Research Article

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Heat transfer behavior in ultrahigh-speed continuous casting mold

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Abstract: The growth rate of the shell thickness in the funnel mold for ultrahigh-speed continuous casting of steel has a significant effect on the shell surface quality. By using the node temperature inheritance algorithm, a three-dimensional transient thermal conductivity model of the liquid steel solidification inside the mold was established, and the effects of casting temperature and speed on the heat transfer behavior of the thin slab were investigated. The results show that with an increase in the casting speed from 4.0 to 6.0 m·min⁻¹, the maximum thickness of the shell at mold exit was reduced from 26 to 12.8 mm, and the maximum temperature of the slab surface at mold exit increased from 1,210 to 1,305°C. However, the increase of casting temperature from 1,550 to 1,560°C had little effect on the surface temperature and thickness of the slab shell.

Keywords: continuous casting, ultrahigh-speed, heat transfer, shell solidification, numerical simulation

1 Introduction

To fulfill the perfect match between the continuous casting and the rolling process, the casting speed of continuous casting is getting faster, and normally the casting speed for

the full endless rolling process must be at least 5.0 m·min⁻¹ [1–3]. The increase in casting speed is favorable to improve production efficiency and to save energy. However, the high casting speed has a significant effect on the heat transfer and the liquid steel solidification inside the mold [4–6], leading to the formation of slab surface defects (i.e., surface longitudinal cracks) and even the steel breakout [7,8]. Therefore, it is a necessity to study the heat transfer behaviors of the ultra-high-speed continuous casting mold and reveal the temperature field and shell growth of the slab.

In past decades, researchers have established a large number of mathematical models to analyze the heat transfer behavior of thin slabs inside the continuous casting mold. Nam et al. [9] established a fluid flow, heat transfer, and solidification-coupled mathematical model to analyze the flow and solidification behavior of molten steel within the funnel mold. Liu et al. [10] established a three-dimensional (3D) fluid flow, heat transfer, and solidification-coupled mathematical model to study the heat transfer behavior inside the mold of both compact strip production and flexible thin-slab casting technology (FTSC) processes. By a 3D coupling model, Ji et al. [11] revealed the initial solidification phenomenon and heat transfer occurring inside the mold along the casting direction. Yang et al. [12] built the 3D mathematical model including models of electromagnetic field to investigate the effect of electromagnetic stirring on the phenomena of heat flow and solidification inside the continuous casting mold. However, few literature about the effect of the high casting speed during the full endless rolling process on the heat transfer behaviors of the continuous casting mold were reported.

The purpose of this study is to investigate the effect of the high casting speed (>5.0 m·min⁻¹) on the heat transfer behaviors of the FTSC continuous casting mold at Tangshan Iron and Steel Co., Ltd. [13]. First, by using the node temperature inheritance (NTI) algorithm, a 3D transient thermal conduction model of the steel solidification inside the mold was established. Second, the effects of casting temperature and casting speed on the heat transfer behavior of the thin slab were determined.

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2 The establishment of the model

2.1 Model assumption

An exact analysis requires solving a 3D mathematical model regarding the phenomena of heat transfer, shell viscoelastic behavior, and fluid flow occurring inside the mold, which would be extremely difficult. To facilitate the analysis, the assumptions are made as follows [14–20]: (1) ignoring the fluid flow and the effective thermal conductivity is used to take the effect of fluid flow on the heat transfer process, and then the heat transfer of the thin slab is simplified as a heat conduction problem; (2) the interfacial thermal resistance between the thin slab shell and mold wall is a constant; and (3) ignoring the effect of mold oscillation on the heat transfer.

2.2 Heat transfer mathematical model

According to Fourier's law and the first law of thermodynamics, the heat transfer and solidification process of the liquid steel are governed by

$$c\rho\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) + q_v, \quad (1)$$

where T is the temperature, °C; ρ is the density, $\text{kg}\cdot\text{m}^{-3}$; τ is time, s; c is the specific heat capacity, $\text{J}\cdot\text{kg}^{-1}\cdot^\circ\text{C}^{-1}$; λ is the thermal conductivity, $\text{W}\cdot\text{m}^{-1}\cdot^\circ\text{C}^{-1}$; and q_v is the heat source at solidification front, $\text{W}\cdot\text{m}^{-3}$.

