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Comparison of the Flow Field in a Slab Continuous Casting Mold between the Thicknesses of 180 mm and 250 mm by High Temperature Quantitative Measurement and Numerical Simulation

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Abstract: In the present work, the flow field in a slab continuous casting mold with thicknesses of 180 and 250 mm are compared using high temperature quantitative measurement and numerical simulation. The results of the numerical simulation are in agreement with those of the high temperature quantitative measurement, which verifies the accuracy and reliability of the numerical simulation. Under the same working conditions, the velocities near the mold surface with the thickness of 180 mm were slightly higher than those of the mold with the thickness of 250 mm. The flow pattern in the 180 mm thick mold maintains DRF more easily than that in 250 mm thick mold. The kinetic energy of the jet dissipates faster in the 250 mm thick mold than in the 180 mm mold. For double-roll flow (DRF), as the argon gas bubbles can be flushed into the deeper region under the influence of strong jets on both sides, the argon bubbles distribute widely in the mold. For single-roll flow (SRF), as the argon bubbles float up quickly after leaving the side holes, the bubble distribution is more concentrated in the width direction, which may cause violent interface fluctuation and slag entrainment. The fluctuation at the steel-slag interface in the mold with 180 mm thickness is greater than that in the mold with 250 mm thickness but less than 5 mm. The increase of mold thickness may lead to a decrease of the symmetry of the flow field in the thickness direction and uniformity of mold powder layer thickness. In summary, the steel throughput should be increased in the 250 mm thick mold compared with that in the 180 mm thick mold.

Keywords: flow field; mold thickness; rod deflection method; numerical simulation; automobile exposed panel

1. Introduction

Automobile exposed panels involve many manufacturing processes, including steel-making processes, such as hot metal pretreatment, converter blowing, secondary refining, continuous casting, hot rolling, cold rolling and hot-dip galvanizing. In the final quality inspection stage, the surface defects formed in the various production stages are interwoven, which increases the difficulty of the determination of the formation-related causes of the defects and the optimization of the corresponding processes. Surface defects caused by continuous casting are mainly divided into three categories: slag entrainment, inclusion, and bubbles. The surface defects caused by continuous casting are usually formed in the continuous casting mold, which account for more than 70% of all kinds of surface defects on automobile exposed panels. As the formation of surface defects in the mold is closely related to its flow field, it is of great significance to study the mold flow field.

Investigations of flow field in the mold are always carried out under different process conditions, such as different casting speeds, throughputs, argon gas flow rates, slab widths, nozzle shapes and immersion depths, all of which have been studied by many researchers.

The flow fields in molds with thin or thick thicknesses have been studied. For thin slab continuous casting molds, Liu et al. [1] carried out numerical and physical simulations on the flow field in a funnel-shaped mold with the section size of 1250×60 mm in compact strip production (CSP). The effects of casting speed, superheating and submerged entry nozzle (SEN) immersion depth on the temperature and flow fields in the mold were discussed. The flow field in the CSP mold is similar to that of a conventional slab mold, and the upper roll flow and the lower roll flow are also present. Under the influence of the funnel-shaped cavity, the lower roll flow space is compressed, and the flow at the outlet of the mold shows the obvious characteristics of piston flow. For the CSP funnel-type mold, Liu et al. [2] found that the maximum velocity and turbulent kinetic energy are near the liquid level, about $1/4$ width of the mold, which corresponds to the large local heat flux. Liu et al. [3] adopted an Euler–Euler model to study molten steel–argon gas two-phase flow in a mold with a section size of 1450×230 mm, and verified the simulation results with a water model experiment. The results show that with the increase of the argon gas flow rate, the double-roll flow (DRF) first changes into an unstable flow (UF) and then develops into a single-roll flow (SRF), and two mechanisms of vortex formation near the surface are observed: uniform shear and non-uniform shear. The liquid level fluctuation was regarded as the main index to evaluate the flow field by some researchers. Yu et al. [4] conducted a numerical simulation on the flow field and surface fluctuations in a medium-thin slab continuous casting mold with a section size of 1530×135 mm, showing that an increase of the casting speed makes the surface fluctuation increase, and that the surface fluctuation is first increased and then decreased with the increase of the argon gas flow rate.

As the fluctuations of the liquid level and the velocities near the surface are sensitive to the casting speed in a thin slab continuous casting mold, the structure optimization of SEN is considered to an important method of flow field optimization in some studies. Gutierrez-Montiel et al. [5] studied liquid level fluctuations in a mold with a section size of 1270×90 mm by conducting numerical simulations combined with water model experiments. The experimental results show that the high velocity and high turbulence intensity near the mold surface with the prototype double-hole SEN leads to severe fluctuation, and slag entrainment caused by the steel-slag interface oscillation was observed. Through the optimization of the nozzle structure, liquid level fluctuation can be significantly reduced. Liu et al. [6] studied the flow field in a 110 mm thin slab mold by industrial experiments and numerical simulation. The results show that the high casting speed and narrow thickness of the mold make the fluctuation and velocity near the steel-slag interface very sensitive and too-easily increased. The symmetry of the flow field in a mold with a four-hole nozzle is better than that of the flow field in a mold with a five-hole nozzle, the surface fluctuation is gentler, and the velocity near the surface is more reasonable. On the basis of electromagnetic braking (EMBr), Hwang and Thomas et al. [7] adopted a new type of double hole SEN, successfully stabilized the violent fluctuation of the mold liquid level under the condition of high casting speed, and realized world-class throughput (up to 8 m/min) on the CEM[®] (Compact Endless casting and rolling Mill) invented by POSCO.

Flow fields in thick slab molds have been studied in detail in many previous works. Zheng et al. [8] studied the liquid level fluctuation of a prototype argon-blowing thick slab mold with a section size of 1500×280 mm using a 1:2.5 water model. The average fluctuation magnitude of the liquid level with the argon gas blowing was 1.8 times higher than that without the argon gas blowing, and the most severe fluctuation area of the liquid level was near the nozzle. With the increase of casting speed, the fluctuation of liquid level first decreases and then increases. And with the increase of nozzle immersion depth, the fluctuation of liquid level first increases and then decreases. Yang et al. [9] studied the flow and temperature fields in a thick slab continuous casting mold with a section size of 2200×400 mm with a water model experiment and numerical simulation. They indicated

that the velocity near the mold surface increases with the increase of the distance from SEN, and the maximum velocity is between 1/4 width and the narrow face. In addition, with the increase of casting speed, the velocity near the mold surface increases, and the impact position of the stream on the narrow face moves down. With the increase of nozzle immersion depth, the velocity near the mold surface decreases, and the impact position of the stream also moves down.

Compared with conventional molds, uniformity of the temperature and composition distributions in a thick slab continuous casting mold are more difficult. Xie et al. [10] studied the flow field in 300, 360 and 420 mm thick molds, which were similar to the flow field in a conventional mold, composed of the upper and lower roll flow. The lower temperature zone was larger and the jet hardly diffused to the wide face, due to the lower casting speed and larger internal space. Some studies have used various methods to overcome this problem. Shen et al. [11] studied the influence of SEN structure on flow field, temperature field and solidified shell distribution in an ultra-thick slab mold with a section size of 2400×420 mm with a 0.55 geometric ratio water model experiment and a numerical simulation. It was found that the fast dissipation of the kinetic energy in the upper roll flow and the low velocity near the mold surface can be overcome to avoid condensed molten steel by the use of a tunnel-bottom SEN.

The characteristics of different turbulence models for the numerical simulation of mold flow fields have been compared in some studies. Liu et al. [12] compared the flow field simulation results of the laminar, standard $K-\epsilon$, renormalization group (RNG) $K-\epsilon$ and low Reynolds number $K-\epsilon$ models with the experimental results of the 1:1 water model, and found that the laminar model had the least calculation cost but insufficient accuracy. As the low Reynolds number $K-\epsilon$ model requires more grids, the standard $K-\epsilon$ model is a better choice.

