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

Hwa-Soo PARK, Hoseok NAM and J. K. YOON

School of Metallurgical and Materials Engineering, Kookmin University, Seoul 136-702, Korea.
1) School of Materials Science & Engineering, Seoul National University, Seoul 151-742, Korea.

(Received on December 25, 2000; accepted in final form on May 10, 2001)

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 optimum operating conditions, has become an important area for quality and productivity improvement. In this study, a three-dimensional numerical model for fluid flow and heat transfer analysis was employed and flow pattern and related phenomena in the parallel type thin slab mold were simulated together with a comparison with our previous study on the funnel type mold. The dependence of the flow on the shape of the SEN was illustrated for both straight and bifurcated nozzles. The bifurcated nozzle creates streamlines of two counter-rotating loops at each half of the mold similar to that of the funnel type mold with a bifurcated nozzle and produces a stabilized meniscus with a low surface velocity. The design of the nozzle port affects the velocity profile at the meniscus, heat transfer and accordingly the solidification process. An inclined bifurcated nozzle with a jet angle of 60° shows more stable velocity profile in the meniscus and more uniform distribution of solidified shell than the other port.

KEY WORDS: fluid flow; heat transfer; numerical simulation; thin slab; ISP-process.

1. Introduction

The modern continuous casting process has become the most important manufacturing step in steel production. Despite the difficulties in obtaining high quality scraps, the thin slab casting process is becoming increasingly used. This process is one of the near-net-shape casting processes, which can produce versatile sizes with small amounts, and is more economical than conventional slab casting. The flow of liquid steel plays a key role in slab quality since it influences the solidification procedure and the floatation of inclusions, thereby the internal structure and the cleanliness of the cast strand. Computational methods that involve coupled heat transfer and fluid flow have become a major research area in the continuous casting process. It is not surprising these days that a simulation is accomplished with 3-dimensional boundary fitted coordinates coupled with stress–deformation calculations. However, there are many questions yet to be solved and the development of more efficient and accurate methods is evermore necessary in the engineering industry.

Many papers regarding numerical simulation on continuous casting have been published for the conventional slab and billet. However, there are not enough reports on the thin slab. Honeyands et al.1) studied fluid flow in the thin slab caster mold using a water model and undertook numerical analysis using a commercial computational fluid dynamics package. O’Connor et al.2) analyzed heat transfer and mold stress for the funnel type mold of the CSP (Compact Strip Production)-process and another study was carried by Nam et al.3) on this type of thin slab caster focusing on fluid flow and heat transfer. In this study, a 3-dimensional numerical model for fluid flow and heat transfer analysis4–5) was employed with the aid of an effective heat capacity algorithm for the solidification6) and flow pattern and related phenomena in the parallel type thin slab mold were investigated. The design of the submerged entry nozzle (SEN) with the electromagnetic brakes is considered to be the most effective controlling factor in the thin slab casting process. The nozzle design is not only the main controlling factor of the flow patterns but also the easiest and most cost-effective component to modify. In this study, several nozzle types were tested and the flow patterns were characterized to propose a proper SEN design.

2. Numerical Analysis Method

The overall numerical simulation is composed of several mutually coupled elementary calculation processes and fluid flow and temperatures profiles were obtained through a coupled analysis of heat transfer between the strand and mold.

2.1. Calculation of Velocity and Temperature Field

The 3-dimensional governing equations for the turbulent fluid motion in a tensor form in the Cartesian coordinate system are as follows.
• Continuity equation:
\[ \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad \cdots \cdots \cdots \cdots \cdots \cdots (1) \]

• Momentum equation:
\[ \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + F_i \quad \cdots \cdots \cdots \cdots \cdots \cdots (2) \]

