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CFD Simulation of Scale Influence on the Hydrodynamics of an Internal Loop Airlift Reactor

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ABSTRACT

In this work, the overall gas hold-up in the riser and down-comer of three internal airlift reactors with a working volume of 10.5, 32 and 200 l at the range of temperatures 18˚C - 21˚C, under atmospheric pressure was simulated using Computational Fluid Dynamics (CFD). The range of superficial gas velocity was 0.5 - 3 cm/s. The three reactors geometrically were similar to each other. CFD simulation and experimental data showed that the gas hold-up in the riser and down-comer increased by increasing the reactor scale. It was concluded that the simulated data were in good agreement with the experimental ones obtained from the literature.

Keywords: Internal Loop Airlift Reactor; Gas Hold-Up; CFD

1. Introduction

Liquid circulation velocity and gas hold-up are the major hydrodynamic parameters and their knowledge is essential for a reliable description of an airlift reactor with internal loop [1]. Internal loop airlift reactors are widely used in biochemical industrial processes because of their simple construction, good heat transfer, low shear rate, low power input and easy scale up [2]. An internal loop airlift reactor is divided into two zones: riser and downcomer zone. There is a vertical baffle between of them and a sparger in bottom of the riser zone. The difference of density between liquid and gas makes the liquid circulation [3]. Recently, many authors have attempted to employ the airlift reactors for organic compounds production [4,5] and wastewater treatment [6]. Internal airlift reactor is the best type of two phase contactors at various aeration processes such as wastewater treatment, animal cell culture and aerobic fermentation (production of enzymes, antibiotics, proteins, biomass and other biotechnology products) [7,8]. Trager *et al*. used a simple laboratory airlift reactor (fermentor) to produce gluconic acid by Aspergillusniger [9]. Park *et al*. used an airlift bioreactor in which the top and bottom of the draft tubes were covered with stainless steel sieves for the production of itaconic acid by Aspergillusterreus [10]. Sajjadi *et al*. investigated the effects of ethanol addition to pure water and its concentration enhancement on the bubbles diameter, gas holdup and flow regime in a split-cylinder airlift bioreactor [11]. They found that an increase in alcohol concentration reduces the bubble diameter.

Joshi *et al*. applied a model for the external loop airlifts [12]. The reactor height of was used as a key-parameter in a model by the other researchers [13,14]. The influence of gas-liquid separator at top of the reactor was considered in an airlift reactor design [15-18] although the influence of the bottom section on the performance of an airlift reactor was already studied [19-22]. Kawase and Moo-Young investigated a model for the liquid behavior prediction in an airlift reactor [23]. Heijnen *et al*. discovered a hydrodynamic model which predicted the circulation velocity in an internal loop airlift reactor [24]. This model can be applied for a two- or three-phase flow in a Newtonian liquid with low viscosity. The most important factors in the design and scale-up of airlift reactors are the influence of the geometry of the system on the flow of different phases present. The distance from the reactor base to the draft tube/baffle (bottom clearance) and the distance from top of the draft tube/baffle to the top of the liquid level (top clearance) have received only minimal attention [25-30]. Molina *et al*. worked with a split cylinder airlift bioreactor, used various sucrose solutions giving viscosities in the range 1.54 - 19.5 mPa·s and reported a decline in the overall gas holdup with increase in viscosity of the sucrose solutions, especially at the highest air rates corresponding to the heterogeneous flow regime. The initial rise in the gas holdup with increase in viscosity inside internal loop airlift bioreactors has been related to the lower bubble rise velocity which leads to higher bubble residence time in the riser and a greater entrapment of the bubbles into the down-comer.

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At the higher viscosity values the higher rate of bubble coalescence has been reported as responsible for the observed decrease in gas holdup with increase in liquid viscosity [31]. For a 78 (wt%) glycerol solution, corresponding to a Newtonian viscosity of 49.57 mPa·s. Wachi *et al*. have reported a lower gas holdup compared to water in a draft tube bubble column but only at high riser gas velocities. Further increase in viscosity, that results in the formation of the slug flow regime, seems to result in an increase in gas holdup with increasing viscosity [32]. For example, Philip *et al*. worked with viscosities in the range 115 - 285 mPa·s inside an internal loop airlift reactor, have reported a rise in the total gas holdup with increase in viscosity. Philip *et al*. attributed this observation to the lower liquid circulation rates and lower single slug rising velocities obtained in the slug flow regime observed at these viscosities [33]. Koide *et al*. studied the effect of viscosity, in the range 0.9 - 13 mPa·s, on the performance of a draft-tube airlift bioreactor, in which the annulus was aerated, and presented their results in from of dimensionless correlations [34].

