

HEAT TRANSFER IN THE PRIMARY COOLING ZONE OF A CONTINUOUS CASTING MACHINE FOR STEEL

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Abstract

The submitted contribution is focused on the mathematical determination of temperature and thermal parameters depending on the heat removal from solidifying steel in the mould, respectively in the primary zone during continuous casting of steel. The main task of primary cooling is primarily the heat dissipation from solidifying steel, therefore the knowledge of temperature fields in the billet and mould is important. As part of the research evaluating the thermal work of the mould, the dependencies of the heat flux density between the steel and the cooling water in the mould were expressed in the primary cooling area. For determining the intensity of heat removal from solidifying steel, parameters of cooling water and temperature gradients along the height and circumference of the working surface of the copper insert of the circular cross-section mould with a diameter of 410 mm and a length of 600 m were used. The research of thermal processes was carried out for two grades of steel, which characterise the group of most frequently cast types of steel. Temperature and thermal parameters were determined for solidification and cooling for steel with a carbon content of 0.17 wt% (grade A) and 0.49 wt% (grade B). The casting speeds of steel were chosen in the range from 0.46 m·min⁻¹ to 0.62 m·min⁻¹. The obtained dependencies will be further used for numerical simulation.

Keywords: Continuous casting, steel, temperature field, heat flux density

1. INTRODUCTION

Continuous casting technology is characterized by high versatility and is the result of the entire previous stage of steel production preparation and its processing immediately before the continuous casting process. The complex and many-condition-dependent process taking place in the mould can be better analysed and subsequently evaluated, assuming that the quantities that change during the casting process are measured directly in the mould [1]. The kinetics of the temperature field of the walls of the mould, which is a result of the heat flows from the liquid steel to the cooling water, generally carries the greatest amount of information about the complex process of solidification in the mould [2]. Assuming an approximately constant thermal resistance of the copper walls of the mould, the coefficient of heat transfer from copper to water and a known temperature of the cooling water, the measurement of heat flows can be replaced by the measurement of individual temperatures in the wall [3]. The measured temperature field is evaluated quantitatively in terms of the magnitude of temperatures, qualitatively with regard to the symmetry of cooling, and further from the point of view of its dynamics, i.e. temperature fluctuations and changes in the symmetry of heat removal over time [4].

2. EXPERIMENTAL SETUP

To monitor the temperature field of the mould at the operating continuous casting machine (CCM), an original methodology for measuring the temperature profiles of the mould was developed, including the design of special sensors [5]. Special NiCr - CuNi type E thermocouples were used for the experimental measurement, which are the most advantageous for measurements in the area of low temperatures. The hot junction was placed in selected places in the wall of the mould. The signal went to the analog inputs of the PC measuring

card, the input channels were sampled with a period of 55 ms and filtered by software, thereby partially eliminating interfering signals. The placement of the temperature probes includes finding the most suitable position in three axes, namely in the casting direction, i.e. the distance from the upper edge of the mould including the choice of one or more horizontal rows of sensors, the distribution of the sensors around the perimeter of the horizontal section of the mould and finally the distance of the measuring connection of the sensor from the working surface of the wall [6].

The position of the temperature probes in the horizontal direction for the purpose of measuring the temperature fields was chosen for distances of 100, 200, 275, 345, 425 and 520 mm from the upper edge of the mould. Thermocouples marked No. N1, N2, N3, N5, N6 and N7 were placed on the great radius (GR) side, thermocouples N8, N9, N10, N12, N13 and N14 on the little radius (LR) side, see diagram on the left Fig. 1. Operational experiments were carried out at CCM No. 1 at TŽ Třinec, Inc. For the perfect contact of the thermocouples with the wall of the mould, the method of inserting temperature probes into copper cylinders was chosen, which were installed in holes drilled in the walls of the mould. The cold ends were connected to the inputs of the measuring computer via the compensation line. The description of places with the distribution of thermocouples and the method of connecting thermocouples are shown in the photos in the right part of Figure 1 [7].

