SIMULATION OF SELECTED PARAMETERS IN CONTINUOUS STEEL CASTING

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Abstract

The presented paper focuses on numerical modelling of temperature fields of a continuously cast billet. The ProCAST software system, which is based on the finite element method, was used as a simulation tool. The finite element method (FEM) is a modern, highly efficient numerical method for solving technical problems of continuous steel casting. It is currently considered to be one of the most effective approximate methods for solving problems described by differential equations. The effect of the change of the casting velocity on the surface and axial temperature was evaluated on the temperature model of a continuously cast billet of rectangular cross-section with dimensions of 150 x 150 mm, and further, the effect of the change of the casting velocity on the metallurgical length was also evaluated. The simulation tasks were characterized by the invariable content of carbon and the invariable casting temperature. In total, twelve simulation tasks were carried out, marked A1 to C4. Specifically the solidification and cooling problems of the billet were solved for steels with a carbon content of 0.07 wt.%, 0.18 wt.% and 0.83 wt.% at a casting velocity from 2.1 to 2.7 $m.min^{-1}$ and casting temperatures from 1500 to 1560 °C. Graphical waveforms of surface and axial temperatures of the billet and metallurgical length were obtained from the simulation results. The results of the simulation tasks will be used to verify and substantiate the model.

Keywords: ProCAST, numerical temperature model, surface temperature, metallurgical length

1. INTRODUCTION

The presented paper shows the basic use of the ProCAST software system, which is widely used for modelling continuous steel casting [1], [2], [3]. Study of the above sources, combined with the calculation results of the simulation tasks, forms the basis of this paper. ProCAST uses the finite element method and has THERMAL, FLOW, RADIATION, STRESS, and MICROSTRUCTURE modules. The THERMAL module was used to design the temperature model. The solution of each task in the ProCAST environment can be divided into three basic stages: design of a numerical model and preparation of input data (pre-processing), actual calculation (processing), and processing of the results (post-processing) [4]. The decisive criterion for obtaining the correct results of the numerical simulation is the design of the optimal network and the correct choice of boundary conditions [5]. A fine network with many elements leads to a good division of the model and corresponds to an accurate calculation. However, this situation leads to long computation times of the simulation. To shorten the computational simulation time, the model was designed using a coarse mesh network and symmetry [6].

Surface conditions in the form of heat flux densities q ($W.m^{-2}$) and heat transfer coefficients α ($W.m^{-2}.K^{-1}$), were used in the calculation, based on whether it was a primary, secondary or tertiary cooling zone [7]. In the primary cooling zone, the heat flux density q ($W.m^{-2}$) between the steel and the cooling water of the mould, i.e., surface condition type II, was entered into the model. When determining the heat removal rate from solidifying steel, the parameters of the cooling water and temperature gradients along the height and perimeter of the working surface of a copper insert of a rectangular cross-section mould, with dimensions of 150 x 150 mm and a length of 1 m, were used. The heat flux density was expressed by a third-degree polynomial. In the secondary cooling zone, the heat transfer coefficient of the cooling water injection was entered into the model [8].

2. BASIC EQUATION OF HEAT TRANSFER EQUATION IN THE FIELD OF CONTINUOUS STEEL CASTING

Heat transfer during continuous steel casting can be understood as a non-stationary process with complex boundary conditions of solution [9]. An analytical solution to this problem is practically impossible, so mathematical or computer modelling, with some simplification of real conditions and a description of those criteria that affect the solidification and cooling process the most, is accepted [10].

The basic equations describing heat transfer and flow in the field of continuous steel casting include: The Continuity equation, Bernoulli's equation, the Navier-Stokes equation of motion and Fourier-Kirchhoff's equation. Below is a description and evaluation of the heat conditions during heat transfer in the primary, secondary and tertiary cooling zones.

Heat transfer in the primary cooling zone

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

$$R_c = \left(\frac{s_0}{\lambda_0} + \frac{1}{\alpha_1} + \frac{s_k}{\lambda_k} + \frac{1}{\alpha_2} \right) \tag{1}$$

where:

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

s_0 - casting bark thickness (steel) (m)

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

α_1 - heat transfer coefficient between the billet shell and the inner wall of the mould ($W.m^{-2}.K^{-1}$)

α_2 - heat transfer coefficient between the mold wall and the cooling water ($W.m^{-2}.K^{-1}$)

s_k - mould wall thickness (m)

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

Heat transfer in the secondary cooling zone

Heat dissipated from the precast surface in the secondary zone thus consists of three components. In places directly cooled by water, heat is consumed to heat the water and partially evaporate it. Heat is shared on the non-wetted surface by radiation and convection. At the points of contact of the surface of the precast with the guide rollers, heat is dissipated by conduction.

