Numerical Analysis of Fluid Flow and Heat Transfer in the Funnel Type Mold of a Thin Slab Caster

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Thin slab casting is an emerging technology offering many economic benefits. In the case of a thin slab caster, the control of fluid flow in a mold is particularly difficult due to the high casting speed and large aspect ratio of the mold. In addition, the knowledge of the transport phenomena is important because melt delivery is directly related to the problems of non-uniform shell growth, surface turbulence and mold powder entrapment. In this study, a 3-dimensional mathematical model has been developed for the coupled analysis of fluid flow, heat transfer and solidification in the funnel type mold using finite volume method based on the body fitted coordinate. The characteristics of transport phenomena in the mold of a thin slab caster were analyzed by numerical simulation. As a result of the simulation, the basic flow pattern could be characterized and the heat transfer calculations could accurately predict the areas where the mold is susceptible to cracking as a result of thermal stress. The predicted shell thickness showed good agreement with the measured thickness at the solidified shell of the break-out products.

KEY WORDS: fluid flow; heat transfer; numerical simulation; thin slab; funnel type mold.

1. Introduction

One of the important recent trends in the steel industry, in order to reduce the cost and to increase the productivity, is near-net-shape-casting.1–3) A typical example is the casting of steel closer to the dimensions of the final product the thin slab casting.3–6) In the thin slab casting process, the small thickness of the slab usually ranging from 50 to 100 mm, allows extraction at high speeds. The casting speed is typically about 4–6 m/min and is faster than the conventional slab caster, which compensates for the small cross-section area. Increased the casting speed leads to a thinner shell and a higher risk of break-out when the heat transfer between the mold and the strand surface is neither uniform nor stable. Furthermore, the feeding of liquid steel into the mold is more difficult due to the narrow shapes of the molds. With regard to the casting mold apparatus, plastic deformation by mechanical force due to the special mold shape and increased friction between the strand and the mold surface in high casting speed conditions in addition to high temperature reduces the mold life. Moreover, surface turbulence is more easily affected in thin slab casting because of a small inner volume space in the mold. Therefore, problems associated with meniscus stability, free surface fluctuations, and mold flux entrapment may be more severe. Consequently surface quality must be carefully monitored and controlled.

The surface and internal defects in the continuously cast slab are closely related to the fluid flow conditions of the liquid steel in the continuous casting mold. Therefore, the control of the steel flow for example, by proper design of submerged entry nozzle and by the optimum operating conditions, has become an important area for quality and productivity improvement.6) Many researches have developed various mathematical models for analyzing of fluid flow in the continuous casting mold. However, most have been confined to continuous casting in the simple geometry such as billet, bloom and conventional slab. There is a poverty of information available in the literature regarding fluid flow in the thin slab casting process. Honeyands et al.7) have studied fluid flow in the thin slab caster mold using a water model and undertook numerical analysis using a commercial computational fluid dynamics package. However, their research was confined to the parallel type mold with simple nozzle shape only and was not applicable to a funnel type mold with complex geometry. O’Connor et al.8) have analyzed heat transfer and mold stress for the CSP (Compact Strip Production)-process and reproduced the areas where the mold was susceptible to cracking as a result of thermal cycling. Furthermore, they predicted the deformed shape of the mold. However, as their study was focused mainly on stress analysis of the mold, convective fluid flow was ignored in the calculation of the mold and steel temperature in spite of they producing relatively good results with regard to deformation.

In this study, a 3-dimensional mathematical model has been developed for the coupled analysis of fluid flow, heat transfer and solidification in a funnel type mold using the
finite volume method based on the body fitted coordinate\textsuperscript{8,10}. This model is capable of calculating three dimensional fluid flow with a complex mold geometry and the characteristics of transport phenomena in the mold of thin slab caster.

