BUBBLES COALESCENCE FREQUENCY AND TRANSITION CONCENTRATION IN A BUBBLE COLUMN

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ABSTRACT

Bubbles coalescence frequency and the transition concentration in a dispersion column were studied experimentally by using ethanol-water mixture as a liquid phase and air as a gas phase. The study was devoted to express the effect of the liquid properties on the performance of the dispersion column, and the experimental work was designed for this purpose, where the range of weight percent of ethanol in water, (0.1-0.7) Wt%, and the range of superficial gas velocity of air, (2.5-30) mm/s.

The experimental runs were planned using the central composite routable design method. The experimental data obtained agreed quite well with a polynomial type of correlations by using computer program.

The experimental data shows that the values of bubble coalescence decrease with increasing superficial gas velocity of air, and ethanol transition concentration was successfully correlated as a function of the superficial gas velocity of air,

$c_t = 0.158214 - 0.010849U_g + 0.00045U_g^2 - 0.000008U_g^3$.   This   equation gives mean deviation of 10.393%.

KEYWORDS

Dispersion column, bubble coalescence, transition concentration

NOTATIONS

a = specific gas-liquid interfacial area, mm^2/mm^3

c_t = transition concentration, $kmol/m^3$

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 ethanol in water, Wt %

x_1, x_2 = coded or independent variables of polynomial equation

Z_o, Z_1, Z_2 = liquid levels in the manometers, mm

GREEK LETTERS

ε_g = gas holdup

ψ = coalescence percentage, %

INTRODUCTION

The most important process in a bubble column is the formation of a gas at the sparger. The smaller the bubbles, the larger is 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 with 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 suggested 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]).

Bubbles 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 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 bubbles 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 ethanol on the performance of dispersion column, gas hold up, bubble size, and gas-liquid interfacial area, were they effected directly by the bubble coalescence frequency. The transition concentration is predicted from bubbles coalescence frequency were it is very important parameter that effect the mass transfer in the bubble column.

EXPERIMENTAL SECTION

Photographing the bubbles and studying the hydrodynamics of bubbles were performed in perspex column of 75mm inside diameter and 1500mm in height, (shown in Figure1a).Two kinds of

perforated plates were used, single-orifice (plate A with d_o=3mm), and multi-orifice (plate B with d_o=1mm, 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 phase used in this work is aqueous solutions of ethanol. The clear liquid height was 1000mm, and liquid temperature was kept at 30°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 bubbles coalescence was performed in the other perspex column of 75mm inside diameter and 1500mm in height, (shown in Figure1b). The head of liquid over the gas injection region was 1000mm. Pairs of bubbles were formed simultaneously at opposite orifices of the two stainless steel capillaries 3mm in diameter and the distance between these orifices was 6.5mm. Two hundred bubbles pairs were contacted in each experimental run and the coalescence percentage was then directly obtained as the number of coalescing bubbles 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., (Jeng et al. [12]):

$$\varepsilon_g = (Z_1 - Z_2)/Z_o \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(1)$$

The photographs of bubbles are taken by digital camera at the speed of 30frames/s, then 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., (Jeng et al. [12]):

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

$$a = 6\varepsilon_g / d_{vs} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(3)$$

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

The experimental parameters of bubble size (sauter mean diameter),

gas holdup, and gas-liquid interfacial area were designed using the central composite rotatable design with the following ranges of process variables:

1. Weight percent of ethanol in water: (0.1-0.7) Wt %.

2. Superficial gas velocity of air (U_g): (2.5-30) 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 as follow, (Montgomery [13], Peters and Timmerhaus [14]):

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

The number of experiments N needed is estimated according to the following equation, (Montgomery [13], Peters and Timmerhaus [14]):

$$N = 2^K + 2K + 1 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(5)$$

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:

$$X_1 = \frac{Wt - 0.4}{0.2121} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(6)$$

$$X_2 = \frac{U_g - 16.25}{9.7227} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(7)$$

RESULTS AND DISCUSSION

1. Non-Linear Regression Analysis

   Second order polynomial regression analysis of the objective functions (sauter mean diameter, gas holdup, gas-liquid interfacial area, and bubbles coalescence percentage) gave Eqs. (8) to (13) respectively in Appendix.

   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".

2. Influence of Process Variables on d_{vs}, ε_g, a, and ψ.

   Two variables were studied in bubble column: weight percent of ethanol 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 in (Table 1).

