Method for Determining the Boundary Condition of Heat Transfer in Mold for Slab Casting

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Abstract. The calculation of temperature field in the mold is important for the study of solidification process of liquid steel. In order to calculate the accurate temperature field of slab in the mod, the boundary condition of heat transfer in the mold should be determined before the calculation of slab temperature. In this paper, the relationship among the average heat transfer coefficient in the mold, the physical properties of steel, the cast condition and the cooling condition is derived according to the energy conservation equation and the Fourier law of heat conduction. Furthermore, the method for determining the parameters related to the formula of boundary heat flux is introduced. Results indicate that the average heat transfer coefficient in the mold ranges from 450 to 2000 W·(m²·°C)⁻¹ for conventional caster with a casting speed ranging from 0.8 and 1.8 m·min⁻¹. The average heat transfer coefficient increases with the increase of casting speed. Besides, the casting speed has an effect on the parameters in the formula of calculating boundary heat flux, which indicates that the casting speed and the cooling condition should be taken into consideration for determining parameters related to the formula of calculating surface heat flux in the mold.

Keywords. Continuous casting, mold, thermal boundary condition, average heat transfer coefficient

1. Introduction

During continuous casting, two stages exist in the solidification process [1], including the first cooling process in the mold, and the second cooling process out of the mold. The calculation of the temperature field of the slab in the mold is the basis of studying the solidification process of the liquid steel. In order to calculate the temperature field of liquid steel in the mold, it is necessary to obtain the boundary condition between the slab surface and the mold. Unlike the second cooling process, the slab in the mold does not contact with the cooling water directly. There are three kinds of medium between the slab surface and the mold: mold flux (a kind of material used to lubricate solidified steel), air gap and copper plate [2]. The thickness, movement, and the thermal conductivity of the three kinds of medium have a great effect on the value of heat transfer coefficient on the slab surface [3]. However, due to the enclosed environment in the mold, it is difficult to measure the properties of mold flux and the thickness of air gap, although various methods were developed to simulate the true state of the mold flux. Therefore, experimental method could not measure the thermal boundary condition between the slab surface and the mold [4].

Present researches indicate that there are two methods used to determine the thermal condition of the mold. The first method is using the surface heat flux as the thermal boundary condition [5-6]. The
second method is using the average heat transfer coefficient as the thermal boundary condition [7]. For the first method, the heat flux is expressed as a function of the remaining time for liquid steel in the mold. This method could be applied to evaluate the tendency of heat flux. However, the effect of the cooling condition of the mold was not taken into consideration. Accurate values of heat resistance of air gap, thermal conductivity, thickness of slag film, and the contact resistance between the slab surface and the mold flux are necessary for determining the parameters in the formula referring to the heat flux [8]. For the second method, the heat transfer coefficient in the mold was considered as a constant which could be solved from the energy conservation equation [9]. Compared with the first method, it is convenient for the second method to measure the related parameters, such as the temperature, flow rate, density, and the heat capacity of cooling water [9]. Unfortunately, a concise expression used to describe the relationship among the heat transfer coefficient, temperature difference of cooling water and casting condition has not been reported.

In this paper, the average heat transfer coefficient between slab and copper plate is considered as a constant. In this situation, the heat referring to the condition could not only be obtained by applying the heat transfer coefficient, but also be solved from the energy conservation by referring the mass of solidified shell or the heat absorbed by the cooling water. Thus, a mathematical model could be established according to the basic regular of heat transfer phenomenon. The advantage of this method is that the average heat transfer could be inverse solved from equations without any parameters related to the physical properties of mold flux. Furthermore, the parameters in the formula referring to the surface heat flux were given by a concise expression. Meanwhile, the multiple linear regression were applied to derived an expression of the average heat transfer coefficient as a function of solidus temperature of liquid steel, casting speed and the cooling conditions in the mold.

2. Mathematical Model of Heat Transfer in the Mold

2.1. The Derivation of the Average Heat Transfer Coefficient
The distribution of medium between the slab and the mold is shown as figure 1. The liquid level is chosen as the zero plane, and the coordinate system is established as figure 2.

![Figure 1. Schematic of distribution of medium between the slab and the mold.](image-url)
Figure 2. Schematic of coordinate system and the temperature distribution between the slab and the mold:(a) coordinate system; (b) temperature distribution.

