INFLUENCE OF COOLING PARAMETERS AND CASTING SPEED ON THE TEMPERATURE FIELD OF THE CONTINUOUSLY CAST STRAND

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Abstract

The paper presents results of simulation of continuous casting process curried out with the developed computer program. The program was created on the basis of the mathematical model of the heat transfer in the continuous casting process. The three-dimensional finite element method has been employed in the solution. Complex boundary conditions of the heat exchange have been taken into consideration, both in the mould as well as in the secondary cooling zones. The worked out model takes into consideration the heat of solidification and the convective heat transport resulting from the movement of the strand. The influence of the casting speed variation and the boundary conditions change on the temperature of round ingot has been analyzed. An influence of the number of water nozzles and variations of the water flux density on the possibility of shortening the time of strip cooling in the secondary zones have been examined.

Keywords: continuous casting of steel, secondary cooling of strand, finite element method

INTRODUCTION

In the process of continuous casting, cooling of liquid steel starts in mould which leads to formation of a solid layer at strand surface. In the secondary cooling zones farther increase of solid layer thickness takes place until complete solidification at the end of metallurgical length of casting line. However, too small thickness of the solid layer can lead to breaking the solid phase under influence of body forces and the leak of liquid steel outside the mould. It has special meaning in designing of mould shape as well as in the determination of continuous casting speed. Study of solidification of the continuous casting strand allows to select parameters of the process in order to increase the productivity of a casting line and to get the best parameters of the final product. Until recently experience was the main possibility of the improvement of casting technology. The development of computer methods has allowed modeling of metallurgical processes and has made possible technology improvement without the necessity of carrying out costly industrial tests. This was the main goal of the computer program development dedicated to analyze cooling conditions in the casting line. The developed computer program is equipped with pre- and post-processing of data. It makes simulation of the continuous casting process efficient. The input data are limited to technological parameters easy to program based on the knowledge of a particular casting line.
1. HEAT TRANSFER IN THE STRAND AND THE MOULD

The transfer of energy in the strand is composed of heat conduction in the solid shell and in the liquid core. In the developed model heat transfer is computed from the equation:

\[
\frac{\partial T}{\partial \tau} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} = \frac{\lambda}{\rho c} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{q_v}{\rho c}
\]

where: \( T \) – temperature, K; \( \tau \) – time, s; \( v_x, v_y, v_z \) – velocity field, m/s; \( \lambda \) - thermal conductivity, W/(m K); \( q_v \) – internal heat source, W/m³; \( c \) – specific heat, J/(kg K); \( \rho \) – density, kg/m³.

The solution of the strand cooling problem is possible if mould surface temperature is known. The mould temperature has been calculated from the transient heat conduction equation:

\[
\frac{\partial T}{\partial \tau} = \frac{\lambda}{\rho c} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)
\]

The finite element method has been employed to solve the heat transfer problem. Numerical model is based on the Galerkin method. Nonlinear shape and weighting function have been employed in the solution. The more detailed description of the three dimensional finite element model has been presented in [2,3].

2. BOUNDARY CONDITIONS

Solution to the general heat transfer eq. (1) should obey the boundary conditions specified on the steel surface. In the mould, on the steel – mould interface \( S_{sm} \) heat flux \( q_{sm} \) must be equal to:

\[
q_{sm} = \alpha_{sm}(T_s - T_m) \quad \text{on} \quad S_{sm}
\]

where: \( \alpha_{sm} \) – combined heat transfer coefficient, W/(m² K); \( T_m \) – mould temperature, K; \( T_s \) – steel surface temperature, K.

Below the mould on the free surface of the strand \( S_f \) convection boundary condition are specified and the heat flux \( q_{sf} \) can be expressed as:

\[
q_{sf} = \alpha_s(T_s - T_{ws}) \quad \text{on} \quad S_{sf}
\]

where: \( \alpha_s \) – convection heat transfer coefficient for water spray or air cooling, W/(m² K); \( T_{ws} \) - air temperature or water spray temperature, K.

