Hydrodynamics and Mass Transfer in a Draft Tube Airlift Reactor with Dilute Alcohol Solutions

B. Albijanić, V. Havran, D. Lj. Petrović, M. Đurić, and M. N. Tekić
Dept. of Chemical Engineering, Faculty of Technology, University of Novi Sad, 21000 Novi Sad, Serbia

DOI 10.1002/aic.11306

The aim of this work was to investigate an influence of different alcohols on the behavior of a draft tube airlift reactor. The main hydrodynamic and mass transfer parameters in 1 wt % aqueous solutions of five aliphatic alcohols were examined. The results showed that alcohol addition enhanced gas holdup and mass transfer coefficient, but led to notable reduction of liquid velocity and hence elongation of circulation time, relative to the values determined for water. By introducing the surface tension gradient as a relevant independent variable, we defined a simple empirical correlation for overall gas holdup, circulation time, and mass transfer coefficient. The proposed empirical correlations have shown a satisfactory agreement between the calculated and the experimental data. © 2007 American Institute of Chemical Engineers *AIChE J,* 53: 2897–2904, 2007

Keywords: multiphase reactors, draft tube airlift reactor, alcohol addition, hydrodynamics, mass transfer

Introduction

Important applications of draft tube airlift reactors (DT-ALRs) include a variety of bioreactions, such as fermentations, where the properties of the liquid phase strongly affect hydrodynamics, bubble behavior, and mass transfer rates. It is considered that the liquid-phase behavior in bioreactors and in coal liquefaction can be simulated by dilute nonviscous aqueous alcohol solutions[1] because one of the significant properties which differs considerably from water is surface tension.[2] Moreover, alcohols may be added during biological treatment processes as an external source of carbon.

Dilute aqueous solutions of alcohols, as surfactants, represent a coalescence inhibiting systems, which (by having an impact on bubble size) influence the global hydrodynamics and mass transfer parameters. The mechanism of the alcohol action on the hindering of coalescence was discussed and described in detail by several authors.[1,3–7] When dissolved in water, polar alcohol molecules tend to adsorb at the gas–liquid interface and may accumulate around the bubbles thus forming a “protective” rigid monolayer that inhibits the coalescence between the bubbles.[7–9] When a bubble moves through a liquid, adsorbed alcohol molecules are pushed to the back of the bubble causing surface tension gradient which opposes the tangential shear stress. Consequently, the increase of the drag on the bubble results in the reduction of the rise velocity.[9] A concise review of studies on the gas holdup, liquid velocity, and volumetric mass transfer coefficient in dilute alcohol solutions in bubble columns (BCs) and airlift reactors is presented in Table 1.

It is well known that addition of relatively small amount of alcohol increases gas holdup in aqueous solutions[1,11–14,18–21] in the BCs and airlift reactors. Also, Zahradnik et al.[6] found that addition of relatively small amount of normal aliphatic alcohol (from ethanol to *n*-octanol) in viscous saccharose solution increased the gas holdup up to 150%. The decrease of surface tension in the presence of alcohol results in smaller average size of bubbles and consequently lower bubble rise velocities.[20] Lesser rise velocities enhance the entrainment of bubbles into the downcomer section of airlift reactor. It has been perceived that the influence of alcohols on gas holdup is increasing with the increase of their concentration and the length of the carbon chain in alcohol molecule, in the BC,[1,12] continuous BC,[1]

Correspondence concerning this article should be addressed to V. Havran at vesnahavran@yahoo.com.

Table 1. The Review of Investigations of Hydrodynamics and Mass Transfer in Dilute Alcohol Solutions in Bubble Columns and Various Types of Airlift Reactors

Contactor Type	Author	D, cm	D_R/D, %	Type of Sparger	Liquid	Investigated Parameters
DT-ALR	Chakravarty et al.[10]	10	59	Multiple orifice, 18 holes, $d = 1.5$ mm	1 and 2% i-butanol	ε_G, ε_{GD}, ε_{GR}, W_{LR}
	Fields and Slater[11]	15.2	63	Porous plate	1% ethanol	ε_G, t_C
	Weiland[12]	20	59	Sinter plate, $d = 150–200$ μm	0.22% isopropanol	ε_G, t_C
	Kennard and Janekeh[13]	22	45	Sinter plate, $d = 150$ μm	10 g/l ethanol, 10 g/l ethanol + CMC	ε_G, U_{LD}, t_C
	Petrović et al.[14]	20	40, 50, 75	Perforated plate, 19 holes, $d = 1$ mm	0.5% *n*-butanol	ε_G, ε_{GD}, ε_{GR}, W_{LD}, k_La
	Wachi et al.[15]	22	54	Perforated plate, 45 holes, $d = 0.5$ or 1 mm	0.25–1% ethanol	ε_{GD}, ε_{GR}, Q_L
	Freitas and Teixeira[2]*	14.2	44	Perforated plate, 30 holes, $d = 1$ mm	10 g/l ethanol	ε_{GD}, ε_{GR}, W_{LR}, W_{LD}, t_C
	Freitas et al.[16]*	14.2	44	Perforated plate, 30 holes, $d = 1$ mm	10 g/l ethanol	ε_{GD}, ε_{GR}, U_{LR}
	Freitas and Teixeira[17]*	14.2	44	Perforated plate, 30 holes, $d = 1$ mm	10 g/l ethanol	k_La
	this work	10.6	51	Single orifice, $d = 4$ mm	0.5 and 1% methanol, ethanol, *n*-propanol, isopropanol, *n*-butanol	ε_G, W_{LD}, t_C, k_La
BC	Kelkar et al.[1]	30, 15.4	–	Perforated plate, $d = 1.6$ mm, $d = 1$ mm	0.5% methanol, ethanol, *n*-propanol, isopropanol, *n*-butanol	ε_G
	Pošarac and Tekić[18]	10.6	–	Single orifice, $d = 4$ mm	0.5 and 1% methanol and *n*-butanol, 0.5 % ethanol, and *n*-propanol	ε_G, k_La
	Camarasa et al.[7]	10	–	Single orifice $d = 5$ mm, multiple orifice, 62 holes $d = 1$ mm, porous glass plate, $d = 10–16$ μm	1×10^{-3} mol/l *n*-butanol, 4×10^{-4} mol/l *n*-pentanol	ε_G
	Zahradnik et al.[6†]	60	–	Two orifices, $d = 1.6$ mm	1 kmol/m^3 methanol, ethanol, *n*-butanol, *n*-pentanol, *n*-heptanol	ε_G
EL-ALR	Pošarac[19]	10.6	–	Single orifice, $d = 4$ mm	0.5 and 1% methanol and *n*-butanol, 0.5 % ethanol, and *n*-propanol	ε_G, k_La
	Al-Masry et al.[8]	22.5	–	Plate sparger, $d = 1$mm	30–100 ppm octanol	ε_G, ε_{GD}, ε_{GR}, U_L, k_La
SR-ALR	El Azher et al.[20]	20 × 20	–	Single orifice, $d = 3.5$ mm	0.05% methanol, *n*-propanol, *n*-butanol	ε_G, k_La, W_{LD}

