Effects of Electromagnetic Brake on Vortex Flows in Thin Slab Continuous Casting Mold

Baokuan Li and Fumitaka TSUKIHASHI

1) School of Materials and Metallurgy, Northeastern University, Wenhua Road 3-11, HePing District, Shenyang, 110004, China. 2) Department of Advanced Materials, Graduate School of Frontier Science, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8561 Japan.

A mathematical model has been developed to understand the vortex flows in the thin slab continuous casting mold associated with the effect of electromagnetic brake (EMBR). The molten steel flows are discharged from the bifurcated ports of the submerged entry nozzle (SEN) in the mold. Low Reynolds number k-ε turbulence model is used to calculate the effective viscosity. Numerical simulation shows that the asymmetric vortices can be produced even though the geometry is symmetrical and inlet flows are steady. Asymmetric flow is caused by the perturbation of numerical error of iteration in simulation instead of actual nozzle clogging, off-centerness of nozzle, and random turbulence etc. The vortex intensity depends on the surface velocity in the mold, which is determined by outflow angle of nozzle and casting speed. The vortices can be significantly suppressed and deformed by the application of static magnetic field, but cannot be vanished completely. The surface velocities decrease significantly with increasing coil currents, and the level of fluctuation heights in the mold becomes remarkably small. Furthermore, the aberration parts in adjacent to SEN caused by the vortices is gently calm. The vertical velocities in the lower part of the mold are suppressed and the plug like flows are formed.

KEY WORDS: continuous casting; electromagnetic brake; thin-slab; vortex flow; mathematical model; simulation.
A few researches\textsuperscript{9,10} were performed on the vortex flows in the continuous casting mold. Authors\textsuperscript{11,12} have studied the flow patterns in the parallel type mold. From our results, it is concluded that the vortices cannot be avoided completely, i.e., the vortex formation occurred near the SEN due to the initial perturbation of the off-center nozzle, nozzle clogging, slide gate and turbulence etc.

In the present work, the vortex flows in the thin slab continuous casting mold with a funnel shaped chamber in the upper portion of the broad side walls are analyzed and the effect of electromagnetic brake on flow fields is also examined. The chamber converges to the mold with decreasing the rectangular cross section of the final casting near the mold exit. The thin slab continuous casting mold with casting speeds up to 6 m/min allows slabs thickness of 50 to 70 mm compared with 150 to 350 mm in conventional continuous slab casting.

2. Mathematical Model

2.1. Formulation Description

A finite difference model has been developed to analyze the fluid flow in the mold region of a thin slab continuous casting of steel as shown schematically in Fig. 1. Generally, one quarter of the mold needs to be modeled because of the assumption of two fold symmetry. However, in the present research, the whole mold is modeled to investigate asymmetric nature of flow. The flow is highly turbulent, even far away from the nozzle, as indicated by the calculated Reynolds number more than 10,000. Lam and Bremhorst\textsuperscript{13} proposed that the Low-Reynolds-number turbulent model is very convenient for implementation, since the wall function is not needed near the mold wall. The elliptic time-averaged transport equations governing this three-dimensional flow are expressed by the following general form:

\[
\nabla \cdot (\rho \mathbf{V} \phi) = \nabla \cdot (\Gamma_\phi \nabla \phi) + S_\phi \tag{1}
\]

where \(\mathbf{V}\) is the velocity vector, with its three components \(u\), \(v\) and \(w\) representing the time-averaged velocities in the \(x\), \(y\) and \(z\) directions, respectively. The variable \(\phi\) represents various time-averaged quantities, i.e., mean velocities, turbulence kinetic energy \((k)\), and turbulence energy dissipation rate \((\epsilon)\). \(\Gamma_\phi\) represents the diffusivity of the transported variable \(\phi\). Pressure force, body force, generation, and destruction are contained in the source term, \(S_\phi\). The various transport equations are summarized in Table 1.

In order to describe the behavior of vortices in flow field, the vorticity \(\omega\) is defined as follows, respectively.

\[
\omega = \nabla \times \mathbf{V} \quad \text{in Cartesian coordinates or} \quad \omega = -\nabla^2 \psi \quad \text{in two dimensional coordinates} \tag{2}
\]

where \(\psi\) is Stream function.

