Structural Optimization of Electromagnetic Swirling Flow in Nozzle of Slab Continuous Casting

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Abstract

During the slab continuous casting process, the flow field of molten steel in the mold plays a decisive role in the quality of the slab. In this paper, electromagnetic swirling flow in nozzle technology is proposed to control the flow field in mold. This technology can drive molten steel to rotate inside the submerged entry nozzle by electromagnetic force, thereby controlling the flow field. This research shows that it can reduce the impact of molten steel on the bottom of nozzle and partly reduce the negative pressure at the upper part of nozzle outlet which is even eliminated by optimizing the structure and angle of nozzle. The area of heat flux of the mold wall becomes larger, and the crest value of heat flux gets lower than that without swirling in nozzle and any nozzle optimization. The meniscus fluctuates smoothly, and the flow velocity at the top surface is within a reasonable range. The temperature field distribution in the mold is uniform which was beneficial to the growth of equiaxed crystal and decreased element segregation.

Keywords Continuous casting · Submerged entry nozzle · Electromagnetic swirling flow · Slab · Numerical simulation

1 Introduction

With the development of continuous casting technology, high-quality slab production has become the goal of steel companies. For slab continuous casting, due to the large width of mold, the molten steel flowing from submerged entry nozzle (SEN) to mold is unstable, causing high level of meniscus fluctuation and affecting the quality of the slab [1]. With the increase in casting speed, the above situations will become more serious [2, 3]. At present, the main technologies used to control the flow behavior in the mold include electromagnetic stirring and electromagnetic brake technologies. The electromagnetic stirring technology

promotes the rotation of molten steel by electromagnetic force [4]. The rotating molten steel washes the columnar crystals at the solidification front, which will increase the equiaxed crystal rate [5]. The electromagnetic brake technology can decrease discharging velocity and impact depth of molten steel from nozzle [6, 7], which stabilizes the flow field, decreases the jet impinging on the wall and reduces the heat transfer of molten steel on the wall [8]. However, since the mold is made of copper, it will shield the magnetic field and affect the efficient of the magnetic field utilization.

The swirling flow in the SEN can effectively improve the uniformity and stability of the outflow from nozzle, stabilize the flow field and temperature distribution and reduce the meniscus level fluctuation in the mold [9–16]. In Japan, the industrial trial of placing a swirl blade in the SEN showed that the temperature distribution and the equiaxed grain rate of billet were significantly improved [17]. For slab continuous casting, mechanical swirling-flow submerge entry nozzle technology could increase the casting speed and improve the surface quality of slabs and steel sheets [18]. Its metallurgical effect was equivalent to that of electromagnetic stirring and electromagnetic brake technologies. However, the swirl blade installed in SEN is

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easily damaged. And the swirl strength cannot be adjusted freely during the production.

Because the nozzle is made of refractory material with low conductivity, a rotating magnetic field can be imposed outside the nozzle. It can drive the rotation of molten steel instead of the swirl blade, thereby achieving similar effects of the mechanical swirling-flow submerge entry nozzle technology [19]. In the authors' previous study, the low-melting-point alloy experiments proved that the electromagnetic swirling flow in nozzle (EMSFN) could generate a certain angle of rotational flow at the outlet of nozzle [20]. The authors also investigated the distribution of flow and temperature fields in round billets under EMSFN by numerical simulation [21, 22]. Due to the different size and shape of mold, the slab casting process is quite different from round and square continuous casting. The SEN used in slab continuous casting is not straight type but bottomed with two outlets. The main problem of slab continuous casting is that the outflow from two outlets is unstable, causing uneven distribution of flow field, excessive meniscus fluctuation, slag entrapment and other issues. The EMSFN can not only efficiently suppress the unstable flow in nozzle, but also have some effects on the flow field which needs to be optimized. In this study, the feasibility of the electromagnetic swirl is verified by comparing the mechanical swirl in nozzle with EMSFN. Then, the three-dimensional flow and temperature field in nozzle and mold are numerically simulated under the condition of EMSFN. The corresponding optimization scheme is also proposed, which will provide a theoretical basis for the upcoming industrial trial.

