Evaluation of Multiphase Phenomena in Mold Pool under In-mold Electromagnetic Stirring in Steel Continuous Casting

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Multiphase phenomena in the application of in-mold electromagnetic stirring in continuous casting were discussed through cold experiment using mercury and numerical simulation by using two fluid model. The result revealed the critical flow rate of argon injected in the submerged entry nozzle, which leads to the change in flow pattern in the bulk liquid metal inside the mold pool. This change does not have a large effect on the flow driven by in-mold electromagnetic stirring because the Lorentz force acts mainly in the vicinity of solidifying shell except for the case of large amount of the argon flow rate. The particle behavior under in-mold electromagnetic stirring in the vicinity of the solidifying shell was also discussed by solving near-wall fluid flow and employing the particle tracking method, which showed the important effect of lift force by the increase in velocity inclination near the solidifying shell by electromagnetic field.

KEY WORDS: continuous casting; multiphase phenomena; electromagnetic stirring; inclusion; numerical simulation.

1. Introduction

Recently, various in-mold flow control techniques have been being developed in order to improve the quality of the cast in steel continuous casting.¹⁾ In each control, optimum conditions to minimize the number of defects have been pursued by magnetohydrodynamic (MHD) analysis and by quality assessment of cast. Through preceding researches, fundamental phenomena inside the molten steel pool in the mold have been revealed. However, it is also well known that the phenomena are combined complex ones among fluid dynamic, thermal and solidification effects and so on, which demands continuing efforts to investigate for the pursuit of better quality of the casts.

In this paper, the multiphase phenomena in the mold pool are discussed through mercury experiments and multiphase analysis by using two fluid model, especially under in-mold electromagnetic stirring (M-EMS) in the steel continuous casting process. Behavior of argon bubbles injected inside the submerged entry nozzle (SEN) to prevent nozzle clogging is known to have a large effect to the molten steel flow, and has been investigated through model experiments with water or molten tin *etc.* It is also studied by employing multiphase analysis.²⁾ However, the important issue to be discussed for gas-liquid phenomena in the steel casting system is the multiphase phenomena inside the SEN³⁾ which can affect the entire flow pattern in the mold pool. In the normal water model, the bubble injected inside the SEN made of acrylic, which has good wettability with water, becomes a relatively small, 3 mm in diameter for example. On the contrary, if the nozzle wall is coated by wax worsening

wettability, an annular multiphase state appears inside the nozzle, which makes fine bubbles and simultaneously very large ones floating up rapidly near the nozzle outer wall to the meniscus. This relation of bad wettability and of multiphase phenomena is similar to the liquid steel and refractory nozzle. This fact can largely change the multiphase phenomena inside the molten steel pool in the mold. For this reason, a mercury model was employed to simulate the multiphase phenomena in this paper.

Also recently the boundary behavior of secondary phases such as argon bubbles and inclusions has been discussed precisely. One important such phenomenon is the entrapment of inclusions to the solidifying shell. The existence of flow velocity in front of solidifying shell is known to be important, because of the detaching force by lift force caused by the velocity gradient, turbulent dissipation *etc.* In this paper, the forces which act on the particle was evaluated by the investigation of flow field near solidifying shell including the boundary layer.

For all this purpose, the experiment has been conducted by using mercury model of continuous casting machine, measuring the bubble diameter injected from SEN through the observation of attached bubbles to the transparent wall and of floated bubbles at the meniscus. This behavior of bubbles was compared with the result of Lagrangian dispersed phase model. Also the employment of in-mold EMS was examined by using linear motor installed in the simulator. In addition, the effect of in-mold EMS on the particle entrapment to the wall was investigated by using numerical simulation of flow field including boundary layer, comparison of the order of forces act on particle and Lagrangian

dispersed simulation.

