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Modelling of breakage rate and bubble size distribution in bubble columns accounting for bubble shape variations

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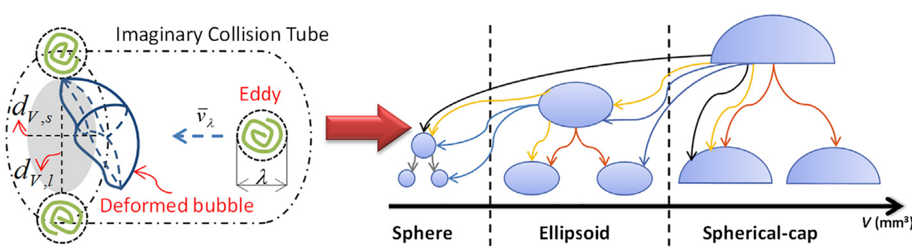
HIGHLIGHTS

- A modified model for prediction of bubble breakage rate was proposed.
- Variation of bubble shapes and different energy requirements were considered.
- Impact of bubble orientation on eddy-bubble collision process was considered.
- Effect of the bubble breakage on the change of bubble interfacial area was demonstrated.

GRAPHICAL ABSTRACT



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ABSTRACT

In the study of meso-scale structures of multi-phase flow in bubble columns, accurate modelling of the interaction between the turbulence eddies and particle/bubble groups is crucial for capturing the heat and mass transfer occurring between the bubbles and surrounding carrier fluid. This work focuses on the influence of bubble shape variations on bubble breakage due to the eddy collision with the bubbles in bubble column flows. An improved breakage model accounting for the variation of bubble shapes was proposed. The improved breakage model coupled with the widely adopted isotropic, homogeneous turbulence kinetic energy spectrums, that are currently available from the open literature, takes into account the different energy requirements in forming the daughter bubbles, i.e. the increase of in surface energy and the pressure head difference of the bubble and its surrounding turbulent eddies. The simulation results compared with experimental data have clearly demonstrated that the improved model effectively describes the various shapes of bubble breakage events, which may consequently have a strong impact on the interfacial area estimation that is crucial for calculation of the transfer rates of mass and heat transfer in the bubble columns.

1. Introduction

Bubble columns are widely used as multiphase contactors for carrying out gas-liquid reactions in chemical, petrochemical, biochemical, pharmaceutical and metallurgical industries, primarily because of the low costs involved in the construction, operation and maintenance process. In addition, bubble columns exhibit excellent heat and mass transfer characteristics, typically due to the increase of interface contact areas. In spite of their simplicity in mechanical design, fundamental properties of the two-phase hydrodynamics associated with the performance of bubble column reactors that are essential for scale-up and process optimisation, are still not fully understood because of the complex nature of multiphase flow, especially the continuous variations and deformation of bubble shapes in the process of bubble rising up through the bubble column.

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Nomenclature

a	long half axis length of an ellipse, m
c	short half axis length of an ellipse, m
C_D	effective drag coefficient for a bubble around a swarm, dimensionless
D	bubble column diameter, m
d	bubble diameter, m
d_{eq}	equivalent bubble diameter, m
d_V	length of virtual axis, m
Eo	Eötvös number, dimensionless
$\bar{e}$	mean turbulence kinetic energy, kg·m^2/s^2
e_s	increase in surface energy, kg·m^2/s^2
F_D	drag force, N/m^3
F_{Lift}	lift force, N/m^3
F_{VM}	virtual mass force, N/m^3
f_V	breakage volume fraction, dimensionless
g	gravity acceleration, m/s^2
H	distance from the bottom surface, m
k	turbulence kinetic energy, m^2/s^2
Mo	Morton number, dimensionless
n	number density per unit volume, m^{-3}
t	time, s
Rc	radius of curvature, m
Re	Reynolds number, dimensionless
S	surface area, m^2
U	superficial velocity, m/s
U_t	terminal velocity, m/s
$\bar{u}_\lambda$	mean velocity of turbulence eddies, m/s
u	velocity vector, m/s
V	volume, m^3

Greek letters

α	phase volume fraction, gas holdup
ε	turbulence dissipation rate, m^2/s^3
λ	characteristic length scale of eddy, m
μ	molecular dynamic viscosity, Pa·s
μ_{eff}	effective turbulence dynamic viscosity, Pa·s
υ	kinematic viscosity, m^2/s
ρ	fluid density, kg/m^3
σ	surface tension, N/m
τ	shear stress, Pa

