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Experimental Study and Theoretical Model Described Transition Regime Parameters and Hydrodynamic Parameters in a Gas-Liquid Dispersion Column

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Abstract

Experimental study of total gas hold-up, bubble diameters and rise velocity of the swarm of bubbles, and regime transition point in dispersion column. The experimental runs were carried out in two perspex columns of 7.5 cm and 15 cm inside diameter. The present work investigated the effect of two system of two-liquid phase (air-water, and air-aqueous-n-propanol solution) in the range (0.05-0.7Wt%), superficial air velocity in the range (0.025-0.3 cm/s) and two air distributor plates of 1.5 mm diameter holes (i.d.= 7.5 cm, holes=36 and free area=1.4%, and i.d.= 15 cm holes=121 and free area=1.2%). In this paper, a Krishna et al., 1999 model has been improved, and the combination of this improved model with derived drift flux model have been described the hydrodynamics of dispersion column operating in homogeneous and heterogeneous flow regimes (i.e. transition regime parameters ε_{trans} and U_{trans}). Photographic technique was used by taking three pictures in different view (different angle) of the dispersion column, to measure the hydrodynamic parameters. From the experimental data, it was found that the addition of a small amount of n-pentanol to distilled water and varying dispersion column diameter, is the main factor that affects, the transition flow regime. Also the experimental results show that the values of total gas hold-up for air-aqueous n-pentanol solution system are greater than the values for air-water system, but the values of total gas hold-up decrease with dispersion column diameter for two systems.

The experimental data show that the values of total gas hold-up and superficial air velocity at transition regime varied with the weight percent of n-pentanol by fitting of second order polynomial regressions for the two dispersion column diameters:

$$\varepsilon_{trans} = a\,Wt^2 + b\,Wt + c$$

$$U_{trans} = d\,Wt^2 + e\,Wt + i$$

Keywords: Dispersion column, transition regime parameters, total gas hold-up, and column diameter influence.

دراسه عمليه وموديل نظري يصفان القيمه المحدده للمنطقه الانتقاليه والقيمه المحدده للخواص الهيدروديناميكيه في عمود التشتييت من غاز - سائل

الخلاصة

لقد تم اجراء دراسه عمليه لكميه الغاز المحتجز الكلي وقطر الفقاعات والسرعه الصعوديه لحشد من الفقاعات ونقطه حدوث المنطقه الانتقاليه فى عمود تشتيت. وقد تمت التجارب باستخدام عمودين

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تشتيت بقطر داخلي 7,5 و15سم. تم دراسة تاثير نظامين هما (هواء-ماء و هواء- محلول مائي للبنتانول- اعتيادي بتراكيز وزنيه مختلفه ضمن المدى (0,05-0,7%) وسرعة الهواء الظاهرية التي تراوحة بين (0,025-0,3 م/ثانيه) باستخدام موزعين للهواء بقطر ثقب 1,5 ملم (قطر عمود=7,5 سم، عدد الثقوب=36 ومساحه التثقيب=1,4% وقطر عمود=15سم، عدد الثقوب=121 ومساحه التثقيب=1,2%).في هذا البحث تم تطوير موديل ل(Krishna et al., 1999) وتم ربط هذا الموديل المطور مع اشتقاق لموديل (Drift Flux) لوصف الخواص الهيدروديناميكيه لعمود التشتيت يعمل عند منطقه الجريان المتجانس ومنطقه الجريان الغير متجانس (القيمه المحدده لمنطقه الجريان الانتقاليه ε_{trans} و U_{trans}). استخدمت تقنيه التصوير باخذ ثلاث صور بمشاهد مختلفه (زوايا مختلفه) لعمود التشتييت، من خلال هذه الصور تم حساب الخواص الهيدروديناميكيه. من خلال النتائج العمليه، تم الوصول الى انه اضافه كميه قليله من البنتانول-الاعتيادي للماء المقطر وتغيير قطر عمود التشتييت هما العاملان الرئيسيان المؤثران على منطقه الجريان الانتقاليه. وكذلك اظهرت النتائج العمليه ان قيم كميه الغاز المحتجز الكلي لنظام هواء-محلول مائي للبنتانول-الاعتيادي اكبر من نضيراتها لنظام هواء-ماء، لكن قيم كميه الغاز المحتجز تقل مع زياده قطر عمود التشتييت للنظامين. بينت النتائج العمليه ان قيم كميه الغاز المحتجز الكلي وسرعه الهواء الظاهريه عند منطقه الجريان الانتقاليه تتغير مع النسبه الوزنيه للبنتانول-الاعتيادي طبقا لعلاقه متعدده الحدود اظهرت نتائج جيده جدا لعمودي التشتييت:

$$\varepsilon_{trans} = a\,Wt^2 + b\,Wt + c$$
$$U_{trans} = d\,Wt^2 + e\,Wt + i$$

Introduction

Dispersion columns are attracting increasing academic and industrial research interest in view of the many potential applications in natural gas conversion technologies (Krishna, Ellenberger and Sie, 1996; and Krishna and Sie, 2000). Dispersion columns are operated either in the homogeneous or heterogeneous flow regime.

