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Gas Hold-Up, Mixing Time and Circulation Time in Internal Loop Airlift Bubble Column

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Abstract

The effects of superficial gas in the riser (V_{gr}) and liquid phase properties on the gas hold-up(ε_g) , mixing time (T_m) and circulation time (T_C) were studied in 8 liter internal air lift loop reactor (down comer-to-riser cross-sectional area ratio = 0.249). Air was used as a gas phase. Water and four aqueous solutions of 10% concentration methanol, ethanol, (were used to simulate the behavior of non-coalescing organic liquids) 50% glycerol and 2% Carboxy Methyl Cellulose (CMC) were used to simulate the behavior of coalescing viscous liquids. Polyethylene-non-porous-solid particles with a concentration of (50) Kg/m^3 were used as solid phase. Superficial gas velocity varied from 0.01 m/s to 0.1 m/s and air dispersed into the center of the draught tube by using a porous gas distributor. The results showed that (ε_g) increased with increasing gas velocity and coalescence inhibition of liquid, while T_m and T_c decrease with increasing gas velocity. It was found that increasing liquid viscosity and coalescence reduces (ε_g) but increases (T_m) and (T_c). The gas holdup was correlated with dimensionless groups and independent parameter with correlation coefficient is 0.967, the following correlation is obtained.

$$\varepsilon_g = A \times \left[\frac{V_g \mu_L}{\sigma_L}\right]^n \left[\frac{g \mu_L^4}{\rho_L \sigma_L^3}\right]^{-m} \left[\frac{C_S}{\rho_S}\right]^K$$

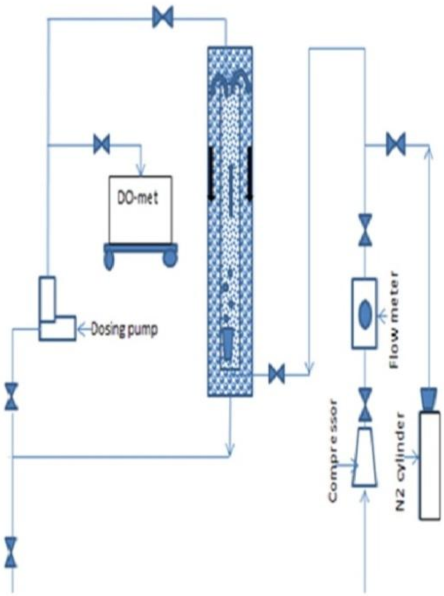
Keywords: *Airlift reactor; mixing time; Circulation time; Liquid-phase properties*

