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Prediction of gas–liquid flow in an annular gap bubble column using a bi-dispersed Eulerian model

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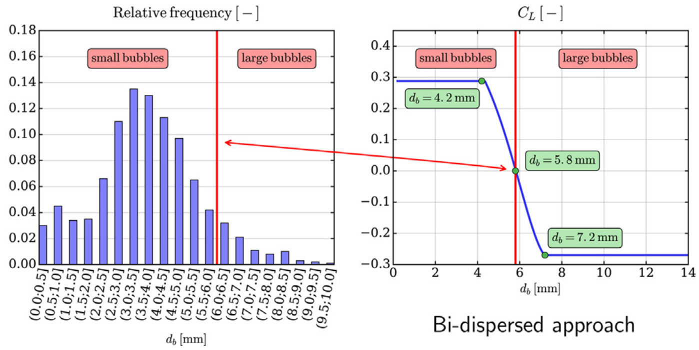
HIGHLIGHTS

- A bi-dispersed model is used to simulate an annular gap bubble column.
- Sufficiently fine mesh size is required to resolve the transient macro structures.
- Mono-dispersed models fail to predict experimental data.
- Inclusion of large bubbles destabilizing effect is relevant for simulation accuracy.
- Total gas holdup is sensitive to small bubbles volume fraction input data.

GRAPHICAL ABSTRACT



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ABSTRACT

We present and discuss numerical results from simulations of the air–water flow in an annular gap bubble column of 0.24 m internal diameter, at air superficial velocities ranging from 0.004 m/s to 0.225 m/s, covering the homogeneous and heterogeneous flow regimes. A bi-dispersed Eulerian model is implemented to account for both the stabilizing and destabilizing effects of small and large bubbles. Sensitivity studies on the mesh element size, time step size and number of outer iterations per time step are performed and most appropriate simulation parameters and mesh are used to predict the gas holdup curve. Comparison with two mono-dispersed models is provided to emphasize the necessity of a bi-dispersed approach for the accurate prediction of the homogeneous flow regime, given the poly-dispersed nature of the flow investigated. Two different approaches for the characterization of the small and large bubbles groups are also discussed. We found that the relative amount of small bubbles is an important input parameter for the present model and can be provided using available empirical correlations or experimental data. The results obtained from the simulations also demonstrated the necessity of a population balance model able to capture the bubbles coalescence and breakup phenomena for the correct prediction of the heterogeneous flow regime.

1. Introduction

Bubble column reactors are well known for their low price-performance ratio wherever heat or mass transfer between various fluids is desired, such as in the chemical, petrochemical, food production or materials processing industries (Shah et al., 1982; Dudukovic, 1999). However, their main drawback is the difficult design and scale-up, due to the complex multiphase flow that builds up as flow rates and dimensions increase (Tarmy and Coulaloglou, 1992). Moreover, in most industrial applications, internal devices are often added to control heat transfer, to foster

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Nomenclature

BSD	bubble size distribution
C_L	lift coefficient
C_μ	model constant
CFD	computational fluids dynamics
CFL	Courant Friedrichs Lewy number
d_b	equivalent bubble diameter [m]
d_c	column inner diameter [m]
$\mathbf{g}$	gravity acceleration [$\mathrm{m\,s^{-2}}$]
h	vertical position [m]
k	turbulent kinetic energy [$\mathrm{m^2\,s^{-2}}$]
l	mixing length [m]
LES	large eddy simulation
$\mathbf{M_I}$	interfacial momentum exchanges term [$\mathrm{kg\,m^{-2}\,s^{-2}}$]
n	number of bubbles in a class
p	pressure [Pa]
PC-SIMPLE	phase coupled semi-implicit method for pressure-linked equations
RANS	Reynolds-averaged Navier-Stokes
Re_b	bubble Reynolds number
RSM	Reynolds stress model
SST	shear-stress-transport
t	time [s]
$\mathbf{u}$	velocity vector [$\mathrm{m\,s^{-1}}$]
U_G	gas superficial velocity [$\mathrm{m\,s^{-1}}$]
U_{swarm}	mean gas rise velocity [$\mathrm{m\,s^{-1}}$]
U-RANS	unsteady Reynolds-averaged Navier-Stokes

