The Effects of Isobutanul Addition on Bubble Size, Gas Holdup, Interfacial Area, Bubble Coalescence, and Transition Concentration in Dispersion Column

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Abstract—The bubble coalescence and the transition concentration in a dispersion column have been experimentally studied in this study work by adopting isobutanol-water mixture as a liquid phase and air as a gas phase. The experimental work included the following experimental variables; the weight percent of isobutanol in water and superficial gas velocity of air. The using of two distributors single-orifice and multi-orifice, bubble size, gas holdup and gas-liquid interfacial area are measured. The experimental results have showed that the isobutanol transition concentration is successfully correlated as a function of superficial air velocity, $c_t=0.072079-0.006408U_g+0.000425U_g^2-0.00001U_g^3$. This equation gives mean deviation of 4.501%.

Index Terms—Gas-liquid dispersion column, bubble coalescence, transition concentration.

NOTATIONS

 $a = \text{specific gas-liquid interfacial area, mm}^2/\text{mm}^3$

 c_A = isobutanol concentration, kmol/m³

 c_t = transition concentration of isobutanol, kmol/m³

 d_{Bi} = diameter of bubbles of size *i*, mm

 d_o = orifice diameter of perforated plate, mm

 d_{vs} = sauter mean diameter of bubbles, mm

K = number of variables in the system

n = number of orifices in perforated plate

 n_i = number of bubbles of size i

N = number of experiments

 r_c = correlation coefficient

 U_g = superficial gas velocity of air, mm/s

Wt % = weight percent of isobutanol in water, %

 x_1 , x_2 = coded or independent variables of polynomial equation

 Z_0 , Z_1 , Z_3 = liquid levels in the manometers, mm.

Greek Letters:

 $\varepsilon_g = \text{gas holdup}$

 ψ = coalescence percentage, %

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I. INTRODUCTION

The most important process in a bubble column is the formation of a gas at the sparger. The smaller the bubbles, the larger are the area for mass transfer between the gas and liquid phases. Bubble swarm behavior in a bubble column is mainly determined by the gas superficial velocity (Heijnen and Riet [1]). Bubble size, bubble rise velocity, bubble size distribution, and liquid and bubble velocity profile have a direct bearing on the performance of bubble columns (Shah et al. [2]). Akita and Yoshida [3] determined the bubble size distribution using a photographic technique. The gas was sparger through perforated plates and single-orifice using various liquids (water, aqueous and pure glycol, methanol, carbon tetrachloride). Saxena A. C and Sexena S. C [4] studied the bubble size distribution in bubble column for the air-water system as a function of gas velocity at room temperature in the two bubble columns. High speed cinephotography and fiber optic probe techniques were used to measure bubble size. They suggest that the bubble size may be dependent on column diameter with smaller bubbles for narrower columns. The bubble size appears to be smaller at the column wall than at distance away from the wall. Gas holdup is one of the most important parameters characterizing the hydrodynamics of bubble columns. It can be defined as the percentage by volume of the gas in the two or three phases mixture in the column (Shah et al. [2]). The influence of gas velocity on gas holdup for alcohols aqueous solutions is reported by Posarac and Tekic [5]. They found that gas holdup value increase with increasing gas velocity and depend significantly on the type of alcohol added. Ruzicka et al. [6] studied experimentally the effect of the column size (height and diameter) on the stability of the homogeneous flow regime. The stability was expressed by values of the critical gas holdup and critical gas flow rate. They concluded from their results that the gas holdup values increases with increasing gas flow rate, and these values are mainly dependent on the bubble column diameter. Zahradnik et al. [7] studied the effect of aliphatic alcohols with different lengths of carbon chain ranging from methanol to octanol on bubble coalescence and gas holdup. The gas-liquid interfacial area is an important design variable in bubble column which depend on the geometry of the apparatus, the operating conditions, and the physical properties of liquid media (Shah et al. [2]). Bubble coalescence plays a significant role in determining bubble size distribution, gas holdup, interfacial area, and bubble rise velocity, which govern the performance of bubble columns and distillation towers (Kim and Lee [8]). Coalescence of bubbles in gas-liquid dispersions will be

Manuscript received October 26, 2013; revised March 20, 2014.