2.2. Electromagnetic Force

Lorenz’s law is applied to calculate the electromagnetic force \((\mathbf{F} = F_x \hat{i} + F_y \hat{j} + F_z \hat{k})\)
where the induced current density \( J \) obeys Ohm’s law;

\[
J = \sigma (E + V \times B)
\]

and \( E = -\nabla \varphi \), where \( \varphi \) represents the electric potential. The continuity of the induced current density is expressed by the following equation:

\[
\nabla \cdot J = 0
\]

\[\text{(6)}\]

hence

\[
\nabla \cdot \nabla \varphi = \nabla \cdot (V \times B)
\]

\[\text{(7)}\]

\( B \) is the magnetic flux density of an imposed magnetic field and is obtained by measurement. The maximum value varies from 0.125 to 0.238 T for the mold gap space under a source current of 200–280 A as shown in Fig. 2.

The mushy zone is not included in the domain of calculation to avoid computational difficulties associated with simulating latent heat evolution at the solidification front. The wall function\(^{14}\) is used to calculate the electric potential at a wall boundary while the electric current enters the solidifying shell.

2.3. Boundary Conditions

Nozzle inlet velocity \( V_{in} \) is calculated by transferring casting speed \( V_c \) on the continuity of flow rate of fluid. The turbulent kinetic energy and its dissipation rate at the inlet are estimated by using the semi-empirical relations\(^{11,12} \) as

\[
k = 0.01 V_{in}^2,
\]

\[
e = 2 k^{1.5} / d_{nozzle},
\]

where \( d_{nozzle} \) is the hydraulic diameter of nozzle.

At the free surface, the normal gradients of all variables are set to be zero, except that the velocity perpendicular to the surface is zero. The vortices produced by numerical model are weaker than observed one, because of the assumption of a fixed free surface. As the result of not allowing the free surface to deform, the downward flow velocity can be reduced. This is because the height of the surface waves cannot be neglected, which is a part of driving force of the downward flow velocity in vortex. At the exit of the domain, fully developed flow is assumed, i.e. normal gradients of all variables are set to be zero.

2.4. Solution Method

Discretization of formulations is conducted by using the control volume integral method. The non-linear coupled equations are solved with the SIMPLEC algorithm. The SEN volume is taken into account by using the blockage technique.\(^{15} \) The compressed cylindrical nozzle is assumed to be rectangle to apply the blockage technique. A combination of an Alternating-Direction-semi-Implicit iteration scheme (ADI) and block correction is used to resolve the discrete nonlinear differentiate equations into algebraic equations. A FORTRAN computer code is independently developed for this problem. The 152×52×152 mesh system is used as main mesh system after grid refinement of solutions.\(^{11} \) When the maximum relative error between successive solutions becomes below 0.1%, the iterations are stopped and converged velocity and turbulence fields can be reasonably obtained. The iterations more than 3000 are required to reach the final convergence starting from an initial assumption of zero velocity.

3. Results and Discussion

A typical mold section of 70 mm×1500 mm with the casting speed of 5.5 m/min is used for calculation. The depth of the SEN is 200 mm and its inlet section is 40 mm×160 mm. The \( L \) in Fig. 1 is set to be 160 mm, and \( W \) changes from 72 to 96 mm.

Numerical studies are conducted to develop a better understanding of the vortexing flow phenomena in the mold. The present simulation is based on the idea that the vortex flows are the result of three-dimensional asymmetrical flow in the mold. Figure 3 shows the computed velocity distribution of a half thickness and free surface, which is expressed in vector and streamline. The vortices are observed on the free surface. Since the existence of complete two fold symmetric flow field is impossible to achieve in the practical operation, any small perturbation causes the asymmetrical flow.

Fig. 2. The measured magnetic flux density for different EMBR coil currents.

Fig. 3. Simulated Flow field in surface and half thickness of continuous casting strand.
3.1. Effects of Outflow Direction of the SEN on the Flow Pattern

The outflow direction of the SEN depends on the nozzle structure and casting speed. When the casting speed is constant, outflow direction of nozzle is decided by nozzle structure, i.e., W/L ratio. The effect of W/L ratio on the surface velocity of molten steel flow is illustrated in Fig. 4. The velocity distributions are anti-symmetric, whereas, the asymmetric parts in two sides are also observed in adjacent to the SEN, because of the effects of vortices near the SEN in the mold. Fluctuations of the top surface level are known to be very detrimental to steel quality. They may lead to entrainment of liquid mold flux, surface depressions and even cracks. A simple correlation[16] is proposed between the time-averaged magnitude of the level fluctuations and the fluctuation energy predicted by the modified $k$–$e$ model for steady state flows. An ideal conversion from $k$ to gravitational potential energy is assumed along the top surface. Equation (8) is obtained by equating these two energies.

$$
p_f k = 0.5(p_f - p)gh \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (8)$$

In this simple model, $k$ represents the turbulent kinetic energy, and $h$ is the distance between the peak and the trough of the average level fluctuation. Figure 5 shows the calculated surface heights of molten steel in the mold for various W/L ratios, scattered values in adjacent to nozzle is caused by the vortices. The effect of nozzle structure on vertical velocity distribution at 0.1 m below the meniscus is shown in Fig. 6, and small asymmetry is appeared only near the nozzle. The symmetry of vertical velocity distribution is displayed at 0.4 m below the meniscus in the mold as shown in Fig. 7. The effect of the nozzle structure on velocity distribution is concentrated on upper part of the mold and decrease with the distance from the meniscus.

