Powder Technology 319 (2017) 139–147

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Population balance modeling of polydispersed bubbly flow in continuous casting using average bubble number density approach

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ARTICLE INFO

Article history:
Received 21 December 2016
Received in revised form 12 June 2017
Accepted 15 June 2017
Available online 24 June 2017

Keywords:
Bubbly flow
Bubble size distribution
ABND model
Continuous casting mold

ABSTRACT

A new methodology of average bubble number density (ABND) model for handling the evolution of polydispersed bubbly flow in the slab continuous casting mold is presented and evaluated. The average bubble number density transport equation coupled with the Eulerian-Eulerian two-fluid model is employed to describe size distribution of bubbles. Various interfacial forces including drag force, lift force, virtual mass force, and turbulent dispersion force are incorporated in this model. SST turbulence model is used with extra source terms introduced to account for the interaction between the bubbles and the liquid. The coalescence of bubbles is formulated according to the random collision driven by turbulence and wake entrainment, and the breakage of bubbles is formulated through considering the impact of turbulent eddies. The intermediate peak and core peak behaviors of void fraction inside the submersed entry nozzle (SEN) are captured very well. Comparisons of gas void fraction, liquid flow pattern, and local bubble size distribution profiles with experimental measurements are provided, showing the applicability and accuracy of the ABND approach in modeling the polydispersed bubbly flow in the slab continuous casting mold.

1. Introduction

Two-phase bubbly flow is encountered in many applications of industrial interest and different engineering areas, e.g. food, chemical, petroleum, mining, and metallurgy engineering. Gas-injection operations in steelmaking and continuous-casting processes have remained an important focus area of research over the last several decades [1–3]. In continuous-casting process, in Fig. 1, argon gas is injected into the submerged entry nozzle (SEN) to prevent the nozzle clogging, and to remove non-metallic inclusions. The flow regimes found in continuous-casting mold show a spectrum of different bubble sizes. Large bubbles rise toward the top surface due to buoyancy and are subsequently removed from the mold, while small bubbles are carried deep into the liquid pool. However, fine argon bubbles are sometimes observed inside the continuous casting slabs, which were trapped by the solidified shell in the casting process. In the subsequent rolling process, these bubbles can lead to the formation of pinhole defects. So understanding the behavior of two-phase flow and the bubble size distribution in the mold is essential for the design of effective methods of removing fine bubbles.

Although some of water model studies have reported the bubble size distribution in the SEN [4,5] or mold [6–8] after air was injected through the SEN, few computational models [7,9] have been actively developed for studying the complex polydispersed bubbly flow in the mold. However, most previous attempts utilized an assumed mean bubble size for simulations of dispersed gas-liquid flow [1,3,10–13]; but not the local bubble size distribution. This assumed size was often adjusted based on attempts to match model predictions to some measured result. Moreover, the fluid flow pattern and gas void fraction were not always predicted well by assumption of the constant bubble size.

Application of the population balance approach (PBA) toward better describing and understanding the complex two-phase flow systems has been given an unprecedented attention [14]. The use of PBA is to account for a record of the number of entities existing within the system, which for bubbly flow are bubbles, whose presence and change may govern the flow behavior of the system. The number of entities is ever-changing depending on the "birth" and "death" processes that create and destroy entities through the state space. In bubbly flow system, the behaviors of coalescence and breakage of bubbles are the examples of such processes. The Multiple Size Group (MUSIG) model [15–19] has been developed to deal with polydispersed multiphase flows in which the dispersed phase features a large variation in its characteristic sizes. This approach provides a framework in which the population balance model can be incorporated into three-dimensional calculations. But a series of additional equations have to be solved to accommodate the range of bubble sizes and its population changes caused by coalescence and breakage of bubbles. Excessive computational calculations are needed to solve a large number of bubble classes for bubbly

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http://dx.doi.org/10.1016/j.powtec.2017.06.034
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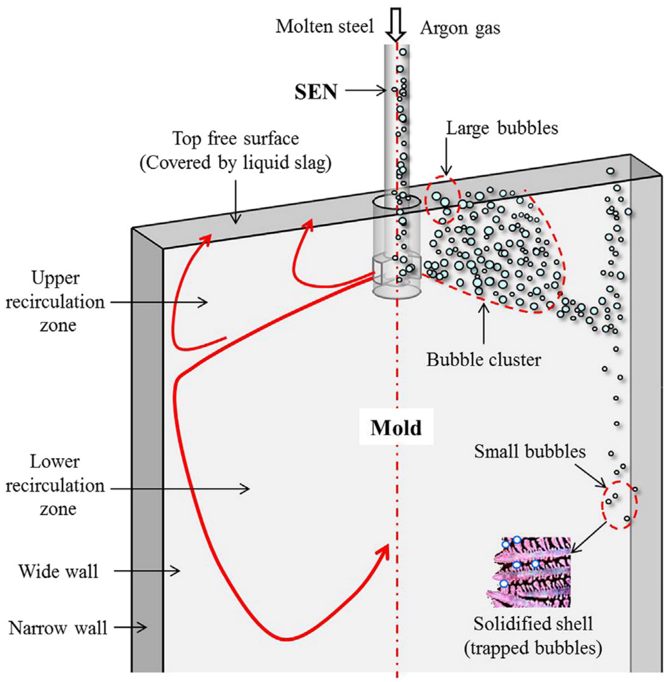

Fig. 1. Schematic of polydispersed bubbly flow in the continuous-casting mold.

flow. Recently, a transport equation for the two-phase interfacial area in bubbly flow system has been developed by some researchers [20,21]. This approach has conducted the developments of refined sink and source terms of the interfacial area concentration based on mechanisms of bubble-bubble and bubble-turbulent eddy random collisions. Similar to the formulation of the interfacial area transport equation, an average bubble number density (ABND) equation was developed by Cheung et al. [22–24] to calculate the vertical bubbly flow. The population balance of bubbles is attuned by the equation source terms describing the temporal and spatial coalescence and breakage mechanisms.