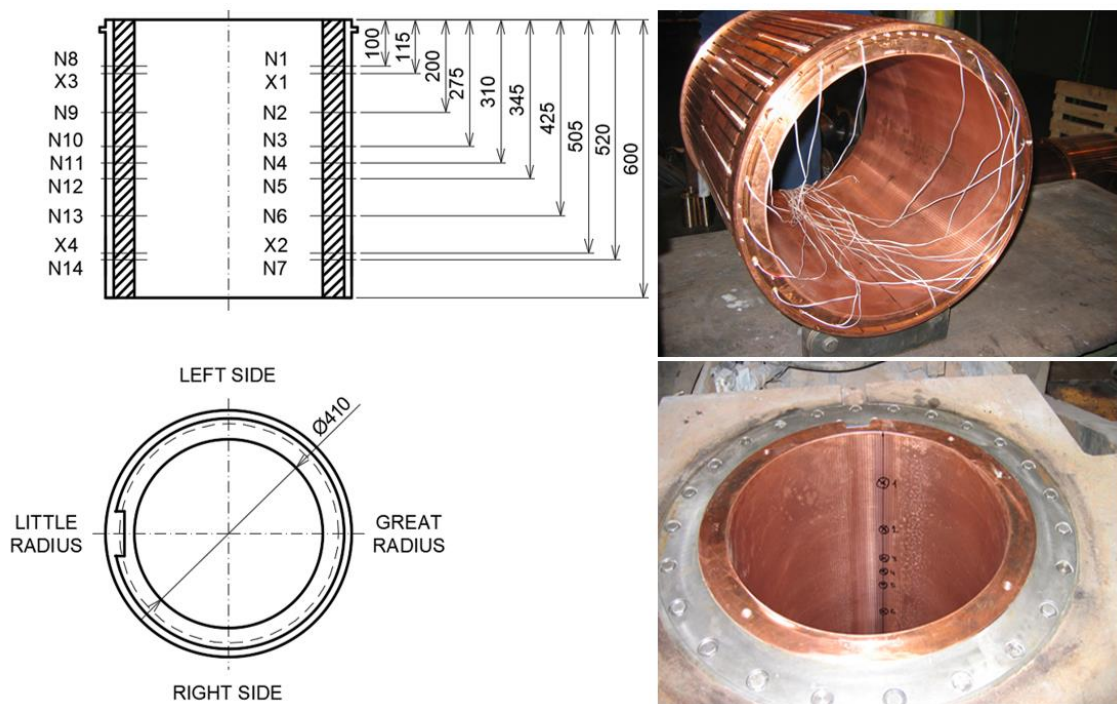


Figure 1 Thermocouple instalation into the mould $\phi 410$ mm

3. DETERMINATION OF HEAT FLUX IN VERTICAL DIRECTION

The intensity of heat removal from the billet in the mould significantly affects the quality of cast steel and is thus a key indicator of continuous casting [8]. The heat dissipation should be as constant as possible at a given point of the mould and uniform along the circumference of the cross-section. Also, the carbon content in steel significantly affects the uniformity of heat removal from the mould [9].

The methodology for determining heat flux densities along the length of the mould can be described as follows. The mould was divided into elementary layers from the surface of the steel to its lower edge. With the help of regression dependencies, calculated for each monitored heat, temperature coefficients were calculated for individual elementary layers, which characterize the relative distribution of temperatures along the length of

the mould. A program based on iteration method, was used to calculate the heat fluxes in individual layers [10]. The sum of the values from all layers must then be equal to the total heat flux from the water according to the relationship:

$$P_w = Q_w \cdot c_{pw} \cdot \rho_w \cdot (t_{w2} - t_{w1}) \quad (W) \quad (1)$$

where:

- P_w - rate of heat flow from water (W)
- Q_w - volume flow of cooling water through the mould ($m^3 \cdot s^{-1}$)
- c_{pw} - specific heat of water ($J \cdot kg^{-1} \cdot K^{-1}$)
- ρ_w - density of water ($kg \cdot m^{-3}$)
- t_{w1} - temperature of cooling water entering the mould ($^{\circ}C$)
- t_{w2} - temperature of cooling water leaving the mould ($^{\circ}C$)