In this research, the effects of scale up on the hydrodynamics of an internal loop airlift reactor in both riser and down-comer were theoretically studied. For this purpose, the Computational Fluid Dynamics (CFD) software was applied to obtain gas hold-up in the riser and down-comer. These data were compared with the experimental data obtained from the literature [1].

2. Modeling

In this work, the Euler-Euler method based on the two-fluid system was applied. Furthermore, each fluid was assumed to be as a continuous phase in each part of the control volume. The phases were dispersed in the interior spaces and diffused within it [35].

2.1. Continuity Equation

The continuity equation for each phase is as:

$$\frac{\partial(\rho_k \alpha_k)}{\partial \mathrm{t}} + \nabla(\alpha_k \rho_k u_k) = S_k \tag{1}$$

where, α, ρ and u are gas hold-up, density and velocity in each phase, respectively. k and S_k are phase type (for liquid phase: $k = 1$ and for gas phase: $k = g$) and source term of phase k in the domain, respectively.

2.2. Momentum Transfer Equation

The momentum transfer equation is derived as following:

$$\frac{\partial(\alpha_k \rho_k u_k)}{\partial t} + \nabla(\alpha_k \rho_k u_k u_k) = -\alpha_k \nabla P + \alpha_k \rho_k g + \nabla \alpha_k \tau_k \pm F_{\mathrm{int}} \tag{2}$$

The right hand of the Equation (2) illustrates pressure difference (the first term), gravity force (the second term), stress (third term) and the ensemble averaged momentum exchange between the intra-phase force (fourth term) [36, 37].

The equations of state for the liquid and gas phases are derived as following:

$$\rho_1 = \mathrm{const} \tag{3}$$

$$\rho_g = \frac{P}{RT_0} \tag{4}$$

$$\alpha_l + \alpha_g = 1 \tag{5}$$

where, α_l and α_g are liquid and gas volume fractions, respectively.

F_{int} takes into account the interaction forces (such as drag force, lift force and added mass force) between phases [38]. The drag and lift forces and turbulent stresses model employed in the current research are described in detail in the literature [39].

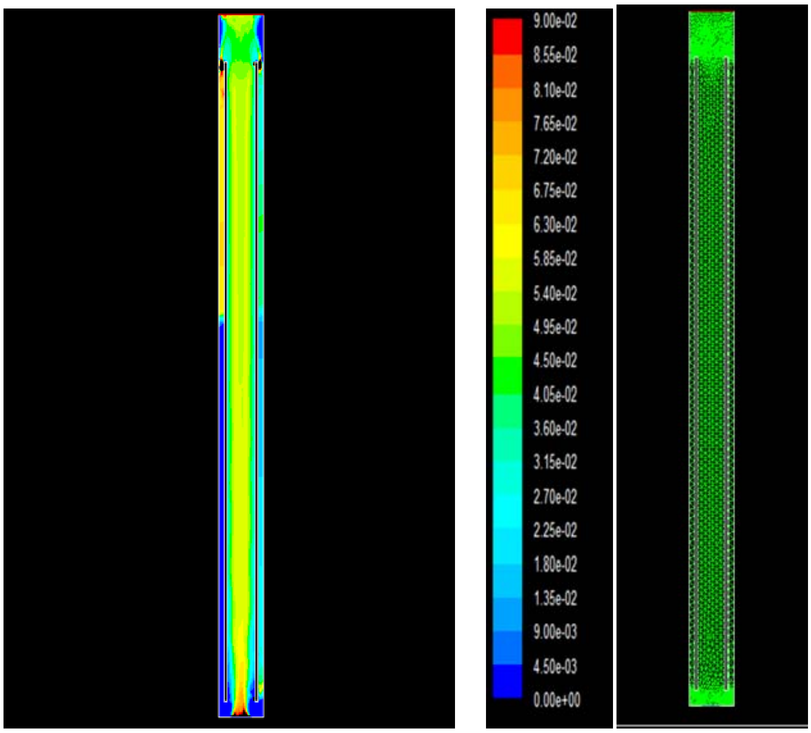
3. Simulation

The reference data were obtained from a published experimental work [1].Three internal loop airlift reactors with different volumes were simulated by fluent (version 6.3) as computational fluid dynamic (CFD). The specifications of three internal loop airlift reactors are shown in **Table 1** [1].