A proper understanding of bubble hydrodynamics as a function of scale (column diameter and height) and physical properties of gas and liquid phases is needed before reliable procedures for scaling-up a bubble reactor of industrial size can be developed. The gas-liquid hydrodynamics in bubble columns is quite complex and influenced by several factors, such as physical properties of gas and liquid, and dispersion height, therefore the scale-up of bubble columns is still poorly (Krishna and Van Baten, 2001; Deckwer,1992; Krishna and Ellenberger,1996; and Wild et al., 2003).

Mohammed, 1997 studied the effect of hydrodynamic interactions in bubbly two-phase flow, these parameters were void fraction, Reynolds number, Weber number, Froude number, and Eotvos number, as well as the effects of void fraction and bubble size on the bubble velocity.

Investigations of design parameters characterizing the operation and transport phenomena of bubble columns have led to a better understanding of the hydrodynamic properties, heat and mass transfer mechanisms, and flow regime characteristics ongoing during the operation (Kantarci et al., 2005).

Gas hold-up is a dimensionless key parameter for design purposes that characterize transport phenomena of bubble column systems (Lou et al., 1999). Gas hold-up, or voidage, is a dimensionless quantity that represents the percentage of the total gas-liquid system that is occupied by the gas. The velocity of gas sparged into the bubble column increases, the gas hold-up also increases. According to gas-liquid theory, the gas hold-up increases linearly with the gas velocity in the bubbly regime (Krishna et al., 1991), while the system in the churn-turbulent phase, the relationship is not linear.

Krishna and Van Baten, 2001 and Van Baten and Krishna, 2003 considered a three phase continuum and assumed that bubbles in the column were either small or large, with different velocities, but with no interaction between them. When industrial systems are considered, higher superficial gas velocities are encountered, and thus, both bubble coalescence and breakup must be taken into account in order to better describe the reactor hydrodynamics.

In gas-liquid two phase systems, bubble breakup and coalescence can greatly influence their overall performance by altering the interfacial area available for mass transfer between the phases. In order to reliable predictive tools for bubble column reactor design, it is essential to obtain some insight into prevailing phenomena through simulation models based on the bubble formation / distraction mechanisms (bubble coalescence and breakup)(Shimizu et al., 2000, and Buwa and Ranade, 2002).

Abdul Aziz, 2007 investigated the hydrodynamics of two-phase downflow bubble column with air-water system, this studied consisted of the effects of superficial gas velocity, nozzle diameter, liquid flow rate on the hydrodynamic parameters, viz. gas hold-up, bubble diameter and bubble velocity.

The major goal of the present research has been the improvement of Krishna et al., 1999 model. The parameters of transition regime (i.e. ε_{trans} and U_{trans}) have been obtained from the combination between this improved model and the derived drift flux model. Also study the influence of dispersion column diameter, properties of liquid phase and superficial air velocity on total gas hold-up, bubble diameters and rise velocity of the swarm of bubbles.

Experimental Setup

Experiments were performed in two perspex cylindrical columns with inner diameters of 7.5, and 15cm. A typical experimental setup is shown in Fig.(1) for 7.5 cm diameter dispersion column. Air was used as the gas phase with varied velocity in the range 0.025-0.3 m/s and the liquid phase used in the experiments consisted of distilled water to which n-pentanol was added with varied weight percent in the range 0.05-0.7 Wt%. Two columns were fitted with similar distributors plate with 1.5 mm diameter holes on a square pitch of 10 mm. In the 7.5 cm diameter column, a total of 36 holes with free area 1.4% were drilled, while in the 15cm diameter column, a total of 121 holes with free area 1.2% were drilled. The experiments were conducted at ambient pressure and temperature conditions. All the experiments were performed with stagnant liquid, while the gas phase was injected and distributed into the liquid phase by passing through the distributor. Each experimental run starts by first filling the column with the appropriate liquid phase at constant L/D_T ratio of 9 above the distributor. The total gas hold-up was measured by visual reading of the dispersion height, according to following equation:

$$\varepsilon_g = \frac{H - H_o}{H} \quad \dots (1)$$

To eliminate optical distortion during the photography of the bubbles, a square box filled with water or aqueous of n-pentanol solution encloses the column.

A high speed digital video camera (Sony DSA-T700, 10.1 MPexil) is used at for direct flow visualization and for bubble diameter of the swarm of bubbles, rise velocity of the swarm of bubbles, as well as gas hold-up measurement, using a steel ring to calibrate the bubble diameter. Three pictures were taken at different view for the column (picture one at the distributor regime, picture two at 30 cm above the distributor regime, and picture three at 60 cm above the distributor regime) at the recording speed of 25 pictures per second. The bubble diameter was estimated from photographic techniques, using equation (2):

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

Developement of Krishna et al., 1999 Model for total Gas Hold-up

Krishna et al., 1999 has a two-phase model for description of the hydrodynamics of bubble columns operating in the churn-turbulent flow regime. In this model a sharp transition from the homogeneous to heterogeneous flow regime is assumed. The superficial gas velocity through the small bubble population is assumed to equal that at the regime transition (U_{trans}). The remainder of the entering gas flows up the column in the form of large bubbles. The superficial gas velocity through the large bubbles is (U_g-U_{trans}). The small bubbles are either spherical or ellipsoidal in shape, depending on the physical properties of the liquid phase. The large bubble fall into the spherical cap regime. The theoretical model applied on column diameters range between 0.05-0.63 m and height to diameter ratio range between 1-80 at two regimes (Krishna et al., 1999, and Krishna and Sie, 2000):

1- Homogeneous Flow Regime

For superficial gas velocities $U_g \leq U_{trans}$, the gas hold-up in this regime is given by:

The relation between gas hold-up and slip velocity for U_L=0 is given by (Wallis, 1962, and Lapidus and Elgin, 1957):

$$\varepsilon_g = \frac{U_g}{V_s} \quad \dots (3)$$

$$V_s = U_{b,small}\left(1 - \varepsilon_g\right) \quad \dots (4)$$

Where:

V_s is the slip velocity between gas and liquid phases.

