DETERMINATION OF THERMAL PARAMETERS IN THE PRIMARY COOLING ZONE OF THE CCS

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Abstract

The present paper is focused on the mathematical and graphical determination of temperature and thermal parameters depending on the heat dissipation from solidifying steel in the mould, respectively in the primary cooling zone of continuous casting of steel (CCS). The main task of the primary cooling is mainly to remove heat from the solidifying steel, therefore knowledge of the temperature fields in the precast and mould is important. As part of the present research to evaluate the thermal performance of the mould, the heat flux density dependencies *q* between the steel and the cooling water in the mould were expressed in the primary cooling region. The cooling water parameters and temperature gradients along the height and perimeter of the working surface of a copper mould insert of square cross-section of 150 x 150 mm and 1 m long were used to determine the heat removal rate from the solidifying steel. The temperature and thermal parameters were determined for the solidification and precooling tasks for two grades of steel with carbon contents of 0.18 wt.% and 0.83 wt.%. Casting speeds were chosen to range from 2.1 $m \cdot min^{-1}$ to 2.7 $m \cdot min^{-1}$ and casting temperatures from 1500 °C to 1550 °C. The obtained dependencies were used for numerical simulation in the ProCAST environment.

Keywords: Primary cooling zone, heat flux density, heat flux, ProCAST

1. INTRODUCTION

The technology of continuous casting is characterized by a high degree of versatility and is the result of the entire upstream stage of steel production preparation and processing immediately prior to the continuous casting process. The complex and multi-condition dependent process taking place in the mould can be better analysed and subsequently evaluated if the variables that change during the casting process are measured directly in the mould. The kinetics of the mould wall temperature field, which is a manifestation of the heat fluxes from the liquid steel to the cooling water, generally carries the greatest degree of information about the complex solidification process in the mould. Assuming an approximately constant thermal resistance of the copper mould walls, a heat transfer coefficient from copper to water and a known cooling water temperature, the measurement of heat fluxes can be replaced by the measurement of individual wall temperatures. The measured temperature field is evaluated quantitatively in terms of the magnitude of the temperatures, qualitatively with respect to the symmetry of the cooling, and in terms of its dynamics, i.e. temperature fluctuations and changes in the symmetry of the heat dissipation over time.

2. HEAT TRANSFER ANALYSIS IN THE PRIMARY COOLING ZONE

In the primary cooling zone, heat is transferred from the solidification front (i.e. from the inside of the casting crust) through the crust, through the gap between the crust and the mould wall, through the mould wall itself and into the cooling water. The mould can be divided in height into three zones according to the nature of the heat dissipation given by the interaction of the crust with the mould surface. The first zone is characterised by good contact of the relatively weak crust with the wall, which is ensured by the pressure of the liquid steel acting on the plastic casting crust [1]. There is usually a continuous layer of casting powder between the casting crust and the mould wall [2]. The second zone is characterised by alternating contact between the casting crust and the mould wall. The crust is already more rigid, but cannot withstand the ferrostatic pressure permanently. At the same time, it is subjected to alternating shrinkage and reheating, which induces dynamic stresses. In the second zone, a gas gap between the crust and the mould wall is temporarily created [3]. The third zone is located in the lower part of the mould and is characterised by a relatively stronger casting crust, which no longer resists ferrostatic pressure and, due to shrinkage, permanently detaches from the mould walls. A stable gas gap is formed between the casting crust and the wall, which significantly limits heat dissipation [4]. The solidification temperature may be considered, for simplified purposes, as the mean temperature between the liquid and the solidus temperature. Theoretical calculations of the heat flux densities in the different parts of the mould are hampered by ignorance of the heat transfer coefficients, which have to be determined mainly by measurement [5].