   Experimental results verify from Figures (2) to (7), the effect of weight percent of ethanol in water on sauter mean diameter, gas holdup, and gas-liquid interfacial area. The sauter mean diameter decreases with increasing weight percent of ethanol in water, but the

gas holdup, and gas-liquid interfacial area increase with increasing weight percent of ethanol 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 ethanol 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 ethanol 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 are supported by Keitel and Onken [15], and Wilkinson et al. [16].

Figures (8 to 13) respectively show the influence of superficial gas velocity of air on sauter mean diameter, gas holdup, and gas-liquid interfacial area. 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. [18].

The effect of design parameter of perforated distributing plates has been demonstrated by all Figures given. 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 bubbles 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].

Bubble coalescence percentage, $\psi\%$ 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 method.

Results of bubbles coalescence measurements are summarized in Figures (14), and (15) in which values of the bubbles coalescence

percentage are plotted against the concentration of ethanol in water, and superficial gas velocity of air. The bubbles coalescence percentage decrease with increasing ethanol concentration in water, and superficial gas velocity of air. The value of transition concentration (c_t) obtained experimentally from Figure (14) by projection. The transition concentration was defined as the concentration resulting in 50% coalescence frequency. This was reported by Lessard and Zieminski [11].

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

$$c_t = 0.158214 - 0.010849U_g + 0.00045U_g^2 - 0.000008U_g^3 \ldots\ldots\ldots\ldots(14)$$

Mean deviation = 10.393%

Correlation coefficient(r_c)= 0.986

Comparison shown in Table (2) proves good agreement of experimental c_t data with those calculated from Eq.(14), for empirical coefficients 0.158214, -0.010849, 0.00045, and -0.000008 determined from experimental data by non-linear regression.

For Plate (A)

$$d_{vs} = 3.656083 - 0.556927X_1 - 0.906199X_2 + 0.383704X_1^2$$
$$+ 0.043601X_2^2 + 0.16325X_1X_2 ....(8)$$

Mean deviation = 5.862%

Correlation coefficient $(r_c) = 0.91$

$$\varepsilon_g = 0.1364 + 0.007911X_1 + 0.031865X_2 + 0.002113X_1^2$$
$$+ 0.004614X_2^2 + 0.00125X_1X_2 ....(9)$$

Mean deviation = 2.983%

Correlation coefficient $(r_c) = 0.983$

$$a = 0.223835 + 0.035601X_1 + 0.110725X_2 - 0.014394X_1^2$$
$$+ 0.034655X_2^2 + 0.00212X_1X_2 ....(10)$$

Mean deviation = 8.942%

Correlation coefficient $(r_c) = 0.976$

For Plate (B)

$$d_{vs} = 3.362048 - 0.418661X_1 - 0.732997X_2 + 0.196752X_1^2$$
$$- 0.150103X_2^2 - 0.036271X_1X_2 ....(11)$$

Mean deviation = 4.715%

Correlation coefficient $(r_c) = 0.932$

$$\varepsilon_g = 0.185994 + 0.013554X_1 + 0.061003X_2 + 0.00338X_1^2$$
$$+ 0.014375X_2^2 + 0.003741X_1X_2 \dots\dots\dots\dots\dots\dots\dots(12)$$

Mean deviation = 2.286%

Correlation coefficient (r_c) = 0.995

$$a = 0.331932 + 0.062893X_1 + 0.223663X_2 - 0.020842X_1^2$$
$$+ 0.100073X_2^2 + 0.03328X_1X_2 \dots\dots\dots\dots\dots\dots\dots(13)$$

Mean deviation = 7.931%

Correlation coefficient (r_c) = 0.987

CONCLUSIONS

1. The surface active additives (ethanol) 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 ethanol 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}, ε_g, and a) was obtain for two perforated plates (A), and (B).

4. Transition concentration of ethanol, characterizing suppression of coalescence in ethanol aqueous solutions, and ethanol concentration

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Table 1. Working range of coded and corresponding real variables.

