190°C and in the upper surface to 1228°C. The temperature range of 1170÷1190°C occurred on the lower side of the charge and reached nearly the axis.

For the temperature distribution resulting during the charge heating the calculations were performed by adopting two analyzed models of the radiative heat transmission. Not-grey gas model was adopted, also known in the bibliography as the grey – not-grey gas model. The following figures show the distribution of the density of heat flux absorbed by the charge in the lower surface (Fig. 4) and the upper surface of the heated charge (Fig. 5).

In the case of the analyzed models of the radiative heat exchange the following heat flux density values, significantly different from each other, were obtained. Also the nature of the curves of distribution of the density of heat flux absorbed by the charge varies. In the case of the zone model the density of heat flux absorbed by the charge on the length of the pusher furnace indicates a maximum value between the 100^{th} and 180^{th} minute of the presence of the charge in the furnace heating zone (Figs. 4, 5). Significantly much lower heat flux density values can be observed in the preheating and compensation zones. The zero heat flux density values of the heat absorbed by the lower surface of the ingot after the 194^{th} minute of the heating process, result from the geometry of the furnace. During this time, the charge moves over the fixed heart of the furnace to equalize the temperature in the cross-section of the charge.

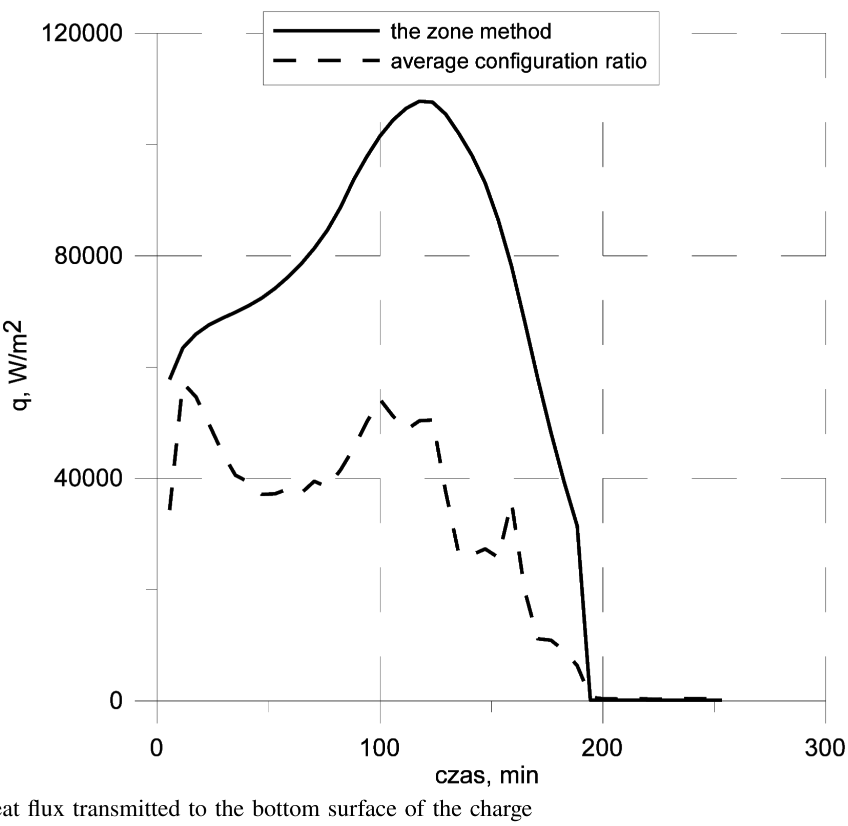

Fig. 4. Variations of the heat flux transmitted to the bottom surface of the charge