2. Experimental Method and the Results

2.1. Experimental Methods

A schematic view of the experimental apparatus is shown in Fig. 1. A mercury model, which is 1/5 scale of the continuous casting machine of 250 mm in thickness, 1 000 mm in width, was employed. The Froude number was used for similarity to determine the flow rate of mercury. The dimensions of the strand pool are 200 mm wide, 50 mm thick and 1 500 mm long. The port angle of the SEN is 15 degrees from the horizontal line and 7.2 liters per minute of mercury, which corresponds to the casting speed of 1.6 meters per minute, was recirculated. Argon gas of 0.05, 0.1 and 0.2 liters per minute was injected to SEN made of acrylic tube at 100 mm above the meniscus of the strand. The size distribution of argon bubbles was measured through the observation of bubbles floating up to the meniscus during 30 sec, by dividing the meniscus into eight parts in width direction and by taking video film from the top of mercury pool. In the experiment, the bubbles were composed not only of large bubbles floating up to the meniscus but also of fine bubbles, which were carried into the strand pool. These very fine bubbles were observed at the acrylic wall, however, this volume was less than 1 % of the total injected argon volume, so that its effect on the total behavior was supposed to be small and was neglected in the experiment. Also, the floating frequency of the large size bubbles whose diameter is more than 10 mm was not periodical, so that their number and the diameter was counted in the flow rate, then separated from the bubbles periodically floating up in the strand pool.

2.2. Experimental Results

Figure 2 shows the relation between the diameter of argon bubbles floating up to the meniscus and their numbers. The correlated function is approximately expressed as $N = k \cdot d^{-4.49}$, where k represents the correction coefficient of the flow rate which is obtained by extracting the volume of argon larger than 10 mm in diameter from the total injected argon to SEN. It is observed that the number of large size argon gas bubbles increases with the total flow rate, and the

Fig. 1. Schematic view of the experimental apparatus to investigate the behavior of argon bubbles.

ratio of the volume of dispersed argon bubbles to the total argon decreases. Figure 3 shows the relation between the frequency of bubbles floating up and the observation area in the width direction, which shows that the amount of argon bubbles increases when the observation area approaches to the SEN.

3. Numerical Simulation Method and Calculated Results

3.1. Method of Numerical Simulation of Fluid Flow and Particle Behavior Analysis

The finite difference method was used for fluid flow analysis by using the k - ϵ model as a turbulence model. For numerical simulation of particles behavior and its interaction with the first phase, the Lagrangian method, which is a kind of two fluid model was employed.⁴⁾ These simulations have been conducted by using the commercial fluid flow analysis code FLUENT. This model is said to be applicable to the volume concentration of less than 10% for the secondary phase. In the simulation, the existence of large size

Fig. 2. Size distribution of measured argon bubbles floating up to the meniscus.

Fig. 3. Floatation frequency of bubbles along width of mercury pool.

argon bubble was neglected by using a modified argon flow rate defined in the experimental section. This effect of large size bubbles should be discussed separately by employing such as volume of fluid method *etc.* Concerning the considered forces acting on the particle, the effect of acceleration, gravity, virtual mass, drag and pressure gradient are taken into consideration, and the other forces such as lift force,⁵⁾ capillary force have not been taken into account. The effect of lift force and capillary force becomes important near the wall, and can be neglected to discuss the behavior in the bulk flow. The size distribution of bubbles was given by the result obtained from the experiments.

Fundamental equations used for the Lagrangian dispersed phase model are as follows.

Equation of continuity for primary phase;

$$\nabla \cdot u = 0 \quad \text{.....(1)}$$

Equation of motion for primary phase;

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\frac{1}{\rho} \nabla p + g + \frac{f}{\rho} + \nabla \cdot v \nabla u + F \quad \text{.....(2)}$$

