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Heat-transfer model on the improvement of continuous casting slab temperature

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Abstract: A heat transfer model on the solidification process has been established on the basis of the technical conditions of the slab caster in No.3 steel works of Wuhan Iron & Steel Corporation, and the temperature field in the solidifying slab was calculated which was verified by the measured slab surface temperature. The influences of the main operating factors including casting speed, spray cooling patterns, superheat of melt and slab size on the solidification process were analyzed and the means of enhancing the slab temperature was brought forward. Raising the casting speed to 1.3 m/min, controlling the flowrate of secondary cooling water and improving the cooling pattern at the lower segments of secondary cooling zone could improve the slab temperature effectively. And the increasing the superheat is adverse to the production of high temperature slab.

Key words: heat transfer; continuous casting; slab; solidification; mathematical model

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Hot charging and direct rolling of continuous casting slab has been one of the most essential technologies for the integrated iron and steel works to save energy, to improve the productivity and quality and to realize the integrated manufacture of steel making, continuous casting and rolling. In the developed countries this technology has been applied widely, but the application of this technology is still in a rather low level in domestic steel works. The production of non-defective slabs with higher temperature is the more important step in this technology. So a heat transfer model on the continuously casting slab solidification has been established and the influences of operating factors on the slab solidification have been investigated to bring forward some helpful references to the production of non-defective slabs with higher temperature.

1 Mathematical model

1.1 Fundamental assumptions

(1) Heat transfer in the direction of width and thickness is recognized as axial symmetry and that along the slab withdrawal direction is neglected.

(2) The density of steel is constant, but the specific heat capacity and the heat conductivity of steel are the functions of temperature.

(3) Considering the convection heat transfer in the liquid core of slab, the effective conductivity is used and the latent heat of solidification is converted into the equivalent specific heat capacity of steel.

1.2 Governing equations

According to the above assumptions, the governing equation is followed:

$$\rho C_{\mathrm{eff}}\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) \qquad (1)$$

where C_{eff} is the equivalent specific heat capacity, which is calculated as following expression [1]:

$$C_{\mathrm{eff}}=\begin{cases} C_{\mathrm{liq}} & T>T_{\mathrm{liq}} \\ C(T)+L\dfrac{\partial f_{\mathrm{sol}}}{\partial T} & T_{\mathrm{sol}}\le T\le T_{\mathrm{liq}} \\ C_{\mathrm{sol}} & T<T_{\mathrm{sol}} \end{cases} \qquad (2)$$

where C_{liq} and C_{sol} are the specific heat capacity of liquid steel and solid steel respectively, T_{liq} and T_{sol} are the temperatures of steel liquidus and solidus curve respectively, and f_{sol} is ratio of soild phase in mushy zone.

1.3 Boundary and initial conditions

(1) Boundary conditions.

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(a) In mould

$$-\lambda\frac{\partial T}{\partial n}|_{\Omega i}=h_{\mathrm{m}i}(T_{\mathrm{s}i}-T_{\mathrm{wf}}) \tag{3}$$

where $h_{\mathrm{m}i}$ is the heat-transfer coefficient of melt in the i layer of the mould, $T_{\mathrm{s}i}$ is slab surface temperature in i layer, and T_{wf} is the temperature of cooling water.

(b) Secondary cooling zone

$$-\lambda\frac{\partial T}{\partial n}|_{\Omega j}=h_{\mathrm{s}j}(T_{\mathrm{s}j}-T_{\mathrm{wf}}) \tag{4}$$

where $h_{\mathrm{s}j}$ is the heat transfer coefficient of slab in the j layer of the secondary cooling zone, which can be calculated as the following expression [2].

$$h_k=h_{\mathrm{a}k}\cdot W_k^r+h_{rk} \qquad (1\le k\le 9) \tag{5}$$

where h_k is the coefficient of convective heat transfer in the k cooling zone, all $h_{\mathrm{a}k}$, r and h_{rk} are the parameters of nozzle, and W_k is the sprayed water density, which is calculated as follows:

$$W_k=\frac{Q_{\mathrm{w}k}}{A_k} \tag{6}$$

where A_k is the sprayed area of the k section, $Q_{\mathrm{w}k}$ is the water flowrate in the k section.

