

# The role of gas disengagement and surface active agents on hydrodynamic and mass transfer characteristics of airlift reactors

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## Abstract

The hydrodynamics and mass transfer characteristics of a 0.7 m<sup>3</sup> external loop airlift reactor were experimentally investigated for superficial gas velocities between 0.02 and 0.18 m s<sup>-1</sup>. The reactor was made of QVF glass sections with 6.5 m in height and 0.225 m in diameter of both riser and downcomer. The effects of the addition of minute quantities of silicone polymer, polypropylene glycol and octanol, on air–water systems were examined. In general, the addition of surface active agents led to significant reductions in volumetric mass transfer coefficients and liquid circulation velocities, relative to the values determined for the air–water system. However, for the gas hold-up, surfactants produced higher values in contrary to antifoams which reduced the gas hold-up due to enhancement of bubbles coalescence. The gas disengagement section was found to have a great effect on the reactor performance, especially when foaming increased in the system. Of the two gas disengagement sections used (namely, closed and open channel) the closed channel configuration failed to remove the increasing small bubbles and the reactor continuity disrupted at high gas throughputs. In contrast, the open channel configuration improved the reactor performance with substantial reduction in downcomer gas hold-up and increase in volumetric mass transfer coefficient. © 1997 Published by Elsevier Science S.A.

*Keywords:* Airlift reactor; Hydrodynamics; Mass transfer; Surfactant; Antifoam; Gas disengagement

## 1. Introduction

Airlift loop reactors are increasingly used in the chemical process industry, fermentations, and wastewater treatment. Their popularity has been attributed to their simple construction, low shear rate, low power consumption and good mixing characteristics. The absence of moving parts and a well characterised flow pattern are other attractive features [1]. Many fermentation broths contain substances which affect interfacial behaviour, frequently leading to the production of foam in all types of bioreactors. It has been suggested that protein concentrations as low as 1 mg l<sup>-1</sup> can cause serious foaming in commercial bioreactors giving rise to severe operating problems and possible reductions in final biomass yields [2]. Foams can be stabilised either by substances such as surfactant molecules which directly enhance foam structure or by

viscous additives which increase foam drainage times [3]. Antifoam compounds are therefore routinely used to suppress foam formation. Possible affects of antifoam addition on the operation and performance of airlift reactors have received scant attention in the literature [4,5].

The addition of antifoam is known to affect hydrodynamics, bubble behaviour and interactions, and mass transfer rates in bioreactors [2,4,5]. Further, the nature and extent of the effect seems to depend upon the type of surfactant used, i.e. sparingly soluble substances, e.g. octanol, polypropylene glycol, and the insoluble ones, e.g. silicone oils [3]. Many of the surface active agents, particularly the oils, are added as emulsions of suspended oil droplets which can destabilise the foams by acting as hydrophobic bridges between the two film surfaces or by displacing the stabilising adsorbed material, e.g. protein, at the bubble/liquid interface. However, those conditions which cause collapse of the foam structure can also favour 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 hold-up. 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 towards the rear of the bubble

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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 of this process is to immobilise 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.  $\leq 1$  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 immobilised and should not suffer drastic reduction in mass transfer potential [6]. It is clear, therefore, that  $k_1a$  values may be affected through changes in  $a$ , the interfacial area and/or changes in  $k_1$ , the mass transfer coefficient.

Koide et al. [7] investigated the effect of a selection of surfactants (aqueous solutions of *n*-hexanol and *n*-octanol) and an antifoaming compound (Nissan Disfoam) on the hydrodynamic and mass transfer characteristics of a rectangular bubble column ( $0.2 \times 0.15 \times 1.5$  m<sup>3</sup>). Bubble sizes, at three locations in the column were measured using photography. Mean bubble size combined with the experimentally determined gas hold-up yielded values for  $a$ , the specific interfacial area. Values of  $k_1$ , the mass transfer coefficient, could then be calculated using the  $k_1a$  measurements. The gas hold-up was increased by the addition of the alcohol surfactant while the antifoam caused a reduction in hold-up 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 hold-up should increase. Gas hold-up in the surfactant solutions increased with surfactant concentration while the decrease in hold-up 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 [4] investigated the effects of silicone antifoam on gas hold-up and mass transfer in a bubble column of 0.23 m diameter and 1.22 m height. A surfactant, Tween 20 (polyoxyethylene sorbitan monolaurate), was added to some of the antifoam solutions. Non-Newtonian behaviour was examined using CMC solutions at three different concentrations. Again, hold-up 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 hold-up 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 hold-up in the solution of lowest CMC concentration whereas slight increases were noted for more concentrated solutions. The addition of antifoams to water caused a dramatic reduction (up to 80%) in  $k_1a$  values over the full ranges of  $V_{sg}$ . This reduction was attributed entirely to a decrease in  $k_1$  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  $k_1a$  was recorded, whereas in the solution of highest viscosity,  $k_1a$  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 hold-up which might be expected to effect  $k_1a$ . However, the authors suggested that the extra hold-up 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 [5] presented more data for the effect of antifoam on bubble column mass transfer performance. Again, it was assumed that the recorded reduction in  $k_1a$  could be attributed to changes in  $k_1$  only. This argument, based upon the work of Koide et al. [7], referred to earlier, was reinforced by the authors who showed that interfacial area,  $a$ , calculated using the equation of Akita and Yoshida [8], was effectively unchanged upon the addition of antifoam.

