Hydrodynamic Characteristics in Internal Air Lift Loop Reactor

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Abstract: Hydrodynamics is an important issue for the design and development of three phase internal air lift loop reactor. This paper deals with the experimental investigations on the effect of superficial gas velocity within the range 0.01-0.1 m/sec and 50 Kg/m concentrations of solid,solid density (853.5 Kg/m³) on the riser gas holdup, mass transfer coefficient and circulation time of a gas-liquid-solid internal airlift loop reactor and it was characterized using Newtonian and non Newtonian systems. Air-water, air-50% glycerol solution, air-10%ethanol solution and air-10%methanol solution are used as Newtonian liquids and air-2% carboxyl methyl cellulose solution (CMC) is used as a non Newtonian liquid. Polyethylene-non-porous-solid particles were used as solid phase. The phase flow rates and concentration of solid particle had a significant effect on the hydrodynamic characteristics of the internal air lift loop reactor such as riser gas holdup ($\varepsilon_r$), mass transfer coefficient ($K_{La}$) and circulation time ($T_c$). From experimental observations $\varepsilon_r$ and $K_{La}$ increased with increasing gas velocity, while $T_c$ decreases with increasing gas velocity.

Key words: Slurry reactor · Mass transfer · Gas hold up · Circulation time · Solids loading · Liquid-phase properties

INTRODUCTION

Three phase internal air lift loop reactors are increasingly used in the fields of chemical and biotechnology as simple and effective contactors for processes involving gases, liquids and solids. The internal loop reactor has found many applications in many industrial processes such as hydrogenation, desulfurization, coal liquefaction, Fisher Tropsch synthesis etc. The simplicity of their design and construction, high heat and mass transfer capacity and excellent mixing properties with low power requirements are making them very attractive [1, 2].

Several investigators have studied the hydrodynamics of three-phase internal-loop airlift reactors. Miyahara and Kawate [3] measured the gas holdup in the riser and the downcomer and the pressure drop at the upper and lower ends of the riser due to flow reversal for a solid-suspended airlift reactor containing low-density particles Karamanev et al. [4] used 3 mm soft polyurethane foam particles in their experiments. They found that the gas holdup decreased significantly with increasing solids loading and the gas holdup was proportional to $V_{La}$ [1,2]. However, most works in the literature that study the hydrodynamics in slurry reactors have been performed under conditions of low solid concentrations. These works showed that particles with typical particle sizes smaller than 100μm are uniformly suspended in both the axial and radial directions in a slurry system [5, 6]. In the concentric tube airlift bioreactor, some geometrical parameters (different height to diameter ratio and different top and bottom clearances) affect gas holdup, liquid circulation, mixing time and the volumetric oxygen transfer coefficient. Extensive study of reactorhydrodynamics and reactor geometrhyenhances theimportance of the geometrical parameters in the design and scale-up of concentric tube airlift bioreactors [7, 8, 9]. To design and operate the air lift loop reactors with confidence, the knowledge of gas-liquid mass transfer is required to characterize the performance of the air lift loop reactor. The main parameter used as an indicator for gas-liquid mass transfer rate is the gas-liquid mass transfer coefficient ($K_{La}$) [10, 11, 12]. A large number of researchers [13, 14, 15, 16, 17, 18, 19] have investigated the
mass transfer performance in the air lift loop reactors together with their hydrodynamic behavior. Airlift reactors are agitated pneumatically and circulation takes place in a defined cyclic pattern through a loop, which divides the reactor into two zones: a flow-upward and a flow-downward zone. The gas-sparged zone or the riser has higher gas holdup than the relatively gas-free zone, the downcomer, where the flow is downward [2]. However, few studies have addressed three-phase airlift reactors with low density solids (<2%, v/v) [20, 21]. The purpose of this study is to clarify experimentally the effects of the gas velocity and liquid phase properties (coalescing, Newtonian and non Newtonian behavior) on gas hold up ($e_g$), circulation time ($T_c$) and mass transfer coefficient ($K_m$) in a solid suspends concentric tube airlift loop reactor when the ratio of draught tube diameter to column diameter is equal to 0.5 and the air is dispersion into the center of the riser.