There are a few high temperature measurement methods for velocity near the mold surface. Rietow and Thomas et al. [13] proposed the nail board experimental measurement method to measure the velocity near the mold surface for the first time. Ren et al. [14] summarized some basic rules of the flow field in the mold by combining the industrial nail board experiment with numerical simulation. Slag entrainment occurs easily near the nozzle due to the floating of bubbles, the maximum velocity near the mold surface appears to around 1/4 its width. The flow field in the mold is symmetrical, under ideal conditions. However, in the nail board experiment, a solidified cold steel slope on the nail was observed, which is too small to be measured many times. Thus, the results can only reflect the situation of a certain moment of the turbulence pulsation. In our previous works, a new high temperature quantitative measurement method, the rod deflection method (RDM), was proposed to measure the velocity near the mold surface. Moreover, the influences of casting speed, argon gas flow rate and nozzle immersion depth on the flow field in the molds with medium [15], narrow [16] and wide [17] width were studied by RDM and numerical simulations.

Although the flow fields in the molds with small or large thicknesses have been respectively studied in some literatures, these studies do not involve the comparison of flow fields in molds with different thicknesses under the same continuous casting conditions. In industrial production, the automobile exposed panels are usually produced in common commercial continuous casters with the mold thicknesses of 230 or 250 mm. However, they are sometimes manufactured with continuous casters with a thickness of only 175 mm, such as in the Anshan Iron and Steel Group Co., LTD., in China. As far as we know, it is difficult to use a continuous caster with a thickness smaller than 175 mm to produce automobile exposed panels to satisfy their strict surface quality requirement. This is the reason why two types of slab mold thickness (i.e., 180 and 250 mm) were selected for the comparison of mold flow fields under the same steel throughput, which was not reported before.

In the present work, the industrial high temperature quantitative measurement of the velocity near the mold surface and a numerical simulation were combined to analyze

the flow field in slab molds with section sizes of 1800×180 mm and 1800×250 mm, respectively. The flow fields in the molds with the different slab thicknesses under the same throughput, argon gas flow rate, nozzle type and nozzle immersion depth were compared. The flow fields at three groups of throughput and argon gas flow rate were compared, respectively. The selected groups of process parameters are commonly used in industrial production, giving them certain representativeness and industrial significance. RDM was used to measure the velocity of molten steel at $1/4$ width and the center of mold thickness near the mold surface. In the numerical simulation, the $K-\epsilon$ two-equation model was adopted to describe the turbulent flow. The volume of fluid method (VOF) was employed to track the steel-slag interface, and the argon gas bubbles were simplified as Lagrangian particles.

2. Rod Deflection Method and Mathematical Models

2.1. Rod Deflection Method for Measuring Velocities

In our previous paper, a new high temperature quantitative velocity measurement method called RDM was proposed [18]. Figure 1a shows the RDM for measuring velocity near the mold surface, and Figure 1b shows the measured position and the flow field in the mold with argon gas blowing. It is seen from the figures that the experimental apparatus consists of four parts: a speed measuring rod, deflection bearing, deflection angle indicator and balance block. The speed measuring rod is inserted vertically into the molten steel for 50 mm at the position to be measured. It can last for 30 s without melting. At this time, the speed measuring rod is subjected to its own gravity and the buoyancy and the impact force of molten steel flowing near the mold surface. The three forces reach torque balance, resulting in the speed measuring rod being deflected at a certain angle. As the turbulent flow field in the mold is unstable, the deflection angle of the speed measuring rod fluctuates slightly. We read more than 10 deflection angle values within the 30 s. Three speed measuring rods were used for the measurements under the same continuous casting condition and we finally obtained more than 30 measurement values. The average velocity of molten steel at the measured position can be calculated from the average value of 30 measurement values. The detailed method can be found in our previous work [18].

This method was adopted to measure the velocity of molten steel near the mold surface at $1/4$ width. As the maximum velocity near the mold surface is usually near this position, the velocity fluctuation here is large and the velocity change is the most sensitive to the process parameters. Therefore, the horizontal velocity component here can be used to describe the flow pattern inside the mold.

The flow patterns in the mold can be divided into DRF, SRF and UF. For DRF, the molten steel jet rushes out from the side hole of the nozzle, impinges on the narrow face, and the jet is divided into two strands, forming upper and lower roll flows, respectively. For SRF, the molten steel jet rises to the top surface near the SEN, to form a single roll flow. For UF, the jet rises to the top surface near the $1/4$ width of mold. If the velocity of molten steel near the mold surface at $1/4$ width is from the narrow face to the SEN, the direction is specified as positive, and the flow pattern is DRF. If the velocity is from the SEN to the narrow face, the direction is specified as negative, and the flow pattern is SRF. If the velocity is sometimes from the narrow face to the SEN and sometimes in the reverse direction, the flow pattern is UF.

In addition, the velocity of molten steel near the mold surface at $1/4$ width is usually the maximum velocity near the mold surface. The velocity fluctuation here is the largest, and the velocity changes are the most sensitive to the process parameters. We chose this typical velocity to compare the experimental and simulated results.

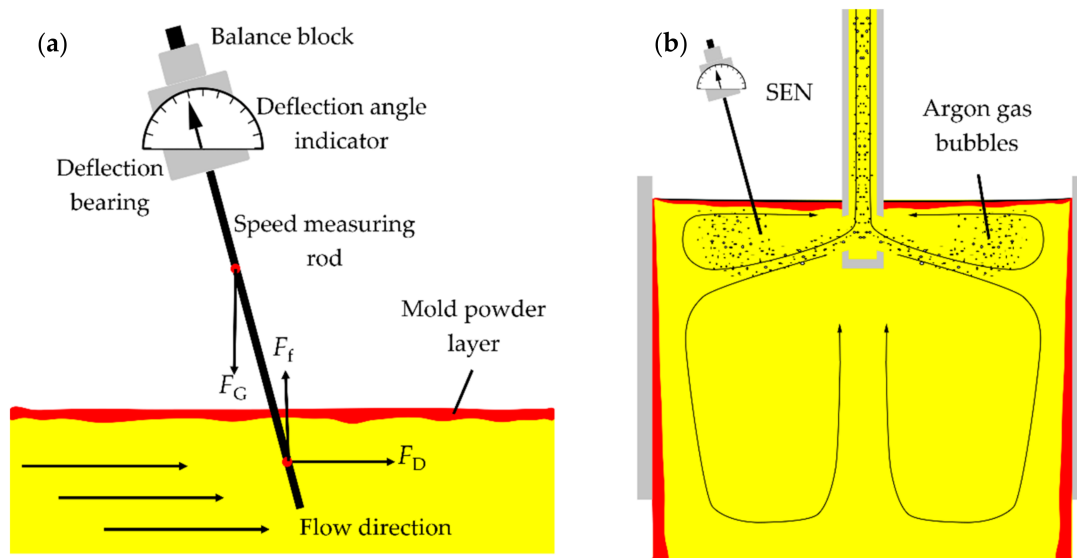


Figure 1. (a) Rod deflection method for measuring velocity near the mold surface; (b) measured position and flow field in a mold with argon gas blowing.

2.2. Mathematical Models

In this study, the turbulent behavior of the flow field is described by the $K-\varepsilon$ two-equation Reynolds-averaged N-S model, and the steel-slag interface is traced by the VOF method. The simulation employs the commercial software Fluent 19.0 (ANSYS Co., Ltd Pittsburgh, PA, USA). The argon bubbles were simplified as Lagrangian particles coupled with a continuous bidirectional phase. For simplicity and to reduce the complexity and calculation cost of the mathematical model, we made the following assumptions: (1) the molten steel and liquid mold powder are a uniform incompressible fluid, and their density and viscosity are constant. (2) The calculation domain was extended to 2.5 m along the casting direction, so that the flow can be fully developed; (3) the argon gas bubbles are simplified into spherical Lagrangian particles with diameters following the Rosin–Rammner distribution, and the coalescence, collision and breaks between the argon gas bubbles are neglected. (4) The effects of the solid mold powder layer and sintering layer in the mold powder on the flow field are ignored, and the thickness of the liquid mold powder layer is assumed to be 15 mm. (5) The mold taper and vibration are ignored.

