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Hydrodynamics and mass transfer investigation in three-phase airlift reactors for sewage and water treatment process by using activated carbon and sludge

Mohammad Ali Salehi*, Nasrin Hakimghiasi

Department of Chemical Engineering, University of Guilan, Rasht, Iran

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ABSTRACT

A bioreactor refers to any manufactured or engineered device that supports a biologically active environment. These kinds of reactors are designed to treat wastewater treatment. Volumetric mass transfer coefficient and the effect of superficial gas velocity, as the most important operational factor on hydrodynamics, in three-phase airlift reactors are investigated in this study. The experiments for the external airlift reactor were carried out at a 0.14 downcomer to riser cross-sectional area ratio, and for the internal reactor at 0.36 and 1. Air and water were used as the gas and liquid phases, respectively, as well as activated carbon/sludge particles as the solid phase. Increasing the superficial gas velocity resulted in greater liquid circulation velocity, gas hold-up, and volumetric mass transfer coefficient; increasing the suspended activated carbon particles resulted in a decreased concentration of activated sludge, downcomer to riser cross sectional area ratio, liquid velocity, gas hold-up and volumetric mass transfer coefficient. The maximum gas hold-up was 0.178 which was attained in the external airlift reactor with a 1 Wt. % of activated sludge at a gas superficial velocity of 0.25 (m/s). The maximum volumetric mass transfer coefficient was 0.0485 (l/s) that was observed in the external airlift reactor containing activated carbon with a 0.00032 solid hold-up. A switch was observed in the activated sludge airlift reactor flow regime at gas velocities higher than 0.15 (m/s) and 0.18 (m/s) in the activated carbon airlift reactors.

1. Introduction

Due to advantages such as low shear stress, low cost, high mass transfer and simple structure, the application of airlift reactors in biotechnology procedures has expanded significantly over the past years. These include aerobic fermentation for food production, sewage treatment, and similar operations [1,2]. Airlifts, like bubble columns, are reactors in which liquids are mixed as air bubbles move through them. This type of reactor is suitable for procedures in which a uniform and fast dispersion of reactants is necessary as well as for multi-phase (liquid-gas-solid) systems that require high mass and heat transfer [1]. Generally speaking, the design and operation of two-phase gas-liquid and three-phase gas-liquid-solid reactors depend on gas hold-up, overall volumetric mass transfer coefficient, and the liquid circulation intensity [3]. These parameters are also functions of gas sparger type, fluid properties, and gas superficial velocity. There have been numerous studies on the effects of the mentioned factors on gas hold-up, liquid circulation velocity and the overall volumetric mass transfer coefficient. Muroyama et al. (1984) examined the hold-up and mass transfer in an airlift reactor with an internal tube using activated carbon particulates; they observed that the hold-up and mass transfer coefficient increased with gas superficial velocity [4]. Merchuk et al. (1996) investigated the effects of seven types of spargers on the gas hold-up in an airlift reactor with internal flow. They

*Corresponding author. Tel: +98 (912) 3598607
E-mail address: masalehi@guilan.ac.ir

showed that in both uniform and transient bubble regimes, the gas recirculation was higher in spargers with small nozzles than larger nozzles due to the smaller bubbles produced. Therefore, gas spargers with small nozzles resulted in a greater hold-up [5]. The numerous studies on hydrodynamics and mass transfer of airlift reactors have made it clear that increasing the gas superficial velocity results in greater hold-up, liquid circulation velocity, and volumetric mass transfer [6-8].

By adding ethanol to the water-air-calcium alginate system, Freitas et al. (2001) observed that the volumetric mass transfer coefficient increased significantly. The addition of alcohol reduced the mass transfer coefficient k_L due to the increased resistance to mass transfer. On the other hand, the ethanol prevented bubble agglomeration and increased the bubble surface area; therefore, it was suggested that the enhanced overall mass transfer coefficient in the system was due to the increased bubble surface area [9]. Jin et al. (2006) examined and compared the hydrodynamics and mass transfer in two (internal and external) activated sludge airlift reactors. Their results showed that hydrodynamic and mass transfer in the external airlift reactors has better performance in compared with internal airlift reactor [8]. Yang et al. (2009) studied the rheological properties of the activated sludge in membrane airlift reactors and claimed that the viscosity of the activated sludge played an important role in oxygen and mass transfer [10]. Al Taweel et al. (2013) studied the effect of electrolyte on mass transfer in airlift reactors with internal tubes. They used sodium chloride salt at a concentration of 0.01, 0.1 and 1 M and observed that an increase in the aeration velocity and salt concentration yielded a greater K_{La} since the bubbles were less cohesive in high concentrations of salt [11]. Three principal airlift reactor operational parameters, namely gas hold-up, volumetric mass transfer coefficient and liquid circulation velocity were measured in this study; the effect of gas superficial velocity and particulate (activated sludge and carbon) concentration on each of the mentioned parameters were examined and compared in the two reactor types (internal and external).

