The influence of the selected parameters of the mathematical model of steel continuous casting on the distribution of the solidifying strand temperature

J. Falkus, K. Miłkowska-PiszczeK*, M. Rywotycki, E. Wielgosz
Faculty of Metals Engineering and Industrial Computer Science, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland
* Corresponding e-mail address: kamilo@agh.edu.pl

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ABSTRACT

Purpose: This paper presents the results of the numerical calculations concerning the influence of the placing of the developing gaseous gap in a mould based on the thickness of the forming shell, and the temperature distribution on the strand length. A cast slab with dimensions of 1100 mm x 220 mm was analysed. The calculations were performed on various heights of the formation of the gap in the mould. Other process parameters, i.e. the casting speed, melt temperature, and the cooling intensity in the secondary cooling zone, were maintained at a constant level.

Design/methodology/approach: The numerical model of the steel continuous casting process, developed with the ProCAST software was used. In the study the effect of the height of the air gap development was examined for five variants. In the heat transfer in the gap model, two basic heat transfer mechanisms were assumed: by radiation and by conductivity.

Findings: The numerical model of the steel continuous casting process with influence of the placing of the developing gaseous gap in a mould was developed. The verification of the calculation results obtained, after conducting a number or mathematical simulations, concerned the shell thickness and its dependence on the height of the air gap. The simulation of the temperature distribution was made for the whole strand.

Research limitations/implications: The numerical model of the steel continuous casting process, with the curved mould should be used to determine the influence of the placing of the developing gaseous gap.

Practical implications: The results of the numerical calculations with heat transfer model, concerning the influence of the placing of the developing gaseous gap in a mould based on the thickness of the forming shell, and the temperature distribution on the strand length.

Originality/value: The calculations were performed on various heights of the formation of the gap in the mould using ProCAST software. The calculated temperature distribution was verified on the basis of an industrial database.

Keywords: Continuous casting of steel; Numerical modelling; FEM

Reference to this paper should be given in the following way:
1. Introduction

There are three mechanisms of heat transfer in the steel continuous casting process: conduction, radiation and convection. After the steel next to the mould surface has been cooled below the solidus temperature, the development of the gap commences. The determination of the actual gap size is difficult due to three factors: the oscillating movement of the mould, the slab movement in the mould related to the casting speed, and the random movement of the slab in the plane that is perpendicular to the casting direction. The presence of mould powder, along with gases in the gap, are additional factors, which make the determination of heat transfer more difficult. As a result the thermal resistance in the gap is difficult to be accurately determined. In the heat transfer in the gap model, two basic heat transfer mechanisms were assumed: by radiation and by conductivity [1].

After leaving the mould, the slab surface is cooled with a water spray and in the air. The heat flux that is then carried away from the surface of the cooling down strand, is proportional to the temperature difference of the strand surface and the cooling medium temperature.

The heat transfer area in the mould may be divided into three zones: the zone of direct contact of the liquid steel with the mould walls; the intermediary zone where a layer of solidified steel appears; and the zone with the developing air gap. The development of the air gap causes a very high temperature gradient between the solidifying strand shell and the mould wall. The change in the gap parameters has a significant influence on the course of the crystallization process, and constitutes a potential source of disturbances for the stable course of the casting process. Therefore for the evaluation of the stability of the system considered it is vital to get to know the influence of the gap geometry on the thermal operation of the mould.

2. The model of heat transfer in the gap

The problem of modelling the temperature field distribution within the steel continuous casting process has been analysed by many authors. Both commercial software and proprietary applications have been used. The description of boundary conditions available in references is often restricted to giving the average values in the mould zone and it does considerably simplify the heat transfer model [2-10]. In the calculations presented, the heat transfer model for the mould described in the references was applied using the commercial ProCAST package. The package uses the enthalpy method to solve the set problem, and this method is described as in the equation [11].

\[
H(T) = \int_0^T c_p(T) \, dt + L(1 - f_s)
\]

where:
- \( H \) – enthalpy kJ/kg,
- \( c_p \) – specific heat, kJ/(kgK),
- \( L \) – transformation heat kJ/kg,
- \( f_s \) – share of solid phase.

The values of specific heat in the function of temperature, presented in Fig. 1 along with the value of transformation heat measured for steel grade S235 were used in the calculations. The chemical composition of steel S235 is presented in Table 1. The transformation heat is 113 kJ/kg.

![Fig. 1. The measured specific heat for steel S235](image)

<table>
<thead>
<tr>
<th>Chemical composition of steel S235</th>
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</thead>
<tbody>
<tr>
<td>C</td>
</tr>
<tr>
<td>0.07</td>
</tr>
<tr>
<td>Cr</td>
</tr>
<tr>
<td>0.15</td>
</tr>
</tbody>
</table>

In the developed model the heat transfer between the cast strand and the mould is performed through the gap. The heat transfer area in the mould is divided into two zones [1,12,13]. In the first one no gaseous gap is assumed. The whole space between the strand and the mould is filled with mould powder (zone 1). As a result of metal contraction a gaseous gap develops at a certain distance from the meniscus. This gap separates the mould powder layer from the mould surface, additionally insulating the strand (zone 2). A diagram of the existing thermal resistances is presented in Fig. 2.