In the simulation, the gas and liquid phases were air and water, respectively. The governing equations and constitutive relations have been discertized based on the finite element method [40]. At t = 0, all of the reactor volume is full of water and the volume fraction of air is equal to zero. The simulation will get steady state after 45 to 60 s. In the current simulation, the Reynolds Stress as Turbulence model and 2D Eulerian model as multiphase model were applied to study the hydrodynamic properties of gas and liquid phases in an internal airlift reactor under unsteady conditions. According to the simulation, the number of meshes was 7868. Boundary conditions for principal equations were assumed without any slip on the walls. For inlet and outlet, the boundary condition was the velocity inlet and the pressure outlet, respectively. The liquid phase was as primary phase and the gas phase was as dispersed phase. **Figure 1(a)** shows the distribution of gas

Table 1. Geometrical details of the reactors [1].

Reactor volume (l)	Dc (m)	H_L (m)	H_{DT} (m)	D_R (m)	H_B (m)
10.5	0.108	1.26	1.145	0.070	0.030
32	0.157	1.815	1.710	0.106	0.046
200	0.294	2.936	2.700	0.200	0.061



(a) (b)

Figure 1. (a) Gas hold-up distribution in the reactor with volume of 10.5 l for water at superficial gas velocity of (U_g) 2 cm/s; (b) Meshes generation in the reactor with volume of 10.5 l.

hold-up in the reactor by volume of 10.5 for water at superficial gas velocity of (U_g) 2 cm/s. **Figure 1(b)** demonstrates the meshes generation.

4. Results and Discussion

Three airlift reactors (10.5, 32 and 200 l) with similar geometry were simulated at 20˚C and at atmospheric pressure. The hold-up in the riser and down-comer was studied, separately. Gas hold-up is an important parameter, because it determines the amount of the gas phase retained in the system at any time.

Figures 2 and **3** show the gas hold-up in the riser and down-comer versus superficial gas velocity for each reactor scale, experimentally [1] and theoretically (CFD). As shown in both figures, the gas hold-up increased by increasing the superficial gas velocity in the riser and down-comer for the three reactors and from superficial gas velocity equal to 0.015 m/s to up of this, the holdup in riser and down-comer increases with lower rate. Furthermore, the gas hold-up in the down-comer properly followed the gas hold-up in the riser in high superficial gas velocities. According to **Figure 3**, the gas hold-up in the down-comer was around zero in low superficial gas velocities. Moreover, a very good agreement between the experimental and theoretical data (CFD) can be observed.

Figure 4 shows gas hold-up in the riser versus gas hold-up in the down-comer based on the experiment and CFD for water. As shown in this figure, there is a linear trend between gas hold-up in the riser (ε_r) and gas hold-up in the down-comer (ε_d) for both experiment and CFD however some deviations were observed for few points. Its reason may be due to the experimental errors or our assumptions during the simulation. Furthermore, this figure clearly shows that gas hold-up increased in down-comer by increasing gas hold-up in the riser. An acceptable agreement was observed between the experimental data and CFD results.

Figure 5 shows overall circulation velocity (V_L) versus superficial gas velocity (U_g) for the experimental data and CFD results. As shown in this figure, overall circulation velocity approximately increased by increasing the superficial gas velocity although some deviations were observed for the reactor of 10.5 l (in the range of 0.0075 - 0.015 m/s for U_g) and for the reactor of 32 l (in the range of 0.005 - 0.015 m/s for U_g). In the most of points, the simulated results followed the experimental trends.

Figure 6 shows the volume fraction of gas with aeration of 0.03 m/s in the reactor of 10.5 l (as an example) in various times (up to steady state condition). As shown in this figure, bubbles rise in the airlift reactor and then bubbles accumulation and gas hold-up occur in it.