When the casting becomes stable, the thermal transfer between the slab surface and the mold could be considered as the steady-state conduction. According to the Fourier law of heat conduction, the horizontal heat flux could be expressed as:

$$q_t = \frac{T_s - T_w}{R_{Tot}}$$  \hspace{1cm} (1)$$

In equation (1), $q_t$ is the horizontal heat flux, MW·m$^{-2}$. $T_s$ is solidus temperature of liquid steel, °C. $T_w$ is temperature of cooling water, °C. $R_{Tot}$ is the total heat resistance between the slab surface and the cooling water, which can be calculated from the sum of the heat resistance for different medium:

$$R_{Tot} = \frac{s_z}{\lambda_s} + \frac{1}{h_f} + \frac{d_{cu}}{\lambda_{cu}} + \frac{1}{h_w}$$  \hspace{1cm} (2)$$

In equation (2), $s_z$ is thickness of solidified shell, m; $\lambda_s$ is the thermal conductivity, W·(m·°C)$^{-1}$. $d_{cu}$ is the distance between the upper line of water channel and the hot face of the copper plate, m. $h_f$ is the average heat transfer between the slab surface and the copper plate, W·(m$^{-2}$·°C)$^{-1}$. The purpose of defining $h_f$ is evaluating the ability of heat transferring from the slab surface to copper plate. $h_w$ is the convection heat transfer coefficient between the cooling water and the copper plate, which can be expressed as a function of the Reynold Number and the Prandtl Number:

$$h_w = 0.023 \frac{\lambda_w}{D} \left(\frac{\rho_w u_w D}{\mu_w}\right)^{0.8} \left(\frac{c_{p_w} \rho_w u_w}{\lambda_w}\right)^{0.4}$$  \hspace{1cm} (3)$$

In equation (3), $\lambda_w$ is the thermal conductivity of water, W·(m·°C)$^{-1}$; $\rho_w$ the density of water, kg·m$^{-3}$; $u_w$ is the flowing rate of water, m·s$^{-1}$; $c_{p_w}$ is the heat capacity of water, J·(kg·°C)$^{-1}$; $\mu_w$ is the viscosity of water, Pa·s; $D$ is the equivalent diameter of water channel, m. The horizontal heat flux in equation (1) could be considered as a function of distance when the change of heat flux on the x-direction is ignored. Thus, the heat through the whole copper plate could be calculated by integrating the $q_t$ with $z$:

$$Q_f = \int_0^H q_t B_0 dz$$  \hspace{1cm} (4)$$
In equation (4), $Q_i$ is the heat through the whole copper plate per second, $W$. $H$ is the height of liquid steel, $m$; $B_0$ is the width or thickness of slab, $m$; For copper plate on the wide face, $B_0$ is the width of slab. For slab on the narrow face, $B_0$ is the thickness of slab. $z$ is distance from liquid level in the mold, $m$. For the convenience of integration, the thickness of solidified shell is expressed as a function of $z$ according to the solidification law:

$$s_z = K \sqrt{t}$$  \hspace{1cm} (5)

In equation (5), $K$ is the solidification coefficient, $m \cdot s^{0.5}$; $t$ is the remaining time of liquid steel in the mold, $s$. The differentiation of $s_z$ is expressed as:

$$\frac{ds_z}{dz} = \frac{ds_z}{dt} \frac{dt}{dz} = \frac{K^2}{2s_z v_c}$$  \hspace{1cm} (6)

In equation (6), $v_c$ is casting speed, m$^3$/s. Combine equation (6) with equation (4):

$$Q_f = \frac{2}{K^2} B_0 v_c (T_z - T_w) f_0 s_0 \frac{\lambda_z s_z}{s_z + \lambda_z R_u} ds_z$$  \hspace{1cm} (7)

In equation (7), $s_0$ is the thickness of solidified shell on the exit of the mold, $m$. $R_u$ is the heat resistance between the slab surface and the copper plate, m$^3$C/W. By integrating the $s_z$, $Q_f$ is expressed as:

$$Q_f = \frac{2}{K^2} B_0 v_c (T_z - T_w) \left( \lambda_z s_0 + \frac{\lambda_z R_u}{s_0 + \lambda_z R_u} \right)$$  \hspace{1cm} (8)

According to the energy conservation, the heat through the whole copper plate is taken by cooling water:

$$Q_f = Q_w = B_o e_w \rho_w c_p \Delta T_w$$  \hspace{1cm} (9)

