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CFD simulation and experimental measurement of gas holdup and liquid interstitial velocity in internal loop airlift reactor

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This paper documents experiments and CFD simulations of the hydrodynamics of our two-phase (water, air) laboratory internal loop airlift reactor (40 l). The experiments and simulations were aimed at obtaining global flow characteristics (gas holdup and liquid interstitial velocity in the riser and in the downcomer) in our particular airlift configurations. The experiments and simulations were done for three different riser tubes with variable length and diameter. Gas (air) superficial velocities in riser were in range from 1 to 7.5 cm/s. Up to three circulation regimes were experimentally observed (no bubbles in downcomer, bubbles in downcomer but not circulating, and finally the circulating regime). The primary goal was to test our CFD simulation setup using only standard closures for interphase forces and turbulence, and assuming constant bubble size is able to capture global characteristics of the flow for our experimental airlift configurations for the three circulation regimes, and if the simulation setup could be later used for obtaining the global characteristic for modified geometries of our original airlift design or for different fluids. The CFD simulations were done in commercial code Fluent 6.3 using algebraic slip mixture multiphase model. The secondary goal was to test the sensitivity of the simulation results to different closures for the drag coefficient and the resulting bubble slip velocity and also for the turbulence. In addition to the simulations done in Fluent, simulation results using different code (CFX 12.1) and different model (full Euler–Euler) are also presented in this paper. The experimental measurements of liquid interstitial velocity in the riser and in the downcomer were done by evaluating the response to the injection of a sulphuric acid solution measured with pH probes. The gas holdup in the riser and downcomer was measured with the U-tube manometer. The results showed that the simulation setup works quite well when there are no bubbles present in the downcomer, and that the sensitivity to the drag closure is rather low in this case. The agreement was getting worse with the increase of gas holdup in the downcomer. The use of different multiphase model in the different code (CFX) gave almost the same results as the Fluent simulations.

1. Introduction

Airlift reactors are pneumatically agitated vessels, and are one among different types of multiphase reactors. They possess good mixing, mass and heat transfer characteristics and they are used in a wide range of industrial applications such as waste water treatment, chemical (e.g. hydrogenations and oxidations) and biochemical processes, and others. The other advantages are simplicity of construction, absence of moving parts, and low power consumption. Their other advantageous features in case of biochemical processes are ease of long term sterile operation, and a hydrodynamic environment suitable for fragile biocatalysts, which are susceptible to physical damage by fluid turbulence or mechanical agitation (Chisti, 1998).

The airlift reactor consists of two interconnected main parts, the riser and the downcomer. Gas is injected into the riser and the resulting difference between average densities in the riser and in the downcomer provides a driving force for liquid circulation. Also solid particles can be present (catalyst, biomass, etc.). There are two main groups of airlift reactors namely, the internal loop airlift reactor and the external loop airlift reactor. The internal loop airlift reactor is a bubble column divided into the two parts by a draft tube inserted into the column. The external loop airlift consists of two separate columns connected with pipes. Other important part, which may or may not be present, is the gas separator. Its purpose is to prevent bubbles from being entrained into the downcomer, which would decrease the driving force for liquid circulation.

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The knowledge of the airlift hydrodynamics is needed for the design of the airlift reactor. Basic global quantities such as gas holdup and liquid velocities in the riser and in the downcomer, total interfacial area, and others are needed to be known. The hydrodynamic and other relevant parameters such as the airlift geometry are interrelated and their relationship can be quite complex and they directly or indirectly influence each other in sometimes not so obvious ways (Chisti, 1998), e.g. the driving force for the liquid circulation is the difference in gas holdups between the riser and the downcomer. This driving force is balanced by friction losses in the riser and the downcomer and in the bottom and top parts of the reactor (influence of bottom and top clearances in the case of internal loop airlifts or losses in connecting pipes in the case of external airlifts and of the airlift geometry in general). However, the resulting liquid circulation in turn affects the riser and downcomer gas holdup and thus the driving force. The gas holdup depends also on bubble slip velocity, which depends on the bubble size. Bubble size is influenced by the gas distributor, coalesce properties of the involved fluids and by turbulence. Turbulence is influenced by liquid circulation, etc.

The relevant hydrodynamic parameters need to be either obtained experimentally or predicted by models of various types. A lot of experimental data have been published in the past on global quantities (holdup, liquid velocities) in airlift reactors and correlations based on these data. A large number of correlations for these parameters are compiled in Chisti (1989), other can be, e.g., in Chisti (1998).