(c) Radiation cooling zone

$$-\lambda\frac{\partial T}{\partial n}|_{\Omega\mathrm{a}}=\varepsilon C_0(T_\mathrm{s}^4-T_\mathrm{a}^4)+h_\mathrm{c}(T_\mathrm{s}-T_\mathrm{a}) \tag{7}$$

where h_c is the coefficient of convection heat transfer, which is calculated as follows [3].

Top surface of slab (x=0):

$$h_\mathrm{c}=1.43(T_\mathrm{s}-T_\mathrm{a})^{\frac{1}{3}} \tag{8}$$

Side surface of slab (y=0):

$$h_\mathrm{c}=1.42((T_\mathrm{s}-T_\mathrm{a})/S_{\mathrm{thi}})^{\frac{1}{4}} \tag{9}$$

(d) Midplanes

$$\begin{cases} x=\dfrac{S_{\mathrm{thi}}}{2},0\le y\le\dfrac{S_{\mathrm{wid}}}{2}, & -k\dfrac{\partial T}{\partial x}=0 \\ y=\dfrac{S_{\mathrm{wid}}}{2},0\le x\le\dfrac{S_{\mathrm{thi}}}{2}, & -k\dfrac{\partial T}{\partial y}=0 \end{cases} \tag{10}$$

(2) Initial condition.

$$T(x,y,t)\big|_{t=0}=T_{\mathrm{cast}} \tag{11}$$

2 Computation and verification

Equation (1) is solved numerically by finite-difference method and the equation group of complete implied format is formulated. The calculating software is programmed in FORTRAN language and needs being input the informative dates including the composition of steel, casting temperature, slab size, casting speed and the pattern of secondary cooling zone. The calculated temperature distribution and the solidified shell thickness of slabs during the solidification process are verified by the measured temperatures at the exit of continuous caster.

Table 1 shows the comparison between the calculated center surface temperatures and the measured values. The table also reflects that the biggest relative error between calculated and measured temperatures is no more than 1.99%. So the model is believable and applicable.

Table 1 Comparison between calculated and measured center surface temperature of slabs at exit of caster

Steel grade	Slab size / mm	T_{cast} / °C	V_{cast} / (m·min^{-1})	Slab temperature / °C		Absolute error / °C	Relative error / %
				Measured	Calculated		
Q195	230×1300	1545	1.2	955	962	−7	−0.72
	250×1500	1545	1.0	900	908	−8	−0.89
	230×1500	1545	1.2	988	972	16	1.62
Q235	230×1300	1542	1.2	971	952	19	1.99
	230×1500	1542	1.2	994	989	5	0.50
	250×1500	1542	1.0	910	907	3	0.25
09CuPTiRE	230×1300	1548	1.2	958	960	−2	−0.21
	250×1500	1548	1.0	892	900	−8	−0.9

3 Application and discussion

The influences of operation factors on slab temperature were investigated through the model. The basic parameters are shown in **table 2**. And **table 3** is the water flowrate of every spray segment.

3.1 Influence of casting speed on slab temperature and shell growth

Figures 1 and **2** show the influences of casting speed (V_c) on slab temperature and shell thickness respectively. As shown in figure 1, the increasing of casting speed can make the temperature of slab exiting caster enhanced evidently. Especially the center temperature of slab (T_{cen}) is effected most greatly. The reason for this is that the increasing of casting speed causes the holding time of slab in the secondary cooling zones shortened and the length of liquid core lengthened. The latent heat of solidification keeps the temperature of slab in a high level. At the same time, the shell thickness in initial solidification stage is thinned with the casting speed increasing, as shown in figure 2, which often easily causes the breakout, bulging, inner cracks or other defects. So the casting speed is limited in the prevention of these unfavorable things from occuring. And as can be seen from figure 1, on the given cooling conditions, if the casting speed is increased to 1.4 m/min, the slab couldn't be solidified completely before arriving at the exit of caster. The other measures, for example, intensifying the cooling capability of mould and secondary cooling zone should be adopted correspondingly.

