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The Optimization of Flow Field and Industrial Production Test of a 180 mm × 650 mm Slab Continuous Casting Mold

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Abstract

The numerical model of a slab mold with a section of 180 mm × 650 mm for three-dimensional flow field analysis was established based on the continuous casting process conditions in a factory. The effects of the immersion depth of the submerged entry nozzle, exit area, casting speed, and the inclination angle of the submerged entry nozzle on the flow field of the mold were analyzed. The results showed that when the immersion depth, exit area, casting speed, and inclination angle were 120 mm, 40 mm × 55 mm, 1.6 m/min, and 15˚, respectively, the slab mold can obtain an ideal flow field, and the free surface velocity and fluctuation can meet the production requirements, which providing a guidance for the optimization of the slab mold flow field. The industrial production test showed that the stronger interaction between the molten steel and the protective slag can be effectively weaken by increasing the inclination angle from 12˚ to 15˚, and the formation of central equiaxed grains can be promoted as well as the quality of continuous casting slabs.

Keywords

Slab Mold, Flow Field, Numerical Simulation, Inclination Angle

1. Introduction

With the metallurgical industry's demands for production efficiency and downstream users' requirements for steel quality continuing to rise, slab quality control is facing increasingly stringent challenges. During the transition from liquid to solid within the mold, molten steel forms a slab with a solidified shell and an incompletely solidified liquid core. The continuous casting process associated with the mold thus becomes critical for controlling slab quality. The flow field formed by molten steel moving within the mold exhibits complex turbulent flow characteristics, featuring randomness, diffusivity, and dissipative behavior. An irrational flow field may pose dual adverse effects. Firstly, excessive flow velocity at the mold's free surface intensifies meniscus turbulence leading to slag entrapment, meniscus exposure, and forming new inclusions, thereby reducing steel cleanliness and degrading slab quality. Secondly, overpowering fluid motion is apt to impede inclusion flotation, disrupt thermal equilibrium, and accelerate erosion of the solidified shell. As a result, the slab shell changes thinner, and elevates the risks of bulging deformation and breakouts, ultimately compromising casting quality and operational stability. Thus, to achieve high-quality continuous casting, the flow state of molten steel within the mold must first be strategically optimized to align with other process requirements.

As strip products account for a substantial proportion and high output in overall steel products, the quality of continuous casting slabs has become a key focus for numerous steel enterprises. Therefore, optimizing the mold flow field serves as an important pathway to enhance slab quality and improve production efficiency. The flow state of molten steel in the slab mold is primarily related to some factors, such as the structure of the submerged entry nozzle, immersion depth, and casting speed [1] [2]. Deng Xiaoxuan *et al.* [3] investigated the influence of the nozzle bottom shape on the mold level characteristics in slab continuous casting and found that the mold level fluctuation under a convex-bottom nozzle was greater than that under a concave-bottom nozzle. A concave-bottom nozzle with a well depth of 10 mm could effectively reduce mold level fluctuations and surface flow velocity, thereby preventing slag entrapment. He Yang *et al.* [4] addressed the issue of slab quality degradation caused by mold level fluctuations during continuous casting. They studied the effects of the Submerged Entry Nozzle (SEN) outlet angle and immersion depth on the flow field in a mold with cross-sectional dimensions of (1520 - 1720) mm × 230 mm. The results showed that mold level fluctuations decreased with increasing nozzle inclination angle, while the surface flow velocity slightly increased. At a casting speed of 1.10 m/min, the surface flow velocities with the nozzle inclination angles of 10˚ and 15˚ were too low, which was unfavorable for inclusion control in the mold. At a casting speed of 1.40 m/min, the mold level fluctuation measured with a 10˚ inclination angle exceeded the critical value, posing a significant risk of slag entrapment. When the nozzle immersion depth was increased from 120 mm to 180 mm and the casting speed rose from 1.10 m/min to 1.40 m/min, the mold level fluctuations with the inclination angles of 15˚ and 20˚ were relatively large, indicating a risk of slag entrapment. Ma Guojun *et al.* [5] examined the influence of casting speed on the steel flow and steel-slag interface fluctuations in a continuous casting mold with cross-sectional dimensions of 210 mm × 1300 mm. The results indicated that as the casting speed increased, the liquid flow velocity in the mold rose, amplifying the fluctuations at the steel-slag interface near the narrow face. This led to a higher likelihood of surface shear-induced slag entrainment and slag eye formation, thereby degrading slab quality. When the casting speed was controlled within 1.0 - 1.2 m/min, a more desirable mold flow field was achieved, with a relatively stable steel-slag interface.

Since the main body of the mold is made of non-transparent materials and the mold operates in a high-temperature environment, it is difficult to directly observe the real-time flow state of molten steel inside the mold during actual continuous casting production. Therefore, research on the flow field inside the mold primarily relies on physical simulation [6]-[8] and numerical simulation [9] [10]. Physical simulation typically uses fluids, such as water or low-melting-point metals, as the working medium. However, these fluids differ in physical properties from actual molten steel, and they also differ in terms of mass transfer and heat transfer behaviors inside the mold. As a result, physical simulation has certain limitations. With the continuous advancement of computer technology, numerical simulation has become a more widely used research method, enabling both qualitative and quantitative studies of the flow field in slab molds.

When producing 45# steel grade slabs with a dimension of 180 mm × 650 mm, a certain steel plant found that the slabs exhibited well-developed columnar crystals and defects such as center and surface cracks. It was speculated that these issues may be related to obvious fluctuations in the liquid level of the continuous casting mold and an unreasonable internal flow field in the mold. Therefore, it was necessary to improve slab quality by optimizing the mold flow field. This study took the slab continuous casting mold of the plant as the research object. To address the issue of unstable flow fields inside the mold, numerical simulation was employed to systematically investigate the effects of process parameters, such as the immersion depth of the Submerged Entry Nozzle (SEN), the exit area of the nozzle, the casting speed, and the inclination angle of the nozzle exit on the molten steel flow field within the mold. The optimal process parameters for achieving the best flow field were determined. The results verified through industrial production trials indicated that increasing the inclination angle of the Submerged Entry Nozzle (SEN) outlet from 12˚ to 15˚ can effectively reduce excessive interaction between molten steel and mold flux, and promote the formation of equiaxed crystals in the center of the slab. This work provided a theoretical reference for formulating reasonable process control technology for slab production and improving the quality of casting slabs.

2. Mathematical Model of the Mold Flow Field for Slab Continuous Casting

2.1. Basic Assumption

In the actual continuous casting production process, the heat transfer, fluid flow, phase change, and gas-liquid interactions of molten steel in the mold are highly complex. These processes are interconnected and mutually influential, making it extremely difficult to accurately simulate and calculate the flow behavior of molten steel in the mold. While ensuring that the calculation results are realistic and reliable, the computational process can be appropriately simplified. In this paper, the standard k-ε model was used to simulate the flow of molten steel in the slab continuous casting mold, and a three-dimensional mathematical model was established. Based on the research content involved in this study, the following assumptions were made regarding the flow and transport behavior of molten steel in the mold [11].

