Two-phase Flow Numerical Simulation of Molten Steel and Argon Gas in a Continuous Casting Mold

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For steel continuous castings, it is essential to control the molten steel velocity at the meniscus, since the velocity is closely related to surface defects on the resultant products. Argon gas is supplied with molten steel into the mold through a submerged entry nozzle to prevent clogging. In this study, to investigate the influence of argon gas on molten steel flow, a numerical simulation was carried out for several casting speeds. The simulation result of a higher casting speed is similar to a casting case in which argon gas is not used. The simulation result of a lower casting speed indicates that as argon gas bubbles ascend near the nozzle, they induce the molten steel to flow with them. The surface velocity magnitude of a lower casting speed is reduced more due to the dispersion by argon gas floatation. In consequence, meniscus molten steel flows from the nozzle to the narrow face of the mold. This flow direction is opposite to a higher casting speed case. By balancing the molten steel throughput and the argon gas flow rate, molten steel flow patterns can be controlled. We can conclude that the argon gas flow ratio is an important element to control the product quality.

KEY WORDS: continuous casting; mold; quality control; simulation; meniscus; steel flow; argon gas.

1. Introduction

During continuous casting of steel, it is possible to entrap some inclusions causing fatal defects on the resultant products. In operation, mold powder is put on the free surface as a thermal insulator and as a lubricant between the mold and the solidified shell. If the mold powder is entrapped in the solidified shell, it would produce surface defects. Molten steel may swirl at the free surface and cause the mold powder to be caught in these vortices. Furthermore, as the surface velocity increases, more mold powder is scraped off by the flow and entrapped in the molten steel. This means that the number of defects strongly depends on the molten steel flow, particularly the surface velocity. As an example, the relationship between surface velocity and surface defects on actual cold rolled coils are shown in Fig. 1. This is reproduced from R. Nishimachi et al., “Steel Flow Control in Mold for Surface Improvement of Ultra Low Carbon Steel” CAMP-ISIJ, 8 (1995), 952 by permission. When the surface velocity is close to zero, the index of surface defects is kept very low. Thus, decreasing the surface velocity is one of the most effective methods to reduce the entrapment of the mold powder.

Very often, argon gas is supplied with molten steel into the mold through a submerged entry nozzle to prevent clogging. When argon gas bubbles burst out at the free surface, mold powder is entrapped in the metal. Argon gas is therefore a potential cause of surface defects. On the other hand, the difference of specific gravity between molten steel and argon gas is thought to be able to change the molten steel flow pattern in a mold. Thus, argon gas may be used to modify or control the molten steel flow.

In this study, molten steel flow with argon gas in a mold has been numerically analyzed for several casting speeds. Some studies on molten steel flow in a mold take argon gas into consideration. There are several numerical methods to treat the secondary phase, such as argon gas in molten steel. In this study, the results of different methods were compared. The velocity of molten steel flow and the distribution of argon gas in a practical continuous casting mold were observed. Finally, the computed results were compared with the observation in a production machine in...
order to confirm the accuracy of the numerical calculations.

2. Calculation Methods and Conditions

2.1. Calculation Methods

Calculations were performed by two different numerical methods to treat the argon gas effect. One is the Discrete Phase Model (DPM) and the other is the Two-Phase Model (TPM). There are two approaches to the Discrete Phase Model: “the mean particle tracking method” and “the stochastic particle tracking method.”

2.1.1. Discrete Phase Model

It is assumed that molten steel is incompressible and isothermal. Basic conservation equations for molten steel flow, namely the mass conservation equation and the momentum conservation equation are written in Eqs. (1)–(2).

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

\[
\frac{\partial (\rho u_j)}{\partial x_j} + \frac{\partial (\rho u_i u_j)}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right) + \rho g_i + F_i \quad \text{(2)}
\]

where, \(u\) is the flow velocity, \(\rho\) is the specific density, \(p\) is the pressure, \(\mu\) is the effective viscosity, \(g\) is the gravitational acceleration, and \(F\) is the momentum sink from the argon gas bubble to the molten steel.