Table 2 Basic parameters of the model

Steel grade	Slab size / mm	T_{cast} / °C	V_{cast} / (m·min^{-1})
Q235	250×1500	1542	1.3

Table 3 Flowrate of sprayed water in secondary cooling zones

Spray segment	I	II	III	IV	V	VI	VII	VIII	IX
Q_{wk} / (L·min^{-1})	256	266	200	210	130	115	126	95	86

For the slab caster of No.3 steel works of Wuhan Iron & Steel Corporation, when the casting speed is increased from 1.0-1.1 m/min at present to 1.3 m/min, the shell thickness of slab exiting the mould is thicker than 20 mm, which is a safety value for production, and the length of liquid core is no more than the metallurgical-length of the caster. The slab center temperature can be increased from 1282°C to 1400°C, the average temperature of slab cross section (T_{ave}) increased from 1104°C to 1205°C, and the central surface temperature (T_{sur}) simultaneously increased from 938°C to 1000°C. So the higher casting speed is an important measure of the production of slab with high temperature.

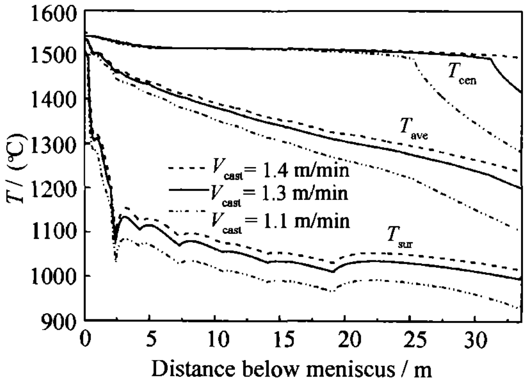

Figure 1 Influence of casting speed on slab temperature.

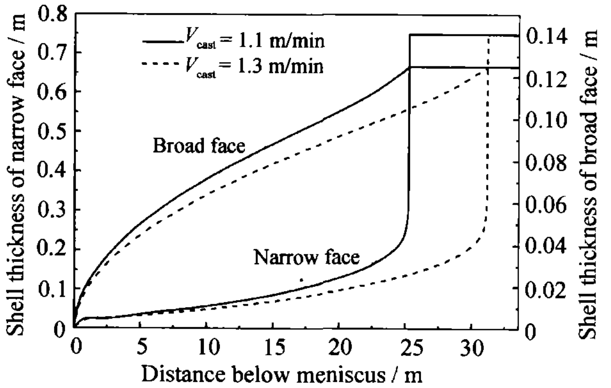

Figure 2 Influence of casting speed on shell thickness.

3.2 Influence of secondary cooling patterns on slab temperature

(1) Water flowrate.

The influences of the water flowrate of secondary cooling zone on the slab temperature and the shell thickness were investigated according to the practical condition of casting speed (1.1 m/min). The results are shown in **figure 3**. The slab temperature is increased obviously as decreasing the water flow rate. As the water flowrate of every spray segment is decreased 30 L/min, the slab central surface temperature at exit of caster is enhanced about 70 to 100°C. This indicates that, on the present condition of the casting speed, the slab with high temperature can be obtained by decrease in flow rate of the secondary cooling water. And at the same time, lessening flow rate of the secondary cooling water can decrease the thermal stress in the metal during solidification, weaken the growth of column crystal, increase the ratio of equiaxed grain and lighten the segregation [4]. The shell thickness curves in figure 3 show that the location of complete solidification of the liquid core can extend to the end of caster with decrease of spray water rate. So an optimal water flowrate to control the location of the final solidification can be calculated according to the metallurgical-length rule.

(2) Cooling patterns at the lower segments of secondary cooling zone.