2. Description of Thin Slab Casting Process

New thin slab casting processes are being developed and explored with experimental or pilot casters. Until now, there were about five main types of mold\textsuperscript{9,11} in the thin slab casting process and the mold types used in these process are funnel type and parallel type. In the case of the CSP process, the vertical type mold has a funnel-shaped bulge in the upper mold region, which facilitates the introduction of the casting nozzle in the meniscus. As the funnel shaped bulge is reduced to the original straight shape, the cross-section becomes rectangular with internal thickness of 50mm at the mold exit. We have focused our attention on the funnel type mold process. The mold is presented in the schematic diagram in Fig. 1. It has a funnel shaped section to allow the access of a more conventional SEN and to provide more space for fluid flow motion as well as to compensate for the shrinkage resulting from the phase transformation. This mold type is more advantageous when compared to the parallel type mold.

SEN design and mold shape determine the fluid flow in the mold, thereby influencing phenomena such as shell growth uniformity, superheat dissipation, inclusion flotation, slag entrapment, meniscus freezing and surface turbulence. In a thin slab caster, high casting speeds and a large mold aspect ratio compound these problems. In this study, the exact geometry of the mold shape, the cooling water slit system and the nozzle shape operating in a works was considered without simplification.

3. Numerical Analysis Method

The overall calculation process is composed of several mutually coupled elementary calculation processes: calculations of the fluid flow and temperatures are obtained through heat transfer analysis between the strand and the mold. Figure 2 shows the procedure details in the numerical calculation.

3.1. Calculation of Velocity Field and Heat Transfer

The 3-dimensional governing equation for the turbulent velocity and temperature fields with tensor form in the Cartesian coordinate system is as follows.

\[ \frac{\partial}{\partial x_i} (\rho u_i \phi) = \frac{\partial}{\partial x_j} \left( \Gamma \phi \frac{\partial \phi}{\partial x_j} \right) + S_{\phi} \] ..........................(1)

where \( \rho \) is the density and \( u_i \) is the velocity component in the \( x_i \)-direction and \( \phi \) can be the dependent variables such as 1 for the continuity equation, velocity \( u_i \), temperature \( T \), turbulent kinetic energy \( k \) and rate of energy dissipation \( \varepsilon \). \( \Gamma \) \( \phi \) is the effective diffusion coefficient of \( \phi \) and \( S_{\phi} \) is the source term of \( \phi \).

When the coordinate system is transformed from the Cartesian coordinate system (\( x, y, z \)) to the general curvilin-

ear coordinate system (\( \xi, \eta, \zeta \)), mapping leads to a one-to-one correspondence between the points on the real domain and those on the transformed space. The governing equation in Eq. (1) can be transformed as follows\textsuperscript{8,11}:

\[ \frac{1}{J} \frac{\partial}{\partial \xi_i} (\rho G^i \phi) = \frac{1}{J} \frac{\partial}{\partial \xi_j} \left( \Gamma \phi \frac{\partial \phi}{\partial \xi_j} \right) + S_{\phi} \] ..........................(2)

where

\[ G^i = J \left( \partial^2 \phi / \partial x_j \partial x_i \right) \quad g^{jk} = \partial^2 \phi / \partial x_j \partial x_k \]

and \( J \) is the Jacobian of the coordinate system transformation. In this study, the covariant velocity components are used as dependent variables.

For simulating turbulence, the \( k-\varepsilon \) turbulent model is used.\textsuperscript{12} Viscosity and diffusion coefficients, that appeared in Eq. (2), mean the effective quantity by turbulent eddy motion which is, in the case of viscosity, described as

\[ \mu_{\text{eff}} = \mu_{\text{liq,min}} + \mu_{\text{turb}} \] ..........................(3)

where the effective viscosity is the sum of the laminar viscosity \( \mu_{\text{laminar}} \) and turbulent viscosity \( \mu_{\text{turb}} \). \( \mu_{\text{eff}} = \rho \partial^2 u_j / \partial x_i \partial x_j = \rho C_n (k^2 / \varepsilon) \) from the \( k-\varepsilon \) model, where \( l, k, \varepsilon \) and \( C_n \) are the mixing length, turbulent kinetic energy, turbulent dissipation energy and a constant (=0.09), respectively.