3.2. Effects of Electromagnetic Brake on the Flow Patterns

When an electromagnetic brake with the 250 A coil current is applied in the thin slab mold, the computed flow...
field on the surface and half thickness of continuous casting strand is shown in Fig. 8. Comparing the results with that shown in Fig. 3, the flow velocities are significantly suppressed and the vortices in the surface are pushed into the back of the SEN in the funnel type mold. Figure 9 shows the effects of coil currents on the surface velocities. The velocities decrease significantly with increasing coil currents. Figure 10 shows the effects of coil currents on the level fluctuation heights in the mold. The meniscus in the mold becomes remarkably steady, and the aberration parts in adjacent to the SEN caused by the vortices is gently calm. Effects of the EMBR coil currents on the vertical velocities in the upper part of the mold are shown in Fig. 11. The velocity distribution becomes symmetry with increasing coil currents. Figure 12 shows the effects of EMBR coil currents on the vertical velocities in the lower part of the mold. It is observed that the recirculation flow is suppressed and the plug-like flows are formed.

From the results of simulation, the mechanism of vortex formation on the surface of molten steel in the mold is the result of shearing of the two surface flows from the mold narrow faces when they meet adjacent to the SEN. Vortex flows are composed of rotation of fluid in the horizontal sections and downward flow. The vortex intensity increases with increasing surface velocity. The vortices can be significantly suppressed and deformed by the static magnetic field application, but not vanished completely.

4. Conclusions

(1) A mathematical model has been developed to analyze vortex flows in the thin slab continuous casting with a
funnel type mold associated with the effect of electromagnetic brake. Numerical simulation shows that the asymmetric vortices can be produced even though the centerline geometrical is symmetry and inlet flows are steady. Asymmetric flow is caused by the perturbation of numerical error of iteration in simulation instead of actual nozzle clogging, off-centerness of nozzle, random turbulence etc.

(2) The vortex intensity depends on the surface velocities in the mold, which are decided by outflow angle of nozzle and casting speed. When the casting speed is constant, outflow direction of nozzle is decided by nozzle structure. The effect of the nozzle structure on velocity distribution concentrates on upper part of the mold and decrease with the distance from the meniscus.

(3) The vortices can be significantly suppressed by the application of static magnetic field, but it cannot be vanished completely. The surface velocities decrease significantly with the increasing of coil currents. The level of fluctuation heights in the mold becomes remarkably small, and the aberration parts in adjacent to the SEN caused by the vortices is gently calm. The vertical velocities in the lower part of the mold are suppressed and the plug like flows are formed.

Acknowledgements
One of the authors, Baokuan Li, is grateful to the National Natural Science Foundation of China for support of this research, Project No. 50474085 and the Liaoning province science and Technology key project, No. 2005221006.

Nomenclature
- \( g \): Acceleration due to gravity (m/s²)
- \( k \): Turbulent kinetic energy (m²/s²)
- \( L \): Nozzle interior width (mm)
- \( p \): Pressure (N/m²)
- \( R_t \): Turbulent Reynolds number, defined as \( R_t = \frac{\rho k^2}{\mu e} \)
- \( R_w \): Turbulent Reynolds number, defined as \( R_w = \frac{\rho k^{1/2} \nu_w}{\mu} \)
- \( u, v, w \): Velocity components (m/s)
- \( W \): Width of nozzle (mm)
- \( V_C \): The casting speed (m/s)
- \( V_{in} \): The inlet velocity of nozzle (m/s)
- \( y_w \): The distance from wall (m)
- \( x, y, z \): The Cartesian coordinates (m)

Greek symbol
- \( \varepsilon \): Rate of turbulent kinetic energy dissipation (m²/s³)
- \( \mu_l, \mu_t, \mu_e \): Laminar, turbulent, and effective viscosities (N·s/m²)
- \( \rho, \rho_0, \rho_i \): Mixture, slag, and liquid densities (kg/m³)
- \( \sigma_B \): Turbulent Schmidt number
- \( \sigma_v, \sigma_e \): Schmidt number for turbulent kinetic energy and its dissipation rate

REFERENCES
12) B. Li and F. Tsukihashi: *ISIJ Int.*, 45 (2005), 30.