2 Model Description

The principle of the EMSFN is that the magnetic field drives the rotation of the molten steel. After simulating the electromagnetic field, the effect of electromagnetic field on the flow and temperature field will be solved.

The analysis of the electromagnetic field is to solve the Maxwell's equations and Ohm's law:

$$\nabla \cdot \vec{B} = 0, \quad (1)$$

$$\nabla \times \vec{H} = \vec{J}, \quad (2)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad (3)$$

$$\vec{J} = \sigma(\vec{E}). \quad (4)$$

When the harmonic magnetic field is considered, the Lorentz force produced is composed of time-dependent and time-independent components. Since the current of this simulation has a higher frequency that is greater than the

response time of the molten steel, the time-dependent component is neglected. The time-independent Lorentz force is as follows:

$$\vec{F} = \frac{1}{2} \text{Re}(\vec{J} \times \vec{B}^*), \quad (5)$$

where $\vec{B}$ is magnetic flux density, T; $\vec{H}$ is magnetic field strength, A/m; $\vec{E}$ is electric field strength, V/m; $\vec{J}$ is induced current density, A/m²; $\vec{F}$ is time-independent Lorentz force, N/m³; $\vec{B}^*$ is conjugate complex number of $\vec{B}$, Re is the real part of a complex quantify.

Three-dimensional incompressible Reynolds-averaged N-S equations of flow field are described as follows:

$$\frac{\partial u_i}{\partial x_i} = 0, \quad (6)$$

$$\begin{aligned} \frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_j u_i)}{\partial x_j} = & -\frac{\partial p}{\partial x_i} \\ & + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) \right] \\ & + F_i, \end{aligned} \quad (7)$$

$$u_i \frac{\partial T}{\partial x_i} = \frac{1}{\rho C_p} \frac{\partial}{\partial x_i} \left(\frac{\partial k_{\text{eff}} T}{\partial x_i} \right), \quad (8)$$

where u_i represents velocity in the x , y and z directions (represented by $i, j = 1, 2, 3$), m/s; p is pressure (Pa); μ is dynamic viscosity (Pa s); ρ is density (kg/m³); δ_{ij} is Kronecker delta (if $i = j$, $\delta_{ij} = 1$ and $i \neq j$, $\delta_{ij} = 0$); $k_{\text{eff}} = k_0 + \frac{C_p \mu_t}{Pr_t}$; T is temperature; k_0 is thermal conductivity (W/(m K)); C_p is specific heat (J/(kg K)); Turbulent Prandtl number Pr_t is 0.85.

In this paper, a standard k - ε turbulent model is used to solve the eddy viscosity μ_t , turbulent kinetic energy k and turbulent dissipation rate ε . The formulas are as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon, \quad (9)$$

$$\begin{aligned} \frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = & \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G_k \\ & - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}, \end{aligned} \quad (10)$$

G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients.

$$G_k = -\rho \overline{u_i u_j} \frac{\partial u_j}{\partial x_i}. \quad (11)$$

The eddy viscosity μ_t is computed by combining k and ε as follows:

$$u_t = \rho C_\mu \frac{k^2}{\varepsilon}. \quad (12)$$

The model constants $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ , σ_k and σ_ε have the following default values:

$$C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.95, C_\mu = 0.06, \sigma_k = 1.0, \sigma_\varepsilon = 1.3.$$

The meniscus height can be calculated by the pressure distribution at the top surface of molten steel [23]:

$$h = \frac{P_{\text{static}} - \overline{P}_{\text{static}}}{(\rho - \rho_{\text{slag}}) \times g}, \quad (13)$$

where P_{static} is static pressure at each point and $\overline{P}_{\text{static}}$ is the average pressure at top surface.