$U_{b,small}$ is the rise velocity of the swarm of small bubbles.

2- Heterogeneous Flow Regime

For superficial gas velocities $U_g \geq U_{trans}$, the total gas hold-up is given by:

$$\varepsilon_g = \varepsilon_{b,large} + \varepsilon_{trans}(1-\varepsilon_{trans}) \quad \dots(5)$$

Where:

$$\varepsilon_{b,large} = \frac{(Ug - U_{trans})}{U_{b,large}} \quad \dots(6)$$

Where:

$U_{b,large}$ is the rise velocity of the swarm of large bubbles.

The equation of rising velocity of the swarm of large bubbles is developed, by considering the spherical cap bubbles, as shown in Fig.(2).

Applying Bernoullis equation in the liquid region between two points (1 and 2), the following equations are obtained:

$$p_1 - p_2 = \rho_L\, g(h_2 - h_1) - \frac{1}{2}\rho_L U_L^2 \quad \dots(7)$$

Let

$$h = h_2 - h_1 \quad \dots(8)$$

From Fig.(2):

$$h = R_{b,large}(1-\cos\theta) \dots(9)$$

Substitution of eqs. (8) and (9) in eq. (7), yields:

$$p_1 - p_2 = \rho_L\, g\, R_{b,large}(1-\cos\theta) - \frac{1}{2}\rho_L U_L^2 \dots(10)$$

The potential flow solution around the spherical portion is (Davies and Taylor, 1950):

$$U_L = \frac{3}{2}U_{b,large}\sin\theta \quad \dots(11)$$

Applying Bernoullis equation in the gas region between two points (1 and 2), velocity of gas phase between points 1 and 2 is equal, yields (Davies and Taylor, 1950):

$$p_1 - p_2 = \rho_g\, g\, R_{b,large}(1-\cos\theta) \quad \dots(12)$$

Substitution of eq. (11) in eq. (10) and equating with eq. (12), yields:

$$U_{b,large}^2 = \frac{8}{9}g\, R_{b,large}\frac{(\rho_L-\rho_g)}{\rho_L}\frac{(1-\cos\theta)}{\sin^2\theta} \quad \dots(13)$$

Take $\lim_{\theta\to 0}\frac{(1-\cos\theta)}{\sin\theta^2} = \lim_{\theta\to 0}\frac{\sin\theta}{2\sin\theta\cos\theta}$

$$= \lim_{\theta\to 0}\frac{1}{2\cos\theta} = \frac{1}{2} \quad \dots(14)$$

For spherical cap bubble (Davies and Taylor,1950):

$$R_{b,large} = 1.13\, d_{b,large} \quad \dots\dots(15)$$

Substitution of eqs. (14) and (15) in eq. (13), yields:

$$U_{b,large} = 0.71\left[d_{b,large}\, g\left(\frac{\rho_L-\rho_g}{\rho_L}\right)\right]^{\frac{1}{2}} \dots(16)$$

The density of liquid phase is greater than that of the gas phase (i.e $\rho_L >> \rho_g$), i.e.:

$$U_{b,large} = 0.71\sqrt{g\, d_{b,large}} \quad \dots(17)$$

To correct this value of rise velocity, it is multiplied by (SF) and (AF)

$$U_{b,large} = 0.71\sqrt{g\, d_{b,large}}\,(SF)(AF) \dots(18)$$

Where two correction factors are introduced into the classical (Davies and Taylor, 1950). The scale correction factor (SF) accounts for the influence of the column diameter and is taken from the work of (Collins, 1967) by the following equation:

$$SF = 1.1e^{(-d_{b,large}/D_T)}$$

$$for\ 0.125 < \frac{d_{b,large}}{D_T} < 0.6 \quad \dots(19)$$

$$SF = 0.496\sqrt{\frac{D_T}{d_{b,large}}} \quad for\ \frac{d_{b,large}}{D_T} > 0.6$$

$$SF = 1 \ \ for \ \ \frac{d_{b,large}}{D_T} < 0.125$$

The acceleration factor (AF) accounts for the increase in the large bubble velocity over that of a single, isolated, bubble due to wake interactions (for a swarm of large spherical cap bubbles in a liquid). Thus the factor increases as the distance between the large bubble decreases, since the average distance between large bubbles decreases as the superficial gas velocity through the large bubble phase increases, a linear relation is postulated for (AF) (for low viscosity liquids).

$$AF = 2.73 + 4.505\left(U_g - U_{trans}\right) \quad \ldots (20)$$

From the present experimental data in this work the values of diameters of the swarm of large bubbles dependence on (U_g-U_{trans}), by the equation given below, using computer program statistica.

$$d_{b,large} = 0.069\left(U_g - U_{trans}\right)^{0.376} \quad \ldots (21)$$

Drift Flux Model

Drift flux model is derived for estimating the values of ε_{trans} and U_{trans}, as shown below. In order to find the transition parameters (ε_{trans} and U_{trans}), Krishna et al., 1999 model is combined with the drift flux model.