Fröhlich et al. [9] characterised a pilot plant airlift tower bioreactor by evaluating phase properties with model media. The 4 m<sup>3</sup> reactor was of an internal loop, 8.43 m in height and 0.692 m in diameter for the outer tower, and 6.8 m in height and 0.559 m in diameter for the inner tower. The model media were tap water, 1% (v/v) ethanol and 0.08 vol.% antifoam agent (Antispumin GH). Axial dispersion coefficient in the gas phase was found to be the highest in the presence of antifoam, intermediate in tap water and the smallest in ethanol solution.

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 reactor design [10–14]. One investigation, which has direct relevance to the present work is that of Nicol and Davidson [15] who studied the effect of surfactants on the hydrodynamics of a circulating bubble column with equal riser and downcomer diameters of 0.24 m and dispersion height of 9.0 m. The surfactants used were *n*-octanol at 200 ppm and bovine serum albumin (BSA) at 0.1–0.3 g l<sup>-1</sup>. The extreme stability of the foam produced by the BSA caused considerable changes in reactor behaviour, since the small bubbles ( $\cong 1$  mm) produced in the riser had an insufficient rise velocity to escape from the liquid in the disengagement section and were, therefore, entrained in the downcomer flow. Gas hold-up in the downcomer reduced the overall lifting action of the reactor. Although there was no determination of mass transfer in this study, the authors clearly showed that the addition of small amounts of surface

active materials can have a profound effect on the performance and hydrodynamic behaviour of the airlift reactor.

## 2. Experimental

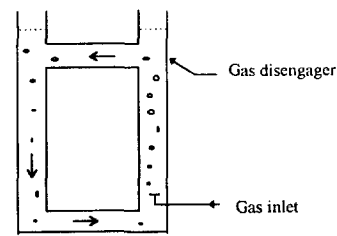
A pilot-plant external loop airlift reactor made of QVF glass sections, with an active volume of 0.7 m<sup>3</sup>, was used in this work. The main dimensions of the reactor are given in Table 1. Air was introduced through a plate sparger (diameter, 0.19 m) with 1 mm perforations and monitored by means of a turbine meter (GH FlowAutomation, UK). The liquid velocity in the downcomer was measured using an electromagnetic flow meter (Flowmetrix, ZA). The output of the electromagnetic flow meter was corrected for the entrained bubbles [16].

Gas hold-up in the riser between tappings 3.32 m apart, was measured using a differential pressure cell (Honeywell, USA), and in the downcomer between tappings 1.1 m apart using an inverted U-tube manometer. For all experiments reported, filtered air from a gas compressor and unfiltered tap water were used.

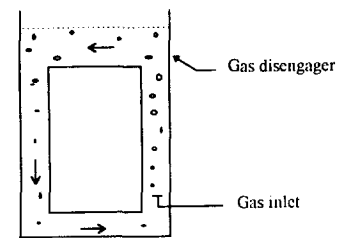
Volumetric mass transfer determinations were made using the dynamic method with a well-mixed model [17–20]. Dissolved oxygen concentrations were monitored continuously using a OXI 196 oxygen meter (WTW, Germany) with a rapid response electrode EO 196 (WTW, Germany). Detailed mathematical modelling is given elsewhere [20].

The effect of surface active agents on the hydrodynamics and mass transfer characteristics of the airlift reactor were studied using octanol, silicone based antifoam (SP) and polypropylene glycol (PPG). Table 2 lists the different concentrations and corresponding surface tension values.

To examine the role of the gas disengagement section on the hydrodynamics and mass transfer characteristics of airlift reactors in the presence of surface active agents, two types of gas disengagers were used in this study, namely closed and



I. Closed channel configuration.



II. Open channel configuration.

Fig. 1. Variations of the airlift reactor disengagement section configuration.

open channel. The closed channel configuration was a circular conduit (length, 1.2 m) with a diameter equal to the riser and downcomer, and the open channel configuration was a rectangular tank (constructed of glass) mounted at the top of the riser and downcomer. The tank was 0.5 m in height, 1.6 m in length and 0.4 m in width. Fig. 1 shows the configuration of both systems. A schematic diagram of the experimental set-up is shown in Fig. 2.

## 3. Results and discussion

### 3.1. Closed channel system

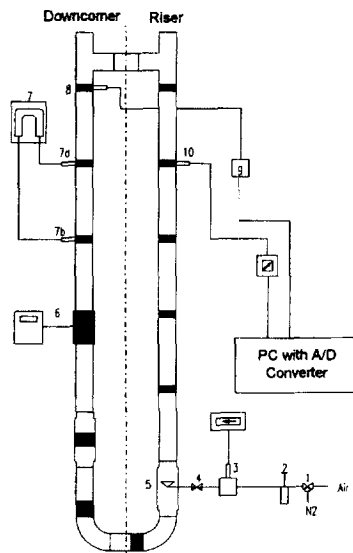
Fig. 3 shows gas hold-up as a function of the riser superficial gas velocity. The addition of SP antifoam is seen to cause a reduction in voidage at all concentrations over the entire range of gas throughputs studied. The most severe reduction corresponds to an antifoam loading of 30 ppm, whereas at higher concentrations there seems to be a gradual approach to the pure water values. The influence of the second surface active agent, PPG, on the hold-up does not appear to depend on PPG concentration until a superficial gas velocity of 0.08 m s<sup>-1</sup> is exceeded. Beyond this velocity, the operating characteristics of the reactor changed dramatically. It was observed that foam formation in the disengagement section became severe, bubble disengagement was impeded and significant volumes of dispersion were displaced with the foam through the constant overflow. The churning effects of this flow lead to increased gas entrainment and drag-down in the downcomer thus giving rise to very high gas hold-ups. The airlift action was disrupted. Gas hold-up for octanol was increased for all concentrations examined but to a lesser extent than those produced by PPG. Fig. 4 shows gas hold-up in the downcomer produced by the three systems. Fig. 5