Figure 1 gives the geometric model of SEN and mold used in this simulation. These required parameters for calculation are shown in Table 1. The inlet velocity of $V = 2$ m/s is fixed. The boundary condition of no shear wall is used at the top surface of molten steel, where the normal velocity is constrained to zero. The boundary condition of no sliding wall is applied to the other walls. The velocity near these walls is determined by the wall function.

Table 1 Simulation parameters

Process parameters	Value
Casting speed	1.52 m/min
Domain width	1320 mm
Domain thickness	230 mm
Domain length	3000 mm
SEN depth	170 mm
ρ	7020 kg/m ³
ρ_{slag}	3000 kg/m ³
μ	0.0062 Pa s
Specific heat capacity	680 J/(kg K)
Thermal conductivity	26 W/(m K)
Current intensity	250 A
Current frequency	50 Hz
Temperature of inlet	1550 °C
Temperature of wall	1525 °C

3 Results and Discussion

3.1 Feasibility Analysis

The study of mechanical swirling in nozzle in Wakayama works gives the results of simulation and water modeling

Fig. 1 Geometric model including an SEN, a mold and an electromagnetic swirling flow generator used in the simulation: **a** wide face side view, **b** narrow face side view, **c** vertical view (unit: mm)

Fig. 2 Mesh in vertical section of the SEN and mold for Wakayama slab: **a** mesh in Ref. [24], **b** mesh used in the simulation in this paper

Fig. 3 Flow field in vertical section of the SEN with a swirl blade: **a** simulation result in Ref. [24], **b** simulation result in this paper

experiment [24]. In this paper, according to the size and parameter given in the reference, a simulation is used to calculate the flow field in both nozzle and mold. After that, a reduction calculation is carried out to verify the accuracy of this simulation. The feasibility of EMSFN is verified by comparing the electromagnetic swirling with the mechanical swirling in nozzle.

The comparison of mesh in Ref. [24] and this paper is given in Fig. 2. It can be seen that the two meshes are similar. On the basis of this model, the computational method of this study is used to verify the results from Wakayama industrial experiment. The results of this simulation and reference are shown in Fig. 3.

The comparisons show that the results of this paper are similar to those given in Ref. [24], which proves the accuracy of the calculation method in this study.

The EMSFN uses the electromagnetic device instead of the swirl blade, which can drive the molten steel swirling in nozzle by Lorentz force. But whether it can achieve the

same effect as mechanical one is not verified yet. Therefore, the swirl blade is replaced by an electromagnetic device at the same position of Ref. [24]. The schematic diagrams of these structures are shown in Fig. 4a, b. Because EMSFN device is installed outside the nozzle, there is no need to change the inner diameter of the nozzle compared with mechanical swirling-flow nozzle. The simulation results of the EMSFN are given in Fig. 4c. Compared with the results of Fig. 3, it can be seen that the flow field at the outlet is similar to the mechanical one. Therefore, it is feasible to replace the swirl blade by EMSFN device, which can be applied widely to all kinds of nozzles.

3.2 Effect of EMSFN on the Magnetic Field and Flow Field

Figure 5 shows the magnetic flux density of the EMSFN device axis. At 250 A and 50 Hz, the magnetic intensity of

Fig. 4 Flow field in vertical section of the nozzle with EMSFN: **a** schematic of mechanical swirling flow nozzle [24], **b** schematic of EMSFN; **c** flow field in vertical section with EMSFN

Fig. 5 Distribution of magnetic flux density in nozzle axis

the molten steel at the center is about 0.3 T. The maximum Lorentz force of the molten steel is about $3.1 \times 10^5 \text{ N/m}^3$, as shown in Fig. 6. Under the same conditions, the Lorentz force calculated by the Spitzer electromagnetic force formula $\bar{F}_\theta = \frac{1}{2} B_0^2 \omega \sigma r$ [25] is about $3.49 \times 10^5 \text{ N/m}^3$, and the magnitude is same.