For a countercurrent flow in a gas-liquid dispersion column, the slip velocity between gas phase and liquid phase equal to drift flux (Wallis, 1962, and Lapidus and Eligin, 1957):

$$V_s = \frac{U_g}{\varepsilon_g} + \frac{U_L}{1-\varepsilon_g} \ldots \ldots \ldots (22)$$

Arrangement of above equation, yields:

$$drift\ flux = V_s\,\varepsilon_g\left(1-\varepsilon_g\right) = U_g\left(1-\varepsilon_g\right) + U_L\,\varepsilon_g \ldots (23)$$

For no flow of liquid phase (i.e. U_L=0):

$$drift\ flux = V_s\,\varepsilon_g\left(1-\varepsilon_g\right) = U_g\left(1-\varepsilon_g\right) \quad \ldots (24)$$

Richardson-Zaki, 1954 drift flux model=

$$U_{b,small}\ \varepsilon_g(1-\varepsilon_g)^n \quad \ldots (25)$$

Zuber-Findlay, 1965 drift flux model

$$\frac{U_g}{\varepsilon_g} = C_o\,U_g + U_{b,small} \quad \ldots (26)$$

Evaluation of Transition Regime Parameters

The following steps are applied:

1. The rise velocity of the swarm of small bubbles $U_{b,small}$ is obtained from the intercept of Zuber-Findlay, 1965 drift flux eq.(26) , by plotting of U_g/ε_g against U_g, where C_o is the distribution parameter accounting for non-uniformly of flow and nature of the gas holdup profile.
2. The data predicted from both drift flux model and Richardson-Zaki,1954 drift flux model eq.(24), and eq.(25) respectively are plotted against gas holdup (ε_g), where (n) is the Richardson-Zaki index. Take n=2, in homogeneous regime.
3. The point of deviation of the experimental values from the Richardson-Zaki curve is taken to indicate the regime transition point (ε_{trans},U_{trans}).

Results and Discussions

The present experimental results of gas hold-up in homogeneous and heterogeneous regime for air-water and air-aqueous n-pentanol solution of (0.05, 0.25, 0.45, and 0.7 Wt %) systems are compared with the results from the present theoretical equation, equations (3) to (21). Fig.(3) and Fig.(4) show the gas hold-up ε_g, as a function of the superficial air velocity, U_g was obtained for water and four typical n-pentanol weight percent used in the present experimental work. A significant increase is observed inthe total gas holdup with increasing n-pentanol addition. In Fig.(5) a comparison is made of the gas hold-up with distilled water in the 7.5 and 15 cm diameter columns. It can be noted that there is a significant decrease in the total gas hold-up with increasing column diameter for constant L/D_T ratio, due to the strong liquid circulations with increasing column diameter, the bubbles are accelerated, this acceleration effect causes a significant reduction in the total gas holdup with increasing column diameter. In order to interpret the results, the first task is to find out the values of the regime transition parameters. The regime transition parameters, ε_{trans} , and U_{trans} can be determined from a drift flux plot. In the drift flux plot the drift flux, $U_g(1-\varepsilon_g)$, is plotted against the gas hold-up ε_g, as shown in Figs.(6) to (15) for the experimental data. The smooth curve in Figs.(6) to (15) are drawn using the Richardson-Zaki formulation, 1954, i.e. drift flux= $U_{b,small}\ \varepsilon_g(1-\varepsilon_g)^n$, n=2 and the bubble rise velocity of a swarm of small bubbles $U_{b,small}$ can be obtained from the Zuber-Findlay, 1965, drift flux equation, $U_g/\varepsilon_g=C_oU_g+U_{b,small}$ by data fitting [see Fig.(16) and Fig.(17)] for both dispersion columns. The Richardson-Zaki formulation, 1954 is valid for the homogeneous bubbly flow regime. The point of deviation of the experimental values from the Richardson-Zaki curve is taken to indicate the regime transition point as shown in Figs.(6) to (15). The influence of n-pentanol weight percent on the values of the transition parameters, ε_{trans} , and U_{trans} is shown in Fig.(18) and Fig.(19) for the whole range of weight percent studied in the experiments. It is clear that the addition of small amounts of n-pentanol has the effect of increasing the values of the transition parameters, ε_{trans} , and U_{trans}. The addition of n-pentanol has the effect of stabilizing the homogeneous bubbly flow regime. The mechanism of the coalescence preventing action of the n-pentanol was explained in details by some authors (Jamialahmadi and Muller-Steinhagen, 1992; Zahradnik et al., 1999).When n-pentanol is added to distilled water, it is strongly adsorbed at the interface. They accumulate around the bubbles forming a protective monolayer and consequently the coalescence between the bubbles will be hindered. This causes a surface tension gradient which opposes the tangential shear stress. This stabilization is caused by suppression of the coalescence tendency of small bubbles. A determination of whether the shift in the regime transition point with aqueous solution of n-pentanol addition is able to explain the increased hold-up observed experimentally is carried out and reported in Figs.(3) to (5). It is clear from Figs.(3) to (5) that the predicated theoretical values of gas hold-up, agree more closely with experimental values, with average error of 29.9 % and 37.5 % for air-water system, 8.02 % and 31.2 % for aqueous n-pentanol solution (0.05 Wt%) system, 5.8 % and 8.2 % for air-aqueous n-pentanol solution (0.25 Wt%) system, 6.7 % and 5.7 % for air-aqueous n-pentanol solution (0.45 Wt%) system, and 8.7 % and 6.2 % for air-aqueous n-pentanol solution (0.7 Wt%) systems, all these are for both dispersion columns 7.5 and 15 cm in diameters.

