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A mathematical model considering the interaction of bubbles in continuous casting mold of steel

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ABSTRACT

To improve the slab quality, it is essential to design an innovative model for understanding the bubbles' behavior in the continuous casting mold. However, the influence of interaction of bubbles on the motion of dispersed phases has not been considered in most of mathematical simulation models. The purpose of the current work was to establish a new model to simulate the motion of gas bubbles in the mold. In this paper, the mathematical model being related to the interaction of bubbles (coalescence, bounce and breakup) was established using the user-defined functions to predict the behavior and distribution of gas bubbles. Introducing the interaction of bubbles, the size of bubbles will change in the process of collision and broken, so the results can give a good explanation to the motion of different size bubbles, and the phenomena of bubbles coalescence, bounce and breakup actually exist. The results show that the larger bubbles float up to the top surface as soon as they get out of the ports, while the smaller bubbles following the flow arrive at the narrow surface. The proposed mathematical model can described the behavior of bubbles exactly in the steel continuous casting process.

1. Introduction

In the continuous casting process of steel industry, argon gas is injected into the mold to prevent clogging, encourage mixingand promote the flotation of solid inclusions from the molten steel. The bubbles enter the mold from the submerged entry nozzle (SEN), plenty of large bubbles escaping from the top surface as soon as they getting out of ports while the smaller sizes being entrapped in the shell, causing pinhole defects. Therefore, in order to reduce the defects, it is essential to design an innovative model for understanding the bubbles' behavior.

Although great efforts were made to study argon gas bubbles motion in continuous casting mold of steel [1–5], the interaction of bubbles is still rarely considered in their researches.

Pfeiler et al. [6] have investigated the transport of the gas bubbles in the SEN and melt pool of steel continuous caster without considering the interaction of bubbles. It is said that the flow pattern of the steel in the melt pool is influenced by the buoyancy force acting at the bubbles and the uneven velocity profile in the nozzle causes a wider spreading of bubbles.

Thomas et al. [7] developed numerical models of fluid, heat and mass transport and applied to study the complex inner-related phenomena of two-phase fluid flow and superheat dissipation.

Lei et al. [8] develop a numerical simulation model, in which level set method and modified heat transfer equation is applied to simulate the dynamic evolution of gas–liquid interface and solidification process.

Lee et al. [9] applied a water model to investigate initial bubble behavior using specially-coated samples of porous MgO refractory to simulate the high-contact angle of steel-argon refractory systems with different permeability.

Zhang et al. [10] presented two approaches to predict the particle entrapment in the full length of a billet caster. The results showed the calculated inclusion distribution in the billet by the full solidification approach agreed with the industrial measurement better than the sink term approach.

Thomas et al. [11] have investigated the behavior of argon bubbles during continuous casting of steel. According to their researches, argon bubble size increases with increasing gas flow rate and decreasing steel flow rate. In the former studies, the gas bubble size is set to be constant and remain the same in the process of flowing the melt. The simplicity of bubble size variation in the calculation fails to account for the effect of bubble size on distribution.

Bessho et al. [12] compared the calculated flow pattern, gas volume fraction in a full-scale water model with experimental observations, pointed out that gas created a great change in the flow pattern.

Sanchez-Perez et al. [13] observed two-way coupled flows in water model experiment and studied the dynamic of coupled and uncoupled two-phase flows using mathematical model.

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Liu et al. [14] simulated the 3D turbulence model flow of the steel melt and the trajectories of individual gas bubbles in continuous casting mold using Eulerian–Lagrangian approach.

Kwon et al. [15] represented bubbles distribution and bubble-particle attachment in the continuous casting system by employing the water and CFD model studies.

Liu et al. [16] developed a Euler–Euler–Large Eddy simulation model to simulate the transient asymmetric two-phase flow in slab continuous casting mold.

The purpose of this study is to develop an innovative model to describe the motion of gas bubbles in the steel continuous mold and further learn the phenomena of bubbles bounce off, coalescence and breakup. Because of introducing the interaction of bubbles, the simulation results can describe the motion of different size bubbles. The equations are solved with the commercial package FLUENT, with the help of extensive user-defined subroutines developed by the author.

2. Governing equations and models

2.1. Fluid-phase hydrodynamics

Mass and momentum conservation for an incompressible fluid are given by

$$\frac{\partial}{\partial t}(\alpha_l \rho_l) + \nabla \cdot \left(\alpha_l \rho_l \vec{v}_l\right) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}\left(\alpha_l \rho_l \vec{v}_l\right) + \vec{u}_l \cdot \nabla\left(\alpha_l \rho_l \vec{v}_l\right) = -\nabla p + \nabla \cdot [\alpha_l(\mu_l + \mu_t)]\nabla \vec{v}_l + \vec{F}_k \quad (2)$$

where α_l is the liquid-phase volume fraction, ρ_l is the liquid-phase density, $\vec{v}_l$ is the fluid-phase average velocity, p is pressure, $\vec{F}_k$ is interaction momentum per unit mass transferred from the discrete phases, μ_l is the liquid viscosity.

