A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 60 2015 Issue 1
DOI: 10.1515/amm-2015-0033

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COMPARISON OF FOUR MODELS OF RADIATIVE HEAT TRANSFER BETWEEN FLAT SURFACE TO EVALUATE THE TEMPERATURE FIELD BASED ON EXAMPLE OF THE CONTINUOUS CASTING MOULD

PORÓWNANIE CZTERECH MODELI RADIACYJNEJ WYMIANY CIEPŁA POMIĘDZY POWIERZCHNIAMI PŁASKIMI NA POLE TEMPERATURY NA PRZYKŁADZIE KRYSTALIZATORA COS

The paper presents the results of research concerning the influence of radiative heat transfer on the strand and mould interface. The four models for determining the heat transfer boundary conditions within the primary cooling zone for the continuous casting process of steel have been presented. A cast slab – with dimensions of 1280×220 mm – has been analysed. Models describing the heat transfer by radiation have been specified and applied in the numerical calculations. The problem has been solved by applying the finite element method and the self-developed software. The simulation results, along with their analysis, have been presented. The developed models have been verified based on the data obtained from the measurements at the industrial facility.

Keywords: continuous casting of steel, heat transfer coefficient, numerical models

W pracy przedstawiono wyniki badań dotyczących wpływu radiacyjnej wymiany ciepła z zastosowaniem różnych modeli do wyznaczenia warunków brzegowych dla procesu ciągłego odlewania stali w obszarze strefy pierwotnego chłodzenia. Analizie poddano wlewek płaski o wymiarach 1280×220 mm. W obliczeniach wykorzystano wybrane zależności opisujące wymianę ciepła przez promieniowanie. Przedstawiono wyniki symulacji oraz ich analizę. Zaprezentowane modele zweryfikowano na podstawie przemysłowej bazy danych. Zadanie zostało rozwiązane metodą elementów skończonych z zastosowaniem autorskiego pakietu numerycznego.

1. Introduction

The continuous casting of steel is a prevailing method for obtaining semi-products. The numerical modelling of this process has been intensified in recent years. The modelling of continuous steel casting requires the application of mathematical models that allow the determination of the temperature field, as well as the thermal and mechanical stresses caused by the bending and unbending of the strand. The liquid steel movement due to mass forces and electromagnetic stirring should be taken into account. Modelling of the temperature distribution in the process of cast strand solidification has been analysed by several authors. The commercial software and own developed numerical formulations have been applied [1-14]. The correct implementation of the boundary conditions of heat transfer is an important factor in obtaining the correct computer simulation with the finite element method. The description of the heat transfer in the gap between the strand and mould follows from the models which were adopted and simplifications that were applied. The cast strand solidification is a complex process. Heat is transferred from the liquid steel through the solidifying layer and the gap to the mould, which is intensively cooled with water. Hot liquid metal reaching the mould through a submerged entry nozzle causes a movement of the liquid steel. The heat transfer between the strand and the mould is complex and difficult to describe. The all three modes of heat transfer: conduction, radiation and convection occur in this process [4]. The mould outer side is intensively cooled with water flowing through channels. The forced convection is the prevailing heat transfer mode. The heat transfer within the primary cooling area is the decisive factor when it comes to the correct and safe operation of the continuous casting machine. This is done by obtaining an adequate thickness of the solidified shell that ensures the required mechanical strength. The character of this process requires the heat to be removed very intensively to ensure that a shell with an adequate thickness, and thus with an adequate strength, is obtained. The basic parameter as regards the process described is the temperature field, which in turn provides the basis for determining other process factors such as the velocity field and stress fields and the thickness of the solidified layer [1,8,12].

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2. Heat transfer models

The temperature field of the solidifying strand is computed for the energy equation:

$$\frac{\partial T}{\partial \tau} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} = \frac{1}{\rho c}\left(\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right)\right) + \frac{q_v}{\varrho c} \tag{1}$$

where:
T – temperature, K
q_v – internal heat source, W
c – specific heat, J/(kg K)
ρ – density, kg/m^3
λ – heat transfer coefficient, W/(m K)
v_x, v_y, v_z – velocity field component, m/s
x, y, z – reference system coordinates, m

The method of solution to equation (1) has been presented in [6]. The solution to equation (1) gives the temperature field $T(x, y, z, \tau)$ in the strand. The solution should meet the boundary conditions at the strand surface. The boundary conditions are adopted as the heat flux at the strand surface in the mould q_{sm}:

$$q_{sm}(x, y, z, \tau) = h_{sm}(x, y, z, \tau)\,(T_s(x, y, z, \tau) - T_m(x, y, z, \tau)) \tag{2}$$

where:
h_{sm} – heat transfer coefficient, W/(m^2 K),
T_s – strand surface temperature, K,
T_m – mould inner surface temperature, K.