Equation of motion for secondary phase;

$$\begin{aligned} \frac{du_p}{dt} = & F_D(u - u_p) + \left(\frac{\rho}{\rho_p} - 1 \right) g_x \\ & + \frac{\rho}{2\rho_p} \frac{d}{dt}(u - u_p) + \frac{\rho}{\rho_p} u_p \frac{\partial u}{\partial x} \quad \text{.....(3)} \end{aligned}$$

where,

$$F_D = \frac{18\mu}{\rho_p D_p^2} \frac{C_D \text{Re}}{24} \quad \text{.....(4)}$$

$$\text{Re} = \rho D_p |u - u_p| / \mu \quad \text{.....(5)}$$

$$f = \sum \frac{18\mu}{\rho_p D_p^2} \frac{C_D \text{Re}}{24} (u_p - u) m_p \Delta t \quad \text{.....(6)}$$

where, u : velocity of primary phase [m/s], t : time [s], p : pressure [Pa], ρ : density of primary phase [kg/m³], ρ_p : density of secondary phase [kg/m³], x : Cartesian coordinate, u_p : velocity of secondary phase [m/s], g_x : x -component of acceleration of gravity, D_p : diameter of secondary phase particle [m], m_p : mass flow rate of secondary phase [kg/s], Δt : increment of time between each iteration [s], C_D : drag coefficient [–], Re : Local Reynolds number, and F : Lorentz force [N/m³].

For the particle behavior analysis, the Lagrangian method was used.

Boundary conditions for flow field are taken as follows.

Wall functions were used for all the walls, and free slip condition for the meniscus. On the trajectory calculation of bubbles, the reflection condition was used for all the walls and the escape condition for the meniscus.

3.2. Results of Numerical Simulation

Figure 4 shows the velocity distribution of primary phase at the center plane with different flow rate of argon gas. In the case of relatively low flow rate of argon, change in flow pattern is restricted to the region near submerged entry nozzle. On the contrary, the increase in the flow rate results in change of flow pattern in the entire region inside the mold. The flow rate of argon of 0.1 liters per minute corresponds to 2 normal liters per minute in the actual continuous casting machine, and 0.2 liters per minute corresponds to about 8 to 10 normal liters per minute by taking into consideration with large size argon bubble which float up near the nozzle. The result shows that the flow near the submerged entry nozzle is affected by the flotation of bubbles, however the flow in the other region is not so much affected by the bubble behavior. The results also show that

Fig. 4. Change in the velocity distribution with the argon flow rate (without EMS).
(a) Case of argon flow rate 0.1 l/min, (b) case of argon flow rate 0.2 l/min.

Fig. 5. Change in the trajectory of bubbles with the argon bubble size (without EMS).
(a) Case of argon bubble 1 mm in diameter, (b) case of argon bubble 2 mm in diameter.

Fig. 6. Comparison of experimental and numerical results for the floatation frequency of argon bubbles to the meniscus.

the numerical simulation by using multiphase analysis is indispensable if the flow rate of argon becomes more than 5 liters per minute in actual continuous machine. **Figure 5** shows the result of the trajectory calculation of argon bubbles 1 and 2 mm in diameter. The larger the bubble size, the floatation near the SEN becomes more dominant. **Figure 6** shows the comparison of numerical and experimental results of floatation frequency of argon bubbles to the meniscus. In the numerical simulation, the size distribution of bubbles is the one obtained from the experimental observation. The figure shows a good agreement between two results and the tendency that the frequency of bubble floatation is dominant near the SEN. This means that the floatation behavior of argon gas in liquid metal can be evaluated by the above-mentioned Lagrangian dispersed phase model if the size distribution of bubbles is precisely known.

4. Influence of Two-phase Flow in the Case of the Flow Driven by Electromagnetic Stirring

In order to clarify the influence of argon injection to the flow, a numerical simulation of two fluid model has been conducted with changing the flow rate of argon gas when the system uses mercury. The flow rate was set to be 0.1

and 0.2 liters per minute, supposing that the existence of large size argon bubbles does not affect the bulk flow pattern. The distribution of argon gas bubbles was supposed to be the one observed in the experiment using mercury without electromagnetic stirring. The parameters of electromagnetic stirring were set as follows. The frequency was chosen to be 20 Hz so as to correspond to the M-EMS, whose height is 50 mm and its core top is set to the meniscus level, used in the actual continuous casting machine through shield parameter. The Lorentz force was set to the value so as to correspond to the M-EMS used in the actual continuous casting machine through an interaction parameter. The Lorentz force distribution was introduced to the external force term in the Navier–Stokes equations which were obtained from the finite element method.⁷⁾

