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Hydrodynamics and Mass-Transfer Studies in a Pilot-Plant Airlift Reactor: Non-Newtonian Systems

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Experimental studies on the effects of surface active agents on the hydrodynamics and mass-transfer performance of a 700 dm^3 pilot-plant external loop airlift reactor have been conducted. The effects of the addition of a silicone polymer antifoam agent on foaming caused by the viscous non-Newtonian solutions of xanthan gum and carboxymethyl cellulose were examined. In general, the addition of the antifoam led to significant reductions in all design parameters, *i.e.*, gas holdup, liquid circulation velocities, and volumetric mass-transfer coefficients relative to the values determined for the air–water system. Presented in this paper are new correlations for riser gas holdup (ϵ_r) and volumetric mass-transfer coefficient ($k_l a$) with effective viscosity (η_{eff}) based on shear rate determined in this reactor. Also, it was found and/or confirmed that the geometric parameter A_d/A_r and V_{sg} had the most effect on the nonadjustable parameters such as riser and downcomer gas holdup, superficial liquid velocity, and specific interfacial area. The disengagement section design has a profound effect on the rate of foaming.

1. Introduction

Conventional bubble columns in which gas is sparged through a pool of liquid are now widely accepted in the chemical industry. With significant developments in biotechnology during the last two decades, several modifications of the bubble column concept have come forth. The airlift loop reactor forms one of the most important classes of the modified bubble column. The airlift concept of employing the hydrostatic pressure difference due to gas injection into a section of the reactor is attractive for applications in both chemical and biotechnology industries. The feasibility of using airlift devices has been established for many processes, for example, aerobic fermentation, treatment of wastewater, and other similar operations. The "Pachuca Tank" used in the metallurgy industry to leach ores of gold, uranium, and other metals is probably the first example of industrial use of this principle for reactor applications (Merchuk and Siegel, 1988). As well as providing good scale-up data, other reasons for the suitability of the airlift fermenter are simple construction with no moving parts, lack of gaskets or glands, good aeration while maintaining a low shear rate, necessary for the culture of fragile micro-organisms (Zenk et al., 1977; Prins and van't Riet, 1987; Beruling et al., 1985; Allan and Scragg, 1986; Wagner and Hempel, 1988; Bugarski et al., 1989).

There are many variations of airlift reactors; however, two basic classes of these reactors need to be distinguished: internal loop airlift reactors, where the division into riser and downcomer is achieved either by installation of a concentric draft tube in the cylindrical column of liquid or by a tightly fitting vertical baffle to give a split cylinder geometry, and external loop airlifts,

where the riser and downcomer are two quite separate tubes connected by horizontal sections near the top and the bottom (Figure 1). The external loop airlift reactors have a lesser variety and modifications center around the gas disengagement section where the riser and downcomer are horizontally connected. The performance of the reactor may be influenced by the design of the gas disengager.

Foaming in fermentation has received scant attention in the scientific literature, which is surprising, since it is one of the main operating problems of commercial fermentation. Foaming is mainly a result of the stabilization of the liquid foam films by the presence of surface-active materials in the fermentation broth. The addition of antifoam is known to affect hydrodynamics, bubble behavior and interactions, and mass-transfer rates in bioreactors (Trinci, 1992; Lee and Tynan, 1988; Kawase and Moo-Young, 1987; Al-Masry, 1993). Further, the nature and extent of the effect seems to depend upon the type of surfactant used, i.e., sparingly soluble substances (for example, octanol and polypropylene glycol) and the insoluble ones (for example, silicone oils) (Prins and van't Riet, 1987). Many of the surface-active agents, particularly the oils, are added as emulsions of suspended oil droplets which can destabilize the foams by acting as hydrophobic bridges between the two film surfaces or by displacing the stabilizing adsorbed material, protein, for example, at the bubble/liquid interface. However, those conditions which cause collapse of the foam structure can also favor the coalescence of bubbles in the body of the liquid. This results in an increase in the mean bubble diameter and a reduction in gas holdup. Both of these effects will tend to reduce the specific interfacial area available for mass transfer. Furthermore, during bubble motion, adsorbed surface-active materials can be swept toward the rear of the bubble, thus creating a surface tension gradient at the surface. This in turn generates shear stresses which inhibit fluid motion close to the bubble and reduce interfacial circulations within the bubble. The net effect

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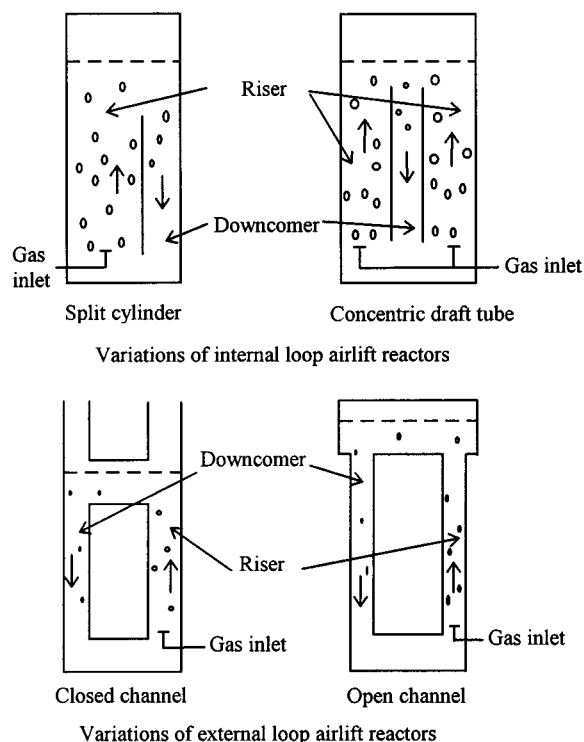
Variations of internal loop airlift reactors

Variations of external loop airlift reactors

Figure 1. Variations of airlift loop reactors.

of this process is to immobilize the bubble interface and to reduce the rate at which fresh liquid can be brought into contact with the bubble surface. In general, small bubbles, i.e., ≤1 mm diameter, tend to have immobile surfaces (and therefore act like solid particles) while large bubbles, i.e., >3 mm diameter, will have only part of the available surface immobilized and should not suffer drastic reduction in mass-transfer potential. It is clear, therefore, that $k_l a$ values may be affected through changes in a, the interfacial area, and/or changes in k_l, the mass-transfer coefficient (Al-Masry, 1993).

