Lattice Boltzmann Method Modeling of Flow Structures and Level Fluctuations in a Continuous Casting Process

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ABSTRACT: Transient flow and level fluctuations in the mold were simulated using the three-dimensional Lattice Boltzmann Method (LBM). The LBM model was verified by measured data from the literature. The transient flow field and the free surface fluctuations in the mold were simulated. The distributions of the coherent structures were also investigated. The results showed that the behavior of the jets with oscillating characteristics on both sides of the submerged entry nozzle (SEN) played an essential role in the development of the turbulent flow in the mold. During jet diffusion, the coherent vortex ring and vortex rib structures were generated. The vortices at the narrow wall were asymmetrical in the mold, accompanied by the development, dissipation, and extinction of the coherent structures in the turbulent flow. The asymmetric flow affected the free surface fluctuations at the top of the mold. The peak and trough fluctuations on both sides of the SEN alternated thereon. The distributions of the free surface fluctuations were quantified at different casting speeds and SEN immersion depths. As the casting speed was increased, the variations and the velocities of the free surface increased; as the SEN immersion depth increased, the fluctuations and the velocities thereof decreased.

1. INTRODUCTION
Flow phenomena are widely present in the continuous casting process: molten steel, with innate transient flow characteristics, directly affects the free surface fluctuation at the top of the mold. Molten steel with multiphase and multiscale features exiting the SEN could form three mold flow patterns: “double roll”, “unstable roll”, and “single roll”, which result from various combinations of casting speed, slab width, argon flow rate, and SEN design (immersion depth), etc. The molten steel impinges onto the narrow wall of the mold at a high velocity and then is split into two streams: one stream impacts the slag layer and the other moves toward the deep pool along the wall, generating a large-scale recirculation accompanied by small-scale vortices. Thus, a “double roll” pattern, consisting of upper and lower circulation zones, is formed. The flow pattern could change from a “double roll” to a “single roll” pattern due to a higher argon flow rate, narrower casting, and shallow SEN immersion depths. The molten steel would first arrive at the meniscus and move toward the deep mold along the narrow wall, hence forming a “single roll” pattern. In practice, steel flow patterns would be neither “double roll” nor “single roll” inside the mold as a result of various casting conditions. Casting plant observations suggest that transient flow patterns with specific behavior in a continuous casting process are associated with the quality of the final product, such as the incidence of slip cracks, pinholes, “pencil pipe” slivers, and blisters. These nonuniform internal and surface defects are mainly related to the transient flow patterns, vortex distributions, and free surface fluctuations in the mold. Therefore, an in-depth understanding of the flow behavior, especially transient flow structures and free surface fluctuations, is significant when aiming to improve the operating conditions and the quality of cast slab products formed during a continuous casting process.

Researchers have developed many mathematical models of transient flow fields to predict level fluctuations in the mold. To simulate various macroscopic flow phenomena, the Reynolds-averaged Navier–Stokes (RANS) method is widely used in turbulent fluids, including the k-ε, k-ω, and Reynolds stress models; however, the RANS model cannot capture transient turbulence and only provides time-averaged variables. A direct numerical simulation (DNS) settles this problem by predicting turbulence at all scales; however, it is almost impossible to simulate such a flow system at a Reynolds number Re > 10⁵ because of the massive amount of computations required. A compromise between RANS and DNS modeling is to employ the LES model. Thomas et al. compared PIV measurements and LES calculated results, indicating that the LES results were consistent with experimental measurements. Liu et al. reproduced various transient flow phenomena in the mold and obtained the asymmetric flow field and corresponding vortices inside the
mold using a single-phase LES model (albeit for a free surface that was assumed to be a fixed plane); however, ignoring the interaction between the internal flow and level fluctuations was impractical. With the development of a flow simulation inside the mold, it has gradually been recognized that the relationship between the mesoscopic and macroscopic processes plays an essential role in the asymmetrical distribution of internal defects in the slab-cast products; however, a macroscopic model (RANS or LES) cannot fully explain the multiscale flow, which can be better described using the LBM method that has attracted increasing interest among those modeling the micro and complicated flow systems. This mesoscopic method combines the advantages of the macroscopic model and the molecular dynamics model. The LBM model could provide a new perspective from which to simulate a multiscale flow in the mold.