Fig.(20), and Fig.(21) show that the values of bubble diameter and bubble rise velocity increase with increasing superficial air velocity for air-water system, while these values decrease with increasing superficial air velocity for air-aqueous n-pentanol solution in two dispersion columns of 7.5 and 15cm. To understand this case, the following items should be known:

1. Small amount of n-pentanol solution added to pure distill water causes a significant decrease in surface tension of liquid., then coalescence inhibiting of small bubbles would be occurred at the lower surface tension of the liquid results in a decrease in bubbles diameter and bubbles rise velocity. (Lu et al., 1994; Camarasa et al., 1999; and Zahradnik et al., 1999).
2. Viscosity promotes bubble coalescence and suppress bubble breakup in the bed. At a low viscosity, the larger drag forces reduce the bubble diameter and bubble rise velocity. At a higher viscosity, the tendency to coalescence and polydispersily prevails over the drag reduction and the uniformity is broken by big bubbles (Mohammed, 1997, Zahradnik et al., 1997; Kuncova and Zahradnik, 1995; Shah et al., 1982; Shah and Deckwer, 1983; Wilkinson et al., 1992; Heijnen and Van Reit, 1984; and Zahradnik et al., 1987).

Correlation of Gas Hold-up and Superficial Air velocity at Regime Transition

The experimental results at the regime transition are represented by second order polynomial regressions of ε_{trans} , and U_{trans} with Wt% for two dispersion column diameters, using computer program statistica as shown in the following:

$$\varepsilon_{trans} = a\,Wt^2 + b\,Wt + c \qquad \ldots(27)$$

$$U_{trans} = d\,Wt^2 + e\,Wt + i \qquad \ldots(28)$$

The constants a, b, c, d, e and i are shown in Table (1) and Table (2). A comparison between the experimental values of gas hold-up and superficial air velocity at transition regime with that of the correlated values show very good agreement, as shown in Fig.(22) and Fig.(23).

Conclusions

The following major conclusions can be drawn from the present investigation:

1. Krishna et al., 1999 model has been improved to describe the hydrodynamics of an air-water and air-aqueous n-pentanol solution dispersion column operating in both homogeneous and heterogeneous flow regimes, this improved model with derived drift flux model gave a very good description of the measured data (ε_g, ε_{trans} , and U_{trans}) in homogenous and heterogeneous flow regimes.
2. The values of ε_{trans}, and U_{trans} increase with increasing the weight percent of n-pentanol, i.e. the regime transition delayed.
3. The column diameter has an inverse effect on the total gas hold-up (i.e. when the column diameter increases the total gas holdup decrease) for air-water system and air-aqueous n-pentanol solution system.
4. The column diameter has a positive effect on the bubble diameter and bubble rise velocity of the swarm of bubbles for air-water system, but this effect has an inverse on the bubble diameter and bubble rise velocity for air-aqueous n-pentanol solution system.
5. The addition of small amounts of n-pentanol to distill water tends to result in a significant decrease in bubble diameter and bubble rise velocity, and increase in the gas hold-up.

Notations

a= constant in polynomial, eq.(27)
AF = acceleration factor, eq.(20)
b= constant in polynomial, eq.(27)
c= constant in polynomial, eq.(27)
C_o= distribution parameter
d= constant in polynomial, eq.(28)
d_{Bi} = diameter of bubble of size i, mm
$d_{b,large}$= large bubble diameter, m
D_T= diameter of dispersion column, m
e= constant in polynomial, eq.(28)
g= gravitational acceleration, m/s^2
h_1= height at point (1), mm
h_2= height at point (2), mm
h= difference height between two points, mm
H= clear liquid height, cm
H_o= dispersion liquid height, cm
i= constant in polynomial, eq.(28)
L= height of dispersion column, cm
n = Richardson-Zaki index
n_i = number of bubbles of size i
p_1= pressure at point (1), pa
p_2= pressure at point (2), pa
$R_{b,large}$= large bubble radius, mm
SF = scale factor given by the Collins relations, eq.(19)
$U_{b,large}$= rise velocity of the swarm of large bubbles, m/s

$U_{b,small}$= rise velocity of the swarm of small bubbles, m/s

U_g = superficial air velocity, m/s

U_L= superficial liquid velocity after moving of swarm of bubbles, m/s

U_{trans}= superficial gas velocity at regime transition, m/s

(U_g-U_{trans}) = superficial gas velocity through the large bubble phase, m/s

V_s= slip velocity between gas and liquid phases, m/s

Wt = weight percent of n-pentanol, %

Greek Symbols

ε_g = total gas hold-up

$\varepsilon_{b,large}$= hold-up of large bubbles

ε_{trans}= hold-up at the regime transition point

ρ_g= air density, kg/m^3

θ= angle

Subscripts

b,large	referring to large bubbles
b,small	referring to small bubbles
g	referring to gas
trans	referring to the transition point
T	column

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Table (1) Constants and regression coefficients of eq.(27) for ε_{trans} with two dispersion column diameters.

