Prediction Study on Vortex Center Position and Surface Velocity in a Steel Continuous Casting Slab Strand Using Mathematical Modeling

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In the current study, the movement of the vortex center position and the prediction of the maximum velocity at the top surface with different casting parameters were studied in a steel continuous casting slab strand using the Eulerian–Eulerian approach. One, two, and three vortexes were generated under the flow pattern of single roll flow, double roll flow, and complex roll flow, respectively. The vortex center position migrated from the meniscus to the submerged entry nozzle in the upper recirculation zone and moved downward along the mold height in the lower recirculation zone with the increasing of the casting speed, respectively. With the increasing of the argon flow rate, the movement trajectory of vortex center was opposite to the increasing of the casting speed. The vortex center position moved from the meniscus to the submerged entry nozzle with the outport angle of submerged entry nozzle increased and migrated from the submerged entry nozzle to the meniscus with mold width increased. In addition, nonlinear fitting for the maximum velocity of the molten steel at the top surface under different cast parameters was performed, and the regression equation was verified by nail board measurements. The on-line prediction of the maximum velocity at the top surface was realized.

KEY WORDS: vortex center position; continuous casting mold; numerical simulation; surface velocity; nail board measurement.

1. Introduction

In the continuous casting process, the molten steel comes from the tundish, pass through a submerged entry nozzle (SEN), and finally jet into the mold. The flow behavior of the molten steel in the continuous casting (CC) mold directly affects the quality of the steel slab.1,2) There are three types of flow patterns inside the mold with different casting parameters, including the double roll flow (DRF), the complex flow (CF), and the single roll flow (SRF).3,4) An undesired flow pattern and higher surface velocity in the mold will cause violent level fluctuations, slag entrainment, argon bubbles and inclusions were trapped by the solidified shell, and even a costly “break-out” happen.5–10) The fluid flow of the molten steel inside the mold was affected by the slab width,1,11–13) casting speed1,3,11,12,14) argon flow rate,15–17) submergence depth of SEN,1,3,13) SEN bottom well type,18–20) SEN outport angle21,22) and shape,23–25) and electromagnetic stirring.26,27) The characteristic parameters of the molten steel flow inside the mold included the jet angle, asymmetric flow, vortex center position in the recirculation zone, top surface profile, and top surface velocity distribution. Recent studies on the effect of casting parameters on the flow behavior of the molten steel inside the CC mold are summarized in Table 1, including investigations performed by physical simulation,11–13,16,21,23,28) mathematical modeling,15,29) and industrial trials.4,30,31) During jets from the SEN moved to the narrow face, vortex was generated at different locations in the recirculation zone of the mold with the variation of different casting parameters. The corresponding relationship was existed between the change of the vortex center position in the recirculation zone of the
2. Computational Models

2.1. Basic Assumptions

The mathematical model that is coupled with the realizable k-ε turbulence model and Eulerian–Eulerian model is established based on the following assumptions:

(1) The molten steel and argon gas are treated as incompressible Newtonian fluids. Each phase has its own velocity field; (2) The coalescence and breakup process of argon bubbles are ignored; (3) The effect of temperature on the molten steel and argon gas is ignored and no chemical reactions take place. (4) Slag phase is not considered; (5) The oscillation and are of the mold are not considered.

2.2. Continuity Equations

The continuity equation is as follows:

\[
\frac{\partial}{\partial t}(\alpha \rho) + \nabla \cdot (\alpha \rho \mathbf{u}_q) = 0
\]

where \( \alpha \) is the volume fraction, \( \rho \) is density in kg/m\(^3\), \( t \) is time in s, \( \mathbf{u}_q \) is the velocity in m/s, respectively. The subscripts \( q \) denotes the liquid phase.

2.3. Interfacial Momentum Equations

The momentum equation is as follows:

\[
\frac{\partial}{\partial t}(\alpha \rho \mathbf{u}_q) + \nabla \cdot (\alpha \rho \mathbf{u}_q \mathbf{u}_q) = -\nabla \cdot (\alpha \tau) - \alpha \mathbf{u}_q \mathbf{p} + \alpha \rho \mathbf{g} + F_{\text{F,eq}}
\]

where \( \tau \) is shear stress in N/m\(^2\), \( \mathbf{p} \) is the pressure in Pa, \( \mathbf{g} \) is the gravity acceleration in m/s\(^2\), and \( F_{\text{F,eq}} \) represents the interfacial forces between the continuous and dispersed phase in N/m\(^2\), respectively. Subscripts \( p \) denotes the gas phase.