The effect of the natural convection due to the density
change with temperature is incorporated into the source term of the momentum equation as follows.\textsuperscript{13)}

\[ F_z = -\rho_{ref} g \beta (T - T_{ref}) \] \hspace{1cm} (4)

Where \( g \) is the gravitational acceleration and \( \beta \) is the thermal expansion coefficient of molten steel, \( \rho_{ref} \) is the density of the steel at the temperature \( T_{ref} \), which is taken as the solidified temperature. In the mushy zone, the buoyancy force is considered only for molten steel in proportion to the liquid fraction.

3.2. Heat Transfer Coefficient between Solidified Shell and Mold

The heat transfer coefficient between the solidified shell and the mold wall was calculated with the series concept of thermal resistance considering radiative heat transfer\textsuperscript{14–16).} Because heat transfer is dependent on the surface temperature of the strand and the mold, it was evaluated at every iteration step in coupled analysis of the strand and the mold temperature. The effect of the air gap was neglected as it is confined to small region of the corner and our study was focused on the fluid flow and global heat transfer between the mold and the strand.

3.3. Microsegregation Analysis and Solidification Model

In order to determine the solid fraction in the mushy zone as a function of temperature, microsegregation analysis of solute element of steel of this system was assessed.\textsuperscript{10,17)} This could be crucial in evaluating the evolution of latent heat and the physical properties of the steel in hand such as viscosity, heat capacity and etc. From this analysis, the solidified temperature and liquidus temperature were obtained. The evolution of latent heat during the solidification of the steel is taken into account by using the effective heat capacity method as follows:

3.4. Grid Generation in Physical Calculation Domain

Figure 3 shows the grid system of the mold and the strand. For numerical analysis of the funnel type thin slab caster, a non-orthogonal curvilinear grid was used to take into account the effect of mold geometry and nozzle shape on fluid flow. The grid of the strand and the mold region are generated, respectively for the coupled analysis of heat transfer between the mold and the strand. Because each grid system was constrained by the nozzle in the strand and by the cooling channel of the mold, the boundary cells at interface between two regions were not matched. The form of the bulge in the funnel shaped mold may vary considerably and the maximum bulges at the meniscus were 30 mm on each side. The mold curvature, as well as the shape and position of the cooling water slit, was considered exactly in the grid system. A quarter of the mold was calculated considering the symmetry, and the calculation domain of the strand was divided into $60 \times 22 \times 51$ cells for the strand and $74 \times 15 \times 57$ cells for the mold.

3.5. Boundary Condition

Several important boundary conditions for the analysis of fluid flow and heat transfer of the funnel type thin slab casting mold can be classified as follows.

(1) Inlet boundary

\[ u_x = u_y = 0, \quad u_z = V_{inlet}, \quad T_{inlet} = T_L + \Delta T \]

\[ k_{inlet} = 0.03 \rho_{inlet}^2, \quad \epsilon_{inlet} = k_{inlet}^{1.5} / (0.07L) \]

where \( V_{inlet} \) and \( T_{inlet} \) are the inlet velocity and the initial temperature of molten steel flowing through the nozzle, respectively and \( \Delta T \) is the superheat of molten steel. The casting direction velocity \( V_{inlet} \) was obtained according to the
balance of the flow rate with the casting speed.

2 Symmetric boundary at the center

\[ \vec{V} \cdot \vec{n} = 0, \quad (\vec{n} \cdot \nabla \vec{V}) = 0, \quad \vec{n} \cdot \nabla \phi = 0 \]

where \( \phi \) is scalar variable such as \( T, k, \) and \( \varepsilon \) and \( \vec{n} \) is unit vector normal to the boundary.

3 Outlet boundary

\[ (\vec{n} \cdot \nabla \vec{V}) = 0, \quad \vec{n} \cdot \nabla \phi = 0, \quad \left[ \sum (\rho \vec{V} \cdot \vec{A}) \right]_{\text{outlet}} = \left[ \sum (\rho \vec{V} \cdot \vec{A}) \right]_{\text{inlet}} \]

where \( \vec{A} \) is the area vector.