Due to the high temperatures, the heat transfer from the precast in the secondary zone is very complicated, because when the precast is sprayed with cooling water, the Leindenfrost effect occurs. In general, the heat dissipated by the cooling water from the surface of the billet can be determined from Newton's equation (2).

$$Q = \alpha_c \cdot (t_p - t_v) \cdot S \cdot \tau \tag{2}$$

where:

Q - heat dissipated by cooling water from the surface of the billet (J)

α_c - total heat transfer coefficient from the billet surface ($W.m^{-2}.K^{-1}$)

t_p - billet surface temperature (°C)

t_v - cooling water temperature (°C)

S - cooled surface area (m^2)

τ - spray time (s)

Heat transfer in the tertiary cooling zone

After the billet leaves the secondary cooling zone, heat is shared from the surface of the billet by radiation and convection in the tertiary cooling zone.

The issue and detailed derivation of the above equations is described in the literature [11], [12].

3. MODELLING IN THE PROCAST PROGRAM

The ProCast program solved the solidification and cooling of a billet of rectangular cross-section with dimensions of 150 x 150 mm. A total of 12 simulation tasks were performed, marked A1 to C4. The simulation tasks were characterized by a constant carbon content (wt.% C) and a constant casting temperature $t_{casting}$ (°C). The variable was the casting velocity v ($m.min^{-1}$). In the first phase, the effect of the change in casting velocity on the surface and axial temperature of the billet was investigated. In the second phase, the effect of the change in casting velocity on the metallurgical length of the billet was investigated [13]. The input values of the simulation tasks are given in **Table 1**.

Table 1 Input values of simulation tasks

Task	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
v ($m.min^{-1}$)	2.1	2.3	2.5	2.7	2.1	2.3	2.5	2.7	2.1	2.3	2.5	2.7
wt.% C	0.07				0.18				0.83			
$t_{casting}$ (°C)	1560				1550				1500			

Figure 1 presents the output from the ProCAST software system. This is a numerical temperature model. The graphical outputs of the C4 simulation task were selected. The left part of the image shows the temperature field in 2D and 3D views. Color resolution characterizes the surface temperature distribution. In the right section, you can see the length of the liquid core from the level in the mould to the place of complete solidification in the entire cross section of the billet. Color resolution characterizes the proportion of the solid phase.

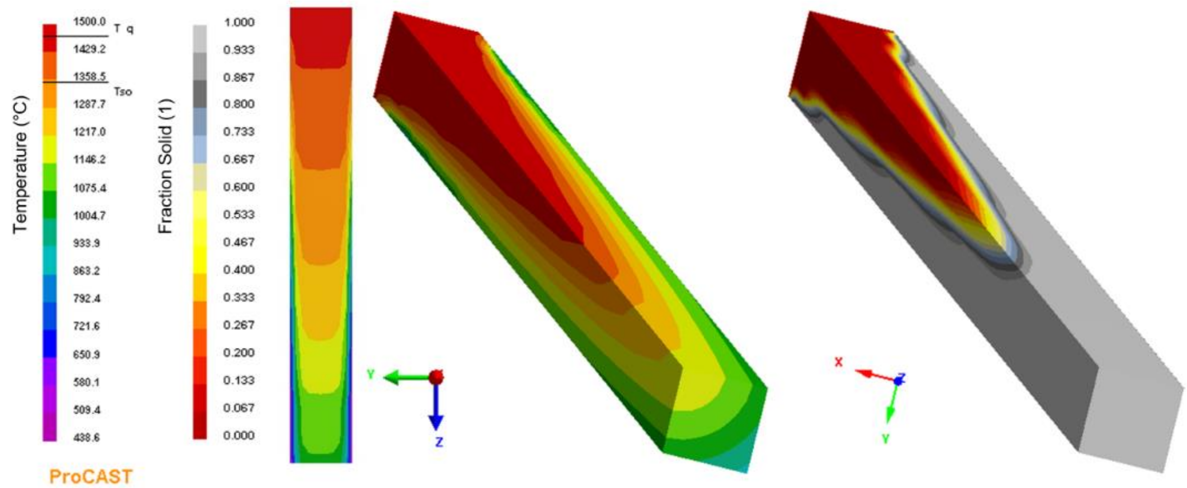

Figure 1 Numerical temperature model

3.1. Effect of change of casting velocity on surface and axial temperature of the billet

In the first phase, the effect of the change of the casting velocity on the surface and axial temperature of the continuously cast billet was investigated using numerical simulation in the ProCAST environment.

Temperatures were subtracted from the results of simulations on a temperature model at distances of L1 = 1.145 m, L2 = 3.687 m a L3 = 16.68 m from the lower edge of the mould. The distances correspond to the real positions of the pyrometers in the experimental measurements [4].