2.3 Finite element model

The section size of the FTSC thin slab is $1,540\text{ mm} \times 92.5\text{ mm}$, and the effective length of the continuous casting mold is $1,125\text{ mm}$. According to the symmetry of the thin slab, $1/4$ thin slab is taken as the geometric model [21]. By using the ANSYS software, Solid 70 element model was used to discrete the geometric model. Then, the geometric model was divided into 136,000 hexahedron elements with 130,896 nodes. Using Intel-Corei7 3.5 GHz CPU and 8 GB memory computer to calculate the model, the running time is about 40 h under single process conditions. Figure 1(a) and (b) shows the overall division of the finite element mesh. In the casting direction, the mesh size is a uniform mesh with 11.2 mm height and a total of 100 grids. Figure 1(c) shows the meshes of the shell cross section. The grids near the shell surface are

Figure 1: 3D finite element model of cast thin slab. (a) Overall grid division, (b) vertical grid division, (c) at the meniscus, (d) intermediate of the mold, and (e) at the mold exit.

finer than those of grids in the steel core. The ratio of mesh step size in the direction of the narrow face is 0.15, and the minimum step size is 2 mm .

2.4 Boundary conditions

Boundary conditions are set as follows: (1) the top of the model, namely the meniscus of the mold, adopts the first type of boundary conditions, and the node temperature is

the casting temperature of molten steel; (2) the thin slab model is a symmetrical structure with a wide face and a narrow face, and the adiabatic boundary conditions are adopted; and (3) the third type of boundary condition is applied to the surface of continuous casting thin slab, where the heat transfer coefficient includes the effects of the convection transfer rate of mold cooling water, the thermal resistance of mold wall, the slag film-mold interfacial thermal resistance, and the thermal resistance of slag film.

3 The solution process and parameter

During the continuous casting process, the initial solidification of the liquid steel occurs in the vicinity of the liquid steel level, and then the solidifying shell is continuously withdrawn downward. When the process of continuous casting reaches the stable casting state, the temperature field of the thin slab reaches the stable state and is time independent. According to the idea of NTI, the coordinates of nodes in the finite element model remain unchanged. During the model calculation, the mold meniscus always maintains a constant of casting temperature, and the node temperature transfers from the upper layer meshes to the next layer meshes within a given time step according to the casting speed. When the time steps are accumulated enough and the temperatures of nodes at mold exit reach the steady state, the temperature field of the thin slab in the mold is finally obtained; details of the calculation procedure can be referred to our earlier studies [21]. In this model analysis, the average heat flow on the surface of the cast slab is calculated from the steady-state temperature field and compared with the actual average heat flow of the mold. The surface boundary conditions of the model are repeatedly corrected to make the numerical analysis results gradually consistent with the actual conditions of continuous casting.

The typical steel type for the FTSC thin slab is steel plate hot-rolled commercial (SPHC), and its chemical composition is listed in Table 1. During normal conditions, the flow rate of cooling water required for the

wide face of the mold is $5,700 \text{ L}\cdot\text{min}^{-1}$, the flow rate for the narrow face is $300 \text{ L}\cdot\text{min}^{-1}$, and the cooling water speed is about $8.3 \text{ m}\cdot\text{s}^{-1}$. The temperature of the inlet cooling water is 30°C . In this study, the casting speed of 4, 5, and $6 \text{ m}\cdot\text{min}^{-1}$ and the casting temperature of 1,550, 1,555, and $1,560^\circ\text{C}$ are investigated, respectively.