Table 1  
Dimensions of the external loop airlift reactor

Item	0.7 m <sup>3</sup> ALR
Riser diameter	0.225 m
Downcomer diameter	0.225 m
Downcomer to riser cross-sectional $A_d/A_r$	1.0
Dispersion height	6.2 m
Nominal riser length	7.5 m
Nominal downcomer length	9.6 m

Table 2  
Surface tension of water with surface active substances

Species	Concentration (ppm)	$\sigma$ (N m <sup>-1</sup> )
Silicone polymer	30–100	0.042–0.046
Polypropylene glycol	30–100	0.038–0.044
Octanol	30–100	0.055–0.064



- 1 Three-way valve
- 2 Pressure regulator
- 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

Fig. 2. Schematic diagram of the experimental apparatus showing the closed channel configuration.

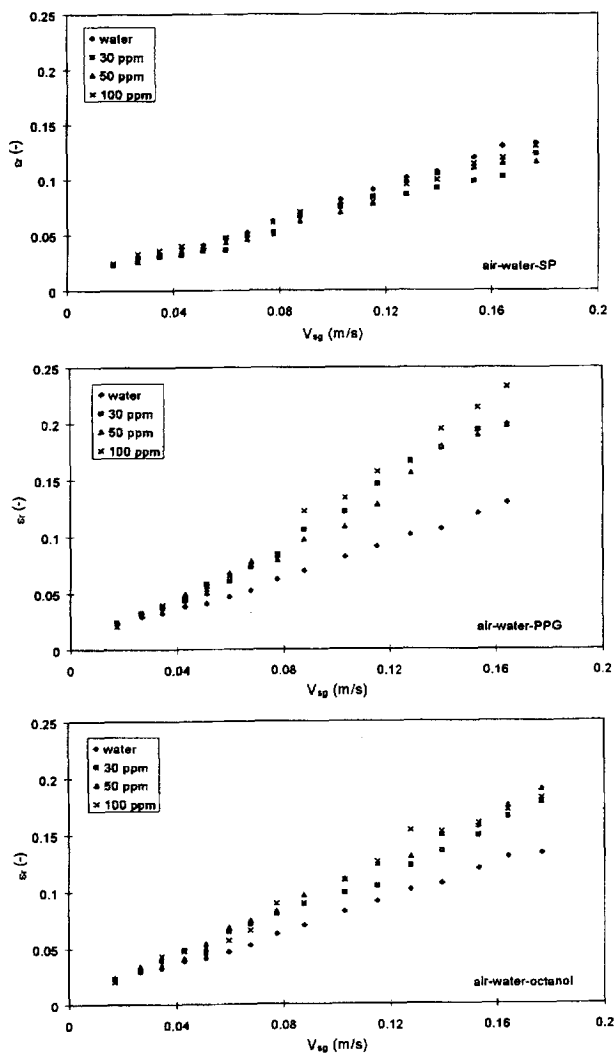


Fig. 3. Gas hold-up versus superficial gas velocity.

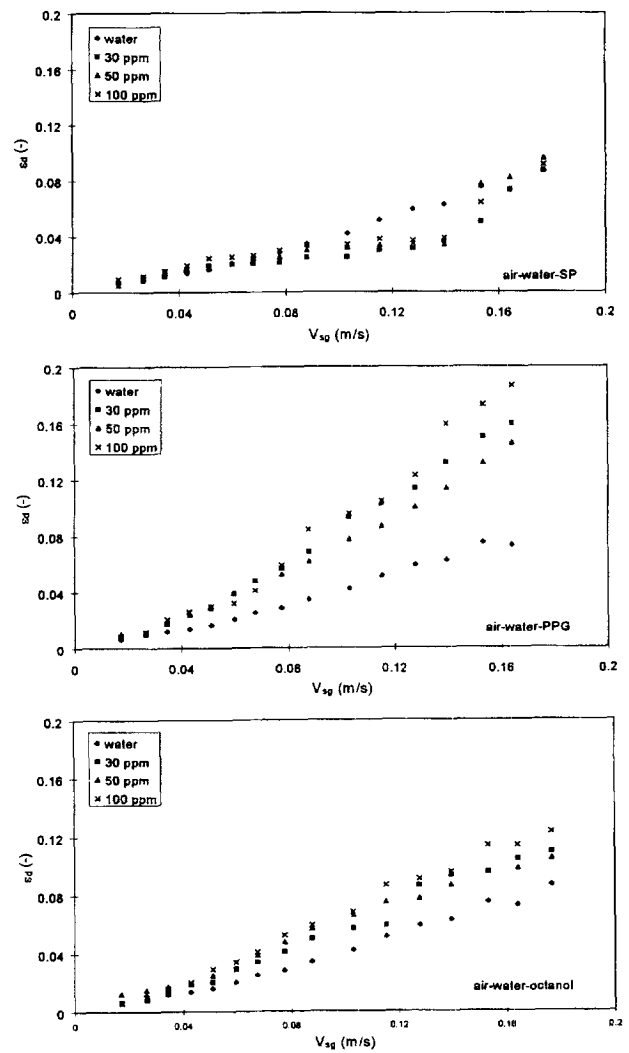


Fig. 4. Gas hold-up in the downcomer versus superficial gas velocity.