I. Introduction

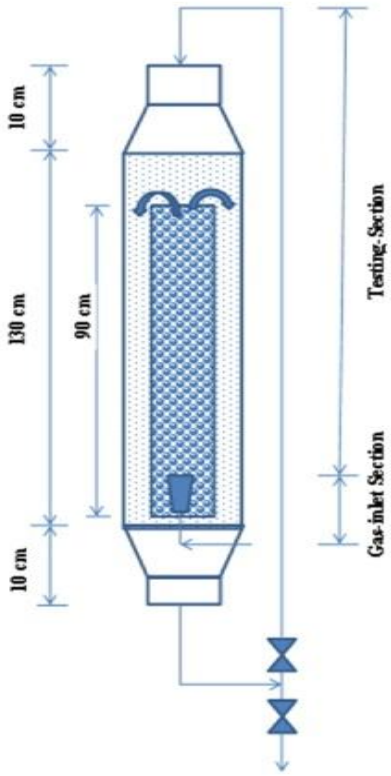
Airlift reactors (ALRs) are suitable for many different processes. They are mainly used as bioreactors in fermentation processes and in the biotransformation of many substances [1, 2]. In wastewater treatment ALRs are increasingly being developed [3-7]. Airlift loop reactors find extensive applications in many areas of chemical engineering, especially for homogeneous as well as heterogeneous single and multiphase systems due to their simple construction and operation, directed circulation flow, good mixing and favorable ratio of interfacial area of energy dissipation rate per unit volume, low investment, operational costs and relatively lower power requirements [8]. The mixing time and circulation time are important hydrodynamic characteristics of airlift reactors [9].The liquid circulation velocity effects on the residence time of gas, mass transfer and mixing time Tm. Studies showed that liquid circulation velocity was affected by the gas flow rate and geometric parameters of the column.[10-12] Liquid circulation occurs due to the difference in hydrostatic pressure or density between the riser and down comer. When gas flow rate increases, the liquid velocity also increases, thereby entraining most of the bubbles from the riser in to the down comer. This will reduce the difference in hydrostatic pressure (compromising the liquid velocity). In general, a higher liquid velocity reduces the residence time of the bubbles in the riser and down comer, as it encourages the recirculation of gas through the down comer and back to the riser. (Weiland et al.[13], Chisti et al. [14], Choi et al. [15], Petrovic and Posarac[16], Bentifraouine et al. [17], and Yazdian et al. [18]) investigated the effects of operating parameters on the hydrodynamic behavior of concentric draft-tube type airlift reactors. They observed a decrease in the mixing time with the decrease of the cross sectional area ratio (*Ad*/*Ar*). They also observed the mixing time increases with increasing the top and bottom clearances [13, 18]. The top and bottom clearances do exert an important effect on gas holdup, mixing time, circulation time, and mass transfer. The analysis and description of the behavior of an ALR involve the study of characteristics such as mixing and circulation time. It is necessary to get information about the interaction between these parameters and the operation variable as well as the design variables, in order to make a correct design of the airlift reactor [19]. Many researchers (Camarasa et al., [20]; Kelkar et al., [21]; Posarac et al., [22]) reported that the addition of small quantities of aliphatic alcohols increased the gas holdup, in comparison to pure water, in bubble columns (BCs), continuous BCs, draft tube airlift reactors (DT-ALRs), Along with the changes in the gas holdup, the induced liquid velocity in ALRs is also affected by alcohol addition. Although a large number of investigations contributed to the knowledge of the effect of various parameters on hydrodynamics and mass transfer characteristics in ALRs, available information frequently showed wide variations and conflicting claims. Molina et al. [23] characterized mixing in a split cylinder airlift bioreactor (Ad/Ar ratio of 1, sucrose solution with viscosity variations of $1.54\pm19.5\times10^{-3}$Pa.s, and V_{gr} of 0 ± 0.039 m/s). It was reported that viscosity had no influence on circulation time, which contradicted the theory (increase in viscosity reduces flow as a result of resistance). According to them, the driving force of circulation has increased with increasing viscosity for any gas flow rate. This was due to the fact that as viscosity increased more bubbles were coalesced with a magnitude of smaller bubbles, where most of these large bubbles were disengaged at the top and smaller ones went through the down comer. This achieved a higher driving force for liquid circulation. Viscosity had little effect on mixing time, which suggests that mixing time was affected by differences in velocities between the gas and liquid phases. Merchuk et al. [24] carried out an extensive study in a concentric tube reactor with seven different spargers (four cylindrical and three porous plates) of varying pore sizes using sea water and NaCl. They reported that the sparger pore size had an impact on the gas holdup and liquid recirculation. The smaller the pore sizes the higher the gas holdup which implied a decrease in the liquid circulation velocity. At a higher gas velocity, mixing time was independent of sparger geometry although the geometry of the sparger and pore size had an impact at a low gas velocity. Finally, the holdup was affected by coalescing and not by the geometry of the sparger used. Miron et al. [25] tested mixing in a bubble column and airlift (split cylinder and draft tube) with a dispersion height of 2 m and working volume of 0.06 m^3 using water and seawater. They reported that, at any gas flow rate the values of mixing parameters in the two fluid media were identical. In all reactors mixing time decreased with increased superficial gas velocity. However, the bubble column gave the shortest mixing time due to the bulk flow as opposed to the airlift where circulation was in a cyclic motion impeding the bulk flow. The contradiction is regularly attributed to the difference in the reactor geometries, experimental conditions and experimental techniques. However the present knowledge suggests that this contradiction is brought about by some complicated phenomena taking place in ALR, such as the bubble size distribution, internal liquid circulation, etc. [26-30]. The purpose of this study is to clarify experimentally the effects of the gas velocity and liquid phase properties (coalescing) on gas hold up (εg), mixing time (T_m) and circulation time (T_c) in a solid suspends concentric tube airlift loop reactor when down comer-to-riser cross-sectional area ratio = 0.249 and the air is dispersion into the center of the riser by using a porous gas distributor.