2. Materials and methods

2.1. Materials

To study the hydrodynamics and mass transfer in the internal airlift reactors and external loop airlift reactor, activated sludge at 1%, 2% and 3% concentrations (prepared from water treatment unit located in Rasht, Iran and activated carbon (MERK™) with 0.00032 and 0.00064 hold-up were used as the solid phase, respectively. Sodium sulfite, Na_2SO_3, (MERK™) was used to absorb oxygen from the liquid and provide an oxygen-free environment. This salt had a high tendency towards bonding with oxygen, thus absorbing it and rendering the water oxygen-free. Therefore, in every flow rate after reaching the steady state,

aeration was stopped and the liquid was deoxygenated using sodium sulfite salt; then, aeration started again for the next flow. These steps were carried out for every flow rate until the end of the experiments.

2.2. Apparatus and experimental method description

A three-phase external loop airlift reactor with a 0.14 down comer-to-riser cross-sectional area ratio was used for the experiments. The bio reactor was made of double glazed glass with a 90 cm height and consisted of three parts, namely the riser (74 cm height and 8 cm diameter), the down comer (55 cm height and 3 cm diameter), and the gas-liquid separator. The temperature was kept constant at the exterior of the reactor using a water bath. The aeration was carried out using an 80W compressor and an antenna sparger with 20 nozzles. The water height was 60 cm without aeration and the volume was 3200 ml. To measure the flow rate of the input air, a rotameter was installed in the line between the compressor and the sparger in a way that it was connected to the sparger from one side and to the compressor from the other. Figure 1 shows the reactor and the equipment.

Fig. 1. The external airlift reactor setup: 1) Gas-liquid separator, 2) External loop, 3) Riser, 4) Compressor, 5) Water bath, 6) Sparger, 7) Air sparger, 8) Laptop, 9) Oxygen sensor, 10) Oxygen meter

The same apparatus was used for the internal airlift reactor with a 0.36 down comer-to-riser cross-sectional ratio, with the external part closed and internal 4 and 5 cm diameter tubes were implemented in the reactor 7cm away from the sparger using metal clips. The internal tubes made up two parts inside the reactor, riser and down comer. Both the riser and down comer were inside the reactor in internal airlift reactors.

2.3. Measuring the hydrodynamics and volumetric mass transfer coefficient

2.3.1. Gas superficial velocity

The superficial velocity of gas was calculated by Equation 1, based on the sparger cross-section area [8]

$$U_G = \frac{R_G}{A_G} \tag{1}$$

where A_G (m^2)was the sparger cross-sectional area, R_G (m^3/s) was the air flow and U_G(m/s) was the gas superficial velocity.

2.3.2. Gas hold-up

Gas hold-up here referred to the overall gas hold-up which was determined by the volumetric expansion method. In fact, the gas hold-up was expressed as the volume increase of the aerated liquid compared to the non-aerated liquid; this was achieved by first measuring the height of the non-aerated liquid column, and then measuring it again after the air bubbles entered the reactor with a specific flow rate. The overall gas hold-up was calculated using Equation 2 [8,12]. The height of the liquid column was assumed to be 60 cm for all the experiments.

$$\varepsilon_g = \frac{H_{LG} - H_L}{H_{LG}} \tag{2}$$

Where ε_g was the overall gas hold-up, H_L was the non-aerated liquid column height, and H_{LG} was the aerated liquid column height.

2.3.3. Liquid circulation velocity

A 0.1 M solution of potassium permanganate dye solution was used to measure the circulation velocity in the down comer of the activated sludge and carbon external loop airlift reactor by injecting 0.4 ml of the permanganate solution to the reactor from the external loop. The circulation velocity was calculated by Equation 3 [7,13].

$$U_{Ld} = \frac{L_d}{t_d} \tag{3}$$

Where U_{LD} was the circulation speed of the liquid in the down comer, L_D was the specified distance in the down comer, and t_d was the required time of permanganate solution to pass down comer length (L_D = 40).
The relation between the circulation velocity of the riser and the down comer is presented as Equation 4 [14].

$$U_{Lr}A_r = U_{Ld}A_d \tag{4}$$

Where U_{LR} and U_{LD} were the liquid velocity in the riser and down comer, respectively; A_r and A_d were the cross-sectional area of the riser and down comer, respectively.