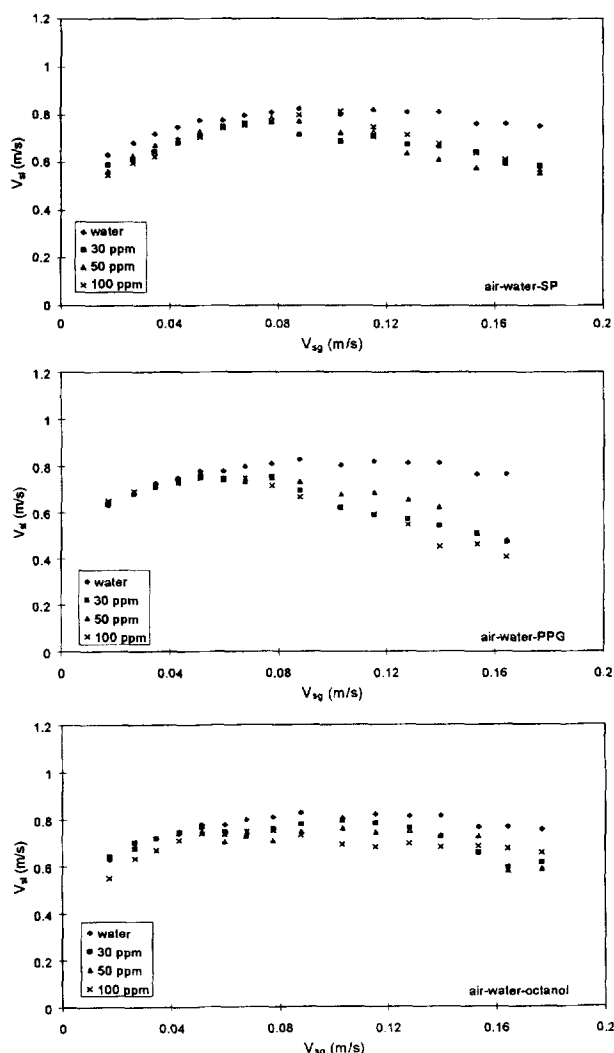


Fig. 5. Liquid circulation velocity versus superficial gas velocity.

summarises the experimental results for the liquid circulation velocity in the presence of SP, PPG and octanol. It is clear that SP and octanol have only marginal effects on the value of the liquid velocity which is consistent with the voidage data. On the other hand the results for PPG at very high superficial gas velocities reflect the operational difficulties described earlier. Volumetric mass transfer coefficients in the presence of various levels of surface active agents are illustrated in Fig. 6. A significant reduction in  $k_L a$  of the order of 50% is apparent. It was noticeable, however, for the SP there was an increase in mean bubble size along with the generation of a large number of small bubbles ( $\approx 1$  mm in diameter). In the case of PPG, up to a superficial gas velocity of  $0.08 \text{ m s}^{-1}$ , there is a noticeable reduction in  $k_L a$ . For higher values of  $V_{sg}$ , the disruption of column performance by the severe foaming conditions again led to quite unreliable determinations. For the octanol, the maximum effects were evident at the highest concentration. The hydrodynamic results for the antifoams revealed several interesting features. The most striking result is the marked difference between reactor performance for the SP system and PPG and octanol systems,