Koide et al. (1985) investigated the effect of a selection of surfactants and antifoaming compounds on the hydrodynamic and mass-transfer characteristics of a bubble column. The gas holdup was increased by the addition of the alcohol surfactant while the antifoam caused a reduction in holdup due to enhancement of the coalescence of the bubbles. However, size measurements suggested that the mean bubble size in the antifoam was less than that in water, leading to the expectation that holdup should increase. Gas holdup in the surfactant solutions increased with surfactant concentration while the decrease in holdup in antifoam solutions was more marked at higher concentrations. Volumetric mass-transfer coefficients were found to decrease for both surfactant and antifoam solutions over the entire range of V_{sg} values.

Kawase and Moo-Young (1987) investigated the effects of silicone antifoam on gas holdup and mass transfer in a bubble column. A surfactant, Tween 20, was added to some of the antifoam solutions. Non-Newtonian behavior was examined using carboxymethyl cellulose (CMC) solutions at three different concentrations. Again, holdup was found to decrease upon addition of antifoam over the full range of gas velocities; however, no concentration effect was apparent. The addition of the surfactant caused an increase in holdup due to a suppression of coalescence. In the CMC

solutions voidage decreased with increasing CMC concentrations (and effective viscosity) due to the formation of large, spherical-cap bubbles. However the addition of antifoam (at 200 ppm) caused a reduction of holdup in the solution of lowest CMC concentration whereas slight increases were noted for more concentrated solutions. The addition of antifoams to water caused a substantial reduction (up to 80%) in $k_l a$ values over the full ranges of V_{sg}. This reduction was attributed entirely to a decrease in k_l at the bubble surface due to hindered internal circulation within the bubble. The addition of the surfactant to the antifoam–water system was found to have no effect on the mass-transfer coefficient. The effect of antifoam on the CMC solutions seemed to depend upon CMC concentration. For the low-viscosity solution, a reduction in $k_l a$ was recorded, whereas in the solution of highest viscosity, $k_l a$ was found to increase. For the intermediate CMC solutions, there was no discernible effect of antifoam. For the non-Newtonian solutions the changes in mass-transfer coefficient were assumed to be attributable to changes in the interfacial area, a. The concentration of antifoam and the addition of a surfactant seemed to have no effect on the mass-transfer results. This was surprising since as noted earlier the addition of surfactant caused a marked increase in holdup which might be expected to effect $k_l a$. However, the authors suggested that the extra holdup is present in the form of very small bubbles which make no significant contribution to mass transfer since their residence time is much greater than the time required to come to equilibrium with the liquid.

In a later study, Kawase and Moo-Young (1990) presented more data for the effect of antifoam on bubble column mass-transfer performance. Again, it was assumed that the recorded reduction in $k_l a$ could be attributed to changes in k_l only. This argument, based upon the work of Koide et al. (1985), referred to earlier, was reinforced by the authors who showed that interfacial area, a, calculated using the equation of Akita and Yoshida (1974), was effectively unchanged upon the addition of antifoam.

Although there are a number of other papers which treat this general area, very few of them can be regarded as being directly applicable to the airlift loop reactor design (Akita and Yoshida, 1974; Dowen, 1979; Fields and Slater, 1983, and Nicol and Davidson, 1988).

Effective viscosity (η_{eff}) is one of the design parameters widely used in the literature to correlate mass-transfer and hydrodynamic parameters for viscous non-Newtonian systems. Non-Newtonian liquids usually obey the power-law relationship between shear rate (γ) and shear stress (τ); therefore, the effective viscosity (η_{eff}) can be estimated using

$$\eta_{eff} = \tau/\gamma = K\gamma^{n-1} \qquad (1)$$

where K is the consistency index and n is the flow index behavior. Some average shear rate has to be known in order to use eq 1. Nishikawa et al. (1977), using a bubble column, presented a linear relationship between the average shear rate and the superficial gas velocity:

$$\gamma = CV_{sg} \qquad (2)$$

They assumed that the effective viscosity of a non-Newtonian system is that of a Newtonian system which yields the same heat-transfer coefficient (at the surface of a jacket or immersed coil) at the same superficial gas

velocity. The constant used in eq 2, using glycerine and millet jelly solutions of known viscosities ($\eta = 0.024-0.7$ Pa·s), was found for non-Newtonian systems (CMC, $\eta_{eff} = 0.005-0.6$ Pa·s) to be equal to 5000 m^{-1}.