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inhibited, when the liquid phase is not pure component, but a mixture, as has been reported by Marrucci and Nicodemo [9]. Zahradnik et al. [10] studied the link the coalescence behavior of bubbles in aqueous electrolyte solutions with the character of gas-liquid beds generated in bubble column reactors and with corresponding values of bubble bed voidage. The experimental programme, performed with the set of nine inorganic salts, included determination of the bubble coalescence frequency in a coalescence cell and measurement of gas holdup in a sieve tray bubble column reactor of 0.14m inside diameter. The aim of the present work is to study the effect of addition of isobutanol on the performance of dispersion column, gas hold up, bubble size, gas-liquid interfacial area, were they effected directly by the bubble coalescence frequency. The transition concentration is predicted from bubble coalescence frequency were it is very important parameters that effect the mass transfer in the bubble column.



Fig. 1. (a) Experimental set-up: (1) bubble column (2) perforated plate (3) manometers (4) air compressor (5) air filter (6) regulating valves (7) rotameter (8) digital camera (9) centrifugal pump (b) Scheme of coalescence cell (1) bubble column (2)capillaries (3) air compressor (4) air filter (5) regulating valves (6) rotameter (7) digital camera (8) centrifugal pump.

II. EXPERIMENTAL SECTION

Photographing the bubbles and studying the hydrodynamics of bubbles were performed in perspex column of 75mm inside diameter and 2000mm in height, (shown in Fig. 1(a)). Two kind of perforated plates were used, single-orfice (plate A) (d_0 =2mm), and multi-orfice (plate B) (d_0 =0.5mm, and n=45) in a triangular pitch. The bubble

column opened to the atmosphere and operated continuously with respect to the gas phase and batch wise with respect to the liquid phase. The liquid used in this work is aqueous solutions of isobutanol. The clear liquid height was 1500mm, and liquid temperature was kept at 26 °C. The gas phase (air) was fed to the bottom of the column through the distributor, after the flow rate had been measured with rotameter. The liquid was discharged from the bottom of the column using centrifugal pump. While the bubble coalescence was performed in the other perspex column of 75mm inside diameter and 1500mm in height, (shown in Fig. 1(b)). The head of liquid over the gas injection region was 1200mm. Pairs of bubbles were formed simultaneously at opposite orifices of the two stainless steel capillaries 2mm in diameter, the distance of orifices was 10mm. One thousand bubble pairs were contacted in each experimental run and the coalescence percentage was then directly obtained as the number of coalescing bubble pairs. The transition concentration, define by Lessard and Zieminski [11] as the concentration corresponding to 50% coalescence, were then determined from the graphs (ψ vs. c_A) showing dependence of the coalescence percentage on the ethanol concentration.

When the bubble column is operated, the volume fraction of gas bubbles in the column can be computed from the heights of liquid levels in the manometer, by following Eq. (1), Jeng *et al.* [12]:

$$\mathcal{E}_g = \left(Z_1 - Z_2\right) / Z_o \tag{1}$$

The photographs of bubbles are taken by digital camera at the speed of 500frames/s, using a steel ball to calibrate the bubble shape. The diameter of each bubble is measured on the photograph and sauter mean diameter is computed, by following Eq. (2), Jeng *et al.* [12]:

$$d_{\nu s} = \left(\sum n_i d_{Bi}^3\right) / \left(\sum n_i d_{Bi}^2\right)$$
(2)

Specific gas-liquid interfacial area per unit volume of the dispersion column was obtained from Eq. (3), Jeng *et al.* [12]:

$$a = 6\varepsilon_g / d_{vs} \tag{3}$$

The experimental parameters of bubble size (sauter mean diameter), gas holdup, and gas-liquid interfacial area were designed using the centrol composite rotatable design with the following ranges of process variables:

1. Weight percent of isobutanol in water: (0.05-0.95) *Wt* %.

2. Superficial gas velocity of air (U_g) : (1.5-28.5) mm/s.

Using two perforated plate [single-orifice (plate A), and multi -orifice (plate B)].

A preliminary step is to setup the relationships between the coded levels and the corresponding real variables. The general relationship is following, (Montgomery [13], Peters and Timmerhaus [14]):

$$X_{coded} = \frac{X_{actual} - X_{center}}{\left[\frac{X_{center} - X_{min\,imum}}{\sqrt{K}}\right]}$$
(4)

The number of experiments N needed is estimated according to the following equation, (Montgomery [13],

Peters and Timmerhaus [14]):

$$N = 2^{K} + 2K + 1 \tag{5}$$

For the purpose of a second-order polynomial regression the central composite rotatable design for two variables was used. The coded levels are related to real process variables as follows:

$$X_1 = \frac{Wt\% - 0.5}{0.3182} \tag{6}$$

$$X_2 = \frac{U_g - 15}{9.5459} \tag{7}$$

III. RESULTS AND DISCUSSION

A. Use Non-Linear Regression Analysis

Second order polynomial regression analysis of the objective function (sauter mean diameter, gas holdup, gas-liquid interfacial area, and bubble coalescence percentage) gave Eqs. (8) to (13) respectively. In the analysis of the experimental results it is possible to determine not only the effect of each individual variable but also the way in which each variable effect depends on the other variables (i.e. interaction). A complete regression results with a computer program named "Statistica".