Figure 7 shows the flow field in the nozzle with or without swirling flow. The flow field in middle section of EMSFN is also shown in this figure. Without swirling flow, the molten steel has no horizontal swirling velocity, as shown in Fig. 7a. In the continuous casting process, the partial opening of the sliding gate or the misaligned stopper is easy to cause a bias flow in nozzle, resulting in the unstable flow in nozzle and mold. That ultimately affects the quality of slab [26]. With swirling flow, the molten

Fig. 6 Lorentz force distributes in middle section of EMSFN device

steel begins to rotate, as shown in Fig. 7b. Under condition of 250 A and 50 Hz, the maximum tangential velocity of the molten steel is about 4.8 m/s, as shown in Fig. 7c. The molten steel is uniformly distributed on the horizontal surface, which contributes to a stable and uniform outflow. Figure 7d shows the wall shear stress distribution of nozzle. It shows that the highest wall shear stress is in the action area of magnetic field and gradually decreases as the liquid flowing in the nozzle. The molten steel with high wall shear stress may wear the nozzle, which needs to be detected and investigated in the industrial trial.

Figure 8 shows the flow field near the nozzle outlets with and without swirling flow. Without swirling flow, the molten steel directly impacts the bottom of nozzle and then flows into the mold along the lower edge of nozzle outlet. There is a negative pressure area on the upper part of nozzle outlets, which may involve slag into the nozzle. The

Fig. 7 Flow field of the molten steel in the SEN with and without swirling: **a** without swirling flow, **b** with swirling flow, **c** distribution of tangential velocity in middle section of EMSFN device, **d** wall shear stress distribution of nozzle with swirling flow

Fig. 8 Flow field of the molten steel in vertical section of the nozzle outlet: **a** without swirling flow, **b** with swirling flow

slag flows out with the main stream causing an adverse effect on the quality of slab. With swirling flow, the rotating molten steel is dispersed due to the centrifugal force. Therefore, the impact on the bottom of nozzle decreases. The angle of outflow is wider than that without

swirling. The negative pressure area on the upper part of nozzle outlet is also reduced, but still exists.

Fig. 9 Flow field distribution near the nozzle outlet after optimization: **a** flow field in vertical section, **b** flow field of nozzle outlet

Fig. 10 Flow field in horizontal section of $z = -500$ mm: **a** without swirling flow, **b** with swirling flow

Fig. 11 Flow field in the mold: **a** without swirling flow (front view), **b** without swirling flow (top view), **c** with swirling flow (front view), **d** with swirling flow (top view)

Fig. 12 Flow field in the mold with swirling flow and nozzle rotation: **a** front view, **b** top view

Fig. 13 Distribution of wall heat flux in wide and narrow surfaces: **a** without swirling flow and no nozzle rotation, **b** with swirling flow and no nozzle rotation, **c** with swirling flow and nozzle rotation

3.3 Optimization of Nozzle Structure

To suppress the negative pressure on the outlet of nozzle, the shape of the nozzle is optimized in this section. The upper edge of the nozzle is curved, and the angle of lower edge is changed from -15° to 15° . Under the condition of 250 A and 50 Hz, the distribution of flow field near the outlet of the nozzle is shown in Fig. 9. The negative pressure near the outlet of the nozzle is completely suppressed after optimization. As shown in Fig. 9b, after discharging from the outlets of nozzle, molten steel flows along the four edges of the outlet, where the nozzle outlet clogging will be reduced [18].

Figure 10 shows the flow field in horizontal section of $z = -500$ mm of nozzle outlets. Without swirling flow, the molten steel is parallel to the wide surface. But when electromagnetic field is applied, the flow deflects a certain angle in clockwise direction, which increases the impact on the wide surface of the mold and changes the overall flow field.

Figure 11 shows the flow field of molten steel in the mold. Without swirling flow, the direction of main flow is parallel to the wide surface of the mold. It forms an upper recirculation zone after impacting on the narrow surface of mold. With swirling flow, the direction of main flow deflects. After flowing out from nozzle, the molten steel

Fig. 14 Meniscus profile and velocity distribution along the center line of wide top surface: **a** meniscus profile, **b** velocity distribution

Fig. 15 Temperature distribution in mold: **a** conventional casting, **b** EMSFN with optimization

impacts on the wide surface and generates a vortex in the horizontal section of the mold. And the flow field in upper and lower recirculation zones is weakened.