Experimental Section: A schematic diagram of the experimental setup in this work is shown in Figures 1, 1.a and 1.b. A Plexiglass column of 0.09 m inside diameter and about 1.30 m total height with draught tube dimensions of 0.045 m inside diameter and 0.09 m total height was used. The top and bottom clearances were maintained constant at 5 cm. The draught tube was fitted with three support legs in the upper and the lower end of the column so as to locate it in a central position at any distance above the base. The column consists of two main sections namely, the gas inlet section and the liquid recycling testing section. The gas inlet section consists of a gas distributor. At the bottom of this section, two lines are connected together before entering the distributor section each line has a value to be opened or closed as required. One of these lines is the air inlet flow. Air compressor supplied the line with the desired amount of air needed; the amount of air was measured using a gas meter. The other line is the nitrogen gas inlet flow. The nitrogen gas was supplied from a cylinder. A gate valve was used in the nitrogen flow, which must be shut off when the air was dispersed into the column and must be opened during the desorption process. The liquid testing section contains two openings, one for liquid out-flow and the other for liquid in flow. The circulation of liquid in the column was achieved using a dosing pump placed in the recycling line. A ball valve placed in the middle of the recycling line was used to take various samples at various times to measure the concentration of the dissolved oxygen during the operation. The column was filled with water to the desired level above the distributor (0.7) m. Then the solid particles (polyethylene 3.4 mm particle diameter and the density 853.5 Kg/m³) were added to the liquid in the column. The concentration of solid particles was (50) kg solid/m³ slurry. Compressed air at (100-150) psig was supplied using a reciprocating compressor. The desired air flow rate was set-up using gate valve and the amount measured with a gas meter. The dissolved oxygen concentration in the liquid phase was measured using oxygen meter device type a (YSI-5100), which consists of a probe metal electrode. The liquid phase (batch) consists of the following systems (only water, water and solid, water, alcohols and solids (Newtonian), water, CMC and solids (non Newtonian)) the chemicals used in the present study were procured from Permula Chemicals Sdn. Bhd., Malaysia. The gas distributor Fig. 1.b was constructed from a ceramic material and the type is aporous gas distributor. The distributor has an equivalent pore diameter of 0.1 mm and free section of 70%.

Results on Gas Hold Up ($e_g$) and Solid Hold Up ($e_s$):

The average gas hold up $e_g$ was calculated from the equation (1) using the data of the clear - liquid height ($H_i$) and the height of the aerated liquid ($H_f$) which was determined by visual observation:

$$ e_g = \frac{H_f - H_i}{H_f - (V_i / S_o)} $$

(1)

(V_i / S_o) In equation (1) is a correction term for the volume of the draft tube [22].

The solid-hold-up was calculated from the equation (2). Using the date of static liquid height ($H_s$) and the height of slurry after adding solid particles ($H_f$):

$$ e_s = \frac{H_f - H_s}{H_f} $$

(2)

The experimental gas hold up was found by measuring the difference between initial liquid height and final liquid height. Since it was rather difficult to read directly the level of the aerated liquid the values of gas hold up thus obtained probably involves an error of about 5%, established via repeated measurements. Fig. 2. Shows the effect of gas velocity for water system with and without solid particles. The gas hold up was found to increase with increasing gas velocity, because the large bubble holdup increases with increasing gas velocity leading to the increase of the overall holdup. But the effect without solid particles is larger than that with solid particles. When the gas velocities above 0.01 m/sec and the liquid phase without solid particles, bubble size is
Fig. 1: (a) Experimental apparatus; (b) column; (c) gas distributor

Fig. 2: Gas hold up versus gas velocity for water system
independent of gas flow rate. The buoyant force of the bubble is opposed by viscous drag of the fluid and if bubble size is independent of gas flow rate, the velocity of bubble rise will show similar independence. Hence increased gas flow rate will increase the gas hold up and ultimately the liquid will see to be filled with bubbles. This is in agreement with the results given by Prakash et al. [23] and Li et al. [24] Fig. 3. Shows, in slurries the presence of solid particles in the liquid might enhance bubble coalescence into larger bubbles and therefore reduces the value of gas hold up. The solid particles retard the bubble rise velocity and prevent increases in bubble size. Fig. 4. Shows the effect of using different liquid phase (alcohols and CMC) respectively, for aqueous solutions of aliphatic alcohols, a considerable increase in the gas holduppin alcohol chain length was observed. The gas hold up decreased in the following order ethanol > methanol > and other systems. The decrease in surface tension in the presence of alcohols was not sufficient to explain this phenomenon. Bubble dynamics and bubble swarm structure in the presence of surfactant solutions can explain this behavior qualitatively. In the presence of alcohols, the bubbles become more rigid and hence have low rise velocities resulting in a bubbly flow regime up to surprisingly high gas velocities (0.08-0.1 m/sec). The viscous solutions of glycerol and CMC show only slightly higher gas holdups than water. In spite of similar a flow property of the CMC and glycerol solutions, gas hold-up in the CMC solution is somewhat larger, due to accompanying coalescence inhibiting. In general, low viscosity liquid exhibit bubble disintegration behavior. Whereas, a trend towards bubble coalescing behavior has been observed with increasing the viscosity of the liquid media, as shown by many investigators [25, 26].

