HEAT TRANSFER COEFFICIENTS BENEATH THE WATER COOLING NOZZLES OF A BILLET CASTER

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Abstract

The accuracy with which the solidification and cooling of a continuously cast billet is investigated depends on the setting of the boundary conditions of the numerical model of the temperature field. An in-house numerical model of the 3D temperature field of a concast billet had been used. This model enables the analysis of the temperature field of the actual blank as it passes through the zero-, primary-, secondary- and tertiary-cooling zones, i.e. through the entire caster.

This paper deals with the derivation of transfer phenomena under the cooling nozzles of the secondary zone. These phenomena are expressed by the values of the heat transfer coefficients (HTCs). The dependences of these coefficients on surface temperature and other operational parameters must also be given. The HTCs beneath the nozzles are given by the sum of the forced convection coefficient and the so-called reduced convection coefficient corresponding to heat transfer by radiation. The definition of the boundary conditions is the most difficult part of the numerical and experimental investigation of the thermokinetics of this process.

Regarding the fact that on a real caster, where there are many types of nozzles (with various settings) positioned inside a closed cage, it is practically impossible to conduct measurement of the real boundary conditions. Therefore, an experimental laboratory device was introduced in order to measure the cooling characteristics of the nozzles. It simulates not only the movement, but also the surface of a blank – and for the necessary range of water flow in the operation and the casting speeds. The transfer phenomena beneath the water cooling nozzles are presented on a simulated temperature field for a real 150×150 mm steel billet under different operational conditions.

1. INTRODUCTION

The presented in-house model of the transient temperature field of the blank from a billet caster (Fig. 1) is unique in that, in addition to being entirely 3D, it can work in real time. It is possible to adapt its universal code and implement it on any billet caster. The numerical model covers the temperature field of the complete length of the blank (i.e. from the meniscus inside the mould all the way down to the cutting torch) with up to one million nodes.

2. HEAT TRANSFER COEFFICIENT BENEATH THE WATER COOLING NOZZLES

The boundary condition situation is outlined in Fig. 2. The cooling by the water nozzles has the main influence and it is therefore necessary to devote much attention to establishing the relevant heat-transfer coefficient of the forced convection. Commercially sold models of the temperature field describe the heat-transfer coefficient beneath the nozzles as a function of the incident quantity of water per unit of area.
They are based on various empirical relationships. This procedure is undesirable. The model discussed in this paper obtains its heat-transfer coefficients from measurements of the spraying characteristics of all nozzles used by the caster on a so-called hot plate in an experimental laboratory [1] and for a sufficient range of operational pressures of water and a sufficient range of casting speeds of the blank (i.e. casting speed). Heat-transfer coefficients obtained in this way are entered into a database of boundary conditions from which (and based on interpolation) the model determines the appropriate heat-transfer coefficient beneath the nozzle for the required temperature of the surface of the blank, the operational pressure of the water and for the required casting speed. The temperature of the ambient beneath the nozzles $T_{amb}$ is taken from the temperature of the water in the secondary zone and the temperature of the ambient out of reach of the nozzles is taken from the atmospheric temperature [1]. This approach represents a unique combination of experimental measurement in a laboratory and a numerical model for the calculation of the non-linear boundary conditions beneath the cooling nozzle.

2.1 Measuring the cooling effect of nozzles

One of the possibilities of how to determine the heat-transfer coefficient beneath the cooling nozzles inside a laboratory is via measurement on a hot plate, which is a
steel plate with installed thermocouples, clamped and electrically heated. The plate can be raised to the required horizontal heating position and after achieving the required temperature, the electrical heating element is removed. The space between the heating element and the plate is filled with argon. During the entire heating process, the flow of argon is maintained constant, which prevents degradation of the quality of the surface of the plate. The reason for using an inert gas was to ensure the same conditions for all experiments and to prevent oxides forming on the heating element and plate. The surface of the investigated plate was “rolled” and covered with a layer of oxides formed during spraying. The oxides were removed from the surface before each successive heating but the surface was not polished [1, 2, 3].

While the experiment is conducted, there is a nozzle with a moving mechanism inserted beneath the plate (the heating element is removed at this stage). During the experiment, the water is pumped through the nozzle from a tank. The water pressure is measured before it enters the nozzle. The temperature of the water and the temperature inside the plate are monitored by a data acquisition system (Fig. 3). The
size of the hot plate is 330×150 mm and thickness is 24 mm. The plate contains 18 thermocouples (1.5 mm in diameter, type K).

The set of thermocouples measures the temperature at a depth of 2.5 mm (from the bottom surface which is sprayed). The top surface of the plate is insulated. Conical water nozzles were used for the measurements. The nozzles are positioned on a moving carriage. Considering the fact that the caster operates within a wide range of casting speeds, the experiments were conducted for extreme casting speeds of 1.5 m/min and 4.0 m/min. More experiments with various flows were conducted for each nozzle.

