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Computational fluid dynamics simulation of hydrodynamics in the riser of an external loop airlift reactor

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ABSTRACT

Local hydrodynamics in the riser of an external loop airlift reactor (EL-ALR) are identified and the performances of three drag models are evaluated in computational fluid dynamics simulation. The simulation results show that the Schiller–Naumann drag model underestimated the local gas holdup at lower superficial gas velocity whereas the Tomiyama drag model overestimated that at higher superficial gas velocity. By contrast, the dual-bubble-size (DBS)-local drag model gave more reasonable radial and axial distributions of gas holdup in all cases. The reason is that the DBS-local drag model gave correct values of the lumped parameter, i.e., the ratio of the drag coefficient to bubble diameter, for varying operating conditions and radial positions. This ratio is reasonably expected to decrease with increasing superficial gas velocity and be smaller in the center and larger near the wall. Only the DBS-local drag model correctly reproduced these trends. The radial profiles of the axial velocity of the liquid and gas predicted by the DBS-local model also agreed well with experimental data.

Introduction

Airlift reactors are widely used in chemical and biochemical industries. Compared with conventional bubble columns, airlift reactors can operate at higher gas throughputs and achieve better mixing and wall heat transfer (Lin et al., 2004). There are two types of airlift reactors, namely, internal-loop airlift reactors (IL-ALR) and external-loop airlift reactors (EL-ALR). An IL-ALR is divided into a riser and a downcomer by adding an internal baffle or a draft tube into a bubble column, whereas a riser is externally connected with a downcomer for an EL-ALR. The injected gas moves upwards through the liquid in the riser and disengages at the top, and the gas-free flow or the flow with lower gas holdup then enters the downcomer section and returns to the riser through a dip-leg. The degree of mixing in risers is generally higher than that in downcomers (Lu, Hwang, & Chang, 1995), and an understanding of multiphase hydrodynamics in risers is essential for the design and scale-up of airlift reactors.

Previous studies on EL-ALRs were mainly experimental investigations of global hydrodynamic parameters, such as the liquid circulation velocity (Kawasaki, Miyakoshi, & Kumazawa, 1998) and riser gas holdup (See, Roberts, & Saez, 1999). Although these parameters are of primary importance for the scale-up of reactors, the local hydrodynamics are needed to evaluate the mixing and mass transfer, which are reflected by the distributions of the gas holdup and liquid velocity in EL-ALRs (Luo, Yuan, Xie, Sun, & Guo, 2013). Empirical and semi-theoretical models based on the mechanical energy balance (Young, Carbonell, & Ollis, 1991) and momentum balance (Glennon, Almasry, Macloughlin, & Malone, 1993) have been developed. However, these models are usually not able to predict the radial evolution of hydrodynamic parameters, and most of them were only proposed for bubble columns and are inadequate for the EL-ALR operated at high superficial liquid velocity (Vial, Poncin, Wild, & Midoux, 2002).

Computational fluid dynamics (CFD) has been used to predict the local (Yang, Wu, Chen, Wang, & Li, 2011) and global hydrodynamics (Xiao, Yang, & Li, 2013) in gas–liquid systems. Most CFD simulations in the literature well capture the time-averaged liquid velocity but fail in the prediction of the radial gas holdup profile (Lucas, Krepper, & Prasser, 2001). CFD simulation has been reported to be sensitive to the closure laws of interfacial interaction forces between the gas and liquid phases such as drag, lift, added mass force, and turbulent dispersion force. Among them, the drag force is considered to be the most critical (Chen, Sanyal, & Dudukovica, 2004). Wang, Wang, and Jin (2004a), Wang, Wang, Zhao, Ren, and

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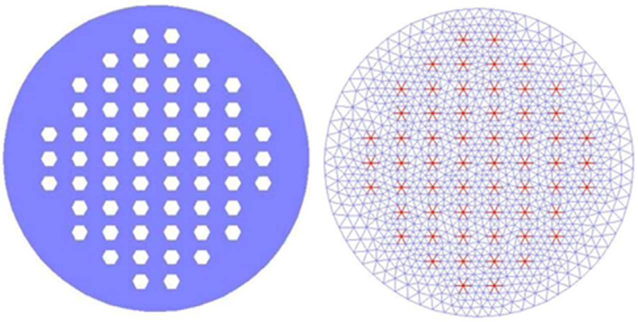

Fig. 1. Gas sparger and the mesh generated for the cross-section.

Table 1
Simulated cases.

Case number	Case 1	Case 2	Case 3
Superficial gas velocity (m/s)	0.023	0.066	0.117
Superficial liquid velocity (m/s)	0.208	0.287	0.32

Jin (2004b) investigated the effect of interphase interaction forces on the accuracy of local hydrodynamic behavior in an EL-ALR, and pointed out that the drag model for large bubbles needs further modification and the lift force should be taken in account to improve the accuracy of the CFD simulation. However, the lift coefficient was an adjustable parameter in their work. Silva, d'Avila, and Mori (2011) employed a population balance model in the CFD framework, and found that the predicted gas holdup was in good agreement with experimental data in the fully developed region near the wall for the case of uniform inlet velocity, but the gas holdup was underestimated for the case using a gas distributor. Roy and Joshi (2008) concluded from CFD simulation that the mixing of EL-ALRs was better than that of bubble columns for the same power input and the same volume of reactor.