The turbulent kinetic energy and the dissipation rate of turbulence kinetic energy are calculated by the realizable k-ε turbulence model:

\[
\frac{\partial}{\partial t}(\rho \alpha k) + \nabla \cdot (\rho \alpha \mathbf{u}_q \mathbf{k}) = -\nabla \cdot \left( \alpha \frac{\mu_T}{\sigma_k} \nabla k \right) + \alpha (G_k - \varepsilon)
\]

\[
\frac{\partial}{\partial t}(\rho \alpha \varepsilon) + \nabla \cdot (\rho \alpha \mathbf{u}_q \varepsilon) = -\nabla \cdot \left( \alpha \frac{\mu_T}{\sigma_k} \nabla \varepsilon \right) + \alpha \rho \varepsilon \left( C_1 S \varepsilon - C_2 \varepsilon^2 \right) + \alpha \rho \frac{\varepsilon^2}{k + \sqrt{\varepsilon k}}
\]

where \( k \) is the turbulent kinetic energy in m\(^2\)/s\(^2\), \( \varepsilon \) is the turbulence kinetic energy dissipation in m\(^2\)/s\(^3\), \( G_k \) represents the generation of turbulence kinetic energy in m\(^2\)/s\(^3\), \( S \) is the modulus of the mean rate of strain tensor. Model constants are \( C_1 = 1.44, C_2 = 1.9, \sigma_k = 1.0, \sigma_\varepsilon = 1.2 \).

Table 1. Research status of gas-liquid two-phase flow phenomena in slab CC molds.

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Jet angle</th>
<th>Asymmetric flow</th>
<th>Vortex center position</th>
<th>Top surface profile</th>
<th>Top surface velocity</th>
<th>Mathematical modeling</th>
<th>Water modeling</th>
<th>Industrial Trial</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>Thomax et al.</td>
<td>Yes</td>
<td>–</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>–</td>
<td>(34)</td>
</tr>
<tr>
<td>1999</td>
<td>Anagnostopoulos et al.</td>
<td>–</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>–</td>
<td>Yes</td>
<td>–</td>
<td>(35)</td>
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<tr>
<td>2002</td>
<td>Kubo et al.</td>
<td>–</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>Yes</td>
<td>–</td>
<td>Yes</td>
<td>(36)</td>
</tr>
<tr>
<td>2004</td>
<td>Ramos-banderas et al.</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>–</td>
<td>(37)</td>
</tr>
<tr>
<td>2007</td>
<td>Zhang et al.</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>Yes</td>
<td>(12)</td>
</tr>
<tr>
<td>2010</td>
<td>Wang et al.</td>
<td>–</td>
<td>–</td>
<td>Yes</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>Yes</td>
<td>(38, 39)</td>
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<tr>
<td>2014</td>
<td>Liu et al.</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
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<td>2014</td>
<td>Singh et al.</td>
<td>–</td>
<td>–</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>Yes</td>
<td>(41)</td>
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<td>2016</td>
<td>Cho et al.</td>
<td>Yes</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>Yes</td>
<td>(42)</td>
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<td>2019</td>
<td>Zhu et al.</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>–</td>
<td>(43)</td>
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<td>2019</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>2020</td>
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<td>–</td>
<td>–</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
<td>–</td>
<td>(45)</td>
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<td>Current study</td>
<td>Zhou et al.</td>
<td>–</td>
<td>–</td>
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<td>Yes</td>
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2.4. Interfacial Forces

In the right-hand side of Eq. (2), the last term represents interfacial forces between two phases, as follows:

\[ F_{\text{iq}} = -F_{\text{pq}} = F_D + F_L + F_{\text{TD}} + F_{\text{VM}} \]  

where \( F_D \) is the drag force, \( F_L \) is the lift force, \( F_{\text{TD}} \) is the turbulent dispersion force and \( F_{\text{VM}} \) is the virtual mass force. These forces were described in detail in the previous work.\(^{34}\)