The two-equation \(k-\varepsilon\) model is adopted as a turbulence model:

\[
\mu = \mu + \mu_i \quad \text{(3)}
\]

\[
\mu_i = C_\mu \rho \frac{k^2}{\varepsilon} \quad \text{(4)}
\]

\[
\rho u_i \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \mu_i \frac{\partial k}{\partial x_j} \right) + G_k - \rho \varepsilon \quad \text{(5)}
\]

\[
\rho u_i \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\mu_i}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad \text{(6)}
\]

where,

\[
G_k = \mu_i \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad \text{(7)}
\]

\[C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92, C_\mu = 0.09, \sigma_k = 1.0, \sigma_\varepsilon = 1.3 \quad \text{(8)}\]

\(\mu\) is the molecular viscosity, \(\mu_i\) is the turbulent viscosity, \(k\) is the turbulent kinetic energy and \(\varepsilon\) is the dissipation of turbulent kinetic energy. These basic equations are solved by the means of a 3-dimensional finite volume method.

As for argon gas, it is assumed to be incompressible and isothermal. The bubble shape is spherical. The bubble size is not changed, so the effect of coalescence and breakup is neglected. The momentum equation for each bubble by the Lagrangian methods, which is written in Eq. (9), is solved to obtain the argon gas bubble trajectory.

\[
\frac{Du_g}{Dt} = -K \left( \frac{u_g-u}{\rho_g} \right) + g \left( \frac{p-p_g}{\rho_g} \right) + \frac{1}{2} \rho \left( \frac{Du}{Dt} - \frac{Du_g}{Dt} \right) + \frac{\rho}{\rho_g} \frac{Du}{Dt} \quad \text{(9)}
\]

\[
K = \frac{3}{4} \rho C_d |u_g-u| \frac{d_g}{g} \quad \text{(10)}
\]

where, \(u_g\) and \(\rho_g\) are the velocity and density of argon gas bubble respectively. \(K\) is the interaction coefficient. \(K\) is a function of argon gas bubble diameter \(d_g\) and the drag coefficient \(C_d\) is a function of the Reynolds number \(Re\).

Computing the trajectory, the momentum change of a gas bubble is calculated as it passes through each control volume, and the quantity is incorporated in the flow calculation as a momentum sink \(F\).

\[
F = \sum \frac{18 \mu}{\rho_g d_g^2} C_f R_e \left( u_g-u \right) m_g \Delta t \quad \text{(11)}
\]

where, \(m_g\) is the mass flow rate of argon gas bubble and \(\Delta t\) is the time step. This two-way coupling is accomplished by alternating the argon gas bubble calculation with the molten steel flow calculation.

When Eq. (9) is solved, we use two different methods, “the mean particle tracking method” and “the stochastic particle tracking method.” In the mean particle tracking method, the mean molten steel flow velocity \(\bar{u}\) is used as the flow velocity \(u\). On the other hand, in the stochastic particle tracking method, the fluctuating gas flow velocity \(u'\) is added to \(\bar{u}\) in order to include the effect of turbulence dispersion of argon gas:

\[
\bar{u} = \bar{u} + u' \quad \text{(12)}
\]

The fluctuating gas flow velocity \(u'\) is expressed with a normally distributed random number \(\zeta\) (namely, zero-mean, unit-variance) and the kinetic energy of turbulence \(k\). Isotropic diffusion and turbulence are assumed here.

\[
u' = \sqrt{\frac{2}{3}} k \quad \text{(13)}
\]

2.1.2. Two-Phase Model

Molten steel and argon gas bubbles are assumed to be incompressible and isothermal. The bubble shape is set to be spherical, and the diameter is set to be constant. The bubble size is not changed same as the Discrete Phase Model. In this model, molten steel and argon gas are treated mathematically as interpenetrating continua. As the volume of a phase cannot occupy the other, the sum of the molten steel volume fraction \(f_s\) and the argon gas volume fraction \(f_g\) is equal to one:

\[
f_s + f_g = 1 \quad \text{(14)}
\]