The most intensive cooling of steel take place in the mould at the meniscus level. In this zone the heat flux density can reached 10 MW/m² [4]. The convection heat transfer coefficient between liquid steel and mould \( \alpha_s \) has been calculated from the Sebana-Shimazaki equation [5] for the Prandtl number \( Pr < 0.1 \):

\[
Nu = 4.8 + 0.025(RePr)^{0.8}
\]

Below the meniscus level solidification of steel take place and a solid shell is formed. It leads to a gap formation between the solid shell and the mould below liquidus temperature \( T_l \). The gap is filled with gases and the combined heat transfer coefficient below the liquidus temperature \( T_l \) has been calculated from the empirical equation:

\[
\alpha_{sm} = \alpha_r + (\alpha_{ls} - \alpha_r) \exp \frac{\tau_{sl} - T_{sm}}{T_{sm}}
\]

where: \( \alpha_r \) – radiation heat transfer coefficient, W/(m² K); \( T_{sm} \) – temperature of the mould powder solidification, K; \( T_{sol} \) – solidus temperature, K. The value of \( \alpha_r \) can be calculated by taking into consideration radiation heat transfer between parallel plates [6].

Outside the mould, strand is cooled by water sprays and air. Cooling in the secondary zones should force continuous decrease in strand surface temperature and speed up steel solidification. Generally the heat transfer coefficient decreases along the strand length starting from the maximum value at the meniscus level. Typical values of the heat transfer coefficient for water spray cooling vary in the range from 200
$W/(m^2 \cdot K)$ to 6000 $W/(m^2 \cdot K)$ [7]. The convection heat transfer coefficient $\alpha_s$ for water spray cooling has been calculated from [8]:

$$\alpha_s = 10^9 \cdot 3.15 \cdot \omega^{0.616} \left[ 700 + \frac{t_s-700}{\exp(0.1t_s-700)+1} \right]^{-2.455} \left[ 1 - \frac{1}{\exp(0.025t_s - 6.25) + 1} \right]$$

(7)

where: $\omega$ – water spray flux rate, $dm^3/(m^2 \cdot s)$, $t_s$ – strand surface temperature, °C.

For air cooling heat convection coefficient $\alpha_s$ can be calculated from the equation published in [9]. On the outer surface of the mould the boundary condition have been calculated in the way described in [6]. Heat balance in the control volume has been employed to improve the finite element solution accuracy [1].

3. ANALYSIS OF THE RESULTS

Analysis of the influence of the cooling conditions and the casting speed on the strand temperature in the continuous casting process has been performed for the round strand with the diameter of 160mm. The computation have been accomplished with the developed computer program MES-COS. The computer software is based on the described heat transfer model in the continuous casting process. Numerical simulation have been performed for the steel of the chemical compositions as: C=0.84%, Mn=2%, Si=1.7%, Cr=0.2%, Ni=0.02%. Solidus temperature was assumed as $T_o=1380°C$, liquidus as $T_l=1450°C$. In the solid state the austenitic transformation boundaries were assumed as: 810°C and 750°C. The analysis has been performed for the arc of casting machine equal 6 m. The inlet temperature of steel was $T_e=1475°C$. Thermo physical properties for the steel employed in computations have been presented in figures 1 and 2. The computations have been carried out for the casting speed of $v_1 = 25 \text{ mm/s}$, $v_2 = 27 \text{ mm/s}$ and $v_3 = 30 \text{ mm/s}$. Length of the secondary cooling zones and the water flux rates employed in computations have been presented in table 1. The influence of the 4th water cooling zone has been analyzed for the casting speed of 25 mm/s and 27 mm/s. The computations have been performed in order to determine the influence of casting speed on strand solidification. Suitable cooling conditions have been selected and water spray flux rates in secondary cooling zones have been proposed. Casting speed increase from 25 mm/s to 30 mm/s did not changed cooling conditions in the mould significantly. In figure 3 variation of the heat transfer coefficient at the strand – mould interface has been presented. The highest value of 2000 $W/(m^2 \cdot K)$ has the combined heat transfer coefficient at the meniscus level. At the exit from the mould the combined heat transfer coefficient has dropped up to 750 $W/(m^2 \cdot K)$. For the examined casting speed the solidified layer at the exit from the mould has had the thickness about 8.5 mm. In figure 4 heat flux variation along the strand length resulted from proposed cooling parameters has been presented. The most intensive cooling takes place at the meniscus level where the heat flux reaches 2.9 $MW/m^2$. Heat flux has dropped rapidly up to 0.9 $MW/m^2$ at the exit from the mould as the solidifications proceed. At the first secondary cooling zone high water flux rate has forced intensive strand cooling and the heat flux has risen up to 1.8 $MW/m^2$. In the second, third and fourth water spray cooling zones the heat flux has dropped up to 7.8 $MW/m^2$, 7.5 $MW/m^2$ and 3.5 $MW/m^2$, respectively. In the case of strand cooling in air the heat flux has decreased up to 0.1 $MW/m^2$. The water spray flux rates in secondary cooling zones has been designed in a way to ensure full strand solidification at the end of casting line. Temperature variations in the strand axis and on the strand surface have been presented in figures 5 and 6. Both for the casting speed of 25 mm/s and 27 mm/s the strand solidification has ended at the distance of 15 m from the meniscus level. In the case of casting speed of 30 mm/s temperature field in the strand longitudinal section has been presented in figure 7. In this case the strand solidification has ended at the distance of 16 m from the meniscus level and the water spray flux rates in zones 2, 3 and 4 have been increased almost twice. The influence of cooling conditions in fourth water spray zone on the strand solidification has been presented in figures 5 and 6. The computations have been performed for the casting speed of 25 mm/s and 27 mm/s. Full solidification has been reached at the
cutting section at the distance of 17m from the meniscus level. It is clear that even minor change in casting speed or cooling parameters may lead to liquid steel leaks.

