Applying of Real-time Heat Transfer and Solidification Model on the Dynamic Control System of Billet Continuous Casting

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In this paper, a real-time mathematical heat transfer model for billet continuous casting of low carbon steel has been presented and solved by finite volume method. This model can be used to simulate the casting conditions which vary frequently. As taking the variation of superheat of liquid steel into consideration in the water flow rate distribution, the fluctuation of billet surface temperature has been decreased. Meanwhile the fluctuation of measured temperature has been largely reduced when it is measured with thermal imager. The mathematical model has been validated by measuring shell thickness and surface temperature in industrial caster. The on-line model can monitor surface temperature and shell thickness along the caster machine in the casting process, and it has been applied on the dynamic control system to adjust the operation parameters. The billet defect has been decreased greatly and the quality of billet has been obviously improved.

KEY WORDS: real-time model; continuous casting; heat transfer; solidification; secondary cooling; dynamic control.

1. Introduction

The continuous casting technology is currently the primary method of producing semi-finished steel shaped products. In this process, the liquid steel is poured into a bottomless mold which is cooled by internal water flow. After the mold the strand enters into the secondary cooling zones, in which it is cooled by water sprays. Finally the strand pass through radiation cooling zone until complete solidification. The heat transfer and solidification of continuous casting have a crucial influence on the strand quality, especially on the formation of surface and internal cracks. In recent years, many mathematical heat transfer models for continuous casting have been developed. However, most of the models1-4 can only be used to simulate steady state casting operations in off-line, and they are not valid to simulate if the casting conditions vary frequently. Some practical situations may force the casting speed and the secondary zones water flow rate to be modified: when the liquid steel temperature in the tundish fluctuates a lot because of temperature nonuniformity in the ladle, when the tundish has to be changed, and when serious defects occur in the mold, etc. So it’s very important to establish the real-time model.5 This research establishes the real-time heat transfer and solidification model, which on-line runs by acquisition operation parameters per 10 s to compute the shell thickness and billet temperature, and it provides the foundation for the on-line process control.6,7

In this paper, a real-time two-dimensional heat transfer and solidification model of billet continuous casting of low carbon steel has been developed and validated by measuring shell thickness and surface temperature in industrial caster. The real-time model has been applied to the plant operations. Accurate online prediction and control allows for flexibility in caster operation. It gives operators the capability to adjust the operation parameters to keep process parameters such as billet surface temperature and solidification end point within desired ranges. The billet defect has been decreased greatly and the quality of billet has been obviously improved.

2. Model of Heat Transfer and Solidification

In order to simulate the continuous casting process of heat transfer and solidification, the following assumptions have been made in the mathematical model6,7:

a) The heat conduction in the withdrawal direction is insignificant compared to that along the cross-sectional direction and therefore can be neglected.

b) The density, specific heat and thermal conductivity of steel are the temperature-dependent properties.

c) The latent heat of steel solidification is converted into an equivalent specific heat capacity in the mushy zone.

d) The convective heat flow in the liquid pool and mushy zone is accounted for by an effective thermal conductivity.

e) The operation parameters are constant during a sampling period.

According to the above assumptions, the heat transfer can be mathematically defined by the following equation:
2. Thermophysical Properties of Steel

The latent heat is generated during phase change between liquidus and solidus temperatures of steel and is expressed by the following equation:

\[
\dot{q} = L \varphi \frac{\partial \varphi}{\partial t} \tag{3}
\]

where \( L \) is the latent heat of fusion, \( \varphi \) is the density of steel, \( \varphi \) is the solid fraction in the mushy zone and it can be expressed in accordance with Eq. (4) below:

\[
\dot{q} = \rho L \frac{\partial \varphi}{\partial t} \tag{4}
\]

Equations (4) and (1) give

\[
\rho \left[ c - L \frac{\partial \varphi}{\partial t} \right] \frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \dot{q} \tag{5}
\]

The \( f_s^{3} \) of low carbon steel can be expressed by the following equation:

\[
f_s = \frac{T_u - T + \frac{2}{\pi} (T_s - T_0)}{(T_u - T_s) \left(1 - \frac{2}{\pi}\right)} \tag{6}
\]

where \( T_u \) is the liquidus temperature of steel, \( T_s \) is the solidus temperature of steel.

The convective heat transfer in the liquid pool and mushy zone is quite difficult to be calculated by using differential equations. The effective thermal conductivity is given by the following linear relationship:

\[
k_{eff} = k_{s} + Ak(1-f_s) \tag{7}
\]

where \( k_{eff} \) is the effective thermal conductivity, \( k \) is the thermal conductivity of solid steel, \( A \) is a constant, and \( f_s \) is the solid fraction in the mushy zone.