The solution of the strand cooling problem also requires the mould surface temperature to be ascertained. This is possible by determining the temperature field of the mould, which at the inner surface intercepts heat from the slab, and at the outer surface gives heat to the water cooling system. The mould temperature field was derived from the solution [6] to the heat conductivity equation:

$$\frac{\partial T}{\partial \tau} = \frac{\lambda}{\rho c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{3}$$

with the boundary condition at the inner surface determined by equation (2), and at the water-cooled outer surface by the equation:

$$q_w(x, y, z, \tau) = h_w(x, y, z, \tau)\,(T_{mw}(x, y, z, \tau) - T_w(x, y, z, \tau)) \tag{4}$$

where:
h_w – heat transfer coefficient, W/(m^2 K),
T_{mw} – mould outer surface temperature, K,
T_w – temperature of water within the channels, K.

The solution of the strand and mould temperature fields obtained with the finite element method can be found in the previous studies [4,6].

The investigations are focused on determining the impact of the radiative heat transfer on the overall heat transfer between the strand surface and the mould. Models describing the heat transfer within the primary cooling zone of the continuous casting strand were implemented into the developed computer program. Two mechanisms of heat transfer were considered – radiation and conduction. In the first model (W1), a constant value of the heat transfer coefficient h_{sm1} = 2000W/(m^{2}K) is assumed. The model describes the condition of a good contact of the cooled strand with the wall of the mould without the presence of a mould powder and other types of resistance to heat transfer. This is the case with the maximum heat transfer coefficient. In the second model (W2), the heat is transferred only by radiation h_{r2}, and the value of the heat transfer coefficient is determined from the equation [15]:

$$h_{sm2}(x, y, z, \tau) = h_{r2} = \frac{1}{\frac{1}{\varepsilon_s} + \frac{1}{\varepsilon_m} - 1}\sigma \frac{T_s^4 - T_m^4}{T_s - T_m} \tag{5}$$

where:
ε_s – emissivity of the strand surface,
ε_m – emissivity of the mould surface,
σ – Stefan-Boltzmann constant, W/(m^{2}K^4).

This case describes the least favourable method of strand cooling, as it did not take conduction and convection heat transfer mechanisms into account. It is constituted as the lower limit of the heat transfer coefficient at the strand and the mould interface.

In industrial practice powders lubricating the mould are applied. This constitutes an additional thermal resistance occurring in the gap between the strand and the mould. In a more accurate models describing heat transfer, it is assumed that a mould powder is present in the gap, either in its liquid or solid state, and that its thickness varies along the mould length [8,9,12]. In the model 3 (W3) it is assumed that the radiation is attenuated by the liquid slag layer in accordance with the equation [12]:

$$h_{r3}(x, y, z, \tau) = \frac{\sigma n^2 \left(T_s^4 - T_{sp}^4\right)}{\left(0,75\beta d_p + \frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_s} - 1\right)\left(T_s^4 - T_{sp}^4\right)} \tag{6}$$

where:
ε_p – emissivity of the mould powder,
T_{sp} – mould powder temperature, K,
d_p – mould powder thickness, m
n – reflection coefficient,
β – absorption coefficient, 1/m.

The heat transfer was completed by an empirical formula describing heat conduction [6]. At the area of contact between the liquid metal and the mould wall heat is transferred by convection. A heat transfer coefficient of h_{con} = 2000 W/(m^{2}K) [4] is assumed in the calculations. The overall heat transfer coefficient is described by the following formula:

$$h_{sm3}(x, y, z, \tau) = h_{r3} + (h_{con} - h_{r3})\, exp\left(\frac{T_s - T_{li}}{T_{so} - T_{za}}\right) \tag{7}$$

where:
h_{con} – convective heat transfer coefficient, W/(m^{2}K),
T_{li} – liquidus temperature, K,
T_{so} – solidus temperature, K,
T_{za} – mould powder solidification temperature, K.