2.3.4. Volumetric mass transfer coefficient

The volumetric mass transfer coefficient was measured via the dynamic method. The reactor content was first oxygen depleted and then re-oxygenated. To this end, the liquid phase was deoxygenated using sodium sulfite salt and then aerated for every flow rate [8]. The oxygen concentration was recorded every 5 seconds until reaching the steady state. This was achieved by using an oxygen meter (DO-5510) whose electrode was submerged 7 cm deep in the water column with its sensor connected to the computer using a cable. The volumetric mass transfer coefficient was calculated by the oxygen transfer balance (Equation 5) [15,16].

$$\frac{dC_L}{dt} = k_L a(C_L^* - C_L) \tag{5}$$

The integration of Equation 5 at t = 0 and C_L = 0 will lead to:

$$C_L(t) = C_L^*[1 - \exp\left(\frac{-k_L a}{t}\right)] \tag{6}$$

Where C_L (mg/L) and C_L^* (mg/l) indicated the oxygen concentration in the bulk solution at time t and the oxygen concentration at a steady state, respectively, which were read from the oxygen meter. According to Equation 6, the overall volumetric mass transfer coefficient was obtained from the slope of ln (C_L^*– C_L) in every flow rate [8,17].

3. Results and discussion

3.1. The effect of gas superficial velocity on the gas hold-up

The effect of gas superficial velocity on the hold-up in activated sludge and carbon airlift reactors is illustrated in Figures 2-4. The gas hold-up increased with the superficial velocity of gas. The gas hold-up variation was steeper in lower velocities and gradually became moderate as the velocity increased to the point where, due to turbulence, smaller changes occurred in the gas hold-up. Increasing the activated sludge concentration resulted in a lower hold-up which was attributed to the higher activated sludge viscosity; the effect of the solid phase concentration was relatively negligible in both the internal and external activated carbon airlift reactors.
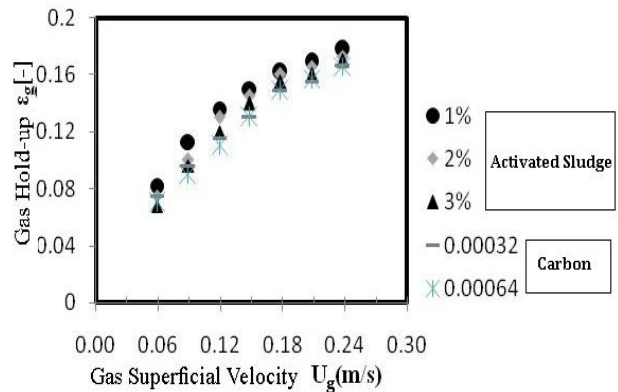

Fig. 2. Comparing the effect of gas superficial velocity on the hold-up in activated sludge and carbon reactors (A$_d$/A$_r$=0.14)
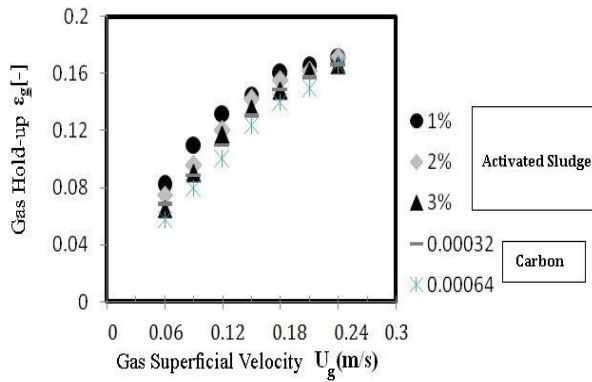
Fig. 3. Comparing the effect of gas superficial velocity on the hold-up in activated sludge and carbon reactors (A$_d$/A$_r$=0.36)
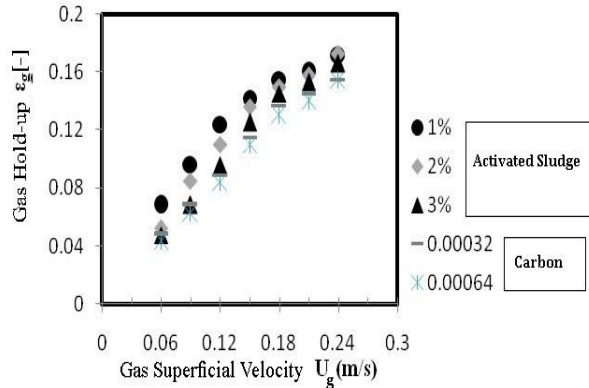