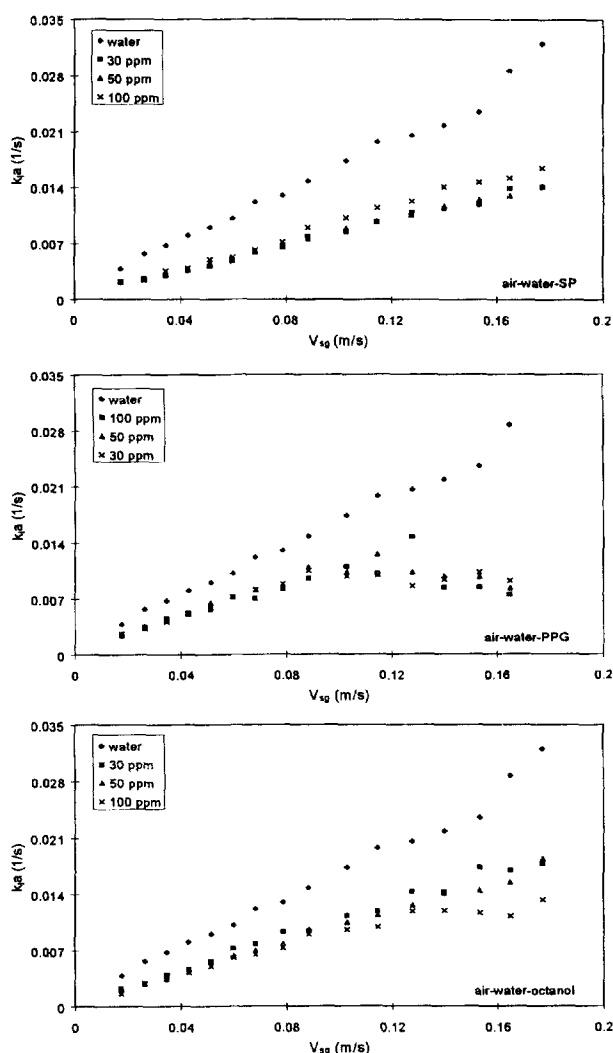


Fig. 6. Volumetric mass transfer coefficient vs. superficial gas velocity.

even though surface tension measurements indicated that interfacial conditions should be similar. These results are consistent with earlier studies [20] carried out in a smaller reactor ( $0.055 \text{ m}^3$ ) that had a similar configuration to that described here.

Slip velocity plots for all surface active agents used are shown in Fig. 7. In the case of the SP antifoam, slip velocities are high relative to the pure water case and show a similar concentration dependence to that exhibited by the voidage and velocity plots. For PPG and octanol, the behaviour of the slip velocity is markedly different. In general, the values are lower than those for water. The foregoing confirms the observation that the two classes of surface active agents behave in quite contrasting ways. The SP appears to promote coalescence, giving rise to large bubbles and high slip velocities, whereas PPG and octanol appear to promote the formation of more uniformly spherical bubbles. It is significant that at each setting of superficial gas velocity, a considerable time was required before steady conditions could be established. Frequently, the electromagnetic flow meter output continued to fluctuate for up to 10 minutes before a constant value was

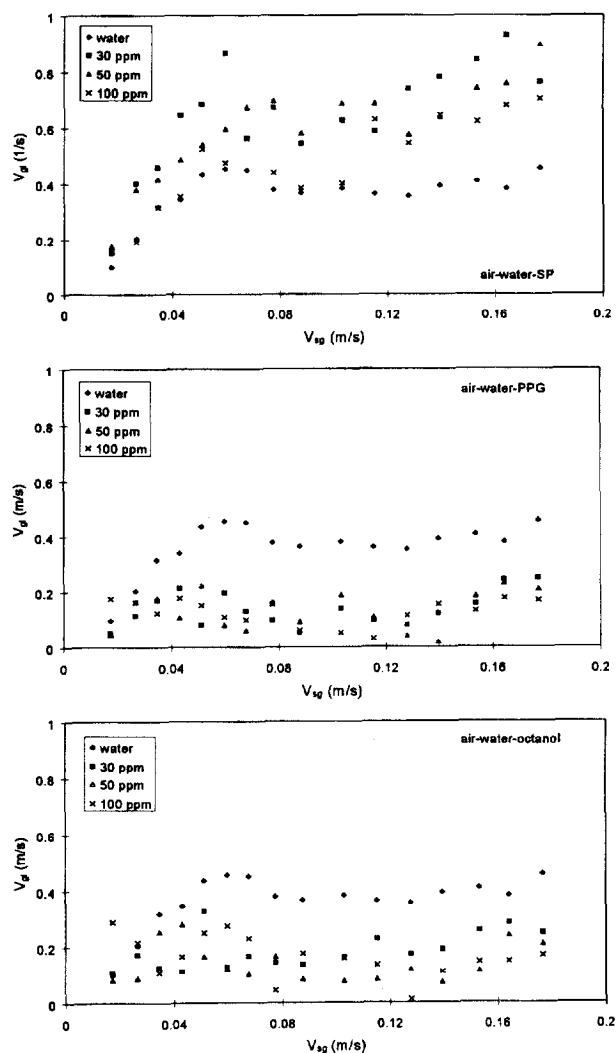


Fig. 7. Slip velocity versus superficial gas velocity for SP, PPG and octanol.

achieved. This lag effect was due to interaction between foam build-up, entrainment and dispersion volume adjustment. This type of behaviour was also observed by Nicol and Davidson [15] and Al-Masry [20]. Dowen [10], in a study investigating mass transfer in tower fermenters (bubble columns), reported comparable behaviour to that noted above for a silicone antifoam (Silcolapse) and polypropylene glycol (P 2000). Slugging was very noticeable with the former material and gas hold-ups were lower than in the air–water system. In contrast, higher hold-ups were reported in the presence of the PPG. The results were interpreted in terms of reduced surface tension in the case of the PPG. Measurements of the surface tension of the Silcolapse indicated surface tension values similar to those for water and the Silcolapse behaviour was interpreted in terms of reduced “intermolecular forces with no contribution to surface rigidity or viscosity”. Walter and Blanch [21], in a detailed investigation of bubble break-up in turbulent pipe flows, proposed that low molecular weight additives (typically  $< C_8$ ) behave in a predictable manner with respect to the maximum stable size of bubble that can withstand a given turbulent environment. However, for