In equation (9), $Q_w$ is heat taken by cooling water per second, $W$; $\Delta T_w$ is the temperature difference between the inlet and the outlet, $^\circ$C; $e_w$ is the volume flux of cooling water per length of a copper plate:

$$e_w = \frac{f_w}{L}$$  \hspace{1cm} (10)

In equation (11), $f_w$ is the volume flux of cooling water in a copper plate, m$^3$/s; $L$ is the width of copper plate, $m$; Equation (9) is expressed as:

$$R_u \ln \left( \frac{\lambda_z R_u}{s_0 + \lambda_z R_u} \right) = \frac{1}{\lambda_z^2} \left( \frac{s_0^2 e_w \rho_w c_p \Delta T_w}{2H(T_z - T_w)} - \lambda_z s_0 \right)$$  \hspace{1cm} (11)

Equation (11) indicates that the average heat transfer coefficient could be calculated by the cooling conditions, the thickness of solidified shell on the exit of mold, and the physical properties of liquid steel. Because the heat taken by cooling water is from liquid steel, the solidified shell could also be used to calculate the value of $Q_w$. The mass flux of solidified shell on the exit of the mold is expressed as:

$$f_s = B_0 s_0 v_c \rho_s$$  \hspace{1cm} (12)

In equation (12), $f_s$ is the mass of solidified shell flowing out of the mold, kg/s. $\rho_s$ is the density of solidified shell, kg/m$^3$. The heat releasing from liquid steel to form solidified shell is expressed as:

$$Q_w = Q_s = f_s (c_p \Delta T_s + \Delta H_s + c_p (T_s - T_a))$$  \hspace{1cm} (13)

In equation (13), $Q_s$ is heat releasing from liquid steel per second, $W$. $T_a$ is degree of under heating for liquid steel, $^\circ$C; $c_p$ is the heat capacity of liquid steel, J/(kg$^\circ$C)$^1$; $\Delta H_s$ is the latent heat of solidified shell, J/kg$^1$; $T_a$ is the average temperature of solidified shell, $^\circ$C. Because the temperature distribution in the solidified shell changes approximately linear with $y$, the $T_a$ is expressed as:

$$T_a = \frac{T_s + T_f}{2}$$  \hspace{1cm} (14)
In equation (14), $T_p$ is surface temperature of solidified shell on the exit of the mold, which can be obtained according to the steady-state conduction law:

$$\lambda_s \frac{T_s - T_p}{s_0} = \lambda_s (T_s - T_w) \frac{1}{s_0 + \lambda_s R_u}$$

Combining the equation (12) with equation (15), the thickness of solidified shell could be expressed as:

$$s_0 = \frac{U_1 + \sqrt{U_1^2 + 4U_0 U_2}}{2U_0}$$

$$U_0 = \frac{1}{2} (T_s - T_w) cp_s + \Delta T_s cp_t + \Delta H_s$$

$$U_1 = \frac{e_w cp_w \rho_w \Delta T_w}{\rho w c} - \lambda_s R_u (\Delta T_s cp_t + \Delta H_s)$$

$$U_2 = \frac{e_w cp_w \rho_w \Delta T_w \lambda_s R_u}{\rho w c}$$

Combining the equation (11) with equation (16), the $h_f$ and $s_0$ could be solved from the two equations with known physical properties of liquid steel, casting condition, cooling condition and temperature difference of cooling water.

2.2. Derivation of Parameters Related to Heat Flux Calculation

The thermal boundary condition in the mold could also be expressed as heat flux from slab surface. The surface heat flux changing with time is expressed as:

$$q_t = A - B \sqrt{t}$$

In Equation (20), parameters A and B are constants used to calculate heat flux. Combining the equation (20) with equation (4), the heat through the whole copper plate per second is expressed as:

$$Q_f = Q_w = \int_0^{t_0} (A - B \sqrt{t}) B_0 v_c dt$$

In equation (21), $t_0$ is the remaining time of liquid steel in the mold, s. By integrating the heat flux with time, the equation (21) could be expressed as:

$$v_c t_0 A - \frac{2}{3} v c t_0^2 B = e_w \rho w c \Delta T_w$$

When the parameter $t$ in equation (20) is equal to $t_0$, $q_t$ could be expressed as the thickness of solidified shell and the average heat coefficient:

$$A - B \sqrt{t_0} = \frac{\lambda_s (T_s - T_w)}{s_0 + \lambda_s R_u}$$

Combining the equation (22) with equation (23), parameter A and parameter B could be expressed as:

$$A = \frac{3 e_w \rho w c \Delta T_w (s_0 + \lambda_s R_u) - 2H \lambda_s (T_s - T_w)}{H (s_0 + \lambda_s R_u) s_0}$$

$$B = \frac{3 \sqrt{v_c} (e_w \rho w c \Delta T_w (s_0 + \lambda_s R_u) - H \lambda_s (T_s - T_w))}{(s_0 + \lambda_s R_u) s_0}$$