*A draft tube airlift reactor with an enlarged degassing zone.
†Addition of alcohol in saccharose solution.

external loop airlift reactor (EL-ALR),[13] and split rectangular airlift reactor (SR-ALR).[20] The increase of alcohol concentration significantly influences bubble coalescence after exceeding the minimal concentration reported by Keitel[22] for aliphatic alcohols used in this work. Further increase of the alcohol concentration has positive effect only up to a limiting value.[2] Beyond this limiting concentration, further addition of alcohol causes only formation of undesirable foam.[7]

Changes in gas holdup values affect liquid velocity, since the difference between gas holdup values in the riser and downcomer sections of an airlift reactor is a driving force for liquid circulation. Therefore, the entrance of bubbles into the downcomer, enhanced by alcohol addition, decreases the driving force and consequently liquid velocity.[14] Many authors[2,13,15,20] found that the presence of alcohol in different types of airlifts decreases liquid velocity in comparison with tap water. El Azher et al.[20] observed stronger impact of *n*-propanol than *n*-butanol in a SR-ALR. But no comprehensive investigation on the effect of different alcohols on the liquid velocity and circulation time in a DT-ALR has been reported.

The literature provides a very limited amount of data for the volumetric mass transfer coefficient (k_La) in dilute alcohol solutions. Mass transfer characteristics of airlift reactors are strongly influenced by their hydrodynamic parameters. By hindering the

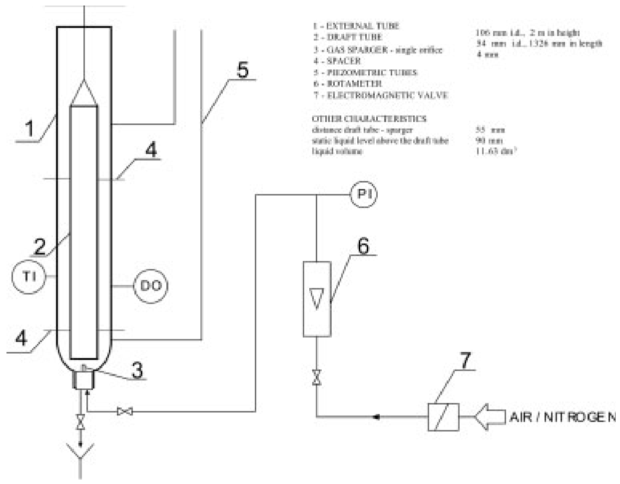

Figure 1. Experimental apparatus.

process of bubble coalescence and hence reducing the mean bubble size, the addition of alcohols results in the increase of gas–liquid interfacial area (a). On the other hand, mass transfer coefficient (k_L) decreases in dilute alcohol solutions when compared with water, probably due to the change in the liquid flow pattern near the interface[23] and its rigidity which increases the resistance to oxygen transfer.[20] Besides that, the oxygen depletion of the important fraction of tiny bubbles increases the inert fraction in the gas phase reducing the solubility of the oxygen.[20] Therefore, the change in volumetric mass transfer coefficient (k_La) is a result of these two opposing factors caused by alcohol addition. It was observed that the increase in the alcohol concentration and the length of the straight chain of alcohol molecule (up to 4 C-atoms) results in the increase of k_La, in the BC[18] and in the EL-ALR.[19] However, in the article of El-Azher et al.,[20] for a split rectangular airlift, contrary conclusions were reported.

It may be observed that none of the studies, published so far, have gone into the details about considering the influence of alcohols on the main hydrodynamic and mass transfer parameters of a DT-ALR. For that reason, the main goal of the present work was to contribute to better understanding of this matter. Overall gas holdup, gas holdup in downcomer, downcomer liquid velocity, circulation time, and volumetric mass transfer coefficient were determined in 1 wt % aqueous solutions of five aliphatic alcohols and tap water as a reference liquid. Empirical correlations for the prediction of overall gas holdup, circulation time, and volumetric mass transfer coefficient are suggested.

Experimental Setup and Measuring Methods

The experiments have been conducted at (20 ± 1)°C and atmospheric pressure in a glass DT-ALR whose geometrical details are shown in Figure 1. In all measurements, air was sparged into the draft tube. The gas flow rates were controlled by a rotameter. Pressure of the gas entering the column was measured by a manometer. Tap water and 1 wt % aqueous solutions of methanol, ethanol, *n*-propanol, isopropanol, and *n*-butanol were used as the liquid phase. Physical properties of the investigated liquids are summarized in Table 2. Surface tension was measured by the number of drops method using a Götze's stalagmometer with an average error of ±1.5%. The surface tension gradient ($d\sigma/dC_A$) was estimated from the slope of the experimental σ versus C_A curve (Figure 2). Density was measured by a densitometer AP PAAR DMA46 with ±0.1 kg/m^3 accuracy. Viscosity was obtained by Ostwald's viscosimeter with an average error of 1%.