2.2.1. Fluid-Phase Hydrodynamics

The conservation of mass and momentum of incompressible fluid can be summarized using the N-S equations as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\mu_l + \mu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \rho g_i + F \quad (2)$$

where $(\mu_l + \mu_t)$ is the equivalent viscosity of the continuous phase in turbulence, which consists of two parts: the molecular viscosity μ_l (Pa·s) and the turbulent viscosity μ_t (Pa·s).

In order to close the N-S equations in the $K-\varepsilon$ two-equation model, the turbulence viscosity μ_t is modeled as follows.

$$\mu_t = C_\mu \rho \frac{K^2}{\varepsilon} \quad (3)$$

Two new quantities, K and ε , are introduced for the modeling of the turbulent viscosity μ_t . In order to close the model, the transport equations of the two quantities need to be introduced:

$$\frac{\partial(\rho K)}{\partial t} + \frac{\partial(\rho u_i K)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\left(\mu_1 + \frac{\mu_t}{\sigma_K} \right) \frac{\partial K}{\partial x_i} \right) + G_K - \rho \varepsilon \quad (4)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\left(\mu_1 + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right) + C_1 \frac{\varepsilon}{K} G_K - C_2 \rho \frac{\varepsilon^2}{K} \quad (5)$$

$$G_K = \mu_t \left(\frac{\partial u_{ij}}{\partial x_j} + \frac{\partial u_{ji}}{\partial x_i} \right) \frac{\partial u_{ij}}{\partial x_j} \quad (6)$$

The constants in Equations (4)–(6) are: $C_\mu = 0.09$, $\sigma_K = 1.00$, $\sigma_\varepsilon = 1.30$, $C_1 = 1.44$, $C_2 = 1.92$.

2.2.2. Lagrange Particle Dynamics for Modeling Argon Gas Bubbles

The argon bubbles in the mold are simplified as spherical Lagrangian particles with diameters following Rosin–Rammler distribution. The force analysis of the argon bubbles is as follows:

$$m_b \frac{du_b}{dt} = F_D + F_P + F_f + F_V + F_g + F_L \quad (7)$$

The expressions of the items in Equation (7) are summarized as follows:

$$F_D = C_D \rho \frac{\pi}{8} d_b^2 (u_b - u) |u_b - u| \quad (8)$$

$$F_P = \rho_b \frac{\pi d_b^3}{6} \frac{du}{dt} \quad (9)$$

$$F_f = \frac{\pi d_b^3}{6} \rho g \quad (10)$$

$$F_V = C_V \rho \frac{\pi}{6} d_b^3 \left(\frac{du}{dt} - \frac{du_b}{dt} \right) \quad (11)$$

$$F_g = \frac{\pi d_b^3}{6} \rho_b g \quad (12)$$

$$F_L = C_L \rho \frac{\pi}{6} d_b^3 (u_b - u) (\nabla \times u) \quad (13)$$

In Equations (8)–(13), C_L , C_V and C_D are the lift coefficient, virtual mass force coefficient and drag coefficient, respectively.

2.2.3. VOF Model for Tracking the Steel–Slag Interface

The VOF model is commonly used to simulate insoluble multiphase flow. It can track the interphase interface accurately. In this study, we used this method to trace the steel–slag interface. According to the VOF model, there are certain phase fractions of molten steel and liquid mold powder in each grid, and the sum of the phase fractions of the two is always equal to 1. The density and viscosity of the continuous phase in each grid is a weighted average that changes with the phase fraction of molten steel and liquid mold powder.

$$\alpha_{\text{steel}} + \alpha_{\text{slag}} = 1 \quad (14)$$

$$\rho = \rho_{\text{steel}} \cdot \alpha_{\text{steel}} + \rho_{\text{slag}} \cdot \alpha_{\text{slag}} \quad (15)$$

$$\mu = \mu_{\text{steel}} \cdot \alpha_{\text{steel}} + \mu_{\text{slag}} \cdot \alpha_{\text{slag}} \quad (16)$$

In addition, the influence of interfacial tension on multiple flows is also considered in this study. The interfacial tension is described by the continuum surface force model

(CSF). The CSF model was proposed by Brackbill et al. [19], who added interfacial tension to the right side of N-S equation in the form of a momentum source term. The resultant force of interfacial tension is the pressure drop at the interface. The pressure drop is related to the interfacial tension coefficient σ and the two principal curvature radii R_1 and R_2 at the interface:

$$p_2 - p_1 = \sigma \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \quad (17)$$

The part in brackets above is actually the curvature k , which is equal to the divergence of the interface unit normal vector $\mathbf{n}$, which can be calculated from the gradient of the molten steel phase fraction α_{steel} . Thus, the curvature k is related to the molten steel phase fraction α_{steel} :

$$\mathbf{n} = \nabla \alpha_{\text{steel}} \quad (18)$$

$$k = \nabla \cdot \hat{\mathbf{n}} \quad (19)$$

In fact, because the two phases are insoluble, the interface is very sharp. If the gradient of phase fraction is too large, it easily leads to numerical overflow. In order to obtain the scalar field of the molten steel phase fraction with sufficient resolution, the grids near the interphase interface are required to be very fine, which increases the calculation cost significantly and is unacceptable. The expression of interfacial tension (interfacial pressure drop) in Equation (17) is not suitable to be realized directly on the grids of the finite volume method, and some approximation and modeling are needed. In the CSF model, the pressure drop of Equation (17) is multiplied by the molten steel phase fraction α_{steel} to obtain the modeling formula for the interface pressure drop (interfacial tension). The modeling formula of interfacial tension describes the surface force, which is converted into volume force by applying the divergence theorem, as follows:

$$F_{\text{vol}} = \sigma \frac{\rho k \nabla \alpha_{\text{steel}}}{\frac{1}{2}(\rho_{\text{steel}} + \rho_{\text{slag}})} \quad (20)$$

2.2.4. Detailed Parameters in Numerical Modeling

In this study, two kinds of slab molds with section sizes of 1800×180 mm and 1800×250 mm were selected as the research objects. In actual production, the concave bottom SEN with inclination angle of 15° was adopted, the immersion depth of the nozzle was 110 mm (distance from molten steel level to upper edge of side hole of SEN), and the argon gas flow rate was 3 L/min or 10 L/min. For the sections of 1800×180 mm and 1800×250 mm, the commonly used steel throughputs were 2.38 t/min and 2.65 t/min. The average diameter of argon gas bubbles was set to be 0.0015 m, and the minimum and maximum diameters were set to be 0.0003 m and 0.003 m, respectively. The diameters of bubbles obeyed the Rosin–Rammler distribution, with the spread parameter of 4.63 fitted by experimental data [20]. The experimental data show that the bubble size distribution did not change dramatically with the gas flow rate, and the above bubble size distribution can cover most gas flow rates. Thus, the variation of the size distribution of argon gas bubble with the argon gas flow rate is neglected. The grid numbers were 1,687,906 and 2,078,345 for the 180 mm thick and 250 mm thick molds, respectively. Figure 2a,b show grid partition for the molds with the thicknesses of 180 mm and 250 mm, and Figure 2c,d show the front view and the side view of SEN. The chemical compositions of the steel grade and physical parameters of the materials involved in the numerical simulation are shown in Tables 1 and 2.