The flow velocity distribution in front of the wide face, on the longitudinal section between two wide faces and of the cross-section at the meniscus without argon gas injection are shown in the **Fig. 7** in the case without and with M-EMS. With M-EMS, recirculating flow is formed at the meniscus region. The point to be remarked is that the lift up of the jet from the port appears similarly to the decrease in port angle, so that the meniscus flow velocity tends to increase, then the interference between electromagnetically driven flow and jet from nozzle becomes evident. **Figure 8** shows the case with argon gas injection, which shows the interaction between the jet from the SEN modified by the existence of gas and the electromagnetically driven flow when the flow rate of gas is increased.

5. Investigation of Particle Behavior Near the Solidifying Shell

In the preceding research, it was shown that the number of inclusions more than 50 micron meter in diameter decreases remarkably with the application of electromagnetic stirring.⁷⁾ An example of the mechanism of this inclusion removal due to the flow imposition is thought to be as fol-

Fig. 7. Comparison of the flow field in mercury pool without and with EMS. (a) Without EMS, (b) with EMS.

Fig. 8. Effect of the argon injection flow rate to velocity distribution stirred by in-mold EMS. (a) Case of argon flow rate 0.1 l/min, (b) case of argon flow rate 0.2 l/min.

flows for example. One is that the boundary layer becomes thinner by the flow imposition so that the residence time of the inclusions decreases. The other is the effect of Saffman's force which gives detaching force to the particles from the solidifying shell.⁷⁾ The entrapment phenomena of particles to the solidifying shell are affected by the various factors such as solidification speed as mentioned before, especially just in the viscous sub-layer, however the comparison of the order of forces acting on the particle shows the dominant effect of drag force and lift force if the inclusion size becomes larger.

As the thickness of the boundary layer is the order of some mm and the mold size is the one of some m, the numerical simulation both boundary layer and bulk is quite

difficult. By this reason, the two dimensional simulation of duct flow has been conducted as follows in order to investigate the state of flow field near the boundary layer under the electromagnetic stirring. With this intention, calculation mesh was also introduced inside the boundary layer, and Large Eddy Simulation was conducted.⁸⁾ The following Smagorinski model is used.

$$\Delta = (\Delta x \Delta y \Delta z)^{1/3} \dots \dots \dots (7)$$

$$v_{SGS} = \Delta \cdot (e_{ij} e_{ij}) \dots \dots \dots (8)$$

Fig. 9. Used mesh for the numerical simulation of the duct flow. (a) Generated mesh for the duct flow analysis, (b) enlarged mesh near the corner of the duct.

Fig. 10. Velocity field obtained by the simulation containing boundary layer analysis without and with EMS. (a) Velocity distribution near wall calculated in case of normal duct flow, (b) velocity distribution near wall calculated in case of flow with EMS.

Fig. 11. Comparison of the velocity profile near wall.

$$e_{ij}e_{ij} = 2 \left\{ \left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial z} \right)^2 \right. \\ \left. + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right)^2 \right\} \quad (9)$$

Fig. 12. Relation between removal velocity and particle size.

In the calculation system, a duct of 250 mm wide and 500 mm long was employed to simulate the meniscus part of mold pool. Symmetric condition is used for the direction of height. One case is unidirectional flow field in the duct, which corresponds to the flow pattern of half of the horizontal section at the meniscus of the mold pool formed by the two port nozzle, and the other case is recirculating flow driven by the electromagnetic force. The maximum velocity level is set to be 40 cm/s which is ordinary given by in-mold electromagnetic stirring in actual application. For the boundary condition at the wall, no-slip condition was used.