1) The molten steel in the mold was treated as an incompressible fluid and considered a homogeneous phase;

2) The effects of solid-phase transformation during solidification, volume shrinkage, and heat transfer on the mold flow field were neglected;

3) Natural convection caused by density variations was neglected;

4) The effects of mold vibration, mold curvature, and mold flux on the flow field were neglected. Note that, in numerical simulation of mold flow field, surface flow velocity and liquid level fluctuation were typically regarded as core indicators to highlight the key mechanisms of molten steel flow, such as reducing slag entrapment and controlling the flotation of inclusions. The role of mold flux was mainly concentrated on heat transfer at the molten steel interface, lubrication, and inclusion adsorption, and mold flux had minimal impact on the overall flow field. Therefore, the effects of mold flux was neglected in here;

5) Heat transfer, phase change, and chemical reactions of the molten steel were neglected;

6) The continuous casting process was considered to be steady-state pouring.

2.2. Mathematical Model

For the flow of molten steel in the slab mold, based on the laws of mass conservation and momentum conservation, the fundamental governing equations included the continuity equation, the momentum equation, and the k-ε turbulence model equation. The specific formulations of each equation were as follows:

1) Continuity equation

$$\frac{\partial\left(\rho v_j\right)}{\partial x_j}=0 \tag{1}$$

where, ρ was the fluid density, kg/m^3; v_j was the velocity in the j-direction, m/s; x_j was the distance in the j-direction, m.

2) Momentum equation

$$\rho\frac{\partial\left(v_i v_j\right)}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu_{\text{eff}}\frac{\partial v_i}{\partial x_j}\right)+\frac{\partial}{\partial x_i}\left(\mu_{\text{eff}}\frac{\partial v_j}{\partial x_i}\right)+\rho g \tag{2}$$

where, v_i was the velocity in the i-direction, m/s; x_i was the distance in the i-direction, m; p was the pressure, Pa; μ_{eff} was the effective viscosity coefficient, kg/(m·s); g was the gravitational acceleration, m/s^2.

3) k-ε equations. The standard k-ε turbulence model was employed owing to its established robustness and computational efficiency, and it was successfully applied in simulating turbulent flow fields in similar industrial continuous casting molds in previous studies [12] [13].

The turbulent viscosity was expressed as follows:

$$\mu_T = C_\mu \frac{k^2}{\varepsilon} \tag{3}$$

k-equation:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\frac{\partial k}{\partial x_j}\right) + \rho P - \rho\varepsilon \tag{4}$$

ε-equation:

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho u_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right) + C_1 \frac{\varepsilon}{k}\rho P - C_2 \frac{\varepsilon}{k}\rho\varepsilon \tag{5}$$

and

$$P = \mu_T \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial \mu_m}{\partial x_m}\delta_{ij}\right) - \frac{2}{3}k\frac{\partial \mu_m}{\partial x_m} \tag{6}$$

where, μ_T was the eddy viscosity coefficient, N/m^2; k was the turbulent kinetic energy, J; ε was the turbulent kinetic energy dissipation rate, W/m^3; t was time, s; u_i and u_j were the energies in the i and j directions, respectively, J; μ was the dynamic viscosity of the fluid, Pa·s; P was the turbulence production term; μ_m was the dynamic viscosity, N·s/m^2; x_m was the coordinate component, m; δ_{ij} was the Kronecker δ symbol, which equals 1 when $i = j$ and 0 otherwise; C_1, C_2, C_μ, σ_k, and σ_ε were empirical constants with values of 1.44, 1.92, 0.09, 1.0, and 1.3, respectively.

2.3. Boundary Condition

The boundary conditions set in this article were described in relation to the following aspects.

1) Tundish nozzle inlet: Defined as a velocity inlet, its velocity was derived from the casting speed, nozzle dimensions, and mold dimensions based on mass conservation. The turbulent kinetic energy and turbulent dissipation rate were determined by Equations (7) and (8), respectively.

The values of k and ε were as follows:

$$k = 0.01 v_{\text{inlet}}^2 \tag{7}$$

$$\varepsilon = \frac{2k^{1.5}}{d_{\text{nozzle}}} \tag{8}$$

where, v_{inlet} was the inlet velocity of the nozzle, m/s; d_{nozzle} was the hydraulic diameter of the nozzle, m.

2) Symmetry plane: The velocity component perpendicular to the symmetry plane and the gradients of all physical quantities in the direction normal to the symmetry plane were zero.

3) Free surface: The same boundary conditions as those for the symmetry plane were applied, while the effects of surface tension and the mold powder layer were neglected.

4) Wall surfaces: Both the mold and nozzle walls were treated as no-slip solid walls. The velocity component perpendicular to the surface and the normal components of other physical quantities were zero. The flow field near the wall region was treated using the standard wall function.

5) Outlet: The velocity at the lower outlet of the mold section was defined as the exit velocity from the mold, which corresponded to the drawing speed of the solidified shell out of the mold during continuous casting.

2.4. Process Conditions

The process parameters used in the simulation calculations are detailed in **Table 1**. The Submerged Entry Nozzle (SEN) structure employed featured a double-port design with a concave bottom and downward-facing outlets.

Table 1. Continuous casting process parameters.

Process parameters	Value
Slab thickness/mm	180
Slab width/mm	650
Mold length/mm	1000
Immersion depth of the submerged entry nozzle/mm	110, 120, 130
Outlet area of the submerged entry nozzle/(mm × mm)	30 × 50, 40 × 55, 50 × 60
Casting speed/(m·min^{-1})	1.5, 1.6, 1.7
Inclination angle/˚	12, 13, 14, 15

3. The Mold Flow Field under Actual Continuous Casting Production Conditions

During the actual continuous casting production with a slab cross-section size of 180 mm × 650 mm, the Submerged Entry Nozzle (SEN) immersion depth, the casting speed, the SEN outlet inclination angle, and the SEN outlet area were 120 mm, 1.6 m/min, 12˚, and 40 mm × 55 mm, respectively. The flow field formed in the longitudinal central section of the mold is shown in **Figure 1**. It can be observed that after the molten steel flows out from the SEN outlet, it forms a strong jet that moves in a straight line. Upon reaching the narrow face of the mold, the jet split into two streams. One flowed upward and the other downward. The upward stream formed an upper recirculation near the meniscus. This recirculation promoted the flotation of inclusions and affected the fluctuation of the free liquid surface, as well as the penetration of the mold flux along the mold surface. The surface velocity of this recirculation played a decisive role in the melting of the mold flux. The downward stream moved along the narrow face of the mold, forming a larger and oppositely directed lower recirculation compared to the upper one. After reaching a certain impact depth, the lower recirculation flowed toward the center of the slab, with its intensity gradually weakening as it extended downward.

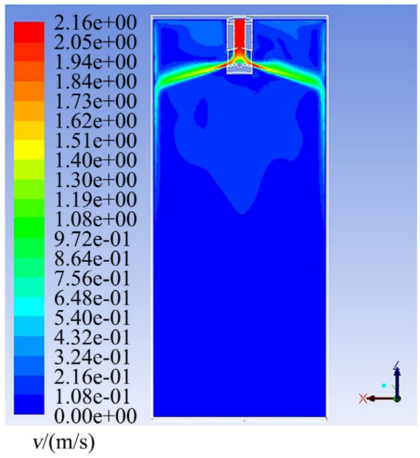


Figure 1. The cloud diagram of flow field in slab mold.