The specific heat capacity and density are expressed by the following equations:

\[
c_{eff} = c - L \frac{\partial \varphi}{\partial T} = c_s \varphi + c_l (1 - \varphi) - L \frac{\partial \varphi}{\partial t} \tag{8}
\]

\[
\rho_{eff} = \rho_s \varphi + \rho_l (1 - \varphi) \tag{9}
\]

where sub-indices \( S \) and \( L \), respectively, indicates solid and liquid state.

2.2. The Boundary Conditions

(1) Initial Condition

The boundary condition to the steady state casting has been assumed to be the same as the pouring or casting temperature \( T_0 \) of the steel.

\[
T = T_0 \tag{10}
\]

where \( T_0 \) is the steel casting temperature, which is measured in tundish.

(2) Mould Cooling Condition

The boundary condition for the strand in the mould has been expressed by the following equation:

\[
-k \frac{\partial T}{\partial n} = q = [26.7 - 3.3\gamma L/v] \times 10^5 \tag{11}
\]

where \( q \) is the mould heat flux density (W/m²), \( L \) is the mould length (m), \( v \) is the casting speed (m/s).
(3) Secondary Cooling Condition

In the secondary cooling zone, heat extracted from the surface of the billet casting is predominated by impinging water sprays and radiation. Therefore, the surface heat flux can be expressed by the following equation:

\[-k \frac{\partial T}{\partial n} = h(T - T_{\text{water}}) + \varepsilon \sigma(T^4 - T_{\text{air}}^4)\] (12)

where \(k\) is the thermal conductivity, \(h\) is the heat transfer coefficient, \(T\) is the strand surface temperature, \(T_{\text{water}}\) is the cooling water temperature, \(\varepsilon\) is the emissivity, \(\sigma\) is the Stefan–Boltzman constant and \(T_{\text{air}}\) is the air temperature.

Heat transfer coefficients \(h\) are calculated by the following equation:

\[h = \frac{1570\\sqrt{w}T_{\text{water}}}{\alpha}\] (13)

where \(h\) is the heat transfer coefficient (W/m²/K), \(w\) is the water flow density (L/m²/s), \(T_{\text{water}}\) is the cooling water temperature, \(\alpha\) is a machine-dependent calibration factor.

In order to lessen the effect of varying superheat, the water distribution of secondary cooling zones is presented based on continuous temperature measurement in tundish and is calculated by the following equation:

\[Q_i = a_iv^2 + b_i\nu + c_i + k_i\Delta T\] (14)

where \(Q_i\) is the water flow rate of respective spray cooling zones (t/h), \(v\) is the casting speed (m/min), \(a_i, b_i, c_i\) are water distribution coefficients, \(k_i\) is the superheat coefficient, \(\Delta T\) is the change of superheat and \(i\) is the number of zones in the secondary cooling segment.

3. Results and Discussion

The real-time two-dimensional heat transfer and solidification model of low carbon steel is based on an actual casting machine in a steel plant of Shannhing Iron & Steel Corporation of China. There are three cooling segments: mould, secondary and radiation cooling segment. The secondary cooling segment has three zones with independently controlled water sprays. In order to test the accuracy and on-line performance of the model, the measured surface temperature and shell thickness were compared to the calculated ones. The parameters of caster and thermal physical properties of Q235 steel used in calculation are shown in Tables 1–3 respectively. The water distribution coefficients in each secondary cooling zone in Eq. (14) are shown in Table 4. The verified model has already been applied to adjust the operation parameters to improve the strand quality and the productivity.

3.1. Test of the Model

In order to test the on-line performance and response to operation conditions of the mathematical model, the surface central temperatures calculated by the on-line model and measured by the thermal imager were compared in the following operation conditions: (I) Water flow rate of each zone was constant and casting speed was changed suddenly from 2.7 to 2.6 m/min. (II) Casting speed was constant and water flow rate of zone 3 was changed suddenly from 7.14 to 6.13 t/h. (III) Casting speed was constant and water flow rate of zone 2 was changed suddenly from 15.55 to 13.38 t/h. (IV) Normal operation condition (the manufacture was automatic without any artificial factor intervention), as shown in Table 5.

There is a great fluctuation on the measured temperatures, because of the influence of the scale on the strand.