The overall gas holdup was determined by the volume expansion technique with an error up to 6.7%. To make the boundary between dispersion and foam more visible, black background was put behind the column and the laboratory was completely darkened. In addition, the top of dispersion was lit up. The aerated dispersion height without foam was used for calculating the overall gas holdup.

The gas holdup values in the downcomer have been obtained by measuring the differential pressure between two sampling ports using piezometric tubes with an error up to 1.7%. Fluctuations of the liquid surfaces in the piezometric tubes were reduced by inserting capillaries (50 mm in length and 1 mm i.d.) at the entrance of the tubes.

The flow follower technique using several glass beads (3 mm in diameter), covered with wax, was chosen to determine the liquid velocity in the downcomer and to measure the circulation time. In this order, density of the flow followers was adjusted to the density of the liquid by modifying the thickness of the wax coating. To ensure that the flow followers were well-wetted, their surface was covered with a waterproof and bubble nonadherent water glass. The time taken by the follower to traverse a known vertical distance was measured and the liquid velocity was determined from an average of 30 measurements at each gas flow rate. The linear velocity of the liquid in the downcomer was calculated by subtracting the settling velocity of the followers from their measured linear velocity. The particles' settling velocity, determined in the liquid phase in the downcomer, was in the range of 2.3–2.7 cm/s, what comprised up to 10% of observed liquid velocity. The maximal error of measurements was up to 7%.

The bubble penetration depth in the downcomer was obtained visually. The border between the swarm of bubbles and bubble free liquid was determined with an accuracy of ±2.5 cm resulting in the average relative error of 14%.

The volumetric mass transfer coefficient was obtained by using the dynamic oxygenation method. For this purpose, the

Table 2. Physical Properties of Liquid Phase at 20°C

Liquid	Surface Tension σ, 10^{-3} N/m	Surface Tension Gradient $-\frac{d\sigma}{dC_A}$, 10^{-3} N/m	Density ρ, kg/m^3	Viscosity μ, 10^{-3} Pas
Tap water	72.7	–	998.2	1.00
Methanol 1 wt %	70.5	0.006	996.3	1.00
Ethanol 1 wt %	67.4	0.025	996.3	1.04
n-Propanol 1 wt %	61.8	0.067	996.4	1.03
Isopropanol 1 wt %	59.6	0.080	996.3	1.04
n-Butanol 1 wt %	48.4	0.199	996.6	1.02

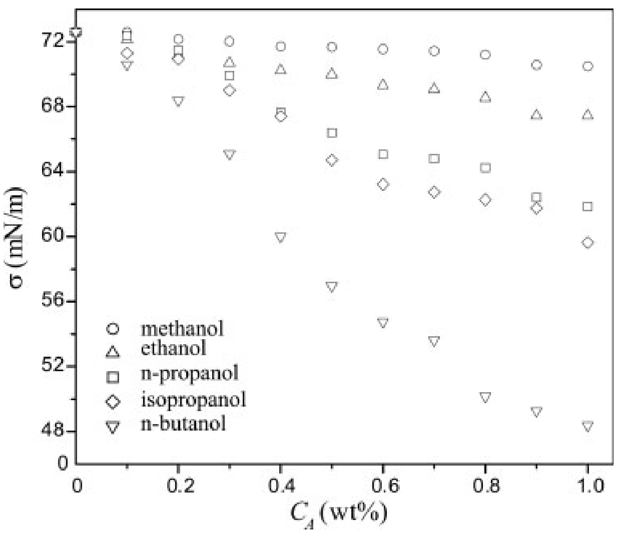

Figure 2. Evolution of surface tension with concentration of aqueous alcohol solution.

liquid was first deaerated by sparging nitrogen. After stopping the nitrogen flow and allowing complete disengagement of the nitrogen bubbles, the air flow was introduced. The dissolved oxygen concentrations in downcomer were obtained by a polarographic DO electrode and by a DO meter (HI 9142 Hanna), neglecting the initial part of the concentration change. The electrode response time, T_E, was determined by response experiments,[24] first dipping the electrode in a liquid sparged by nitrogen and then quickly immersing it in the mixed liquid sparged with air. The amount of time required to record 63.2% of the saturation DO concentration after a step change in concentration, resulted in the average value of the T_E for all examined liquids of about 11 s. The volumetric mass transfer coefficient was calculated by using a model which assumed an ideally mixed liquid phase and negligible effect of the dynamics of the oxygen electrode:

$$\frac{dC_L}{dt} = \frac{k_L a}{1-\varepsilon_G}(C_L^* - C_L) \tag{1}$$

A good agreement between measured and predicted C_L values, with a maximal relative error of 8.4%, was achieved. In the range of our experiments, values of $k_L a t_C$ were much smaller than 2 and therefore satisfied criterion of André et al.[25] for the assumption of a well-mixed liquid phase. The effect of the probe dynamics could be neglected since in all cases, $k_L a$ values were less than 0.1 s^{-1},[24,26,27] and the response time of the probe was smaller than $k_L a^{-1}$.[28,29]

Results and Discussion

Hydrodynamics

Hydrodynamics in the Downcomer. Three different bubble regimes in the downcomer, which strongly influenced hydrodynamics and mass transfer, were observed according to the measured and visually perceived presence of the gas phase in this section of airlift reactor. With respect to these regimes, Figure 3 simultaneously presents the gas holdup in the downcomer and interstitial downcomer liquid velocity curves, divided into three parts, together with the bubble penetration depth (expressed as a percent of the downcomer length). The transition between regimes corresponds to the changes of the slopes of presented measurements.