In recent years, more attention has been paid to the application of LBM models. Shen et al.7 simulated the two-dimensional flow in a continuous mold using the incompressible Lattice Boltzmann–Gross–Krook (LBKG) model. It was found that the flow patterns were asymmetrical at Re > 3000. In addition, to improve the applicability of the LBM in describing the turbulent flow at a high Re, the LBM model can be coupled with a large eddy simulation (LES) for various turbulent simulations. The advantage of the LBME-LES is that the local strain can be calculated from the second-order moment of the nonequilibrium distribution function, thus rendering the calculation more efficient. Yu et al.9 simulated the turbulence at a high Re and compared the LBM-LES with a DNS simulation. The results showed that the LBME-LES model could capture large-scale flows. Pirker et al.10 predicted that bubble accumulation inside the SEN was related to secondary vortices within the SEN, showing the potential application of the LBM model to the prediction of a complex flow. In addition, for interface problems, such as level interface fluctuations during a continuous casting process, the LBM method can also provide more possibilities for simulating real free surface fluctuations.

Thiery et al.11 proposed a single-phase LBM model for a free surface flow using mass and momentum fluxes throughout the interface to replicate the evolution of metal foams. In particular, it is easy to track the free boundary in the LBM method where the dynamics of the gas phase can be neglected and only the single-phase free boundary is solved. The LBM coupled with the treatment scheme of the free surface boundary is more efficient; however, it is difficult to model applying a single-phase macroscopic continuous paradigm. Thus, the LBM method with a free surface scheme can provide a deeper understanding of the transient flow field, vortices, and free surface fluctuations at a mesoscopic level to improve the quality of slab products.

Flow phenomena are widely present in the continuous casting process. The molten steel from a submerged entry nozzle (SEN) causes complex flow patterns, oscillating jets, and corresponding coherent vortices inside the continuous casting mold. These complex phenomena have multiphase and multiscale characteristics, resulting in the asymmetric distribution of interior defects of the final casting slab. With the development of the mesoscopic model, it is gradually recognized that the mesoscopic fluid plays a significant role in the formation and distribution of the circulations, coherent vortices in the turbulent flow, and other vortices inside the mold. The macroscopic model (RANS) cannot, however, fully explain the multiscale interactions in the mold, such as the relationship between the mesoscopic and macroscopic systems. The multiscale flow can be better described by the LBM model at the mesoscale. The LBM model can bridge the gap between the continuous and discrete flow and also show the potential advantages of describing associated complicated flow behaviors at very small scales in the continuous mold, which is also of practical concern (when aiming to achieve a high quality of casting steel); however, at present, research into multiscale systems regarding the interaction between the mesoscopic and macroscopic phenomenon is insufficient. There are few studies on the application of the mesoscopic LBM on the transient flow patterns, the jet behaviors, and coherent vortices inside the mold, especially the flow patterns and free surface fluctuations inside the mold under different conditions in the mesoscopic model.

As ongoing work to apply the LBM model for the continuous casting process, the objective of the present study is to investigate the effect of varying operating conditions on the flow patterns and level fluctuations in the mold. The simulation results were also compared with other published measurements to verify the accuracy of the LBM model. The behaviors of the jets affecting the asymmetric flow patterns were simulated under steady-state operating conditions. The evolution of coherent vortices and corresponding vortex structures within the turbulent jets was also investigated. Finally, the effects of operating conditions on flow structures and level fluctuations were quantified.

2. MODEL ESTABLISHMENT

2.1. LBM Model. The governing equation of the Lattice Boltzmann Method is given by12

\[ f_i(x + c_i t + \delta t, x, t) = \frac{1}{\tau_{LB}}(f_i(x, t) - f^{eq}_i(x, t)) + \vec{F}_i \]

where \( c_i \) represents the discrete lattice velocities, \( \delta \) is the time step, \( f_i(x, t) \) is the discretized distribution function, \( \tau_{LB} \) is the dimensionless relaxation time, \( \vec{F}_i \) is the gravitational force as proposed by Buick,\(^{13}\) \( f^{eq}_i(x, t) \) is the Maxwell distribution equilibrium function

\[ f^{eq}_i(x, t) = \rho \omega \left[ 1 + \frac{c_i \mu}{C_s^2} + \frac{(c_i \mu)^2}{2C_s^4} - \frac{u^2}{2C_s^2} \right] \]

where \( C_s \) is the speed of sound, \( C_s = 1/\sqrt{3} \), and \( \omega \) is the weight according to the lattice discretization, given by

\[
\begin{align*}
\omega_i & = \begin{cases} 
1/3 & i = 0 \\
1/18 & i = 1 - 6 \\
1/36 & i = 7 - 18 
\end{cases} \\
\end{align*}
\]

A D3Q19 model\(^{14}\) was adopted in this study where D3 denotes three dimensions and Q19 is the number of discrete velocities (Figure 1).