In the model 4 (W4) it is assumed that the mould powder forms a screen that insulates the strand surface from the

mould. The radiative heat transfer coefficient is determined from [13]:

$$h_{r4}(x,y,z,\tau) = \frac{1}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_s} + \frac{2}{\varepsilon_p} - 2} \sigma \frac{T_s^4 - T_m^4}{T_s - T_m} \tag{8}$$

The overall heat transfer coefficient h_{sm4} has been supplemented by conduction according to equation (7). The determined heat transfer coefficients – as functions of mould length are presented in the graph (Fig. 1). The distributions of heat transfer coefficient along the mould are compared in Fig. 1. The overall heat transfer coefficient is compared to the ones that were determined for the heat transfer only by radiation described as variants W3 and W4. All values of the heat transfer coefficient are between the two boundaries determined from models W1 and W2. These models describe the heat transfer at the maximum and minimum level, respectively.

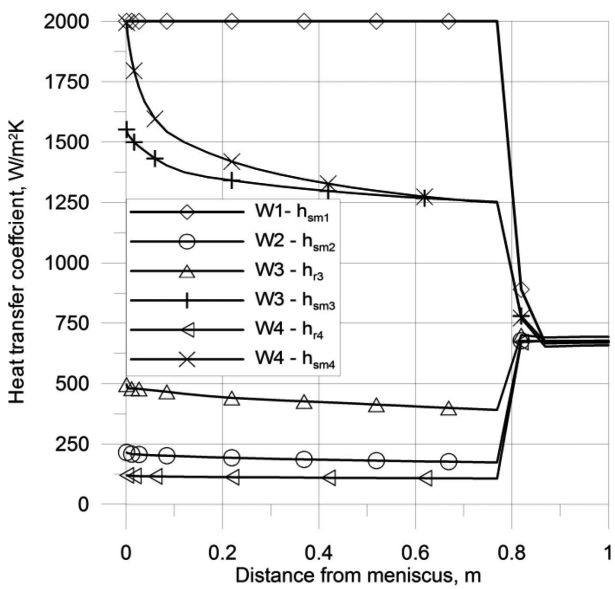

Fig. 1. Variations of the heat transfer coefficient along the mould length

3. Calculation results

Analysis was conducted for the process of continuous casting of the S320GD steel in a mould with dimensions of 1280×220 mm. The chemical composition of the examined steel is presented in Table 1. The solidus and liquidus temperatures for the steel examined are 1753 K and 1803 K, respectively. The liquid steel casting temperature was 1823 K, and the casting speed was 0.0167m/s.

TABLE 1

Chemical composition of examined steel, %

C	Mn	Si	P	S	Cr	Ni	Cu	Al	V	Mo
0.07	0.6	0.03	0.02	0.018	0.15	0.15	0.15	0.045	0.02	0.05

The thermophysical properties of the steel were determined from the thermodynamic databases and measurements described in [8]. The data has been implemented in the developed computer program. The obtained results of the heat conduction coefficient, density, and specific heat as a function of temperature have been presented in Fig. 2.

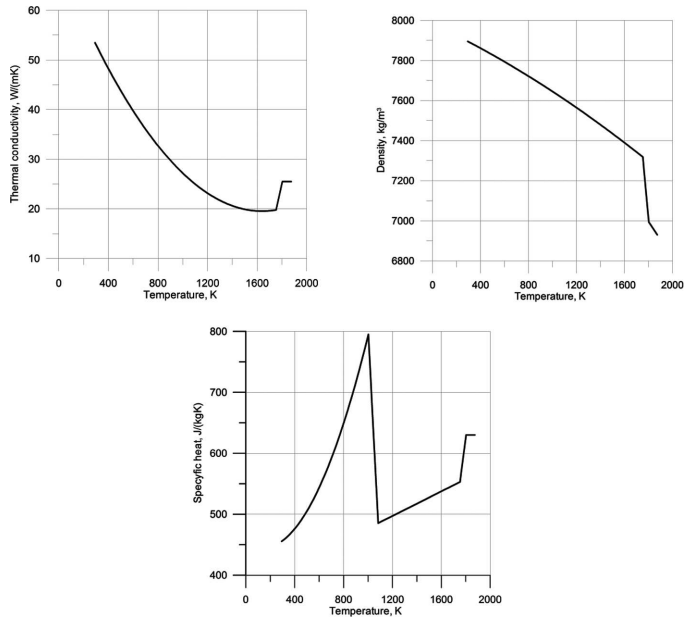

Fig. 2. Heat conduction coefficient, density and specific heat as functions of temperature [8]

Validation of the developed models was performed by comparing the overall heat at the mould surface determined from the numerical calculations to the heat calculated from measurements of the cooling water flow and the temperature rise at the continuous casting machine mould. The cooling water measurement results are presented in Table 2.