The significance of equation (23) and equation (24) is combing the parameters A and B with casting speed, steel grade and cooling conditions, which is expected to reveal the thermal boundary condition in the mold under different working conditions. Furthermore, the parameters related to mold flux are unnecessary for calculation, which is practical for normal using. In equation (23) and equation (24), parameters $R_u$ and $s_0$ should be solved from equation (11) and equation (16). It is noted that the thickness of solidified shell derived from heat flux would not satisfy the solidification if the equation (20) is used as boundary condition. The values of physical properties used in the mathematical are listed in table 1.
Table 1. Parameters related to physical properties used in mathematical model.

| Parameters                                      | Values  |
|------------------------------------------------|---------|
| Under heat of liquid steel $T_s$, °C           | 25      |
| Solidus temperature $T_{so}$, °C                | 1465    |
| Heat capacity of liquid steel $cp_l$, J/(kg°C)$^{-1}$ | 670    |
| Latent heat $H_s$, J/kg$^{-1}$                 | 270000  |
| Heat capacity of solidified shell $cp_s$, J/(kg°C)$^{-1}$ | 730    |
| Thermal conductivity of solidified shell $\alpha_s$, W/(m°C)$^{-1}$ | 30     |
| Density of solidified shell $\rho_s$, kg/m$^3$  | 7800    |
| Viscosity of water $\eta_w$, Pas               | 0.000656|
| Density of water $\rho_w$, kg/m$^3$            | 1000    |
| Flow rate of water $u_w$, m/s$^{-1}$           | 7.4     |
| Heat capacity of water $cp_w$, J/(kg°C)$^{-1}$ | 4200    |
| Temperature of water $T_w$, °C                  | 45      |
| Thermal conductivity of water $\alpha_w$, W/(m°C)$^{-1}$ | 0.6    |
| Thermal conductivity of copper plate $\alpha_{cu}$, W/(m°C)$^{-1}$ | 300    |
| Width of copper plate $L$, m                    | 1.85    |
| Distance between upper line and hot face $d_w$, m | 0.025  |
| Height of liquid level $H$, m                   | 0.80    |

3. Discussion

3.1. Influence Factors of the Thickness of Solidified Shell on the Exit of Mold

The According to values presented in reference [10] and reference [11], the cooling condition of conventional mold and the thin-slab mold used for high casting speed are applied to calculate the average heat transfer coefficient. The results are listed in table 2.

Table 2. Cooling condition and average heat transfer coefficient for different mold.

| Parameters                                      | Conventional mold | Thin-slab mold |
|------------------------------------------------|--------------------|----------------|
| Section size                                    | 1400 mm×170 mm     | 1250 mm×50 mm  |
| Width of copper plate $L$, m                    | 0.165              | 0.153          |
| Distance between upper line and hot face $d_w$, m | 0.020              | 0.008          |
| Height of liquid level $H$, m                   | 0.80               | 1.0            |
| Casting speed $v_w$, m/s$^{-1}$                 | 0.0486             | 0.1014         |
| Volume flux of water $e_w$, m$^3$s$^{-1}$       | 7.4                | 12.4           |
| Temperature difference $T_{w}$, °C              | 8                  | 8              |
| Average heat transfer coefficient $h_f$, W/(m°C)$^{-1}$ | 1360.7            | 2413.9         |
| Thickness of solidified shell on exit $s_0$, m  | 0.0138             | 0.0081         |

From the values of table 2, the average heat transfer coefficient of mold used for thin-slab with high casting speed is obviously higher than that of conventional mold used for casters with low casting speed, which indicates that the rate of heat transfer from slab surface is different for different working conditions. The different heat transfer ability leads to various thermal boundary conditions during continuous casting. Two factors cause this phenomenon. The first is the change of surface temperature of slab, and the second is the flowing state of mold flux. Although it is difficult to measure the physical properties by industrial scene, quantification of the thermal condition could be realized by analysing the heat transfer process. The average heat transfer coefficient changing with casting speed is shown in figure 3.