In the present work, the use of population balance model and Eulerian-Eulerian two-fluid model for gas-liquid polydispersed bubbly flow is demonstrated through the implementation of the average number density transport equation. The coalescence of bubbles is formulated according to the random collision driven by turbulence and wake entrainment, and the breakage of bubbles is formulated through considering the impact of turbulent eddies. The predicted results of gas void fraction, liquid flow pattern, and local bubble mean diameter are compared with the previous measured data.

2. Model formulation

The ABND transport equation coupled with the Eulerian-Eulerian two-fluid model is employed to describe bubble size distribution inside the continuous casting mold. Shear Stress Transport (SST) turbulence model is used to calculate the turbulence viscosity. Various interfacial forces including drag force, lift force, virtual mass force, and turbulent dispersion force are incorporated in this model. The coalescence of bubbles is formulated according to the random collision driven by turbulence and wake entrainment, and the breakage of bubbles is formulated through considering the impact of turbulent eddies. Fig. 2 shows the procedure details of solution methodology of this model.

2.1. Eulerian-Eulerian two-fluid model

The mathematical model presented in the present work is based on the Eulerian-Eulerian two-fluid model. The liquid phase is treated as continuous fluid, while the gas phase is considered as dispersed fluid.

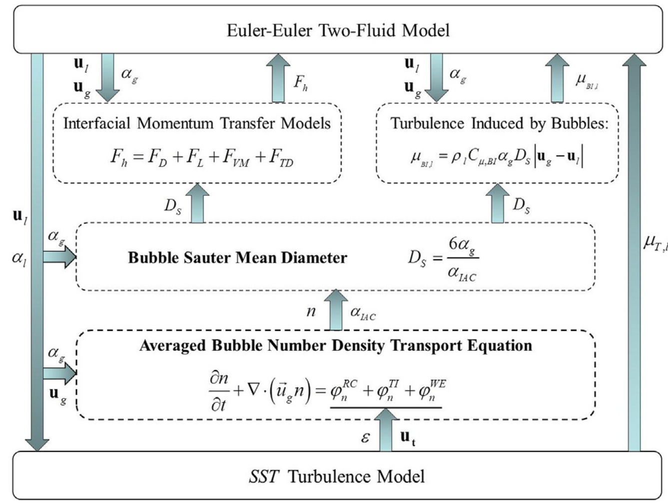

Fig. 2. Graphical presentations of the ABND model.

The continuity and momentum equations of the two phases can be written as:

$$\frac{\partial(\rho_h \alpha_h)}{\partial t} + \nabla \cdot (\alpha_h \rho_h \mathbf{u}_h) = 0 \tag{1}$$

$$\frac{\partial(\rho_h \alpha_h \mathbf{u}_h)}{\partial t} + \nabla \cdot (\alpha_h \rho_h \mathbf{u}_h \mathbf{u}_h) = -\alpha_h \nabla P + \alpha_h \rho_h \mathbf{g} - \nabla \cdot \left[\alpha_h \left(\mu_{T,h} + \mu_{BI,h}\right)\left(\mathbf{u}_h + \mathbf{u}_h^{\mathrm{T}}\right)\right] + F_h \tag{2}$$

where α, ρ, and $\mathbf{u}$ are the void fraction, density, and velocity of each phase. The subscript $h = l$ or g denotes the liquid or gas phase.

The model proposed by Sato & Sekiguchi [25] is used to take account of the turbulence induced by the movement of the bubbles. The expression is:

$$\mu_{BI,l} = \rho_l C_{\mu,BI} \alpha_g D_S |\mathbf{u}_g - \mathbf{u}_l| \tag{3}$$

With a model constant $C_{\mu,BI}$ equal to 0.6.

2.1.1. Shear Stress Transport model

The turbulence viscosity is calculated using the Shear Stress Transport (SST) model:

$$\mu_{T,l} = \frac{\rho \alpha_l k}{\max(\alpha_l \omega, SF_1)}, \quad S = \sqrt{2 S_{ij} S_{ij}} \tag{4}$$

The ensemble-averaged transport equations of the SST model are given as:

$$\frac{\partial \rho_l \alpha_l k}{\partial t} + \nabla \cdot (\alpha_l \rho_l \mathbf{u}_l k) = \nabla \cdot \left(\alpha_l \frac{\mu_{T,l}}{\sigma_{k,SST}} \nabla k\right) + \alpha_l P_k - \rho_l \beta_{SST} k \omega \tag{5}$$

$$\frac{\partial \rho_l \alpha_l \omega}{\partial t} + \nabla \cdot (\alpha_l \rho_l \mathbf{u}_l \omega) = \nabla \cdot \left(\alpha_l \frac{\mu_{T,l}}{\sigma_{\omega,SST}} \nabla \omega\right) - 2\rho_l \alpha_l (1 - F_2) \frac{1}{\sigma_{\omega,SST}\, \omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} + \alpha_l \gamma \frac{\omega}{k} P_k - \rho_l \beta_{SST} \tag{6}$$

The blending functions of F_1 and F_2 are given by:

$$F_1 = \tanh\left(\Phi_1^2\right), \quad \Phi_1 = \max\left(\frac{\sqrt{k}}{0.09 \omega D_S}, \frac{500 \mu_l}{\rho_l \omega D_S^2}\right) \tag{7}$$