The macroscopic quantities are simulated using the moments of the distribution functions

\[ \rho = \sum_i f_i \]

\[ \rho u = \sum_i c_i f_i \]
\[ \rho + \Delta = \Delta + \Delta + \Delta \]

where \( \rho \) is the macroscopic density and \( u \) is the macroscopic velocity.

2.2. LES Model. The subgrid scale stresses \( \tau_{ij} \) is given by the Smagorinsky subgrid model\(^{15}\)

\[ \tau_{ij} = \frac{1}{3} \delta_{ij} \tau_{kk} = -2 \nu \overline{S}_{ij} \]  

(6)

where \( \delta_{ij} \) is the Kronecker delta function and \( \overline{S}_{ij} \) is expressed as the large-scale strain-rate tensor. The viscosity \( \nu \) in the Smagorinsky model is defined as

\[ \nu = \nu_0 + \nu_{\text{eddy}} \]  

(7)

\[ \nu_{\text{eddy}} = C \Delta |\overline{S}| \]  

(8)

where \( \nu_0 \) is the kinematic viscosity, \( \nu_{\text{eddy}} \) is the eddy viscosity given by \( \nu_{\text{eddy}} = C \Delta |\overline{S}| \), \( \Delta \) is expressed as the minimum size, and \( C \) is the Smagorinsky constant, which depends on the size of the grid, such that \( 0.1 \leq C \leq 0.2 \).

The relaxation time \( \tau_{\text{LB}} \) can be expressed as

\[ \tau_{\text{LB}} = 3(\nu_0 + C \Delta |\overline{S}|) + \frac{1}{2} \]  

(9)

\[ |\overline{S}| = \sqrt{\nu_0^2 + 18 C \Delta |\Pi_{ij} - \Pi_{ij}^\alpha|} \]  

(10)

\[ \Pi_{ij} = \sum_{\alpha} \epsilon_{\alpha} \epsilon_{\alpha} f_i^\alpha - f_i^eq \]  

(11)

where \( |\overline{S}| \) is the intensity of the local filtered stress tensor and \( \Pi_{ij} \) is the local nonequilibrium stress tensor.

2.3. Free Surface Model. The single-phase LBM model is used here to simulate the liquid–gas interface in the mold. The evolution of the single-phase LBM model occurs only at the fluid nodes, and dynamic effects arising in the gas phase can be ignored. The free interface between the two phases is solved using the filled fraction \( \alpha \). When \( \alpha \) is 0 or 1, it is expressed as an empty cell or a full cell; when \( \alpha \) is close to 0 or 1, it indicates that the lattice changes between the interface, the liquid, and the gas cell. The interface is tracked by calculating the change in mass between adjacent cells. The mass of the liquid phase at the interface is defined by\(^{16}\)

\[ m = \alpha (\Delta x)^3 \rho \]  

(12)

The mass balance between the liquid phase and interface lattice is given by\(^{17}\)

\[ \Delta m_i(x, t) = \begin{cases} 0 & \text{if } x + c_i \text{ is the gas} \\ f_i(x + c_i, t) - f_i(x, t) & \text{if } x + c_i \text{ is the liquid} \\ \frac{\alpha(x + c_i, t) + \alpha(x, t)}{2} - f_i(x + c_i, t) - f_i(x, t) & \text{if } x + c_i \text{ is the interface} \end{cases} \]  

(13)

The mass exchange between the two interface lattices should satisfy the strictures of conservation of mass as follows:

\[ \Delta m_i(x, t) = -\Delta m_i(x + c_i) \]  

(14)

The equation governing the mass exchange across the interface is defined by

\[ \Delta m(x, t + \Delta t) = \Delta m(x, t) + \sum_{i=0}^{18} \Delta m_i(x, t + \Delta t) \]  

(15)

When \( m < 0 \) or \( m > 0 \), the interface lattice is transformed into a gas-phase or a liquid-phase lattice, respectively, so that a new interface lattice is formed. The liquid phase of the interface lattice is uniformly dispersed to the new interface lattice to ensure conservation of mass as soon as possible.

The distribution function cannot migrate directly from the liquid phase to the gas phase, and vice versa, thus only liquid-phase flows were calculated. The momentum exchange at the interface of the gas phase is expressed as the sum of the equilibrium distribution functions pointing to the direction of the interface lattice and in the opposite direction

\[ f_i(x, t + \Delta t) = f_i^eq(\rho_A, c_i) + f_i^eq(\rho_A, c_i) - f_i(x, t) \]  

(16)

where \( i \) is contrary to direction \( c_i \), \( c_i \) is the velocity at position \( x \), and \( \rho_A \) is related to the atmospheric pressure.

