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Implementation of an improved bubble breakup model for TFM-PBM simulations of gas–liquid flows in bubble columns

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HIGHLIGHTS

- An improved bubble breakup model was implemented in a gas–liquid TFM-PBM model.
- The log-normal bubble size distributions were validated against literature data.
- A generic TFM-PBM model for the simulations of bubble columns was established.
- The simulation results of $D=0.44$ m bubble column of Chen et al. (1998) were improved.

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ABSTRACT

An improved bubble coalescence and breakup model was implemented in the inhomogeneous TFM-PBM model for buoyancy-driven gas–liquid bubbly flows. The bubble coalescence was modeled by considering bubble collisions induced by turbulent fluctuations, buoyancy driven, wake entrainment, and viscous shear, and the liquid film drainage model was used for the description of the coalescence efficiency of collisions. The bubble breakup was analyzed in terms of bubble interactions with turbulent eddies which coupled the restriction of surface energy with the capillary pressure. A generic TFM-PBM model was developed and applied for the simulations of bubble columns operated in different flow regimes. The evolutions of the bubble size distributions were simulated and validated for literature data of a $D=0.14$ m cylindrical bubble column at gas superficial velocities 0.03 and 0.45 m/s, respectively. Furthermore, a well documented $D=0.44$ m bubble column was simulated, and the predicted distributions of the gas holdup and liquid velocity were compared with the experimental measurements of Chen et al. (1998). The model showed the capacity of describing the gas–liquid fluid dynamics of bubble columns operated in both bubbly and churn-turbulent flow regimes.

1. Introduction

Computational fluid dynamics (CFD) has become an important approach for analyzing the hydrodynamics of buoyancy-driven gas-liquid flows, and the Two-Fluid Model (TFM) has been frequently employed in the simulations of the bubble columns (Sanyal et al., 1999; Wang et al., 2003; Chen and Fan, 2004; Chen et al., 2005; Cheung et al., 2007; Tabib et al., 2008; and Xu et al., 2014; among others). However, a generic TFM model for the gas–liquid bubble columns operated in different flow regimes has not been well established due to the lack of reasonable closure models that describe the gas–liquid interface transport phenomena. The interface interactions are mainly induced through the drag force that liquid exerts on the bubble surface due to viscosity, the lift force caused by the shear flows around the bubbles, and the turbulent dispersion force due to the collisions of liquid eddies. Therefore, the interface closure model relies on (1) the theoretical formulation of each interaction force, (2) the model of the bubble induced turbulence of the liquid phase, (3) the descriptions of bubble sizes, which are considered to be closely connected to the models of the interaction forces and the turbulence (Xu et al., 2013).

In most early TFM simulations of dispersed gas–liquid flow, the spatial time-variation of the bubble sizes were not considered and a constant bubble size was used instead (Sanyal et al., 1999; Oey et al., 2003; Zhang et al., 2005; Tabib et al., 2008; and Rzehak and Krepper, 2013; among others). The simplification of the bubble size model limits the TFM simulations to a bubbly flow regime, because the bubble size distribution in such a condition is narrow and the interaction between bubbles is relatively weak. However, for a bubble column operated in a churn-turbulent regime, the

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Nomenclature

Roman letters

A	bubble cross-sectional area, m^2
A_{ij}	bubble impact area, m^2
$b(v_i: v_j)$	breakup frequency, s^{-1}
B_B	production of bubble by breakup, kg^{-1} m^{-3} s^{-1}
B_D	destruction of bubble by breakup, kg^{-1} m^{-3} s^{-1}
c_f	surface area increase coefficient
$c(v_i, v_j)$	coalescence rate, m^{-3} s^{-1}
$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, C_μ	constants, 1.42, 1.68, 1.3, 0.0845
C_B	production of bubble by coalescence, kg^{-1} m^{-3} s^{-1}
C_D	destruction of bubble by coalescence, kg^{-1} m^{-3} s^{-1}
C_d	drag coefficient
C_{lift}	lift coefficient
d	bubble diameter, m
d_b	Sauter mean bubble diameter, m
D	bubble column diameter, m
Eo	Eötvös number
f_{bv}	bubble breakup volume fraction
$\mathbf{F}_{gl}$, $\mathbf{F}_{lg}$	interfacial momentum exchange term, kg m^{-2} s^{-2}
g	acceleration due to gravity, 9.81 m s^{-2}
$G_{k,l}$	production of turbulent energy, kg m^{-1} s^{-3}
h_0, h_f	liquid film thickness, m
H	liquid height, m
k	turbulent kinetic energy, m^2 s^{-2}
k_{gl}	covariance of the velocities of liquid and bubble, m^2 s^{-2}
K_{gl}, K_{lg}	inter-phase momentum exchange coefficient, kg m^{-3} s^{-1}
n	number of bubbles per unit volume, m^{-3}
$\dot{n}_\lambda$	number of eddies per unit volume, m^{-4}
N	number of bubble bins
$p_c(d_i, d_j)$	coalescence efficiency
$p_b(d_i: d_{j,k})$	breakup efficiency
pdf	bubble size distribution, m^{-1}
r_{ij}	equivalent radius, m^{-1}
Re	Reynolds number
S_i	Source term of i-th bubble group, m^{-3} s^{-1}
t	time, s
$t_{contact}$, $t_{drainage}$	contact/drainage time between bubbles, s
$\mathbf{u}$	velocity vector, m s^{-1}
$\mathbf{u}_{dr}$	drift velocity vector, m s^{-1}
u_b	bubble rise velocity, m s^{-1}
u_t	turbulent velocity, m s^{-1}
u_v	liquid velocity gradient, m s^{-1}
u_w	wake entrainment velocity, m s^{-1}
$\bar{u}_\lambda$	eddies turbulent velocity, m s^{-1}
U_g	superficial gas velocity, m s^{-1}
u, v, w	velocity component, m s^{-1}
v	bubble volume, m^3
w	collision frequency, m^{-3} s^{-1}
x, y, z	spatial coordinates, m