longer chain containments, the use of the nominal value of surface tension (determined by the usual methods) seriously underestimates the size of the maximum stable bubble. This greater stability was attributed to an enhanced surface elasticity which arises because long-chain molecules take longer to orient themselves and adsorb at much slower rates. For antifoams the results of this work generally agree with trends reported in the literature [3,4,13,20,22]. It has been shown that the type of antifoam used will certainly influence the hydrodynamic and interfacial interactions in the column. While the choice of antifoam system and concentration to be used in a particular application may well depend on other factors, the hydrodynamic effects cannot be ignored. The effect of antifoams on mass transfer coefficients was very significant, giving reductions of approximately 50–60% relative to those in pure water. Referring again to the plot in Fig. 7, a significant increase in slip velocity is observed for all SP concentrations. This results from the formation of, on average, larger bubbles in the riser which lead to an associated reduction in the interfacial area,  $a$ . It seems reasonable to attribute the differences between water and SP antifoam results to this decrease in  $a$ . Within the range of antifoam concentrations investigated here, there is very little effect of concentration on the  $k_1 a$  reduction. The trend in slip velocities as SP concentration increases suggests two opposing effects, namely a decrease in  $k_1$  and an increase in interfacial area  $a$  (via changes in diameter and hold-up). These effects would appear to give  $k_1 a$  values which are broadly independent of concentration and this, to some extent, qualitatively explains the experimental findings. The  $k_1 a$  reduction is again observed for the PPG and octanol concentrations. In contrast to the SP antifoam, for octanol, there appears to be a concentration dependence of  $k_1 a$ . The slip velocity plot (Fig. 7) indicates substantially concentration-independent behaviour. There may, if anything, be a slight increase in average bubble size, which could contribute to a reduction in the interfacial area,  $a$ , but this effect is unlikely to explain the experimentally determined reductions in  $k_1 a$ , of approximately 50–60%, shown in Fig. 6. In this case, it would appear that it is the mass transfer coefficient  $k_1$  which has experienced a reduction. The mass transfer behaviour for all of the antifoam solutions shows a gradual increase with gas throughput. In fact, the variation for all conditions is adequately described by mostly linear relationships.

### 3.2. Open channel system

It is clear from the above observations and those noticed by Al-Masry [20], that the importance of the gas disengagement section, in the performance of its function, particularly for systems with foam formation potential, cannot be over-emphasised. The gas disengagement section configuration, determines what fraction of the gas coming out of the riser recirculates into the downcomer or disengages and escapes at the top of the reactor. This in turn affects the reactor driving force for liquid circulation, which consequently affects all

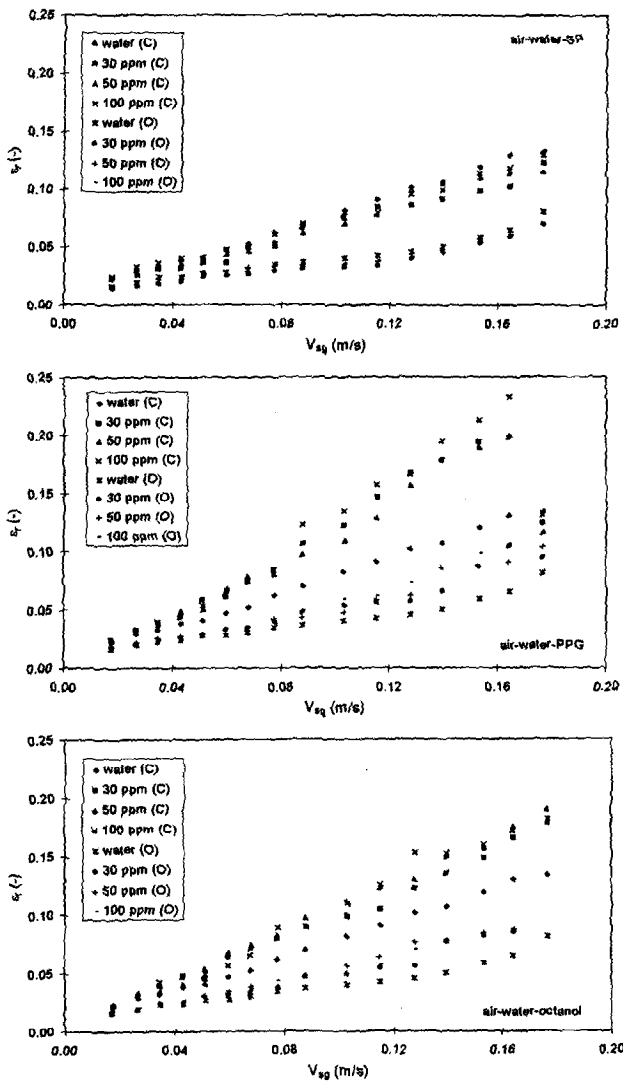


Fig. 8. Comparison of riser gas holdup using both closed (C) and open (O) channel configurations.

the hydrodynamics and mass transfer characteristics of the reactor.

Choi et al. [23], studied the effects of three gas–liquid separators on the hydrodynamics and oxygen transfer of a  $0.1 \text{ m}^3$  split-channel airlift reactor. The fluid investigated was air–water only. The authors reported a different behaviour in the system hydrodynamics and oxygen transfer in each separator. These changes were explained as “emanating from a combination of the gas–liquid separating ability of the design and its hydraulic resistance”. It is clear that there is limited published work that is directly related to this important aspect of the airlift reactor design.