The total thermal resistance in the primary cooling zone, where heat transfers from the solidification front through the crust, through the gap between the crust and the mould wall, through the mould wall itself and into the cooling water, can be expressed by equation (1).

$$R_c = \left(\frac{s_0}{\lambda_0} + \frac{1}{\alpha_k} + \frac{s_k}{\lambda_k} + \frac{1}{\alpha_w} \right) \tag{1}$$

where:

R_c - total thermal resistance ($m^2 \cdot K \cdot W^{-1}$)

s_0 - thickness of casting crust (steel) (m)

λ_0 - average coefficient of thermal conductivity of the solidified crust of the billet ($W \cdot m^{-1} \cdot K^{-1}$)

α_k - heat transfer coefficient between the billet shell and the inner wall of the mould ($W \cdot m^{-2} \cdot K^{-1}$)

α_w - heat transfer coefficient between the mould wall and the cooling water ($W \cdot m^{-2} \cdot K^{-1}$)

s_k - mould wall thickness (m)

λ_k - coefficient of thermal conductivity of the mould wall ($W \cdot m^{-1} \cdot K^{-1}$)

If the temperature of the cooling water is such that no steam is generated, the heat transfer coefficient can be determined from the criterion equation (2). In addition to the similarity numbers *Nu*, *Re*, *Pr*, there is also a correction factor for wall temperature in equation (2), which is expressed by the fraction of the dynamic viscosities of the water at temperatures t_w and t_2.

$$Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \cdot \left(\frac{\eta_w}{\eta_2} \right)^{0.11} \tag{2}$$

where:

Nu - Nusselt number (1)

Re - Reynolds number (1)

Pr - Prandtl number (1)

ψ - correction coefficient (1)

η_w - dynamic viscosity of water at temperature t_w (Pa·s)

η_2 - dynamic viscosity of water at mould surface temperature t_2 (Pa·s)

The value of the coefficient ψ cannot be determined in advance because the temperature at the wall surface is not known before the calculation. The value of the correction factor is therefore calculated for each point on the wall surface only during the solution.

3. EVALUATION OF THE THERMAL WORK OF THE MOULD

The magnitude of the heat fluxes can best be determined by direct calculation from the temperatures measured in the mould using a pair of thermocouples, which must be placed at the same level along the height of the mould and at different distances from the surface of the inside of the mould [6]. However, in practical measurements on the mould, the thermocouples were only ever placed one at a given level along the height of the mould and therefore the heat fluxes could not be calculated by this method, nor could the position of the thermal axis.

Therefore, a methodology was used to calculate the heat fluxes according to which, from known boundary conditions, the monitoring of the mould heat work can be done by monitoring the temperature fields, since the temperatures at a given mould location depend practically linearly on the heat flux density from the precast. A constant temperature and cooling water flow rate is a prerequisite [7]. The following input values were chosen for the experiment, see **Table 1**.

Table 1 Input values of the experiment

Steel	$t_{casting}$ (°C)	Casting speed ($m \cdot min^{-1}$)			
0.18 wt.% C	1550	2.1	2.3	2.5	2.7
0.83 wt.% C	1500				