4 Results and discussion

4.1 Validation of the model

To validate the model, the thickness of a breakout shell at $6 \text{ m}\cdot\text{min}^{-1}$ casting speed in Taiyuan Iron & Steel (Group) Co was measured (Figure 2), and the thickness of the funnel shell was 7.1 mm measured at a casting speed of $6 \text{ m}\cdot\text{min}^{-1}$. The measured shell thickness is 7.0 mm , as shown in Figure 3. It can be seen that the calculated shell thickness matches the measured shell thickness very well, suggesting that the built model is able to simulate the heat transfer phenomena occurring inside the continuous casting mold.

4.2 The influence of the casting temperature

4.2.1 Slab temperature distribution

Figure 4 shows the temperature of the thin slab surface at different casting temperatures. It can be seen that with an increase in casting temperature, the high-temperature zone of the slab moves down. When the casting temperature increases from 1,550 to $1,560^\circ\text{C}$, the shell surface temperature increases from 6 to 10°C at the same position. Thus, the

Figure 2: Verification of slab shell thickness.

Table 1: Chemical composition of SPHC (wt%)

C	Si	Mn	P	S	Al	T_L ($^\circ\text{C}$)	T_S ($^\circ\text{C}$)
0.050	0.020	0.310	0.008	0.005	0.030	1,527	1,478

Figure 3: Thickness of slab shell at $6 \text{ m} \cdot \text{min}^{-1}$ casting speed.

surface temperature of the thin slab increases slightly with an increase in the casting temperature.

4.2.2 Surface temperature and shell thickness along the casing direction

Figure 5(a) shows the shell surface temperature at different casting temperatures in the middle line of the slab wide face along the casing direction, where the casting speed is set as $6 \text{ m} \cdot \text{min}^{-1}$. At 400 mm below the meniscus, the surface temperature of 1,449, 1,452, and 1,458°C is corresponding to the casting temperature of 1,550, 1,555, and 1,560°C, respectively. At 800 mm below the meniscus, the surface temperature of 1,333, 1,335, and

1,338°C is corresponding to the casting temperature of 1,550, 1,555, and 1,560°C, respectively. At the outlet of the mold, the surface temperature of 1,305, 1,308, and 1,310°C is corresponding to the casting temperature of 1,550, 1,555, and 1,560°C, respectively. Therefore, the shell surface temperature in the middle line of the slab wide face increases slightly (about 10°C) with an increase in casting temperature from 1,550 to 1,560°C.

Figure 5(b) shows the shell thickness in the middle line of the slab wide face under different casting temperatures along the casing direction, where the casting speed is set as $6 \text{ m} \cdot \text{min}^{-1}$. With an increase in casting temperature from 1,550 to 1,560°C, the thickness of the shell in the middle line of the slab wide face decreases by about 0.4 mm. At 400 mm below the meniscus, the shell thickness of 2.2, 2.0, and 1.8 mm is corresponding to the casting temperature of 1,550, 1,555, and 1,560°C, respectively. At 800 mm beneath the meniscus, the shell thickness of 5.4, 5.2, and 5 mm is corresponding to the casting temperature of 1,550, 1,555, and 1,560°C, respectively. At the mold exit, the shell thickness of 6.7, 6.5, and 6.2 mm is corresponding to the casting temperature of 1,550, 1,555, and 1,560°C, respectively. It is concluded that the change of casting temperature had less effect on the heat transfer and shell growth on the wide face of the thin slab.

Figure 6(a) shows the shell surface temperature in the middle line of the slab narrow face along the casing direction, where the casting speed is set as $6 \text{ m} \cdot \text{min}^{-1}$. The shell temperature at the outlet of the mold of 1,242, 1,247, and 1,258°C is corresponding to the casting temperature of 1,550, 1,555, and 1,560°C, respectively. It implies that

Figure 4: Shell surface temperature under different casting temperatures: (a) 1,550°C, (b) 1,555°C, and (c) 1,560°C.