Coded level	Wt (%)	U_g (mm/s)
-1.414	0.1	2.5
-1	0.187	6.527
0	0.4	25.97
1	0.612	16.25
1.414	0.7	30

Table 2. Transition concentration of the ethanol addition to the water.

c_t (exp.) kmol/m³	c_t (cal.) kmol/m³
0.025	0.028782
0.052	0.044433
0.06	0.06757
0.112	0.104431
0.13	0.133785
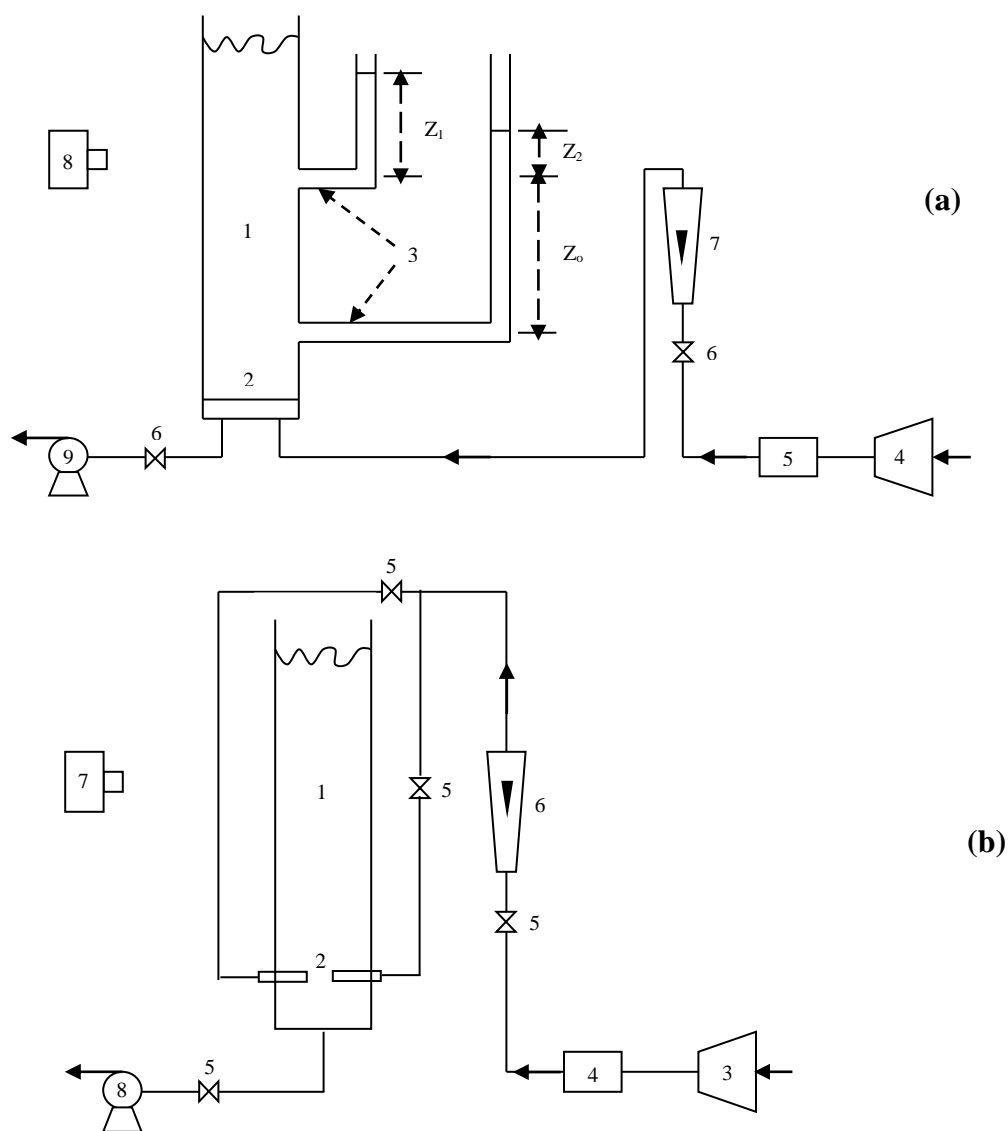
Figure (1) : (a) experimental setup : (1) bubble column (2) perforated plate (3) manometers (4) air compressor (5) air filter (6) regulating valves (7) rotameter (8) digital