1. Introduction

The molten steel flow in a mold for continuous casting is unstable, and vortexing flow exists in the free surface. It is believed to be a significant contribution to mold powder entrapment; the entrapped flux may be carried deeply into the mold by the vortexing flow and results in the uncleanness of the steel. Water modeling studies by Li have revealed the existence of the vortex in the mold adjacent to the submerged entry nozzle (SEN) even when the SEN is located in the center of the mold. He concluded that the existence of vortex in the mold was the result of biased flow between the SEN ports, generated by effects of the slide gate, nozzle clogging, turbulent flow, etc.

It is found that most of the inner defects appear around the SEN, which shows that the vortex flow is a significant caution to mold powder entrapment and inner defects of slab. Water modeling studies are most widely adopted in the research of vortexing flow in mold. Li simulated the "biased vortex" (the vortex with off-center SEN) by the \( k-\varepsilon \) two-equation model, however, the "turbulent vortex" (the vortex with center SEN) was not mentioned. Takatani simulated the transient fluid flow with the effect of Ar gas by large eddy simulation (LES) model, but the vortexing flow was not described.

In this study, the "turbulent vortex" and the "biased vortex" are simulated by large eddy simulation model, which is verified by experimental results. A self-designed vortex brake and the electromagnetic brake (EMBR) are adopted to eliminate the vortexing flow in mold.

2. Mathematical Model

2.1. Calculation of Velocity Field

The LES equations are obtained by filtering Navier–Stokes equations using the top-hat filter and read

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0 \quad \text{...............}(1)
\]

\[
\frac{\partial u_j}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left\{ \nu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \tau_{ij} \right\} + \frac{1}{\rho} \vec{F}_j \quad \text{...............}(2)
\]

where the subgrid-scale (SGS) stress tensor \( \tau_{ij} = 2\nu_S S_{ij} + (1/3) \tau_{ii} \delta_{ij} \) and the resolved strain-rate tensor read

\[
S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad \text{...............}(3)
\]

The eddy viscosity \( \nu_S = (C_s \Delta)^{1/4} \Gamma \), where \( \Gamma = \sqrt{2\gamma S} \) and \( C_s \) is the Smagorinsky coefficient. In this study \( C_s = 0.1 \) is adopted. \( \vec{F} \) is the electromagnetic force.
2.2. Calculation of Electromagnetic Force

The electric current density induced in the moving conducting fluid under DC magnetic field is given by the Ohm’s equation:

\[ \mathbf{J} = \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B}) \] ...........................................(4)

In the foregoing equation, electric field intensity \( \mathbf{E} \) can be expressed as gradient of electric potential \( \phi \). Then the following equation is obtained:

\[ \mathbf{J} = \sigma (\nabla \phi + \mathbf{u} \times \mathbf{B}) \] ...........................................(5)

The induced current should satisfy the continuity equation

\[ \nabla \cdot \mathbf{J} = 0 \] ...........................................(6)

Substitution of Eq. (5) into Eq. (6) gives

\[ \nabla \cdot (\sigma \nabla \phi) = \nabla \cdot (\sigma (\mathbf{u} \times \mathbf{B})) \] ...........................................(7)

The electromagnetic force is obtained by the follow equation

\[ \mathbf{F} = \mathbf{J} \times \mathbf{B} \] ...........................................(8)

2.3. Boundary Condition

The inlet velocity is calculated by transferring the casting speed. At the exit, the condition of fully developed flow is adopted, i.e., normal gradients of all variables for fluid flow are set to zero. Near the wall, empirical “wall-law” function is employed to define the Smagorinsky coefficient:

\[ C_s = C_s \alpha (1 - \exp(-\gamma^2/26)^{1/2}) \] ...........................(9)

Boundary condition for the electric potential used in this study is set as the following:

At the meniscus and mold wall\(^7,8\)

\[ \nabla \phi = (\mathbf{u} \times \mathbf{B})_n \] ...........................................(10)

At the end of casting direction\(^7,8\)

\[ \phi = 0 \] ...........................................(11)

3. Verification of Mathematical Model

In order to verify the mathematical model, the fluid flow in the experimental device designed by Thomas\(^9,10\) is simulated. Figure 1 shows the comparison between the computational and the experimental results. The agreement between the computational and experimental results can be seen to be excellent.