The liquid-phase volume fraction, α_l is defined as

$$\alpha_l = 1 - \frac{\sum_i V_{d,i}}{V_{\text{cell}}} \quad (3)$$

where$V_{d,i}$ is the volume occupied by the discrete phases and V_{cell} is the volume of the grid cell.

μ_t in Eq. (2) is the turbulent viscosity, which is defined as

$$\mu_t = C_\mu \rho_l \frac{k^2}{\varepsilon} \quad (4)$$

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

$$\alpha_l \rho_l \left(\frac{\partial k}{\partial t} + \vec{u}_l \cdot \nabla k\right) = -\nabla\left(\alpha_l \frac{\mu_l}{\sigma_k} \nabla k\right) + \alpha_l G_k - \alpha_l \rho_l \varepsilon \quad (5)$$

$$\alpha_l \rho_l \left(\frac{\partial \varepsilon}{\partial t} + \vec{u}_l \cdot \nabla \varepsilon\right) = -\nabla\left(\alpha_l \frac{\mu_l}{\sigma_\varepsilon} \nabla \varepsilon\right) + \alpha_l C_1 \frac{\varepsilon}{k} G_k - \alpha_l C_2 \rho_l \frac{\varepsilon^2}{k} \quad (6)$$

$$G_k = \mu_t \left(\frac{\partial u_{i,j}}{\partial x_j} + \frac{\partial u_{i,j}}{\partial x_i}\right) \frac{\partial u_{i,j}}{\partial x_j} \quad (7)$$

The values of the constants are $C_\mu = 0.09$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, $C_1 = 1.44$, $C_2 = 1.92$.

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

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

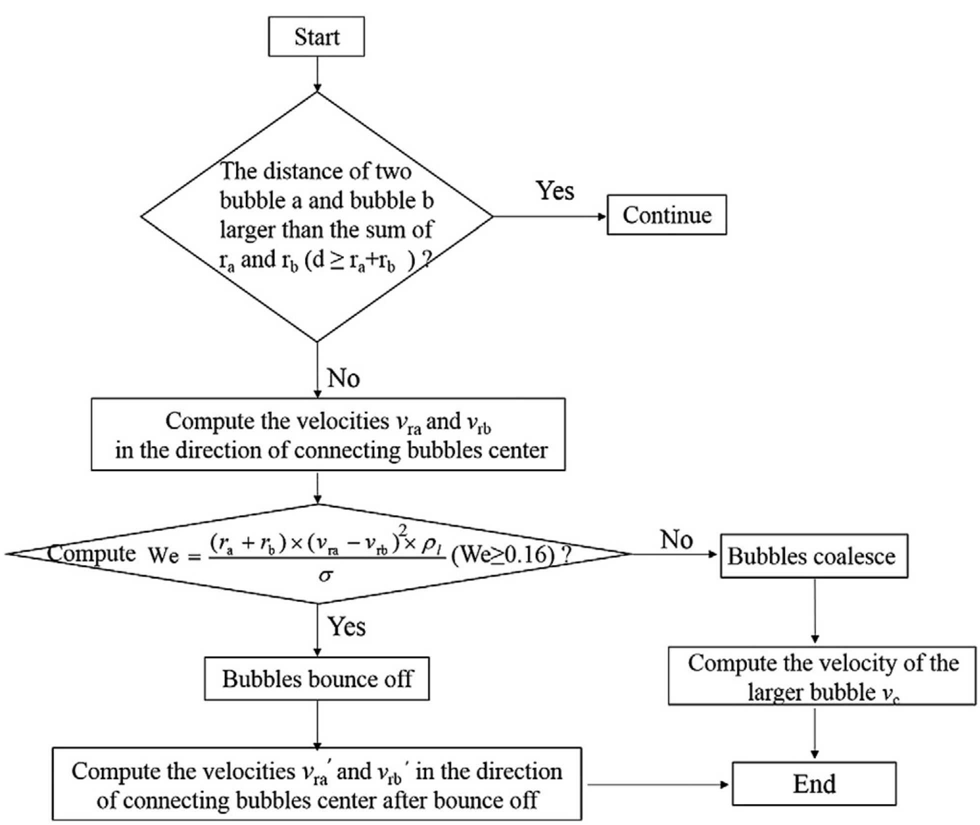

Fig. 1. Flow chart for the model of bubbles collision.