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**Table 1.** Geometry of the billet caster.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section size (m x m)</td>
<td>0.15 x 0.15</td>
</tr>
<tr>
<td>Mold length (m)</td>
<td>0.85</td>
</tr>
<tr>
<td>Spray zone length (m)</td>
<td></td>
</tr>
<tr>
<td>Zone 1</td>
<td>0.32</td>
</tr>
<tr>
<td>Zone 2</td>
<td>1.95</td>
</tr>
<tr>
<td>Zone 3</td>
<td>5.69</td>
</tr>
<tr>
<td>Measuring point (m)</td>
<td>12.51</td>
</tr>
</tbody>
</table>

**Table 2.** Chemical composition of Q235 steel (in mass%).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.20</td>
</tr>
<tr>
<td>Si</td>
<td>0.27</td>
</tr>
<tr>
<td>Mn</td>
<td>0.55</td>
</tr>
<tr>
<td>P</td>
<td>0.025</td>
</tr>
<tr>
<td>S</td>
<td>0.025</td>
</tr>
</tbody>
</table>

**Table 3.** Thermal physical properties of Q235 steel.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquidus temperature (°C)</td>
<td>1515</td>
</tr>
<tr>
<td>Solidus temperature (°C)</td>
<td>1485</td>
</tr>
<tr>
<td>Heat capacity of liquid steel (kJ/kg/K)</td>
<td>0.84</td>
</tr>
<tr>
<td>Heat capacity of solid steel (kJ/kg/K)</td>
<td>0.67</td>
</tr>
<tr>
<td>Density of liquid steel (kg/m³)</td>
<td>7000</td>
</tr>
<tr>
<td>Density of solid steel (kg/m³)</td>
<td>7600</td>
</tr>
<tr>
<td>Heat conductivity of liquid steel (W/mK)</td>
<td>34.0</td>
</tr>
<tr>
<td>Heat conductivity of solid steel (W/mK)</td>
<td>29.4</td>
</tr>
<tr>
<td>Heat of fusion (kJ/kg)</td>
<td>270</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**Table 4.** Water distribution coefficients in each secondary cooling zone.

<table>
<thead>
<tr>
<th>Zone</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>1.44</td>
<td>0.72</td>
<td>0.87</td>
<td>0.06</td>
</tr>
<tr>
<td>Zone 2</td>
<td>3.16</td>
<td>-3.99</td>
<td>2.96</td>
<td>0.05</td>
</tr>
<tr>
<td>Zone 3</td>
<td>1.02</td>
<td>-1</td>
<td>2.2</td>
<td>0.005</td>
</tr>
</tbody>
</table>

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surface. Some areas of the strand surface are covered by the scale and some are not, especially the air gap that formed between the scale and the strand surface can cause the fluctuation above 150°C. The pyrometer is spot measurement, so it’s very difficult to reflect the actual surface temperature. In the radiation region, the surface temperature gradient of billet is very little in the withdrawal direction, so it was assumed that the temperature in a small 10 cm (in the withdrawal direction) \times 5 cm (in the transverse direction) rectangle area at measured point (12.51 m) neighborhood doesn’t change and the top temperatures are near the actual surface temperatures. The effect of the scale has been reduced through multipoint measuring with thermal imager in the rectangle area and selecting the maximal temperature as the measured temperature. The temperature fluctuation can be reduced to within 10°C. Figures 2–5 show that the calculated surface temperatures and measured ones are below 10°C at measured point by changing operation conditions.

In addition, shell thicknesses were measured at 3.07 m, 8.71 m, 12.44 m from the meniscus using shooting nails, which include FeS, whose solute distribution has a very significant difference when sulfur element diffuses between liquid and solid. So the shell thickness can be gained at the shooting nails position by the sulfur print. From the Table 6 and Fig. 6, a consistent result of shell thickness between available experimental data and numerical results is obtained, and the maximal relative error is less than 3.7%.

### Table 5. Operation conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting speed (m/min)</td>
<td>2.7 to 2.6</td>
<td>2.61</td>
<td>2.61</td>
<td>Normal operation condition</td>
</tr>
<tr>
<td>Water flow rate (t/h)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>zone 1</td>
<td>13.53</td>
<td>13.55</td>
<td>13.55</td>
<td></td>
</tr>
<tr>
<td>zone 2</td>
<td>15.63</td>
<td>15.55</td>
<td>15.55 to 13.38</td>
<td></td>
</tr>
<tr>
<td>zone 3</td>
<td>7.14</td>
<td>7.14 to 6.13</td>
<td>6.13</td>
<td></td>
</tr>
</tbody>
</table>