camera (9) centrifugal pump (b) Scheme of coalescence cell (1) bubble column (2) capillaries (3) air compressor (4) air filter (5) regulating valves (6) rotameter (7) digital camera (8) centrifugal pump.
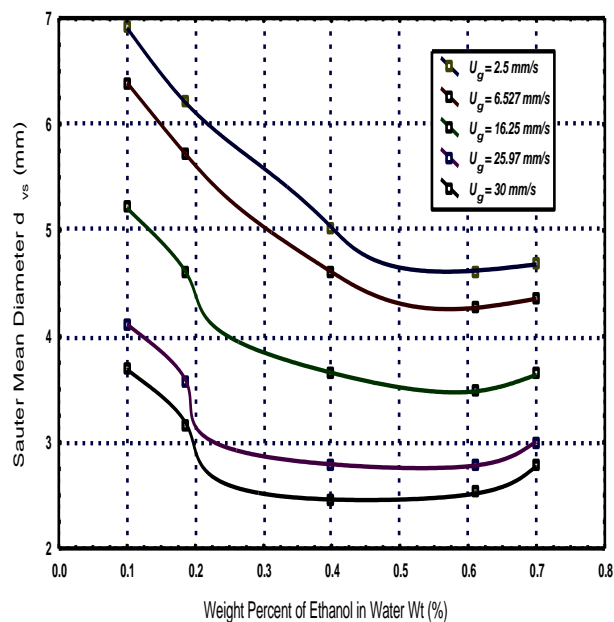
Fig.(2): Variation of the sauter mean diameter versus Wt % for plate (A).
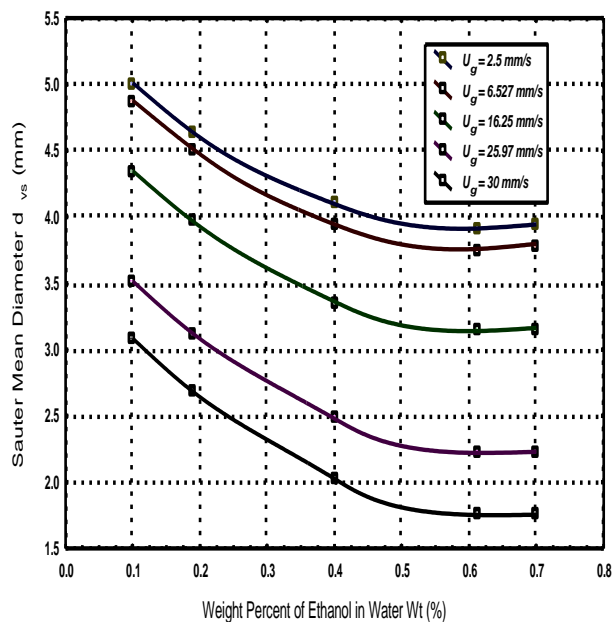
Fig.(3): Variation of the sauter mean diameter versus Wt % for plate(B).
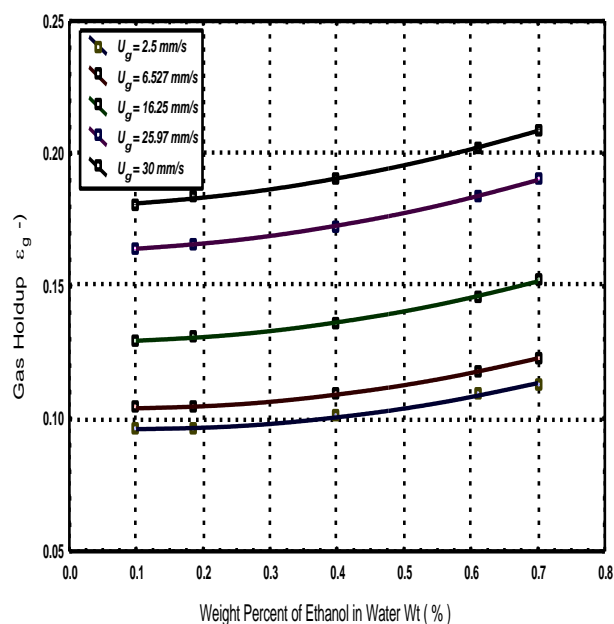