![Fig. 2. A diagram of thermal resistances for heat transfer between the strand surface and the mould](image)
The heat transfer coefficient in the mould \([\text{W/m}^2\text{K}]\) is:

\[
h = \frac{1}{R_{sk}}
\]

(2)

where:

\[
R_{sk} = R_{air} + R_{slag}
\]

(3)

The heat resistance of the mould powder \([\text{m}^2\text{K}/\text{W}]\) is:

\[
R_{slag} = \frac{d_{slag}}{\lambda_{slag}}
\]

(4)

In the model of heat transfer in the gaseous gap, two basic heat transfer mechanisms were assumed: by radiation and by conductivity \([1,13,14]\):

\[
\frac{1}{R_{air}} = \frac{1}{R_{\text{cond}}^{air}} + \frac{1}{R_{\text{rad}}^{air}}
\]

(5)

The radiation heat transfer was calculated from the radiation law between two flat surfaces: the mould powder and the mould \([4]\):

\[
R_{\text{rad}}^{air} = \frac{1}{h_r}
\]

(6)

\[
h_r = \varepsilon_{s} C_o \left( \frac{T_2^4 - T_k^4}{T_2 - T_k} \right)
\]

(7)

where:

\(\varepsilon_{s}\) - substitute emissivity coefficient;

\(T_2\) - mould powder surface temperature, K,

\(T_k\) - mould inner surface temperature, K.

The mould powder surface temperature was determined on the basis of the condition of equality of heat fluxes. The conduction thermal resistance is:

\[
R_{\text{cond}}^{air} = \frac{d_{air}}{\lambda_{air}}
\]

(8)

The size of the area filled with powder was determined on the basis of average values of powder consumption in the process of steel continuous casting.

3. Variants of calculations

A model of a mould with a height of 900 mm and a wall thickness of 40 mm, along with a strand with a height of 23 m and a radius of 10.5 m, was developed with the ProCAST software package. The level of mould filling for all analysed cases was 850 mm.

Based on industrial data for the primary cooling zone, the heat transfer coefficient responsible for heat abstraction by the water flowing in the mould channels was assumed as 18000 \(\text{W/m}^2\text{K}\).

The temperature distribution in the mould powder is presented in Fig. 3.

Fig. 3. The strand surface temperature in the mould

On the basis of the obtained results, five points in the mould wall were arbitrarily chosen where the beginning of the gap development was simulated:

- The gap at a distance of 100 mm from the steel meniscus,
- The gap at a distance of 200 mm from the steel meniscus,
- The gap at a distance of 400 mm from the steel meniscus,
- The gap at a distance of 700 mm from the steel meniscus,
- The gap at a distance of 800 mm from the steel meniscus.

Next, the temperature values at the selected heights were read as the starting points for the developing air gap. This was the basis for the development of five sets of the heat transfer coefficient values in the mould depending on the height of the gap occurrence within. The heat transfer coefficient in the mould is a function of gaseous gap and slag layer thickness.

For the secondary cooling zone, which was broken down into seven sub-zones, a constant set of heat transfer coefficients was assumed. It was determined on the basis of the actual flows of the cooling water in individual sub-zones, and is strictly related to the strand withdrawal speed. The value of 0.8 m/min was assumed for all five variants (Fig. 4).

4. Calculation results

The verification of the calculation results obtained, after conducting a number of mathematical simulations, concerned the shell thickness and its dependence on the height of the air gap. The simulation of the temperature distribution was made for the whole strand.

The temperature distribution in the mould for the analysed cases is presented in Fig. 5.

In addition the shell thickness and the metallurgical length were compared for the individual variants. The results are presented in Table 2.
Depending on the height of the gap development in the mould, the solidified slab at the mould outlet ranges from 15 to 22 mm. We obtain the lowest value for variant 1, or for the gap developed closest to the steel meniscus in the mould. As expected, the highest shell thickness was obtained for variant 5, or for the gap developed 50 mm from the mould end. No significant influence of the height of the gap development on the metallurgical length was found, which for the calculated simulations ranged between 12.4 and 12.8 m.

The strand temperature difference at the mould outlet ranged from 882 to 1003°C for the five variants. For the modelled variants similar temperature distribution results were obtained. Note that the nature of the temperature distribution curve in the secondary cooling zone was the same as for the modelled variants. The strand temperature difference measured on the length of 23 m ranged from 832°C to 850°C.

### 5. Conclusions

In the study the effect of the height of the air gap development was examined for five variants. The numerical model of the steel continuous casting process, developed with the ProCAST software correctly and stably responds to a change in the heat transfer coefficient. The numerical simulations confirmed the negative effect of the air gap occurrence in the mould and its influence on the actual heat abstraction and the related strand shell thickness immediately downstream the mould outlet. At the same time one can observe that differentiation concerning the strand temperature is much lower already in the secondary cooling zone. Also the differences of the metallurgical length of the strand are fairly low. It leads to a conclusion, that the control of the developing gap is relevant mainly for the casting process safety because an increase in its size may lead to the formation of too thin shell, exposed to mechanical impact of the liquid core of the strand cast. The quantitative influence of the gap size on the shell thickness is clearly illustrated by the data in Table 2.

### Acknowledgements

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### References