4. Results and Discussion

4.1. Calculation Conditions

The geometrical parameters and the thermophysical properties of steel for simulation are listed in Table 1. The slab size used in the calculation was limited by the capability of the computer, so it was scaled to a proper value to reduce the computational load. Figure 2 illustrates the structure of the SEN and the positions of the magnetic field and the vortex brake used in this study. A 360\(\times\)30\(\times\)750 rectangular grid system was used with a time step of 0.0008 s. 300 s flow was simulated for each operating parameter.

Table 1. Geometrical parameters and thermophysical properties of steel for simulation.

| Parameters          | Values                        |
|---------------------|-------------------------------|
| Mold size, mm       | 720(width)\(\times\)60(thickness)\(\times\)1500(length) |
| Nozzle, mm          | 25(thickness) \(\times\)50(width) |
| Depth of nozzle, L, mm | 80, 100, 120, 140, 160, 180  |
| Port angle of nozzle, \( \theta \) | \(-15, 0, 15, 30, 35\)         |
| Casting speed, m/min | 1.5                          |
| Density of molten steel, kg/m\(^3\) | 7020                        |
| Viscosity of molten steel, \( \eta \) | \(5.59 \times 10^{-3}\)       |
| Magnetic flux density, T | 0.1                          |
| Position of magnetic field, DL, mm | 0, 30, 60, 120               |
| Height of the magnetic brake, H, mm | 60                            |
4.2. Mechanism of the Vortexing Flow

Figure 3 shows the instantaneous flow fields in half thickness of the slab with center SEN ($L=120\,\text{mm}$, $\theta=35^\circ$). The computational results agree well with the experimental results reported by Ref. 11. The two re-circulating flows are unsymmetric and the flow pattern varies periodically with time though the SEN is located at the centerline of the mold. Figure 4 shows flow fields in the free surface with center SEN. (a) is the time averaged flow field and (b)–(f) are instantaneous flow fields. It can be seen that the time averaged flow field is symmetric while the instantaneous flow fields are unsymmetric and the vortexing flow pattern in (b)–(f) varies periodically with time. Vortexing flow is the result of shearing of the two surface flows from the narrow face of mold when they meet adjacent to the SEN. It can be found from Fig. 3 that the two surface flows come from the two upward re-circulating flows, therefore, a conclusion can be drawn that the unsymmetric upward re-circulating flows, which are caused by turbulent energy of the fluid, lead to the unsymmetric flows in the free surface. In this study, the vortexing flow with center SEN was named “turbulent vortex” since it was caused by turbulent energy of the fluid. The turbulent vortex decreases when it moves downward from the free surface and is destroyed by

![Flow fields in half thickness of slab with center SEN.](image)

![Flow fields in the free surface with center SEN.](image)
the jet flow at the outlet of the nozzle as shown in Fig. 5. It can be seen from Figs. 4 and 5 that the turbulent vortex is composed of rotation of fluid in the horizontal section and the downward flow.

The resident time (the total time of the vortexing flow appearing in the free surface) and depth (the distance from the free surface to the horizontal section where the vortex is destroyed) of the vortex and the surface velocity are important characters of the turbulent vortex. Increase of the resident time and the surface velocity will increase the possibility of slab entrapment. Increase of the depth of the vortex will make the entrapped flux move more deeply into the mold. The influence of the SEN port angle and the SEN depth to the resident time of turbulent vortex and maximum surface velocity was studied. The increase of the SEN port angle and the SEN depth increases the residence time of turbulent vortex and decreases the maximum surface velocity as shown in Figs. 6–9.

The vortex with off-center SEN, which is named “biased vortex” in this study, is another type of vortex existing in the free surface. The biased vortex with a 10 mm biased distance of SEN from the mold centerline to the left-hand

Fig. 5. Flow fields at selected horizontal sections in mold (t=300s).

(a) Flow field in the free surface

(b) 50mm below the surface

(c) 100mm below the surface

(d) 120mm below the surface

Fig. 6. Influence of SEN port angle to the residence time of turbulent vortex in the surface.

Fig. 7. Influence of the SEN depth to the residence time of turbulent vortex in the free surface.

Fig. 8. Influence of SEN port angle to the maximum velocity in the surface.