TABLE 2

The results of the measurement on the CCS – mould line

	Water flow rate, m^3/s	Water temperature increase, deg
fixed wall 1	7.56E-4	6.19
loose wall 2	7.85E-4	6.14
fixed wall left	12.0E-4	5.89
loose wall right	11.0E-4	6.00

The temperature distributions at the strand surface in the primary cooling zone for all models are presented in Fig. 3.

The shape of surface temperature curves is correct in each of the models that were applied for the calculations of the heat transfer in the gap between the strand and mould. The distributions obtained are considerably differ from one another along the strand length. The maximum surface temperature was achieved with model W2, with the minimum value of the heat transfer coefficient. The temperature at the mould exit was 1533 K The minimum surface temperature was found for model W1 and at a level of 979 K. The other models – W3 and W4 – have given temperatures of 1163 K and 1073 K respectively. Heat fluxes transferred from the solidifying strand to the cooled mould are presented in Figure 4. The curves show a significant diversity of heat transfer along the strand length in the primary cooling zone. The highest value of the heat flux has been obtained from the model W1, while the

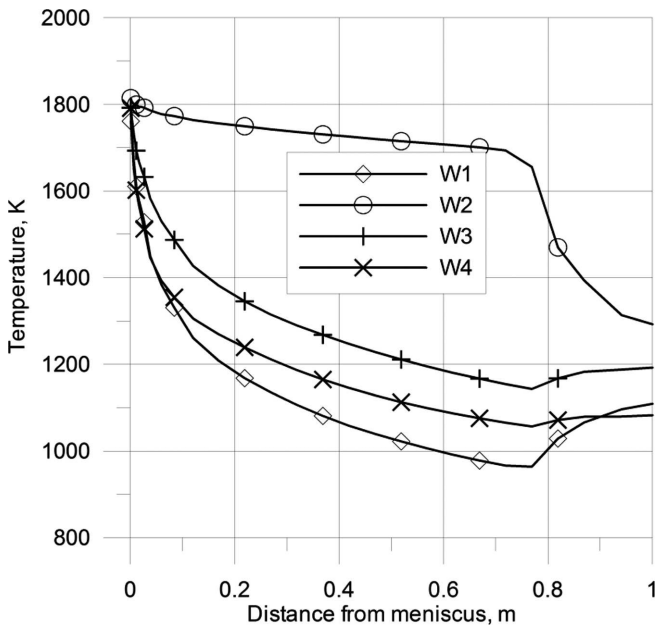

Fig. 3. The strand surface temperature distributions along the strand length

lowest one with the model W2. The differences result from the applied heat transfer model and the resulting value of the heat transfer coefficient. For other models, the heat fluxes are between W1 and W2 models. In order to verify the accuracy of models, the overall heat flux was determined and compared with that determined on the basis of the measurements at the continuous casting machine. The results have been presented in Table 3.

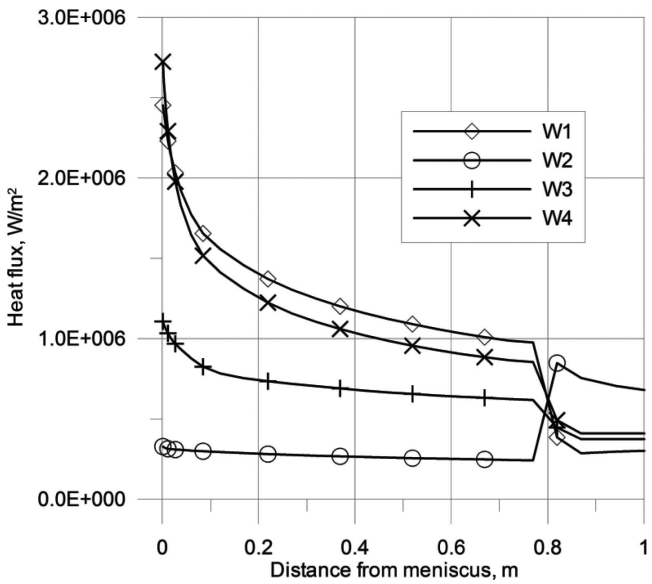

Fig. 4. The heat flux distributions along the strand length

A lowest difference of 4.16% between the determined and calculated heat fluxes occurs in model W4. The highest difference ΔQ of all the analysed solutions of 76.25% occurs in the model W2, for which the heat transfer is only described by radiation. The application of the model in which the slag layer is considered as a screen has allowed obtaining the results that are similar to the industrial measurements. The measurement of the parameters as regards the water witch cooled the mould is amongst the most easily available measurements in industrial practice. It allows rapid monitoring of the mould operation and the amount of heat transferred.