At low gas flow rates (up to 0.012 m/s), induced liquid circulation velocity is insufficient to draw bubbles into the downcomer. Therefore, only small bubbles (d < 1 mm) contributed to very low downcomer gas holdup. As it can be seen in Figure 3, the maximal gas holdup in the downcomer was 3% in the case of 1% *n*-butanol, while bubble penetration depth did not overcome 30%. The entrainment of larger bubbles (3–5 mm) started at the downcomer liquid velocity of about 20 cm/s, which is in agreement with the values reported by Weiland.[12] This liquid velocity equals the bubble rise velocity resulting in a stationary swarm of bubbles. When the liquid velocity in the downcomer became higher than the bubble rise velocity, bubbles from the downcomer were being dragged with the liquid into the riser. The recirculation of bubbles through the column started at a superficial gas velocity of about 0.04 m/s.

Similar observations were reported on water in a DT-ALR[14,30,31] and in the batch mode of BASE reactor.[32] The transitions between regimes correspond to the boundaries in the operation conditions. As such, they are important factors in a correct designing of airlift reactors, which either operate with complete disengagement (regime I) or with gas recirculation

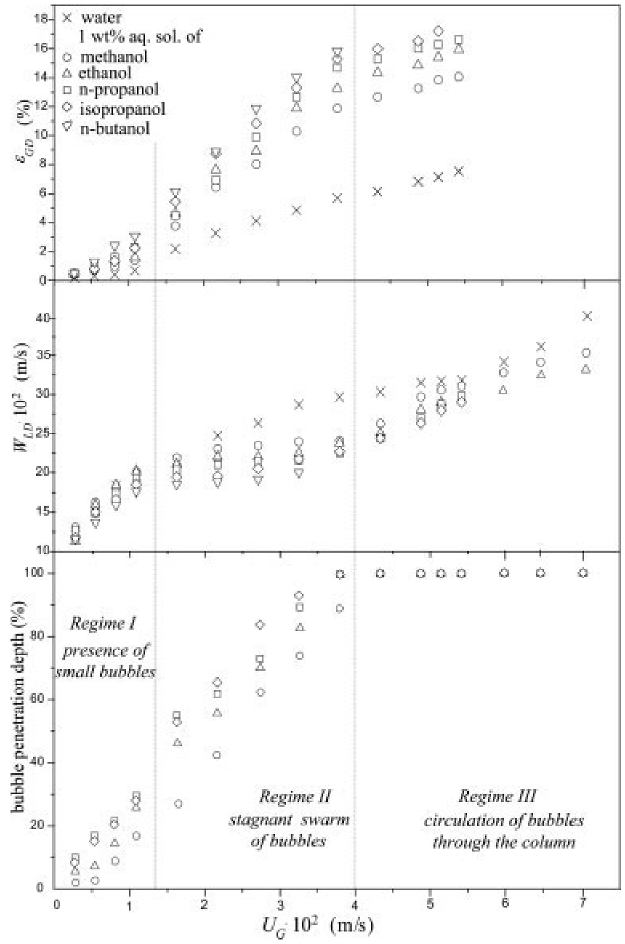

Figure 3. Hydrodynamic regimes in the downcomer.

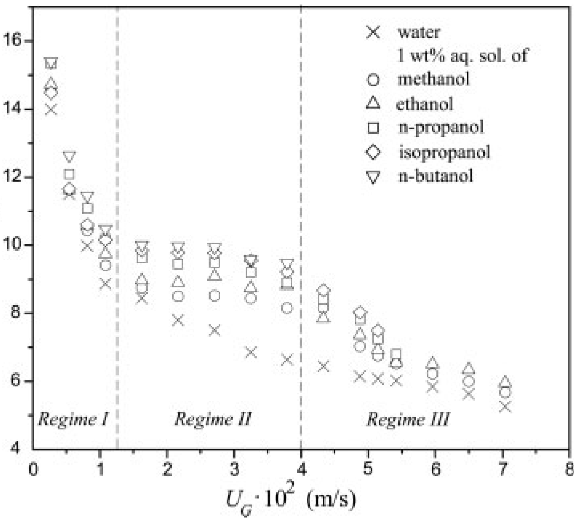

Figure 4. Circulation time as a function of superficial gas velocity and type of alcohol.

(regime III). Heijnen et al.[30] suggest that this especially refers to the transition from the second to the third regime since, at large-scale reactors, bubble recirculation almost always occurs. As many factors affect the change of regime in an airlift reactor (not only its geometry but also bubble coalescence, viscosity or the presence of solid particles), the characteristic transition points are still determined empirically.

As depicted in Figure 3, the transition between regimes, in alcohol solutions, occurred at slightly lower superficial gas velocities when compared to tap water. This may be explained by a tendency of alcohols to reduce the average bubble size. Because of the reduced bubble rise velocity of the smaller bubbles, its entrainment into the downcomer is enhanced what fastens the transitions between the mentioned regimes.

It may be observed, from Figure 3, that the alcohol addition increases the gas holdup in the downcomer, in the following order:

$$\text{water} < \text{methanol} < \text{ethanol} < n-\text{propanol} < \text{isopropanol} < n\text{-butanol} \qquad (2)$$

The effect of alcohols remains weak at low gas flow rates (regime I) because the amount of gas in the reactor is still small and the influence of the liquid-phase surface tension is not significant. As bubbles start to fill out the downcomer (regime II), the effect of the coalescence inhibition by alcohols becomes strong thus intensifying the differences between systems. At $U_G \approx 0.04$ m/s, the gas holdup in the downcomer is almost twofold higher in 1 wt % solution of methanol and 2.7 times in 1 wt % solution of *n*-butanol than that obtained in tap water.