Fig. 9. Influence of the SEN depth and the maximum velocity in the surface.
side was simulated in the present work. Figure 10 shows the biased flow fields in the free surface. (a) is the time averaged flow field and (b)–(e) are the instantaneous ones. It can be found from the comparison of Figs. 4(a) and 10(a) that the biased vortex is the result of shearing of the two asymmetric surface flows caused by the biased flow when they meet adjacent to the SEN and located at the low-velocity side. This phenomenon was also described and proved by experimental observation in Ref. 3). The two surface flows come from the two upward re-circulating flows as shown in Fig. 3, so the strength of the free surface flow is decided by the port angle and position of the SEN. When the SEN port angle is positive (in this paper 35°), the upward re-circulating flow on the narrow side gets weaker and that on the wide side gets stronger, so the surface flow on the narrow side gets weaker and the biased vortex is located at the narrow side. Opposite results can be obtained with negative SEN port angle. The flow pattern of the biased vortex varies with time as shown in Figs. 10(b)–10(e). A conclusion can be drawn from the comparison of the patterns of turbulent vortex and those of biased vortex that the biased vortex is caused by the biased flow and the turbulent energy of the fluid. The resident time of biased vortex is longer than that of turbulent one and the surface velocity with off-center SEN is larger than that with center SEN.

Figure 11 shows the flow fields at selected horizontal sections with off-center nozzle at \( t = 300 \) s. The biased vortex decreases when it moves downward from the free surface and is destroyed by the jet flow at the outlet of the nozzle. It can be seen from Figs 10 and 11 that the turbulent vortex is composed of rotation of fluid in the horizontal section and the downward flow too.
From the forgoing numerical analysis, the mechanism of vortex formation in the free surface may be summarized as follows. Vortexing flow is the result of shearing of the two unsymmetric surface flows from the mold narrow faces when they meet adjacent to the SEN. The unsymmetric surface flow comes from the unsymmetric upward re-circulating flow, which is caused by turbulent energy of the fluid for turbulent vortex and caused by biased flow and the turbulent energy of fluid for biased vortex as shown in Fig. 12.

### Table 2. Comparison of vortexing characters with and without vortex brake.

|                      | Turbulent vortex | Biased vortex |
|----------------------|------------------|---------------|
| Residence time, s    | 250              | 9.3           | 296           | 146.7        |
| Depth, mm            | 120              | 10            | 120           | 10           |
| Velocity, m/s        | 0.0372           | 0.0402        | 0.0335        | 0.00601      |

From the forgoing numerical analysis, the mechanism of vortex formation in the free surface may be summarized as follows. Vortexing flow is the result of shearing of the two unsymmetric surface flows from the mold narrow faces when they meet adjacent to the SEN. The unsymmetric surface flow comes from the unsymmetric upward re-circulating flow, which is caused by turbulent energy of the fluid for turbulent vortex and caused by biased flow and the turbulent energy of fluid for biased vortex as shown in Fig. 12.

#### 4.3. Vortexing Flow Suppression Methods

From the analysis of the mechanism of vortex formation, two suppression methods of the vortexing flow are suggested based on two ways: one is to suppress the surface velocity and the other is to remove the downward component of the vortex.

##### 4.3.1. Vortex Brake Application

The turbulent vortex and the biased vortex with vortex brake are simulated in this study. In these cases, \( L = 120 \text{ mm}, \theta = 35^\circ \) and a 10 mm biased distance of the SEN from the centerline to the left-hand side are chosen. The vortex brake, the length of which is 100 mm, is 10 mm below the free surface. Table 2 shows the comparison of vortexing characters with and without vortex brake. The flow pattern with vortex brake may be summarized as follows. The vortexing flow below the vortex brake is eliminated and the residence time of turbulent vortex is decreased by 96.9% and that of biased vortex is decreased by 49.8%, while the surface velocity is a little enhanced by the vortex brake. A conclusion may be drawn from the computational results that the vortex brake can eliminate the turbulent vortex and suppress the biased vortex significantly.

Two baffles are added to the vortex brake to eliminate the biased vortex as shown in Fig. 13. The resident time of the biased vortex is decreased to 22.2 s. A conclusion can be drawn on the basis of these findings that the turbulent vortex can be eliminated by removing its downward component near the SEN and the biased vortex, which is stronger than the turbulent vortex, can be suppressed significantly by removing its downward component and suppressing the fluid flow in the free surface.