The heat flux in the individual layers is obtained from the heat flux values related to the surface of the layer and then plotted in graphs. Input parameters of the calculation, i.e. pouring speed v_z ($m \cdot min^{-1}$), relative level height h (%), control height h_{reg} (mm), inlet water temperature t_{w1} ($^{\circ}C$), outlet water temperature t_{w2} ($^{\circ}C$) volume flow of cooling water Q_w ($m^3 \cdot s^{-1}$) were obtained from melting data sheets and data files. Temperatures in the walls of the mould on the side of the little and great radius were measured by thermocouples according to the diagram in **Figure 1** above. The exact distribution of the thermocouples along the length of the mould is summarized in **Table 1**.

Table 1 The position of the thermocouples along the length of the crystallizers

Distance from upper edge of mould	Relative distance from upper edge of mould	Thermocouple	
		GR	LR
L (mm)	ζ (1)		
75 = h_{vo}	0.00	–	–
100	0.05	N1	N8
200	0.24	N2	N9
275	0.38	N3	N10
310	0.45	N4	N11
345	0.51	N5	N12
425	0.67	N6	N13
520	0.85	N7	N14
600 = L_m	1.00	–	–

The quantity h_{vo} indicates the so-called free height of the mould, the height that is not in contact with the liquid steel, for which the following relation applies:

$$h_{vo} = h_{reg} \cdot [(100 - h) \cdot (100)^{-1}] \quad (m) \quad (2)$$

where:

- h - relative height of steel in the mould (%)
- h_{reg} - control height, characteristic for the given mould (m)

For the dimensionless, relative height of the mould ζ in the range 0 to 1 in contact with liquid steel, following relation can be used:

$$\zeta = (L - h_{vo}) \cdot (L_m - h_{vo})^{-1} \quad (1) \quad (3)$$

where:

L_m - length of the mould (m)

The values of the average temperatures in the region of the free height of the mould and the lower edge of the mould are determined by linear extrapolation from the obtained sets of temperatures. The temperature of the cooling water in the mould, depending on its dimensionless height, is determined by linear interpolation from the inlet t_{w1} and outlet t_{w2} of the cooling water according to the equation:

$$t_w = a + b \cdot \zeta \quad (^\circ\text{C}) \quad (4)$$

where:

a, b - regression constants of linear function (1)

ζ - dimensionless height of the mould (1)

In the region of the free height of the mould, this temperature corresponds to the outlet temperature of the cooling water, at the end of the mould, at its lower edge, then to the inlet temperature of the cooling water – the counter-current exchanger system. The length of the mould is divided into $n-1$ layers with an equidistant step, and in each of these layers the dimensionless coordinate and the actual temperature value are determined by linear interpolation. A temperature simplex of the form is introduced:

$$\Theta_i = t_{sk}^{L=L_{vrstva}} \cdot (t_{sk}^{L=L_{kr}})^{-1} \quad (1) \quad (5)$$

where:

$t_{sk}^{L=L_{vrstva}}$ - the actual temperature of the mould insert in a particular $n-1$ layer ($^\circ\text{C}$)

$t_{sk}^{L=L_{kr}}$ - the actual temperature of the mould insert at the lower edge of the mould ($^\circ\text{C}$)

Then the calculation of the rate of heat flow P_i of a particular layer takes on an iterative character.

$$P_i^{vrstva} = \Theta_i \cdot P^* \quad (\text{W}) \quad (6)$$

where:

P^* - rate of heat flow at the lower edge of the mould (W)

With regard to the iterative calculation, the condition of balance between heat fluxes obtained by summation

$\sum_{i=1}^{n-1} P_i^{vrstva}$ and the heat flow removed by the cooling water must apply:

$$\sum_{i=1}^{n-1} P_i^{vrstva} = P_w \quad (\text{W}) \quad (7)$$

The heat flux of a particular layer is determined according to the equation:

$$q_i^{vrstva} = P_i^{vrstva} \cdot (S^{vrstva})^{-1} \quad (\text{W} \cdot \text{m}^{-2}) \quad (8)$$

where:

S^{vrstva} - area of the layer (m^2)

Using the described methodology, heat fluxes along the length of the mould were calculated for both investigated steel grades. A prerequisite for a correct evaluation of the uniformity of heat removal from the mould is the inclusion of the influence of the casting speed [10]. In operating conditions, these speeds were different for the individual cast melts, and therefore each carbon group was further divided according to the casting speed. Brand A was measured sequentially at casting speeds of 0.46, 0.50 and 0.52 $\text{m} \cdot \text{min}^{-1}$, and brand B was measured at casting speeds of 0.50, 0.54 and 0.62 $\text{m} \cdot \text{min}^{-1}$. From **Figure 2** below, it can be seen that the heat removal from the mould along its length is closely related to the proportion of carbon in the steel. Low-carbon steels exhibit greater shrinkage during solidification than steels with a higher carbon content, and therefore a larger gas gap is created in the lower part of the mould, which results in a more significant decrease

in heat flux. In both graphs, three curves are shown for each casting speed. It is confirmed that this indicator has a significant effect on heat flux.

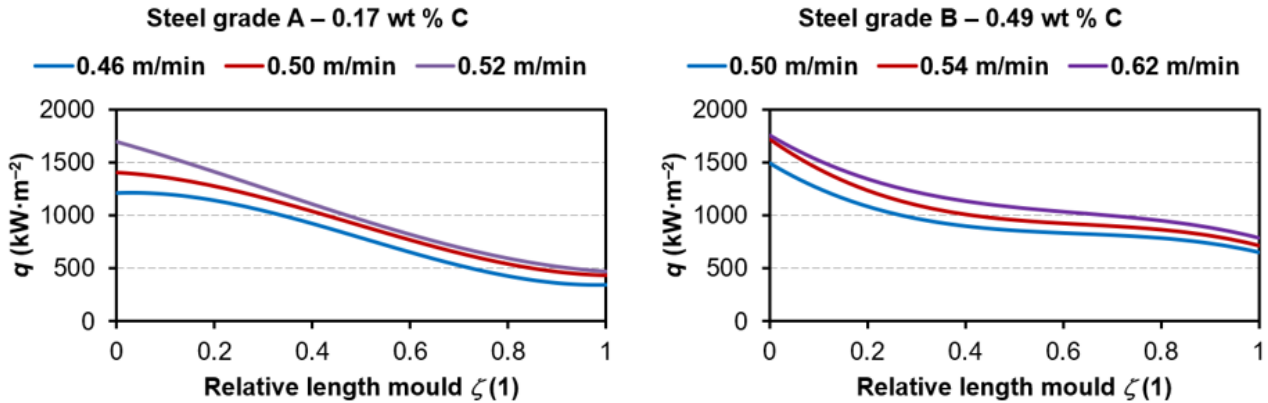


Figure 2 Dependence of the heat flux density on the height of the mould

Heat fluxes along the length of the mould for individual grades and casting speeds were expressed by polynomials of the third degree, as shown below **Table 2**. The expressed heat flux polynomials will be used in the next phase of the research for numerical simulation, specifically they will be rewritten into a user function in the environment of the casting simulation software, where they will represent the surface condition of 2nd kind for the primary cooling area.