Popovic and Robinson (1988) investigated hydrodynamics of external loop airlift reactors using Nishikawa's expression to correlate ϵ_r and V_{sl} for viscous Newtonian and non-Newtonian solutions, and they are given by the equations

$$\epsilon_r = 0.465 \, V_{sg}^{0.65}\left(1 + \frac{A_d}{A_r}\right)^{-1.06} \eta_{eff}^{-0.103} \quad (3)$$

and

$$V_{sl} = 0.23 \, V_{sg}^{0.32}\left(\frac{A_d}{A_r}\right)^{0.97} \eta_{eff}^{-0.39} \quad (4)$$

Equations 3 and 4 are valid according to the following experimental conditions: $0.11 \leq A_d/A_r \leq 0.44$, $0.02 \leq \eta_{eff} \leq 0.5$ Pa·s, and $0.02 \leq V_{sg} \leq 0.26$ m/s.

In a later study, Popovic and Robinson (1989) reported mass-transfer coefficients for external loop airlift reactors, using non-Newtonian aqueous solutions of various carboxymethyl cellulose (CMC) concentrations ($0.02 \leq \eta_{eff} \leq 0.5$ Pa·s) and a viscous Newtonian sucrose solution ($\eta = 0.019$ Pa·s). A superficial gas velocity range of $0.02 \leq V_{sg} \leq 0.26$ m/s and downcomer to riser cross-sectional area ratio $0 \leq A_d/A_r \leq 0.444$ was abided by. The η_{eff} values of the CMC solutions were calculated from the power-law model, and shear rates were calculated from the correlation of Nishikawa et al. (1977). The authors assumed that the slip velocity in the downcomer was negligible, and hence the interphase mass-transfer rate in that zone could be neglected. A correlation for $k_l a$ for CMC was derived as follows:

$$k_l a = 2.14 \times 10^{-3} V_{sg}^{0.52}\left[1 + \frac{A_d}{A_r}\right]^{-0.85} (\eta_{eff})^{-0.89} \quad (5)$$

A general correlation for $k_l a$ for the two systems mentioned above was given by

$$k_l a = 0.5 \times 10^{-2} V_{sg}^{0.52} D_L^{0.5} \times$$
$$\left[1 + \frac{A_d}{A_r}\right]^{-0.85} \eta_{eff}^{-0.89} \rho_L^{1.03} \sigma_L^{-0.75} \quad (6)$$

where D_L is the liquid phase oxygen diffusivity ($0.33 \leq D_L \times 10^9 \leq 2.53$ m^2/s), and σ_L is the surface tension ($59 \leq \sigma_L \times 10^3 \leq 79$ N/m). Equation 6 is valid only within the physical property range of the above two systems. The geometric parameter A_d/A_r and the superficial gas velocity were found to have the most significant effects on the mass-transfer coefficients, with $k_l a$ decreasing with increasing A_d/A_r ratio.

One of the serious shortcomings of eqs 3–6 is that they used Nishikawa et al.'s (1977) shear rate correlation (for bubble columns) to derive correlations for airlift reactors. There is also strong criticism in the literature about the validity of Nishikawa's correlation even for bubble columns (Chisti and Moo-Young, 1988; Al-Masry, 1993).

2. Experimental Procedures

A pilot-plant external loop airlift reactor with 700 dm^3 volume, constructed of QVF borosilicate glass sections

Figure 2. Schematic of experimental apparatus.
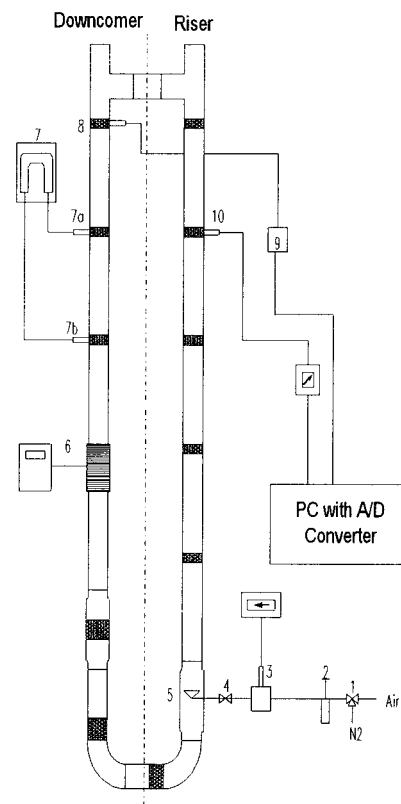
1. Three-way valve
2. Pressure regulator and oil filter
3. Turbine flowmeter
4. Control valve
5. Sparger
6. Electromagnetic flowmeter
7. Inverted U-tube manometer
7(a,b). Pressure tappings
8. Conductivity probe
9. Conductivity meter
10. Oxygen probe and meter

Table 1. Important Dimensions of the External Loop Airlift Reactor

volume	0.7 m^3
riser diameter	0.225 m
downcomer diameter	0.225 m
downcomer to riser cross-sectional area A_d/A_r	1.0
dispersion height	6.2 m
nominal riser length	7.5 m
nominal downcomer length	9.6 m

(Corning Co., U.K.), was employed for all the experimental investigations. Details of its dimensions are given in Table 1 and a schematic of the apparatus is shown in Figure 2. Oil-free air (from a compressor) was employed as the working gas for the system and nitrogen was used for purposes of purging. Either gas was introduced through a perforated plate sparger with 1 mm perforations and monitored by means of a turbine meter (GH FlowAutomation, U.K.). Gas holdup in the riser was measured between two pressure tappings 3.32 m apart, using a differential pressure cell (Honeywell, Minneapolis, MN). Gas holdup in the downcomer was measured between two pressure tappings 1.1 m apart using an inverted U-tube manometer. An electromagnetic flowmeter (Flowmetrix, South Africa) located in the downcomer was used to measure liquid velocities. Hence, the superficial liquid velocity based upon the downcomer area is given by

$$V_{ld} = (V_{ld})_{measured}(1 - \epsilon_d) \quad (7)$$

Volumetric mass-transfer determinations were made using the dynamic method with a well-mixed model