Column diameter (cm)	Coefficients			Correlation coefficient	Average absolute error (%)
	a	b	c		
7.5	-0.0261	0.174	0.193	0.994	1.662
15	-0.0975	0.2304	0.174	0.986	3.194

Table (2) Constants and regression coefficients of eq.(28) for U_{trans} with two dispersion column diameters.

Column diameter (cm)	Coefficients			Correlation coefficient	Average absolute error (%)
	d	e	i		
7.5	-0.00588	0.00786	0.0247	0.999	0.0257
15	-0.00689	0.00897	0.0241	0.991	0.458

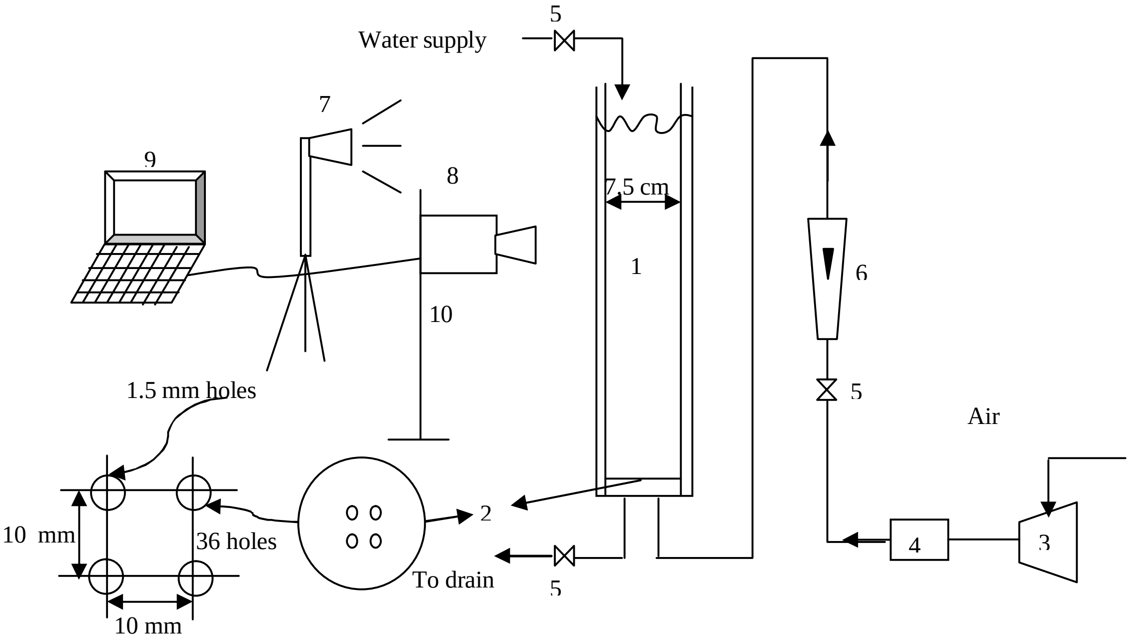

Figure (1) Typical experimental setup for the 7.5 cm diameter column: (1) dispersion column: (2) distributor: (3) compressor: (4) air filter: (5) regulating valves: (6) rotameter: (7) Halogen lamp (8): video camera: (9) computer system (PC): (10) mobile stand camera.

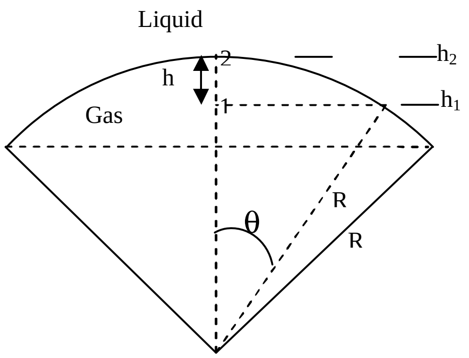

Figure (2) Spherical cap bubble.