**Mass Transfer Coefficient Results:** The physical absorption of oxygen in the air by the liquid was employed to determine the mass transfer coefficient. A material balance of oxygen in the liquid gives:

\[
K_{La} = \frac{-2.303(1-\varepsilon_g - \varepsilon_S)}{t} \log \frac{C_{Sa} - C_i}{C_{Sa} - C_o}
\]  (3)

Rearranging equation (3) gives

\[
\log \frac{C_{Sa} - C_i}{C_{Sa} - C_o} = \frac{K_{La}}{2.303(1-\varepsilon_g - \varepsilon_S)} t
\]  (4)

Plotting the left hand side of equation (4) with (t), the average slope of the plot will give the term 
\[
K_{Ls}/2.303(1-\varepsilon_g - \varepsilon_S)
\]

the values of \((\varepsilon_g)\) and \((\varepsilon_S)\) were determined as mentioned in (1) and (2) respectively, then 
\((K_{Ls})\) can be calculated. Fig. 5. Shows that the mass transfer coefficients increase with increasing gas velocity. The axial dispersion coefficient\((D_x)\) increases with increasing gas velocity and therefore increases \((K_{Ls})\). Fig. 6. Shows the effect of solid particle concentration on 
\((K_{Ls})\). The presence of solid particle in the liquid will decrease the axial dispersion coefficient and it enhances bubble coalescence. The bubble size will be larger and occupying larger space in the column and therefore reduces 
\((K_{Ls})\). At a higher gas velocity (0.1) m/sec, the effect of solid particles on 
\((K_{Ls})\) will be less than in low gas velocities (0.03m/sec).

**Circulation Time Results:** The method proposed by [27, 28] was used to determine the circulation time. The circulation time is the time between two successive crossing of tracer particle, in the same direction, through a chosen plane. The reference plane was chosen to be the medium - height plane and the particle was a colored tracer (black) of foam of about 5 mm diameter, which becomes totally impregnated when immersed in the liquid and thus reaches the liquid density. The black tracer particle was clearly visible in liquids, an average of five measurements under the same conditions were taken. It appears that liquid circulation time depends on many interacting (or interrelated) parameters, e.g., bubble size, bubble rise velocity and gas hold-up in addition to the physical properties of liquid and solid as well as solid concentration. The circulation process in loop reactors consists of combined effects occurring in the draft tube, annular space and in the top and bottom deflection zones. Circulation in the up and down flow zones is produced by axial dispersion which mainly results from the difference between the velocities of gas and liquid phases. The axial circulation fraction of the overall circulation loop increases with the start of gas circulation since bubbles which coalesce in the annular space rise against the liquid flow and therefore considerably speed up the circulation process. The intensive circulation in the deflection zones is caused by differences between velocities in the up and down flow zones. In the top zone, circulation is intensified by the formation of a ring vortex above the draft tube. Fig. 7. Shows that in general the overall effect of presence of alcohols (water-methanol, water-ethanol)
Fig. 3: Gas hold up versus solid concentration for a water system for various gas velocities

Fig. 4: Gas hold up versus gas velocity for different liquid phase system

Fig. 5: Mass transfer coefficient versus gas velocity for water systems
Fig. 6: Mass transfer coefficient versus gas velocity for different liquid phase system

![Mass transfer coefficient vs gas velocity]

Fig. 7: Effect of gas velocity on circulation time for different liquid phase system

![Circulation time vs gas velocity]

Table A1: Physical-properties for pure liquids at $T = 20 ^\circ C$

<table>
<thead>
<tr>
<th></th>
<th>$\rho$ (kg/m$^3$)$10^3$</th>
<th>$\mu$ (CP)</th>
<th>$\sigma$ (dyn/cm)</th>
<th>$\nu$ (cm$^2$/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0.998</td>
<td>1.002</td>
<td>72.86</td>
<td>1.004</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.791</td>
<td>0.584</td>
<td>22.61</td>
<td>0.738</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.789</td>
<td>1.200</td>
<td>22.27</td>
<td>1.520</td>
</tr>
<tr>
<td>Glycerol</td>
<td>1.261</td>
<td>1.005</td>
<td>6304</td>
<td>0.796</td>
</tr>
<tr>
<td>CMC</td>
<td>1.008</td>
<td>K=0.012 ps.s$^n$ n=0.8</td>
<td>75</td>
<td>1.23</td>
</tr>
</tbody>
</table>