II. Experimental Section

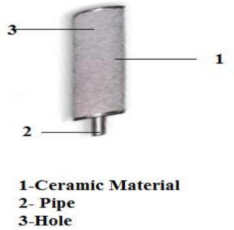
A schematic diagram of the experimental setup used in this work is shown in Figures 1, 1a and 1b. A concentric a plexiglass tube airlift reactor of an inside diameter of 0.9 m and about a total height of 1.3m with draught tube dimensions inside diameter of 0.045m and a total height 0.9 m was used. The top and bottom clearances were maintained constant at 5 cm. The volume of the reactor was 8 liter and $Ad\ /Ar = 0.249$, where the Ad is the downcomer superficial area (m^2) and Ar is the riser superficial area (m^2). The water level in the reactor was 0.95 m. 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 valve 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; in the experiment, the amount of air was measured using a gas meter. The other line is the nitrogen gas inlet flow. The nitrogen was supplied from a cylinder. A gate valve was used in the nitrogen flow, which must be shut off when the air was sparged to 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. The column was filled with water to the desired level above the distributor (0.95) m. Then the solid particles (polyethylene 3.4mm particle diameter and the density 853.5 Kg/m^3) were added to the liquid in the column. The concentration of solid particles was (50) kg solid $/m^3$slury. The water is fed to the top of the column and discharged from the bottom of the column using a dosing pump. 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 was measured with a gas meter. The liquid phase (batch) consists of the following systems (only water, water-ethanol, water-methanol,water-glycerol and water-CMC) the chemicals used in the present study were procured from Permula Chemicals Sdn.Bhd., Malaysia. The gas distributor in Fig (1.c) was constructed from a ceramic material and the type is a multi hole tuyere. The distributor has an equivalent pore diameter of 0.15 mm and a free section of 80%.



(a)



(b)



(c)

Figure 1: (a) Experimental-Apparatus; (b) Column and (c) Gas distributor

Table 1: Physical-properties for pure liquids at *T* = 20 °C

	ρ(kg/m^3) 10^3	μ (CP)	σ (dyn/cm)	ν_L (cm^2/se)
Water	0.998	1.002	72.86	1.004
Methanol	0.791	0.584	22.61	0.738
Ethanol	0.789	1.200	22.27	1.520
Glycerol	1.261	1.005	6304	0.796
CMC	1.008	K=0.012 ps.s^n n=0.8	73	1.23

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:

$t = K \gamma^n$

Where:-

K: Ostwald factor (consistency index)

n: flow behavior index

γ: shear rate 1/sec

T: shear stress

$\mu_{eff} = \gamma^{n-1}$

where μ_{eff}: effective liquid phase viscosity Pa.s

Y = 5000 Vg [31]

Where Vg: gas velocity m/sec.