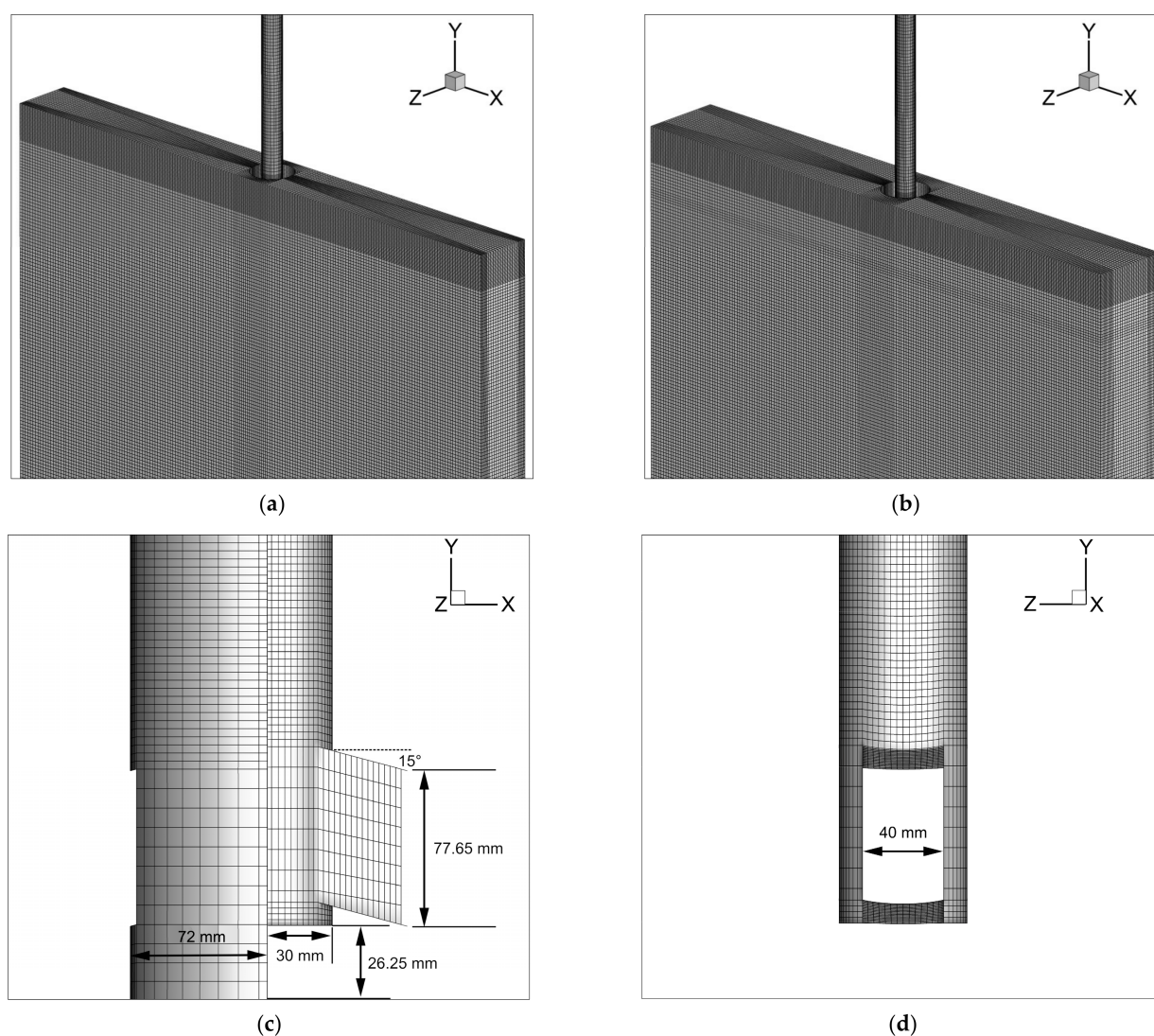


Figure 2. (a) Grid partition for the mold with the thickness of 180 mm; (b) grid partition for the mold with the thickness of 250 mm; (c) front view of geometric details of the concave bottom SEN with inclination angle of 15°; (d) side view of nozzle side hole.

Table 1. Chemical compositions of the steel grade (mass%).

C	Si	Mn	P	S	Als	Nb	Ti
0.0015	0.0057	0.15	0.0126	0.0105	0.044	0.012	0.0417

Table 2. Physical parameters used in the numerical simulation.

Material	Density (kg/m ³)	Viscosity (Pa·s)	Interfacial Tension Coefficient (N/m)	Interfacial Tension Coefficient (N/m)
Liquid mold powder	2600	0.5	1.192	-
Molten steel	7020	0.0062		1.5
Argon gas	0.27	2.13×10^{-5}	-	

Table 3 lists the boundary conditions adopted in the numerical simulation. There were six cases in the numerical simulation; the specific parameters of the cases are detailed in Table 4. For each case, we first carried out the transient simulation of the mold flow field without argon gas blowing for 30 s, and then the argon gas was introduced for 20 s. When

the flow field stabilized, the transient simulation still lasted for another 10 s with argon gas blowing, and the calculation results are the average values from the final 10 s.

Table 3. Boundary conditions in the numerical simulation.

Boundary Name	Flow Field Boundary Condition	Boundary Condition for Lagrangian Particles
Inlet	Velocity inlet	Escape
SEN	Non-slip wall	Reflect
Mold surface	Free-slip Wall	Escape
Wide face	Non-slip wall	Trap
Narrow face	Non-slip wall	Trap
Outlet	Pressure outlet	Escape

Table 4. Specific parameters of the cases in the numerical simulation.

Case Number	Mold Width (mm)	Mold Thickness (mm)	Throughput (t/min)	Argon Gas Flow Rate (L/min)	Flow Pattern
1	1800	180	2.38	3	DRF
2	1800	250	2.38	3	SRF
3	1800	180	2.65	3	DRF
4	1800	250	2.65	3	DRF
5	1800	180	2.65	10	SRF
6	1800	250	2.65	10	SRF

3. Results and Discussion

3.1. Comparison of High Temperature Quantitative Measurement and Numerical Simulation Results

In this study, six working conditions were selected to compare the flow fields in slab molds with two kinds of thicknesses under three different groups of throughputs and argon gas flow rates: low throughput and low argon gas flow rate (Figure 3), high throughput and low argon gas flow rate (Figure 4), and high throughput and high argon gas flow rate (Figure 5). It can be seen that all the calculated results are consistent with the high temperature quantitative measurement results.

As shown in Figures 3–5, the slab thickness has a great influence on the velocities near the surface and the flow pattern in the mold. In the three different groups of throughputs and argon gas flow rates, the velocities near the 180 mm thick mold surface were obviously higher than in the 250 mm thick mold. In addition, maintaining the flow pattern in the 180 mm thick mold as that of the DRF was easier than in the 250 mm thick mold under the same working conditions.

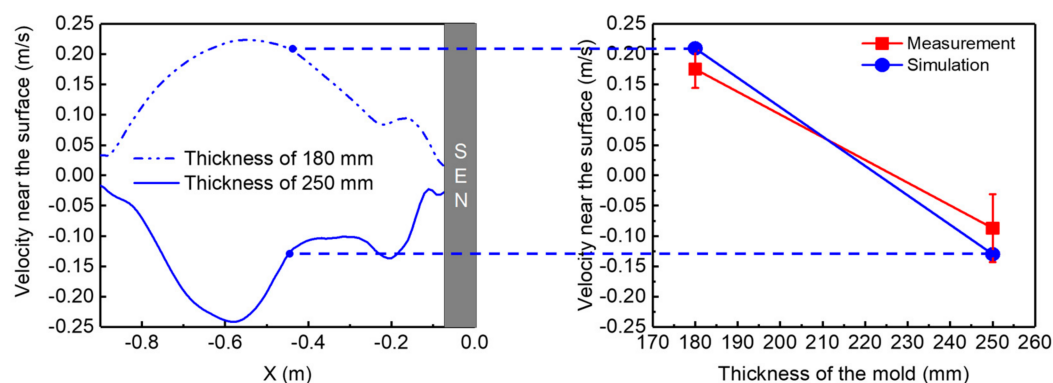


Figure 3. Comparison of velocities near the mold surface between slab thicknesses of 180 and 250 mm at 1800 mm width, 3 L/min argon gas flow rate and 2.38 t/min throughput.