**Fig.1.** Density and specific heat as a function of temperature for the steel employed in computations

**Fig.2.** Heat conduction coefficient as a function of temperature for the steel employed in computations

**Fig.3.** Variation of the heat transfer coefficient at the mould – strand interface for various casting speeds.

**Fig.4.** Heat flux variation along the strand length for the casting speed of 25 mm/s.
**Fig. 5.** Temperature variations in the strand axis and on the strand side surface for the casting speed of 25 mm/s

**Fig. 6.** Temperature variations in the strand axis and on the strand side surface for the casting speed of 27 mm/s

**Fig. 7.** Temperature field in the strand longitudinal section from 6th to 12th meter of the metallurgical length for the casting speed of 30 mm/s and the cooling conditions specified in table 1.

**Table 1.** Length of the secondary cooling zones and the water spray flux rates employed in the strand temperature computations.

<table>
<thead>
<tr>
<th>No.</th>
<th>Casting speed, mm/s</th>
<th>Water spray flux rate $\dot{w}$, dm$^3$/(m$^2$ s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Zone 1</td>
</tr>
<tr>
<td>1.</td>
<td>25</td>
<td>9,7</td>
</tr>
<tr>
<td>2.</td>
<td>27</td>
<td>9,7</td>
</tr>
<tr>
<td>3.</td>
<td>30</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Length of the secondary cooling zone, m</td>
<td>0,3</td>
</tr>
</tbody>
</table>
4. CONCLUSIONS

Common tendency to improve productivity of steel plants has resulted in increase of casting speed. As a result of it more efficient cooling systems have had to be used in the casting line. Water flux rate is one of the most important parameters which can be employed to control rate of strand cooling. Further, the length of the secondary cooling zones have to be determined in order to ensure a proper strand solidification. Computer simulations have been efficiently used to solve these problems. The computer simulation have shown that increase in casting speed from 25 mm/s to 30 mm/s has minor effect on the strand temperature in the mould. However, the change in casting speed must be closely correlated with the water spray flux rate employed in the secondary cooling zones. The speed of cooling is limited by the stress and strain development, which can lead to fracture formation on the strand surface. The developed computer program is equipped with pre- and post-processing of data. It makes simulation of the continuous casting process efficient. The input data are limited to technological parameters easy to program based on the knowledge of a particular casting line. The computation have been performed on a personal computers equipped with Intel Core 2 Duo CPU T7300 2.00 GHz and the computation time did not exceeded 30 minutes.

LITERATURE


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