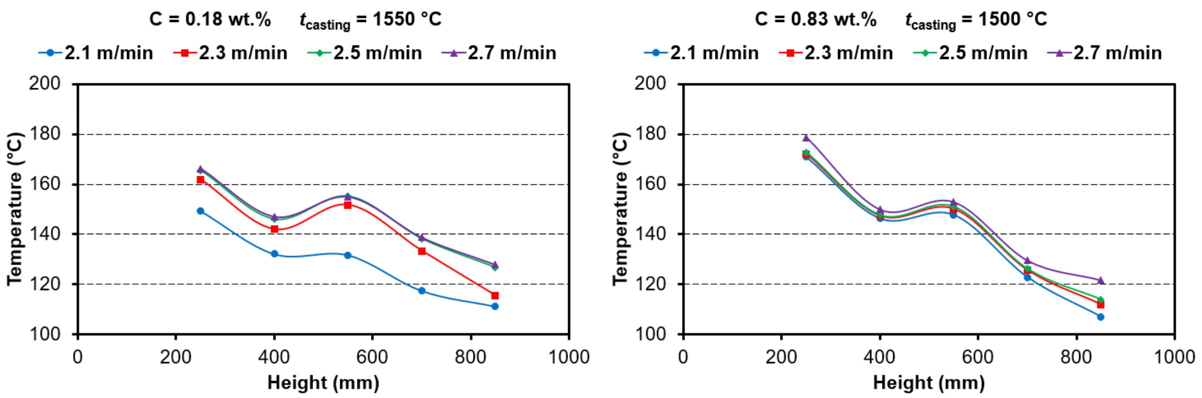

Figure 1 Temperature profile SR

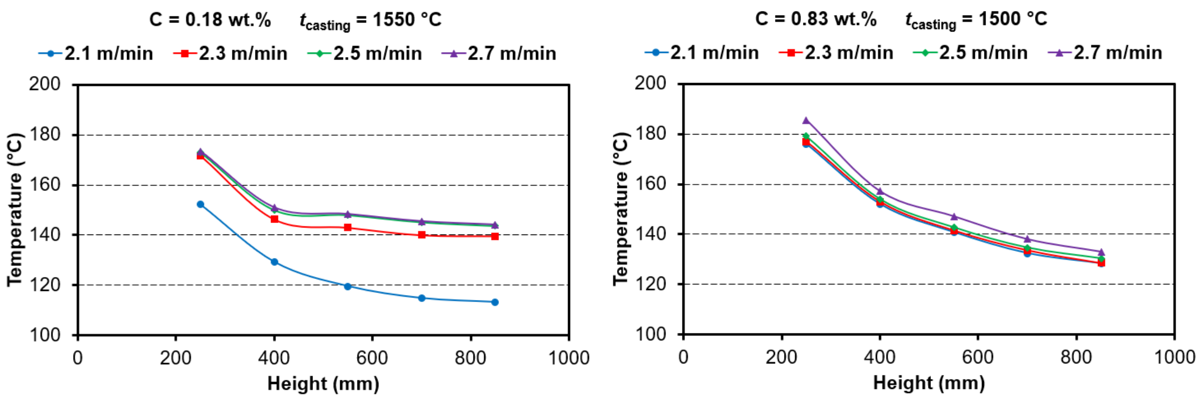

Figure 2 Temperature profile LR

The experimental measurements were carried out on a square mould with dimensions 150 x 150 mm and length of 1 m. On the large (LR) and small (SR) radius sides, 5 thermocouples were placed at distances of 250, 400, 550, 700 and 850 mm from the top edge of the mould. The time courses of the temperature profiles are presented in **Figure 1** and **Figure 2**. For perfect contact of the thermocouples with the mould wall, it was proposed to embed the thermocouples in copper rollers, which were installed in holes drilled in the mould wall. Special NiCr - CuNi type E thermocouples were used for experimental measurements, which are the most suitable for measurements in the "low" temperature range.

The heat transfer from the mould to the cooling water can be described by equation (3)

$$q = \frac{t_k - t_w}{\frac{s_k}{\lambda_k} + \frac{1}{\alpha_w}} \tag{3}$$

where:

q - heat flux density ($W \cdot m^{-2}$)

λ_k - thermal conductivity coefficient of the mould ($W \cdot m^{-1} \cdot K^{-1}$)

s_k - mould wall thickness (m)

t_k - mould wall temperature (°C)

t_w - cooling water temperature (°C)

α_w - heat transfer coefficient from the outer surface of the mould to the cooling water stream ($W \cdot m^{-2} \cdot K^{-1}$)

This equation shows that when calculating the heat fluxes, it was necessary to take into account the temperature of the cooling water, as this value was not constant over the height of the mould and this change had to be taken into account. On the other hand, the values of the thermal conductivity coefficient of the mould and the heat transfer coefficient were almost invariable and were therefore further treated as constants. The measured data sets contained information about the inlet temperature of the cooling water and the temperature difference at the inlet and outlet of the mould. From these data a linear dependence of the temperature rise was created. On this type of CCS, the water entered the mould from the bottom, therefore its temperature increased towards the top of the mould. From this dependence, the temperature of the water at the locations where the thermocouples were placed was determined and their differences were calculated from the temperature pairs thus created. These were then plotted versus the relative height of the mould and regression relationships were found using polynomial functions.