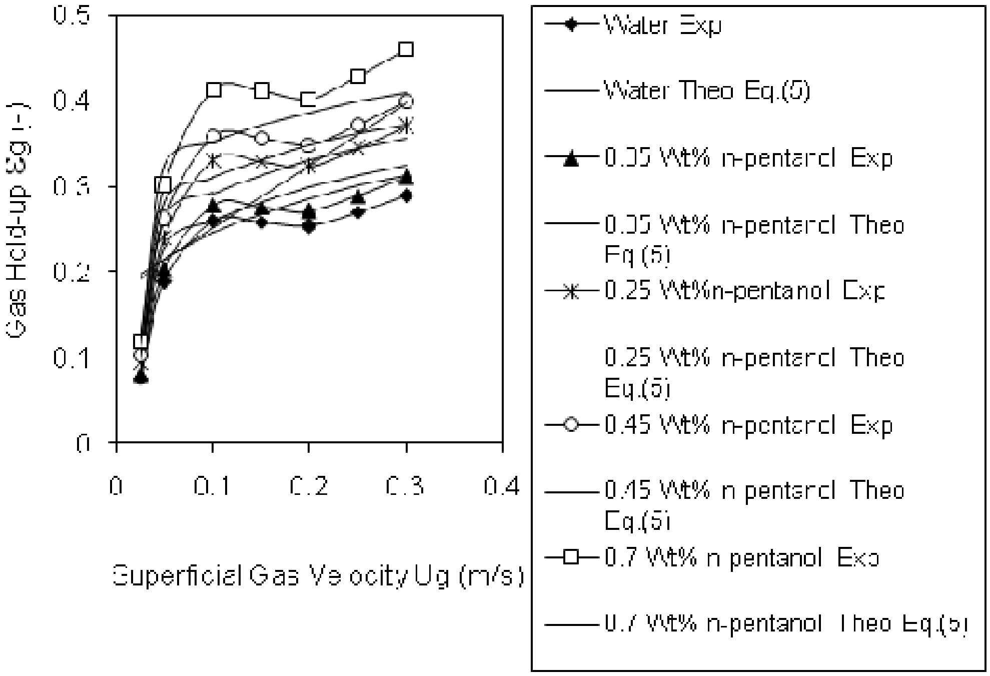

Figure (3) Influence of n-pentanol addition on gas hold-up in dispersion column of 7.5 cm diameter.

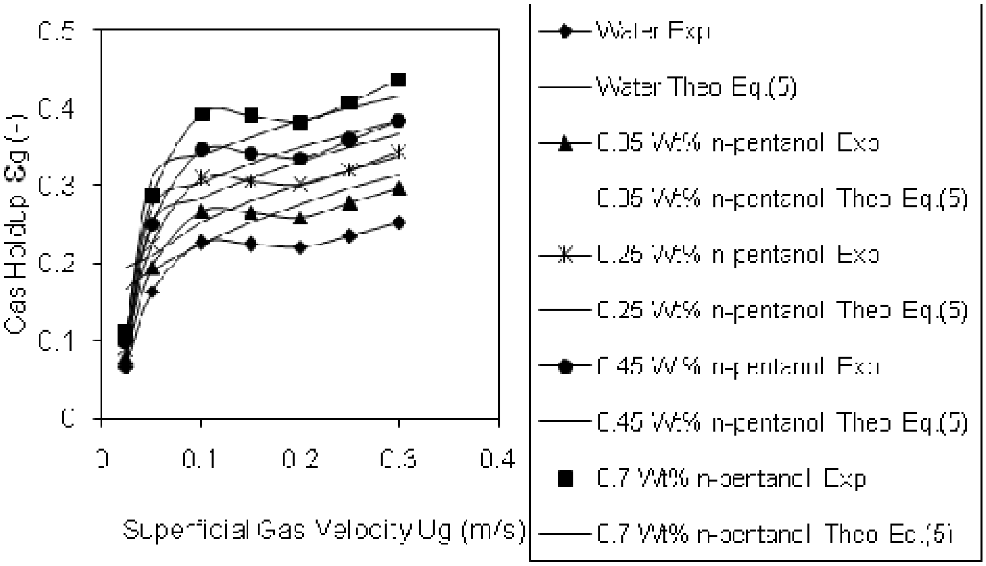

Figure (4) Influence of n-pentanol addition on gas hold-up in dispersion column of 15cm diameter.

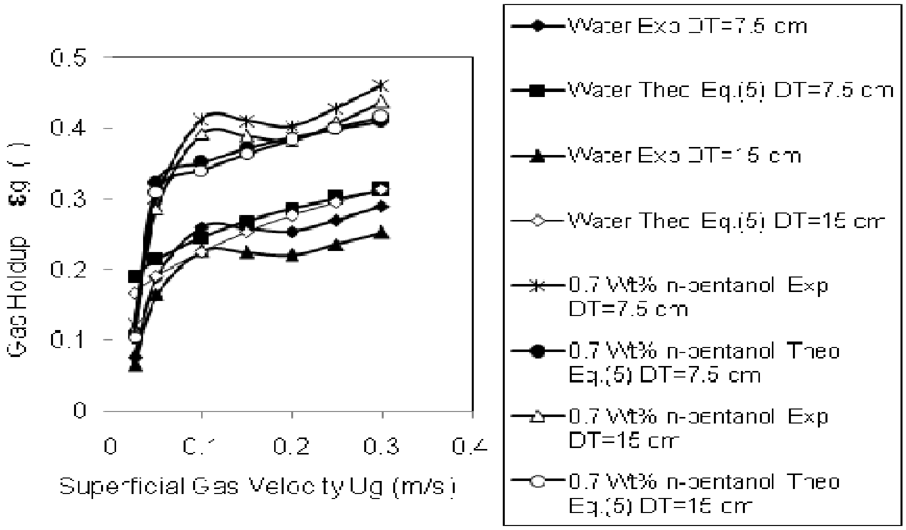

Figure (5) Influence of column diameter on gas hold-up in dispersion column for air-water and air-aqu. n-pentanol sol. (0.7 Wt%) systems.