Table 2. Rheological Properties of Xanthan Gum Solutions

xanthan (wt %)	flow index n (−)	consistency index k (Pa·s^n)
0.01	0.92	0.002
0.05	0.54	0.041
0.10	0.51	0.101
0.20	0.32	0.519

(Weiland and Onken, 1981; Bello and Robinson, 1985; Chisti and Moo-Young, 1988; Popovic and Robinson, 1989; Al-Masry, 1993). For the mass-transfer determinations, the column was purged with nitrogen until the level of oxygen dropped to ≅0.5 mg/L before air could be introduced into the column. This was done for every flow rate of air used. The average test duration was varied between 20 and 2 min. Dissolved oxygen concentrations were monitored continuously using an OXI 196 oxygen meter (WTW, Germany) with a rapid response electrode EO 196 (WTW, Germany). A material balance on the oxygen in the batch liquid phase yields

$$\frac{dC_L}{dt} = k_l a(C_E - C_L) \tag{8}$$

and the oxygen electrode signal delay is given by

$$\frac{dC_p}{dt} = K_p(C_L - C_p) \tag{9}$$

Simultaneous solution of eqs 8 and 9 yields

$$\frac{C_E - C_L}{C_E - C_{L0}} = \frac{K_p e^{-k_l a t} - k_l a e^{-K_p t}}{K_p - k_l a} \tag{10}$$

Equation 10 was expressed in the form

$$C_L = C_E - (C_E - C_{L0})\frac{K_p e^{-k_l a t} - k_l a e^{-K_p t}}{K_p - k_l a} \tag{11}$$

and the two parameters $k_l a$ and K_p were determined from a nonlinear regression program Polymath (Cache Co., Austin, TX). The probe used to determine the dissolved oxygen concentration from which the $k_l a$ values were determined was located about one-third along the riser. The probe was mounted horizontally, at 90° to the flow direction, to minimize bubble impacts and to ensure a reasonable level of mixing at the membrane surface.

Both Newtonian and non-Newtonian fluid systems were studied. For Newtonian fluids, (filtered) tap water from the municipal water supply was used. Microbiological cultures often behave as non-Newtonian fluids (Kawase and Moo-Young, 1987). In order to simulate the rheological behavior of these cultures, aqueous solutions of polymer carboxymethyl cellulose (CMC) (Sigma Chemicals, St. Louis, MO) and xanthan gum (Sigma Chemicals, St. Louis, MO) were used. The effects of surface-active agents on the hydrodynamics and mass-transfer parameters were studied using silicone polymer antifoam (Sigma Chemicals, St. Louis, MO).

The rheological properties of xanthan and CMC solutions were obtained using a Brookfield Viscometer (Model LVDVII+). The power-law parameters are given in Tables 2 and 3.
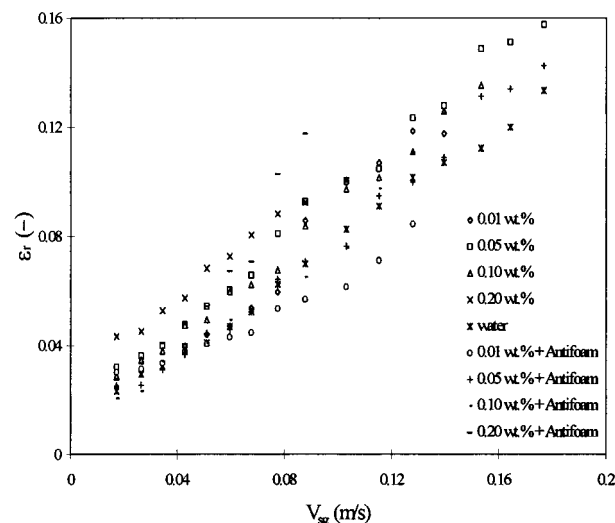
Figure 3. Riser gas holdup vs superficial gas velocity for xanthan gum solutions.

Table 3. Rheological Properties of CMC Solutions

system	flow index n (−)	consistency index k (Pa·s^n)
CMC1	0.98	0.006
CMC2	0.96	0.011
CMC3	0.81	0.174

Table 4. Surface Tension Data for Xanthan Gum Solutions

xanthan (wt %)	σ (N/m)	σ (N/m) + 15 ppm SP
0.01	0.0696	0.0566
0.05	0.0669	0.0501
0.10	0.0682	0.0525
0.20	0.0663	0.0522

Table 5. Surface Tension Data for CMC Solutions

system	σ (N/m)	σ (N/m) + 15 ppm SP
CMC1	0.0688	0.0479
CMC2	0.0664	0.0429
CMC3	0.0590	0.0445

The surface tension of the different solutions was measured using a torsion balance (White Electrical Co. Ltd., U.K.) with a 4 cm duNouy platinum ring. Surface tension data, with and without antifoams, for all the systems investigated are presented in Tables 4 and 5.