Graphical waveforms of surface $t_{surface}$ and axial t_{axis} of billet temperatures were obtained from the simulation results, see **Figure 2**. The upper curves in the presented figure represent the temperatures in the billet axis, and the lower curves represent the billet surface temperatures. The temperatures in the billet axis gradually decrease from the beginning, after reaching the temperature of a solid, the cooling rate increases. Temperature jumps in the secondary cooling zone, caused by the individual rows of cooling nozzles, are evident in the progression of the surface temperatures of the billet. In the lower part of the secondary zone, the surface temperatures increase and when the billet passes to the tertiary cooling zone, the temperature decrease slows down.

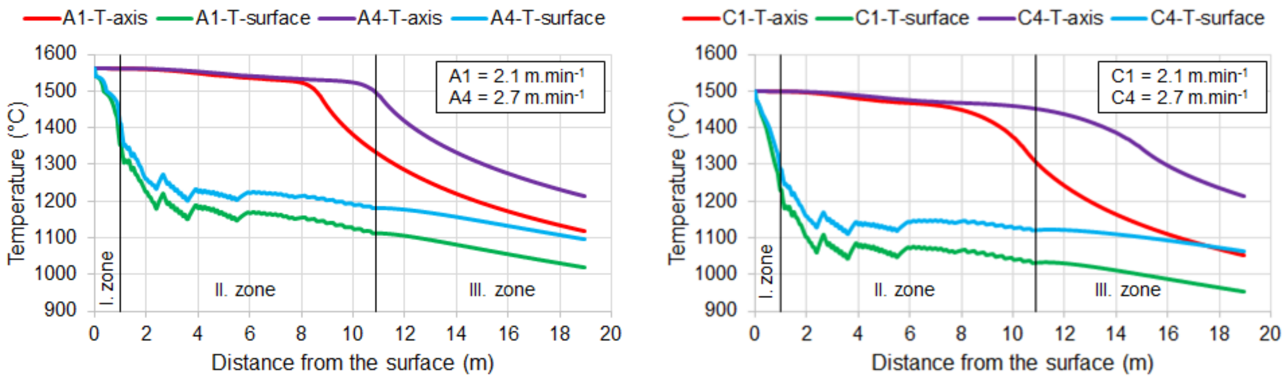

Figure 2 Course of surface and axial temperatures for steels A and C

From the results obtained, it can be stated that the increased casting velocity is reflected in the increase of the surface and axial temperatures of the continuously cast billet. At higher casting velocities, less heat is dissipated by the cooling water. The resulting thinner casting crust is pressed more intensively against the mould wall, which leads to an increase in the heat flux density from the billet to the mould wall [14]. The shorter time the billet remains in the mould contributes to an increase in surface area and temperature. The increased casting velocity at the axial temperature of the billet is reflected mainly in the tertiary cooling zone. The subtracted surface and axial temperatures for the boundary velocities are given in **Table 2**.

Table 2 Calculated values of simulation tasks

Task		A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
v	$(m.min^{-1})$	2.1	2.3	2.5	2.7	2.1	2.3	2.5	2.7	2.1	2.3	2.5	2.7
$t_{surface, L1}$	(°C)	1226	-	-	1260	1186	-	-	1230	1103	-	-	1160
$t_{surface, L2}$	(°C)	1174	-	-	1220	1138	-	-	1195	1071	-	-	1133
$t_{surface, L3}$	(°C)	1037	-	-	1113	999	-	-	1104	970	-	-	1079
$t_{axis, L1}$	(°C)	1558	-	-	1559	1548	-	-	1549	1497	-	-	1499
$t_{axis, L2}$	(°C)	1543	-	-	1549	1530	-	-	1537	1477	-	-	1485
$t_{axis, L3}$	(°C)	1142	-	-	1243	1099	-	-	1241	1079	-	-	1248

Subsequently, a comparison of the surface temperature readings from the simulation results with the experimental values was performed. The experimental values measured by radiation pyrometers on a real casting machine at positions L1, L2 and L3 from the lower edge of the mould are 20 to 30 °C lower than the surface temperatures obtained on the numerical temperature model. This difference is due to the determination of the emissivity value of the steel, which depends on both the surface temperature itself and the chemical composition of the steel. This fact can significantly distort the values of the surface temperatures calculated by numerical simulation. A problem influencing the measurement of surface temperatures by radiation pyrometers is also the scale layer, which arises as a result of the technological process on the surface of the cooling billet. The scales have a different emissivity value than the "clean" surface of the billet and significantly affect the measurement of the actual surface temperature.