3. Industrial Trials

Figure 1 illustrates the schematic of the nail board measurement in a CC mold. The nail board measurement can be used to detect the surface velocity, top surface level, and liquid slag depth.\(^{8,35,36}\) Three rows of SUS304 stainless steel nails (10 mm in diameter and 100 mm in length) were installed on a wooden board. The testing was performed at the same time on both sides of the SEN. Details can be seen in the author’s previous work.\(^{34}\) The surface velocity of the molten steel in the mold can be calculated by the following empirical equation:\(^{37}\)

\[ V_s = 0.624 \phi_{\text{lump}}^{-0.606} h_{\text{lump}}^{0.567} \]  

where \( V_s \) is the steel surface velocity in m/s, \( \phi_{\text{lump}} \) is the lump diameter in mm, and \( h_{\text{lump}} \) is the difference of lump height in mm.

4. Numerical Details

Figure 2 shows the schematic of calculation model and mesh structures. The computational domain was divided into hexahedral grids with approximate 750,000 cells. Geometric dimensions and casting parameters used in...
the current simulation are listed in Table 2. The dimension of the SEN is shown in Fig. 3. The CFD code ANSYS-FLUENT was used to solve both the mass and the momentum governing equations of each phase. For the computational inlet, the velocity of the molten steel and argon flow rate was given based on the casting speed and argon flow rate. The volume fraction of the molten steel and argon gas were set at the inlet. The increase in volume during heating of the injected argon gas was considered in the simulation and the expansion coefficient was 6.05 according to the study of Liu et al. The argon flow rate was set as 4 to 50 NL/min for the top surface of the mold, the degassing boundary condition was used which allowed the gas rather than the liquid steel to leave. The no-slip boundary condition was adopted along walls. Monitor solution variables (e.g., velocity components and argon volume fraction) were selected locations in the flow to see if the flow is fully developed and statistically steady. The convergence criteria of each variable was set to $1 \times 10^{-4}$. The time step was set as 0.0005 s, and the total calculation time was 100 s to obtain a steady state simulation.

5. Effect of Casting Parameters on Vortex Center Position

5.1. Transformation of Flow Pattern

Figure 4 shows the transition of flow pattern inside the mold at different casting speeds. The flow pattern varied from the DRF to CF and SRF with the increasing of the argon flow rate. The impact point of the jet on the narrow face moved upward and the upper recirculation zone gradually disappeared with the argon flow rate increased from 4 NL/min to 10 NL/min and 14 NL/min, respectively.

5.2. Effect of Casting Speed and Argon Flow Rate on Vortex Center Position

Figure 5 shows the effect of casting speed and argon flow rate on the vortex center position inside the mold with 1 000 mm mold width. The submergence depth of SEN was 150 mm and the SEN outport angle was 15° down. One, two, and three vortexes were formed when the flow pattern was SRF, CF, and DRF, respectively. In Fig. 5(a), the vortex center position is close to the upper recirculation zone under the SRF. There was a vortex near the 1/4 mold width and the meniscus in the upper recirculation zone under the CF, respectively. The vortex near the 1/4 mold width disappeared and only a vortex existed in the upper recirculation zone under the DRF. With the increasing of the casting speed, the vortex near the 1/4 mold width moved toward the SEN and the trajectory was marked as “L1”. The vortex near the meniscus moved to the lower left area and the trajectory was marked as “L2”. The vortex in the lower recirculation zone moved down along the mold height and the trajectory was marked as “L3”. In Fig. 5(b), with the increasing of the argon flow rate, vortex center trajectories are exactly opposite to trajectories under different casting speeds.

The variation of vortex center position inside the mold at different casting speeds and argon flow rates with 1 435 mm and 1 600 mm mold width are shown in Figs. 6 and 7, respectively. Under the constant argon flow rate, as the casting speed increased, the vortex center position migrated from the narrow face to the SEN in the upper recirculation zone and moved downward along the mold height in the lower recirculation zone, respectively. In contrast, under the constant casting speed, as the argon flow rate increased, the vortex center position migrated toward the meniscus in the upper recirculation and moved upward along the mold height in the lower recirculation zone, respectively.
5.3. Effect of SEN Outport Angle and Mold Width on Vortex Center Position

Figure 8 shows the effect of SEN outport angle on the vortex center position inside the mold. The mold width was 1800 mm, casting speed was 1.0 m/min, argon flow rate was 10 NL/min, and submergence depth of SEN was 170 mm. The flow pattern maintained DRF as the SEN outport angle increased from 15° to 20° and 25°. The vortex center position in the upper recirculation zone moved from the narrow face to the SEN with increasing of the SEN outport angle and in the lower recirculation zone moved downward along the mold height, respectively.