The models of four cooling patterns with the model have been studied: pattern 1 is normally; 2 is no spraying at the last segment; 3 is half of water flowrate sprayed at the tow last segments; 4 is no spraying at the last segment and half of flowrate at the second last segment. **Figure 4** presents the effects of cooling patterns on the slab temperature. The T_{sur}, T_{ave} and the slab corner temperature (T_{cor}) are enhanced greatly with the lessening of water sprayed at the end of secondary cooling zone. But the T_{cen} is little influenced. That is to say, decrease of water flowrate in final spray cooling zone is not limited by the length of slab liquid core, so it is a effective measure to improve the temperature. At present, for the slab caster of Wuhan Iron & Steel Corporation, that the slab temperature continuously falls in the horizontal section on account of too much water sprayed in this zone [5]. As for as the cooling pattern 2, no water spray at the last segment of secondary cooling zone, the slab temperature is re-raised up sharply, which is likely to cause the surface defect of slab, especially for the steel grade of high-sensitivity of hot cracking. So this pattern is not advisable. As regard as the cooling pattern 3 and 4, the slab temperature is re-rising gradually, and at the same time, the defect of slab is controlled. Therefore, taking the slow-cooling pattern at the lower part of secondary cooling zone may be favourable for realizing the production of high temperature slab, but it is limited by the permissible temperature gradient in slab.

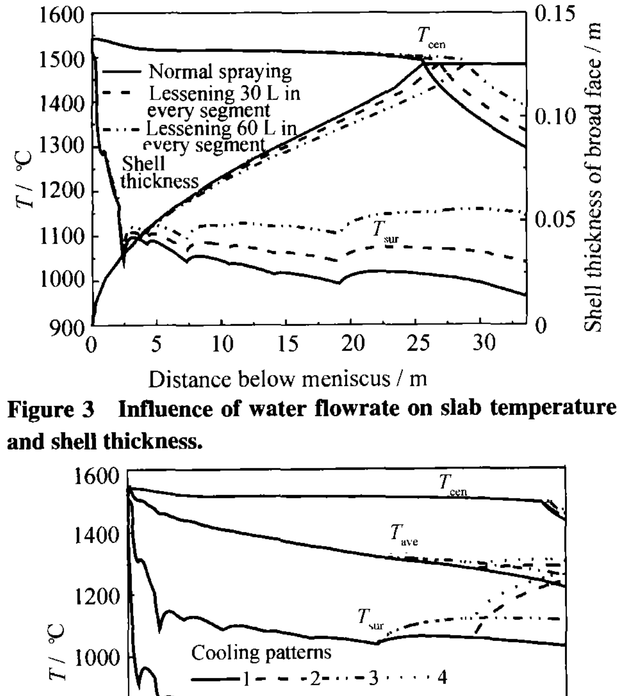

Figure 3 Influence of water flowrate on slab temperature and shell thickness.

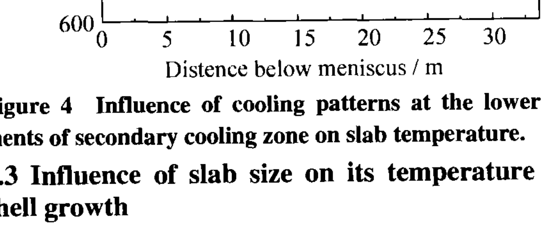

Figure 4 Influence of cooling patterns at the lower segments of secondary cooling zone on slab temperature.

3.3 Influence of slab size on its temperature and shell growth

Figures 5 and **6** show the influences of slab size on the temperature and shell growth in the solidification process. As can be seen from figure 5, the slab temperature rises up with the increase of the slab size. And the variation of slab width has little influence on T_{sur}, but has great effect on T_{ave} and T_{cen}. The reason for this is that the increase of slab size has little effect on the shell thickness in initial solidification stage and so T_{sur} is little influenced, and with the slab size increase, the position of complete solidification extends to the caster end in final solidifying stage, as shown as figure 6, which makes T_{ave} and T_{cen} of large-sized slab enhanced. And as a result, the slab size can be increased properly to improve the temperature. In production, when the slab width is adjusted up online, the measures that the increasing of cooling water in mould and secondary spray zone or the decreasing of casting speed, must be taken to make the slab solidified completely and prevent the slab from bulging and breakout occurring. This is the reason that the 250mmx1500mm slab is casted at 1.0 m/min and the 230 mmx1300 mm slab is casted at 1.2 m/min in No.3 steel works of Wuhan Iron & Steel Corporation.