where \( \rho \) is the density, \( u_i \) the velocity component in the \( x_i \)-direction, \( p \) the pressure, \( \mu_{eff} \) and effective viscosity of the fluid flow. \( F_i \) is the source term, which corresponds to the natural convection term in this case. For simulating turbulence, the \( \kappa-\varepsilon \) turbulent model was used. The viscosity which appeared in Eq. (2), means the effective quantity by turbulent eddy motion, which is the sum of the laminar viscosity, \( \mu_{laminar} \) and turbulent viscosity, \( \mu_{turb} \). \( \mu_{turb} = \rho \mu_0 \left( \frac{d\varphi}{dy} \right) = \rho C_p(\kappa/\varepsilon) \) from the \( \kappa-\varepsilon \) model, where \( l, \kappa, \varepsilon \) and \( C_p \) are the mixing length, turbulent kinetic energy, turbulent dissipation energy and a constant (=0.09), respectively. \( \kappa \), the turbulent kinetic energy, and \( \varepsilon \), the dissipation rate of this energy both obey the classical convective-diffusive equations. The model constants are the assigned values proposed by Launder and Spalding. 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:
\[ F_i = -\rho_{ref} g \beta (T-T_{ref}) \quad \cdots \cdots \cdots \cdots \cdots \cdots (3) \]

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 solidification temperature. In the mushy zone, the buoyancy force is considered only for molten steel in proportion to the liquid fraction.

Heat transfer is obtained from the following equation.
\[ \frac{\partial}{\partial x_j} (\rho C_p u_j T) = \frac{\partial}{\partial x_j} \left[ (k + k_{turb}) \left( \frac{\partial T}{\partial x_j} \right) \right] + S_T \quad \cdots \cdots \cdots \cdots \cdots \cdots (4) \]

where \( T \) is the temperature, \( C_p \) the specific heat of the liquid metal and \( k \) the thermal conductivity, respectively. The turbulent conductivity \( k_{turb} \) is readily deduced from the turbulent viscosity by setting the Prandtl number for turbulence equal to 1.5

The following equivalent heat capacity model was used to describe the heat conduction involving melting and solidification:
\[ C_p = \begin{cases} 
C_{p,m} & T < T_i \\
C_{p,m} + L \left( \frac{dT}{df} \right) & T_s \leq T < T_i \\
C_{p,l} & T \geq T_i 
\end{cases} \quad \cdots \cdots \cdots \cdots \cdots \cdots (5) \]

where \( C_{p,m} \) is the heat capacity in the mushy zone, \( L \) latent heat of fusion, \( C_{p,l} \), heat capacity, \( f_s \) solidification fraction, \( T_i \) liquidus temperature, and \( T_s \) melting point of Fe, respectively.

When the coordinate system is transformed from Cartesian \((x, y, z)\) to the general curvilinear 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 equations in Eqs. (1), (2) and (4) can be transformed as follows:
\[ \frac{1}{J} \frac{\partial}{\partial \xi} \left( \rho G \phi \right) = \frac{1}{J} \frac{\partial}{\partial \eta} \left( \rho u_i \phi \right) + S_i \quad \cdots \cdots \cdots \cdots \cdots \cdots (6) \]

where \[ G = \frac{\partial}{\partial \xi} \left( \frac{\partial \phi}{\partial \xi} \right), \quad g^i = \frac{\partial \phi}{\partial \xi} \frac{\partial \phi}{\partial \eta} \]

and \( J \) is the Jacobian of the coordinate system transformation. \( \phi \) can represent the dependent variables such as 1 for the continuity equation, velocity \( u \), temperature \( T \), turbulent kinetic energy \( \kappa \) and rate of energy dissipation \( \varepsilon \). \( \Gamma_\phi \) is the effective diffusion coefficient of \( \phi \) and \( S_i \) is the source term of \( \phi \). In this study, the covariant velocity components are used as dependent variables.

2.2. 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 as in the case of a previous study. Because heat transfer is dependent on the surface temperature of the strand and mold, it was evaluated at every iteration step in the coupled analysis where the strand and the mold temperature were calculated alternately until convergence. The effect of the air gap was neglected as it is confined to small region of the corner in this case and our study was focused on fluid flow and global heat transfer between the mold and the strand.

2.3. Grid Generation in Physical Calculation Domain

A schematic of the mold of a thin slab caster and its grid system is shown in Fig. 1. The strand is surrounded by copper mold plates. Slots are in the back of the wide side and holes are in the narrow side of the mold for cooling. A quarter of the mold was calculated considering the symmetry, and the calculation domain was divided into 63 × 22 × 51 cells for the strand and 93 × 13 × 49 for the mold plate.