Figure 5: The shell surface temperature and shell thickness in the middle line of the slab wide face under different casting temperatures: (a) temperature and (b) shell thickness.

the shell surface temperature in the middle line of the slab narrow face increases with an increase in casting temperature from 1,550 to 1,560°C, whereas the location of maximum shell surface temperature moves downward

along the casting direction. Figure 6(b) shows the shell thickness at the mold exit of 8.3, 8.1, and 8 mm is corresponding to the casting temperature of 1,550, 1,555, and 1,560°C, respectively. Therefore, it implies that the shell

Figure 6: The shell surface temperature and shell thickness in the middle line of the slab narrow face under different casting temperatures: (a) temperature and (b) shell thickness.

thickness in the middle line of the slab narrow face decreases with an increase in casting temperature.

4.2.3 Surface temperature and shell thickness at mold exit

Figure 7 shows the surface temperature and thickness of shell at different casting temperatures on the wide face at mold exit under different casting temperatures, where the casting speed is set as $6 \text{ m} \cdot \text{min}^{-1}$. As Figure 7a shows, the shell surface temperature tends to decrease from the center of the wide face to the corner, where the maximum temperature is about $1,310^\circ\text{C}$ in the center of the wide face, which then sharply decreases from $1,250$ to 850°C within the locations $700\text{--}900 \text{ mm}$ away from the center of the wide face, and the minimum temperature of 850°C is located at the shell corner. When the casting temperature is $1,550$, $1,555$, and $1,560^\circ\text{C}$, the shell surface temperature 200 mm away from the center of the wide face is $1,255$, $1,262$, and $1,271^\circ\text{C}$; the shell surface temperature 400 mm away from the center of the wide face is $1,240$, $1,244$, and $1,249^\circ\text{C}$; and the shell surface temperature 750 mm away from the center of the wide face is $1,072$, $1,076$, and $1,081^\circ\text{C}$, respectively. Thus, the shell surface temperature on the wide face at mold exit increases with an increase in the casting temperature.

As Figure 7b shows, the shell thickness tends to increase from the center of the wide face to the corner, where the minimum thickness is about 8.0 mm in the center of the wide face, which then sharply decreases from 8.0 to 14.5 mm within the locations $700\text{--}900 \text{ mm}$ away from the center of the wide face, and the maximum thickness of 14.5 is located at the shell corner. When the casting temperature is $1,550$, $1,555$, and $1,560^\circ\text{C}$, the shell thickness 200 mm away from the center of the wide face is 7.9 , 7.5 , and 7.1 mm ; the shell thickness 400 mm away from the center of the wide face is 8.4 , 8.2 , and 8 mm ; and the shell thickness 750 mm away from the center of the wide face is 12.8 , 12.4 , and 12 mm , respectively. Thus, the shell thickness on the wide face at mold exit decreases with an increase in the casting temperature.

Moreover, with an increase in the casting temperature, the shell surface temperature on the narrow face at mold exit increases, and the shell thickness on the narrow face at mold exit decreases. The minimum temperature and maximum shell thickness are located at the shell corner might be due to the 2D heat transfer of the mold corner. As Figure 8a shows, the shell surface temperature at mold exit tends to decrease from the center of the narrow face to the corner, where the casting speed is set as $6.0 \text{ m} \cdot \text{min}^{-1}$. The maximum temperature is about $1,250^\circ\text{C}$ in the center of the narrow face, which then sharply decreases from $1,250$ to 850°C within the

Figure 7: The surface temperature and thickness of shell on the wide face at mold exit under different casting temperatures.

Figure 8: The surface temperature and thickness of shell on the narrow face at mold exit under different casting temperatures: (a) temperature and (b) shell thickness.

locations 30–35 mm away from the center of the narrow face, and the minimum temperature of 850°C is located at the shell corner. When the casting temperature is 1,550, 1,555, and 1,560°C; the shell surface temperature 20 mm away from the center of the narrow face is 1,224, 1,227, and 1,235°C; and the shell thickness is 8.2, 8.1, and 8.0 mm. Moreover, the casting temperature is 1,550, 1,555 and 1,560°C; the shell surface temperature 35 mm away from the center of the narrow face is 1,023, 1,025, and 1,029°C; and the shell thickness is 14.6, 14.4, and 14.1 mm.

