HEAT TRANSPORT IN MOULD FOR CONTINUOUS CASTING OF STEEL

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Abstract

Heat processes in the primary cooling area have decisive influence on the quality of casted production. Even formation of casting crust in mould depends on its thermal work, related to distribution of temperature along the height of individual mould walls, which affects operation of the whole casting machine in fundamental way. The knowledge of round blank temperature field during its casting and cooling makes possible to solve the problematic of inner structure, surface quality, blank mechanical properties, metallurgical length, casting crust thickness growth for different casting velocities and steel overheating. For each mould there is correlation between the thermal flow, which is removed from solidifying steel to cooling water, and temperature of the mould copper wall. From the temperature profile along the wall height or circumference it can be deduced, how tight is the contact between the blank surface and the mould wall and thus what intensity and evenness of heat removal is in the place in question. The heat removal should be, as far as possible, constant in the mould location and even along the circumference of cross-section. Variable removal of heat induces tension within crust and when critical values are exceeded, cracks occur, which may even result in a breakout. From the view of cast production quality it is necessary to monitor and optimize these processes.

1. INTRODUCTION

The technology of continuous casting is characterized by its variety and is a result of the whole previous phase of steel making preparation and processing immediately before the continuous casting process. This complicated and on many conditions depending process that takes place in a mould can be better analysed and consequently evaluated provided that the quantities that change during the casting process are measured directly on the mould.

The kinetics of the temperature field of the mould walls that are a manifestation of the temperature flows from liquid steel to cooling water generally carry the largest measure of information about a complicated process of the solidification in the mould. If the approximately constant heat resistance of the copper mould walls, coefficient of heat transfer from copper to water, and the temperature of the cooling water are assumed, the measurement of heat flows can be substituted by measuring of the individual temperatures in the wall. The measured temperature field is quantitatively evaluated from the point of view of temperature values, qualitatively with regard to the cooling symmetry, and further from the point of view of its dynamics, i.e., the temperature fluctuations and changes in symmetry of temperature in time.

An intensity of removed heat has a significant influence on a thickness of a solidified casting crust that is different not only for each casting, the temperature and chemical composition of steel, physical parameters of the mould and blank, but it also changes in time.

2. REMOVAL OF HEAT FROM THE MOULD

The size of heat flows can be best determined from the direct calculation from temperatures measured in the mould by a pair of thermocouples that must be placed in the same level in different heights of the mould and
in various distances from the surface of the inner mould side. During practical measurements on the mould only one of these thermocouples was always placed in a given level of the mould height, so this method could not calculated the heat flows, nor a position of a heat axis.

A new methodology was used to calculate the heat flows, according to which monitoring of the heat work of the mould can be done by monitoring of heat fields under known boundary conditions, since temperatures in the given location on the mould depend practically linearly on the heat flow density from the blank. The assumption is maintaining of a constant temperature and flow of the cooling water.

The experimental measurement was performed in the circular mould with the length of 600 mm and diameter of 410 mm. On the sides of small and large radius there were always 6 thermocouples in the distances of 100, 200, 275, 345, 425, and 520 mm from the mould upper edge. In order to achieve a perfect thermocouple contact with the mould wall we have designed building the thermocouples into copper cylinders that were installed into the holes drilled in the mould wall. The special NiCr – CuNi, type E thermocouples that are the most suitable for measurement of “low” temperatures were used for the measurement.

A long-term research [1,2] confirmed that a significant factor that influences the character of heat removal is the steel chemical composition. Therefore two steel types that represent two most cast steels were selected for the experiment. The low carbon steel type A contained 0.16 mass % C, and the medium carbon steel type B had 0.49 mass % C.

Another assumption for the correct evaluation of heat removal uniformity from the mould was inclusion of the casting speed. Under operational conditions these casting speeds differed for individual casts, therefore each carbon group was subdivided according to the casting speed values. The type A was gradually measured in speeds of 0.46, 0.50, and 0.52 m.min⁻¹, and the type B for casing speeds of 0.50, 0.54, and 0.62 m.min⁻¹.

The heat transfer from the mould to the cooling water can be described by the following equation:

\[ q = \frac{t_m - t_w}{\frac{s}{\lambda} \frac{1}{\alpha} + \frac{1}{\alpha}} \text{ (W.m}^2\text{)} \]

kde \( \lambda \) is mould heat conductivity coefficient (W.m⁻¹.K⁻¹),
\( s \) - mould wall thickness (m),
\( t_m \) - mould wall temperature (°C),
\( t_w \) - cooling water temperature (°C),
\( \alpha \) - coefficient of heat transfer from the mould outer surface to cooling water (W.m².K⁻¹).

This equation shows that during the calculation of heat flows it was necessary to take into account the cooling water temperature also, since this quantity was not constant along the mould height, and this change must have been accounted for. On the other hand the mould heat conductivity coefficient values and the values of the heat transfer coefficient were almost constant, therefore they were used as constants. The measured data files contained information about the inlet cooling water temperature and the temperature difference at the mould inlet and outlet. A linear relationship of the temperature increase was created from these data. Water is on this type of cooling device coming up to the mould that is why its temperature increased toward the upper part of the mould. In this relationship temperatures were read in places with the thermocouples and from these temperature pairs their differences were calculated. These pairs were then
entered into the graphs in relation with the relative mould height and the regression relationships were found using polynomial functions.

The mould was further divided to elementary planes from the steel level up to the lower edge of the mould. Using the regression relationships calculated for each monitored casting the temperature coefficients for each elementary plane that characterize the relative temperature arrangement along the height of the mould were calculated.