By comparing the two results, the swirling flow can uniform the flow field in the nozzle, resulting in a stable and uniform nozzle outflow. However, the swirling flow in nozzle also makes the main flow deflect in horizontal direction, increasing the impact on the wide surface of mold. Therefore, in order to further develop the swirling effect, the structure of the nozzle needs to be optimized. Through the optimization, the advantages of EMSFN can be fully exerted, and the adverse effects thereof can be suppressed.

In order to reduce the impact of molten steel on the wide surface under the swirling effect, the nozzle is rotated 5 degree in the opposite direction of the swirling flow. Figure 12 shows the front view and top view of the flow field in the mold after rotating the nozzle. After the nozzle rotation, the flow in the upper recirculation zone is strengthened. The impact of the molten steel on the wide surface becomes weaker. Figure 13 shows the heat flux distribution on the wall surface of the mold under three conditions, without swirling flow and no nozzle rotation, with swirling flow and no nozzle rotation, with swirling flow and nozzle rotation. At the condition without swirling flow and no nozzle rotation, the highest heat transfer area on the mold wall appears on the narrow side, and the maximum heat flux is $5.8 \times 10^5 \text{ W/m}^2$. At the condition with swirling and no nozzle rotation, the cooling area of mold increases and the maximum cooling area of the mold appears near the wide surface. However, the highest value of cooling rate on the mold surface with swirling flow and no nozzle rotation is higher than that without swirling flow and no nozzle rotation, which may lead to break out accident. At the condition with swirling flow and nozzle rotation, the cooling area distributes more uniformly. This enhances heat transfer of the mold, which is conducive to uniform growth of the shell.

Figure 14 shows the comparison of meniscus profile and velocity distribution along the center line of wide top surface between conventional casting (without swirling flow and no nozzle rotation) and EMSFN with optimization (with swirling flow and nozzle rotation). During the conventional casting, the meniscus profile of molten steel fluctuates greatly. The height difference between the highest point and the lowest point is 12 mm. The velocity of top surface between nozzle and narrow surface of mold

exceeds the reasonable velocity range (0.1–0.3 m/s) [27]. Compared with the conventional continuous casting process, the optimized EMSFN can control meniscus profile within 6 mm. Moreover, the velocity distribution on the upper surface of the molten steel is more stable, and it is within the reasonable range.

Figure 15 shows the distribution of temperature field in the mold. During the conventional casting, the temperature near the narrow face and the temperature gradient in the mold are higher. Due to high heat transfer coefficient of mold during EMSFN with optimization, the cooling rate of molten steel is strengthened. The temperature field is uniform, which is beneficial to the growth of the equiaxed crystal and decrease in the element segregation [28]. And because of lower flow velocity on the top surface, the temperature in meniscus of EMSFN with optimization is lower than that of conventional casting. However, the velocity on the top surface is in a reasonable range, which will not have effect on the melting of slag.

4 Conclusions

In this work, three-dimensional numerical simulations of electromagnetic field, flow field and temperature field in nozzle and mold during slab continuous casting with EMSFN are studied. By optimizing the structure of the nozzle, the adverse effects of the EMSFN are eliminated. The following results were obtained:

1. The swirling flow can stabilize the flow in nozzle, resulting in a stable uniform outlet flow. It also can reduce the impact of molten steel on the bottom of the nozzle.
2. The curved upper edge of nozzle suppresses the negative pressure in the upper part of the outlet and helps to prevent slag involved.
3. After optimizing nozzle structure, EMSFN reduces the impact of the molten steel on the wide surface of the mold, and the distribution of the cooling area at mold wall becomes uniform.
4. EMSFN can stabilize the meniscus level fluctuations and decrease the velocity of molten steel at the top surface. The temperature field distribution in the mold becomes uniform.

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