In summary, with an increase in the casting temperature from 1,550 to 1,560°C, the shell surface temperature increases from 1,305 to 1,310°C at the center of the mold wide face, from 1,242 to 1,258°C at the center of the mold narrow face, and from 1,072 to 1,081°C at mold corner, whereas the shell thickness decreases from 6.7 to 6.2 mm at the center of the mold wide face, from 8.3 to 8 mm at the center of the mold narrow face, and from 12.8 to 12 mm at mold corner.

4.3 The influence of the casting speed

4.3.1 Slab temperature distribution

Figure 9 shows the temperature of the thin slab surface at different casting speeds. It can be seen that with an increase

in the casting speed, the high temperature zone of the slab moves down. When the casting speed increases from 4 to 6.0 m·min⁻¹, the shell surface temperature increases by 30–55°C at the same position. Thus, the surface temperature of the thin slab increases with an increase in the casting speed.

4.3.2 Surface temperature and shell thickness variation characteristics

Figure 10 shows the shell surface temperature and the shell thickness at different casting speeds in the middle line of the slab wide face along the casting direction, where the casting temperature is set at 1,550°C. Figure 10(a) shows when the casting speed is 4.0, 5.0, and 6.0 m·min⁻¹; the shell surface in the middle line of the slab wide face about 400 mm below the meniscus is 1,366, 1,396, and 1,435°C; and the shell surface at mold exit is 1,209, 1,251, and 1,305°C, respectively. Figure 10(b) shows when the casting speed is 4.0, 5.0, and 6.0 m·min⁻¹, the shell thickness in the middle line of the slab wide face about 400 mm below the meniscus is 3.7, 2.6, and 2.0 mm and the shell thickness at mold exit is 9.6, 7.9, and 6.6 mm, respectively. Therefore, it can be concluded that the increase in casting speed will lead to the

Figure 9: Shell surface temperature under different casting speeds: (a) 4.0 m·min⁻¹, (b) 5.0 m·min⁻¹, and (c) 6.0 m·min⁻¹.

increase of shell surface temperature and the decrease of the shell thickness in the middle line of the slab wide face.

Figure 11 shows the shell surface temperature and the shell thickness in the middle line of the slab narrow face along the casting direction, where the casting temperature is set as 1,550°C. Figure 11(a) shows that when the casting

speed is 4.0, 5.0, and 6.0 m·min⁻¹, the shell surface in the middle line of the slab narrow face at mold exit is 1,102, 1,167, and 1,242°C, respectively. Figure 11(b) shows that when the casting speed is 4.0, 5.0, and 6.0 m·min⁻¹, and the shell thickness in the middle line of the slab narrow face at mold exit is 10.0, 8.0, and 6.5 mm, respectively. Therefore, it is also concluded that the increase in casting

Figure 10: The shell surface temperature and shell thickness in the middle line of the slab wide face under different casting speeds: (a) temperature and (b) shell thickness.

Figure 11: The shell surface temperature and shell thickness in the middle line of the slab narrow face under different casting speeds: (a) temperature and (b) shell thickness.

Figure 12: The surface temperature and thickness of shell on the wide face at mold exit under different casting speeds: (a) temperature and (b) shell thickness.

Figure 13: The distribution of narrow face outlet temperature and shell thickness at mold exit under different casting speeds: (a) temperature and (b) shell thickness.

speed will lead to the increase of shell surface temperature and the decrease of the shell thickness in the middle line of the slab narrow face.