In this section, results obtained in the open channel configuration are presented. To study the role of the gas disengagement section, data was obtained for the same conditions as those in the closed channel configuration. Comparison of results obtained in closed and open channel configurations are presented in Figs. 8–11. Gas hold-ups for SP, PPG and octanol systems are shown in Fig. 8. It is clear that the open channel configuration has affected the gas hold-up compared

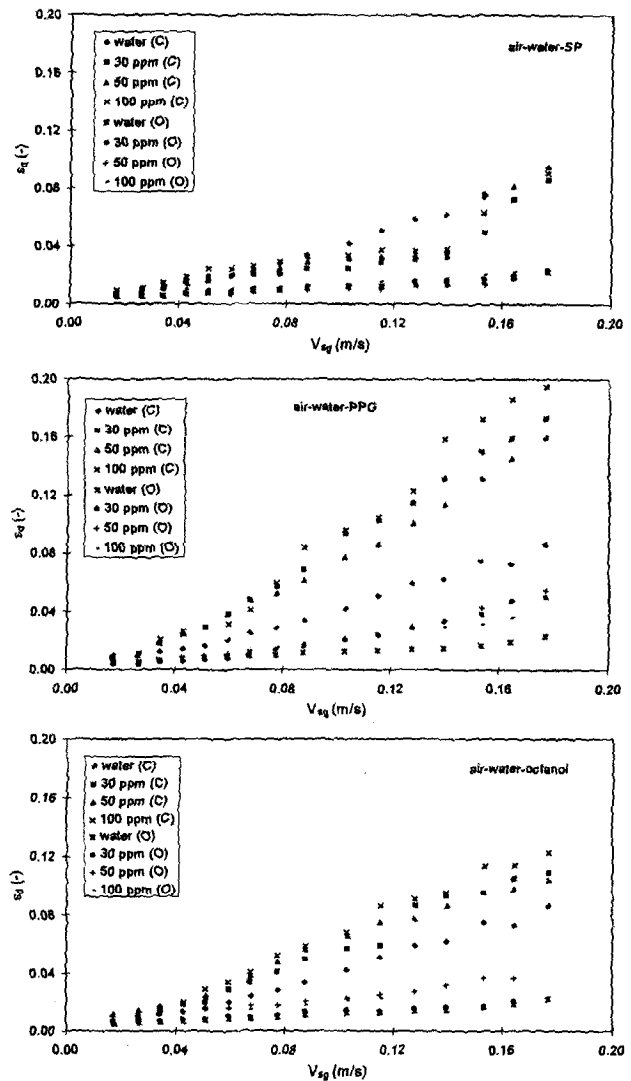


Fig. 9. Comparison of downcomer gas holdup using both closed (C) and open (O) channel configurations.

to the closed channel configuration. For the air–water system, the open channel configuration reduced the riser gas hold-up by an average of 30%, an indication of reduction in the amount of entrained gas bubbles in the downcomer. This is supported by results for downcomer gas hold-up shown in Fig. 9. The effects of adding surface active agents to the system are similar to those explained in the above section (i.e. Section 3.1), and repeated here in the same fashion. There was no disruption of the column continuity at high gas throughputs for PPG and octanol. This is an important improvement of the gas-disengagement section performance. Liquid circulation profiles (Fig. 10) show an increase in superficial liquid velocity with increasing superficial gas velocity for all the values in the range examined. However, surface active agents had marginal effects on liquid circulation velocities which is consistent with gas hold-up profiles in the downcomer.

Volumetric mass transfer coefficients are shown in Fig. 11. One noticeable effect is the tremendous increase in volumetric mass transfer coefficient values compared to those

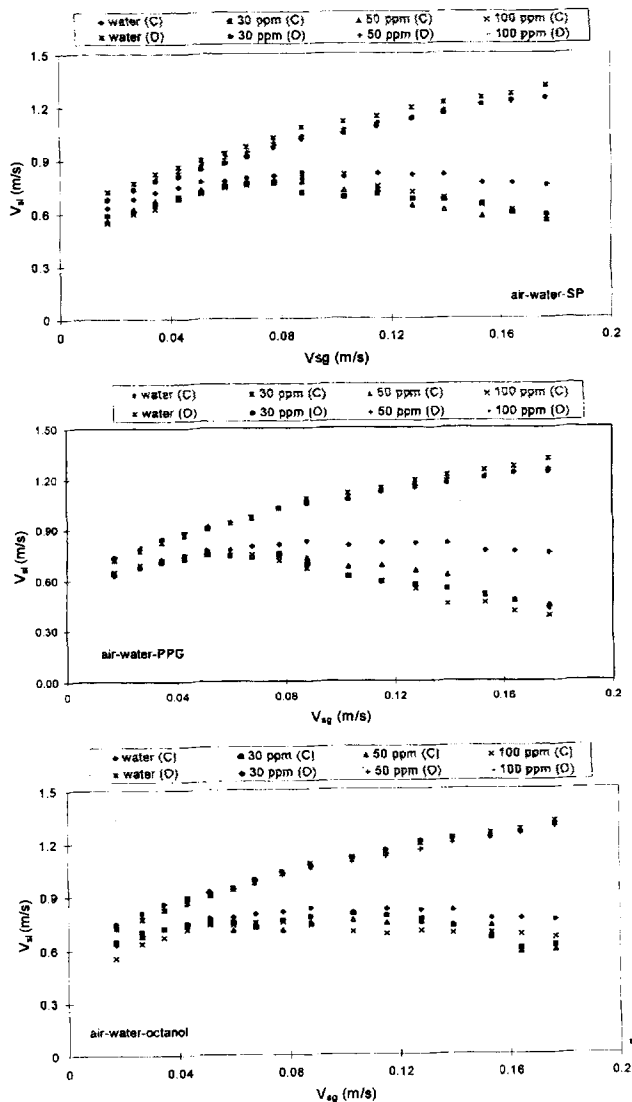


Fig. 10. Comparison of liquid circulation velocity using both closed (C) and open (O) channel configuration.