The variation in the flow velocity of the molten steel at the free surface of the mold is shown in **Figure 2**. The calculations indicated that the maximum flow velocity at the free surface can reach up to 0.45 m/s, occurring in the region near the narrow face of the mold. For the molten steel at the free surface of the mold, the optimal range of surface flow velocity was 0.20 - 0.40 m/s [14]. Excessively high flow velocity made the free-surface molten steel more active, which was not conducive to the melting of the mold flux, increasing the likelihood of slag entrapment, and reducing the quality of the cast slab. Therefore, under actual production conditions, the flow velocity of the free-surface molten steel exceeded the reasonable process requirements.

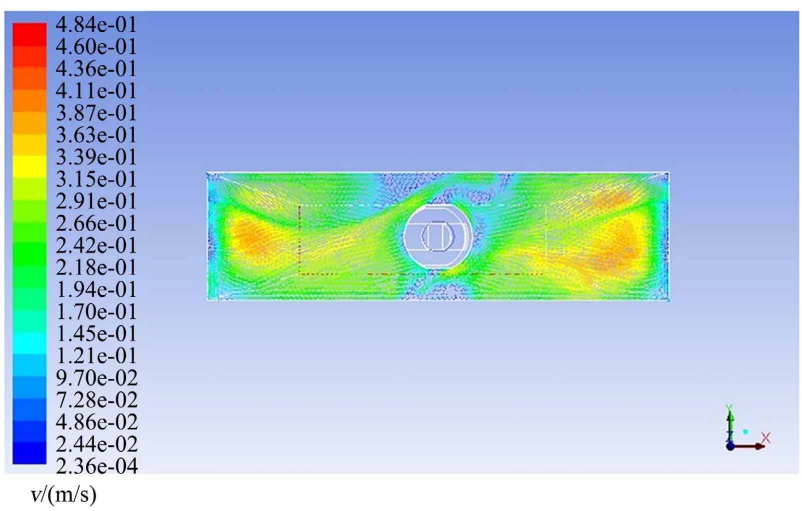


Figure 2. The free surface velocity distribution of liquid steel in a slab mold.

The fluctuation of the molten steel surface in the mold is shown in Figure 3. As can be seen from the figure, near the nozzle, the surface molten steel was primarily characterized by negative fluctuations, with the maximum negative fluctuation reaching −5.21 mm. Near the narrow face of the mold, the surface molten steel was mainly dominated by positive fluctuations, with the maximum positive fluctuation reaching 12.71 mm. The unstable flow of molten steel inside the mold can easily lead to instability at the interface between the molten steel and the mold flux, causing the liquid mold flux to be drawn into the molten steel, resulting in slag entrapment and the formation of inclusions, which adversely affect the quality of the cast slab. In addition, unreasonable surface fluctuations can disrupt the stable state of the liquid slag layer, leading to uneven inflow of liquid slag and causing surface cracks in the cast slab. In actual production, when the surface fluctuation exceeds ±5 mm [15], the probability of quality issues in the cast slab caused by excessive free-surface fluctuations increases significantly. Under the current continuous casting process conditions at the plant, the negative fluctuations of the molten steel surface in the mold were relatively severe, exceeding the reasonable range of surface fluctuation. Based on the analysis of the flow velocity and fluctuation of the molten steel surface in the mold under the current plant conditions, it can be concluded that the mold flow field under actual continuous casting process conditions was not conducive to improving the quality of the cast slab and requires further optimization.

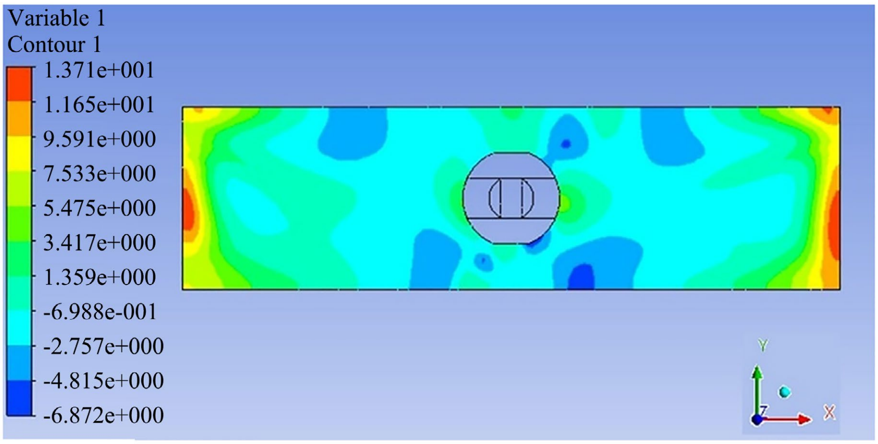


Figure 3. The fluctuation cloud diagram of liquid steel on the free surface of the slab mold.

4. Results and Analysis

4.1. The Influence of the Immersion Depth of the Nozzle on the Flow Field

During the continuous casting process, the molten steel in the tundish is poured into the mold through a Submerged Entry Nozzle (SEN). The immersion depth of the nozzle determines the state of the upward reflux flow, which in turn affects the temperature of the free liquid surface, the movement of the liquid slag, and the melting performance of the mold flux. A reasonable immersion depth can effectively prevent slag entrapment and improve the quality of the cast slab [16]. Therefore, it was necessary to investigate the influence of the SEN immersion depth on the flow field in the mold. When the exit area of the submerged entry nozzle, the nozzle outlet inclination angle, and the casting speed were 40 mm × 55 mm, 12˚, and 1.6 m/min, respectively, the flow fields in the mold were studied at immersion depths of 110 mm, 120 mm, and 130 mm. The distribution of the flow field in the longitudinal central section of the mold is shown in **Figure 4**. It can be observed that when the immersion depth was 110 mm, the molten steel flowing out of the nozzle exit formed an asymmetric flow field. The molten stream on one side had difficulty in reaching the narrow face of the mold, while the stream on the other side could reach it. This was likely due to significant energy dissipation during the molten steel flow and uneven static pressure distribution after the steel exited the nozzle [17]. Studies have shown [18] that a shallow immersion depth can easily lead to an asymmetric flow field in the mold, causing unreasonable liquid surface fluctuations and uneven temperature distribution inside the mold, which are major causes of surface cracks and slag entrapment in casting slab. Those issues should be avoided in production. When the immersion depths were 120 mm and 130 mm, the flow fields formed after the molten steel exiting the nozzle were similar and exhibited quasi-symmetric. The flow fields on both sides of the nozzle in the mold showed symmetry, ensuring uniform temperature distribution of the molten steel in the nozzle exit region, thereby promoting uniformity of the initial shell and contributing to improved cast slab quality. From the above analysis, it can be concluded that an immersion depth of 110 mm was not conducive to improving cast slab quality.