Table 2: Physical properties for mixtures used with various concentrations at T=20°C

	ρ (kg/m^3)10^3	μ (CP)	σ (dyn/cm)	ν_L (cm^2/sec)
Water-Methanol 10%	0.9815	0.795	22.63	0.8226
Water-Ethanol 10%	0.981	0.910	22.64	0.9400
Water-glycerol 50%	1.126	6.00	64	0.8905
Water-CMC 2%	1.009	K=1.320 Pas^{n}n=0.5	69	0.09051

2.1 Gas Hold Up (ε_g) and Solid Hold Up (ε_s) Measurements

The average gas hold up ε_g was calculated from the equation (1) usingthe data of the clear - liquid height (H_L) and the height of the aerated liquid (H_F) which was determined by visual observation:

$$\varepsilon_g = \frac{H_F - H_L}{H_F - (V_i / S_o)} \qquad (1)$$

(V_i / S_o) In Eq (1) is a correction term for the volume of the draft tube [32] the solid-hold-up was calculated from the equation(2).Using the date of static liquid height (HF) and the height of slurry after adding solid particles ($HF^/$):

$$\varepsilon_s = \frac{\overline{H}_F - H_L}{\overline{H}_F} \qquad (2)$$

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.

2.2 Mixing Time Measurement

Visual monitoring of acid - base reaction between HCL and NaOH was chosen among the various methods presented in the literature for measuring mixing time.

$$HCl + NaOH \longrightarrow NaCl + H_20$$

Methyl red was used as the indicator of the above neutralization reaction. Twenty milliliters of 2N NaOH with about 30 ml of methyl red indicator were added to the liquid which turned deep yellow. When the liquid was not deep colored, the further methyl red indicator was added. After setting the operating conditions and at time = 0, an amount slightly in excess of the stoichiometric quantity of 2N HCl solution (about 21 milliliters), placed in a small beaker, was added to the surface of the liquid near the wall [33, 34]. The mixing time was taken at the time necessary to obtain a complete color change to red. This technique is reliable [33, 34]. An average of three measurements under the same conditions were taken. The technique has been used by a number of workers [see for example the most valuable papers of Brennan and Lehrer [33] , Hiby [35] and Mavros, P., [34].

2.3 Circulation Time Measurement

The method proposed by (Lu et al., [36]; Guy et al., [37]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.

III. Gas hold up result

Figures (2), (3) and (4) show the influence of gas velocity for different liquid phase systems (water, water-ethanol, water-methanol, water-glycerol and water-CMC) on gas hold-up when the down comer-to-riser cross-sectional area ratio = 0.249. In general the gas hold-up increases with increasing gas through put (gas velocity), but interact mutually, depending on liquid phase properties. Many Literatures revealed that increasing superficial gas velocity increased the gas holdup [38, 39, 28, 30]. The variation of a gas holdup in the riser (ε_g) with superficial gas velocity for air-alcohol-solid systems are shown in Figure 3. The experiments were carried out with constant solids (polyethylene 3.4mm particle diameter and the density 853.5 Kg/m^3) loading of 50$Kg/m^3$and the desired liquid height above the distributor (0.75) m. 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 (0.1 m/sec).This was mainly due to the suppression of bubble coalescence i.e. number of small bubbles produced in the riser had an insufficient bubble rise velocity to escape from the liquid,for aqueous solutions of aliphatic alcohols, a considerable increase in the gas hold-up in alcohol chain length was observed. The gas hold up decreased in the following order ethanol > methanol. 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. A similar trend was observed by Koide et al., [40], Nicol and Davidson [41] and Al-Masry and Dukkan[42].The solid particles retard the bubble rise velocity and prevent increases in bubble size. Figure(4). Shows the effect of gas velocity on gas hold-up using different liquid phase (Glycerol and CMC) with solid suspend respectively .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. [43, 44]

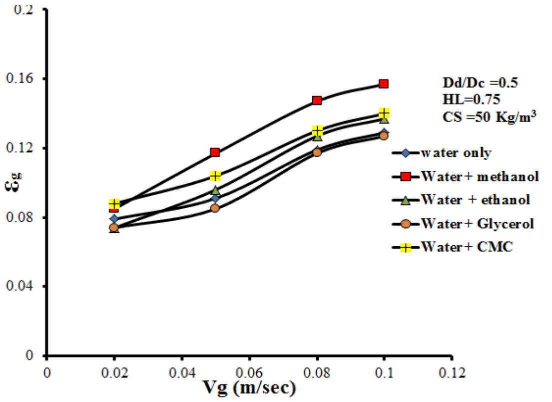


Figure 2:Effect of gas velocity on gas hold up with different liquid phase systems.