3.2. Effect of change of casting velocity on metallurgical length of the billet

In the second phase, the effect of the change in casting velocity on the metallurgical length of the continuously cast billet was investigated. The metallurgical length is defined as the length of the liquid core from the level in the mould to the point of complete solidification in the entire cross-section of the continuously cast billet. The development is aimed at extending the metallurgical length with the aim of increasing the casting performance while reducing the radius of the casting arc. This is also related to savings in investment costs of continuous steel casting equipment.

The metallurgical lengths for the individual simulation tasks (A1 to C4) were read from a numerical temperature model and converted into a graphical form. The metallurgical lengths of the simulation problems can be deduced from the bar graphs below in the left part of **Figure 3**. For the simulation problem A1 the metallurgical length of 7.7 m was subtracted. For the simulation problem A4 the metallurgical length of 11.2 m was subtracted. The increase in the casting velocity from 2.1 m.min^{-1} to 2.7 m.min^{-1} for steel A will be reflected in an increase in the metallurgical length by 3.5 m. The metallurgical length 9.0 m was subtracted for the simulation task B1 and 12.3 m for the simulation task B4. The increase of the casting velocity for steel B is reflected by an increase of the metallurgical length by 3.3 m. For the simulation task C1, the metallurgical length of 10.6 m was subtracted, and 15.1 m was subtracted for the simulation task C4. The increase in casting velocity for steel C is reflected in an increase in the metallurgical length by 4.5 m. In the right part of **Figure 3**, a graph is further presented, where the trend lines were interspersed with points of metallurgical lengths calculated by numerical simulation. The dependence of the metallurgical length was captured by a polynomial of the 2nd degree. **Figure 3** shows that with increasing casting velocity and increasing carbon content in the steel, the distance at which the entire cross section of the billet solidifies increases.

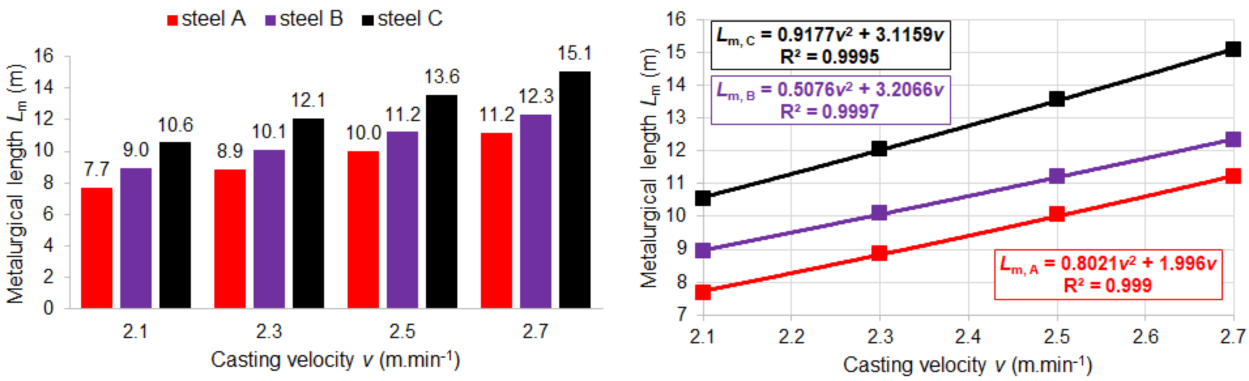

Figure 3 The influence of the casting velocity change on the metallurgical length

4. CONCLUSION

Optimization of the continuous steel casting process is not possible through modelling alone. Working closely in tandem with the results of experimental measurements is always necessary, as these results bring into the system the characteristic features of a particular casting machine. To approximate the real values, it is also necessary to focus on specifying the boundary conditions. The main problem is to determine the value of the heat transfer coefficient α (W.m^{-2}.K^{-1}) in the secondary cooling zone. A numerical model in the ProCAST environment was used to simulate the solidification and cooling of a billet of rectangular cross-section 150 x 150 mm for steel with a carbon content of 0.07 wt.%, 0.18 wt.% and 0.83 wt.% at a casting velocity of 2.1 to 2.7 m. min^{-1}. In the first phase, the effect of the change in casting velocity on the surface and axial temperature of the billet was investigated. In the second phase, the effect of the change in casting velocity on the metallurgical length was investigated. Graphical waveforms of surface and axial temperatures of the billet and metallurgical length were obtained from the simulation results. From the presented results, it can be stated that the increased casting velocity is reflected in the increase of surface and axial temperature. As the casting velocity increases and the carbon content of the steel increases, so does the distance at which the entire cross section of the billet solidifies. Using the results of the simulations, the functional dependence of the thickness of the casting crust on the variable parameters, for example at the point of exit from the mould, can also be evaluated. The results achieved will be used to verify and substantiate the model.

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