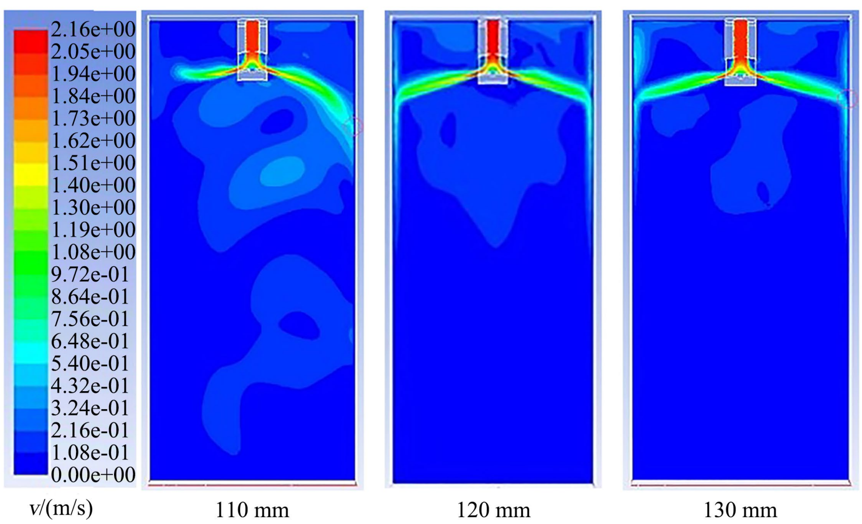


Figure 4. The cloud diagrams of flow field in the slab mold under different immersion depths of the submerged entry nozzle.

When the immersion depths of the Submerged Entry Nozzle (SEN) were 120 mm and 130 mm, respectively, the velocity distributions of the molten steel at the free surface of the mold were shown in **Figure 5**. As the immersion depth of the SEN increased from 120 mm to 130 mm, the maximum velocity of the molten steel at the free surface increased from 0.45 m/s to 0.48 m/s. This may be attributed to the enhanced shear effect of the upward reflux on the steel-slag interface, which increased the probability of slag entrainment [19]. The fluctuation conditions of the molten steel at the free surface under the two immersion depths are shown in **Figure 6**. It can be observed that in the region near the narrow face of the mold, the fluctuations of the molten steel at the free surface were predominantly upward, and as the SEN immersion depth increased from 120 mm to 130 mm, the fluctuation height increased from 12.71 mm to 20.29 mm. In the region near the SEN, the fluctuations were predominantly downward, and as the SEN immersion depth increased from 120 mm to 130 mm, the fluctuation height increased from −5.21 mm to −5.72 mm. Based on the above results, it can be concluded that neither reducing nor increasing the immersion depth of the SEN alone can meet the requirements of actual continuous casting production. Other measures were needed to optimize the flow field inside the mold.

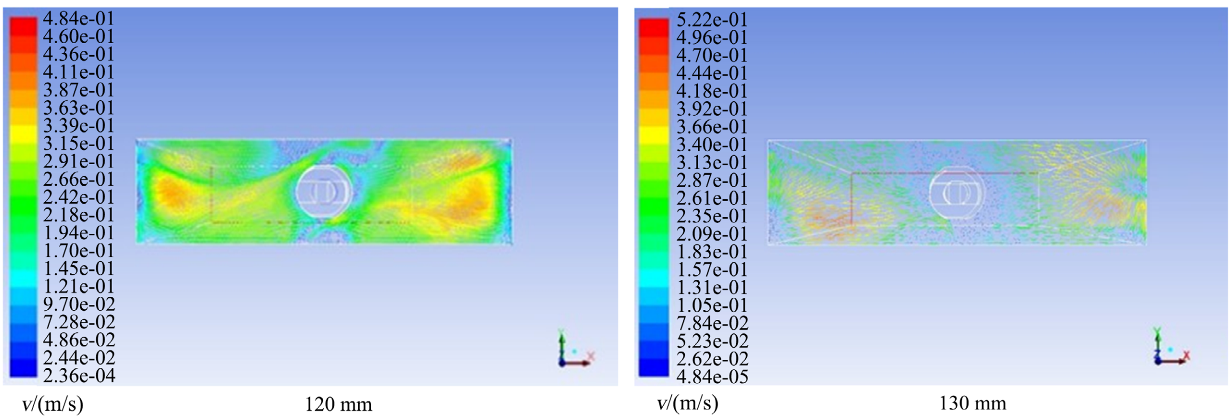


Figure 5. The free surface velocity distributions of liquid steel in slab mold under different immersion depths of the submerged entry nozzle.

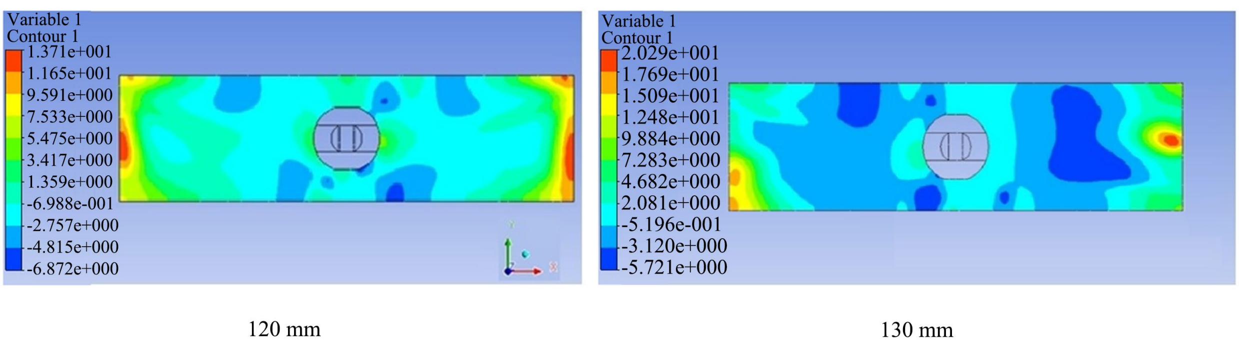


Figure 6. The fluctuation cloud diagrams of liquid steel on the free surfaces of slab mold under different immersion depths of the submerged entry nozzle.

4.2. The Influence of the Nozzle Outlet Area on the Flow Field

The flow field in the slab mold is closely related to the outlet area of the Submerged

Entry Nozzle (SEN). If the outlet area of the nozzle is either too large or too small, it can easily lead to an unbalanced flow of molten steel at the outlet. A properly sized nozzle outlet area can appropriately increase the flow resistance of the molten steel at the outlet, which helps the molten steel flow out from both sides of the nozzle to form a more balanced flow and thereby optimizes the flow field [20]. When the immersion depth of the submerged entry nozzle, the nozzle outlet inclination angle, and the casting speed were 120 mm, 12˚, and 1.6 m/min, respectively, the flow fields in the slab mold were studied under three different nozzle outlet area conditions, namely 30 mm × 50 mm, 40 mm × 55 mm, and 50 mm × 60 mm. The distribution of the flow field in the central longitudinal section of the mold is shown in **Figure 7**. It can be observed that under the conditions of 30 mm × 50 mm and 40 mm × 55 mm nozzle outlet areas, the flow field distributions were similar and exhibited a generally symmetrical pattern. However, when the nozzle outlet area was 50 mm × 60 mm, after the molten steel flowed out from the nozzle outlet, it began to rise before reaching the narrow face of the mold, and the symmetry of the flow field decreased. The upward deflection of the left-side flow stream became more pronounced. This was mainly because the excessively large nozzle outlet area caused an imbalance in the outflow of molten steel from the two sides of the nozzle [21].