3. Results and Discussion

3.1. Xanthan Gum Solutions. The effect of antifoam agent on the gas holdup in aqueous solutions of xanthan gum is shown in Figures 3 and 4. In the pure xanthan aqueous solutions, the addition of xanthan to water increased the gas holdup in both the riser and downcomer across all the concentrations. All the aqueous solutions of xanthan were very viscous, except for the 0.01 wt % which exhibited a rheology that was similar to water. For these viscous systems, a considerable fraction of very small bubbles (≤1 mm) in diameter were entrained in the reactor. As the concentration of xanthan was increased, more small bubbles were entrained, which supports the trend of increasing gas holdup with increasing xanthan concentration. Flow in the downcomer was countercurrent with large slugs (1−5 cm) rising upward and small bubbles (1−20 mm) going downward. Severe foaming was experienced for xanthan and because of the difficulty in removing most of the gas bubbles before the liquid journey into the
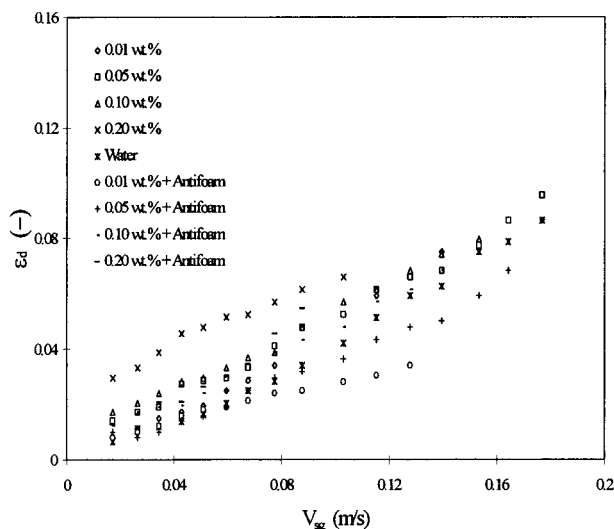
Figure 4. Downcomer gas holdup vs superficial gas velocity for xanthan gum solutions.
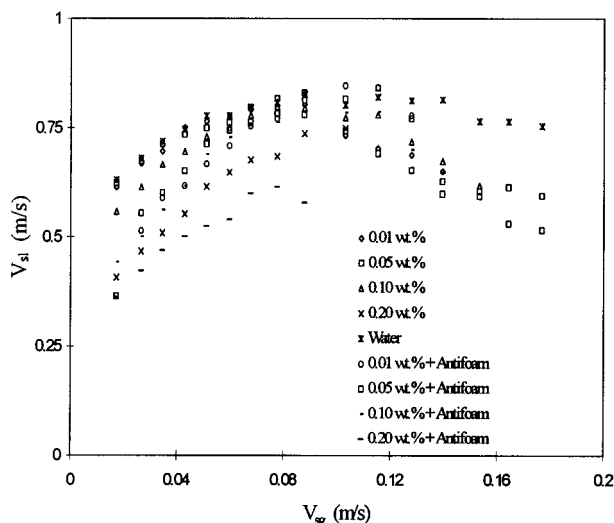

Figure 5. Superficial liquid velocity vs superficial gas velocity for xanthan gum solutions.

downcomer, the small bubbles were entrained and continued circulating in the system, leading to large gas holdup. Figure 5 shows a decrease in liquid velocity, with the highest (most viscous) concentration causing the greatest reduction. The effect of the addition of SP antifoam to the xanthan solution was noticeable immediately, with a change in the noise of the circulating solution as soon as the antifoam was injected, becoming more vigorous probably due to the formation of rigid spheres. Another observation when the antifoam was injected was that the turbidity of the solution decreased due to the enhancement of the coalescence of the tiny bubbles. The higher concentrations of xanthan caused a great increase in the riser gas holdup, while a marginal effect was observed for the others. A trimodal bubble size was noted in the downcomer for the higher concentrations of xanthan: 1−5 cm diameter rigid spheres rising up, and 1−3 mm diameter round bubbles accompanied by (4−15 mm) spherical-cap bubbles going down. A reduction in the downcomer gas holdup was noticed for the lower concentrations of xanthan as opposed to an increase for the more viscous solutions. The results for the liquid velocity show a slight difference from that of pure xanthan alone.
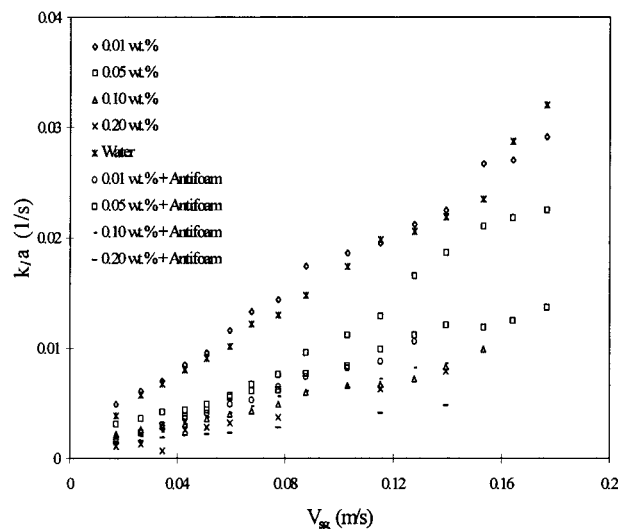

Figure 6. Volumetric mass-transfer coefficient vs superficial gas velocity for xanthan gum solutions.

As discussed earlier, the Ostwald de Waele (or power law) model is often used to describe a fluid's dependence on the shear rate. The effective viscosity can be calculated if the shear rate for a particular system is known. Use of the Nishikawa correlation (eq 2) for airlift reactors has generated some controversy in the literature since it has been developed exclusively for use for bubble columns. The shear rate correlations used in this work were derived by Al-Masry and Chetty (1996) using the same external loop airlift reactor, and on the basis of the downcomer liquid velocity. The authors proposed the following correlations describing the effective shear rate as a function of V_{sg} for xanthan gum solutions (eq 12) and for CMC solutions (eq 13):

$$\gamma_{eff} = 14795 V_{sg}^{2} + 128.76 V_{sg} + 0.4996 \quad (12)$$

$$\gamma_{eff} = 27625 V_{sg}^{2} + 358.32 V_{sg} + 22.54 \quad (13)$$

for the experimental conditions $0.002 \leq V_{sg} \leq 0.06$ m/s and $A_d/A_r = 1$. The ensuing hydrodynamic and mass-transfer correlations shown in this study are derived using the shear rate correlations given by eq 12 and 13.

