SIMPLE CORRELATIONS FOR BUBBLE COLUMNS AND DRAFT TUBE AIRLIFT REACTORS WITH DILUTE ALCOHOL SOLUTIONS

Ivana M. Šijački, Radmilo R. Čolović, Milenko S. Tokić and Predrag S. Kojić

Simple empirical correlations were developed to predict gas holdup, liquid circulation time, downcomer liquid velocity and volumetric mass transfer coefficient in dilute alcohol solutions in bubble columns and draft tube airlift reactors with single orifice sparger. Also, new experiments were conducted with diluted alcohol solutions to n-octanol, expanding the experimental data from C1 up to C8. The proposed empirical correlations include, beside the superficial gas velocity, the alcohol chain length as the only factor to characterize the liquid phase. The suggested correlations have shown good agreement between the calculated and the experimental data.

KEY WORDS: Bubble columns, draft tube airlift reactors, dilute alcohol solutions, hydro-dynamics, mass transfer

INTRODUCTION

Bubble columns and airlift reactors have important applications as bioreactors (in biomass production or production of different metabolites), as chemical reactors and as contactors in the wastewater treatments. In these contactors, the properties of the liquid phase strongly affect hydrodynamics, bubble behavior and mass transfer rates. Dilute alcohol solutions are important, as the liquid phase. They can be used to simulate the liquid phase behavior in bioreactors and in coal liquefaction (1). The only property of these solutions, which differs considerably from water, is their surface tension (2).

The influence of alcohols on the gas holdup is proportional to their concentration and to the length of the carbon chain in the alcohol molecule, in the bubble column (BC) (1, 3), continuous BC (1), external loop airlift reactor (EL-ALR) (4), draft tube air lift reactor (DT-ALR) (5,6) and split rectangular airlift reactor (SR-ALR) (7). Also, the addition of alcohol influences volumetric mass transfer coefficient ($k_{l,a}$). The increase in both the alcohol concentration and the length of the straight chain of alcohol molecule results in the increase of $k_{l,a}$, in the BC (3), the EL-ALR (4) and in the DT-ALR (5,6).
Only a few studies on the hydrodynamics and mass transfer in dilute alcohol solutions in bubble columns and draft tube airlift reactors with single orifice sparger have been published, so far (3, 5, 6, 8).

The correlations for prediction of gas holdup and volumetric mass transfer coefficient were proposed in various forms based on investigations in different systems. Some of the correlations can be used for predicting hydrodynamics and mass transfer in aqueous solutions of alcohols with an acceptable error (3, 5, 6, 9). In deriving the correlation, the main issue was choosing a representative characteristic of the liquid phase. In the case of addition of alcohols, it is obvious that the only physical property that is to be different from water is the surface tension (3, 5, 9), as the change in viscosity and density is negligible, or the surface tension gradient can be used in correlations (6, 10), in order to include the effect of solution concentration on physical properties.

The aim of this paper was to propose simple correlations that could be used to predict the main characteristics: gas holdup, liquid circulation time, downcomer liquid velocity and volumetric mass transfer coefficient, in BCs and DT-ALR, with aqueous solutions of alcohols and with a single orifice sparger as a gas distributor. In order to improve the correlations and validate their form, the existing experimental data (3, 5, 6, 8) were broadened by additional experiments, conducted in DT-ALR with dilute alcohol solutions from methanol to \(n\)-octanol. The concentration of each alcohol was chosen based on the research of Keitel (11), as the value of the upper limiting concentration. It has been shown that increasing alcohol concentration above the limiting value, only enhances the bubble coalescence and liquid phase frothing (2, 8), with no major influence on hydrodynamics. In case of isopropanol, the concentration is chosen equal to \(n\)-propanol.

**EXPERIMENTAL**

The experiments were conducted at 20±1°C and atmospheric pressure in a glass DT-ALR, with geometrical details presented in Fig. 1. The air, sparged through a single orifice into the draft tube, was used as the gas phase. Tap water and diluted alcohol solutions from methanol to \(n\)-octanol were used as the liquid phase.