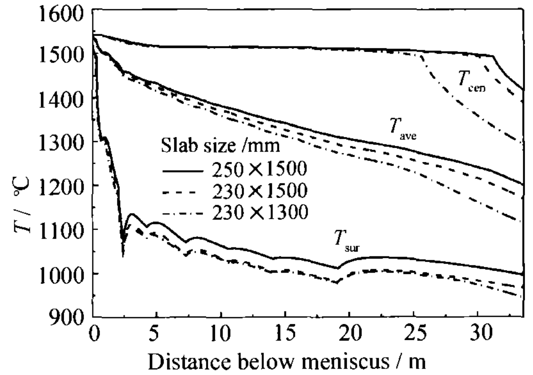

Figure 5 Influence of slab size on its temperature.

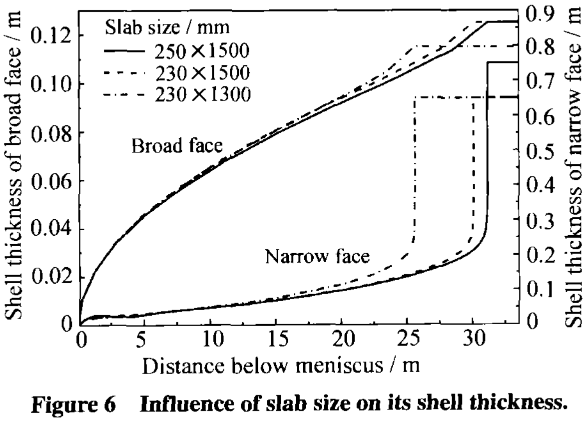

Figure 6 Influence of slab size on its shell thickness.

3.4 Influence of superheat on slab temperature

Figure 7 shows the influence of superheat on the slab temperature. As can be seen, the increase of superheat has little effect on slab temperature at the caster end. But in the initial solidification stage, a higher superheat causes the slab temperature enhanced markedly, then the shell growth gets slower and the shell gets thinner, and hence, the slab bulging, breakout and other defects are easily resulted in and the casting speed must be cut down. As a conclusion, the superheat must be exactly controlled.

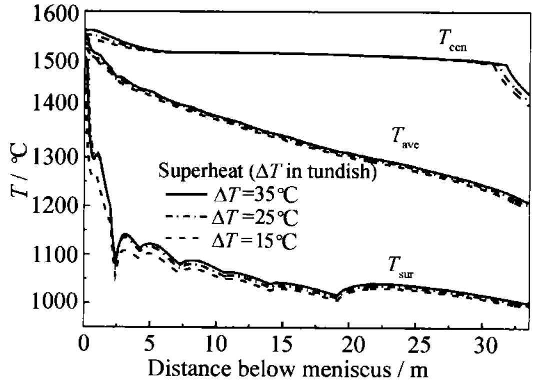

Figure 7 Influence of superheat on slab temperature.

4 Conclusions

(1) A finite-difference heat-transfer model on slab solidification has been formulated to predict the temperature field and solidification status in the process of casting under different operating conditions.

(2) Casting speed, the pattern of spray cooling zone and slab size are the main factors of influencing the slab temperature. And the superheat should be exactly controlled low.

(3) For the slab caster of Wuhan Iron & Steel Corporation, both the lessening of the water in spray cooling zone and the enhancing of the casting speed can make the location of complete solidification extend to the end of caster and improve the slab temperature. For the steel grade of insensitivity to hot-cracking, lessening the water sprayed or stop spraying at the lower part of secondary cooling zone can improve the slab temperature at most and have little effect on the location of complete solidification.

(4) Enhancing the casting speed and adjusting the patterns of secondary cooling zone are the effective measures to produce slab with high temperature. But these measures are limited by the shell thickness, metallurgical-length of caster and the defects of slab.

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