The solution of CMC (carboxy methyl cellulose) shows non Newtonian, pseudo plastic behavior, which can be described by the power law of Ostwald and deweale:

$t = K \cdot \epsilon^n$

where:

- $K$: Ostwald factor (consistency index)
- $n$: flow behavior index
- $\epsilon$: shear rate 1/sec
- $T$: shear stress
- $\mu = \mu_{eff} \cdot \epsilon^n$
- $\mu_{eff}$: effective liquid phase viscosity Pa.s
- $Y = 5000 \cdot V_g$ [31]

where $V_g$: gas velocity m/sec.
Table A2: Physical properties for mixtures used with various concentrations 20°C

<table>
<thead>
<tr>
<th></th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$\mu$ (CP)</th>
<th>$\sigma$ (dyn/cm)</th>
<th>$\nu_c$ (cm$^2$/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-Methanol 10%</td>
<td>0.9815</td>
<td>0.795</td>
<td>22.63</td>
<td>0.8226</td>
</tr>
<tr>
<td>Water-Ethanol 10%</td>
<td>0.981</td>
<td>0.910</td>
<td>22.64</td>
<td>0.9400</td>
</tr>
<tr>
<td>Water-glycerol 50%</td>
<td>1.126</td>
<td>6.00</td>
<td>64</td>
<td>0.8905</td>
</tr>
<tr>
<td>Water-CMC 2%</td>
<td>1.009</td>
<td>K=1.320 Pas$^{n=0.5}$</td>
<td>69</td>
<td>0.09051</td>
</tr>
</tbody>
</table>

The circulation time ($T_c$) was found to increase in the presence of solid particles because the solid particles retard the bubble rise velocity and losses in power dissipation at the solid-liquid interface therefore the ($T_c$) is larger than that in water. At high values of gas velocity about 0.1 m/sec the $T_c$ of different systems become equal because of the liquid velocities approach a constant value.

**CONCLUSIONS**

The presence of suspended solid particles in the internal air lift loop reactor when the ratio of the draught tube diameter to column diameter equal to 0.5 reduce the values of holdup $e_g$ and the volumetric liquid-phase mass transfer coefficient $K_{Li}$. The reduction of $e_g$ and $K_{Li}$ values due to an addition of solid particles to the column increases with increasing liquid phase (water, alcohols and solids, Newtonian and water, CMC non-Newtonian) viscosity.

The gas hold-up and mass transfer coefficient in an air lift loop reactor, where gas is dispersed into the center of the base of the inner draught tube using a porous multi hole distributor increase with increasing gas velocity, for $V_g$ equal or less than 0.1m/sec, only for the case of (water, glycerol and solids) system, the mass transfer coefficient reaches its maximum at a gas velocity of 0.02m/sec. This observation is in agreement with many experimental works [29, 30].

The circulation time in air lift loop reactor increase with increasing liquid phase viscosity and in the presence of solid particles.

The circulation time in the air lift loop reactor decrease with increasing gas velocity.

**Nomenclature:**

- $a$: Specific gas-liquid interfacial area based on aerated liquid volume m$^{-1}$
- $C_i$: Concentration of dissolved oxygen at any time p.p.m
- $C_0$: Initial Concentration of dissolved oxygen p.p.m
- $C_{Sat}$: Saturated concentration of dissolved oxygen p.p.m
- $C_s$: Solid particle concentration K/g/m$^3$
- $D_c$: Column diameter
- $D_L$: Diffusivity of oxygen in solution m$^2$/sec
- $D_A$: Axial dispersion coefficient (liquid) m$^2$/sec
- $g$: Acceleration of gravity m/sec$^2$
- $H_L$: Static slurry height (m)
- $H_{ef}$: Level of aerated slurry (m)
- $\bar{H}_{ef}$: Level of liquid phase+ solids (m)
- $K_L$: Liquid phase mass transfer coefficient (m.s$^{-1}$)
- $K_{Ls}$: Overall mass transfer coefficient, based on aerated slurry volume. (Sec$^{-1}$)
- $S_c$: Slurry column
- $t$: Time (min)
- $V_g$: Gas velocity (m/sec)

**Greek Letters:**

- $\sigma$: Gas hold up
- $\varphi$: Solid hold up
- $\rho_L$: Liquid phase density kg/m$^3$
- $\rho_s$: Solid phase density kg/m$^3$
- $\mu_L$: Liquid phase viscosity(Cp)
- $v_L$: Kinematic viscosity of liquid phase (cm$^2$/sec)
- $\sigma$: Liquid phase surface tension dyne/cm

**Subscripts:**

- G: gas
- L: liquid

**REFERENCES**