3. Calculation and Validation

3.1. Calculation Details. The computational domain included the original mold and SEN with a bifurcated nozzle and a bottom well. Figure 2 shows a schematic diagram of the geometry and boundary conditions in the mold. The lattice spacing was set to 2 mm, and the resolved scale was 0.005 m. Approximately 600,000 elements were used in the LBM model. The initial time-step for these simulations was 0.002 s. The inlet boundary conditions were based on the bounce-back function. A constant velocity was adopted at the inlet condition for the nonequilibrium portion of the distribution functions. A constant velocity was adopted at the inlet boundary conditions were based on the bounce-back function. A constant velocity was adopted at the inlet boundary conditions were based on the bounce-back function.

3.2. Model Validation. 3.2.1. Flow Field. In a previous study, an LBM model was verified by comparing different models and measurements from a water-based experiment. Here, the accuracy of the model for the flow velocity in the mold was qualitatively validated by using analytical data from a water experiment.\(^{18}\) In that water model, the velocity distributions at distances of 51, 102, 460, and 921 mm from the mold SEN were measured by a hot-wire anemometer.

Figure 3 shows a comparison of the simulated and measured velocity distributions.
experimental results. As can be seen from the figure, both qualitatively and quantitatively, the predicted velocities were in good agreement with measured data. There were some minor differences in the region from 0.2 to 0.25 m below the meniscus at a distance of 102 mm from the SEN. This might be due to uncertainties in the experimental measurements or the averaged results thereof.

3.2.2. Free Surface Fluctuation. Free surface behaviors are significant with regard to the formation of defects in continuously cast slabs.20 The fluctuation and shape of the level fluctuations determine the accuracy of the mathematical model. We investigated free surface fluctuations inside the mold from previous experimental results under two different conditions, as shown in Figure 4a,b. The free surface fluctuations were considered in the comparison based on the measurements by Kalter et al.19 at different velocities of 1 and 1.5 m/s. Figure 4a shows the model predictions corresponding to free surface fluctuations at different velocities. From the figure, the model predictions and experimental results generally agreed well with each other. The level fluctuated more as the velocity increased. Also, the model predictions for free surface fluctuations were also validated through measurements by Kalter et al.19 at different SEN immersion depths of 150 and 250 mm. Figure 4b shows the model predictions corresponding to free surface fluctuations at different SEN immersion depths. It was also seen that the prediction of free surface fluctuations was consistent with measured data. The results show that level fluctuation amplitudes decreased as the SEN immersion depth increased.

4. RESULTS AND DISCUSSION

4.1. Flow Structures. 4.1.1. Flow Field. It is necessary to investigate the transient flow field and jet patterns in the mold. Figure 5 shows the temporary movement of mesoscopic fluid particles at a casting speed of 1.3 m/min and an SEN immersion depth of 120 mm at the same time. Figure 5a−c represent the entire, half, and central plane of the mold, respectively. It was apparent from the figure that the high-speed jet exiting the SEN impacted the narrow wall of the mold, and two separate streams then moved toward the free surface or the deep pool along the narrow wall of the mold. Here, it is also worthwhile investigating the behavior of jets and their effects on the flow field in the mold. Figure 6 shows the jets at a central plane of the mold at 40, 55, and 70 s. As can be seen from the figure, the high-speed jets entrained surrounding fluid particles. The jets near the wall of the mold oscillated, thus accelerating the onset of and exacerbating flow field instability. To better analyze the behavior of these jets in the mold, the upper left area of the mold was selected to illustrate the transient behavior of the oscillating jets in the mold at different times. At 40 s, the jets directly impacted the narrow wall of the mold and generated two recirculation zones; at 55 s, the jets near the narrow wall oscillated upward to the
they moved together along the jets, as seen in Figure 7a,b. The evolution of coherent vortices mainly included the jets impinging on the wall, the vortex rings breaking into more small vortices whereafter some coherent vortices moved toward the free surface, and the remainder diffused along the narrow wall of the mold, as shown in Figure 7c,d. The evolution of these coherent vortices revealed the oscillating behavior of the jets in the mold.