In this paper, we evaluate a new drag model termed the DBS-local model for the CFD simulation of EL-ALRs. The new drag model was developed in our previous work employing the dual-bubble-size (DBS) model; i.e., taking the energy-minimization multi-scale (EMMS) approach for gas–liquid flow (Chen, Yang, Ge, & Li, 2009; Jiang, 2015; Yang, Chen, Ge, & Li, 2010; Yang, Chen, Zhao, Ge, & Li, 2007). The model has already been integrated into the CFD simulation of bubble columns (Xiao et al., 2013; Yang et al., 2011) and the IL-ALR (Xu, Jiang, Yang, & Zhu, 2015). We found that the simulated overall and local gas holdup and the axial liquid velocity agreed well with the experimental data.

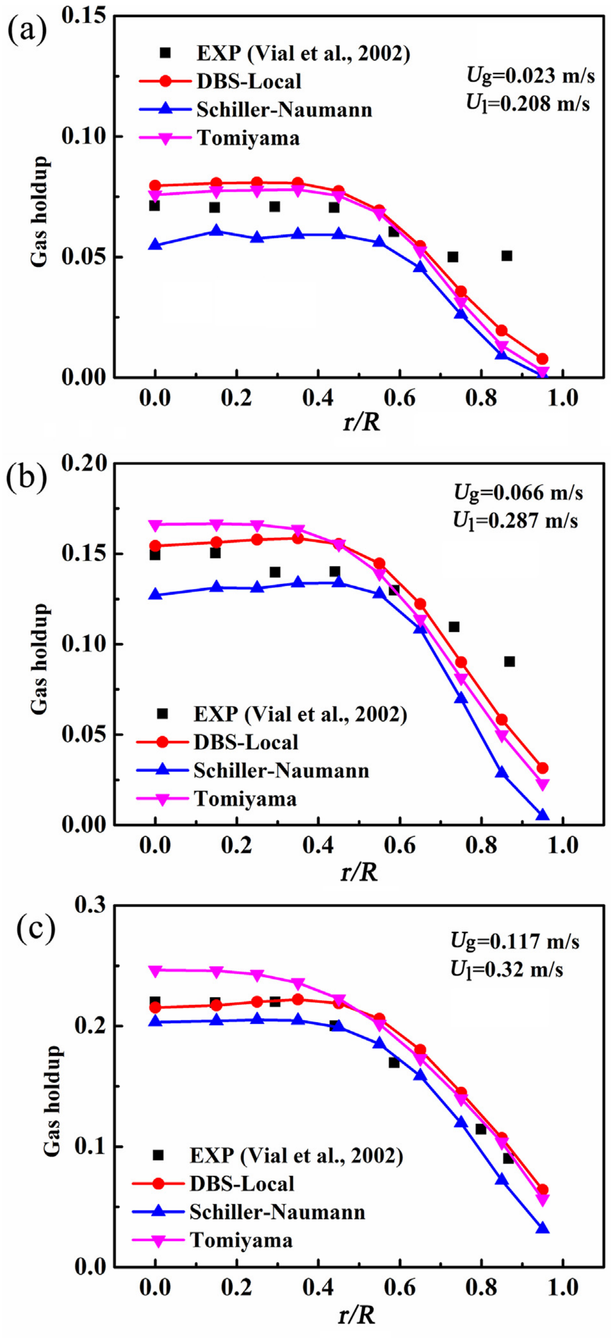

Fig. 2. Radial distribution of the gas holdup.

CFD modeling

Governing equations

The numerical simulation was carried out using a two-fluid model in which the continuous liquid phase is treated as the primary phase and the dispersed gas as the secondary phase. The conservation equations for the mass and momentum are formulated as

$$\frac{\partial(\alpha_k\rho_k)}{\partial t}+\nabla\cdot(\alpha_k\rho_k\mathbf{u}_k)=0,\quad (k=\text{liquid}\ \ \text{or}\ \ \text{gas}) \tag{1}$$

$$\frac{\partial(\alpha_k\rho_k\mathbf{u}_k)}{\partial t}+\nabla\cdot(\alpha_k\rho_k\mathbf{u}_k\mathbf{u}_k)=-\alpha_k\nabla P+\mu_{k,\mathrm{eff}}\alpha_k\left[\nabla\mathbf{u}_k+(\nabla\mathbf{u}_k)^T\right]+\alpha_k\rho_k\mathbf{g}+\mathbf{F}_k^D, \tag{2}$$

where α_k denotes the volume fraction and $\mathbf{u}_k$ denotes the velocity of the kth phase. $\mathbf{F}_k^D$ represents the drag force. The turbulence is modeled by the RNG k–ε model for the mixture phase as recommended by Laborde-Boutet, Larachi, Dromard, Delsart, and Schweich (2009).

Drag models

The interfacial forces include the drag, lift, added mass force, and turbulent dispersion force. It is generally believed that the drag is the predominant force in modeling the gas–liquid flows of bubble columns (Chen, 2004) and the magnitude of the drag force was found to be more than 100 times that of the other forces (Laborde-Boutet et al., 2009). Although there have been many studies on the lift force (Elena Díaz, Montes, & Galán, 2009; Kulkami, 2008; Lucas & Tomiyama, 2011; Van Nierop et al., 2007), an appropriate model for the lift coefficient is not available and the role of lift or turbulent

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