For Plate (A):

$$d_{vs} = 4.299955 - 1.01878X_1 - 0.188403X_2 - 0.237526X_1^2$$

+0.012549X_2^2 - 0.05X_1X_2

Mean deviation = 5.04%Correlation coefficient (r_c) = 0.976

$$\varepsilon_g = 0.384505 + 0.1093791X_1 + 0.01884X_2 - 0.008504X_1^2$$

-0.008504 $X_2^2 + 0.005X_1X_2$

Mean deviation = 3.065%Correlation coefficient (r_c) = 0.989

$$a = 0.536559 + 0.412624X_1 + 0.054318X_2 + 0.200963X_1^2$$
$$-0.022438X_2^2 + 0.033508X_1X_2$$
(10)

Mean deviation = 8.055%Correlation coefficient (r_c) = 0.986

For Plate (B):

$$d_{vs} = 3.559963 - 0.845203X_1 - 0.154991X_2 - 0.194397X_1^2$$

+0.013166X_2^2 - 0.04X_1X_2

Mean deviation = 4.999%Correlation coefficient (r_c) = 0.977

$$\begin{split} \varepsilon_g &= 0.427029 + 0.121356X_1 + 0.020886X_2 - 0.009784X_1^2 \\ &- 0.009784X_2^2 + 0.005478X_1X_2 \end{split}$$

Mean deviation = 3.021%Correlation coefficient (r_c) = 0.989

$$a = 0.624825 + 0.382013X_1 + 0.09886X_2 + 0.108246X_1^2$$

-0.016472X_2^2 + 0.0956X_1X_2 (13)

Mean deviation = 11.683%Correlation coefficient (r_c) = 0.985

B. Influence of Process Variables on dvs, εg , a, and ψ .

Two variables were studied in dispersion column: weight percent of isobutanol in water, and superficial gas velocity of air, for two perforated plates (A) and (B). The meanings of code numbers for all Figures are given below (Table I).

TABLE I: WORKING RANGE OF CODED AND CORRESPONDING F	REAL
VADIADIES	

VARIABLES			
Coded Level	Wt (%)	$U_g (\mathrm{mm/s})$	
-1.414	0.05	1.5	
-1	0.1818	5.4541	
0	0.5	15	
1	0.8182	24.5459	
1.414	0.95	28.5	

Experimental results verify from Fig. 2 to Fig. 7, the effect of weight percent of isobutanol in water on sauter mean diameter, gas holdup, and gas-liquid interfacial area for two perforated plates (A) and (B). The sauter mean diameter decreases with increasing weight percent of isobutanol in water, but the gas holdup, and gas-liquid interfacial area increase with increasing weight percent of isobutanol in water, for two perforated plates, but in perforated plate (B) they had higher values than those of perforated plate (A). This increase can be attributed to the addition of small amount of isobutanol to the water in a bubble column has the effect of retarding the coalescence of the gas bubbles. This makes the number of gas bubbles per unit volume larger, size smaller, terminal rising velocity slower, and residence time in the column liquid longer, and consequently the volume fraction occupied by the gas phase, and gas-liquid interfacial area per unit volume larger. This phenomenon can be explained as isobutanol in water acts as a surfactant which hinders bubble coalescence by accumulating at the gas-liquid interface and orienting their hydrophilic group into liquid film surrounding the gas bubble and thus creating repulsive electric forces when two bubbles come close to each other. The concentration of the hydrophilic molecules at the surface increases with surfactant concentration and results in a lower surface tension. These notation supported by Keitel and Onken [15], and Wilkinson et al. [16].



Weight Percent of Isobutanol Wt (%)



(11)

(12)

(8)

(9)



Weight Percent of Isobutanol Wt (%)

Fig. 3. Influence of isobutanol addition on sauter mean diameter for plate (B).



Weight Percent of Isobutanol Wt (%)

Fig. 4. Influence of isobutanol addition on gas hold-up for plate (A).



Weight Percent of Isobutanol Wt (%)

Fig. 5. Influence of isobutanol addition on gas hold-up for plate (B).



Fig. 6. Influence of isobutanol addition on interfacial area for plate (A).