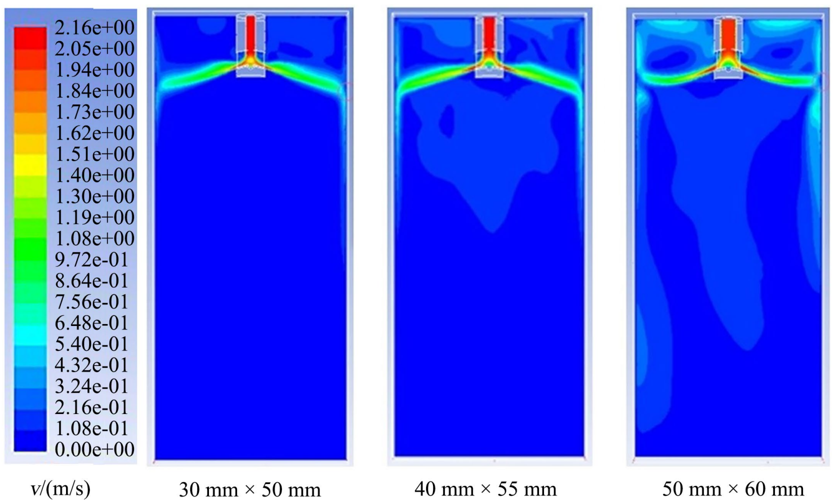
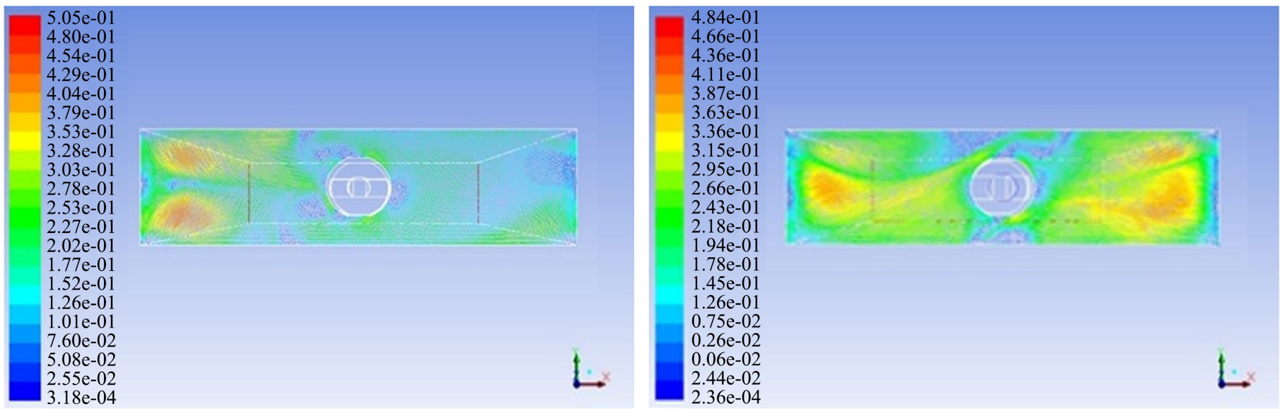


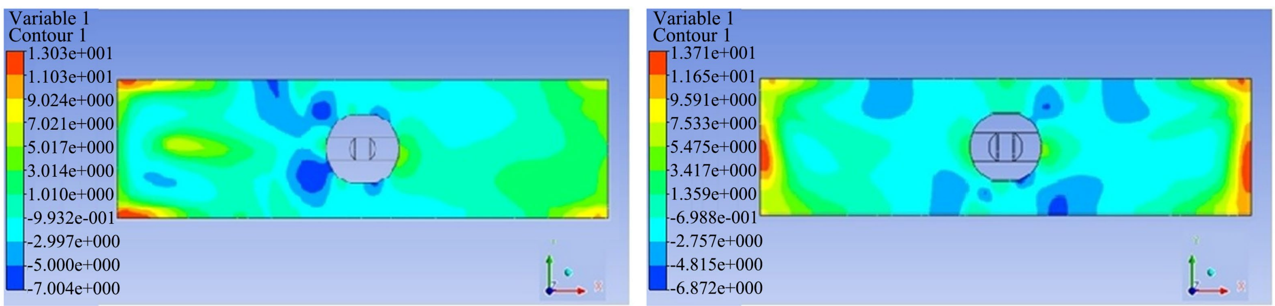
Figure 7. The cloud diagrams of flow field in slab mold under different exit areas of the submerged entry nozzle.

Under the conditions of nozzle outlet areas of 30 mm × 50 mm and 40 mm × 55 mm, the velocity distribution of molten steel at the free surface of the mold is shown in **Figure 8**. The maximum velocities in both cases were 0.45 m/s, which were higher than the required liquid surface velocity for production. The surface fluctuation conditions under these two nozzle outlet areas were shown in **Figure 9**, with fluctuation ranges of −7.00 mm to 13.03 mm and −5.21 mm to 12.71 mm, respectively. It can be concluded that reducing the nozzle outlet area on the basis of 40 mm × 55 mm led to an intensification of both positive and negative surface fluctuations. This was mainly because a smaller nozzle outlet area increased the pressure inside the nozzle, thereby increasing the kinetic energy of the molten steel at the nozzle exit, which in turn resulted in higher surface velocity and greater fluctuation. Based on the above results, it was manifested that neither reducing nor increasing the outlet area of the Submerged Entry Nozzle (SEN) can meet the requirements of actual continuous casting production. Other methods must be employed to optimize the flow field within the mold.



v/(m/s) 30 mm × 50 mm *v*/(m/s) 40 mm × 55 mm

Figure 8. The free surface velocity distributions of liquid steel in slab mold under different exit areas of the submerged entry nozzle.



30 mm × 50 mm 40 mm × 55 mm

Figure 9. The fluctuation cloud diagrams of liquid steel on the free surfaces of slab mold under different exit areas of the submerged entry nozzle.

4.3. The Influence of Casting Speed on the Flow Field

During the continuous casting process, changes in the casting speed determine the variation in the steel throughput. Under the same conditions, a lower casting speed results in a smaller velocity of the molten steel stream at the nozzle outlet, which can easily lead to biased flow, affecting the flow field inside the mold and causing defects such as longitudinal cracks on the surface of the cast slab. Conversely, an excessively high casting speed increases the velocity of the molten steel stream exiting the nozzle, thereby increasing the impact pressure on the narrow face of the mold and enhancing the upward reflux. This leads to excessive fluctuation of the liquid surface and can also drive the liquid slag layer near the narrow face toward the center of the mold, resulting in an uneven distribution of the slag layer thickness and promoting the formation of surface defects on the cast slab. An appropriate casting speed ensures effective flow of the molten steel at the free surface, which helps enhance temperature compensation and uniform distribution of the molten steel at the free surface within the mold, thereby reducing the occurrence of casting defects. Therefore, it was necessary to consider the influence of casting speed on the mold flow field. When the immersion depth of the Submerged Entry Nozzle (SEN), the nozzle outlet area, and the nozzle outlet inclination angle were 120 mm, 40 mm × 55 mm, and 12˚, the changes in the mold flow field under casting speeds of 1.5 m/min, 1.6 m/min, and 1.7 m/min were studied. The flow field in the longitudinal central section of the mold is shown in Figure 10. It can be observed that under the same conditions, when the casting speed varied, the basic characteristics of the flow field inside the mold did not change significantly, and the overall distribution of the flow field remained largely similar.