Fig.(4): Variation of the gas hold up versus Wt % for plate(A).
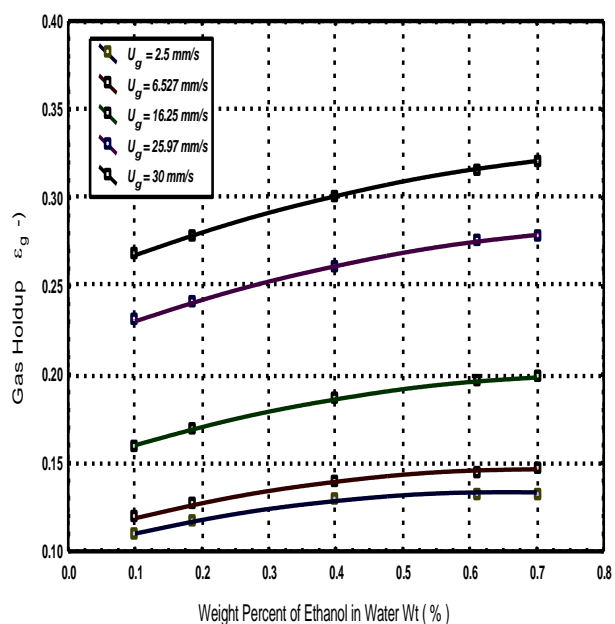
Fig.(5): Variation of the gas hold up versus Wt % for plate(B).
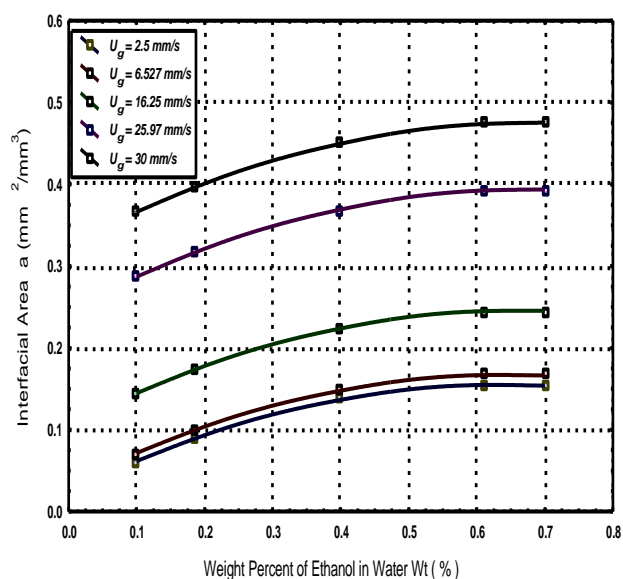
Fig.(6): Variation of the a versus Wt % for plate(A).
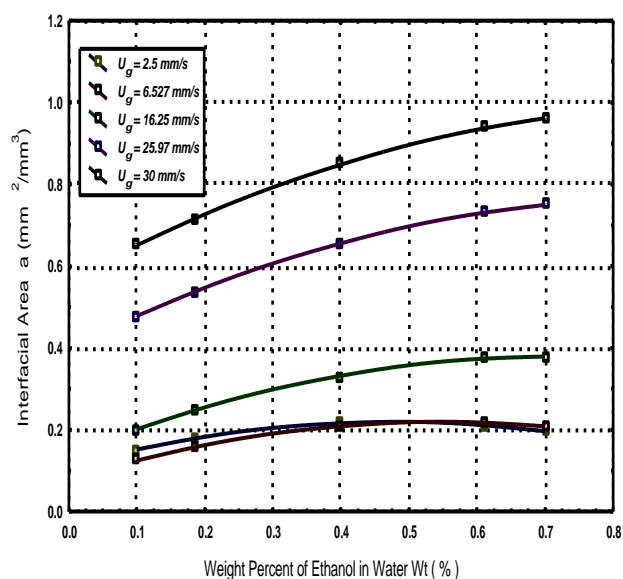
Fig.(7): Variation of the a versus Wt % for plate(B).
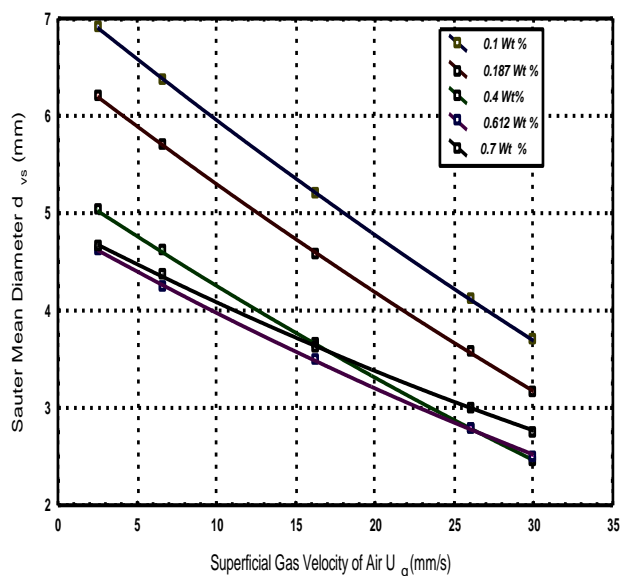
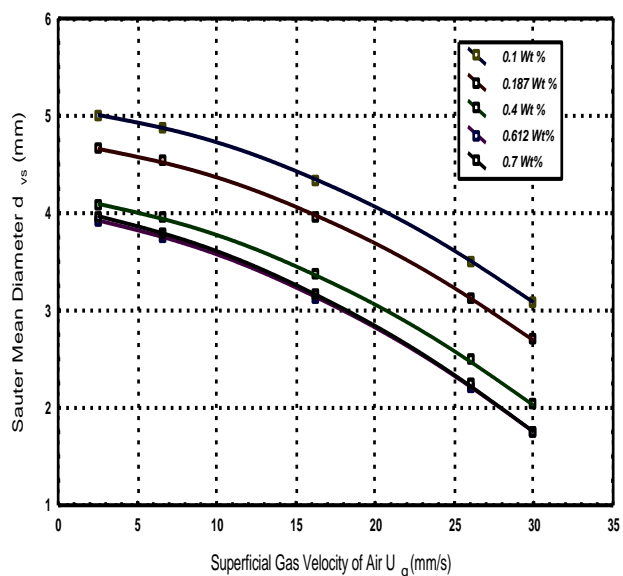Fig.(8): Variation of the sauter mean diameter versus gas velocity for plate(A).