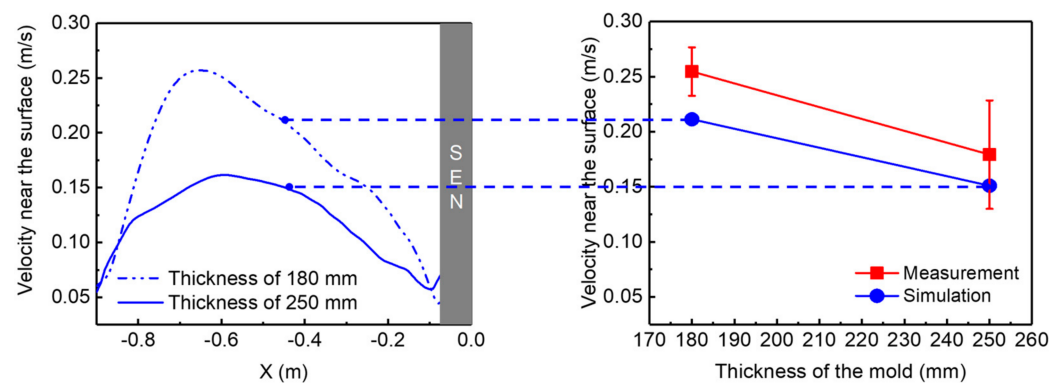


Figure 4. Comparison of velocities near the mold surface between slab thicknesses of 180 and 250 mm at 1800 mm width, 3 L/min argon gas flow rate and 2.65 t/min throughput.

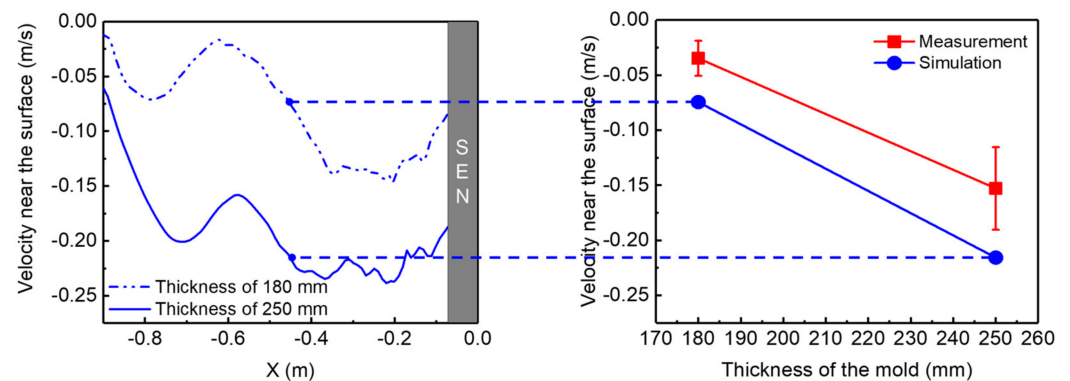


Figure 5. Comparison of velocities near the mold surface between slab thicknesses of 180 and 250 mm at 1800 mm width, 10 L/min argon gas flow rate and 2.65 t/min throughput.

Along with the throughput increase from 2.38 to 2.65 t/min, the velocities near the mold surface with different thicknesses increased. The change range of the velocities near the 250 mm thick mold surface were obviously larger than near the 180 mm thick mold surface, with the flow pattern changed from SRF into beneficial DRF. The throughput in the 250 mm thick mold should be larger, which also can improve production efficiency.

As the argon gas flow rate increased from 3 L/min to 10 L/min, the velocities of molten steel near the mold surface decreased sharply with the flow pattern changing from DRF to SRF in the two kinds of mold.

3.2. Velocity Distribution in the Mold

Figure 6 shows the velocity fields in the thickness center slice of the molds, and the velocity magnitude is distinguished by color. In addition to the slab thickness, the throughput and argon gas flow rate are pairwise consistent in Figure 6a–f. Owing to the symmetry of the computational domain and boundary conditions, the velocity field was roughly symmetrical in the width direction.

For DRF, the direction of the velocities near the mold surface is from the narrow face to the nozzle, so that the slag particles entrained near the steel-slag interface were not easily captured by the solidified shell on the narrow face, which is conducive to improving the surface quality of the slab. Owing to the decrease of throughput and the increase of the argon gas flow rate, the DRF tends to develop into a UF, and eventually turns into a SRF. For SRF, the direction of the velocities near the mold surface is from the nozzle to the narrow face, so the molten steel flow is very likely to bring the slag particles, inclusions and bubbles into the vicinity of the newly solidified shell to cause surface defects. In addition, the velocities of molten steel scouring down along the narrow face near the meniscus may reach or even exceed 0.4 m/s, as shown in Figure 6e. This region is crucial for the formation

and growth of the initial solidified shell, so the SRF is not conducive to the formation of the initial solidified shell. For the continuous casting process, the DRF is beneficial to the improvement of the surface quality and the stable production, while the SRF is the flow pattern that should be avoided.

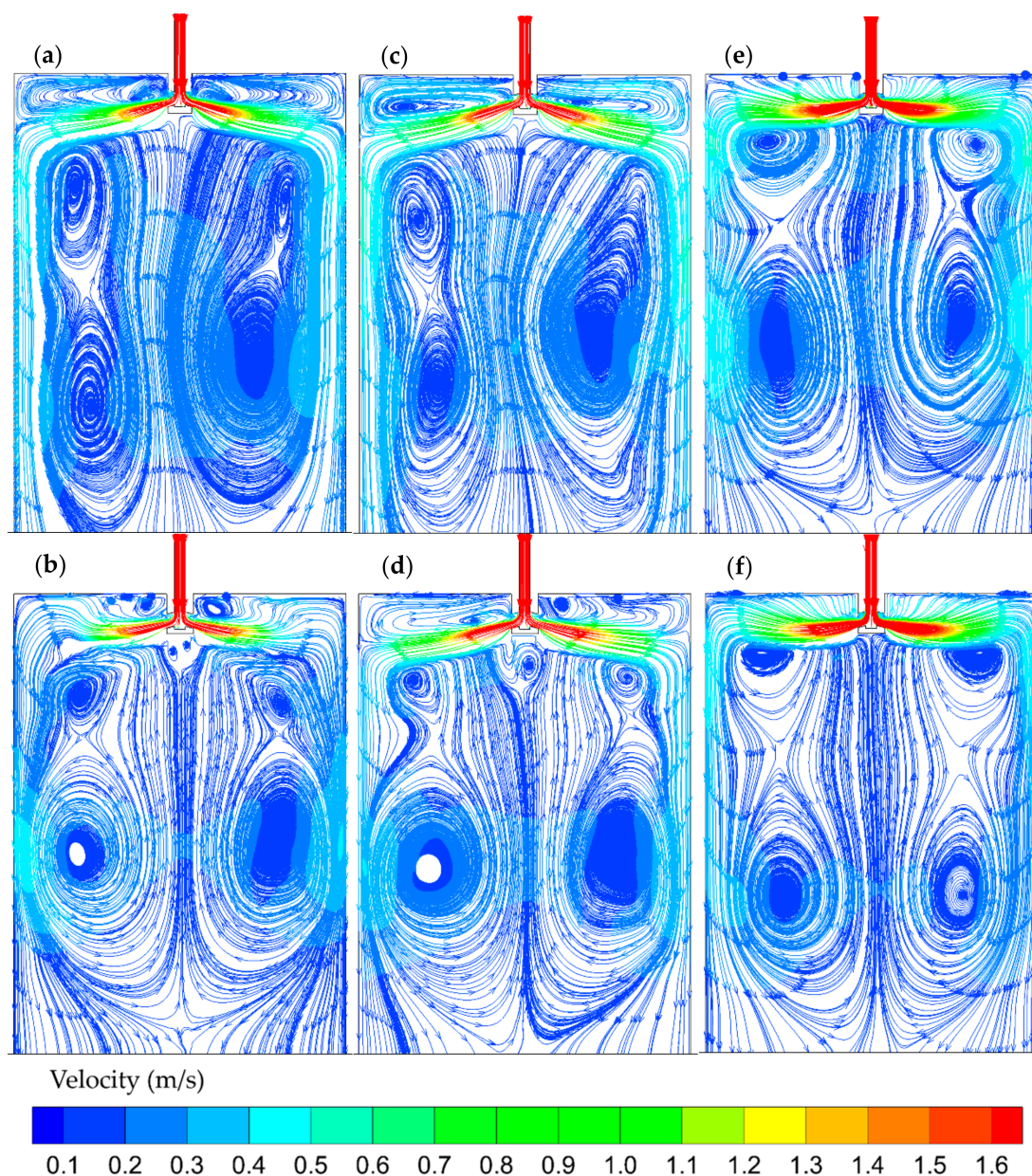


Figure 6. Velocity fields on the thickness center slice of the mold in (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5, (f) case 6.