The riser gas holdup was correlated by

$$\epsilon_r = 0.9856 V_{sg}^{0.8747} \eta_{eff}^{0.0577} \quad (14)$$

according to the following experimental conditions: $0.002 \leq V_{sg} \leq 0.06$ m/s, $0.32 \leq n \leq 0.92$, $0.002 \leq k \leq 0.519$, and $A_d/A_r = 1$. For comparison, the correlation proposed by Popovic and Robinson (1989), and by this work, is given in Figure 11. The data of this work and that of Popovic and Robinson (1988) are very close, almost superimposed. The effective viscosity has a weak influence on the riser gas holdup and this is supported by the fact that although Popovic and Robinson (1988) used a different shear rate correlation to estimate the effective viscosity, the comparison between theirs and this work is fairly close.

The volumetric mass-transfer coefficients for aqueous xanthan solutions with and without SP antifoam is shown in Figure 6. In general the addition of xanthan to water exhibited a decrease in volumetric mass-transfer coefficients that were directly dependent on concentration. The lowest concentration of xanthan had

almost no effect on the mass transfer, while increasing the xanthan concentration caused a great reduction in $k_l a$ values. The addition of SP antifoam to xanthan seemed to have a weak effect on the downcomer gas holdup and the superficial liquid velocity but a strong effect on the riser gas holdup and the mass-transfer characteristics. The $k_l a$ values dropped by about 40% with added antifoam as opposed to without. The antifoam enhanced the coalescence of the tiny bubbles and this is consistent with the drop in $k_l a$ values since the coalescence of bubbles decreased the interfacial area available for mass transfer.

The volumetric mass-transfer coefficients measured in the xanthan gum solutions were correlated by

$$k_l a = 0.0032 \, V_{sg}^{0.7271} \eta_{eff}^{-0.5282} \qquad (15)$$

for the experimental conditions mentioned above. This work is compared to the correlation proposed by Popovic and Robinson (1989) and is shown in Figure 11. Prediction of mass-transfer coefficients by Popovic and Robinson highly overestimates the experimental results of this work. The reasons for this could be that (1) their correlation is based on a shear rate correlation used for bubble columns and (2) their equation yielded very high values for effective viscosity, thereby raising the values for $k_l a$. It should also be mentioned that Popovic and Robinson (1988, 1989) neglected downcomer entrainment in all of their mass-transfer evaluations and considered the downcomer as a "dead" zone with regard to mass transfer. They reported that the rise velocity in highly viscous liquids is negligible, and therefore, there is no slip between the phases in the downcomer. It must be stressed that there is a strong effect of the mode of operation on $k_l a$. The $k_l a$ values increase with decreasing A_d/A_r, approaching a maximum value for $A_d/A_r = 0$. The increased liquid velocity with increased A_d/A_r ratio acts to lower the riser gas holdup and, hence, reduces the specific interfacial area available for mass transfer in this section.

3.2. Carboxymethyl Cellulose Solutions. Many workers have used CMC as their model media for filamentous microbiological cultures rather than xanthan gum because CMC solutions are transparent as opposed to the opacity of xanthan solutions; therefore CMC solutions afford a better view of the bubble size distribution than xanthan. The effect of SP antifoam on the gas holdup in the CMC aqueous solutions is shown in Figures 7 and 8. In the pure CMC aqueous solutions, the addition of CMC to water caused a decrease in the gas holdup in both the riser and the downcomer. As the viscosity of the solution was increased, the turbulence in the riser subsided and the bubble size distribution increased. Larger bubbles, some spanning half the width of the column diameter, were present in the riser along with 1−15 mm diameter small bubbles. For the more viscous CMC solutions bubble clusters (spherical-cap bubbles with a tail of small round bubbles) were observed to creep upward along the downcomer wall. The residence time of bigger bubbles is very small, since they rise rapidly through the riser, hence leading to lower gas holdup in the CMC solutions compared to that in water. Like xanthan, the superficial liquid velocity (Figure 9) decreased as the solution became more viscous. The gas holdup for CMC1 was lowered due to the addition of antifoam. The antifoam, however, caused an increase in the holdup for
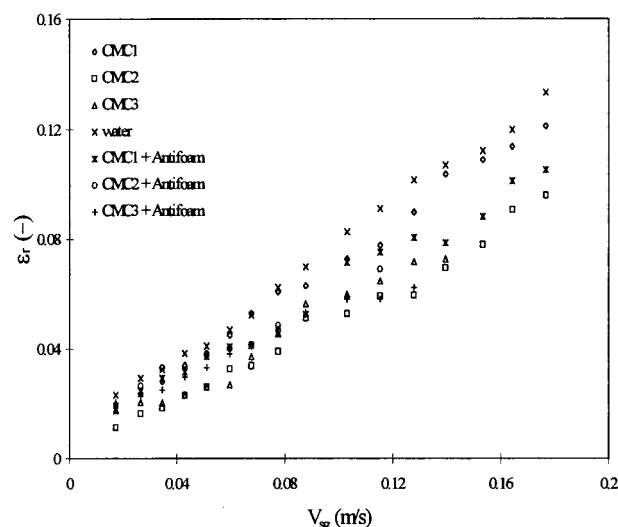