Basic conservation equations for each phase are given in
Eqs. (15) and (16) for the mass conservation equation and the momentum equation, respectively:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = \frac{\partial}{\partial x_i} \left( D \frac{\partial \rho}{\partial x_i} \right) \tag{15}
\]

\[
\frac{\partial}{\partial t}(f_q P_q u_q) + \frac{\partial}{\partial x_i}(f_q P_q u_i u_q) = -f_q \frac{\partial P}{\partial x_i} + f_q \mu \frac{\partial u_i}{\partial x_j} + \frac{\partial P}{\partial x_i} + K_{r,q}(u_{e,i} - u_{q,i}) \tag{16}
\]

\[
q = \begin{cases} \frac{1}{t}, & \text{for steel} \\ \frac{1}{g}, & \text{for argon} \end{cases}
\]

\[
D = \frac{\mu}{\rho S_{Ce}} = \frac{\mu_t}{0.7 \rho_t} \tag{17}
\]

\[
K = \text{the interaction coefficient. It is a similar expression}
\]

The bubble size is set at 0.5, 1 or 2 mm in diameter. In order to find a proper bubble diameter, three cases setting different bubble diameter are calculated. The Reynolds number can be estimated from the dimensions of the submerged entry nozzle exit. The order of magnitude is about 10^5, which makes it necessary to consider the effects of turbulence. The boundary wall at the meniscus is assumed to be slip because the mold powder on the meniscus is well melted. The boundary wall in the mold is assumed to be hydro-dynamically non-slip. Widely used wall function was proposed by Launder and Spalding^{24}, adopts:

\[
U^* = \frac{1}{\kappa} \ln(Ey^*) \tag{19}
\]

\[
U^* = \frac{U_{r}C_{\mu}^{1/4}k_{p}^{1/2}}{\tau_{u}} \tag{20}
\]

\[
y^* = \frac{\rho C_{\mu}^{1/4}k_{p}^{1/2}y_{p}}{\mu} \tag{21}
\]

where, \(\kappa\) is the von Kármán’s constant (= 0.42), \(E\) is the empirical constant (=9.81), \(U_r\) is the mean velocity of the molten steel at point \(P\), \(k_p\) is the turbulent kinetic energy at point \(P\), \(y_p\) is the distance from point \(P\) to the wall.

### 3. Results

#### 3.1. Calculated Molten Steel and Argon Gas Flow Pattern

**3.1.1. The Effect of Casting Speed**

For Case 1, the diameter of the argon gas bubble is set at 1 mm. The velocity vectors of molten steel are shown in Fig. 2. The viewing planes are slices at the center-thickness and near the free surface. Argon gas trajectories and contours of the argon gas volume fraction are shown in Fig. 3. For contours of the argon gas volume fraction, the viewing plane is a slice at the center-thickness only. The argon gas volume fraction is indicated by color scale. From white to black, the argon gas volume fraction increases. In Case 1, it is operated with a high casting speed and a low volume fraction of argon gas. The general flow pattern seems to be the same for all methods. Molten steel flows from the exit of the submerged entry nozzle to the narrow face of the mold.
mold, and diverges at the narrow face mold wall. After the divergence, some of it flows upward and some of it flows downward. Close to the meniscus, molten steel flows from the narrow face toward the nozzle. However, if we focus on the distribution of argon gas, slight differences are found. When the mean particle tracking method of the Discrete Phase Model is used, argon gas emerges from the port of the submerged entry nozzle, goes to the narrow face wall and then ascends up to the free surface. When the stochastic particle tracking method of the Discrete Phase Model is used, some argon gas particles ascend nearer the nozzle. But still no argon gas exists around the nozzle. In the case of the Two-Phase Model, some argon gas accumulates near the nozzle, although it is mainly carried to the narrow face wall.