The turbulent pulsations at the wall of the mold result in complex vortex structures near the wall of the mold. Figure 8 shows the evolution of turbulent vortex structures near the narrow wall of the mold at different times. As shown in the figure, the development of the coherent structure in the mold was divided into the following stages: at 40 s, the coherent vortices at the left-hand side of the mold developed along with the narrow wall and diffused from the narrow wall to the center of the mold (Figure 8a). At 50 s, the coherent vortices were concentrated near the right-hand narrow wall, and they then moved downward (Figure 8b). It was noted that the development, dissipation, and extinction of these coherent vortices also occurred in the mold. The interactions of coherent structures caused more for a complex turbulence regime to develop. The asymmetric coherent structures formed near the wall of the mold also reflected the periodical changes in the flow field in the mold.

4.2. Field Variations. 4.2.1. Effect of Casting Speed. The macroscopic flow field can be statistically inferred from the movement of the mesoscopic fluid particles in the mold. Here, the effect of the casting speed on the time-averaged velocity of the mesoscopic flow in the mold was quantified. Figure 9 shows the mesoscopic fluid particles at different casting speeds of 1.1, 1.4, and 1.7 m/min during a given period of 30 s. As can be seen from the figure, the velocity of the mesoscopic fluid with its high momentum exiting from SEN increased with increasing casting speed, and the impact point near the wall moved downward accordingly.

To quantify the time-averaged velocity of this mesoscopic fluid motion, Figure 10 shows the time-averaged velocity at the central plane of the mold at a distance of 5 mm from the left-hand wall under the same conditions. The results showed that the velocity first increased and then decreased below the meniscus, while the velocity increased again and then decreased at the impingement point near the wall (within 0.4 m below the meniscus). The trend in the velocity distribution was consistent at different casting speeds, which reflected the aforementioned “double roll” pattern inside the mold. It can be seen from the figure that the time-averaged velocity on the vertical line increased with the casting speed increasing from 1.1 to 1.7 m/min, and the maximum value was 0.65 m/s. The influence of the casting speed on the time-averaged velocity of the flow field in the mold was significant.

4.2.2. Effect of SEN Immersion Depth. The effect of different SEN immersion depths on the time-averaged motion of the mesoscopic flow in the mold was elucidated. Figure 11 shows the mesoscopic fluid particle motion in the mold at different SEN immersion depths of 90, 120, and 160 mm. It can be seen from the figure that the range of upper circulations in the mold gradually increased with increasing depth of SEN immersion, and the impact point moved down accordingly. When the immersion depth of the SEN was increased from 90 to 160 mm, the distances traveled upward by the fluid increased, and the circulation paths had an increased radius in

Figure 4. Comparison of measured and calculated level fluctuations at different conditions: (a) velocities and (b) SEN immersion depths.
the mold, resulting in a slower flow velocity in the upper circulatory gyre.

To quantify the flow velocity in the mold, Figure 12 shows the time-averaged velocity at the center plane at a distance of 5 mm from the narrow wall of the mold at different SEN immersion depths of 90, 120, and 160 mm. The influence of the SEN immersion depth on the position of the impact point was also obvious. It can be seen from the figure that the maximum velocity and corresponding impact point increased with the SEN immersion depth. The maximum velocity was found between 0.3 and 0.4 m below the meniscus, and the maximum average speed increased from 0.3 to 0.5 m/s. In addition, the effect of the SEN immersion depth affected the velocity at the bottom of the flow field in the mold (albeit only slightly). When the immersion depth of the SEN increased from 90 to 160 mm, the velocity at the bottom thereof was increased from 0.11 to 0.15 m/s.

4.3. Free Surface. 4.3.1. Free Surface Vortices. Many researchers have predicted the level fluctuations and vortices inside the mold using mathematical models that often simplified the free surface as a plane. Differing from these studies, we simulated the movement of the mesoscopic fluid particles in the free surface under steady-state operating conditions using a single-phase LBM coupled with a free surface and statistically calculated the macroscopic morphology of free surface fluctuations. Figure 13 shows the three-dimensional movements of the mesoscopic fluid in the free surface at a casting speed of 1.4 m/min. In the figure, the solid and dotted circles indicated clockwise and counterclockwise vortices, respectively. At 40 s, the two vortices generated were located on both sides of the SEN. At 55 s, one vortex was found near the left-hand side of the SEN, and the other two vortices were located to the right of the SEN; at 70 s, the two vortices were on the right-hand side of the SEN. Vortices were found near the SEN because the higher-speed fluid and the lower-speed fluid flowed in opposite directions near the SEN. Furthermore, a vortex, appearing randomly at a lower position between the SEN and the narrow wall, was also found. The vortices may be formed at a lower region between the SEN and the narrow wall. The position, size, and distribution of the vortices were related to fluctuations of the free surface, as predicted by the LES model when coupled with the free surface method; however, macroscopic models (RANS/LES) were less well able to capture this phenomenon.