TABLE 3

Results of calculations of the heat fluxes for all the models

Model	W1	W2	W3	W4
Overall heat transfer Q, W	3.21E+06	6.47E+05	1.76E+06	2.84E+06
Difference ΔQ, W	4.89E+05	-2.08E+06	-9.65E+05	1.13E+05
Difference ΔQ, %	17.96	-76.25	-35.44	4.16

4. Conclusion

The paper presents four models describing the heat transfer within the gap between the strand and the mould. In model W1, direct contact was assumed between the surfaces, as well as a constant heat transfer coefficient. In model W2 only the heat transfer by radiation between the two parallel surfaces was taken into account. These two methods determine the boundary values of the heat transfer coefficient – the minimum and the maximum. In models W3 and W4, consideration was given to the presence of mould powder in the gap, forming an additional thermal resistance to the heat flow between the solidifying strand and the mould. In the former it was assumed that it was a semitransparent barrier that attenuates radiation; in the latter the mould powder was considered as a classic thermal screen. The results of the calculations for model W4 have the lowest error as regards the determined heat flux when compared to industrial measurements. The considerable difference in the results of the temperature field calculations for an improper model may lead to incorrect results of other numerical calculations such as microstructure or thermal stresses development.

Acknowledgements

The study performed as part of the regular activity, AGH University of Science and Technology, Faculty of Metals Engineering and Industrial Computer Science, Work No. 11.11.110.226.

REFERENCES

[1] M. Hojny, M. Głowacki, Steel Research international **79**, 868 (2008).
[2] A. Cwudzinski, Archives of Metallurgy and Materials **58**, 1077-1083 (2013).
[3] L. Sowa, A. Bokota, Archives of Metallurgy and Materials **56**, 359-366 (2011).
[4] T. Telejko, Z. Malinowski, M. Rywotycki, Archives of Metallurgy and Materials **54**, 837-844 (2009).
[5] J.K. Park, B.G. Thomas, I. V.Samarasekera, Ironmaking and Steelmaking **29**, 5, 359-375 (2002).
[6] Z. Malinowski, T. Telejko, B. Hadała, Archives of Metallurgy and Materials **57**, 1, 325-331 (2012).
[7] M. Rywotycki, K. Miłkowska-Piszczek, L. Trebacz, Archives of Metallurgy and Materials **57**, 385-393 (2012).
[8] A. Buczek, A. Burbelko, P. Drożdż, M. Dziarmagowski, J. Falkus, M. Karbowniczek, Tomasz Kargul, K. Miłkowska-

Piszczek, M. Rywotycki, K. Sołek, W. Ślęzak, T. Telejko, L. Trębacz, E. Wielgosz, Modelowanie procesu ciągłego odlewania stali - monografia, Radom 2012.

[9] J. Falkus, K. Miłkowska-Piszczek, M. Rywotycki, E. Wielgosz, Journal of Achievements in Materials and Manufacturing Engineering **55**, 2, 668-672 (2012).

[10] B. Hadała, A. Cebo-Rudnicka, Z.Malinowski, A. Gołdasz, Archives of Metallurgy and Materials **56**, 367-377 (2011).

[11] B. Hadała, Z. Malinowski, Computer Methods in Materials Science **9**, 302-307 (2009).

[12] Y. Meng, B.G. Thomas, Metallurgical and Materials Transactions B **34B**, 685 (2003).

[13] K. Miłkowska-Piszczek, J. Falkus, Metalurgija **53**, 4, 571-573 (2014).

[14] K. Miłkowska-Piszczek, M. Korolczuk-Hejnak, Archives of Metallurgy and Materials **58**, 4, 1267-1274 (2013).

[15] S. Wiśniewski, T.S. Wiśniewski, Wymiana ciepła, Warszawa, 1997.

Received: 20 March 2014.