From Case 1 to Case 3, casting speed is gradually reduced and the gas volume fraction is increased maintaining the same argon gas flow rate. Similar to the Fig. 2, the velocity vectors of molten steel for Case 3 are shown in Fig. 4. Argon gas trajectories and contours of the argon gas volume fraction are shown in Fig. 5. The diameter of the argon gas bubble is also set at 1 mm. In Case 3, argon gas distribution is quite different for each method. When the mean particle tracking method is applied, argon gas still does not float near the nozzle. But when the Two-Phase Model is applied, argon gas mainly rises along the nozzle. In this case, the flow pattern for each method is also fairly different. Paying attention to the meniscus, when the mean particle tracking method is used, molten steel flows from the narrow face toward the nozzle. When the stochastic particle tracking method is used, molten steel flows in the opposite direction symmetrically with respect to the middle point between the narrow face and the nozzle. Under the Two-Phase Model, molten steel flows from the nozzle toward the narrow face. It is opposite to the result of the mean particle tracking method. This is because molten steel is more entrained by argon gas floated close to the nozzle.

3.1.2. The Effect of Argon Gas Bubble Size
The formation of the molten steel flow pattern is affected by different argon gas bubble diameter settings. The case when the casting speed is 1.7 m/min, namely Case 3, is considered. Argon gas trajectories and contours of the argon gas volume fraction in which the argon gas bubble size is set at 0.5 mm in diameter are shown in Fig. 6. The same as in Fig. 6, Fig. 7 shows the results of 2 mm in diameter. Also see Fig. 5. The smaller bubbles are carried to the narrow
face of the mold by the molten steel flow from the nozzle. The larger bubbles float up to the meniscus near the nozzle. Under the Discrete Phase Model, some of the bubbles which have a diameter of 2 mm do not come out from the nozzle and remain inside the nozzle. Therefore, bubbles with a diameter over 2 mm hardly affect the molten steel flow in a mold and setting the size of the diameter over 2 mm as a typical bubble size will not be a good choice with this method in this casting condition.

3.2. Comparing Observation and Calculation

The results of the simulation are validated by the velocity measurement of the molten steel and the investigation of argon gas floating distribution in an actual operational continuous casting mold.

3.2.1. Surface Velocity

The molten steel velocity beneath the free surface was measured using an immersed bar.25 One edge of the immersion bar was fixed. The angle of inclination of the bar by metal flow $\phi$ was measured. From the moment balance around the pivot of the bar, the angle $\phi$ is converted to the velocity magnitude. The schematic view of the surface velocity measurement apparatus is shown in Fig. 8.

The calculated and observed surface flow velocity profiles are shown in Fig. 9. The argon gas bubble size is set at 1 mm in diameter in these calculations. Calculated results are plotted with lines, and measured data are plotted with circles. For Case 1, there were few operation opportunities, so no measured data is available. Positive velocity indicates flow in a direction toward the nozzle and vice versa. We can say that the results of the Two-Phase Model fit the observed data more than others. For all cases, the results of the Two-Phase Model are compared with the results in which argon gas is not considered. As the molten steel jet is more dispersed with an increasing argon gas volume fraction, the velocity magnitude reduces and tends to shift to the minus flow direction at the meniscus.

Again, the difference of the bubble size setting is checked. Figure 10 shows the surface flow velocity profiles for Case 3. The diameters of the argon gas bubbles in this case are set at 0.5 and 2 mm. See also Fig. 9c). There are some discrepancies between the results of different calculation methods. However, some qualitative tendencies can be found. When the bubble size is 0.5 mm in diameter, the argon gas is carried far away from the nozzle. Molten steel flows from the narrow face to the nozzle at the majority of the meniscus. When the diameter is set at 1 mm, argon gas floats up nearer to the nozzle. Molten steel flow is dispersed and weakened by the argon gas. In the condition of bubbles with a diameter of 2 mm, molten steel upstream is formed near the nozzle because of the floating argon gas. Therefore, at the meniscus molten steel tends to flow from the nozzle toward the narrow face, particularly around the nozzle. Under the setting of the 1 mm in diameter, the profile of the Two-Phase Model fits the observed data very much. It is concluded that bubbles with a diameter of
around 1 mm take the lead in the formation of the molten steel flow pattern under this casting condition.