4.3.3 Surface temperature and shell thickness at mold exit

Figure 12 shows the surface temperature and thickness of shell at different casting speeds on the wide face at mold exit along the casing direction, where the casting temperature is set as 1,550°C. As Figure 12a shows, the shell surface temperature tends to decrease from the center of the wide face to the corner, where the maximum temperature is about 1,200–1,300°C in the center of the wide face, which then sharply decreases from 1,200 to 725°C within the locations 700–900 mm away from the center of the wide face, and the minimum temperature of 725°C is located at the shell corner. When the casting speed is 4.0, 5.0, and 6.0 m·min⁻¹, the shell surface temperature 200 mm away from the center of the wide face is 1,191, 1,228, and 1,268°C, and the shell thickness is 11.0, 9.0, and 7.0 mm (Figure 12b), respectively. When the casting speed is 4.0, 5.0, and 6.0 m·min⁻¹, the shell surface temperature 400 mm away from the center of the wide face is 1,159, 1,200, and 1,234°C, and the shell thickness is 12.5,

9.3, and 8 mm (Figure 12b), respectively. When the casting speed is 4.0, 5.0, and 6.0 m·min⁻¹, the shell surface temperature 700 mm away from the center of the wide face is 1,201, 1,094, and 1,150°C and the shell thickness is 26.0, 17, and 12.0 mm (Figure 12b), respectively. Thus, with an increase in the casting speed, the shell surface temperature on the narrow face at mold exit increases, and the shell thickness on the narrow face at mold exit decreases.

As Figure 13a shows, the shell surface temperature at mold exit tends to decrease from the center of the narrow face to the corner where the casting temperature is set as 1,550°C. The maximum temperature is about 1,100–1,250°C in the center of the narrow face, which then sharply decreases from 1,250 to 725°C within the locations 30–35 mm away from the center of the narrow face, and the minimum temperature of 725°C is located at the shell corner. When the casting speed is 4.0, 5.0, and 6.0 m·min⁻¹, the shell surface temperature 20 mm away from the center of the narrow face is 1,086, 1,152, and 1,224°C and the shell thickness is 13.0, 10.0, and 8.0 mm (Figure 13b), respectively. It can be seen that with an increase in the casting speed, the shell surface temperature on the narrow face at mold exit increases and the shell thickness on the narrow face at mold exit decreases.

In summary, with an increase in the casting speed from 4.0 to 6.0 m·min⁻¹, the shell surface temperature

increases from 1,209 to 1,305°C at the center of the mold wide face, from 1,102 to 1,242°C at the center of the mold narrow face, from 1,201 to 1,150°C at the mold corner, whereas the shell thickness decreases from 9.6 to 6.6 mm at the center of the mold wide face, from 10 to 6.5 mm at the center of the mold narrow face, from 26 to 12 mm at the mold corner.

5 Conclusion

The high casting speed has a significant effect on the heat transfer and the liquid steel solidification inside the mold, leading to the formation of slab surface defects (i.e., surface longitudinal cracks) and even the steel breakout. By using the NTI algorithm, a 3D transient thermal conductivity model of the liquid steel solidification inside the mold was established, and the effects of casting temperature and casting speed on the heat transfer behavior of the thin slab were investigated. The main results are made as follows:

- (1) The developed 3D solidification heat transfer model of the thin slab within a funnel mold can optimize the process parameters of thin slab continuous casting, according to the distribution law of shell temperature and thickness at different positions in thin slab continuous casting. The built model is able to simulate the heat transfer phenomena occurring inside the continuous casting mold.
- (2) In summary, with an increase in the casting temperature from 1,550 to 1,560°C, the shell surface temperature increases from 1,305 to 1,310°C at the center of the mold wide face, from 1,242 to 1,258°C at the center of the mold narrow face, from 1,072 to 1,081°C at the mold corner, whereas the shell thickness decreases from 6.7 to 6.2 mm at the center of the mold wide face, from 8.3 to 8 mm at the center of the mold narrow face, from 12.8 to 12 mm at the mold corner.
- (3) In summary, with an increase in the casting speed from 4.0 to 6.0 m·min⁻¹, the shell surface temperature increases from 1,209 to 1,305°C at the center of the mold wide face, from 1,102 to 1,242°C at the center of the mold narrow face, from 1,201 to 1,150°C at mold corner, whereas the shell thickness decreases from 9.6 to 6.6 mm at the center of the mold wide face, from 10 to 6.5 mm at the center of the mold narrow face, from 26 to 12 mm at the mold corner.

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