#### 3.2. Application in the Plant Operation

The verified real-time model has already been applied to the plant operations. The secondary cooling scheme follows the target temperature control principle. There is one set point near the end of respective spray cooling zones. Target temperatures at set points are obtained by the steel heat mechanics performance. The spray water flow is continuously controlled during varying operation conditions to maintain the desired target temperature. The operation parameters of the billet caster have been adjusted to improve the produc-
tivity and the strand quality. The reheating occurs when the strand passes from a spray cooling zone with a high cooling efficiency to one with a lower cooling rate, and it must be limited as a function of steel grade and casting operation parameters. This reheating leads to the development of tensile stresses at the solidification front, which can induce cracking. The maximum permissible reheating range along the machine has been chosen to be equal to 80°C. If the reheating exceeds the critical value, internal cracking may occur. If cracks appear to be likely, their location and extent is determined from the transverse temperature profile at the point along the strand where the critical reheating has occurred. Using the model-predicted pool profile, the position of the start of cracking in a billet with respect to the meniscus could be determined quantitatively. It was taken to be the distance below the meniscus at which the calculated shell thickness equaled the distance between the inside tip of an observed crack and the outside surface of the billet. A spray system which has been designed to minimize reheating will reduce the possibility of crack formation. Figure 7 shows the surface central temperature, central temperature and shell thickness before and after applying the real-time model to adjust. The surface reheating has been reduced at the secondary cooling zones, and the surface temperature of billet in secondary cooling and straightening area is in plastic area. So the quality of billet has been improved.

The careful control of the strand surface temperature at the straightening point is very important in the casting operation. The strand surface must be at a temperature outside the low ductility trough observed in steels and at a temperature either higher than the high-temperature limit of the ductility trough or lower than the low limit in order to avoid transverse surface cracking and other defects. The bottom of the ductility trough for steels is usually located between 700°C and 750°C, depending on steel composition, mainly in low carbon steels, which is the temperature where the γ–α transformation starts, so the surface temperature must be less than $T_{γ–α}$. The upper limit of the low ductility through corresponds to the transition between the transgranular fracture and intergranular fracture. This upper temperature limit can vary between 900°C and 1100°C, depending on the composition of steel. Limiting the strand surface above the upper limit of the low ductility temperature, transversal cracks are also reduced. In this work it was considered that the strand surface temperature is kept above the upper limit of the low ductility range, and the strand surface temperature at the straightening point is about 1050°C depending on the carbon content. Figure 8 shows the solidification end point and the billet surface central temperature at the straightening point (14 m) as a function of time during casting speed fluctuation operation. The billet has been entirely solidified before straightening and the strand surface temperature is avoided entering the embrittlement temperature area at the straightening point.

### Table 6. Comparison between calculated and measured shell thicknesses ($f_r=1$).

<table>
<thead>
<tr>
<th>Casting speed (m/min)</th>
<th>Water flow rate (l/h)</th>
<th>Distance from meniscus (m)</th>
<th>Shell thickness (mm)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>zone 1</td>
<td>zone 2</td>
<td>zone 3</td>
<td>calculated</td>
<td>measured</td>
</tr>
<tr>
<td>3.07</td>
<td>28</td>
<td>27</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>2.7</td>
<td>13.53</td>
<td>15.63</td>
<td>7.14</td>
<td>8.71</td>
</tr>
<tr>
<td>12.44</td>
<td>67</td>
<td>69</td>
<td>2.9</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 6.** Measured and calculated shell thickness ($f_r=1$).

**Fig. 7.** Comparison the surface central temperature, central temperature and shell thickness ($f_r=1$) before and after applying the real-time model.

**Fig. 8.** Simulated surface central temperature at straightening point and solidification end point during casting speed fluctuation operation.
point, meanwhile the strand surface temperature fluctuates slightly. Figure 9 shows the micrographs before and after applying the real-time model. The temperature of straightening point is controlled to keep above the upper limit of the low ductility range and the variation of superheat of liquid steel is considered in the water flow rate distribution. What’s more, the temperature at the set points which are near the end of respective spray cooling zones is controlled to maintain the desired target temperature. So the strand quality has been obviously improved.

4. Conclusions

In this paper, according to the finite volume method, a real-time two-dimension heat transfer and solidification model for continuous casting has been developed. This model can be used to simulate the casting conditions which vary frequently. The on-line performance of the mathematical model has been tested. The difference between calculated surface central temperatures and measured ones are below 10°C at measured point by changing operation conditions. The calculated shell thicknesses can be consistent with the measured ones, and the maximal relative error is less than 3.7%.

The fluctuation of billet surface temperature has been decreased by taking the variation of superheat of liquid steel into consideration in the water flow rate distribution. Meanwhile the fluctuation of measured temperature has been reduced to under 10°C when it is measured with thermal imager.

According to the real-time heat transfer model, the surface temperature of billet in secondary cooling and straightening area is controlled in the plastic area and the billet defect has been decreased greatly, and the quality of billet has been improved obviously.

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