3.2.2. Argon Gas Floating Distribution

The schematic view of the argon gas detecting apparatus is shown in Fig. 11. A sampling hood was placed over the meniscus, and the floating gas was pumped up from the hood into a sampling bag. The gas sample was analyzed by a mass spectrometer, and the argon gas floating distribution was calculated. Sampling was performed at three positions: near the nozzle, 1/4 width and near the narrow face of the mold for Case 2.

The measured and calculated data are shown in Fig. 12. All calculations are performed with the diameter of the bubble set at 1 mm. The results of the Two-Phase Model agree with the measured data. Floatation is concentrated around the nozzle and progressively reduced as it goes further away from the nozzle toward the narrow face. The measurement taken near the nozzle is slightly larger than that found in the Two-Phase Model, but the measurement taken near the narrow face of the mold is a little bit smaller. In actual casting, a range of argon gas bubble sizes exists with larger bubbles floating readily near the nozzle and smaller bubbles floating further away from the nozzle. The larger bubbles give rise to a higher floating ratio near the nozzle. Similarly, smaller bubbles give rise to a lower floating ratio near the narrow face. The schematic view of bubble size distribution effect is shown in Fig. 13. The simplicity of constant bubble size in the calculation failed to account for the effect of bubble size distribution. In order to have better accuracy quantitatively, the bubble size distribution has to be considered.

3.3. Validity of Calculation Method

For Case 1, namely the low gas volume fraction case, calculated results for all calculation methods are similar. However, for the higher gas volume fraction case, the accuracy of the Two-Phase Model was better than the others. Differences of each method are discussed here.

In the Discrete Phase Model, the interaction between par-
Particles and the effects of the particle volume are disregarded. Each bubble trajectory is traced independent from the others. Therefore, when the gas volume fraction is higher, the Discrete Phase Model is inappropriate. The limitation of the gas volume fraction is estimated about 10%. In addition, the initial position of each bubble has to be set in the Discrete Phase Model. Therefore, the results are dependent on where the bubbles are located initially. There should be as many bubbles set as possible. However, the number will always be smaller compared to the actual phenomena.

In the Two-Phase Model, the concept of volume fraction for each phase is introduced. Coupling is achieved through the pressure and interphase exchange coefficients.
Therefore, the accuracy of the Two-Phase Model was still good for the higher gas volume fraction case. However, as a set of conservation equations that has the similar structure for each phase is solved simultaneously, the computational load is heavy. It becomes heavier with an increasing phase number. As different size argon gas bubbles are treated as a different phase, to set a bubble size distribution is not practical from the viewpoint of the computational load. Compared with the Two-Phase Model, the Discrete Phase Model is more practical under the setting of a bubble size distribution.

Considering the circumstances mentioned above, the usage of each method regarding molten steel flow analysis in a mold are summarized. When the gas volume fraction is less than about 10%, both the Discrete Phase Model and the Two-Phase Model give good results. However, the Discrete Phase Model can be chosen for the reason of a light computational load. It will give a better result if a bubble size distribution is set. When the gas volume fraction is more than about 10%, the Two-Phase Model should be chosen. For practical usage, the bubble size effect has to be overlooked.

4. Conclusion

We concluded that numerical calculation is applicable to study about the effects of argon gas on molten steel flow. The simulations show that argon gas reduces metal flow momentum at the nozzle exit, and the surface velocity is also reduced. When the argon gas volume fraction is increased large enough, molten steel will be deflected upward by the up-flowing argon gas as it floats to the surface. The upward flow near the nozzle changes the meniscus velocity direction, resulting in a flow from the mold center toward the narrow face. Thus, by balancing the molten steel throughput and the argon gas flow rate, molten steel flow patterns can be controlled. We can conclude that the argon gas flow ratio is an important element to control the product quality.

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