As shown in Figure 6a,c,e, for the slab mold with the thickness of 180 mm, the flow pattern changes into an SRF only when the argon gas flow rate increases to 10 L/min. At the low argon gas flow rate of 3 L/min, the flow patterns are always DRF. In Figure 6a, one can see that with low argon flow rate and low throughput, the carrying capacity of the jet to the argon bubbles becomes weak, and the vortex center is close to the nozzle. Nevertheless, DRF can be maintained. For the 180 mm thick mold, the critical throughput for the transition from SRF to DRF was smaller.

For the slab mold with the thickness of 250 mm, the DRF pattern only appeared with the high throughput of 2.65 t/min and the low argon gas flow rate of 3 L/min, as shown in

Figure 6b,d,f. In the 250 mm thick mold, a larger throughput can be used without worrying about the risk of slag entrainment due to the excessive velocities near the mold surface, and large argon flow should be avoided.

Figure 7 shows the velocity fields on the width of $X = -0.8, -0.6, -0.4, -0.2, 0.2, 0.4, 0.6, 0.8$ m slices of the mold, in which the molten steel jet can be observed in the cross-sectional direction. With the increase of the distance away from the side hole, the sectional area of the jet increases gradually while the central velocity of the jet decreases. Furthermore, by the pair comparisons in Figure 7a–f on the width of the $X = \pm 0.2, X = \pm 0.4$ slices, the area with velocity greater than 0.1 m/s in the 180 mm thick mold was larger than that in the 250 mm thick mold under the same working conditions. The internal space of the 250 mm thick mold was larger than that of the 180 mm thick mold, and the kinetic energy of the jet dissipated faster. Therefore, for the 250 mm thick mold, a larger throughput should be employed, which is beneficial to make up for the fast diffusion of kinetic energy and promote the uniformity of velocity and temperature.

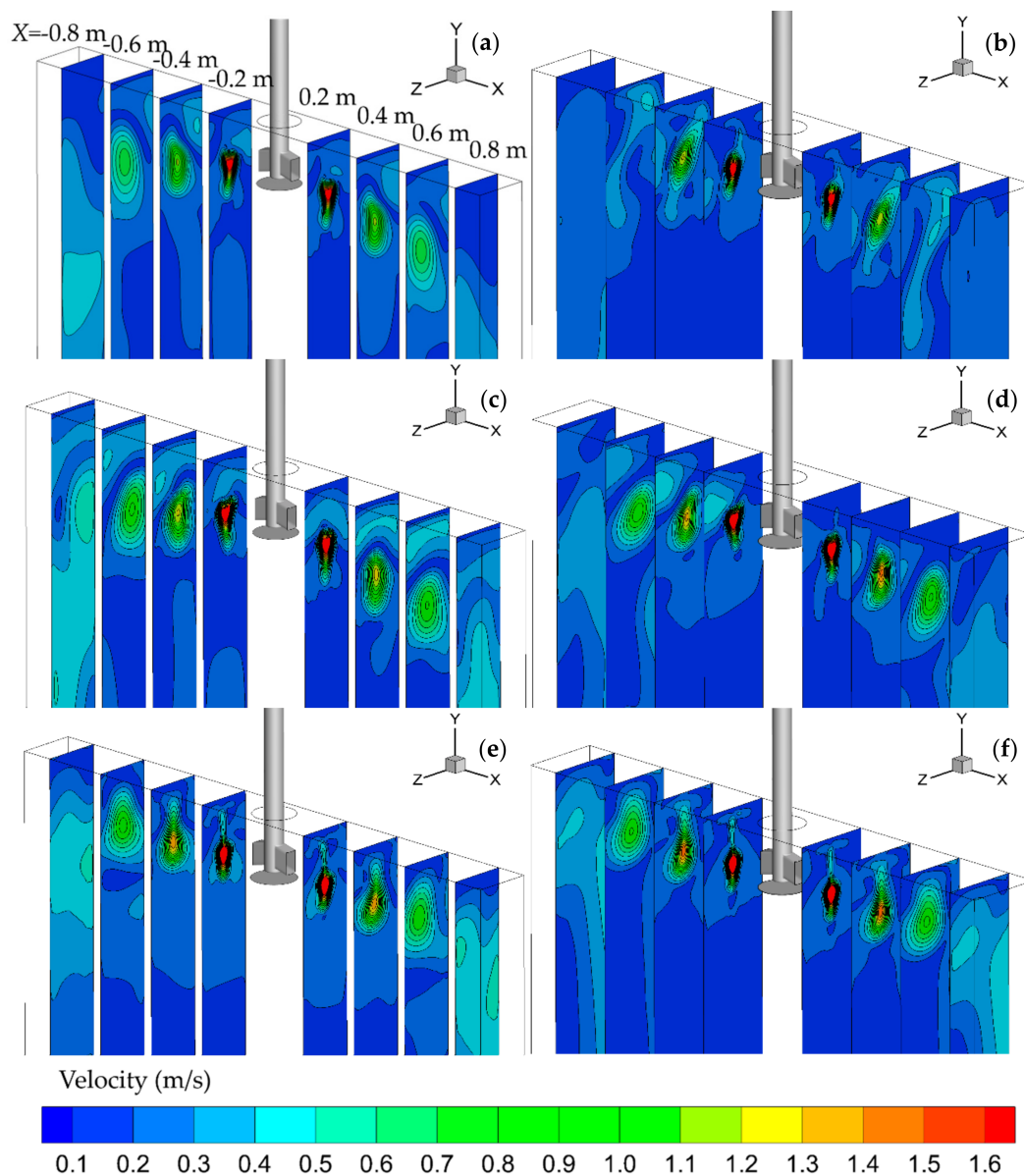


Figure 7. Velocity fields on the width of $X = -0.8, -0.6, -0.4, -0.2, 0.2, 0.4, 0.6, 0.8$ m slices of the mold, in (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5, (f) case 6.

3.3. Argon Bubble Distribution

Figure 8 shows the distribution of argon bubbles in the molds. The bubble sizes are distinguished by different colors.