5. Conclusion

In this research, two-phase air-water flow in internal loop

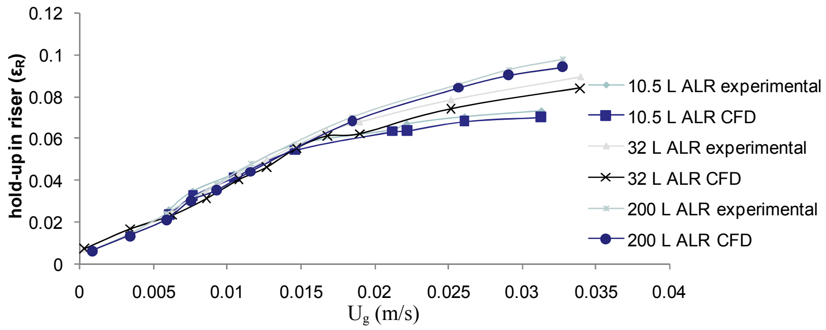


Figure 2. Comparison between the experimental data and CFD results for gas hold-up in the riser versus superficial air velocity (U_g).

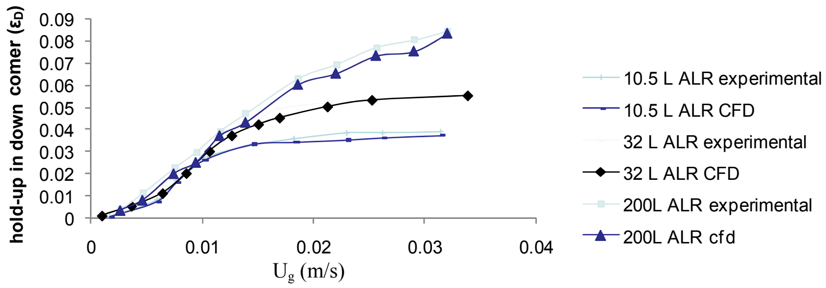


Figure 3. Comparison between the experimental data and CFD results for gas hold-up in the down-comer versus superficial air velocity (U_g).

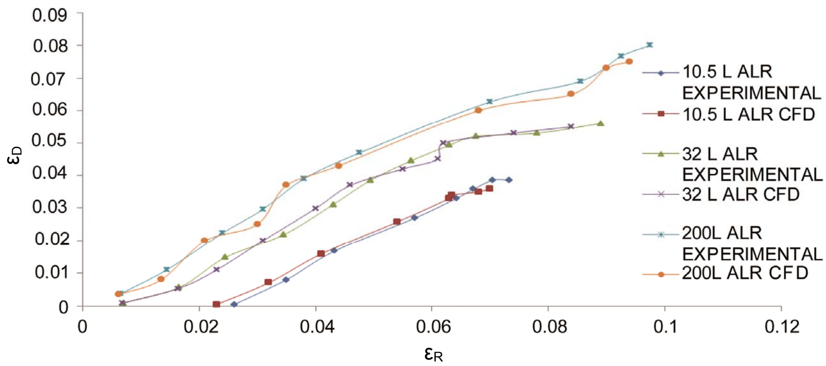


Figure 4. Gas hold-up in the riser versus gas hold-up in the down-comer based on the experiment and CFD.

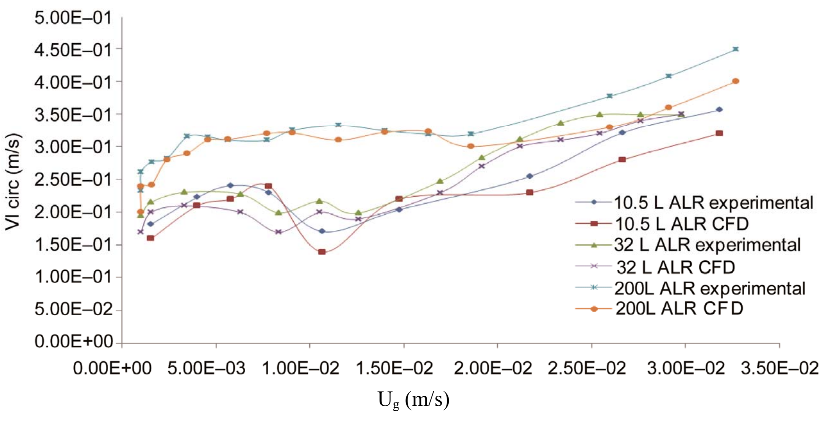


Figure 5. Comparison between experimental data and CFD results for overall circulation velocity versus superficial gas velocity (m/s) in the riser.