Our results also showed that the alcohol addition caused a decreasing of liquid velocity in the downcomer, in the order opposite to the order (Eq. 2). When compared to water, the decline of liquid velocity ranges from 10% observed in 1 wt % methanol solution to 20% determined for the solution of *n*-butanol. There are no significant differences between our results and the experimental data obtained by Petrović et al.[14] and El Azher et al.[20] Nevertheless, Freitas and Teixeira[2] and Freitas et al.[16] got about 50% lower values of the downcomer interstitial liquid velocity what partly might be explained by the shorter draft tube used in their work and consequently lower driving force for the liquid circulation.

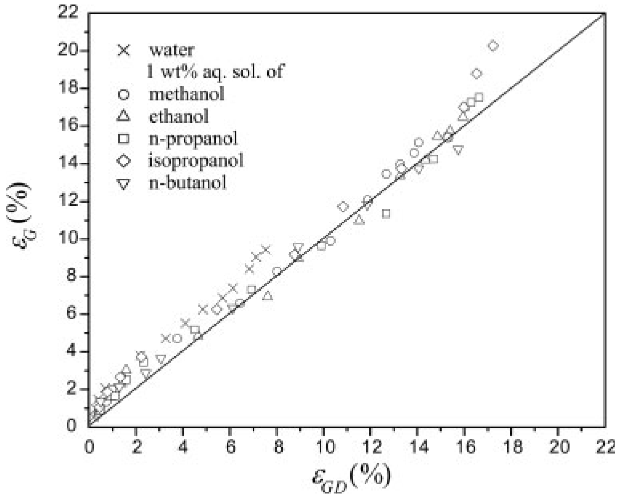

Figure 5. Comparison between overall gas holdup and gas holdup in the downcomer.

The influence of superficial gas velocity and type of alcohol on the values of circulation time is presented in Figure 4. The existence of three bubble regimes in the downcomer is obvious. Namely, the circulation time decreases with the increase of superficial gas velocity for the first and the third regime. For the second regime, the circulation time remains almost constant in alcohol solutions, but decreases, with increasing gas throughputs, in water. At the same gas flow rate, longer circulation times were achieved in the solutions of alcohols with higher number of C-atoms. Our results for circulation time are lower for about 25% than those obtained by Freitas and Teixeira[2] and Kennard and Janekeh[13] and even 50% than Weiland[12] who all applied sinter plate sparger. Nevertheless, differences between our measurements and the results of Fields and Slater[11] are not significant.

Overall Gas Holdup. Figure 5 presents a comparison between the overall gas holdup and the gas holdup in the

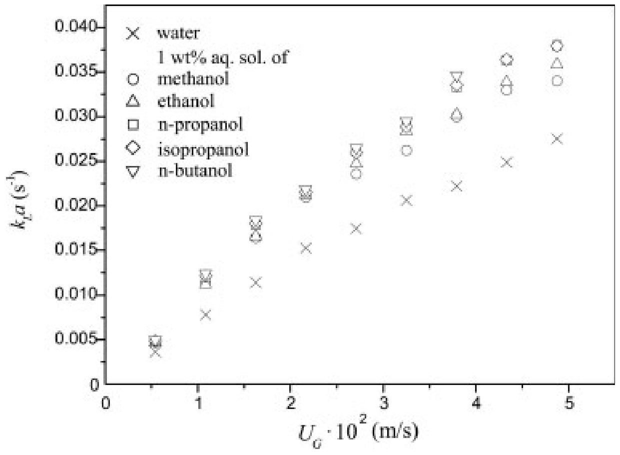

Figure 6. Effect of type of alcohol on volumetric mass transfer coefficient.

Table 3. Values of Correlation Parameters for the Overall Gas Holdup, Circulation Time, and Volumetric Mass Transfer Coefficient

y (Eq. 3)	Regime	p_1 ± Error(p_1)	p_2 ± Error(p_2)	p_3 ± Error(p_3)	p_4 ± Error(p_4)	R^2	n
ε_G		1.65 ± 0.13	0.97 ± 0.02	0.20 ± 0.02	1.52 ± 0.07	0.99	73
t_C (s)	I	2.48 ± 0.11	−0.29 ± 0.01	0.49 ± 0.12	0.27 ± 0.05	0.98	24
	II	5.04 ± 0.30	−0.11 ± 0.01	0.24 ± 0.04	0.52 ± 0.05	0.87	36
	III	1.12 ± 0.13	−0.56 ± 0.04	0.23 ± 0.05	0.52 ± 0.06	0.94	34
k_La (s^{-1})		0.28 ± 0.02	0.77 ± 0.02	0.15 ± 0.02	0.71 ± 0.05	0.99	52

downcomer. At higher gas flow rates, the overall gas holdup is about 10% higher than the gas holdup in the downcomer for systems air–alcohols and 25% higher for tap water. Since, at the value of parameter $D_R/D = 0.51$, downcomer comprises about 75% of the total airlift volume, it is expected that ε_{GD} and other related factors, determine the overall gas holdup, in reactors of this kind of geometry. It may also be observed, from Figure 5, that the differences between the values of the overall gas holdup and the gas holdup in the downcomer decrease with superficial gas velocities.

The overall gas holdup is also strongly influenced by the type of the alcohol, i.e., by the number of carbon atoms in the alcohol molecule, as presented in the order (Eq. 2). Similar conclusions were reported by other authors whose investigations were performed in BC,[18] EL-ALR,[19] and SR-ALR.[20] In this work, the greatest increase was achieved in the solution of *n*-butanol, 2.4 times higher overall gas holdup when compared to water, while in the solution of methanol minimal increment was observed (1.5 times). The effect is particularly significant at higher superficial gas velocities.

Although molecules of *n*-propanol and isopropanol have the same number of C-atoms, isopropanol showed stronger effect, particularly at higher U_G values, very probably due to the higher surface tension gradient. This is in disagreement with the results of Kelkar et al.[1] who found higher values of the overall gas holdup in *n*-propanol solution than in isopropanol solution, but in case of BC. Quite opposite to our opinion, these authors denied the influence of surface tension on the overall gas holdup in water–alcohol solutions.