recorded in the closed channel configuration. This could be explained in terms of a substantial reduction of the entrained small bubbles in the downcomer. These bubbles are usually depleted from oxygen and act as a sink when they recirculate and mix with the fresh bubbles in the riser. Again, the surface active agents decreased the reactor mass transfer capacity by 20–50%.

#### 4. Conclusions

The external loop airlift reactor geometry provides a flexible and easily controlled environment for gas liquid contacting, is relatively insensitive to changes in fluid properties and can accommodate systems of widely differing characteristics. However, processes which give rise to severe foaming will lead to operational difficulties and, in extreme cases, will destroy the continuity of the flow loop, if the gas-liquid separator is not designed carefully. Design of an effective gas

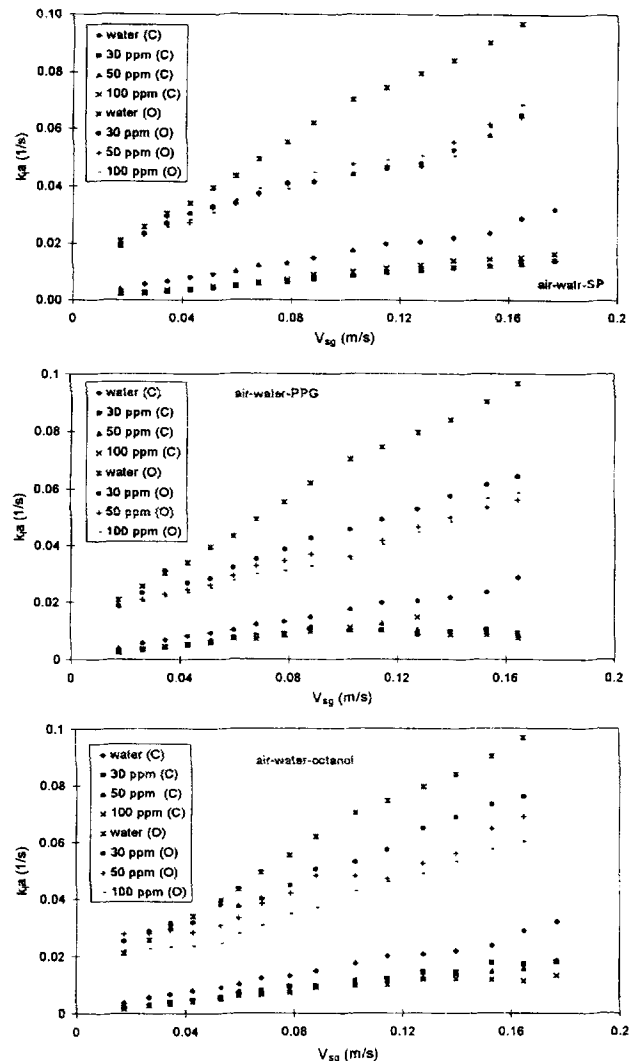


Fig. 11. Comparison between volumetric mass transfer coefficients using closed (C) and open (O) channel configurations.

disengagement section, where most of the small bubbles entering the downcomer can be removed, is a very important step in improving airlift reactors performance. From this work, open channel configuration of the gas separator proved to be the best design for foaming and non-foaming systems. Closed channel configuration of the gas separator must be avoided.

The addition of small amounts of surface active agents reduced the mass transfer capacity of the reactor quite severely by 20–50%. Furthermore, the effect depended on the type of surface active agent used.

#### 5. Nomenclature

- $a$  specific internal area based on volume of dispersion,  $m^2/m^3$
- $A_r$  riser cross-sectional area,  $m^2$
- $A_d$  downcomer cross-sectional area,  $m^2$
- $k_l$  liquid phase mass transfer coefficient,  $m^2 s^{-1}$
- $k_{La}$  volumetric mass transfer coefficient,  $s^{-1}$



$t$	time, s
$U_g$	linear gas velocity = $V_{sg}/\epsilon$ , $m\ s^{-1}$
$V_{gl}$	slip velocity = $U_g - v_l$ , $ms^{-1}$
$v_l$	linear liquid velocity = $V_{sl}/(1 - \epsilon)$ , $m\ s^{-1}$
$V_{sg}$	superficial gas velocity, $m\ s^{-1}$
$V_{sl}$	superficial liquid velocity, $m\ s^{-1}$
$\epsilon_r$	riser gas hold-up, fraction
$\epsilon_d$	downcomer gas hold-up, fraction
$\sigma$	surface tension, $N\ m^{-1}$

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