The concentrations of the alcohols and the physical properties of the liquid phase at 20°C are summarized in Table 1. Densities of liquids were measured by a densitometer AP PAAR DMA46 with ±0.1 kg/m³ accuracy. Surface tensions of liquid phases were obtained by tensiometer (Torsion Balance Model OS) with ±0.0001 N/m accuracy. The surface tension gradient \((-d\sigma/dC_A)\) was estimated from the slope of the experimental \(\sigma\) versus \(C_A\) curve (Fig. 2).
Fig. 1. Experimental setup

Fig. 2. Evolution of surface tension with concentration of aqueous alcohol solutions
Table 1. Surface tension and surface tension gradient of used liquid phases at 20°C

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Concentration $C_A$, wt %</th>
<th>Density $\rho$, kg/m³</th>
<th>Surface Tension $\sigma$, $10^{-3}$ N/m</th>
<th>Surface Tension Gradient $-d\sigma/dC_A$, $10^{-3}$ N·m²/mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>tap water</td>
<td>0</td>
<td>1000</td>
<td>72.4</td>
<td>-</td>
</tr>
<tr>
<td>Methanol</td>
<td>3.2</td>
<td>921.61</td>
<td>66.1</td>
<td>0.006</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.46</td>
<td>988.06</td>
<td>70.4</td>
<td>0.025</td>
</tr>
<tr>
<td>$n$-propanol</td>
<td>0.036</td>
<td>999.10</td>
<td>71.9</td>
<td>0.067</td>
</tr>
<tr>
<td>Isopropanol</td>
<td>0.036</td>
<td>998.99</td>
<td>71.7</td>
<td>0.080</td>
</tr>
<tr>
<td>$n$-butanol</td>
<td>0.011</td>
<td>999.74</td>
<td>71.8</td>
<td>0.199</td>
</tr>
<tr>
<td>$n$-pentanol</td>
<td>0.0057</td>
<td>999.87</td>
<td>71.7</td>
<td>1.082</td>
</tr>
<tr>
<td>$n$-hexanol</td>
<td>0.0051</td>
<td>999.89</td>
<td>69.9</td>
<td>1.985</td>
</tr>
<tr>
<td>$n$-heptanol</td>
<td>0.002</td>
<td>999.96</td>
<td>67.8</td>
<td>4.141</td>
</tr>
<tr>
<td>$n$-octanol</td>
<td>0.002</td>
<td>999.96</td>
<td>65.0</td>
<td>15.205</td>
</tr>
</tbody>
</table>

The overall gas holdup was determined by the volume expansion technique with an error less than 10%. The aerated dispersion height without foam was used for calculating the overall gas holdup. The gas holdup values along the column were obtained by measuring the differential pressure at five points (in the draft tube and in the downcomer) using the piezometric tubes. The relative average error of the measurement was up to 2%. A hot probe method, developed for this purpose, was used to determine the liquid velocity in the downcomer (12). The mean relative error of this method was ±5%.

**RESULTS AND DISCUSSION**

The main aim of this paper was to suggest simple empirical correlations to predict crucial hydrodynamic and mass transfer quantities. The processed data in this investigation, beside the ones obtained in these experiments, were taken from the experiments of Pošarac and Tekić (3), Albijančić (5), Albijanić et al. (6) and Camarasa et al. (8). In these studies experiments were conducted in BCs and DT-ALR with single orifice as air sparger and with dilute alcohol solutions as the liquid phase.

As already mentioned, a representative characteristic of diluted alcohol solutions might be surface tension. Fig. 2 shows evolution of surface tension with the concentration of alcohol solution. The surface tension gradient was estimated from the slopes of these experimental curves (Table 1). It is obvious that the surface tension gradient is a function of $C_N$-value. By applying the regression analysis (13) on these experimental data the correlation was obtained in the following form:

$$-\frac{d\sigma}{dC_A} = 0.0034 \cdot \frac{e^{1.31 \cdot C_N}}{C_N}$$

with the coefficient of determination $R^2=0.99$.