4.3.2. Free Surface Fluctuations. To quantify the transient changes in the free surface fluctuations, Figure 14 shows the variation in the free surface in the mold at different times. It can be seen from the figure that the free surface was asymmetrical: peak and trough fluctuations thereon alternated between corresponding values of 15 and 10 mm, respectively. It can be seen that the level fluctuation near the left-hand narrow wall was higher than that on the right-hand side thereof, as shown in Figure 14a,c. The higher position appeared near the narrow wall of the mold due to the upward jet inside the mold. The results show that the single-phase LBM model coupled with a free surface model could provide a new method with which to study free surface fluctuations in the mold, simulate the movement of mesoscopic fluid particles, and thus ascertain the macroscopic morphology of surface fluctuations in the mold. This also explains practical effects observed in a steel plant: although there was no sliding nozzle opening or closing, SEN internal blockages, or any change in operating parameters, the free surface fluctuations remained asymmetrical.

4.3.3. Effect of Casting Speed. Here, the macroscopic topography of the free surface fluctuations was also studied. Figure 15 shows the time-averaged free surface fluctuations at different casting speeds of 1.1, 1.4, and 1.7 m/min, respectively. The red (near the narrow wall) and blue zones (between the narrow wall and the SEN wall) represented the higher and lower positions of the free surface. It was apparent...
from the top view of the fluctuation that as the casting speed increased, the time-averaged fluctuation gradually increased.

The effect of different casting speeds on the time-averaged fluctuations was quantified. **Figure 16** shows the time-averaged variation of the surface free on both sides of the SEN at different casting speeds over a period of 30 s. It can be seen from the figure that the free surface fluctuations gradually decreased in the middle position between the narrow wall and the SEN. As the casting speed was increased from 1.1 to 1.7 m/min, the fluctuations near the narrow wall increased in amplitude to a significant extent. The casting speed also had a significant effect on the morphology and the free surface fluctuations.

The fluctuating velocity of the free surface at the top of the mold also exhibited transient characteristic level fluctuations. To study the effect of the casting speed on the changes in the free surface velocity, **Figure 17** shows the macroscopic fluctuating velocity of the free surface at different casting speeds under the same conditions. It was apparent from the top view that, as the casting speed increased, the fluctuating velocity between the SEN and the narrow wall gradually increased.

The fluctuating velocity of the free surface at the centerline on both sides of the SEN was quantified at different casting speeds, as shown in **Figure 18**. The maximum fluctuating velocity in the mold was at a distance between \( x = -0.4 \text{ m to } x = -0.3 \text{ m} \) and \( x = 0.3 \text{ to } x = 0.4 \text{ m} \) from the SEN. As the casting speed was increased from 1.1 to 1.7 m/min, the fluctuating velocity of the free surface increased, and the locus of the peak velocity moved from the narrow wall toward the SEN. The fluctuating velocity of the free surface between the SEN and the narrow wall was 0.35 m/s when the casting speed was 1.7 m/min. The results showed that the effect of the casting speed on the maximum fluctuating velocity of the free surface in the mold was significant. Thus, increasing the casting speed increased the fluctuation velocity.
speed can significantly increase the fluctuating velocity in the mold.

4.3.4. Effect of SEN Immersion Depth. It is also necessary to study the effect of the SEN immersion depth on the level fluctuations in the mold. Figure 19 illustrates the macroscopic average fluctuations of the free surface at different SEN
immersion depths of 90, 120, and 160 mm. The red area (near the narrow wall) indicated the higher level position, and the blue area (between the narrow wall and the SEN wall) shows the lower level position. It was apparent from the top view that the smallest fluctuations appeared in the middle position on both sides of the mold when the SEN immersion depth was relatively small (90 mm). This was because the shallow immersion depth of the SEN caused an increase in the upward flow near the narrow wall, and a fluctuating trough was then formed in the middle position between the SEN and narrow wall of the mold.

Figure 20 shows the time-averaged level fluctuations on both sides of the SEN at different immersion depths. It can be seen from the figure that the maximum fluctuations also appeared at the narrow walls on both sides of the mold. The effect of SEN immersion depth on the maximum fluctuation was obvious: as the immersion depth was increased from 90 to 160 mm, the average fluctuation amplitude near the narrow wall was reduced to 6 mm. The effect of SEN immersion depth on the morphology and variations of the free surface was also apparent. As the SEN immersion depth was increased, the free surface fluctuation amplitude gradually decreased.