Our results, for the overall gas holdup, range as follows: $0.25 \times 10^{-2} - 5 \times 10^{-2}$ m/s of U_G and 0.6–20% of ε_G. These intervals match completely the results obtained by Petrović et al.[14] and covers partially the results obtained by Fields and Slater.[11] However, our overall gas holdup values are lower than those obtained by Weiland[12] and Kennard and Janekeh[13] but higher than those obtained by Pošarac[19] and El Azher et al.[20] These discrepancies may be attributed to the differences in reactor design and operating conditions. Type of sparger is very important, especially when coalescence inhibiting solutions are involved.[33,34] Small sparger holes, typical of sinter plates, generate lesser bubbles than do the single orifices and allow better gas dispersion, improving in that way gas holdup.

Mass transfer

The experimental results presented in Figure 6 show that the volumetric mass transfer coefficient (k_La) increases with the superficial gas velocity as well as with the addition of alcohols. The alcohol addition has the same effect on the volumetric mass transfer coefficient as on the gas holdup, i.e., the increase of k_La values follows the order (Eq. 2). These observations agree with the data of many authors,[14,17–19] but differ from the results of El Azher et al.[20] It may be supposed that the increase of interfacial area (a), caused by an increase of the gas holdup, overcomes the decrease of mass transfer coefficient (k_L), in the presence of alcohols. The largest k_La values are observed in 1 wt % solution of *n*-butanol which are up to 1.6 times higher than k_La values in tap water. Our k_La results completely correspond with the results found by Petrović et al.[14] and somewhat covers the results attained by El Azher et al.[20] Our k_La values are higher than those reported by Pošarac[19] and Freitas and Teixeira,[17] but lower than those obtained by Pošarac and Tekić,[18] who applied the BC with the same diameter and sparger as the column used in this work. This is in agreement with the observations of Merchuk and Siegel,[35] Chisti,[33] Lu et al.,[36] who noticed lower values of k_La for airlift reactors comparing with BC.

Correlations

By applying the regression analysis to the measured data obtained in these investigations, overall gas holdup (ε_G), circulation time (t_C), and volumetric mass transfer coefficient (k_La) were correlated with the superficial gas velocity (U_G) and the surface tension gradient ($d\sigma/dC_A$). The general form

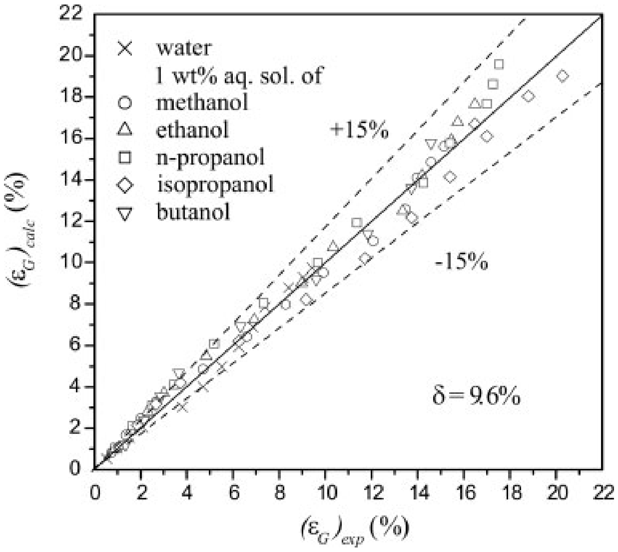

Figure 7. Comparison between calculated and experimental values of overall gas holdup.

of the proposed correlation is as follows:

$$y = p_1 U_G^{p_2}\left[1 + \left(-\frac{d\sigma}{dC_A}\right)^{p_3}\right]^{p_4} \tag{3}$$

where y presents: ε_G, t_C or k_La.

The proposed correlation is highly nonlinear, related to its parameters, so a nonlinear correlating had to be done. For this purpose, software LAB Fit[37] was applied. A quality of fit was expressed by standard quantifiers (the coefficient of the correlation (R^2) and the errors of parameters). Table 3 contains all relevant data originated from the applied statistics. The parameters for circulation time are presented in terms of the flow regimes. Values of t_C on the boundary between two regimes were used for determination of correlation parameters in both regimes. All correlations yield a satisfactory agreement with the experimental results (Figures 7–9). It can be seen that Eq. 3 for the overall gas holdup predicts about 77% of the experimental data with 15% error. The correlation for the volumetric mass transfer coefficient predicts about 89% of the experimental data with an error of 15% or less.