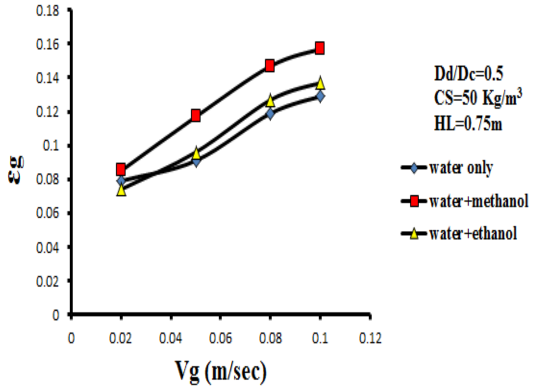


Figure 3: Effect of gas velocity on gas hold up for water, water-methanol and water-ethanol systems.

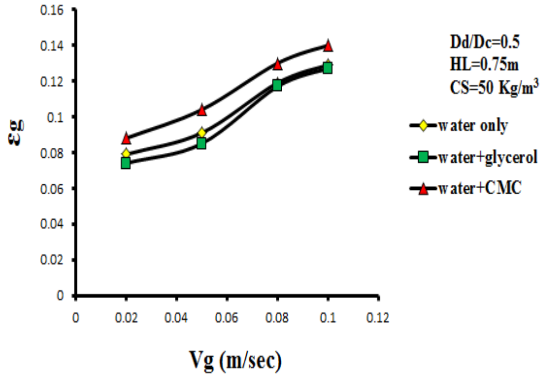


Figure 4:Effect of gas velocity on gas hold up for water, water-glycerol and water-CMC systems.

3.1 Gas Holdup Correlation

Dimensional analysis was used to correlate gas hold-up with gas velocity and liquid properties. It was assumed that (ε_g) is a function of the following factors:-

$$\varepsilon_g = f\,(V_G, \mu_L, \rho_L, \sigma_L, g) \qquad (3)$$

In case of using solid particles, the factors (C_S and ρ_S) will be added to the equation above.

$$\varepsilon_g = f\,(V_G, \mu_L, \rho_L, \sigma_L, g, \rho_S, C_S) \qquad (4)$$

It is possible to predict that there must be a functional relationship between these variables and that the relationship is independent of the units of measure. The simplest form for a function is one in which the variables are multiplied or divided by one another in such a way that dimensionless groups arise. From experimental results, it can be seen that (ε_g) increases with increasing (V_g) and decreases with increasing (μ_L and σ_L), so the resulting correlation applied to predict the gas hold-up for air-water system. The equation will have the form

$$\varepsilon_g = A \times \left[\frac{V_g \mu_L}{\sigma_L}\right]^n \left[\frac{g \mu_L^4}{\rho_L \sigma_L^3}\right]^{-m} \left[\frac{C_S}{\rho_S}\right]^K \qquad (5)$$

The statistical analysis was performed using the capabilities of SPSS software to obtain the values of A, n, m and k.

The final correlation is given by:-

$$\varepsilon_g = 0.242 \times \left[\frac{V_g \mu_L}{\sigma_L}\right]^{0.408} \left[\frac{g \mu_L^4}{\rho_L \sigma_L^3}\right]^{-0.189} \left[\frac{C_S}{\rho_S}\right]^{0.805} \qquad (6)$$

Where: - $\left[\frac{V_g \mu_L}{\sigma_L}\right]$ = Capillary Number

$\left[\frac{\mu_L^4 g}{\rho_L \sigma_L^3}\right]$ = Morton Number

A= 0.242
n= 0.408
m= 0.189
K= 0.805
R^2= 0.967

IV. Mixing time and circulation time results

It appears that liquid circulation and mixing 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 1iquid and solid as well as solid concentration. The mixing process in loop reactors consists of combined effects occurring in the draft tube, annular space and in the top and bottom deflection zones. Mixing 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 mixing fraction of the overall mixing 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 mixing process. The intensive mixing in the deflection zones is caused by differences between velocities in the up and down flow zones. In the top zone, mixing is intensified by the formation of a ring vortex above the draft tube. Figures (5), (6), (7), (8), (9) and (10) shows the effect of gas velocity for different liquid phase systems (water, water-ethanol, water-methanol, water-glycerol and water-CMC) on T_m and T_C when the down comer-to-riser cross-sectional area ratio = 0.249. The figures reveal the following:

(i) The mixing time and circulation time for [water-CMC, water-glycerol, figures (7) and (10)] decreases with increases gas velocity. Because of increases viscosity (water-glycerol system which has a viscosity 6 times that of pure water, table A2), therefore the T_m and T_C are larger than that in water. This is in agreement with literature (e.g. Franz et al [45]).

(ii) In general the overall effect of presence of alcohols [water-methanol, water-ethanol, figure (6)] is that increases the mixing time. These systems represents a strongly coalescence inhibiting systems this leads to a higher gas hold-up in the annular space which decreases the hydrostatic driving force for liquid circulation, therefore the effect of gas velocity on liquid circulation time is approximately similar to that for water figure (9). This is in agreement with the literature (e.g. Pandit and Joshi [46]).

(iii) At high values of gas velocity about 0.1 m/sec the T_m and T_C for different systems become equal because of the liquid velocities approach a constant value.

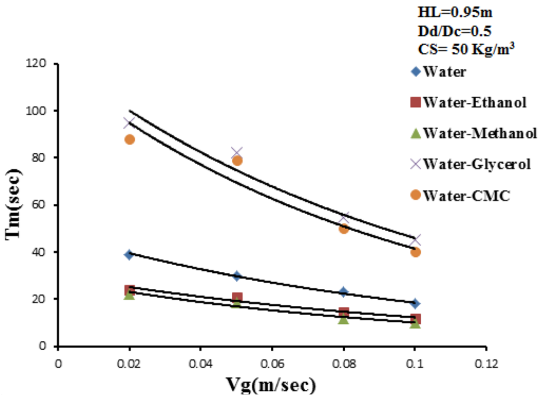


Figure 5:Effect of gas velocity and solid content on mixing time for different liquid phase system.

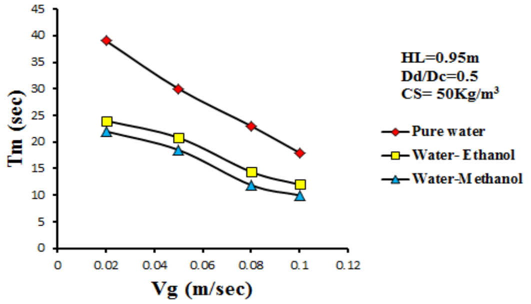


Figure 6:Effect of gas velocity and solid content on mixing time for (water, water- methanol, water-ethanol) systems.

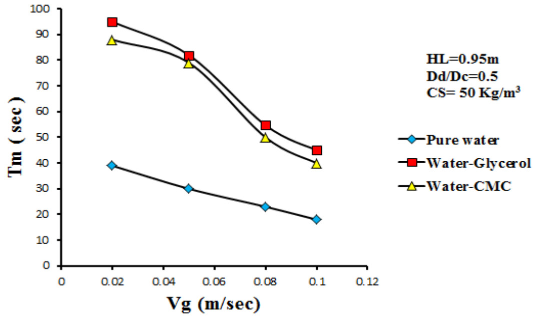


Figure 7:Effect of gas velocity and solid content on mixing time for (water, water- glycerol, water-CMC) systems.