Fig.(9): Variation of the sauter mean diameter versus gas velocity for plate(B).
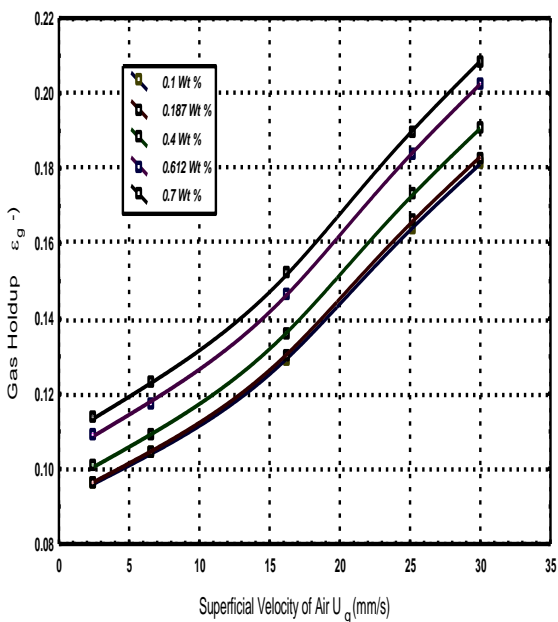
Fig.(10): Variation of the gas hol up versus gas velocity for plate(A).
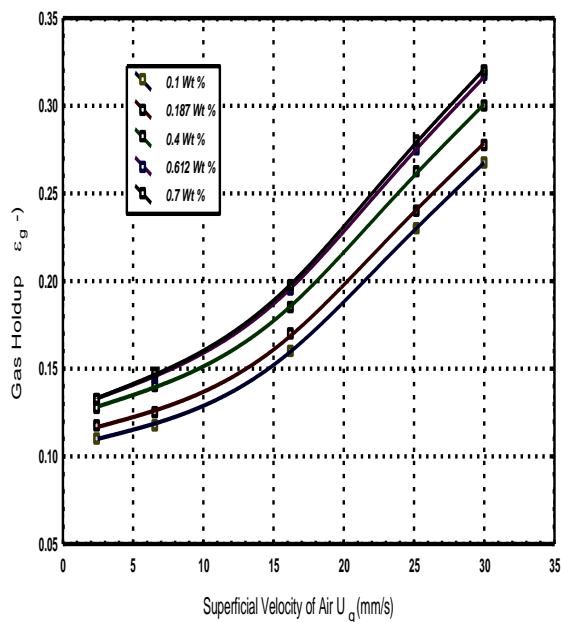