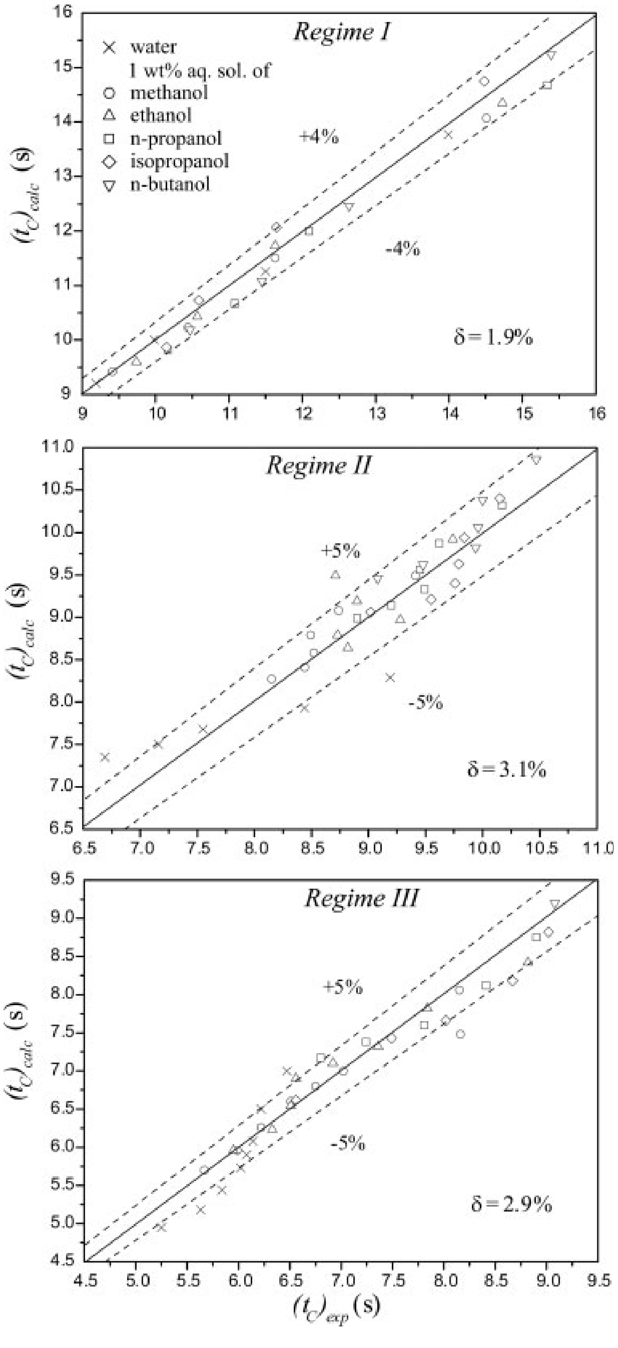

Figure 8. Comparison between calculated and experimental values of circulation time.

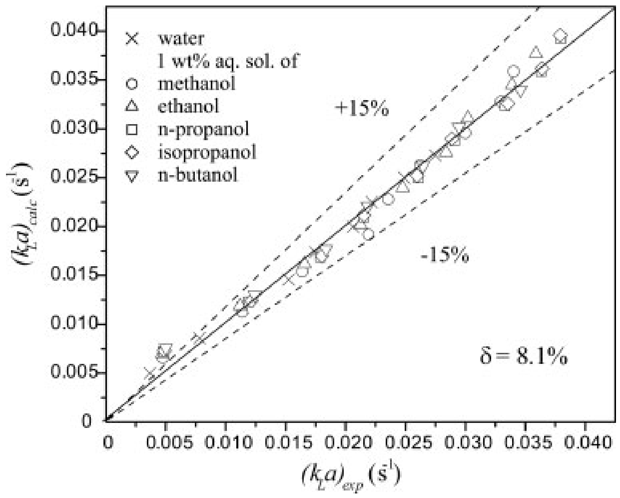

Figure 9. Comparison between calculated and experimental values of volumetric mass transfer coefficient.

Conclusions

In this article, the influence of alcohol addition on main hydrodynamic and mass transfer characteristics of a DT-ALR was studied. Gas holdup, liquid velocity, circulation time, and volumetric mass transfer coefficient were determined in 1 wt % solutions of five aliphatic alcohols. The results showed that the increase of the surface tension gradient, as a consequence of alcohol addition, has a strong impact on hydrodynamics and, hence, mass transfer characteristics of airlift reactor. The increase of surface tension gradient corresponds to the increase of the number of carbon atoms in alcohol molecule. Three different bubble regimes in the downcomer, which strongly influenced hydrodynamics and mass transfer, were observed. The correlations to fit the experimental gas holdup, circulation time, and volumetric mass transfer coefficient data were proposed. A satisfactory agreement between the experimental and calculated data was achieved. The experimental data and the proposed correlations should contribute to the better understanding of the behavior of a DT-ALRs applied to the systems with dilute aliphatic alcohol solutions.

Acknowledgments

This research was supported by the Ministry for Science and Environmental Protection of the Republic of Serbia (Project No. 142045).

Notation

a = specific interfacial area, m^2/m^3
C_A = concentration of alcohol, wt %
C_L = dissolved oxygen concentration, mol/m^3
d = diameter of orifice, mm
D = diameter of column, m
k_La = volumetric mass transfer coefficient, s^{-1}
Q = flow rate, m^3/s
t = time, s
T_E = response time of oxygen electrode, s
U = superficial velocity column area based, m/s
W_L = interstitial liquid velocity, m/s

Greek letters

δ = average relative error
ε = holdup
μ = dynamic viscosity, Pa s
ρ = density, kg/m^3
σ = surface tension, N/m