2.4. Boundary Conditions

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

- Inlet Boundary
\[ u_i = u_j = 0, \quad u_j = V_{inlet}, \quad T_{inlet} = T_i + \Delta T \]

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

- Symmetric Boundary at the Center
  \[ \mathbf{V} \cdot \mathbf{n} = 0, \quad (\mathbf{n} \cdot \nabla)|\mathbf{V}| = 0, \quad \mathbf{n} \cdot \nabla \phi = 0 \]
  where \( \phi \) is a scalar variable such as \( T, k \) and \( \varepsilon \) and \( \mathbf{n} \) is unit vector normal to the boundary.

- Outlet Boundary
  \[ (\mathbf{n} \cdot \nabla)|\mathbf{V}| = 0, \quad \mathbf{n} \cdot \nabla \phi = 0, \]
  \[ \left[ \sum (\rho \mathbf{V} \cdot \mathbf{A})_{\text{outlet}} \right] = \left[ \sum (\rho \mathbf{V} \cdot \mathbf{A})_{\text{inlet}} \right] \]
  where \( \mathbf{A} \) is the area vector.

- Boundary between the Cast Strand and the Mold
  \[ \mathbf{V} \cdot \mathbf{n} = 0, \quad \mathbf{V} \cdot \mathbf{t} = V_{\text{cast}}, \quad q = h(T_{\text{strnad}} - T_{\text{mold}}) \]
  where \( T_{\text{strnad}} \) and \( T_{\text{mold}} \) are the surface temperatures of the cast strand and the mold respectively and \( \mathbf{t} \) is the unit vector tangential to the surface of the strand toward the casting direction. The law-of-wall for the turbulent kinetic energy and the rate of energy dissipation were 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.\(^{11,12}\)

- 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.\(^{13}\)

- Surface of Strand below the Mold Exit
  \[ \mathbf{V} \cdot \mathbf{n} = 0, \quad \mathbf{V} \cdot \mathbf{t} = V_{\text{cast}}, \]

\begin{table}[h]
\centering
\caption{The simulation conditions.}
\begin{tabular}{|c|c|}
\hline
Parameter & Value \\
\hline
Slab width & 1090 mm \\
Slab thickness & 75 mm \\
Type of SEN & straight nozzle, bifurcated nozzle \\
Mold length & 1000 mm \\
Casting speed & 5.0 m/min \\
Tundish superheat & 30°C \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Thermo-physical properties of steel used in thin study.}
\begin{tabular}{|c|c|c|}
\hline
Parameter & Value \\
\hline
Density & 7200 kg/m\(^3\) \\
Latent heat of fusion & 2.72 \times 10^3 J/kg \\
Laminar viscosity & 6.7 \times 10^{-5} Pa \\
ZDT & 1494.5°C \\
Liquids Temperature & 1527.7°C \\
\hline
\end{tabular}
\end{table}

\[ q = h(T_{\text{strnad}} - T_{\text{air}}) + \varepsilon \sigma (T_{\text{strnad}}^4 - T_{\text{air}}^4) \]

where \( T_{\text{strnad}} \) and \( T_{\text{air}} \) are the temperatures of the air-mist spray and the air, respectively. The heat transfer coefficient by the air-mist spray in the secondary cooling zone below the mold exit could be determined according to the design of the cooling system.\(^{14}\)

- Boundary of Mold
  The effect of cooling water in the mold was imposed by determining the heat transfer coefficient through the following relation.\(^{15}\)

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

where \( Nu, \text{Re} \) and \( \text{Pr} \) are the Nusselt number, Reynolds number and Prandtl number, respectively.

3. Results and Discussion

The simulation conditions and the material properties considered in the analysis are respectively listed in Tables 1 and 2. The flow pattern and related phenomena in the parallel type thin slab mold were simulated together with a comparison with our previous study on the funnel type mold.\(^{3}\)

In thin slab casting, both the flattened straight nozzle and bifurcated nozzle are used in practice. The schematics of the nozzle geometry used in our simulation are shown in Fig. 2. For the parallel type mold, the bifurcated nozzle shape is rather simplified so that inner thickness of flattened nozzle is fixed, while the nozzle shape varies 3-dimensionally in the case of the funnel type mold.