Assuming the linear relation: surface tension vs. alcohol solution concentration, with the surface tension gradient as a slope, and having in mind the connection between sur-
face tension gradient and the \( C_N \)-value, it can be concluded that surface tension is also a function of \( C_N \)-value. Recently, Zeppieri came to the same conclusion, i.e., he noticed the relation between the surface tension and \( C_N \)-value (14). A strong relation between the \( C_N \)-value, on one hand, and the surface tension and the surface tension gradient on the other, suggests that the \( C_N \)-value could be the only variable which expresses the influence of dilute alcohol solutions on hydrodynamics and mass transfer.

So, simple correlations were introduced by processing the data obtained in our experiments and the experiments of other authors (3, 5, 6, 8):

\[
y = p_1 U_{G}^{p_2} (1 + C_N)^{p_3}
\]

where \( y \) represents: \( \varepsilon_G \), \( t_C \), \( W_{LD} \) or \( k_L a \).

An additional corroboration of the suggested equations was performed through the comparison of the experimental and calculated values in the case of \( n \)-propanol and isopropanol, with the same number of C-atoms. A good agreement is achieved, regardless of the structural differences between these two alcohols. Table 2 contains the values of the estimated parameters in the proposed equations, along with the standard quantifiers - the coefficient of determination (R\(^2\)) and the errors of parameters (expressed as a % of a value).

**Table 2.** Values of correlation parameters for the gas holdup, liquid circulation time, liquid velocity and volumetric mass transfer coefficient

<table>
<thead>
<tr>
<th>( y ) (Eq.2)</th>
<th>Regime</th>
<th>( p1 \pm Error(p1) )</th>
<th>( p2 \pm Error(p2) )</th>
<th>( p3 \pm Error(p3) )</th>
<th>( R^2 )</th>
<th>( n )</th>
<th>( \delta \ (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_G )</td>
<td>I</td>
<td>1.58 ± 5.7%</td>
<td>0.86 ± 2.3%</td>
<td>0.18 ± 5.6%</td>
<td>0.93</td>
<td>349</td>
<td>26.4</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>2.46 ± 4.9%</td>
<td>-0.29 ± 3.4%</td>
<td>0.06 ± 16.7%</td>
<td>0.98</td>
<td>24</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>5.07 ± 5.7%</td>
<td>-0.11 ± 9.1%</td>
<td>0.16 ± 6.2%</td>
<td>0.87</td>
<td>36</td>
<td>2.9</td>
</tr>
<tr>
<td>( t_C ) (s)</td>
<td>I</td>
<td>1.15 ± 11.3%</td>
<td>-0.56 ± 7.1%</td>
<td>0.16 ± 6.2%</td>
<td>0.94</td>
<td>34</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>3.09 ± 19.1%</td>
<td>0.61 ± 6.6%</td>
<td>-0.12 ± 8.3%</td>
<td>0.93</td>
<td>29</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>0.63 ± 9.5%</td>
<td>0.27 ± 7.4%</td>
<td>-0.18 ± 5.5%</td>
<td>0.89</td>
<td>45</td>
<td>3.4</td>
</tr>
<tr>
<td>( W_{LD} ) (m/s)</td>
<td>I</td>
<td>3.11 ± 12.8%</td>
<td>0.74 ± 5.4%</td>
<td>-0.16 ± 6.2%</td>
<td>0.91</td>
<td>65</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>1.45 ± 14.5%</td>
<td>1.24 ± 3.2%</td>
<td>0.41 ± 9.8%</td>
<td>0.90</td>
<td>159</td>
<td>22.6</td>
</tr>
</tbody>
</table>