To study the effect of SEN immersion depth on the fluctuating velocity in the mold, Figure 21 shows the fluctuating velocity of the free surface at different SEN immersion depths under the same conditions. It is apparent from the top view that, as the SEN immersion depth increased, the fluctuating velocity of the liquid level at the middle position gradually decreased.

The time-averaged velocity of the free surface on both sides of the SEN at different immersion depths was also quantified, as shown in Figure 22. The maximum fluctuating velocity in the mold was also found between $(x = -0.4 \text{ m to } x = -0.3 \text{ m})$ and $(x = 0.3 \text{ m to } x = 0.4 \text{ m})$. As the SEN immersion depth increased from 90 to 160 mm, the fluctuating velocity was significantly reduced. As the SEN immersion

Figure 13. Free surface fluctuations and the three-dimensional vortices generated at the top of the mold at different times of (a) 40, (b) 55, and (c) 70.
depth increased, the velocity peak moved toward the SEN direction. When the SEN immersion depth was 60 mm, the fluctuating velocity of the free liquid surface reached a maximum of 0.32 m/s at the middle position between the SEN and the narrow wall. The depth of SEN immersion also had a significant effect on the fluctuating velocity in the mold; therefore, increasing the SEN immersion depth can reduce the fluctuating velocity of the free surface.

In summary, casting speed and SEN immersion depth affect flow structures and surface fluctuations in the actual casting process. The molten steel emerging from the bifurcated SEN may cause “single roll” and “double roll” patterns. The “double roll” flow pattern does not occur every time. Due to a slow casting speed and shallow SEN immersion depths, the molten steel would travel up to the free surface then to the narrow faces and finally flow into the deep pool along the narrow surface, resulting in a “single roll” pattern arising from a “double roll” pattern. In practice, flow patterns change throughout the casting process, and the flow would exhibit neither a “double roll” nor “single roll” pattern inside the mold due to temporary variations in casting conditions. Also, casting speed and SEN immersion depth also affect surface fluctuations, which are closely related to slag entrainment in
the actual process. In this case, the larger casting velocity and shallower SEN immersion depth can make the onset of the slag entrainment more likely to occur inside the mold and vice versa. Practice in a steel plant indicated that flow patterns with specific behavior and a free surface fluctuation could affect the surface and internal defects of the final casting slab.

5. CONCLUSIONS

The three-dimensional LBM model coupled with the free surface was used to simulate the flow field and level fluctuations in the mold. The vortex structures were investigated and the variation processes of the free surface under different operating conditions were examined. The main conclusions are as follows:

(1) Comparing the calculated results with measurements from a water model, the accuracy of the LBM model for predicting the transient flow structures and free surface fluctuations inside the mold was verified. The single-phase LBM model coupled with the free surface model not only provided a new method with which to simulate the flow pattern and oscillating jets in the mold but also revealed more

Figure 18. Time-averaged velocities of the free surface at the centerline on both sides of SEN in the mold at different casting speeds.

Figure 19. Top view of macrofluctuations of the free surface in the mold at different SEN immersion depths: (a) 90, (b) 120, and (c) 160 mm.

Figure 20. Time-averaged fluctuation of the free surface in the centerline on both sides of SEN in the mold at different SEN immersion depths.

Figure 21. Top view of the macro-velocity field of the free surface in the mold at different SEN immersion depths: (a) 90, (b) 120, and (c) 160 mm.

Figure 22. Time-averaged velocities of the free surface at the centerline on both sides of SEN in the mold at different SEN immersion depths.
moved together during jet diffusion. Asymmetrical rib structures were broken into smaller vortices, accompanied by the development, dissipation, and extinction of the vortices near the wall of the mold. The coherent vortices near the wall of the mold showed an asymmetrical distribution, which reflected the periodical change in the flow field inside the mold.

(3) Casting speed and SEN immersion depth exerted a significant influence on the behaviors of the free surface in the mold. The alternative occurrence of peak and trough fluctuations also showed asymmetric distributions. The random vortices generated between the SEN and the narrow wall, and vortices adjacent to the SEN were also found. The position, size, and distribution of the vortices generated were related to free surface fluctuations in the mold. As the casting speed increased, the variations and the velocities of the free surface increased; as the SEN immersion depth increased, the fluctuations and the velocities thereof decreased.

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Funding

This research was funded by the National Natural Science Foundation of China (grant no. 51174122), Key Laboratories of Fine Chemicals and Surfactants in Sichuan Provincial Universities, and Key Laboratory of Comprehensive Utilization of Vanadium and Titanium Resources in Sichuan Province.