Subscripts

b	bubble
g	gas
i	i-th class bubble
j/k	daughter bubble
l	liquid/long axis
s	short axis/surface

The flow regime is one of the most fundamental studies in the bubble columns, because the flow characteristics are strongly related to the prevailing flow regime. In general, the flow regime in bubble columns can be classified as homogeneous regime, transition regime, heterogeneous regime and slug flow regime (Shah et al., 1982). For fermentation process or cell culturing purposes, the bubble column usually operates at homogeneous regime. The homogeneous flow regime can be further distinguished into the mono-dispersed homogeneous regime and the poly-dispersed homogeneous flow regime, depending on the superficial velocities and the associated bubble size distributions (Besagni and Inzoli, 2016b). The mono-dispersed homogeneous regime may not exist if the large bubbles are aerated due to large diameter orifices on the sparger (Besagni and Inzoli, 2016a). The transition flow regime is characterized by large flow macro-structures with large eddies and a widened bubble size distribution (Guedon et al., 2017), in which case, the turbulent eddies induced by the "coalescence-induced" large bubbles may make increasingly significant contributions to the turbulence generated in the column.

The time-dependent behaviour of flow patterns and features inside the bubble column are significantly influenced by the rising bubbles based on the experimental observations reported in the open literature (Pourtousi et al., 2014). The bubbles induce the turbulence through the wake and interactions among the bubbles. These should be taken into account in CFD modelling of bubble column flows and the differences between different simulation methods have to be considered. Two major CFD modelling approaches currently adopted are the *Eulerian-Lagrangian* (E-L), which considers the dispersed phase as discrete entities (Delnoij et al., 1997; Sokolichin et al., 1997; Xue et al., 2017a, 2017b), and the *Eulerian-Eulerian* (E-E), which describes the dispersed phase as interpenetrating the continuous phase (Krishna et al., 1999; Lehr et al., 2002). It has been recognised that the use of both numerical approaches can lead to reliable prediction results only when the appropriate modelling for bubble induced fluid motion are introduced. The E-E approach usually relies on the closure models that describe the gas–liquid interphase transport phenomena through a certain averaging. In the meantime, the associated closure models need to consider the effect of turbulence induced by bubble motions, the interphase momentum exchange caused by interactions between the gas-liquid two phases, and the bubbles size distribution, while these are closely related to the turbulence and the interphase interaction forces. A number of CFD studies have been conducted to assess the suitability of various turbulence models for CFD bubble columns (Laborde-Boutet et al., 2009; Masood et al., 2014; Sokolichin and Eigenberger, 1999; Tabib et al., 2008; Zhang et al., 2006) and the effect of interphase interactions (Li and Zhong, 2015; Pourtousi et al., 2014; Rzehak and Krepper, 2013; Xiao et al., 2013; Yang et al., 2011). The interphase interactions can be assumed to be induced through the composition of various forces such as the drag force that liquid exerts on the bubble surface due to viscosity (Deen et al., 2000; Krishna and van Baten, 2001; Ranade and Tayalia, 2001), the lift force which is caused by the shear flow around the bubbles and the virtual mass force due to the local acceleration (Deen et al., 2001; Delnoij et al., 1997; Lucas et al., 2005; Lucas and Tomiyama, 2011; Rampure et al., 2007; Sankaranarayanan and Sundaresan, 2002; Sokolichin et al., 2004; Tabib et al., 2008; Tomiyama, 1998; Zhang et al., 2006). These previous CFD studies on bubble column flow often employed the assumption of a unified bubble diameter, which can only generate reliable predictions when the bubble size is narrowly distributed. However, CFD modelling of gas-liquid two-phase flow behaviours has to take into account the bubble size distributions and the bubble-bubble interactions because these are very influential factors in the calculation of the gas-liquid interfacial area. There are different ways to consider the effect of bubble sizes. For example, based on Krishna and van Baten (2001), Guedon et al. (2017) explicitly classifies the bubbles into two groups in the simulations. On the contray, Xiao et al. (2017) and Zhou et al. (2017) have applied the energy minimisation multi-scale EMMS based Dual-Bubble-Size DBS drag model, which implicitly considered the bubble sizes and shapes by using a lumping coefficient C_D/d_B to replace the traditional drag coefficient closure. Also, a more direct way is to derive the bubble size distributions from