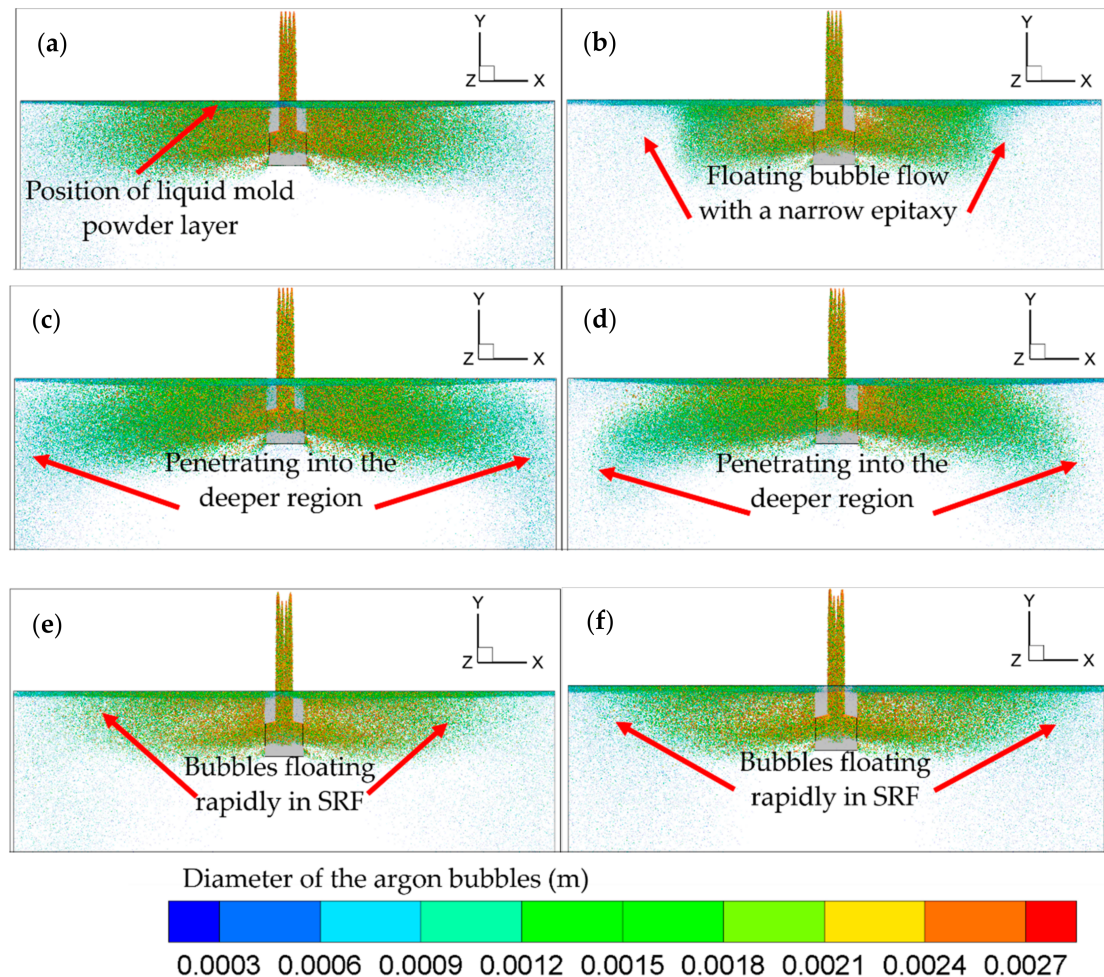


Figure 8. Distribution of the argon bubbles in the mold, in (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5, (f) case 6.

On the whole, argon gas bubbles mostly float up near the nozzle. The smaller the bubble size, the larger the ratio of surface area to volume, the better the followability of bubble with the continuous phase, and the farther the injection distance away from the nozzle. Near the mold surface in the liquid mold powder layer, dense bubbles became stuck due to the much larger viscosity of the liquid mold powder than that of the molten steel.

For the DRF, as the argon bubbles can be flushed into deeper regions under the influence of strong jets on both sides, the argon bubbles were distributed widely in the mold. Among them, the throughput in Figure 8c,d is higher than that in Figure 8a, so there are more intense DRFs in Figure 8c,d. Accordingly, the impact depth of argon bubbles in Figure 8c,d is also larger than that in Figure 8a. For the SRF, as the argon bubbles float up quickly after leaving the side holes, the bubble distribution is more concentrated in the width direction and the bubbles float up earlier, as shown in Figure 8b,e,f.

Argon gas flow can prevent blockage in the nozzle, reduce jet velocities and promote inclusion floating in a continuous casting process. However, an excessive argon gas flow rate makes the liquid level near the nozzle fluctuate dramatically, increasing the risk of slag entrainment, promoting the transformation of the flow pattern into SRF, and even leading to the occurrence of slag layer holes, resulting in the reoxidation of the exposed molten steel. Therefore, a large argon gas flow rate should be avoided in production.

3.4. Profile and Fluctuation of Steel-Slag Interface

Figure 9 shows the profiles of the steel-slag interface at the end of the simulation. In this study, the iso-surface with the liquid mold powder phase fraction of 0.5 is regarded as the steel-slag interface. In the figures, the computation initialization is set as 0 mm at the height of the horizontal plane of the just-completed steel-slag interface.

For the DRF in Figure 9a,c,d the liquid mold powder was concentrated around the nozzle under the influence of the shear stress of the molten steel. The molten steel of the upper roll flow impinges on the narrow face and then bends upward, impinging on the steel-slag interface near the narrow face. These two factors jointly cause the phenomenon that the steel-slag interface is high on both sides and low in the middle of the width. The increase of mold thickness may lead to the decrease of uniformity of the mold powder layer thickness, as shown in Figure 9d.

For the SRF in Figure 9e,f with larger argon gas flow rates, argon bubbles floated up near the nozzle in large quantities, resulting in a very thin liquid mold powder layer near the nozzle, and the profile of the steel-slag interface in local areas exceeded 7 mm. A large number of argon bubbles floating near the nozzle will lead to severe fluctuation of the liquid level and increase the risk of interface instability and slag entrainment. The interface fluctuation can be reduced by changing the flow pattern to DRF, with larger throughput and a smaller argon flow rate.

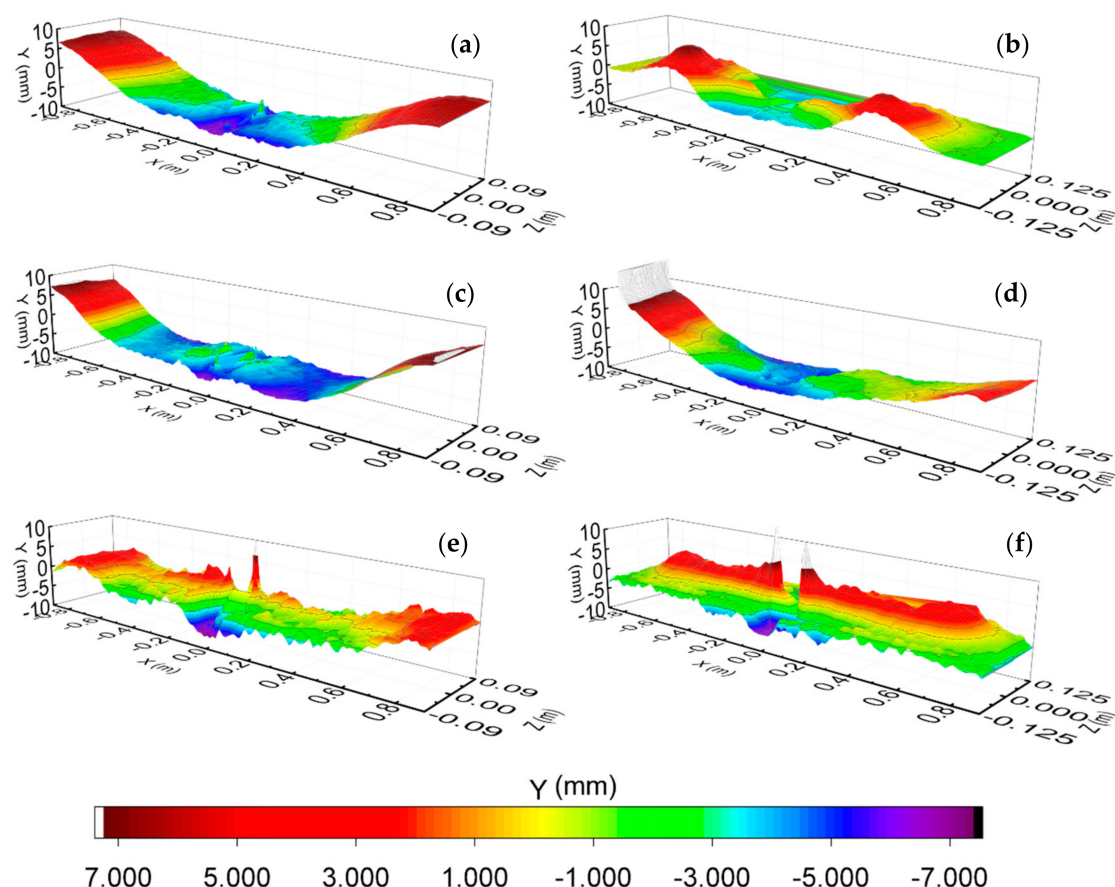


Figure 9. Profiles of steel-slag interface in the mold, in (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5, (f) case 6.

Figure 10 shows the top view of the contours of the fluctuation at the steel-slag interface at the end of the calculation, which was calculated by the difference between the instantaneous pressure and the time average pressure at the steel-slag interface.