Fig. 8-Fig. 13 respectively show the influence of superficial gas velocity of air on sauter mean diameter, gas holdup, and gas-liquid interfacial area, for two perforated plates (A) and (B). The sauter mean diameter decreases with increasing superficial gas velocity of air, but the gas holdup, and gas-liquid interfacial area increase with increasing

superficial gas velocity of air, for two perforated plates. This increase is attributed to the fact that in higher superficial gas velocity of air, small bubbles are formed with a lower rising velocities leading to a large residence time and consequently higher values of gas holdup, and these small bubbles have large gas-liquid interfacial area. This was reported by Zahradnik *et al.* [7].



Fig. 7. Influence of isobutanol addition on interfacial area for plate(B).

The effect of design parameter of perforated distributing plates has been demonstrated by all Figures given below. The values of gas holdup and gas-liquid interfacial area for perforated plate (B) were higher than those for perforated plate (A). The difference between two perforated plates is due to the smaller orifice diameter in the perforated plate (B), higher number of bubble are formed per unit volume, and the bubble size produced would be smaller and large gas-liquid interfacial areas lead to a higher gas holdup as compared with that in a perforated plate (A). This was reported by Zahradnik and Fialova [17], and Zahradnik *et al.* [18].





Fig. 8. Influence of superficial gas velocity on sauter mean diameter for plate

Fig. 9. Influence of superficial gas velocity on sauter mean diameter for plate (B).



Superficial Gas Velocity Ug (mm/s)

Fig. 10. Influence of superficial gas velocity on gas hold-up for plate (A).



Superficial Gas Velocity Ug (mm/s)

Fig. 11. Influence of superficial gas velocity on gas hold-up for plate (B).



Superficial Gas Velocity Ug (mm/s)

Fig. 12. Influence of superficial gas velocity on interfacial area for plate (A).



Superficial Gas Velocity Ug (mm/s)

Fig. 13. Influence of superficial gas velocity on interfacial area for plate (B).

Bubble coalescence percentage, ψ % is the number of occurrence of coalescence within a certain volume element of the column per unit time, and their values were calculated by photographic technique. Results of bubble coalescence measurements are summarized in Fig. 14 and Fig. 15 in which values of the bubble coalescence percentage are plotted against the concentration of isobutanol in water, and superficial gas velocity of air. The bubble coalescence percentage decrease with increasing isobutanol concentration in water, and superficial gas velocity of air. The value of transition concentration (c_i) obtained experimentally from Fig. 14 by projection. The transition concentration was defined as the concentration resulting in 50% coalescence frequency. This was reported by Lessard and Zieminski [11].



isobutanoi Concentration CA (kmole/mº)

Fig. 14. Influence of isobutanol concentration on bubble coalescence percentage.



Fig. 15. Influence of superficial gas velocity on bubble coalescence percentage.

Analysis of experimental data showed that, within the experimental set, the isobutanol transition concentration was successfully correlated as a function of superficial gas velocity of air:

$$c_t = 0.072079 - 0.006408U_g + 0.000425U_g^2 - 0.00001U_g^3$$
(14)

Mean deviation = 4.501%

Correlation coefficient (r_c)= 0.996

Comparison shown in Table II proves good agreement of experimental c_t data with those calculated from Eq.(14), for empirical coefficients 0.072079, -0.006408, 0.000425, and -0.0001 determined from experimental data by non-linear regression.

TO THE WATER		
$c_t(exp.)$ kmol/m ³	$c_t(cal.)$ kmol/m ³	
0.0625	0.06339	
0.05	0.048221	
0.0375	0.039278	
0.03125	0.029473	
0.0125	0.013387	

TABLE II: TRANSITION CONCENTRATION OF THE ISOBUTANOL ADDITION TO THE WATER

IV. CONCLUSION

- 1) A surface active additives (i.e. isobutanol) in an effective means of improving the operating efficiency of bubble column, has the effect of retarding the coalescence of gas bubbles
- 2) The bubble size (sauter mean diameter) is found to decrease with increasing weight percent of isobutanol in water, and superficial gas velocity of air, whereas the gas holdup is found increased resulting in an increase in gas-liquid interfacial area.
- 3) When central composite rotatable design technique was used, a relationship was found between process variable (Wt, and U_g) and $(d_{vs}, \varepsilon_g$, and a) was obtain for two perforated plates (A), and (B).
- 4) Transition concentration of isobutanol, characterizing suppression of coalescence in isobutanol aqueous solutions, and isobutanol concentration was correlated as a function of superficial gas velocity of air.
- 5) The relation between the transition concentration of isobutanol and superficial gas velocity was polynomial equation.

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