Figure 7. Riser gas holdup vs superficial gas velocity for CMC solutions.
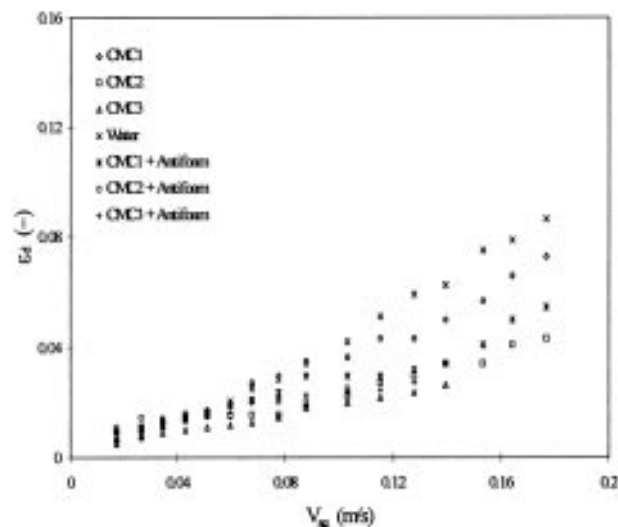

Figure 8. Downcomer gas holdup vs superficial gas velocity for CMC solutions.

the more viscous solutions, i.e., CMC2 and CMC3. This observation was also noted by Kawase and Moo-Young (1987) who studied the effects of antifoam agents on CMC solutions in a bubble column. The addition of antifoam to the least viscous solution caused a decrease in the gas holdup due to bubble coalescence. For the more viscous solutions, the addition of antifoam may have enhanced bubble breakup rather than bubble coalescence, thereby causing an increase in gas holdup.

A correlation for the gas holdup in the riser was developed and is given by

$$\epsilon_r = 0.3245 \, V_{sg}^{0.9032} \eta_{eff}^{-0.0925} \qquad (16)$$

according to the following experimental conditions: $0.002 \leq V_{sg} \leq 0.06$ m/s, $0.81 \leq n \leq 0.98$, $0.006 \leq k \leq 0.174$, and $A_d/A_r = 1$. Figure 12 shows that the gas holdup for this work was lower than that predicted by Popovic and Robinson (1989) with the ratio $A_d/A_r \leq 0.444$. This is consistent with the fact that as the A_d/A_r ratio is increased, then the gas holdup decreases. Popovic and Robinson (1989) observed that the superficial gas velocity had a strong influence on the riser gas holdup, while the effective viscosity had a weak
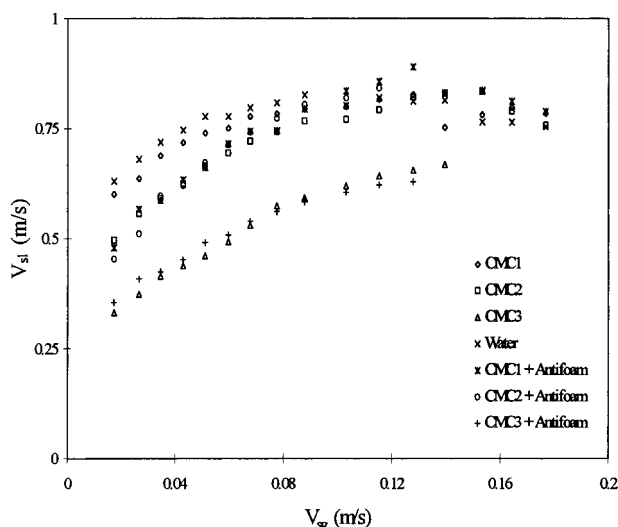
Figure 9. Superficial liquid velocity vs superficial gas velocity for CMC solutions.
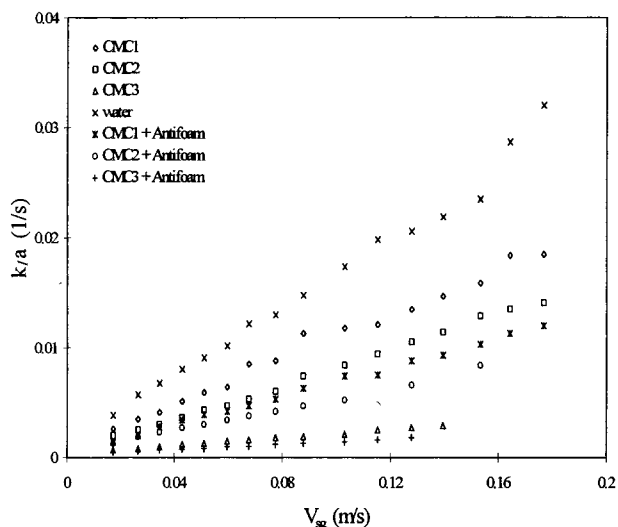

Figure 10. Volumetric mass-transfer coefficient vs superficial gas velocity for CMC solutions.

effect. This statement is true for this work in regard to the gas velocity and regarding the effective viscosity. The rheology of the CMC solutions was found to have a slight effect on the riser gas holdup, with the more viscous solutions causing slightly greater reductions in voidage than the least viscous solution.