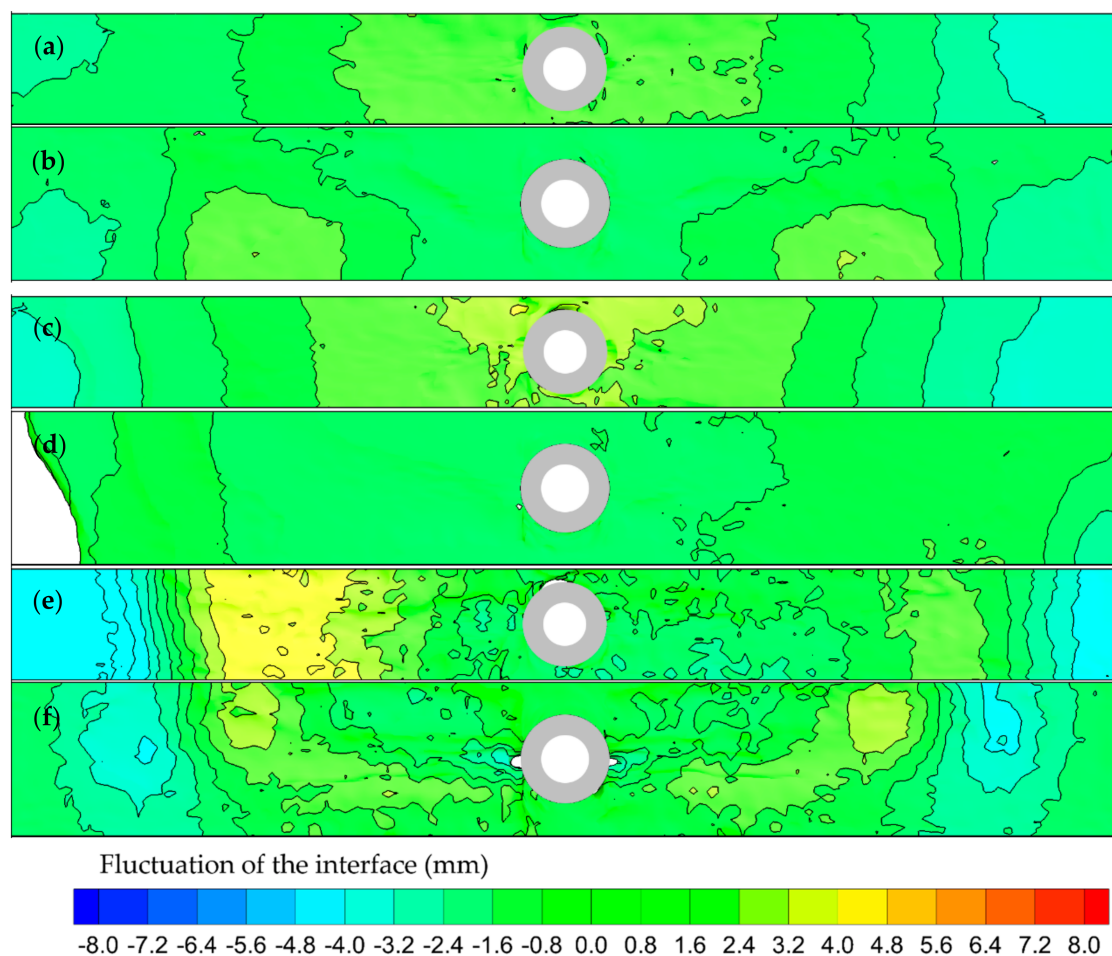


Figure 10. Top view of the contours of the fluctuation at the steel-slag interface, in (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5, (f) case 6.

Comparing Figure 10a,c,e for the 180 mm thick mold with Figure 10b,d,f for the 250 mm thick mold, it can be seen that, under the same working conditions, the fluctuation magnitude of the steel-slag interface in the 250 mm thick mold was slightly smaller than in the 180 mm thick mold. This was because the surface velocities in the mold with 180 mm thickness were larger than in the mold with 250 mm thickness, and the rising bubbles in the mold with 180 mm thickness produce greater agitation on the mold surface profile than in the mold with 250 mm thickness. Therefore, a larger throughput can be adopted in the 250 mm thick mold to improve production efficiency, while the surface fluctuation is still within a reasonable range. Nevertheless, the increase of mold thickness will increase the importance of flow perpendicular to the wide face, which leads to the decrease of the symmetry of steel-slag interface fluctuation in the Z direction, as shown in Figure 10b,f.

4. Conclusions

In the present work, the flow fields in slab continuous casting molds with thicknesses of 180 and 250 mm are compared based on high temperature quantitative measurements and numerical simulations. The conclusions are as follows:

- (1) The results of the numerical simulation are in good agreement with those of high temperature quantitative measurement, which verifies the accuracy and reliability of the numerical simulation.
- (2) Under the same continuous casting conditions, the velocities near the surface of the mold with the thickness of 180 mm were slightly higher than those in the mold with the thickness of 250 mm. For the 180 mm thick mold, the critical throughput for the

- transition from SRF to DRF was smaller. The flow pattern in the 180 mm thick mold maintained DRF more easily than that in the 250 mm thick mold. The kinetic energy of the jet dissipated faster in the 250 mm thick mold. For the 250 mm thick mold, a larger throughput should be employed, which is beneficial to make up for the fast diffusion of kinetic energy and promotes the uniformity of velocity and temperature.
- (3) For the DRF, as the argon bubbles can be flushed into deeper regions under the influence of the strong jets on both sides, the argon bubbles distributed more widely in the mold. For the SRF, as the argon bubbles float up quickly after leaving the side holes, the bubble distribution was more concentrated in the width direction, which may cause violent interface fluctuation and slag entrainment.
 - (4) Under the same continuous casting conditions, the fluctuation at the steel-slag interface in the mold with 180 mm thickness was greater than that in the mold with 250 mm thickness. Under the same steel throughput, DRF is easier to be form in the mold with 180 mm thickness than in the mold with 250 mm thickness. Therefore, a larger throughput can be adopted in the 250 mm thick mold to promote DRF formation while the surface fluctuation is still within a reasonable range.

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Nomenclature

i, j, k	indices for different spatial coordinate directions
$\rho, \text{kg m}^{-3}$	density of continuous phase
$u (u_i, u_j, u_k), \text{m s}^{-1}$	velocity of continuous phase
p, Pa	pressure
t, s	time
$x (x_i, x_j, x_k), \text{m}$	location vector
$g (g_i, g_j, g_k), \text{m s}^{-2}$	gravity acceleration vector
$\mu_l, \text{Pa s}$	liquid viscosity
$\mu_t, \text{Pa s}$	turbulent viscosity
$F, \text{N m}^{-3}$	momentum exchange caused by the inter phase force traction
$K, \text{m}^2 \text{s}^{-2}$	turbulent kinetic energy
$\varepsilon, \text{m}^2 \text{s}^{-3}$	turbulent energy dissipation rate
$u_{ij}, \text{m s}^{-1}$	velocity perpendicular to the i, j plane
m_b, kg	bubble mass
$u_b, \text{m s}^{-1}$	bubble velocity
$\rho_b, \text{kg m}^{-3}$	bubble density
d_b, m	bubble diameter
F_D, N	drag force

F_P , N	pressure gradient force
F_f , N	buoyancy
F_V , N	virtual mass force
F_g , N	gravity force
F_L , N	lift force
α_{steel} , 1	volume fraction of molten steel
α_{slag} , 1	volume fraction of liquid mold powder
ρ_{steel} , kg m ⁻³	density of molten steel
ρ_{slag} , kg m ⁻³	density of liquid mold powder
μ_{steel} , Pa s	viscosity of molten steel
μ_{slag} , Pa s	viscosity of liquid mold powder
σ , N·m ⁻¹	interface tension coefficient
R_1, R_2 , m	principal radii of curvature at the two-phase interface in orthogonal directions
p_1, p_2 , Pa	pressure on both sides of the two-phase interface
k , m ⁻²	interface curvature
$\hat{n}$, m ⁻¹	unit normal vector of the interface
n , m ⁻¹	normal vector of the interface
F_{vol} , N m ⁻³	interface tension volume force

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