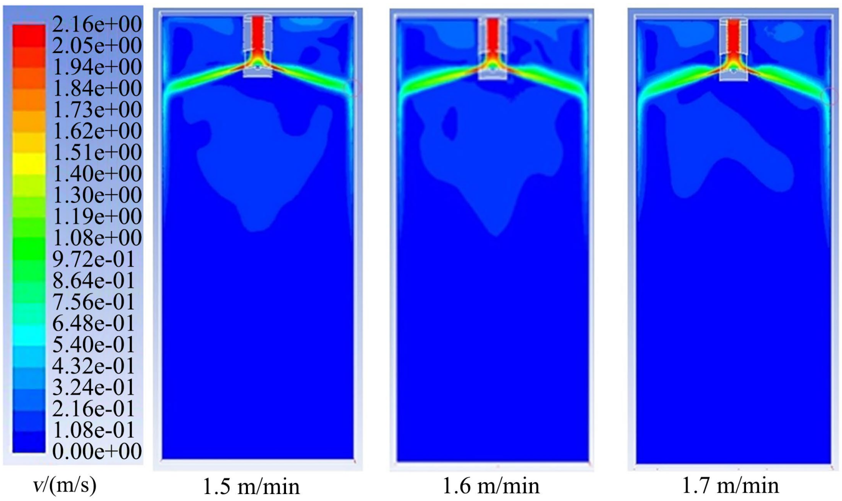


Figure 10. The fluctuation cloud diagrams of liquid steel on the free surfaces of slab mold under different exit areas of the submerged entry nozzle.

The velocity distribution of the free-surface molten steel under different casting speeds is shown in Figure 11. Under the casting speeds of 1.5 m/min, 1.6 m/min, and 1.7 m/min, the maximum flow velocities were 0.41 m/s, 0.45 m/s, and 0.39 m/s, respectively. The fluctuation conditions of the free-surface molten steel under different casting speeds are shown in Figure 12. When the casting speed was 1.5 m/min, the fluctuation range of the free surface was from −5.75 mm to 16.71 mm; at 1.6 m/min, it was from −5.21 mm to 12.71 mm; and at 1.7 m/min, it was from −4.60 mm to 15.15 mm. It can be observed that as the casting speed increased or decreased, the positive fluctuation of the free surface became significantly stronger, while the negative fluctuation decreased with increasing casting speed. Increasing the casting speed led to enhanced turbulent kinetic energy of the upward return flow at the mold top, which in turn increased the impact intensity of the upward return flow on the steel-slag interface, thereby intensifying the fluctuations at the interface. Excessive fluctuation of the free surface was not conducive to maintaining the stability of the steel-slag interface and can easily lead to defects such as molten steel exposure and slag entrapment, thereby deteriorating the quality of the cast slab. When the casting speed was reduced, as can be seen from Figure 12, the fluctuation on one side of the free surface was weaker while on the other side was stronger. This may be due to the fact that the turbulent kinetic energy of the upward return flow was stronger on one side and weaker on the other after the molten steel flowed out from the nozzle, resulting in a slight flow deviation. Therefore, taking into consideration the velocity and fluctuation conditions of the free surface, a casting speed of 1.6 m/min was deemed appropriate.

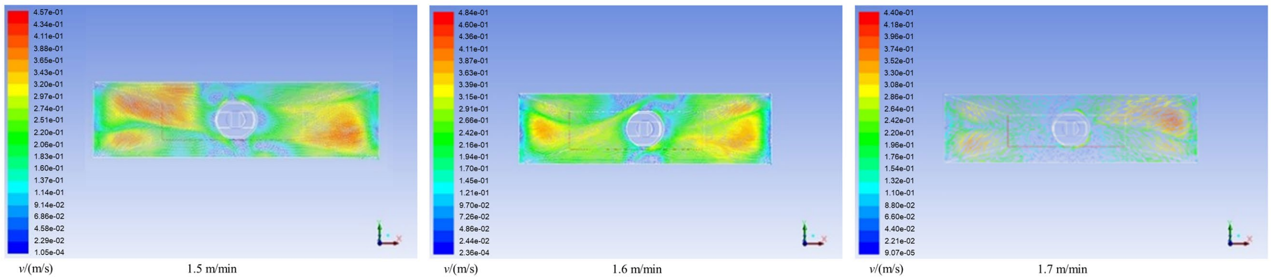


Figure 11. The free surface velocity distributions of liquid steel in slab mold under different casting speeds.

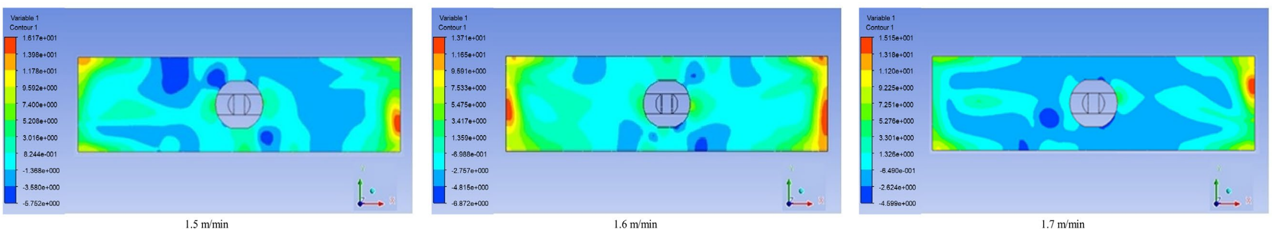


Figure 12. The fluctuation cloud diagrams of liquid steel on the free surfaces of the slab mold under different exit areas of the submerged entry nozzle.

4.4. The Influence of the Inclination Angle of the Submerged Entry Nozzle Outlet on the Flow Field

The change in the inclination angle of the nozzle outlet has a significant impact on the morphology of the flow field inside the mold. When the inclination angle of the nozzle outlet is relatively small, the distance that the molten steel flows from the nozzle outlet to the narrow face of the mold is shortened, and the velocity attenuation of the molten steel is slower. After the jet impacts the narrow face, a relatively strong upward return flow is formed. When the inclination angle of the nozzle outlet increases, the jet direction of the molten steel flowing from the nozzle outlet deflects downward toward the lower part of the mold, the distance that the molten steel travels to reach the narrow face is increased, and due to the influence of resistance and gravity, the turbulent kinetic energy of the upward return flow decreases. Therefore, it was necessary to study the influence of the inclination angle of nozzle outlet on the flow field in the mold. When the immersion depth of the Submerged Entry Nozzle (SEN), the nozzle outlet area, and the casting speed were 120 mm, 40 mm × 55 mm, and 1.6 m/min, respectively, the changes in the mold flow field under nozzle outlet inclination angles of 12˚, 13˚, 14˚, and 15˚ were investigated. The flow field at the central longitudinal section of the mold is shown in **Figure 13**. It can be seen that under the same conditions, when the inclination angle varied, the basic characteristics of the flow field inside the mold did not change significantly, and the distribution of the flow field remained largely similar.