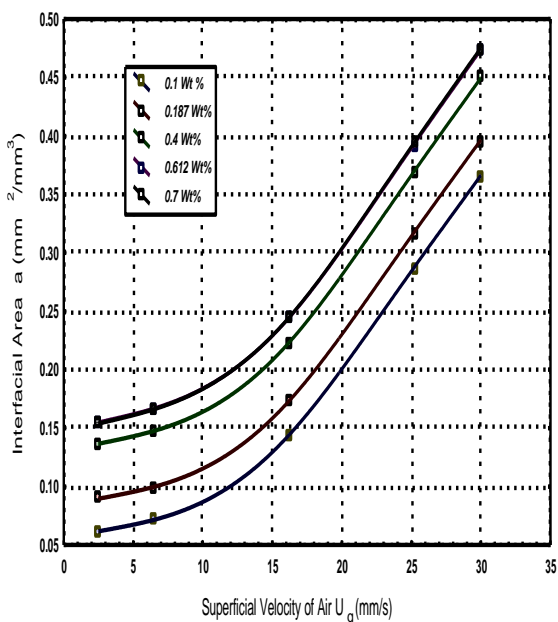*Fig.(11): Variation of the gas hold up versus gas velocity for plate(B).*

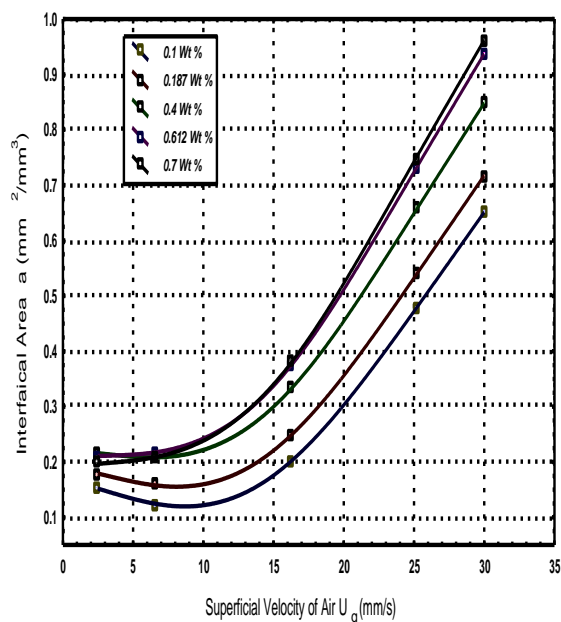*Fig.(12): Variation of the a versus gas velocity for plate(A).*

Fig.(13): Variation of the a versus gas velocity for plate(B).

معدل اندماج الفقاعات والتركيز الانتقالي في العمود الفقاعي

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الخلاصة

تم دراسة اندماج (تلاحم) الفقاعات والتركيز الانتقالي في منظومة العمود الفقاعي من خلال إجراء تجارب عملية وذلك باستخدام مزيج الايثانول/الماء كطور سائل والهواء كطور غازي، تم التركيز في هذه الدراسة على تأثير خصائص السائل على أداء منظومة العمود الفقاعي. تم تصميم التجارب العملية لتؤدي الغرض أعلاه وفقا للمديات العملية، النسبة الوزنية للايثانول في الماء بين (0.1–0.7) % وسرعة الهواء الداخلة للعمود بين (2.5–30) ملم/ثانية.

تم تصميم التجارب العملية باستخدام طريقة (Central composite rotatable design) وكانت النتائج المستحصلة مطابقة بصورة جيدة جدا مع العلاقة المتعددة الحدود التي تم الحصول عليها بواسطة برامج تسمى (Statistica). ان فعالية الايثانول على منع اندماج الفقاعات تزداد بزيادة تركيز الايثانول في الماء. كما أثبتت التجارب إن قيم اندماج الفقاعات تقل بزيادة سرعة الهواء الداخلة ، وقد تم إيجاد علاقة متعددة الحدود تربط بين التركيز الانتقالي للايثانول وسرعة الهواء الداخلة، $c_t = 0.158214 - 0.010849U_g + 0.00045U_g^2 - 0.000008U_g^3$. أعطى النموذج متوسط انحراف مقداره 10,393%.

الكلمات الدالة

برج فقاعي، اندماج الفقاعات، التركيز الانتقالي.