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CALCULATION OF THE BOUNDARY CONDITIONS IN THE CONTINUOUS CASTING OF STEEL PROCESS

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This paper presents the relationship between the technological cooling parameters in the continuous casting machine and the boundary conditions implemented in the numerical model. A heat transfer model for the primary and secondary cooling zones in the continuous steel casting process was formulated, plus a description of boundary conditions was proposed, based on this model. Numerical calculations were performed with the ProCAST software for the S235 steel, and the format cast 220 × 1 100 mm. Calculation results were verified on the using our own measurements of the strand surface temperature in the cooling chamber.

Key words: continuous casting of steel, numerical modelling, boundary conditions, cooling parameters

INTRODUCTION

Continuous casting of steel is a new and developing casting process, the purpose being to improve the steel cast strand quality and to increase the yield. Many authors have taken up the subject of modelling the temperature distribution in the steel continuous casting process [1-8]. Numerical modelling of the solidification processes requires formulating a heat transfer model, along with a precise calculation of the boundary conditions. These must be correlated with the continuous casting machine technological parameters. Describing the heat transfer model in the continuous steel casting process is a complex task, as all three mechanisms of heat transfer occur in this process: conduction, radiation and convection [9-11]. The following processes influence the heat transfer in the continuous steel casting process: conduction and convection in the liquid steel area, conduction in the solidified shell, heat transport between the outer layer of the solidified shell and the mould wall surface, heat conduction in the mould, heat transfer in the mould between the channel walls and the cooling water, heat transfer within the secondary cooling zone by convection and radiation, heat transfer between the solidifying strand and the rolls by conduction. Additionally, the thermal effects related to the phase transformations that accompany the solidification have a significant influence on the heat transfer model.

INDUSTRIAL RESEARCH

A complete technological description of the continuous casting machine operating in the Krakow Unit of ArcelorMittal Poland has been compiled as part of this industrial research. These studies covered 55 heats for 7 different steel grades. Information was gathered on the most important technological parameters in the continuous steel casting process. Control parameters were read directly from the system implemented in the continuous casting machine. The most important parameters, which were further used to determine the boundary and initial conditions that were necessary for the implementation of the numerical model of the continuous casting of steel, were the flows of cooling water in the individual spray zones / dm^3/min, the cooling water temperature both for the primary and the secondary cooling zone / °C, the cooling water pressure / bar, the liquid steel temperature within the tundish / °C, the temperature difference in the cooling water within the mould channels / °C and the casting speed / m/min. Because of the need to verify the model calculations, additional temperature measurements of the strand surface within the secondary cooling chamber were made during the heats investigated. A two-colour optical pyrometer and a thermovision camera were used.

THE BOUNDARY CONDITIONS IN THE NUMERICAL MODEL

In the study, a heat transfer model was used in which the temperature field could be determined by solving the Fourier equation:

$$\frac{\partial(\rho c_p T)}{\partial t} = \frac{\partial}{\partial x}(\lambda \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\lambda \frac{\partial T}{\partial z}) + Q \qquad (1)$$

where ρ is the density / kg/m; c_p is the specific heat / kJ/kgK; λ is the thermal conductivity / W/mK; t is the time / s; T is the temperature / K; Q is the heat source term / W/m^3 ; x, y, z are the 3D coordinate axes. The solution of the Fourier equation should meet those

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boundary conditions declared on the strand surface. In the formulated numerical model of the continuous steel casting process, these boundary conditions may be declared in three various ways. The equation below describes the second (the Neumann condition) and the third-type of boundary conditions [12]:

$$Q = Flux + \alpha (T - T_a) + \sigma \, \varepsilon (T^4 - T_a^4) \qquad (2)$$

where *Flux* is the heat flux / W/m²; α is the heat transfer coefficient / W/m²K; T_a is the ambient temperature / K; σ is the Stefan-Bolzmann constant / W/m²K⁴; ε is the emissivity. The heat flux may be defined in the program directly as the *Flux* value (the Neuman condition), as well as with the convection (α - substitute heat-transfer coefficient), and with the radiation models (ε - emissivity).

THE PRIMARY COOLING ZONE

The mould outer side is intensively cooled with water flowing through the channels. Heat is transferred by the forced convection. Calculating the heat transfer coefficient, with water-cooling in the mould channels based on the available formulas, is complex because of the method of heat transfer to the water flowing through the channel. To determine the average heat transfer coefficient, the following formula may be applied for the outer surface of the mould [10]:

$$\alpha_W = \frac{Nu \lambda_w}{d_k} x_k \qquad (3)$$

where Nu is the Nusselt number; λ_w is the thermal conductivity for the cooling water / W/mK; x_k is the share of water-cooled mould area; d_k is the cooling channel diameter / mm. The heat transfer coefficient was calculated at 24 000 W/m²K, using the dependence 3. The x_k value of 0,75 was assumed for these calculations, meaning that 75 % of the total mould area was cooled by having water flowing through its channels. It is a complicated task to formulate a model of heat transfer in the mould. The main difficulty is the effect of an air gap forming immediately after the steel has cooled to the solidus temperature under the liquid steel meniscus surface. The oscillatory movement of the mould, and in addition, the strand movement in the mould with a variable casting speed, strongly influence the actual dimensions of the gap. The presence of the mould powder and gases within the gap makes this description even more problematic. The air gap increases its dimensions with the distance from the liquid steel meniscus, which consequently causes an increase in the heat resistance. The heat transport mechanism between the solidifying strand shell and the mould wall may be divided into two components - the conduction and the radiation. The convection in this area may be neglected due to the small size of the air gap. The total air transfer coefficient on the strand - mould path may be presented by the formula:

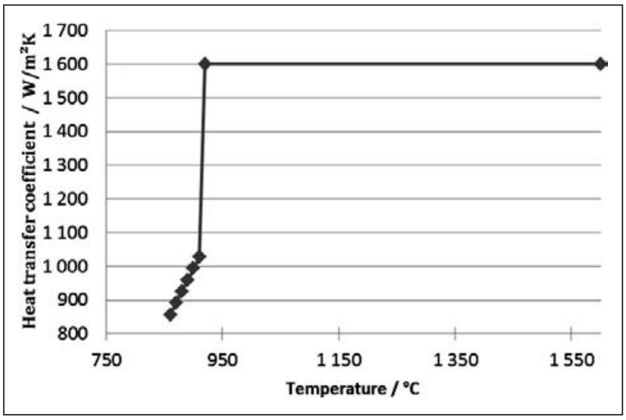

Figure 1 Heat transfer coefficient α_{wk} versus temperature [13]

$$\alpha_{wk} = \alpha_c + \alpha_r \qquad (4)$$

where α_c conduction heat transfer coefficient, α_r radiation heat transfer coefficient. Assuming that the mould wall and the strand are two parallel slabs located close to each other, it may be accepted that the density of heat flux transferred by radiation is expressed by the equation [9]:

$$\alpha_r = \varepsilon_z \sigma \frac{T_{wl}^4 - T_{kr}^4}{T_{wl} - T_{kr}} \qquad (5)$$

where ε_z is the substitute emissivity coefficient; σ is the Stefan – Boltzmann radiation constant / W/m²K⁴; T_{wl} is the strand surface temperature / K; T_{kr} is the mould wall inner surface temperature / K. The heat transfer by conduction may be calculated from the empirical formula [9]:

$$\alpha_c = (\alpha_l - \alpha_r) \exp^{\frac{T_{wl} - T_{sol}}{200}} \qquad (6)$$

where α_c is the substitute conduction heat transfer coefficient / W/m²K; α_l is the substitute convection heat transfer coefficient for liquid steel / W/m²K; T_{sol} is the solidus temperature / K. The heat transfer coefficient achieves its maximum value only when the heat is transferred from the liquid steel to the mould. The changes in the heat transfer coefficient are presented in Figure 1.

THE SECONDARY COOLING ZONE

Not knowing the temperature of the solidifying strand temperature, a simplified formula may be applied to calculate the heat transfer coefficients for the individual spray zones [14]:

$$\alpha_{spray} = 10\, v + (107 + 0{,}688\, v)\, w \qquad (7)$$

where *v* is the water drops' velocity / m/s; *w* is the water flux density / dm³/m²s. For the secondary cooling zone, based on the numerical values of the water flux density, a set of heat transfer coefficients was calculated for each of the spray zones. Table 1 presents the values of heat transfer coefficients calculated for the strand casting speed of 1 m/min.

Table 1 **Heat transfer coefficients for seven spray zones**

Spray zone	Heat transfer coefficient / W/m^{2}K
1	800
2	480
3	530
4	320
5	240
6	210
7	200

The applied method for determining the heat transfer coefficient value is very useful for defining new cooling programmes or modifying those that exist [13].

RESULTS OF CALCULATIONS

The temperature distribution within the whole volume of the solidifying strand was calculated based on the speed of 1 m/min. The numerical calculations were made with the ProCAST 2013 software. The verification of results involved the checking of the thickness of the shell leaving the mould and analysing the liquid core length. In addition, the calculated strand surface temperature was compared with those values measured at reference points with a pyrometer. The thickness of the shell, after leaving the mould, was 2,51 cm, and the length of the liquid core was 16,73 m. The above values conform to the continuous caster manufacturer's guidelines. Table 2 presents the calculated and measured values of the temperature of the strand surface at the reference points.

Table 2 **Strand surface temperature calculated and measured at the reference points**

	Measured temperature /°C	Calculated temperature /°C
First measurement point	860	861
Second measurement point	910	912

The first reference point was located at a distance of about 2,5 m under the mould (on the first continuous caster segment). The second was located on about 18 m of the continuous casting machine directly after the exit of the secondary cooling chamber. Also the temperature distribution for the mould was calculated. It allowed the boundary conditions in the primary cooling zone to be verified not only on the basis of the actual industrial data (flows of water through the channels for each of the mould walls), but also on the balance calculations.

CONCLUSION

This paper presents a method for calculating the boundary conditions based on the technological cooling parameters for the selected continuous steel casting machine. The formulated heat transfer model was divided into the primary cooling zone and the secondary cooling zone, which included the individual spray zones of the continuous steel casting machine. The presented method allows the calculation of the heat transfer coefficients on the basis of flows of cooling water in the individual cooling zones. The calculated values of the boundary conditions were used for conducting the numerical simulation. Verification of the calculation results has allowed the confirmation of the effectiveness of the developed method of correlating the technological cooling parameters of the continuous steel casting process with the definition of boundary conditions.

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