4 Boundary between the cast strand and the mold

\[ \vec{V} \cdot \vec{n} = 0, \quad \vec{V} \cdot \vec{t} = V_{\text{cast}}, \quad q = h(T_{\text{strad}} - T_{\text{mold}}) \]

where \( T_{\text{strad}} \) and \( T_{\text{mold}} \) are the surface temperatures of the cast strand and the mold and \( \vec{t} \) is the unit vector tangential to the surface of the strand toward the casting direction. Because the funnel type mold surface was curved in 3 dimensional space, the velocity boundary condition must be carefully imposed and the law-of-wall for the turbulent kinetic energy and the rate of energy dissipation is adopted. The surface temperature of the opposite region corresponding to the boundary cell was obtained by interpolation and the heat transfer coefficient between the solidified shell and the mold wall was calculated with a function of the surface temperature related to the mold flux used.

5 Free surface of the melt

The boundary condition is similar to that of the symmetry plane except that the appropriate heat flux was added considering the heat extraction by the upper mold flux layer.\(^{18}\)

6 Surface of strand below the mold exit

\[ \vec{V} \cdot \vec{n} = 0, \quad \vec{V} \cdot \vec{t} = V_{\text{cast}}/2, \quad q = h(T_{\text{strad}} - T_{\text{am}}) + \varepsilon \sigma (T_{\text{strad}}^4 - T_{\text{air}}^4) \]

where \( T_{\text{am}} \) and \( T_{\text{strad}} \) are the temperatures of the air-mist spray and the air and the resin, respectively. The heat transfer coefficient by the air-mist spray in the secondary cooling zone below the mold exit could be determined with the cooling system.\(^{19}\)

7 Boundary of mold

The effect of cooling water in the mold was imposed by determining the heat transfer coefficient through the following relation.\(^{8,20}\)

\[ \text{Nu} = \frac{hD}{k} = 0.23 \text{Re}^{0.8} \text{Pr}^{0.4} \]

where Nu, Re and Pr are the Nusselt number, Reynolds number and Prandtl number respectively.

4. Results and Discussion

The casting conditions and the material properties considered in the analysis are listed in Table 1 and Table 2. The flow pattern and the related phenomena in the funnel type thin slab mold were investigated.

| Element | C  | Si  | Mn  | P   | S   |
|---------|----|-----|-----|-----|-----|
| mass t% | 0.06 | 0.045 | 0.86 | 0.015 | 0.008 |

Table 2. Chemical composition of the carbon steel in thin study.

4.1 Flow Pattern and Heat Transfer in Funnel Mold

Figure 4 shows the flow pattern in the funnel type mold. As we know from the stream trace, the inlet flow pouring from the SEN is propagated into the mold along the bottom of the SEN and dispersed making a recirculating flow. The basic flow pattern is characterized by four large recirculations and two small eddies near the narrow face of the mold, which is a somewhat unusual case in that it cannot be expected from previous studies on the conventional slab caster.\(^{21-25}\) The upper recirculations are dominant and there are additional recirculating flows beneath the nozzle. The lower recirculation in the region and a nearly-uniform flow is obtained at the exit of the mold. This flow pattern is different from that of the conventional slab caster and this is due to the funnel type mold shape and flattened bifurcated SEN. Most of all, the strong jet flow impinges with the inclined wall of the funnel shape mold and is decelerated due to the solidified shell. Because the upper region is large compared to the lower part, the flow is mainly redirected upward and there is no recirculation in the lower region. The strong jet flow downward with jet angle of 60° is diverged in the funnel region and cannot run against the narrow surface strongly. At the end of the mold exit, the flow is nearly uniform. It is noteworthy that there is a small recirculating
flow at the corner region of the mold. This is shown more clearly by the meniscus velocity profile as shown in Fig. 5. The flow pattern is somewhat changed differently in the upper part of the mold and from the surface velocity shown in Fig. 5, the local opposite flow directed from the SEN towards the narrow face is expected near the narrow wall of the mold. Figure 6 shows the calculated heat transfer coefficient and Fig. 7 shows the temperature profile of the mold. The heat transfer pattern is strongly dependent on the flow pattern in the mold so the heat energy is propagating around the inlet region. Because there is no impinging point of the nozzle jet flow on the narrow face, re-melting of the solidified shell was not expected.