As shown in figure 3, when the casting speed and flow rate of cooling water are given, the high temperature difference of cooling water between inlet and outlet means the strong ability of heat transfer,
which is characterized by a high value of average heat transfer coefficient. For conventional casters, the casting speed ranges from 0.8 to 1.8 m·min\(^{-1}\), and value of \(h_f\) ranges from 450 to 2000 W·(m\(^2\)°C\(^{-1}\)). With the increase of casting speed, the surface temperature increases, and the thickness of solidified shell decreases, leading to the increase of temperature gradient between the slab surface and the cooper plate. The high temperature gradient results in the high surface heat flux. In this case, the difference of temperature between inlet and outlet would increase so that more heat could be taken by the flowing cooling water. With the increase of temperature of slab surface, the flowing rate of mold flux between the slab and the copper plate will increase due to the low viscosity under high temperature. Meanwhile, the thickness of mold flux decreases because of the weak ability of crystallization under high temperature. Therefore, the value of \(h_f\) increases with the increase of casting speed. For the mold used for thin-slab, the value of average heat transfer coefficient may exceed 2400 W·(m\(^2\)°C\(^{-1}\)).

![Figure 3. Average heat transfer coefficient between the slab and the mold for different casting speed: (a) 0.8 m·min\(^{-1}\); (b) 1.2 m·min\(^{-1}\); (c) 1.6 m·min\(^{-1}\); (d) 2.0 m·min\(^{-1}\).](attachment:image)

Multiple linear fitting is applied to obtain a concise expression of the \(h_f\):

\[
\ln h_f = 60.324e_w - 15.2538v_c + 0.24164\Delta T_w - 0.0054u_w - 0.0012T_s + 5.64945
\]  

(26)

The scope of application for equation (26) is described as follows: 1) The casting speed is 0.8~2.0 m·min\(^{-1}\); 2) The temperature difference of cooling water is 5~10 °C; 3) The volume flux of cooling water per length per second: 0.02~0.04 m\(^4\)·s\(^{-1}\); 4) The flowing rate of cooling water: 6~10 m·s\(^{-1}\); 5) The solidus temperature of liquid steel: 1400~1490 °C. If the values of the five parameters are in the designative scope, the relative coefficient of equation (26) is 0.96.

For mold used for high casting speed, equation (27) is more appropriate, and the scope of application is described as follows: 1) The casting speed is 4.0~6.0 m·min\(^{-1}\); 2) The temperature difference of cooling water is 7~11 °C; 3) The volume flux of cooling water per length per second: 0.045~0.070 m\(^4\)·s\(^{-1}\); 4) The flowing rate of cooling water: 9~13 m·s\(^{-1}\); 5) The solidus temperature of liquid steel: 1400~1490 °C. If the values of the five parameters are in the designative scope, the relative coefficient of equation (27) is 0.98.

\[
\ln h_f = 36.895e_w - 5.4648v_c + 0.23525\Delta T_w - 0.006u_w - 0.00138T_s + 6.18132
\]  

(27)
3.2. Distribution of Surface Heat Flux

According to the data presented in table 2, the size of copper plate and the cooling condition of different mold are used to calculate parameter A and parameter B by using equations (24) and (25), as shown in table 3.

| Parameters | Conventional mold | Thin-slab mold |
|------------|--------------------|----------------|
| A          | 1545734.1          | 2797900.1      |
| B          | 73196.6            | 238382.6       |

The calculated results of parameter A indicate that the heat flux near meniscus in thin-slab mold is about 2.8 MW·m⁻². However, for conventional mold, the heat flux near meniscus is about 1.5 MW·m⁻², which is lower than that of thin-slab mold with high casting speed. The calculated results of parameter B indicate that the decreasing tendency during casting is more obvious for the thin-slab mold with high casting speed. Similar conclusion could also be inferred by analyzing the expression of the two parameters. For a mold with given cooling conditions, the heat taken by cooling water increases with the increase of casting speed. Thus, the values of \( f_w \) and \( T_w \) in equation (24) and equation (25) will increase, which leads to the increase of parameter A and parameter B.

