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Mathematical Modeling of Multi-sized Argon Gas Bubbles Motion and Its Impact on Melt Flow in Continuous Casting Mold of Steel

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Abstract: The 3D turbulence k-ε model flow of the steel melt (continuous phase) and the trajectories of individual gas bubbles (dispersed phase) in a continuous casting mold were simulated using an Eulerian-Lagrangian approach. In order to investigate the effect of bubble size distribution, the radii of bubbles are set with an initial value of 0.1−2.5 mm which follows the normal distribution. The presented results indicate that, in the submerged entry nozzle (SEN), the distribution of void fraction is only near the wall. Due to the fact that the bubbles motion is only limited to the wall, the deoxidization products have no access to contacting the wall, which prevents clogging. In the mold, the bubbles with a radius of 0.25−2.5 mm will move to the top surface. Larger bubbles issuing out of the ports will attack the meniscus and induce the fluid flows upwards in the top surface near the nozzle. It may induce mold powder entrapment into the mold. The bubbles with a radius of 0.1−0.25 mm will move to the zone near the narrow surface and the wide surface. These small bubbles will probably be trapped by the solidification front. Most of the bubbles moving to the narrow surface will flow with the ascending flow, while others will flow with the descending flow.

Key words: continuous casting; bubble; multi-sized distribution; dispersed phase; void fraction

In continuous casting molds, argon gas is injected into the submerged entry nozzle (SEN) to prevent clogging[1,2]. A certain range bubbles are formed in the molds due to highly turbulent motions of molten steel flow. Most of bubbles will move to the top surface. Also, some of large bubbles issuing out of the ports attack the meniscus and induce mold powder entrapment into the mold. Some of small bubbles will be trapped by the solidification front, such as "pencil pipe" blister defects. So, both argon bubbles motion and their effects on flow are closely related to defects of the final products. Although great modeling efforts are made to study argon gas bubbles motion in continuous casting mold of steel[1,3-8], the argon gas bubble size is set to be constant in their study. The simplicity of constant bubble size in the calculation fails to account for the effect of bubble size distribution. In order to have better accuracy quantitatively, the bubble size distribution should be considered. There is no general formula to express the bubble size distribution in the mold. However, some studies have discussed the experimental bubble size distribution. For example, Takatani et al.[6] have investigated the bubble size in the low melting point alloy mold model. It is said that the radius of the bubbles is around 0.5 mm and the volume of bubbles with a radius over 2.5 mm is small. Toh et al.[9] have investigated the bubble size in the mercury mold models which showed that the volume of very fine bubbles is less than 1% of the total argon gas volume. Based on these studies, in this paper, the size distribution of normal distribution is assumed as a simple function to fit the character as mentioned above. The minimum bubble radius is 0.1 mm and the maximum bubble radius is 2.5 mm.

In order to investigate the effect of bubble size distribution, the radii of bubbles are set with an initial value of 0.1−2.5 mm which follows the normal

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distribution. This work is aimed to study the role of multi-sized argon gas bubbles motion and its impact on the occurring melt flow. The equations are solved with the commercial package FLUENT, with the help of extensive user defined subroutines developed by the author.

1 Governing Equations and Models

1.1 Fluid-phase hydrodynamics

Mass and momentum conservation for an incompressible fluid are given by

$$\frac{\partial}{\partial t}(\alpha_1\rho_1)+\frac{\partial}{\partial x_j}(\alpha_1\rho_1\vec{v}_j)=0 \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_1\rho_1\vec{v}_i)+\frac{\partial}{\partial x_j}(\alpha_1\rho_1\vec{v}_i\vec{v}_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\{\alpha_1(\mu_1+\mu_t)\}+F_k \tag{2}$$

where, α_1 is the fluid-phase volume fraction; ρ_1 is the fluid-phase density; $\vec{v}_i$ is the fluid-phase velocity of the ith component; t is time; x_j is jth spatial coordinate; p is pressure; $\vec{F}_k$ is interaction momentum per unit mass transferred from the bubbles; μ_1 is the fluid viscosity and μ_t is the turbulent viscosity, which is defined as

$$\mu_t=C_\mu\rho_1\frac{k^2}{\varepsilon} \tag{3}$$

where, k is the turbulent kinetic energy; ε is dissipation rate of k and C_μ is empirical constant.

The fluid-phase volume fraction α_1 is defined as

$$\alpha_1=1-\frac{\sum_i V_{d,i}}{V_{cell}} \tag{4}$$

where, i is the number of bubbles which visit that control volume; $V_{d,i}$ is the volume occupied by the ith bubble and V_{cell} is the volume of the control volume.