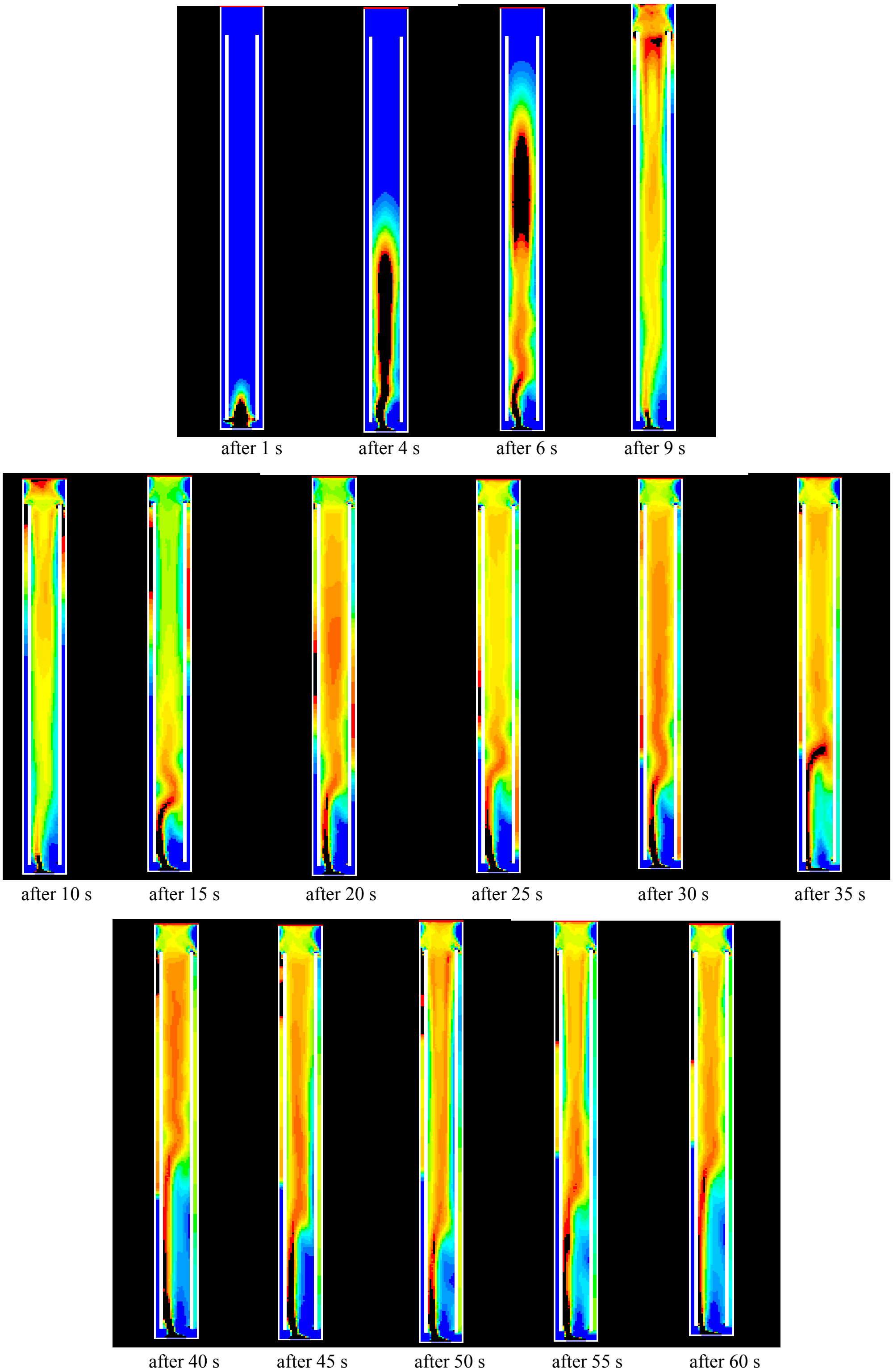


Figure 6. Volume fraction of air with aeration of 0.03 m/s in the reactor of 10.5 l.

airlift reactors [three various scales (10.5, 32 and 200 l)] was simulated using CFD. The results showed that the gas hold-up in the riser and down-comer for the three reactors increased by increasing the superficial gas velocity. Furthermore, an increase in superficial air velocity in the riser increased the overall circulation velocity for the three same reactors. These outputs were also supported by the published experimental work. Therefore, the simulated results were in very good agreement with the experimental data. It was concluded that the CFD is a very useful and accurate tool for scaling-up, as well.

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