2.2 Measurement results

Fig. 4, 6 and 8 present the measured values of the heat transfer coefficients processed by the temperature model software. This entails merely the selection of the results for the limit water flows and for three different kinds of geometry of water nozzles. For each nozzle configuration, there is a graph of the maximal value of the heat transfer coefficient dependent on the surface temperature, the course of the heat transfer coefficient across and through the centre of the nozzle, the course of the heat transfer coefficient in the direction of motion in the centre of the nozzle and the 2D graph of the heat transfer coefficient beneath the nozzle. These graphs are plotted for a surface temperature of 800 °C.

Together with the information on the dependence of the heat transfer coefficients on the temperature of the surface of the blank, it is necessary to remember the so-called Leidenfrost temperature [1]. This is the surface temperature at which the character of the heat transfer changes significantly. A continuous layer of vapour, forming at the surface at high temperatures is disrupted and the heat transfer coefficients leap to higher values. Significantly more intensive drops of the surface temperature while passing under the nozzles also correspond to this state. The graphs indicate that with the water nozzles used on a billet caster, this influence is significant and usually occurs at temperatures below 800 °C. Simultaneously, it is necessary to realise that a temperature difference works against this effect according to Eq. (1).

The cooling effect of the nozzles can be assessed differently, e.g. according to the maximal value of the heat transfer coefficient beneath the nozzle, according to the mean value of the coefficient. The most suitable way of assessing the nozzle, however, is according to the value of the heat flow, based on Eq. (1), that the nozzle rejects from the cooled surface.

\[ \dot{Q} = 2\int_{0}^{t_{\text{max}}} \int_{-z_{\text{max}}}^{+z_{\text{max}}} htc_{xz}(T_{\text{surface}} - T_{\text{amb}}) \cdot dx \cdot dz \]  

(1)

where \( htc_{xz} \) – is the heat transfer coefficient beneath the nozzle at the coordinates \( x \) and \( z \); \( T_{\text{surface}} \) – is the temperature of the steel surface (here it is considered constant over the entire area); \( T_{\text{amb}} \) – is the temperature (here it is the temperature of the cooling water at 20 °C).

The resultant heat flows calculated according to Eq. (1) for surface temperatures of 500, 700, 900 and 1100 °C in dependence on water flow are plotted in Fig. 5, 7 and 9. The graphs indicate that the influence of the surface temperature takes effect for temperatures lower than 800 °C. Another observation is that with an increase in water flow, the cooling effect of the nozzles in most cases increases. This increase however varies with each nozzle, or nozzle configuration. This must be taken into account in the case that the cooling nozzles are designed for dynamic control of the secondary cooling.
2.4.3. THE EFFECT OF THE SECONDARY COOLING

The setting of the secondary cooling and its optimization is a very complicated problem. The cooling curve describes the dependence of the necessary flows [l/min] on the casting speed [m/min] – always for a specific intensity of cooling characterized by the consumption of the cooling water per 1 kg of cast steel.
Fig. 6. The characteristic of the nozzle and the rejected heat flow using the 4565L nozzle in dependence on the water flow and surface temperature

a) Flow through one nozzle at 1.61 l/min  
b) Flow through one nozzle at 9.85 l/min

Fig. 7. The heat transfer coefficient for the 4565L nozzle

Based on the knowledge of these curves for various consumptions of cooling water per unit of mass of cast steel from 7 l/kg and 17 l/kg, the temperature of the blank was calculated and presented in Fig. 10. These cooling curves are established for the given caster for the cooling zones I to IV. In a real operation, there are only four zones I, II, III and IV set up (i.e. regulated) for simplicity. Splitting the amount of water between II A and II B and then between III A and III B is preset and cannot be changed during casting.
Fig. 8. The characteristic of the nozzle and the rejected heat flow using the 2045L nozzle (2 nozzles following each other)

a) Flow through one nozzle at 0.71 l/min  
b) Flow through one nozzle at 2.90 l/min

Fig. 9. The heat transfer coefficient for the 2045L nozzle

The graph in Fig. 11 shows the resultant temperature field for individual cooling curves. This basic set of graphs serves the user in that it is possible to assess which of the cooling curves is optimal for the given cast steel. It is necessary to know that the cooling curves are sorted according to the amount of water entering all zones and, regarding individual curves, the amount of water is rationed among the zones.
4. CONCLUSIONS
The value of the heat transfer coefficient on the surface of the blank, as it enters the secondary-cooling zone, significantly affects the process simulation from the viewpoint of the temperature field, the metallurgical length, and also other technological properties.
Each nozzle had been measured separately on the hot model, on which the hot surface of the blank, which is cooled by a moving nozzle, can be modelled. The temperatures measured on the surface of the model can be entered into an inverse task to calculate the intensity of spraying, which, in turn, can determine the heat transfer coefficient using a special mathematical method.

REFERENCES

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