3.1. Flow Pattern and Temperature Profile in Parallel Type Thin Slab Mold

Before the results obtained from the simulation of bifurcated nozzle types and their flow patterns are presented, the flow generated by a straight nozzle will be discussed. Figure 3 shows the flow pattern and temperature profile with the straight nozzle in the parallel type mold. As shown in Fig. 3(a), the inlet flow pouring down from the SEN is propagated into the mold and dispersed making a recircu-
lating flow. The basic flow pattern is characterized by a pair of large recirculations and small eddies near the narrow face of the mold. There was no recirculation in the lower region and uniform flow was obtained at the exit of the mold. Figure 3(b) shows the temperature profile of the strand. The heat transfer pattern is strongly dependent on the flow pattern in the mold so the heat energy is propagating around the inlet region.

3.2. Heat Transfer and Solidification

The characteristics of the heat transfer and solidification are shown in Figs. 4 and 5. Figure 4 shows the calculated heat flux between the mold and strand and Fig. 5 shows the development of the solidified shell along the casting direction. Because the distance between two mold plates is short and the flow is downward with a straight nozzle, there is no impinging point of the nozzle jet flow on the narrow face. As a result, re-melting of the solidified shell at the narrow face did not occur. Instead, the shell thickness along the center of the wide face was comparatively low.

3.3. Weak Point of Parallel Type Mold

Liquid flow along the top free surface is very important to steel quality. If the horizontal surface velocity is too large, the shear flow and possible accompanying vortices may entrain mold flux into the steel. Figure 6 shows the surface flow around the nozzle, which was adopted to demonstrate the strong velocity at the meniscus of the molten steel. At the corner of the submerged nozzle, there is a sudden increase in the horizontal velocity. When up-coming flow is directed to the center of the slab and passes the rear of the nozzle, the submerged nozzle makes the surface narrower. This decrease in surface area around the nozzle is responsible for the sharp rise in flow velocity. Small eddy currents can easily be made as two opposing surface flows from the narrow face run against each other at the center of the channel region between the nozzle and the mold hot face. This will result in not only mold flux entrap-
ment but also in nonuniform heat transfer at the center of wide face due to the deficient inflow of mold flux. In the case of the Compact Strip Production process, which is contrast to the parallel type mold that is modified from the conventional mold shape, the vertical type mold has a funnel-shaped bulge in the upper mold region.

Figure 7 shows the schematics of the funnel type mold (a) and the flow pattern (b). Its special shape facilitates the introduction of the SEN and provides more space for fluid flow motion in the meniscus in addition to compensating for shrinkage resulting from a phase transformation during casting. These factors contribute to meniscus stabilization although the high cost of mold equipment and maintenance is still a problem that needs to be overcome in the funnel type mold.

In the case of the parallel type mold, the strong sub-surface velocity near the nozzle is expected to slow down after applying the electromagnetic brakes, which are occasionally installed in the manufacturing industry. However, we tried to use a modified submerged entry nozzle to reduce surface instability. Initially, it was estimated that the fluid flow with a bifurcated entry nozzle might reduce surface turbulence. Then a numerical simulation with various nozzle jet angles was carried out. Varying the geometry of the bottom dividers and nozzle port angle shown in Fig. 2 can control the nozzle jet angle, although the port angle is not exactly same as the jet angle. Figure 8 shows the streamlines obtained with various nozzle jet angles and Fig. 9 shows the surface velocities at meniscus in each case. From this figures, it was found that in this case, a downward nozzle jet angle of 60°, similar to that in Fig. 7(b), could be the most advantageous among them.

3.4. Effects of Nozzle Geometry

Figure 10 gives a comparison of the flow patterns using two different types of nozzle; left part was with the straight nozzle and the right represents flow with a bifurcated nozzle using a jet angle of 60°. As can be seen from the streamlines, the flow patterns are very different. The bifurcated nozzle creates streamlines of two counter-rotating loops at each half of the mold similar to that of the funnel type mold with a bifurcated nozzle. The size of the loops can be changed by the nozzle jet angle as show in Fig. 8. These two counter directive flows suppress each other and diminish the subsurface velocity near the submerged nozzle. The surface velocities in the two cases are plotted in Fig. 11. The sudden increase in the horizontal velocity beside the nozzle wall was diminished in the case of the bifurcated nozzle. From this, it is estimated that the inclined bifurcated SEN has an advantage in stabilizing the meniscus.