Table 2 Heat flux dependencies

wt% C	m·min ⁻¹	$q = q_3 \cdot \zeta^3 + q_2 \cdot \zeta^2 + q_1 \cdot \zeta + q_0$ (kW·m ⁻²)
0.17	0.46	$q = 2.0264 \cdot 10^3 \zeta^3 - 3.0767 \cdot 10^3 \zeta^2 + 1.8107 \cdot 10^2 \zeta + 1.2136 \cdot 10^3$
	0.50	$q = 1.5870 \cdot 10^3 \zeta^3 - 2.3106 \cdot 10^3 \zeta^2 - 2.4592 \cdot 10^2 \zeta + 1.4013 \cdot 10^3$
	0.52	$q = 8.5631 \cdot 10^2 \zeta^3 - 7.8477 \cdot 10^2 \zeta^2 - 1.2934 \cdot 10^3 \zeta + 1.6947 \cdot 10^3$
0.49	0.50	$q = -2.1482 \cdot 10^3 \zeta^3 + 4.0818 \cdot 10^3 \zeta^2 - 2.7755 \cdot 10^3 \zeta + 1.4967 \cdot 10^3$
	0.54	$q = -2.4170 \cdot 10^3 \zeta^3 + 4.6692 \cdot 10^3 \zeta^2 - 3.2566 \cdot 10^3 \zeta + 1.7187 \cdot 10^3$
	0.62	$q = -1.9514 \cdot 10^3 \zeta^3 + 3.7084 \cdot 10^3 \zeta^2 - 2.7256 \cdot 10^3 \zeta + 1.7569 \cdot 10^3$

Figure 3 shows the average values of the heat flux for individual grades of steel depending on the casting speeds. The presented results confirm that the value of the heat flux increases with increasing carbon content and with increasing casting speed.

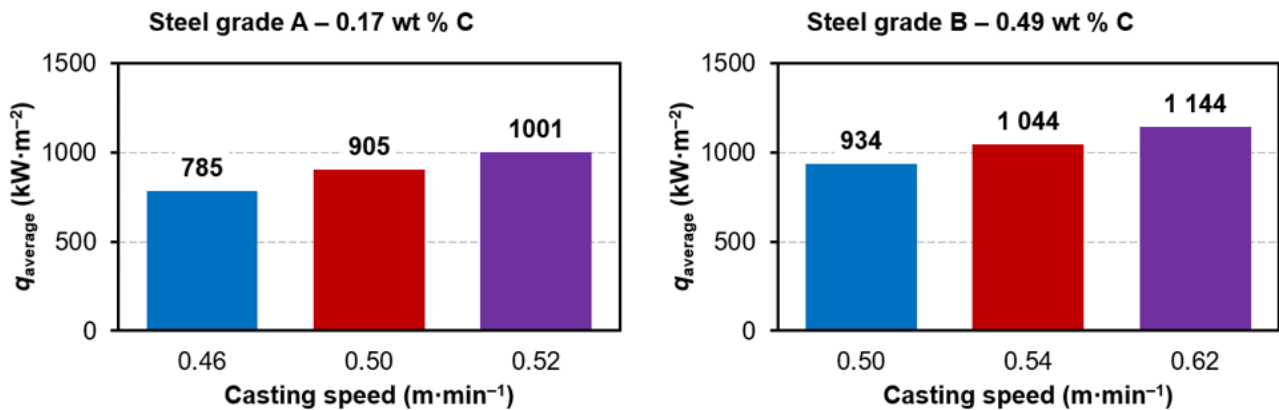


Figure 3 Average heat fluxes

4. CONCLUSION

The contribution describes the research of thermal processes in the primary cooling zone from the point of view of the evaluation of heat flow densities depending on the chemical composition of the steel and the casting speed. The work deals with mould of circular profile with a diameter of 410 mm and a length of 600 mm. Two grades of steel were selected for the processing and evaluation of the measured data. Low carbon steel (grade A – 0.17 wt% C) and medium carbon steel (grade B – 0.49 wt% C). Casting speeds for both grades were chosen in the range from 0.46 m·min⁻¹ to 0.62 m·min⁻¹. Using the proposed calculation methodology for heat dissipation into the cooling water, the course of the heat flux was determined depending on the chemical composition of the steel and the casting speed. After evaluating the results, it can be stated that a smoother decrease in heat flux was achieved in low-carbon steel, where more even heat removal from the mould was observed. In the next phase of the research, numerical simulations will be carried out to determine the temperature fields. The objective of the numerical simulations will be to determine the optimal parameters of the continuous steel casting process.

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