Fig. 4. Comparing the effect of gas superficial velocity on the hold-up in activated sludge and carbon reactors (A$_d$/A$_r$=1)

In comparing the activated sludge and carbon airlift reactors using Figures 2-4, we observed that the flow regime switch occurred at velocities higher than 0.15 m/s for the activated sludge reactors and at velocities higher than 0.18 m/s for the activated carbon reactors. The activated sludge liquid had a non-Newtonian behavior; in agreement with the properties of this type of fluids, it generated bigger bubbles and therefore, switched faster to a non-uniform regime [18]. Since the airlift reactors based on water with round carbon particulates had Newtonian behavior, it switched to non-uniform regimes at higher velocities.

3.2. The effect of gas velocity on liquid circulation velocity

Figures 5 and 6 show the effect of the gas superficial velocity on the liquid circulation at the down comer and riser of the activated sludge and carbon external airlift reactors.
The difference in density in the riser and down comer of the airlift reactors provided the driving force for the liquid movement and circulation. By increasing the gas superficial velocity, the liquid circulation velocity increased both at the down comer and riser, while increasing the sludge concentration and solid hold-up resulted in lower velocities. This occurred because the friction between the particles and resistance to flow increased with the sludge concentration and solid hold-up and thus, decreased the liquid velocity. The slope of liquid velocity variation was

steeper at lower gas velocities because at low flows the uniform bubble flow regime governed the system. By increasing the superficial velocity of the gas, the flow became turbulent and a non-uniform flow regime occurred. In Activated carbon and sludge reactors a linear relation was observed between the superficial velocity of gas and the velocity of liquid at 0.06<U$_g$<0.15 and 0.06<U$_g$<0.18 respectively, in addition a power law relation was observed in higher velocities U$_g$≥.015 and U$_g$≥.018
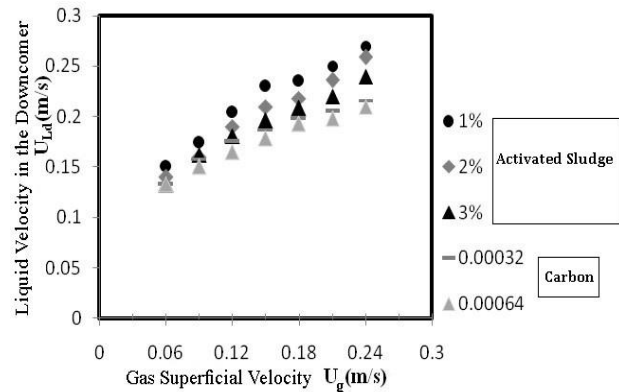

Fig. 5. Comparing the effect of gas superficial velocity on liquid velocity at the downcomer of the activated sludge and carbon external airlift reactor.
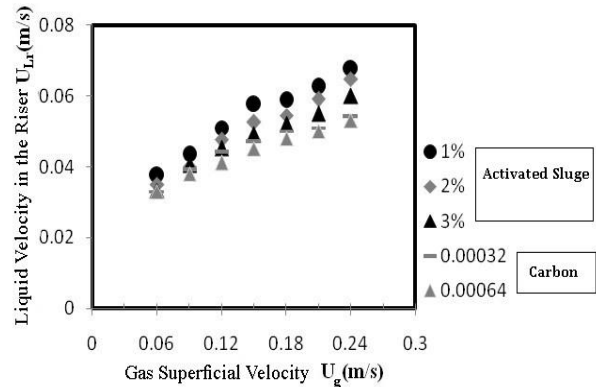

Fig. 6. Comparing the effect of gas superficial velocity on liquid velocity at the riser of the activated sludge and carbon external airlift reactor.

3.3. The effect of gas velocity on the overall mass transfer coefficient

The effect of the superficial velocity of gas on the overall mass transfer coefficient in the activated sludge and carbon airlift reactors is illustrated in Figures 7-9. Increasing the superficial velocity led to a greater gas volume fraction in the liquid and a higher mass transfer rate in all the three reactors. In low velocities there were small bubbles, therefore the K$_L$a increased with a steeper slope while in higher velocities the K$_L$a changed with a slower slope due to the formation of larger bubbles in the riser gas hold-up. For the same gas velocity, as the activated sludge concentration and solid hold-up (activated carbon particles) increased, the