For the gas holdup, Eq. 2 predicted about 68% of experimental data with an error of 20% or less (Fig. 3). The parameters for liquid circulation time were calculated based on data of Albijanić (5) and Albijanić et al. (6) as the only available data. The parameters for liquid circulation time and liquid velocity (Table 2) were calculated for three different bubble regimes: regime I (small bubbles in the downcomer), regime II (stagnant swarm of bubbles in the downcomer) and regime III (circulation of bubbles through the column).
Fig. 3. Comparison between calculated (Eq. 2) and experimental values of gas holdup

Comparison between calculated and experimental values both of circulation time and liquid velocity is given in Fig. 4 and Fig. 5. The correlation for volumetric mass transfer coefficient predicts about 52% of experimental data, in a range of 20% error (Fig. 6). However, a significantly smaller error was achieved for the higher superficial gas velocities.
Fig. 4. Comparison between calculated and experimental values of gas holdup

Fig. 5. Comparison between (Eq. 4) calculated (Eq. 4) and experimental values of downcomer liquid velocity
Fig. 6. Comparison between calculated (Eq. 4) and experimental values of volumetric mass transfer coefficient

CONCLUSION

Simple correlations were proposed for prediction of basic hydrodynamic and mass transfer characteristics of BCs and DT-ALRs with dilute alcohol solutions (from methanol to \(n\)-octanol) and with single orifice as a gas distributor. The correlations include the number of C-atoms in a molecule chain, as the only variable to specify the physical properties of dilute alcohol solutions. A good agreement between the experimental and the calculated data was achieved. Based on the simplicity of the proposed correlations it is to be expected that their useful application in reactors design.

ACKNOWLEDGEMENT

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Notation:

\[ C_A = \text{concentration of alcohol, wt\%} \]
\[ k_{L}a = \text{volumetric mass transfer coefficient, 1/s} \]
\[ C_N = \text{number of C-atoms in alcohol molecule chain} \]
\[ t_c = \text{liquid circulation time, s} \]
\[ d = \text{diameter of the orifice, mm} \]
\[ U_G = \text{superficial gas velocity, m/s} \]
$D$ = diameter of the column, m
$W_{LD} = \text{downcomer interstitial liquid velocity, m/s}$
$D_R = \text{diameter of the riser, m}$

Greek letters:

- $\delta$ = average relative error
- $\varepsilon_G = \text{gas holdup}$
- $\rho = \text{density, kg/m}^3$
- $\sigma = \text{surface tension, N/m}$

Subscripts:

- $C = \text{circulation}$
- $D = \text{downcomer}$
- $G = \text{gas phase}$
- $L = \text{liquid phase}$
- $R = \text{riser}$

REFERENCES


ПРЕДВИЂАЊЕ ОСНОВНИХ ХИДРОДИНАМИЧКИХ И МАСЕНОПРЕНОСНИХ КАРАКТЕРИСТИКА У БАРБОТАЖНИМ КОЛОНAMA СA И БЕЗ УНУТРАШЊЕ ЦЕВИ СA РАЗБЛАЖЕНИМ РАСТВОРИМА АЛКОХОЛА

Ивана М. Шијачки, Радмило Р. Чоловић, Миленко С. Токић и Предраг С. Кojiћ

У овом раду предложене су корелације за предвиђање садржаја гаса, времена рециркулације течности, брзине течности у силазној цеви и запреминског коефицијената прелаза масе у барботажним колонама са и без унутрашње цеви, са једноструким уводником као дистрибутором гаса и разблаженим растворима алкохола као течном фазом. Расположиви експериментални подаци употребљени за извођење корелација проширили су новим експериментима са разблаженим растворима С1-С8 алкохола. Предложене корелације укључују, поред привидне брзине гаса, дужину ланца молекула алкохола (број С-атома), као једину величину која карактерише течну фазу. Предложене корелације омогућавају врло добро предвиђање експерименталних података. Захваљујући једноставном облику, може се очекивати успешна примена изведенih корелација при пројектовању оваквих типа реактора.

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