Greek letters

α	volume fraction
Δt	time step size [s]
ϵ	turbulent dissipation rate [$\mathrm{m^2\,s^{-3}}$]
ϵ_G	gas holdup
μ	dynamic viscosity [$\mathrm{kg\,m^{-1}\,s^{-1}}$]
ν	kinematic viscosity [$\mathrm{m^2\,s^{-1}}$]
ω	specific dissipation rate [$\mathrm{s^{-1}}$]
ρ	density [$\mathrm{kg\,m^{-3}}$]
σ	surface tension coefficient [$\mathrm{N\,m^{-1}}$]
$\bar{\tau}$	viscous and Reynolds stresses tensor [$\mathrm{kg\,m^{-1}\,s^{-2}}$]

Subscripts

G	gas phase
k	k-th phase
large	large bubbles group
L	liquid phase
small	small bubbles group

bubble break-up or to limit liquid phase back mixing (Youssef et al., 2013). These elements can have significant effects on the multiphase flow inside the bubble column reactor and the prediction of these effects is still hardly possible without experimentation (Youssef et al., 2013).

Annular gap bubble columns are reactors with vertical internal pipes. Understanding the two-phase flow inside such devices is relevant for some important practical applications. The influx of gas, oil and water inside a wellbore casing represents a multiphase flow inside concentric or eccentric annuli (Kelessidis and Dukler, 1989; Hasan and Kabir, 1992; Das et al., 1999a,b; Lage and Time, 2002). Heat exchangers, water-cooled nuclear reactors, serpentine boilers and plunging jet reactors also constitute industrial equipments where a complex multiphase flow inside annuli occurs. The availability of experimental data on such configuration is however relatively scarce (Cumming et al., 2002; Al-Oufi et al., 2010, 2011; Besagni et al., 2014b,a, 2016; Besagni and Inzoli, 2016a,c). Predictive tools also still rely on empirical or semi-empirical models, which validity is limited to the operating conditions used in the calibration of the model coefficients.

In general, the global and local flow properties in bubble column reactors are related to the prevailing flow regime, which can be distinguished in the homogeneous and the heterogeneous flow regimes (Nedeltchev and Shaikh, 2013). The homogeneous flow regime – associated with small gas superficial velocities – is referred to as the flow regime where only "non-coalescence-induced" bubbles exist, e.g. as detected by the gas disengagement technique (Besagni and Inzoli, 2016b). The homogeneous flow regime can be further distinguished into the "pure homogeneous" (or "mono-dispersed homogeneous") flow regime and the "pseudo-homogeneous" (or "poly-dispersed homogeneous" or "gas maldistribution") flow regime, the latter being characterized by the presence of large bubbles whose lift coefficient is negative. The transition from the homogeneous to the heterogeneous flow regime is a gradual process in which a transition flow regime occurs. The transition flow regime is identified by the appearance of the "coalescence-induced" bubbles (Besagni and Inzoli, 2016b) and is characterized by large flow macro-structures with large eddies and a widened bubble size distribution due to the onset of bubble coalescence. At high gas superficial velocities, a fully heterogeneous flow regime is reached; it is associated with high coalescence and breakage rates and a wide variety of bubble sizes (Montoya et al., 2016). It is worth noting that, in a large diameter bubble column, the slug flow regime may not be detected because of the well-known Rayleigh–Taylor instabilities. The transitions between the different flow regimes depend on the operation mode, design parameters and working fluids of the bubble column. For example, using a sparger that produces mainly very small bubbles the homogeneous flow regime is stabilized (Mudde et al., 2009), whereas the mono-dispersed homogeneous flow regime may not exist if large bubbles are aerated (Besagni and Inzoli, 2016a) up to a "pure heterogeneous" flow regime from the beginning (Ruzicka et al., 2001). Since in industrial-scale reactors the gas is usually aerated through large spargers with large orifices, a pseudo-homogeneous flow regime is expected at most. Therefore, in order to contribute to the existing discussion on the simulation of industrial reactors, this paper concerns the numerical modeling of the pseudo-homogeneous flow regime in large-scale bubble columns. Indeed, despite the numerical modeling of multiphase flows for large-scale applications is a raising area of research, there is a lack of studies and there is no agreement on the modeling strategies.

Numerical modeling of bubble column reactors using computational fluid dynamics (CFD) is a promising way of predicting, without introducing much empirical factors, the complex multiphase flow developing inside bubble column reactors. The increasing interests in such a predictive tool is also due to the ongoing growth of efficient and economical computational resources during the last decade. Among the available modeling techniques, the Eulerian multi-fluid approach is the most pursed one to simulate bubble column reactors (Jakobsen et al., 2005). It treats each phase as inter-penetrating continua and relies on an ensemble averaging of the multiphase Navier–Stokes equations, which requires closures for the flow turbulence and inter-phase mass, momentum