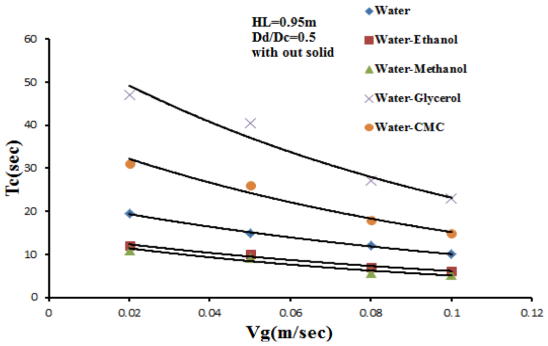


Figure 8:Effect of gas velocity on circulation time for different liquid phase system.

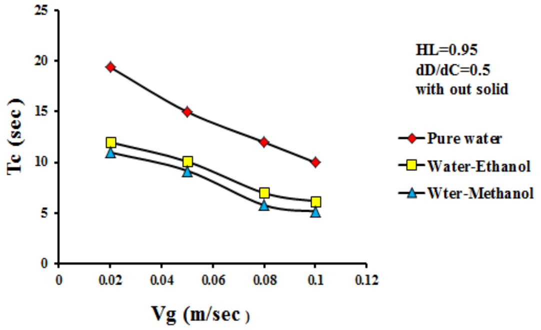


Figure 9:Effect of gas velocity and solid content on circulation timefor (water, water-methanol, water-ethanol) systems.

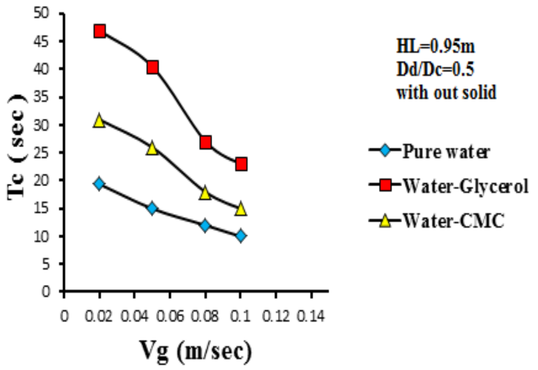


Figure 10:Effect of gas velocity and solid content on circulation timefor (water,water- glycerol, water-CMC) systems.

V. Conclusions

For the present study the following conclusions were made:-

1. The gas hold-up increase with increasing gas velocity for *Vg* ≤ 0.1 m/sec and decrease with increasing liquid surface tension in 8 liters air lift loop reactor in the presence of alcohol and suspended solid particles (polyethylene)and the down comer-to-riser cross-sectional area ratio = 0.249.
2. The mixing time and circulation time decreases with increasing gas velocity for Vg ≤ 0.1 m/sec in the air lift loop reactor when the down comer-to-riser cross-sectional area ratio = 0.249, and the reactor volume equal to 8 liters.
3. The circulation velocity decreases with increasing viscosity and coalescence inhibition of the liquid phase.
4. Higher viscosities enhance internal friction losses, while stronger coalescence inhibition results in a higher gas hold-up in the annular space which decreases the hydrostatic driving force for liquid circulation.

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_{Sa}	Saturated concentration of dissolved oxygen p.p.m
C_S	Solid particle concentration K_G/m^3
D_C	Column diameter
D_i	Diffusivity of oxygen in solution m^2/sec
D_L	Axial dispersion coefficient (liquid) m^2/sec
g	Acceleration of gravity m/sec^2
H_L	Static slurry height (m)
H_F	Level of aerated slurry (m)
$\overline{H}_F$	Level of liquid phase+ solids (m)
K_L	Liquid phase mass transfer coefficient ($m.s^{-1}$)
K_{La}	Overall mass transfer coefficient, based on aerated slurry volume. (Sec^{-1})
Sc	Slurry column
t	Time (min)
V_g	Gas velocity (m/sec)

Greek letters

ε_g	Gas hold up
ε_s	Solid hold up
ρ_L	Liquid phase density kg/m^3
ρ_S	Solid phase density kg/m^3
μ_L	Liquid phase viscosity(C_p)
ν_L	Kinematic viscosity of liquid phase (cm^2/sec)
σ_L	Liquid phase surface tension dyne/cm

Subscripts

G	gas
L	Liquid

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