The effect of mold width on the vortex center position inside the mold is shown in Fig. 9. Casting parameters under
each cross-section were normal production parameters. The SEN outport angle was 15° down. With the mold width increased from 800 mm to 1800 mm, the vortex center position in the upper recirculation zone moved from the SEN to the narrow face and moved downward along the mold height in the lower recirculation zone, respectively.

5.4. Mechanism of Vortex Center Position Migration

Figure 10 illustrates the mechanism of vortex center position migration inside the mold at different casting speeds. In Fig. 10(a), jets from the SEN outport are lifted towards the top surface by the buoyancy force of argon bubbles at the smaller casting speed forming a SRF. The vortex center position under the SRF was close to the upper recirculation zone of the mold. In Fig. 10(b), as the casting speed increased slightly, part of jets move up toward the top surface after leaving SEN outport, another part of fluid continue as a down-jet impinged on the narrow face, and then flow from the narrow face to the SEN. The flow stream from the narrow face and the SEN collided forming a CF and generating two vortexes. In Fig. 10(c), most argon bubbles break up by the shear force of the molten steel which lead to the buoyancy force of argon bubbles on the molten steel became weaken as the casting speed increased. The vortex near the 1/4 mold width moved toward the SEN and the vortex near the meniscus moved to the lower left area, respectively. In Fig. 10(d), the momentum of the molten steel is huge at higher casting speed, and the buoyancy effect of argon bubbles on the molten steel is ignored which resulted in the vortex near the SEN disappeared. Then, only one vortex existed in the upper recirculation zone indicating the flow pattern was DRF. With the casting speed increased, the potential energy

Fig. 5. Variation of vortex center position inside the mold at different casting speeds and argon flow rates with 1000 mm mold width. (Online version in color.)

Fig. 6. Variation of vortex center position inside the mold at different casting speeds and argon flow rates with 1435 mm mold width. (Online version in color.)
of the molten steel flowing downward was large which led to the vortex center position in the lower recirculation zone gradually moved downward along the mold height.

**Figure 11** illustrates the mechanism of vortex center position migration inside the mold at different argon flow rates. In Fig. 11(a), jets from SEN outport are hardly affected by argon bubbles at small argon flow rate. All of the molten steel flowed as a down-jet impinged on the narrow face forming a DRF. In Fig. 11(b), the part of jets move up toward the top surface after leaving SEN outport with the argon flow rate increased slightly and the vortex center position was close to the SEN. In Fig. 11(c), the number and size of argon bubbles increased with the increasing of the argon flow rate which result in most jets from SEN outport were lifted towards the top surface by the large buoyancy force. The molten steel which flowed towards the top surface drove the vortex center position from the SEN to the narrow face. In Fig. 11(d), all of the molten steel move to the top surface when the argon flow rate exceed an extreme value which lead to the vortex in the upper recirculation zone disappears. With the argon flow increased, the buoyancy of argon bubbles on the molten steel enhanced which resulted in the vortex center position in the lower recirculation zone gradually moved upward along the mold height.

6. Online Prediction of Surface Velocity

6.1. Surface Velocity Distribution

**Figure 12** shows the variation of the maximum velocity at the top surface at different casting speeds. The mold width was 1300 mm, submergence depth of SEN was 150 mm, and the SEN outport angle was 15° down. The
Fig. 10. Mechanism of vortex center position migration inside the mold with the increasing of the casting speed. (Online version in color.)

Fig. 11. Mechanism of vortex center position migration inside the mold with the increasing of the argon flow rate. (Online version in color.)