K_La decreased because higher viscosity or solid hold-up promoted bubble agglomeration and a reduction of gas-liquid interface. These results were in agreement with the results presented by Jin et al. (2006) [8].
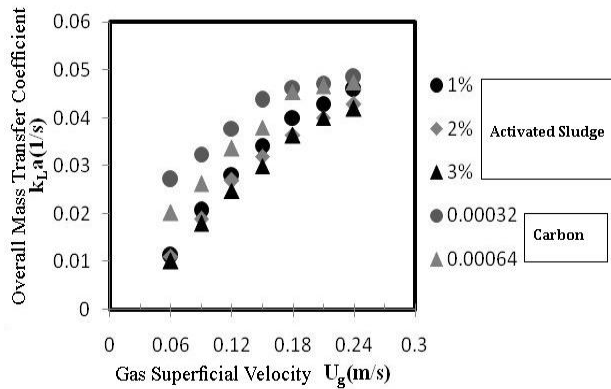

Fig. 7. Comparing the effect of superficial velocity of gas on the overall mass transfer coefficient in activated sludge and carbon reactors (A_d/A_r=0.14)

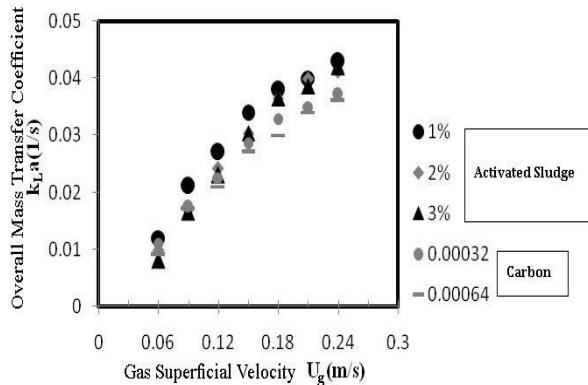**Fig. 8.** Comparing the effect of superficial velocity of gas on the overall mass transfer coefficient in activated sludge and carbon ctors (A_d/A_r=0.36)

Fig. 9. Comparing the effect of superficial velocity of gas on the overall mass transfer coefficient in activated sludge and carbon reactors (A_d/A_r=0.36)
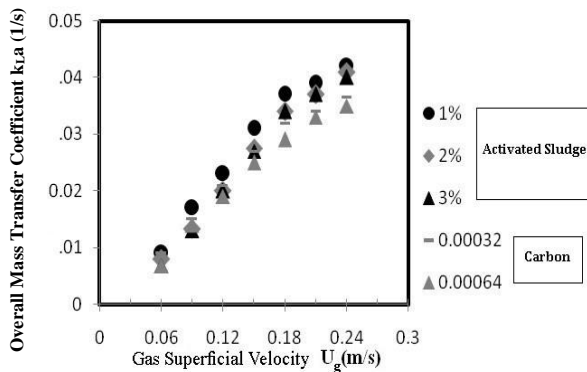
The results in the two active sludge and carbon reactors showed a greater K_La difference between the external loop activated carbon airlift reactor and the internal airlift

reactor compared to their difference in the active sludge airlift reactors. In other words, the effect of A_d/A_r on mass transfer in activated carbon airlift reactors was more than activated sludge reactors; the reason could be the different properties of the fluids.

4. Conclusions

The aim of this study was to examine and compare the effect of the superficial velocity of gas on the hydrodynamics and mass transfer of activated sludge and carbon in internal and external airlift reactors. An increase in the superficial velocity of gas resulted in greater gas hold-up, liquid circulation velocity and volumetric mass transfer coefficient. Meanwhile, increasing the concentration of activated sludge and carbon particulates reduced the hydrodynamics and K_La due to the generation of larger bubbles and a reduction of gas-liquid interface. The results showed that the external activated carbon and sludge airlift reactors performed better than the internal airlift reactors. Furthermore, it was found that the activated sludge reactors had non-Newtonian behavior while the activated carbon reactors had Newtonian behavior.

Nomenclature

U_G: Gas superficial velocity(m/s)

R_G: Air flow rate(m^3/s)

A_G: Sparger cross-sectional area(m^2)

ε_g: Overall gas holdup

H_L: Non-aerated liquid column height(m)

H_{LG}:   Aerated liquid column height(m)

U_{LD}:   Liquid velocity in downcomer(m/s)

U_{LR}:   Liquid velocity in riser(m/s)

t_d: Time(s)

L_D: Specified distance in downcomer(m)

A_r: Riser Cross sectional area(m^2)

A_d: Downcomer cross sectional area(m^2)

$C_L(t)$:   Oxygen concentration in bulk solution at time

C_L^*:   oxygen concentration at steady state (mg/l)

K_La: Volumetric mass transfer coefficient$(1/s)$

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