4.2. Temperature Profile of the Mold

The temperature contours of the hot face are shown in Fig. 8 and the temperature profiles of the mold at various cross-sections along the casting direction are shown in Fig. 9. The mold hot face temperature is highest 50 mm below the meniscus and decreases along the casting direction. The region where the funnel shape ends had a very high temperature, which affected the mechanical strength of the mold material copper. This is understood as a phenomenon caused by impinging of melt that is reflected and redirected by the inclined wall of the funnel shape mold and the convex mold curvature. This agrees with the observation that mold scratch often occurs as a result of thermal stress during the casting operation and that internal cracks are observed when the copper plate structure are examined.²³

4.3. Solidification of Steel

Figure 10 shows the solidified shell thickness distribution. The solidified shell grows as the residence time increases along the casting direction and shows a rather uniform distribution. Nevertheless, along the position of the wide face that is directly influenced by the nozzle jet flow, the shell thickness is small compared to other regions. The calculated surface temperatures of the cast strand in the five parts of the thin slab are shown in Fig. 11. At the initial state, the strand surface temperature in the narrow face wall is low relative to that of the wide face and shows a somewhat different pattern due to the small eddy flows near the narrow face. However, as solidification progresses, the surface temperature of the narrow face does not decrease rapidly due to impinging of hot molten steel jetted from nozzle. The surface temperatures of the wide face, just below the meniscus, are related with the temperature of the

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**Fig. 5.** Calculated sub-surface velocity.

**Fig. 6.** Calculated heat transfer coefficient.

**Fig. 7.** Temperature profile of strand in funnel type thin slab caster.
mold hot face and the pattern coincides with the fact that the region where the funnel shape ends has a high surface temperature. However, as solidification further progresses, the temperatures of the funnel region are higher than other regions. Below the mold exit, the surface temperatures of the strand increase due to recalescence.

Fig. 8. Temperature contour at hot face of mold.

Fig. 9. Temperature profile of the mold in a transverse section at various distance from meniscus.

Fig. 10. Temperature profile and distribution of solidified shell at various distances from meniscus.

Fig. 11. The surface temperature along the casting direction from the meniscus.
Figure 12 shows the temperature contours at the mold exit. The point data is the measured shell thickness at the break-out shell and shows good agreement with the predicted shell thickness from the calculations.

5. Conclusion

A mathematical model, which calculates fluid flow, as well as heat transfer in the funnel type mold of a thin slab caster was developed. The effect of the funnel shape of the mold was analyzed and the characteristics of fluid flow and heat transfer in this type of mold were examined.

The following results were obtained through the numerical simulation.

(1) The basic flow pattern is characterized by four large recirculation and two small eddies near the narrow face of the mold. The fluid flow motion is different from that of a conventional slab caster and this is due to the funnel shape of mold and a flattened bifurcated SEN.

(2) The mold hat face temperature is highest at 50 mm below the meniscus and decrease along the casting direction. The region where the funnel shape ends shows a very high temperature, which affects the mechanical strength of the copper material mold. This is good agreement with the observation that mold scratch often occurs as a result of thermal stress during the casting operating and that internal cracks are observed when the copper plate structure is examined. The model accurately predicted the areas where the mold is susceptible to cracking as a result of thermal stress.

(3) The model simulated solid shell development at the mold exit and the predicted shell thickness. It shows a good agreement with the experimental data at the break-out shell. The solidified shell grows gradually as the residence time increases along the casting direction and shows a rather uniform distribution. Nevertheless, along the position of the wide face that is directly influenced by the nozzle jet flow, the shell thickness is small compared to other regions.

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