The heat flux from the mould cooling water was calculated according to relation (4)

$$P = Q_{m,w} \cdot c_{p,w} \cdot \Delta t_w \tag{4}$$

where:

P - heat flux (W)

$Q_{m,w}$ - mass flow rate of water through the mould ($kg \cdot s^{-1}$)

$c_{p,w}$ - specific heat capacity of water ($J \cdot kg^{-1} \cdot K^{-1}$)

Δt_w - temperature difference between water inlet and outlet (°C)

The mould was further divided into elementary surfaces from the steel surface to the bottom edge of the mould. Using the regression dependencies calculated for each melt observed, temperature coefficients were calculated for each elemental surface to characterize the relative temperature distribution along the height of the mould.

For the calculation of heat fluxes, a program was used that works on the principle of iterative method, according to which the heat fluxes in individual layers can be calculated [8]. The sum of the values from all layers must then equal the total heat flux from the water, which was calculated from the values stored in the data files as the product of the volumetric flux, density, specific heat capacity and the temperature difference at the inlet and outlet of the mould. The heat flux density in each element is obtained from the heat flux values related to the layer area and then plotted on graphs [9].

Figure 3 shows the values of the heat flux densities q (kW·m^{-2}) for the two tested steel grades as a function of the dimensionless coordinate (mould height). It can be seen from the figures that the heat dissipation from the mould along its length is closely related to the proportion of carbon in the steel. The low carbon steel (C = 0.18 wt.%) shows lower heat flux values at the steel surface and its heat dissipation is more uniform along the mould height than that of the high carbon steel (C = 0.83 wt.%). At the bottom of the mould for both grades of steel, a gas gap has already developed, resulting in a more pronounced decrease in heat dissipation. It is also evident from the curves in the presented figure that the casting speed has a significant effect on the heat dissipation [10].

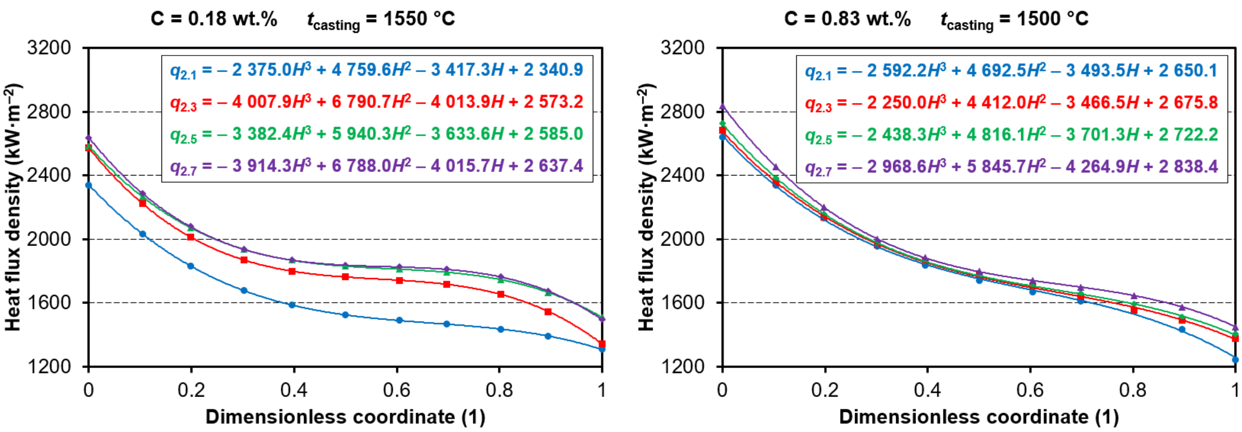

Figure 3 Heat flux density along the height of the mould

The heat flux densities along the mould height for each casting rate were expressed by a third degree polynomial. The expressed heat flux density polynomial was subsequently rewritten into a user function in the ProCAST environment to represent a type II surface condition for the primary cooling zone.