The streamlines take effect at the impinging point of the hot stream from the nozzle and thereby affect the overall solidification procedure. The solidified shell thickness distributions at the transverse sections of middle and exit of mold are plotted in Fig. 12. The left half represents the solidified shell with a straight nozzle and right part represents the other. The unevenly distributed solidifying shell grows as the residence time increases along the casting direction and shows a rather uniform distribution at the mold exit. The impinging point, which in conventional slab casting usually occurs on the narrow side of the wall, was not critical in thin slab casting and the minimum thickness of the solidified shell in the transverse section was observed at the wide face of strand indicated by the circle in Fig. 12. Usually, the shell thickness of the region coincident with the center of the downward streamlines is small as the flow direction at port directly affects the solidifying shell. The
solidification retardation as a result of direct steel flow in the upper region is more severe with a straight nozzle than with bifurcate nozzle.

3.5. Temperature Profile of Mold

The temperature profiles of the mold are shown in Fig. 13. As in the previous figures, the left half shows the temperature with the straight nozzle and right half represents the other. The joint section part, where the segment is connected by bolt, has a higher temperature than the other part adjacent to cooling water slit. The hot face temperature of the mold is highest 40 mm below the meniscus and decreases along the casting direction.

4. Conclusion

A numerical model was developed to assist in understanding the flow patterns, solidification and the characteristics of fluid flow and heat transfer in a parallel type mold. The dependence of the flow on the shape of the SEN was illustrated for both straight and bifurcated nozzles. The bifurcated nozzle produces a stabilized meniscus with a low velocity. The design of the nozzle port affects the velocity.

Fig. 8. Streamlines of fluid flow with various nozzle jet angles: (a) downward 80°, (b) downward 60°, (c) downward 45°.

Fig. 9. Surface velocity with various nozzle jet angles.

Fig. 10. Comparison of flow patterns with different nozzle type: (a) straight nozzle, (b) bifurcated nozzle.
profile at the meniscus, heat transfer and accordingly the solidification process. An inclined bifurcated nozzle with a jet angle of 60° shows more stable velocity profile in the meniscus and more uniform distribution of solidified shell than the other port. A minimum thickness region of the solidified shell was observed at the wide face of the strand, which was coincident with the center of the downward streamlines. By calculating the effect of the SEN on flow in thin slab casting it can be concluded that the proper design of the SEN can greatly enhance the processing conditions for optimum output.

Acknowledgements

This work was supported by financial contributions of Pohang Steel Company and the publication cast of this article was provided by Brain Korea 21 Program, Ministry of Education, Korea.

REFERENCES

1) T. Honeyands and J. Herbertson: Steel Res., 66 (1995), 287.
2) T. G. O’Connor and J. A. Dantzig: Metall. Mater. Trans. B, 25B (1994), 443.
3) H. Nam, H.-S. Park and J. K. Yoon: ISIJ Int., 40 (2000), 886.
4) J.-E. Lee, J. K. Yoon and H. N. Han: ISIJ Int., 38 (1998), 132.
5) J.-E. Lee, H. N. Han, K. H. Oh and J. K. Yoon: ISIJ Int., 39 (1999), 435.
6) M. Rappaz: Int. Mater. Rev., 34 (1989), 93.
7) W. Frost and T. H. Moulden: Handbook of Turbulence, Vol. 1, Plenum Press, New York, (1987).
8) W. M. Kays and M. E. Crawford: Convective Heat and Mass Transfer, McGraw-Hill, New York, (1993).
9) A. D. Brent, V. R. Voller and K. J. Reid: Numer. Heat Transfer, 13 (1988), 297.
10) K.C. Karki: Ph. D. Thesis, University of Minnesota, (1986).
11) K. Kim, H. N. Han, T. Yeo, Y. Lee, K. H. Oh and D. N. Lee: Ironmaking Steelmaking, 24 (1997), 249.
12) H. N. Han, J.-E. Lee, T. Yeo, Y. M. Won, K. Kim, K. H. Oh and J. K. Yoon: ISIJ Int., 39 (1999), 445.
13) R. M. McDavid, B. G. Thomas and F. M. Najjar: Metall. Mater. Trans. B, 27 (1996), 672.
14) J. K. Brimacombe, I. V. Samarasekera and J. E. Late: Continuous Casting, Vol. 2, The ISS-AIME, Warrendale, PA, (1984), 29.
15) J. E. Kelly, K. P. Michalek, T. G. O’Connor, B. G. Thomas and J. A. Dantzig: Metall. Trans. A, 19A (1988), 2589.