#### 4.3.2. Electromagnetic Brake Application

On the basis of the mechanism of vortexing flow, suppressing the surface velocity and the downward flow of the vortex by EMBR is expected to eliminate the vortexing flow. The turbulent vortex and the biased vortex with different positions of magnetic field are simulated in this study. The residence time, the depth of the vortex and the surface velocity are considered. Figure 14 shows the flow fields of half-thickness with center SEN with and without EMBR. Figure 15 shows the flow fields at selected sections with center SEN with EMBR when \( DL = 30 \text{ mm} \). The comparison of the vortexing characters with different positions of the magnetic field is listed in Table 3.

It can be seen from Figs. 14 and 15 that the upward re-circulating flows is suppressed by the magnetic field, therefore, the surface velocity is decreased. The flow field in the magnetic field covered section is suppressed significantly and the vortexing flow is eliminated. With the moving of the magnetic field from the centerline of the outlet of the SEN to the free surface, the surface velocity is suppressed gradually and the depth of the turbulent vortex and the biased vortex is decreased as shown in Table 3. When the magnetic field is located at the free surface, the turbulent vortex and the biased vortex in the free surface are almost eliminated.

The position of the magnetic field does not have linear influence on the residence time of the vortexing flow. A new model is introduced to explain the influence of the position of the magnetic field to the residence time of the vortexing flow and the surface velocity as shown in Fig. 16. On the basis of the mechanism of vortexing flow, suppression of the jet flow and the upward re-circulating flow is helpful to suppress the vortexing flow. When the magnetic field is located at the centerline of the outlet of the SEN, the jet flow and the upward re-circulating flow are suppressed,
Table 3. Comparison of vortexing characters with different positions of magnetic field.

| Turbulent vortex | Biased vortex |
|------------------|---------------|
| Residence time, s | Without EMBR DL=120mm | DL=60mm | DL=50mm | DL=30mm | Without EMBR DL=0mm |
| Depth, mm        | 250           | 102     | 274.8   | 237.6   | 6      | 296 | 7 |
| Velocity, m/s    | 0.0372        | 0.0244  | 0.0179  | 0.0084  | 0.0063 | 0.0535 | 0.0083 |
so the residence time of the vortexing flow is decreased to 102 s. However, when the magnetic field moves from DL = 120 mm to DL = 60 mm, the jet flow is not suppressed and upward flow is weakly suppressed because the direction of the stream and the induced electric current are parallel near the surface of the walls, therefore, the residence time of the vortexing flow is decreased only to 247.8 s. When the magnetic field moves from DL = 60 mm to DL = 30 mm, the direction of the stream changes a little as shown in Fig. 16(c), so the suppression of the magnetic field to the upward flow is a little stronger. The best position of the magnetic field for suppressing the vortexing flow is DL = 0, where the flow in the free surface is directly suppressed by the magnetic field and the vortexing flow is almost eliminated.

5. Conclusions

The instantaneous and time-averaged patterns of turbulent vortex and biased vortex were simulated using a self-developed large eddy simulation model and the following conclusions were obtained.

1) Vortexing flow is the result of shearing of the two unsymmetric surface flows from the mold narrow faces when they meet adjacent to the SEN. The unsymmetric surface flow comes from the unsymmetric upward re-circulating flow, which is caused by turbulent energy of the fluid for turbulent vortex and caused by biased flow and turbulent energy of the fluid for biased vortex.
2) Increase of the SEN port angle and the SEN depth increases the residence time of the turbulent vortex and decreases the velocity in the free surface.
3) Both of the turbulent vortex and the biased vortex are decreased when they move downward from the free surface and destroyed by the jet flow at the outlet of the SEN.
4) The vortexing flow is composed of rotation of fluid in the horizontal section and the downward flow and can be suppressed by suppressing the surface velocity and removing the downward component of the vortex near the SEN.
5) The vortex brake can eliminate the turbulent vortex and suppress the biased vortex significantly by removing the downward component of the vortex.
6) With the moving of the magnetic field from the centerline of the outlet of the SEN to the free surface, the surface velocity is decreased gradually and the depth of the turbulent vortex and the biased vortex is decreased, the residence time is increased when the magnetic field moves from DL = 120 mm to DL = 60 mm and then decreased. The best position of the magnetic field for suppressing the vortexing flow is DL = 0, where the flow in the free surface is directly suppressed by the magnetic field and the vortexing flow is almost eliminated.

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