4. NUMERICAL SIMULATION IN PROCAST

Figure 4 presents the output from the ProCAST software system [11,12]. This is a numerical 3D temperature model. The graphical outputs of the simulation tasks for casting speeds of 2.1 and 2.7 m·min^{-1} with a carbon content of 0.18 wt.% were selected. The color resolution characterizes the surface temperature distribution. It is clear from the figure that the increased casting rate results in an increase in the surface temperature of the precast [13]. The above is related to the fact that less heat is removed by the cooling water at higher casting speeds. The resulting thinner casting crust is pressed more intensely against the mould wall, resulting in an increase in the heat flux density from the precast to the mould wall.

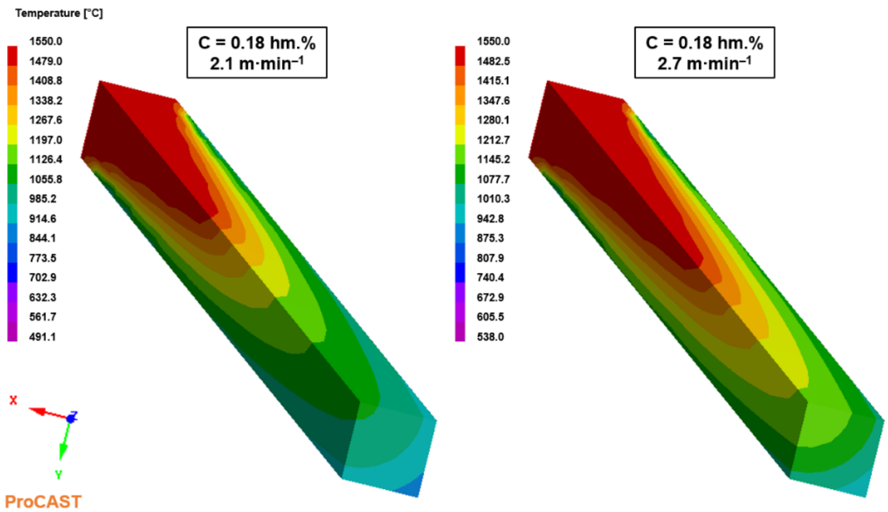

Figure 4 Numerical temperature model

5. CONCLUSION

The paper describes the investigation of thermal processes in the primary cooling zone in terms of the evaluation of temperature profiles and heat flux densities depending on the chemical composition of the steel and the casting rate. The primary cooling zone was defined on a rectangular mould profile with dimensions of 150 x 150 mm and a length of 1 m. Two steel grades were selected for processing and evaluation of the measured data. Low carbon steel (C = 0.18 wt.%) and high carbon steel (C = 0.83 wt.%). The casting speeds for both steel grades were chosen in the range from 2.1 $m \cdot min^{-1}$ to 2.7 $m \cdot min^{-1}$. Using the measured temperature profiles in the mould wall and the calculated heat dissipation to the cooling water, the heat flux density profiles were determined as a function of steel chemical composition and casting speed. After evaluation of the results, it can be concluded that a smoother decrease in temperatures and heat flux densities was achieved for the low carbon steel, where a more uniform heat dissipation from the mould was observed. Subsequently, simulation calculations were performed to determine the temperature fields in ProCAST. From the simulations obtained, it can be concluded that they allow to define the optimal parameters of the continuous casting process of steel. The use of the results obtained in the simulation processes gives very high economic benefits and also reduces the number of technological tests that are associated with the actual optimization of the continuous casting process of steel.

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