Figure 9 shows the employed mesh, in which meshes are introduced near the boundary so as to enable the calculation of boundary layer thickness and velocity inclination. However, in the direction along the duct, the mesh is coarsened so that the structure of detailed flow along this direction cannot be simulated enough and only the boundary layer growth and velocity inclination can be discussed. Figures 10 and 11 shows the results of flow field calculation. In the case of the duct flow driven by pressure inclination, the thickness of boundary layer becomes 3 mm, and in the case of the flow driven by electromagnetic force, it becomes 1 mm. On the velocity inclination near the boundary, it becomes three times larger in the latter case than the former one. As the Saffman's force is proportional to the square root of velocity inclination and to the velocity difference, the value becomes five times larger in the case of electromagnetically driven flow than in the flow driven by pressure gradient. In the preceding research, the effect of body force was neglected in the boundary layer in case of flow driven by electromagnetic stirring. This was because the thickness of the boundary layer was thin enough, so that the body force is negligible. However it became clear that the effect of body force is not negligible even inside the thin boundary layer and has a strong effect on the estimation of the value of Saffman's lift force which is shown by the following expression.

$$1.62\mu(u-u_p)\sqrt{\left|\frac{\partial u}{\partial y}\right|}\frac{D_p^2}{\sqrt{\nu}} \quad (10)$$

Figure 12 shows the relation between the removal velocity perpendicular to the wall, which was obtained by solving the equation of motion perpendicular to the wall, and the diameter of the particles. The removal velocity becomes larger with the diameter of the particle. Its value becomes dominant when the diameter becomes the order of hundred

micron meters to the solidification speed calculated from the simple solidification law that the thickness of the shell is proportional to the square root of solidification time, which is much lower than the above mentioned velocity. This can directly show the important role of the lift force in the removal phenomena of inclusions with EMS.

6. Conclusions

The effect of argon gas injected in the submerged entry nozzle on the flow inside the mold was investigated through cold experiment using mercury which can simulate the phenomena occurring in the combination of liquid steel and refractory because of bad wettability compared to the water model. The result was also discussed by using two fluid model. Through this research, the effect of argon gas on the molten steel flow inside the mold becomes remarkable if the flow rate of argon gas becomes more than 5 normal liters per minute. In the actual continuous casting machine, the flow rate of argon is from 2 liters per minute to 10 liters per minute, so that the value of 5 is a crucial one, which should be contemplated in the flow control in operation. With the application of in-mold electromagnetic stirring, the flow in the vicinity of the solidifying shell is principally decided by the electromagnetically driven flow and the effect of argon gas is relatively small except for the fact that the uniformity of flow velocity in front of solidifying shell along the wide face should be taken into consideration if the flow rate becomes large enough.

As a second part of the report, the boundary phenomena under electromagnetic phenomena and particle behavior was discussed through numerical simulation. As a result, it was shown that the thickness of the boundary layer becomes one third and the lift force becomes five times as large as the one in pressure gradient driven flow. Moreover, from the analysis of dispersed phase model, it was shown that the removal velocity is much larger than the solidification speed, which contributes to the removal of large inclusions by use of in-mold electromagnetic stirring.

Nomenclature

C_D	: Drag coefficient [–]
d	: Diameter of bubble [m]
D_p	: Diameter of secondary phase [m]
f	: External force [N/m ³]
F	: Lorentz force [N/m ³]
g_x	: x component of acceleration of gravity vector [m/s ²]
m_p	: Mass flow rate of secondary phase [kg/s]
N	: Frequency of float up of bubbles
p	: Pressure [Pa]
t	: Time [s]
Re	: Local Reynolds number [–]
u	: Velocity of primary phase [m/s]
u_p	: Velocity of secondary phase [m/s]
x, y, z	: Cartesian coordinate [m]
δ	: Skin depth [m]
μ	: Viscosity [Pa·s]
ν	: Kinematics viscosity [m ² /s]
ρ	: Density of primary phase [kg/m ³]
ρ_p	: Density of secondary phase [kg/m ³]
Δt	: Time step [s]

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