The volumetric mass-transfer coefficients in aqueous CMC solutions with and without SP antifoam are plotted against the superficial gas velocity in Figure 10. The addition of antifoam showed a substantial reduction in the volumetric mass-transfer coefficients. It should also be noted that foaming was evident only in the lowest concentration of CMC and absent for both the higher concentrations CMC2 and CMC3. This could attribute to why there is hardly any difference in mass transfer between CMC2 and CMC3 with antifoam. The volumetric mass-transfer coefficient was correlated by

$$k_{\mathrm{l}}a = 0.0023 V_{\mathrm{sg}}{}^{0.8797} \eta_{\mathrm{eff}}{}^{-0.6966} \tag{17}$$

according to the experimental conditions mentioned before. This correlation is compared to the work of Popovic and Robinson (1989) and presented in Figure 12. As expected from previous work on CMC solutions,
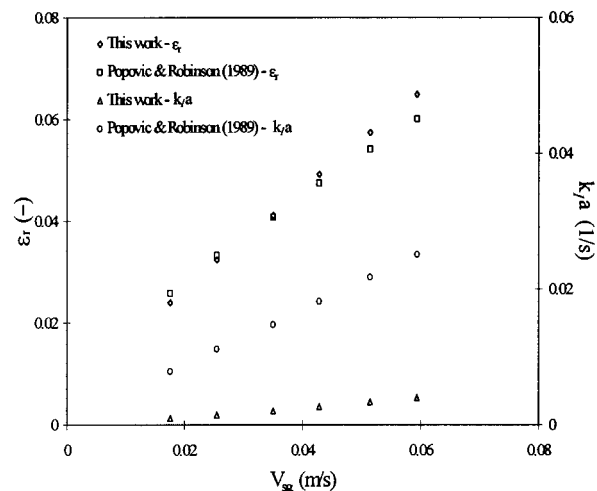

Figure 11. Riser gas holdup and volumetric mass-transfer coefficient vs superficial gas velocity for xanthan gum solutions.
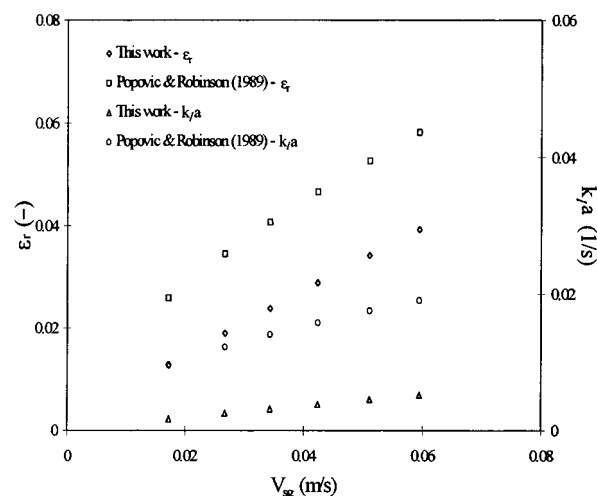

Figure 12. Riser gas holdup and volumetric mass-transfer coefficient vs superficial gas velocity for CMC solutions.

the mass-transfer coefficient increased significantly with increasing superficial gas velocity and decreased with increasing CMC viscosity. The influence of reactor geometry $A_{\mathrm{d}}/A_{\mathrm{r}}$ on $k_{\mathrm{l}}a$ is evident with Popovic and Robinson's correlation ($A_{\mathrm{d}}/A_{\mathrm{r}} \leq 0.444$) yielding higher mass-transfer values than those in this work ($A_{\mathrm{d}}/A_{\mathrm{r}} = 1$).

4. Conclusions

The external loop airlift reactor geometry provides a well-defined flow path, high gas capacity, low shear levels, and an easily controlled environment. However, processes that give rise to severe foaming will lead to operational difficulties and, in extreme cases, will destroy the continuity of the flow loop. For many of the experimental investigations performed in this work, entrainment of small bubbles in the downcomer was unavoidable. This phenomenon should not be ignored and must be quantified since it affects the driving pressure difference and also the volumetric mass-transfer coefficient in the reactor. Design of an effective gas disengagement section where most of the small bubbles entering the downcomer can be removed is a very important step in improving an airlift reactor's performance.

In general, the addition of small amounts of antifoam agent led to significant reductions in gas holdup, liquid

circulation velocities, and volumetric mass-transfer coefficients, relative to the values obtained for the air–water systems.

For the non-Newtonian systems studied, xanthan gum and CMC, the mass-transfer coefficients were significantly reduced. This reduction was found to be directly dependent on concentration for both systems. To identify conclusively the mechanism by which mass transfer is reduced, the interfacial area must be independently measured. The geometric parameter A_d/A_r and superficial gas velocity were found and/or confirmed as being the parameters which most affect the nonadjustable parameters such as riser and downcomer gas holdup, superficial liquid velocity, and interfacial area. The effective viscosity had a significant effect on the volumetric mass-transfer coefficient but only a relatively weak effect on riser gas holdup.

Nomenclature

a = specific interfacial area (m²/m³)
A_d = downcomer cross-sectional area (m²)
A_r = riser cross-sectional area (m²)
C_E = equilibrium oxygen concentration (mg/L)
C_L = dissolved oxygen concentration (mg/L)
C_{L0} = initial dissolved oxygen concentration (mg/L)
C_P = concentration registered by oxygen probe (mg/L)
D_L = liquid phase oxygen diffusivity (m²/s)
k_l = liquid phase mass-transfer coefficient (m²/s)
$k_l a$ = volumetric mass-transfer coefficient (1/s)
K_p = effective probe constant (1/s)
t = time (s)
V_{sg} = superficial gas velocity in the riser (m/s)
V_{sl} = superficial liquid velocity in the riser (m/s)
V_{ld} = downcomer superficial liquid velocity (m/s)

Greek Symbols

ρ = density (kg/m³)
ϵ = gas holdup
γ = shear rate (1/s)
τ = shear stress (N/m²)
σ = surface tension (N/m)
η = viscosity (Pa·s)

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