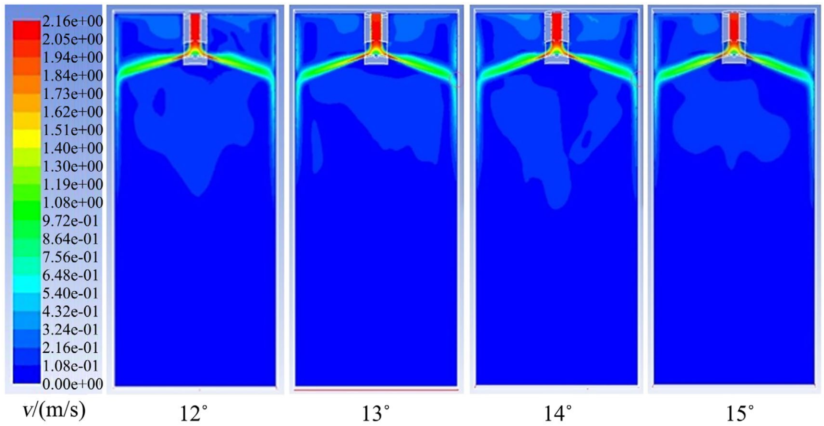


Figure 13. The cloud diagrams of flow field in slab mold under different immersion nozzle inclination angles.

The velocity distribution of the free-surface molten steel under different inclination angles is shown in **Figure 14**. It can be observed that as the inclination angle increased, the maximum velocity of the free-surface molten steel showed a decreasing trend, with values of 0.45 m/s, 0.41 m/s, 0.41 m/s, and 0.40 m/s, respectively. When the inclination angle was relatively small, molten steel flowing out of the nozzle impacted the narrow face of the mold and generated a strong upward return flow. The high turbulence intensity of this upward return flow led to a greater velocity of the free-surface molten steel. The fluctuation of the free liquid surface under different nozzle outlet inclination angles is shown in **Figure 15**. It can be seen that as the inclination angle increased, the molten steel surface fluctuation decreased. This was because a smaller inclination angle resulted in greater turbulence intensity of the upward return flow, which intensified the fluctuation of the liquid surface. When the nozzle outlet inclination angle was 15˚, the fluctuation range of the free liquid surface was between −4.00 mm and 3.00 mm, which fell within a reasonable range. Based on the above analysis, under the same conditions, the inclination angle of 15˚ can achieve a reasonable mold flow field.

5. Industrial Production Test

To improve the quality of the cast slab, based on the results of numerical simulation calculations, the steel plant conducted a mold flow field optimization

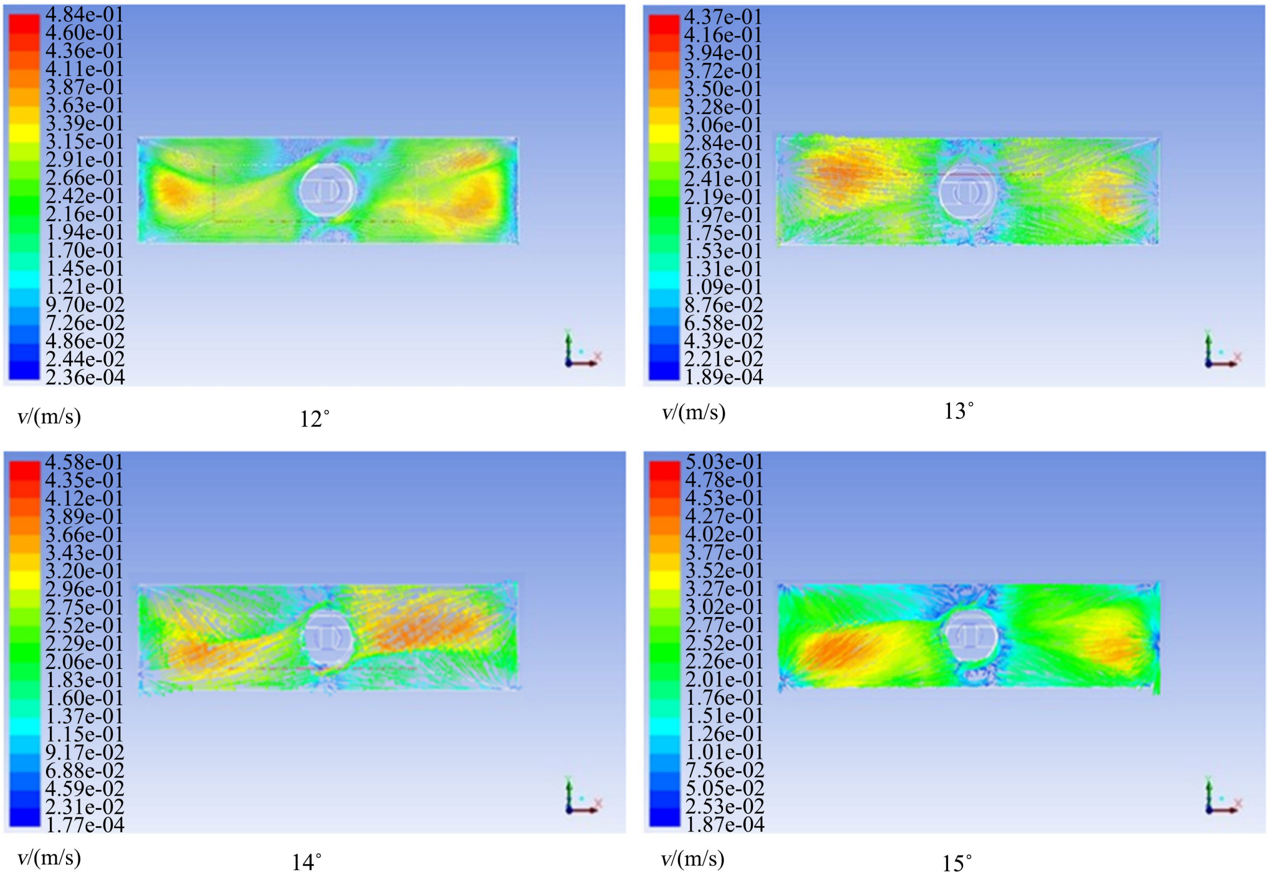


Figure 14. The free surface velocity distributions of liquid steel in slab mold under different immersion nozzle inclination angles.