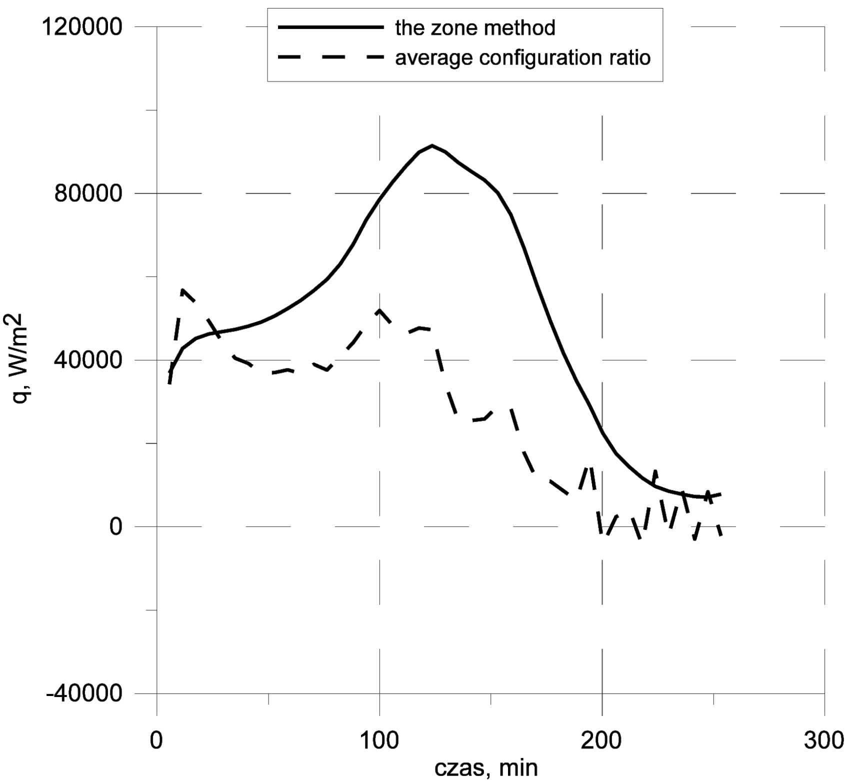

Fig. 5. Variations of the heat flux transmitted to the top surface of the charge

The significantly lower heat flux densities were obtained in the case of numerical simulations using an average coefficient of configuration. The maximum value of the density of heat flux absorbed by the lower and the upper surface does not exceed 60 kW/m^2. Such values were recorded in both preheating and heating zone of the furnace. In the case of the preheating zone, the maximum value may be due to a large temperature difference between the charge surface and the furnace atmosphere. In turn, the maximum heat flux density value in the heating zone occurs as in the case of the zone model, providing that it absorbs almost 2 times lower values. In the final heating period in the preheating zone, in the case of the upper surface, a decline in the value of the heat flux density down to negative values of approx 4.5 kW/m^2 were observed. In this case, the reason may also be the temperature difference between the upper surface and the furnace atmosphere which characterizes the charge after leaving the heating zone.

4. Conclusions

This study presents the results of calculations of the distribution of heat flux density on the length of a pusher furnace, obtained using two different models of radiation. The radiation models widely regarded as highly effective, especially in terms of rapidity of the calculations performed were adopted for a comparison. The time of calculation in the two computing variants did not exceed 3 hours. The calculations were performed using the Author's software and the finite components method. The maximum values of the density of heat flux absorbed by the charge was observed in the case of the zone model. Significantly lower range of the heat flux density value was obtained with the model based on an average configuration ratio. This may be due to not considering the nature of the configuration ratio distribution on the length of the heating furnace, which was included in the zone model. In both analyzed models, the lowest heat flux density values were obtained in the equalization zone of the furnace, when the charge was moved on the constant furnace heart.

REFERENCES

[1] J.H. Jang, D.E. Lee, M.Y. Kim, H.G. Kim, Investigation of the slab heating characteristics in a reheating furnace with the formation and growth of scale on the slab surface. International Journal of Heat and Mass Transfer **53**, 4326-4332 (2010).

[2] M. Kieloch, Ł. Piechowicz, J. Boryca, A. Klos, Numerical analysis of correlation between heat consumption and the steel loss for scale in the charge

heating process. Archives of Metallurgy and Materials **55**, 3, 647-656 (2010).

[3] S.H. Han, S.W. Baek, S.H. Kang, C.Y. Kim, Numerical analysis of heating characteristics of a slab in a bench scale reheating furnace. International Journal of Heat and Mass Transfer **50**, 2019-2023 (2007).

[4] J.G. Kim, K.Y. Huh, I.T. Kim, Three-dimensional analysis of the walking-beamtype slab reheating furnace in hot strip mills, Numerical Heat Transfer A **38**, 589-609 (2000).

[5] J.G. Kim, K.Y. Huh, Prediction of transient slab temperature distribution in the reheating furnace of a walking-beam type for rolling of steel slabs, ISIJ International **40**, 1115-1123 (2000).

[6] C.-T. Hsieh, M.-J. Huang, S.-T. Lee, C.-H. Wang, Numerical modeling of a walking-beam-type slab reheating furnace: Numer. Heat Transfer A **53**, 966-981 (2008).

[7] M.-J. Huang, C.-T. Hsieh, S.-T. Lee, C.-H. Wang, A coupled numerical study of slab temperature and gas temperature in the walking-beam-type slab reheating furnace, Numerical Heat Transfer A **54**, 625-646 (2008).

[8] C.-T. Hsieh, M.-J. Huang, S.-T. Lee, C.-H. Wang, A numerical study of skid marks on the slabs in a walking-beam type slab reheating furnace, Numerical Heat Transfer A **57**, 1-17 (2010).

[9] Z. Li, P.V. Barr, J.K. Brimacombe, Computer simulation of the slab reheating furnace, Canadian Metallurgical Quarterly **27**, 187-196 (1998).

[10] J. Harish, P. Dutta, Heat transfer analysis of pusher type reheat furnace, Ironmaking & Steelmaking **32**, 151-158 (2005).

[11] B.Y. Yang, C.Y. Wu, C.J. Ho, T.-Y. Ho, A heat transfer model for skidmark formation on slab in a reheating furnace, Journal of Materials Processing and Manufacturing Science **3**, 277-295 (1995).

[12] M.Y. Kim, A Heat transfer model for the analysis of transient heating of the slab in a direct-fired walking beam type reheating furnace, International Journal of Heat and Mass Transfer **50**, 3740-3748 (2007).

[13] D. Lindholm, B. Leden, A finite element method for solution of the threedimensional time-dependent heat-conduction equation with application for heating of steels in reheating furnaces, Numerical Heat Transfer A **35**, 155-172 (1999).

[14] S.H. Han, S.W. Baek, M.Y. Kim, Transient radiative heating characteristics of slabs in a walking beam type reheating furnace. International Journal of Heat and Mass Transfer **52**, 1005-1011 (2009).

[15] J.H. Jang, D.E. Lee, C. Kim, M.Y. Kim, Prediction of furnace heat transfer and its influence on the steel slab heating and skidmark formation in a reheating furnace. ISIJ International **48**, 1325-1330 (2008).

[16] Z. Rudnicki, Modelowanie matematyczne radiacyjnego przepływu energii, Gliwice 2003.

[17] Z. Malinowski, Numeryczne modele w przeróbce plastycznej i wymianie ciepła. AGH Uczelniane Wydawnictwa Naukowo-Dydaktyczne, Kraków, 2005.

[18] R. Straka, A. Buczek, A. Gołdasz, M. Rywotycki, T. Telejko, Analiza porównawcza modeli promieniowania cieplnego w piecu przepychowym. Materiały XIV Sympozjum Wymiany Ciepła i Masy, 511-516, Szczecin 2010.

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