To calculate the temperature flows we used a program that works based on an iteration method, according to which the temperature flows in the individual layers can be calculated. The sum of these layer values then has to be equal the total temperature flow of water that was calculated from the values residing in the data files, like a product of the volume flow, density, specific heat capacity, and temperature differences between the inlet and outlet to the mould. The heat flow density in individual elements is obtained from the temperature flows relative to the plane areas and consequently drawn to the graphs.

![Graph 1](image1.png)

**Fig. 1** Heat flow along the relative height of mould at the type A.

![Graph 2](image2.png)

**Fig. 2** Heat flow along the relative height of mould at the type B.

The Fig. 1 and 2 show values of the heat flows for both investigated steel types. The pictures show that the removal of heat from the mould along its height is closely related to the ratio of carbon in the steel types. The low carbon steel shows larger contraction during solidification than steel with a higher carbon content, therefore a larger gas gap is created in the lower part of the mould that consequently signifies a more significant decrease in heat removal. Both graphs always show three curves for each casting speed. It shows that also this indicator has a significant influence for heat removal. During higher casting speeds the thinner casting crust is more intensely pushed against the mould walls, which leads to a higher density of the heat flow from the blank to the mould wall. A shorter time period of the blank remaining in the mould contributes to an increase in the blank surface temperature and further increase in the heat removal. The higher surface temperature slows down contracting and enables a better contact of the blank with the inner mould wall. However, excessively high casting speeds lead to cracks and outbreaks due to weakening of the casting crust.

3. **SIMULATION OF THE HEAT PROCESSES**

Working conditions in the mould have a direct influence on the creation of uniform casting crust and the surface quality of a blank. The effort to prevent outbreaks caused fast progress of operational systems for
continuous monitoring of heat and mechanical quantities in mould lately. Beyond this there was a large amount of theoretical and experimental research focused on obtaining of knowledge of continuous casting processes and finding relationships between heat and mechanical quantities in mould and technological parameters. The question of mathematical modelling lies in insufficient knowledge of heat transfer along the mould circumference. Because during casting there is an irregular movement of a blank towards individual mould sides, which causes inequalities in removal of heat from the blank, which consequently shows in inequalities in the casting crust thickness along the mould diameter [3].

In order to simulate heat processes in the primary cooling area we used calculated values of the heat removal from the previous experiment. We have used a simulation program (Fig. 3), that is based on the numerical method whose fundamentals lie in discretization of variables and has significant potential possibilities of utilization under computer modelling conditions.

This method is typical for repeatability of simple algebraic operations. It enables obtaining of problem solutions in a finite number of discrete places (nodes) of a chosen differential network or finite element network along its whole area.

A part of the program is an extensive information database, including thermo-physical properties (density, specific heat capacity, heat conductivity coefficients, viscosity, etc.). The program also solves tension states during continuous casting, or a structure of steel in the so called segregation module. The calculation network has been set for vertical casting on a circular mould.

The physical description of simulated quantities has been performed on the basis of the continuity equation, Navier–Stokes equation, and the Fourier heat conductivity equation. In case of tension and deformation state simulations we have used the tension determination and deformation equations and structure transformation diagrams. The temperature layout during solidification, or cooling is calculated not only along the nodes, but in the whole casting blank volume.

Fig. 3 Numerical program for simulation of heat processes.
The simulation target was to find the progress of solidification for the two steel types, one of them low (type A) and the other medium carbon one (type B), and to compare them. Different values of heat flows obtained at different casting speeds show, just like previously [4], that it is possible to compare objectively only the steel types with constant speeds. For this reason the castings with the constant casting speed of 0.5 m.min\(^{-1}\) were consequently compared. The simulation progress for low carbon steel is shown on the following pictures. The Fig. 4 show increase of the casting crust along the mould height, the Fig. 5 shows temperature distribution during simulation.

The casting crust starts being created in the meniscus area, where the level of liquid metal meets the mould wall surface. The process of casting crust creation is complicated and is related to a number of other phenomena during continuous casting. The liquid steel which is in contact with the mould wall is intensely cooled and starts to solidify along the wall. The crust thickness increases with the distance from the steel level [5]. A required crust thickness at the mould outlet depends on the size of the cast blank profile and casting speed. For larger profiles the crust thickness can be considered sufficient at 25 mm, for small rectangular formats (approx. up to 100 mm) 10 mm is sufficient. During unequal solidification the crust thickness along the wall is not uniform and conditions for the crust rupture in the weakest point are created. The Fig. 6 shows the found increased casting crust thickness for both steel types. At the mould outlet the casting crust thickness is 21.2 mm for the low carbon steel and 25.4 mm for the medium carbon one.
The different values for both casting types are caused by the different ration of carbon in the steels. This is primarily in the area of peritectic steels that show larger contraction during solidification than steels with a higher carbon content. The intensity of heat removal that was lower in the low carbon steels, especially at the bottom part of the mould, also influences the size of solidified crust significantly. The casting crust thickness can be increased by casting with lower casting speeds, which is, however, not beneficial for performance of a casting machine. Another possibility is adjusting the mould conicity in the critical areas of the steel contraction.

4. CONCLUSION

Based on experimental research on the operation equipment for continuous casting of steel blanks we have analyzed the mould heat work from the point of view of suitable heat removal in the primary cooling area. Using the measured temperature profiles in the mould wall and the calculated heat removal into cooling water we have determined the heat flow progressions related to the chemical composition of steel and the casting speed. Consequently we have done simulation calculation to obtain the temperature fields and thicknesses of casting crusts. From obtained simulations we can state that they enable determination of optimum parameters for continuous steel casting processes. Using of the results obtained during the simulation processes also provides high economic benefits and further lowers a number of technological tests connected to the optimization process of steel continuous casting itself.

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LITERATURE