Superscript

$*$ = equilibrium

Subscripts

C = circulation
D = downcomer
G = gas phase
L = liquid phase
R = riser

Literature Cited

1. Kelkar BG, Godbole SP, Honath MF, Shah YT, Carr NL, Deckwer WD. Effect of addition of alcohol on gas holdup and backmixing in bubble column. *AIChE J*. 1983;29:361–369.
2. Freitas C, Teixeira JA. Effect of liquid-phase surface tension on hydrodynamics of a three-phase airlift reactor with an enlarged degassing zone. *Bioprocess Eng*. 1998;19:451–457.
3. Schügerl K, Lücke J, Öls U. Bubble column bioreactors. *Adv Biochem Eng*. 1977;7:1.
4. Keitel G, Onken U. Inhibition of bubble coalescence by solutes in air/water dispersions. *Chem Eng Sci*. 1982;37:1635–1638.
5. Jeng JJ, Maa JR, Yang YM. Surface effects and mass transfer in bubble column. *Ind Eng Chem Process Des Dev*. 1986;25:974–978.
6. Zahradnik J, Kuncova G, Fialova M. The effect of surface active additives on bubble coalescence and gas holdup in viscous aerated batches. *Chem Eng Sci*. 1999;54:2401–2408.
7. Camarasa E, Vial C, Poncin S, Wild G, Midoux N, Bouillard J. Influence of coalescence behaviour of the liquid and of gas sparging on hydrodynamics and bubble characteristics in a bubble column. *Chem Eng Process*. 1999;38:329–344.
8. Al-Masry WA, Dukkan AR. The role of gas disengagement and surface active agents on hydrodynamics and mass transfer characteristics of airlift reactors. *Chem Eng J*. 1997;65:263–271.
9. Krishna R, Urseanu MI, Dreher AJ. Gas hold-up in bubble columns: influence of alcohol addition versus operation at elevated pressures. *Chem Eng Process*. 2000;39:371–378.
10. Chakravarty M, Singh HD, Baruah JN, Iyengar MS. Liquid velocity in a gas-lift column. *Indian Chem Eng*. 1974;16:17–22.
11. Fields PR, Slater NKH. Tracer dispersion in a laboratory air-lift reactor. *Chem Eng Sci*. 1983;38:647–653.
12. Weiland P. Influence of draft tube diameter on operation of airlift loop reactors. *German Chem Eng*. 1984;7:374–385.
13. Kennard M, Janekeh M. Two- and three-phase mixing in a concentric draft tube gas-lift fermentor. *Biotechnol Bioeng*. 1991;38:1261–1270.
14. Petrović LjD, Pošarac D, Duduković A, Skala D. Hydrodynamics and mass transfer in a draft tube bubble column. *J Serbian Chem Soc*. 1991;56:227–240.
15. Wachi S, Jones AG, Elson TP. Flow dynamics in a draft-tube bubble column using various liquids. *Chem Eng Sci*. 1991;46:657–663.
16. Freitas C, Fialova M, Zahradnik J, Teixera JA. Hydrodynamic model for three-phase internal and external loop airlift reactor. *Chem Eng Sci*. 1999;54:5253–5258.
17. Freitas C, Teixeira JA. Oxygen mass transfer in a high solids loading three-phase internal-loop airlift reactor. *Chem Eng J*. 2001;84:57–61.
18. Pošarac D, Tekić MN. Gas holdup and volumetric mass transfer coefficient in bubble columns with dilute alcohol solutions. *AIChE J*. 1987;33:497–499.
19. Pošarac D. *Investigation of Hydrodynamics and Mass-Transfer in a Three Phase External-Loop Airlift Reactor*, PhD Thesis. Novi Sad, Serbia: University of Novi Sad, 1988.
20. El Azher N, Gourich B, Vial C, Soulami Bellhaj M, Bouzidi A, Barkaoui M, Ziyad M. Influence of alcohol addition on gas hold-up, liquid circulation velocity and mass transfer coefficient in a split-rectangular airlift bioreactor. *Biochem Eng J*. 2005;23:161–167.
21. Chakravarty M, Begum S, Singh HD, Baruah JN, Iyengar MS. Gas hold-up distribution in a gas-lift column. *Biotechnol Bioeng Symp*. 1973;4:363–378.
22. Keitel G. *Untersuchungen zum Stoffaustausch in Gas-Flüssig—Dispersionen in Rührschlaufenreaktor und Blasensäule*, Doctoral Dissertation. Dortmund, Germany: Universität Dortmund, 1978.
23. Yoshida F. Bubble column research in Japan. *Chem Eng Technol*. 1988;11:205–212.
24. Nakanoh M, Yoshida F. Gas absorption by Newtonian and non-Newtonian liquids in a bubble column. *Ind Eng Chem Process Des Dev*. 1980;19:190–195.
25. André G, Robinson CW, Moo-Young M. New criteria for application of the well-mixed model to gas-liquid mass transfer studies. *Chem Eng Sci*. 1983;38:1845–1854.
26. Yagi H, Yoshida F. Gas absorption by Newtonian and non-Newtonian fluids in sparged agitated vessels. *Ind Eng Chem Process Des Dev*. 1975;14:488–493.
27. Keitel G, Onken U. Errors in the determination of mass transfer in gas-liquid dispersions. *Chem Eng Sci*. 1981;36:1927–1932.
28. Tribe LA, Briens CL, Margaritis A. Determination of the volumetric mass transfer coefficient (kla) using the dynamic "Gas Out-Gas In" method: analysis of errors caused by dissolved oxygen probes. *Biotechnol Bioeng*. 1995;46:388–392.
29. Tung HL, Chiou SY, Tu CC, Wu WT. An airlift reactor with double net draft tubes and its application in fermentation. *Bioprocess Eng*. 1997;17:1–5.
30. Heijnen JJ, Hols J, Van der Lans RGJM, Van Leeuwen HLJM, Mulder A, Weltevrede R. A simple hydrodynamic model for the liquid circulation velocity in a full-scale two- and three-phase internal airlift reactor operating in the gas recirculation regime. *Chem Eng Sci*. 1997;52:2527–2540.
31. Blažej M, Kiša M, Markoš J. Scale influence on the hydrodynamics of an internal loop airlift reactor. *Chem Eng Process*. 2004;43:1519–1527.
32. van Benthum WAJ, van der Lans RGJM, van Loosdrecht MCM, Heijnen JJ. Bubble recirculation regimes in an internal-loop airlift reactor. *Chem Eng Sci*. 1999;54:3995–4006.
33. Chisti MY. *Airlift Bioreactors*. London: Elsevier Applied Science, 1989.
34. Merchuk JC, Contreras A, Garcia F, Molina E. Studies of mixing in a concentric airlift reactor. *Chem Eng Sci*. 1998;53:709–719.
35. Merchuk JC, Siegel MH. Air-lift reactors in chemical and biochemical technology. *J Chem Technol Biotechnol*. 1988;41:105–120.
36. Lu X, Ding J, Wang Y, Shi J. Comparison of the hydrodynamics and mass transfer characteristics of a modified square airlift reactor with common airlift reactors. *Chem Eng Sci*. 2000;55:2257–2263.
37. Silva Wilton P, Cleide MDPS. LAB Fit Curve Fitting Software (Nonlinear Regression and Treatment of Data Program) V 7.2.38 (1999–2007).

Manuscript received May 11, 2007, and revision received July 26, 2007.