Notes

The authors declare no competing financial interest.

REFERENCES

(1) Yuan, Q.; Vanka, S. P.; Thomas, B. G.; Sivaramakrishnan, S. Computational and experimental study of turbulent flow in a 0.4-scale water model of a continuous steel caster. Metall. Mater. Trans. B 2004, 35, 967–982.
(2) Knoepke, J.; Hubbard, M.; Kelly, J.; Kittridge, R.; Lucas, J. Steelmaking Conference Proceedings; Warrendale: PA, 1994, 381–88.
(3) Liu, H.; Yang, C.; Zhang, H.; Zhai, Q.; Gan, Y. Numerical simulation of fluid flow and thermal characteristics of thin slab in the funnel-type molds of two Casters. ISIJ Int. 2011, 51, 392–401.
(4) Torres-Alonso, E.; Morales, R. D.; García-Hernández, S. Cyclic Turbulent Instabilities in a Thin Slab Mold. Part II: Mathematical Model. Metall. Mater. Trans. B 2010, 41, 675–690.
(5) Yuan, Q.; Thomas, B. G.; Vanka, S. P. Study of transient flow and particle transport in continuous steel caster molds: Part I. Fluid flow. Metall. Mater. Trans. B 2004, 35, 685–702.
(6) Liu, Z.; Li, B.; Jiang, M. Transient Asymmetric flow and bubble transport inside a slab continuous-casting mold. Metall. Mater. Trans. B 2014, 45, 675–697.
(7) Zhang, X. J.; Shen, H. F. Lattice BGK model simulation of asymmetric flow inside a continuous slab casting mold. J Hydrodyn. Ser. B 2006, 18, 431–435.
(8) Hou, S.; Sterling, J.; Chen, S. A.; Doolen, G. D. A Lattice boltzmann subgrid model for high Reynolds number flows. arXiv preprint comp-gas/9401004, 1994.
(9) Yu, H.; Girimaji, S. S. Near-field turbulent simulations of rectangular jets using lattice Boltzmann method. Phys. Fluids 2005, 17, 239–283.
(10) Pirker, S.; Kahrzinanovic, D.; Schneiderbauer, S. Secondary vortex formation in bifurcated submerged entry nozzles: numerical simulation of gas bubble entrapment. Metall. Mater. Trans. B 2015, 46, 953–960.
(11) Thürey, N.; Körner, C.; Rüde, U. Interactive free surface fluids with the lattice Boltzmann method; University of Erlangen-Nuremberg: Germany, 2005.
(12) He, X.; Luo, L. S. Theory of the lattice Boltzmann method: From the Boltzmann equation to the lattice Boltzmann equation. Phys. Rev. E 1997, 56, 6811.
(13) Buick, J.; Greated, C. Gravity in a lattice Boltzmann model. Phys. Rev. E 2000, 61, 5307.
(14) Qian, Y. H.; D’Humières, D.; Lallemand, P. Lattice BGK models for Navier-Stokes equation. Europhys. Lett. 1992, 17, 479.
(15) Smagorinsky, J. General circulation experiments with the primitive EQUATIONS. Mon. Weather Rev. 1963, 91, 99–164.
(16) Anderl, D.; Bogner, S.; Rauh, C.; Rüde, U.; Delgado, A. Free surface lattice Boltzmann with enhanced bubble model. Comput. Math. Appl. 2014, 67, 331–339.
(17) Körner, C.; Thies, M.; Hofmann, T.; Thürey, N.; Rüde, U. Lattice Boltzmann model for free surface flow for modeling foaming. J. Stat. Phys. 2005, 121, 179–196.
(18) Thomas, B. G.; Huang, X.; Sussman, R. C. Simulation of argon gas flow effects in a continuous slab caster. Metall. Mater. Trans. B 1994, 25, 527–547.
(19) Kalter, R.; Tummers, M. J.; Kenjereš, S.; Righolt, B. W.; Kleijn, C. R. Oscillations of the fluid flow and the free surface in a cavity with a submerged bifurcated nozzle. Int. J. Heat Fluid Flow 2013, 44, 365–374.
(20) McDavid, R. M.; Thomas, B. G. Flow and thermal behavior of the top surface flux/powder layers in continuous casting molds. Metall. Mater. Trans. B 1996, 27, 672–685.
(21) Green, S. I.; Sheldon, I. Fluid Mechanics and its Applications. Kluwer Academic Publisher; 1995, 427, 470.
(22) Hunt, J. C.; Wray, A. A.; Moin, P. Eddies, streams, and convergence zones in turbulent flows. 1988.