Greek letters

α	void fraction
ε	turbulent dissipation rate, m^2 s^{-3}
γ	shear strain rate, s^{-1}
λ	eddy size, m
μ	dynamic viscosity, kg m^{-1} s^{-1}
π	≈3.1415926
ρ	density, kg m^{-3}
σ	surface tension, kg m^{-2}
σ_k, σ_ε	dispersion Prandal number, 0.75, 0.75
τ	stress, kg m^{-3}
ξ	eddy size divided by parent bubble size
$\Pi_{k,l}$	bubble-induced turbulence term, m^2 s^{-3}
$\Pi_{\varepsilon,l}$	bubble-induced turbulence term, m^2 s^{-4}
Θ	coefficient for wake entraining

Subscripts

b	bubble index
g	gas index
l	liquid index
i, j	phase index, number index

flow structure becomes very complex. The bubble coalescence and breakup results in a wide distribution of bubble sizes which is greatly different from the assumption of a constant bubble size.

The dynamic variation of the bubble sizes and their distributions in buoyancy driven gas–liquid flows have been modeled using the population balance model (PBM). With PBM, the bubbles are represented by a number of size bins, and usually, can be classified into two discrete size groups: a small size group (with bubbles smaller than 5.8 mm) and a large size group (with bubbles larger than 5.8 mm) according to the sign change of lift force (Tomiyama et al., 2002; Lucas et al., 2003; and Krepper et al., 2008). The mass and momentum transfer between the two discrete phases is accounted for by the computations of the birth and death rates due to the coalescence and breakup of bubbles. In the past decades, substantial efforts have been made to develop a bubble coalescence and breakup models (Prince and Blanch, 1990; Luo and Svendsen,1996; Martinez-Bazan et al., 1999; Lehr and Mewes, 2001; Wang et al., 2003; Zhao and Ge, 2007; Liao and Lucas, 2009, 2010; Solsvik and Jakobsen, 2015; among others), while a generic bubble coalescence and breakup model has not yet been established in combination with the TFM-PBM simulations due to the complexity of the transport phenomena resulting from bubble coalescence and breakup.

For the bubble coalescence process, several criteria have been proposed, and the film drainage model of Shinnar and Church (1960) was widely acknowledged among others. According to the film drainage model, a liquid film is firstly formed when two bubbles come close due to an overpressure; the liquid film begins to drain sequentially, and finally results in film rupture and bubble coalescence. While, if the pressure force is insufficient to overcome the viscosity force of the thin film, the bubbles bounce back without coalescence. The coalescence probability depends on the intrinsic contact time and drainage time between the bubbles. Howarth et al. (1964) suggested that the attraction force between two colliding interfaces was too weak in comparison with the turbulent force to control the coalescence probability, and concluded that whether coalescence will occur or not depended on the impact of colliding fluid particles. Note that during energetic collisions, when the approach velocity of two colliding bubbles exceeds a critical value, the dominant mechanism is an immediate coalescence without liquid film capturing and thinning. Lehr et al. (2002) introduced an empirical model using a critical approach velocity based on the experimental observation. In all mechanisms mentioned above, contact and collision is the premise of coalescence. The collision between bubbles is usually caused by their relative velocity, and the relative motion may occur due to a