It is easy to obtain a conclusion from above analysis that the casting speed will not only influence the remaining time of liquid steel in the mold, but also the parameters A and B used to calculate the surface heat flux. Therefore, if the surface heat flux of slab is used as the thermal boundary condition in the mold, the casting condition and the cooling condition should be taken into consideration for choosing appropriate values of parameter A and parameter B.

3.3. Influence Factors of the Thickness of Solidified Shell on the Exit of Mold

The results of the thickness of solidified shell on the exit of mold under different conditions are shown in figure 4. As shown in figure 4, the flow rate of cooling water has a slight effect on the thickness of solidified shell, but the average heat transfer coefficient has a large effect on the value of \( s_0 \). When the value of \( h_f \) is given, the \( s_0 \) increases slightly with the flow rate due to the increase of Reynolds Number. When the value of \( f_w \) is given, the \( s_0 \) increases with the average heat transfer coefficient.

![Figure 4. Thickness of solidified shell on exit of mold for different casting speed.](image)
Multiple linear fitting is applied to obtain a concise expression of the $s_0$:

$$\ln s_0 = 18.768e_w - 34.71\nu_c + 0.07498\Delta T_w - 6.2 \times 10^{-16}u_w - 2.808 \times 10^{-5}T_w - 4.678 \quad (28)$$

The scope of application for equation (28) is the same with equation (26), and the relative coefficient of equation (28) is 0.98. For mold used for high casting speed, equation (29) is more appropriate. The scope of application for equation (29) is the same with equation (27), and the relative coefficient of equation (29) is 0.99.

$$\ln s_0 = 8.797e_w - 10.026\nu_c + 0.05626\Delta T_w - 2.5 \times 10^{-16}u_w - 3.22 \times 10^{-5}T_w - 5.022 \quad (29)$$

The sum of contact heat resistance between slab and mold flux, the heat resistance of slag film and the heat resistance of air gap could be calculated according to the average heat transfer coefficient.

$$\frac{1}{h_f} = R_s + R_f + R_g \quad (30)$$

In equation (30), $R_s$ is the contact heat resistance between slab and mold flux, m$^2$C·W$^{-1}$. $R_f$ is the heat resistance of slag film, m$^2$C·W$^{-1}$. $R_g$ is the heat resistance of air gap. For conventional mold listed in table 2, the sum of $R_s$, $R_f$ and $R_g$ is $7.35 \times 10^{-4}$ m$^2$C·W$^{-1}$. The heat resistance of copper plate is $0.67 \times 10^{-4}$ m$^2$C·W$^{-1}$. The heat resistance between the cooling water and the copper plate is $0.35 \times 10^{-4}$ m$^2$C·W$^{-1}$. Therefore, the sum of $R_s$, $R_f$ and $R_g$ accounts for 88% of total heat resistance, but the heat resistance of cooling water only accounts for 4% of total heat resistance. This result indicates that the heat releasing from slab surface is controlled by the transfer between slab surface and copper plate. Increasing the flow rate of cooling water could decrease the heat resistance between the water and the copper plate. However, the sum of $R_s$, $R_f$ and $R_g$ could not be changed by the cooling water. In another word, the increase of flow rate of cooling water promotes the heat transfer of the water-copper interface, but not the slab-copper interface. As a result, it is almost impossible to increase the velocity of solidification by enhancing the flow rate of cooling water.

4. Conclusions

(1) The average heat transfer coefficient between the slab and the copper plate could be obtained according to the physical properties, casting conditions and cooling conditions. For conventional mold with a casting speed of 0.8–1.8 m·min$^{-1}$, the average heat transfer coefficient is 450–2000 W·(m$^2$C)$^{-1}$. The average heat transfer coefficient increases with the increase of casting speed. For the thin-slab mold with a high casting speed, the average heat transfer coefficient exceeds 2400 W·(m$^2$C)$^{-1}$.

(2) Parameters in the formula using to calculate the surface heat flux depends on the casting speed and the cooling conditions of the mold. The parameter $A$ and the parameter $B$ increases with the increase of casting speed.

(3) The heat releasing from slab surface is controlled the transfer between slab surface and copper plate. When the casting speed is given, the thickness of solidified shell is influenced by the average heat transfer coefficient. The velocity of solidification could not be increased by enhancing the flow rate of cooling water.

Acknowledgments

The authors would like to thank the important Science & Technology Specific Project in Jiangxi Province (20194ABC28011) for financial support.

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