Fig. 12. Effect of (a) casting speed, (b) argon flow rate, and (c) submergence depth of SEN on the maximum velocity at the top surface. (Online version in color.)
molten steel velocity was approximately maximum at 1/4 mold width at different casting parameters. The maximum velocity increased with the increasing of the casting speed, decreasing of the argon flow rate, and decreasing of the submergence depth of the SEN. The maximum velocity near the narrow face was larger than that near the SEN.

6.2. Surface Velocity Fitting

The fitting results of the maximum velocity at the top surface with 1300 mm mold width under different casting parameters are shown in Fig. 13. Then, the prediction equation for calculating the maximum velocity at the top surface of the mold was obtained as follows:

\[ V_{\text{max}} = C \times V_c^{1.65} \times Q_{\text{arg}}^{-0.22} \times H_{\text{SEN}}^{-0.78} \] ........(7)

where \( V_{\text{max}} \) is maximum velocity at the top surface of the mold in m/s, \( V_c \) is casting speed in m/min, \( Q_{\text{arg}} \) is argon flow rate in NL/min, \( H_{\text{SEN}} \) is submergence depth of the SEN in mm, and \( C \) is coefficient, respectively.

Different casting speeds, argon flow rates, and submergence depths are brought into Eq. (7) to calculate the value of \( V/C \), as shown in Fig. 14. Then, the coefficient \( C \) was determined and the final prediction equation of the maximum velocity at the surface of the mold was acquired as follows:

\[ V_{\text{max}} = 9.2 \times V_c^{1.65} \times Q_{\text{arg}}^{-0.22} \times H_{\text{SEN}}^{-0.78} \] ........(8)

The prediction equations of the maximum velocity for 1000 mm, 1600 mm, and 1800 mm mold widths are shown in Fig. 15. The prediction equation for 1000 mm mold width was:

\[ V_{\text{max}} = 31.9 \times V_c^{1.33} \times Q_{\text{arg}}^{-0.42} \times H_{\text{SEN}}^{-0.98} \] ........(9)

The prediction equation for 1600 mm mold width was:

\[ V_{\text{max}} = 11.64 \times V_c^{1.54} \times Q_{\text{arg}}^{-0.27} \times H_{\text{SEN}}^{-0.71} \] ........(10)

The prediction equation for 1800 mm mold width was:

\[ V_{\text{max}} = 0.38 \times V_c^{1.84} \times Q_{\text{arg}}^{-0.04} \times H_{\text{SEN}}^{-0.1} \] ........(11)

6.3. Industrial Trials Verification

The maximum velocity of the molten steel at the top surface by the numerical simulation is compared with that of the nail board measurement, as shown in Fig. 16. The maximum velocity was calculated by the Eqs. (6) and (8). The predicted velocity was in a satisfactory agreement with the measured one, indicating that the maximum velocity of the molten steel at the top surface can be obtained by the prediction equation.

![Fig. 13. Fitting of the maximum velocity of molten steel at the top surface of mold with different (a) casting speeds, (b) argon flow rates, and (c) submergence depths of SEN. (Online version in color.)](image-url)

![Fig. 14. Determination of the coefficient in the fitting equation for 1300 mm mold width. (Online version in color.)](image-url)
Conclusions

The movement of vortex center position and the prediction of maximum velocity at the top surface were numerically studied with varied dimensions. The effect of casting speed, argon flow rate, SEN outport angle, and mold width on the vortex center position migration were investigated. The maximum velocity at the top surface of the mold at different casting parameters was fitted and the prediction equation was validated by nail board measurements. The main conclusions were summarized as follows:

1. With the increasing of the casting speed, the vortex...
center position moved from the meniscus to the SEN in the upper recirculation zone and migrated downward along the mold height in the lower recirculation zone. The vortex center position moved from the SEN to the meniscus with the increasing of the mold width, respectively.

(2) The vortex center position moved from the meniscus to the SEN with the increasing of the SEN outport angle and migrated from the SEN to the meniscus with the increasing of the mold width, respectively.

(3) The maximum velocity at the top surface increased with the increasing of the casting speed, decreasing of the argon flow rate, and decreasing of the submergence depth of the SEN. The maximum velocity near the narrow face was larger than that near the SEN.

(4) Good agreement has been obtained between numerical simulation predictions and nail board measurements of the maximum velocity at the top surface of the mold. The on-line prediction of the maximum velocity at the top surface under different cast parameters was realized.

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