The standard k-ε model is used to model turbulence, which means that the following transport equations of k and ε are solved.

$$\alpha_1\rho_1 v_j\left(\frac{\partial k}{\partial t}+\frac{\partial k}{\partial x_j}\right)=\frac{\partial}{\partial x_j}\left(\alpha_1\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right)+\alpha_1 G_k-\alpha_1\rho_1\varepsilon \tag{5}$$

$$\alpha_1\rho_1 v_j\left(\frac{\partial \varepsilon}{\partial t}+\frac{\partial \varepsilon}{\partial x_j}\right)=\frac{\partial}{\partial x_j}\left(\alpha_1\frac{\mu_1}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right)+\alpha_1 C_1\frac{\varepsilon}{k}G_k-\alpha_1 C_2\rho_1\frac{\varepsilon^2}{k} \tag{6}$$

$$G_k=\mu_t\frac{\partial v_j}{\partial x_i}\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}\right) \tag{7}$$

where, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients; C_1 and C_2 are empirical constants; σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively. The values of the empirical constants are $C_\mu=0.009$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.3$, $C_1=1.44$, $C_2=1.92$.

$\vec{F}_k$ in Eq. (2) is the source term for momentum exchange with the bubbles, obtained as follows

$$\vec{F}_k=\frac{-\sum_i^{N_{b,cell}}(\vec{F}_{d,i}+\vec{F}_{vm,i})}{V_{cell}} \tag{8}$$

$$\vec{F}_{d,i}=C_d\frac{\rho_1|\vec{v}-\vec{v}_{d,i}|(\vec{v}-\vec{v}_{d,i})}{2}\frac{\pi d_{d,i}^2}{4} \tag{9}$$

$$\vec{F}_{vm,i}=\frac{1}{6}\pi d_{d,i}^3 C_{vm}\rho_1\frac{d}{dt}(\vec{v}-\vec{v}_{d,i}) \tag{10}$$

where, $\vec{F}_{d,i}$ and $\vec{F}_{vm,i}$ are the drag force and virtual mass force of the ith bubble, respectively; C_d is the drag coefficient; C_{vm} is the virtual mass coefficient; $\vec{v}$ is the fluid-phase velocity; $\vec{v}_{d,i}$ is the velocity of the ith bubble and $d_{d,i}$ is the diameter of the ith bubble.

1.2 Dispersed phase dynamics

The bubbles are treated as discrete phases and their motions are governed by Newton's second law, i. e.

$$m_d\frac{d\vec{v}_d}{dt}=\vec{F}_d+\vec{F}_b+\vec{F}_{vm}+\vec{F}_g \tag{11}$$

where, m_d is the mass and $\vec{v}_d$ is the velocity. On the right-hand side of Eq. (11), $\vec{F}_d$ is the drag force; $\vec{F}_b$ is the buoyancy force; $\vec{F}_{vm}$ is the virtual mass force and $\vec{F}_g$ is the gravity force.

The drag force is given by

$$\vec{F}_d=C_d\frac{\rho_f|\vec{v}-\vec{v}_d|(\vec{v}-\vec{v}_d)}{2}\frac{\pi d_d^2}{4} \tag{12}$$

The drag coefficient C_d depends on the flow regime and the fluid properties:

$$C_d=\frac{24}{Re_d} \qquad Re_d<2 \tag{13}$$

$$C_d=\frac{24}{Re_d}(1+0.15Re_d^{0.687}) \qquad 2<Re_d<500 \tag{14}$$

$$C_d\approx 0.44 \qquad Re_d>500 \tag{15}$$

where, Re_d is the bubble Reynolds number and defined as $Re_d=\frac{\rho_1 d_d\,|\vec{v}-\vec{v}_d|}{\mu_1}$.

In Eq. (11), the buoyancy force is given by

$$\vec{F}_b=-\frac{1}{6}\pi d_d^3\rho_1\cdot\vec{g} \tag{16}$$

The virtual mass force is given by

$$\vec{F}_{vm}=\frac{1}{6}\pi d_d^3 C_{vm}\rho_1\frac{d}{dt}(\vec{v}-\vec{v}_d) \tag{17}$$

The gravity force is given by

$$\vec{F}_g=\frac{1}{6}\pi d_d^3\rho_1\cdot\vec{g} \tag{18}$$