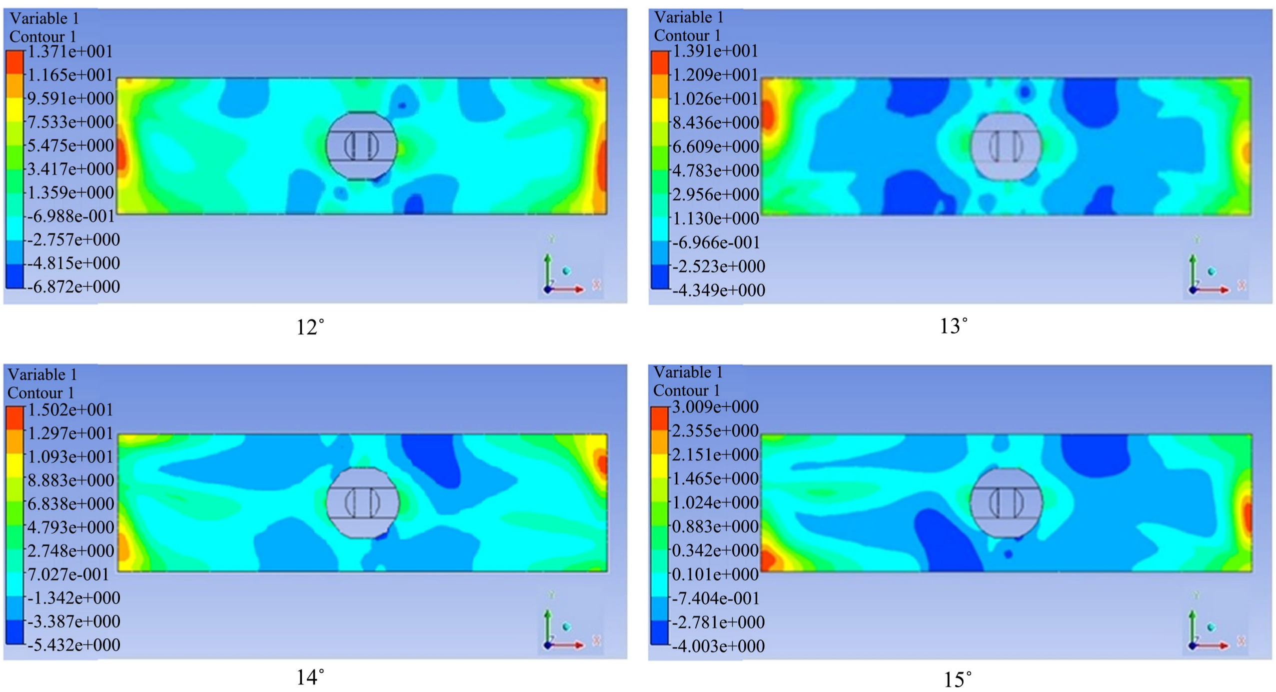


Figure 15. The fluctuation cloud diagrams of liquid steel on the free surfaces of slab mold under different immersion nozzle inclination angles.

production trial on the two-strand slab continuous casting line when producing 45# steel with a cross-sectional size of 180 mm × 650 mm. The outlet inclination angle of the Submerged Entry Nozzle (SEN) for Strand 1 was set at 12˚, while the trial Strand 2 was adjusted to 15˚. All other production process control parameters remained consistent between the two strands. As shown in **Figure 16**, during the continuous casting process, the mold liquid level conditions varied with the SEN outlet inclination angles. When the angle was 12˚, flames on the mold liquid surface were clearly visible and could not be covered even when mold flux was added, indicating strong upward recirculation flow and excessive heat transfer between the upward recirculation and the mold flux. This suggested an unreasonable flow field inside the mold. In contrast, when the SEN outlet inclination angle was adjusted to 15˚, the flame phenomenon on the mold liquid surface was significantly weakened, and the newly added mold flux could effectively cover the flames. This indicated that the upward recirculation flow was reduced, which helped to decrease the flow velocity and fluctuation of the steel at the free surface, thereby improving the mold flow field.

12˚ 15˚

Figure 16. The fluctuation cloud diagrams of liquid steel on the free surfaces of slab mold under different immersion nozzle inclination angles.

The internal quality of the cast slabs produced under different submerged entry nozzle outlet inclination angles is shown in **Figure 17**. It can be observed that, compared to the slab produced with a 12˚ SEN inclination angle, the slab produced with a 15˚ SEN inclination angle exhibited an expanded central equiaxed crystal zone, resulting in a higher proportion of equiaxed crystals to columnar crystals in the slab. This indicated that, during the continuous casting process, increasing the inclination angle of the submerged entry nozzle outlet optimized the flow field within the mold, leading to a more reasonable temperature distribution. A rational flow field was beneficial to improving thermal uniformity, which can effectively suppress temperature fluctuations in the mold and reduce the temperature gradient at the solidification front. As a result, the growth advantage of columnar crystals was weaken, and the thermodynamic conditions were more favorable for dendrite fragmentation and survival in the liquid pool as well as the nucleation of equiaxed crystals. This, in turn, facilitated the proper growth and formation of both equiaxed and columnar crystals in the slab, thereby improving the overall quality of the casting slabs.

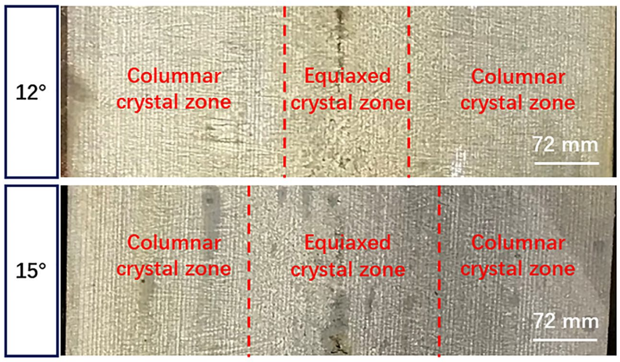


Figure 17. The internal quality of the continuous casting slabs with different immersion nozzle inclination angles.

6. Conclusions

This paper focused on the slab continuous casting process with an actual production cross-section size of 180 mm × 650 mm at a certain steel plant. By employing numerical simulation methods to optimize the flow field within the mold, the influence of process parameters, such as the immersion depth of the Submerged Entry Nozzle (SEN), the exit area of the nozzle, the casting speed, and the inclination angle of the nozzle exit, on the mold flow field. The main conclusions were summarized as follows.

1) Under the current applying continuous casting process conditions, using a submerged entry nozzle immersion depth of 120 mm, a casting speed of 1.6 m/min, a nozzle exit inclination angle of 12˚, and a nozzle exit area of 40 mm × 55 mm, the flow velocity and fluctuation of the molten steel at the free surface of the mold were excessively high, failing to meet the production requirements for improving slab quality.

2) By optimizing the process parameters, including the immersion depth of the submerged entry nozzle, the nozzle exit area, the casting speed, and the nozzle exit inclination angle, and comparing the flow velocity and fluctuation of the molten steel at the free surface under different conditions, it was found that, under the current continuous casting process, increasing the nozzle exit inclination angle from 12˚ to 15˚ resulted in a maximum flow velocity of molten steel at the free surface of 0.40 m/s and a fluctuation range of −4.00 mm to 3.00 mm. The flow field within the slab mold met the production process requirements.

3) Industrial production trials indicated that increasing the submerged entry nozzle exit inclination angle from 12˚ to 15˚ was beneficial to reduce the intensity of the upward reflux, and avoid excessive interaction between the molten steel and the mold flux, as well as lead to a more uniform temperature distribution within the mold. This promoted the formation of equiaxed crystals in the center of the slab, thereby improving the quality of the cast slab.

Note that the findings were specific to the 45# steel grade and mold geometry investigated, and considerably more work will need to be further explored and discussed to thoroughly investigate the practical effect and applicability of the submerged entry nozzle with a 15˚ inclination angle applied in the other steel grades' continuous casting conditions.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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