Many of the correlations presented in the literature are restricted in their validity to the same reactor size, type and gas–liquid system used in their development (Young et al., 1991). As a rule, these correlations are system specific, being of little use in design or scaleup, where the usual requirement is for estimation of expected performance in larger or geometrically different reactors or fluids (Chisti, 1998). Some authors employed models based on mechanical energy balance in the airlift reactor, e.g. Verlaan et al. (1986), Chisti (1989), and Heijnen et al. (1997). However, information about friction losses (friction coefficients) must be provided as an input parameter for these models. More recent experimental measurements of airlift global hydrodynamic characteristics (riser and downcomer holdup and velocities) can be found, e.g., in van Baten et al. (2003), Blazej et al. (2004), Merchuk et al. (1998) and van Benthum et al. (1999) (internal loop airlifts) or in Freitas et al. (2000) and Vial et al. (2002) (external loop airlifts). There were also papers published on local gas holdup and/or local liquid velocity measurements. Luo and Al-Dahhan (2008, 2010) measured liquid velocity profiles, turbulent quantities using the CARPT technique and gas holdups profiles using computed tomography in an internal loop airlift reactor. They observed significant effect of top and bottom clearances on the flow. They also observed that the bubbles are prone to concentrate in the riser center in radial direction and the change from bubbly to churn-turbulent flow at superficial gas velocity of 2 cm/s. Local gas holdups and/or liquid velocities in external loop airlift reactors were measured, e.g. by Young et al. (1991), Vial et al. (2002), Wang et al. (2004), Cao et al. (2007), Utiger et al. (1999), or Lin et al. (2004).

Apart from experiments, empirical correlations or theoretical models such as the models based on mechanical energy balance, CFD simulations can be an another tool, which can be used to study airlift hydrodynamics. There are two main groups of multiphase flow models usable for simulations on bubble column/airlift scale. In Euler–Euler models all phases are treated as interpenetrating continua, while in Euler–Lagrange models the motion of individual particles is tracked through the continuous fluid. The Euler–Lagrange models, which track the motion of every single particle (approximated as a mass point with closure equation for the interphase forces), can be used for smaller scale problems with low gas holdup. Only Euler–Euler models (mixture model and "full" Euler–Euler model) were used in the presented work, thus only Euler–Euler models are considered in the following text. The main advantage of CFD simulations if compared to experiments is that no experimental apparatus has to be built; the equipment dimensions and working fluids can be easily changed in simulations; etc. However, the quality of the CFD simulation predictions, of course, greatly depends on how well or how badly the employed CFD models, submodels and closure equations describe flow phenomena occurring in the airlift reactor. Since the gas–liquid flows are very complex with flow phenomena occurring on a wide range of space and time scales, modeling of gas–liquid flows is still an open subject and far from being complete. It is still necessary to validate simulation results against experiments. Euler–Euler models need closures for all relevant interphase force (drag, lift, added mass, etc.), for the turbulence (due to single phase flow and due to bubbles) and models for bubble coalescence and break-up, because the bubble size figures in most of the closure equations. Sokolichin et al. (2004) discussed the relevance of individual interphase forces for the simulation and also turbulence modeling issues in their review paper. They observed a weak dependency of simulation results (in partially aerated rectangular bubble column) on the employed value of the bubble slip velocity. They explained this weak dependence by the fact that the bubble total velocity was the sum of the bubble slip velocity and the liquid velocity, which can be relatively high, so the change in the bubble slip velocity had lower impact on the calculated gas holdup. It could be expected from the same reason that the similar behavior (weak dependence of gas holdup on the bubble slip velocity) could be found in airlift simulations, if bubbles are present only in the riser and the downcomer holdup is zero, and may be the dependence could be even weaker due to the more ordered flow in the airlift if compared to the bubble column. However, if there is nonzero gas holdup in the downcomer, then the effect of the bubble slip velocity could be much stronger due to countercurrent flow of both phases in the downcomer. It is then not surprising that some authors did simulations of airlifts and obtained good agreement with experiments even when inappropriate closure for drag force was used (e.g. Schiller–Naumann correlation for rigid sphere drag used for 5 mm equivalent diameter air bubble in water) in cases with zero downcomer gas holdup.

There are a number of papers dedicated to the Euler–Euler CFD simulations of airlift reactors.

External loop airlift simulation comparisons of radial profiles of gas holdup and liquid velocity can be found, e.g. in Vial et al. (2002), Roy et al. (2006), or Cao et al. (2007). The comparison of average gas holdup and liquid velocities with experiments for internal loop airlifts and for zero downcomer gas holdup can be found, e.g. in Mudde and van den Akker (2001) (rectangular airlift), van Baten et al. (2003), or in Huang et al. (2008), who also reported weak dependence of the simulation results on the bubble velocity prescribed on the top boundary condition. Simulations for cases with nonzero downcomer holdup were done, e.g. by Oey et al. (2001), Huang et al. (2010), Talvy et al. (2007) or Jia et al. (2007). Talvy et al. (2007) compared vertical and horizontal profiles of gas holdup in riser and downcomer, and horizontal liquid velocity profiles in downcomer with experiments in a rectangular airlift. Jia et al. (2007) compared simulated and experimental horizontal profiles of gas holdup and liquid in a rectangular airlift and found a good agreement.

2. Goals

The *primary goal* was to test the ability of our CFD simulation setup to capture global characteristics of the flow in our experimental 50 l internal loop airlift with enlarged degassing zone (riser and downcomer mean liquid interstitial velocities and gas