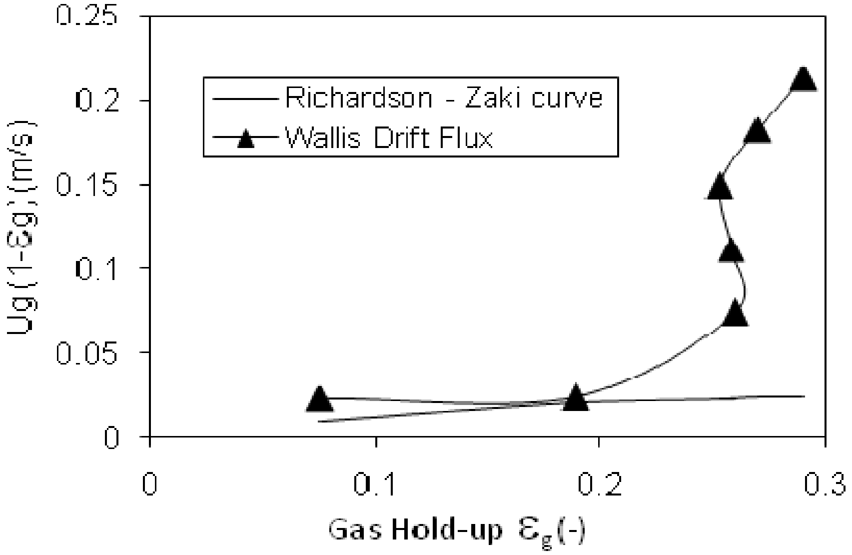

Figure (6) Wallis plot to determine transition parameters in dispersion column of 7.5 cm diameter for air-water system.

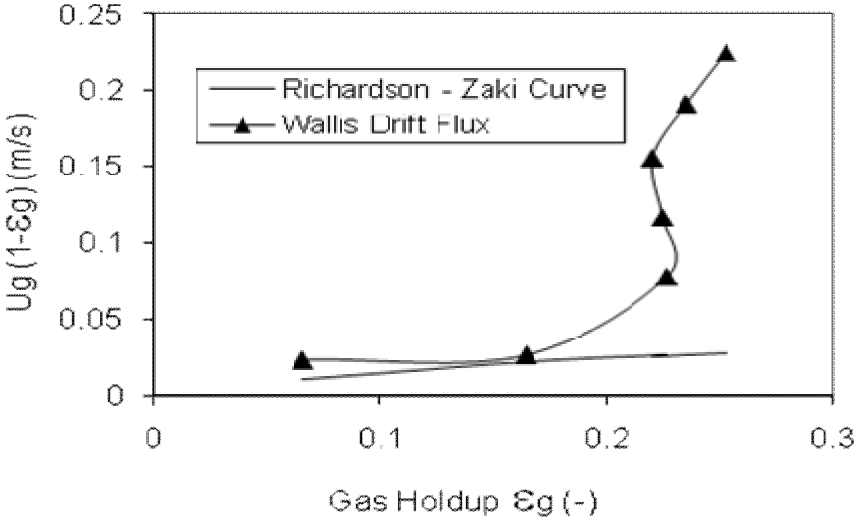

Figure (7) Wallis plot to determine transition parameters in dispersion column of 15 cm diameter for air-water system.

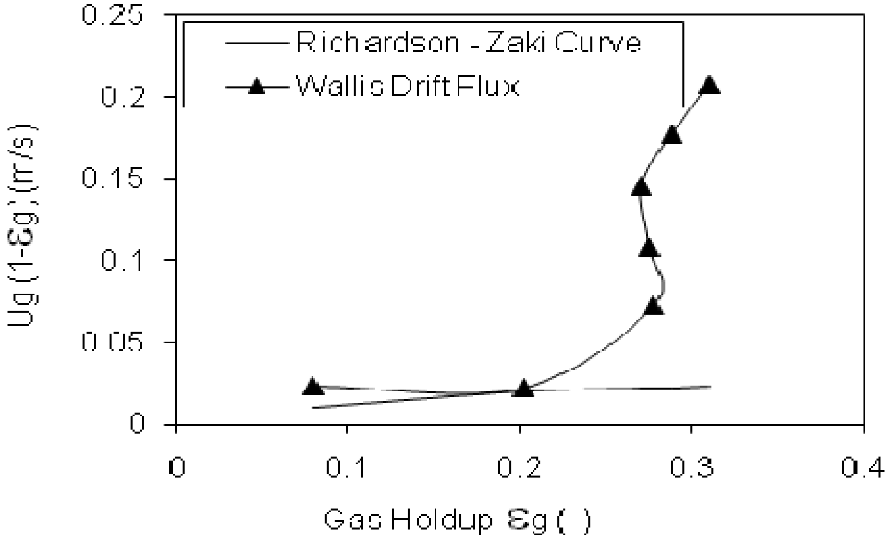

Figure (8) Wallis plot to determine transition parameters in dispersion column of 7.5 cm diameter for air-aqu. n-pentanol sol. (0.05 Wt%) system.

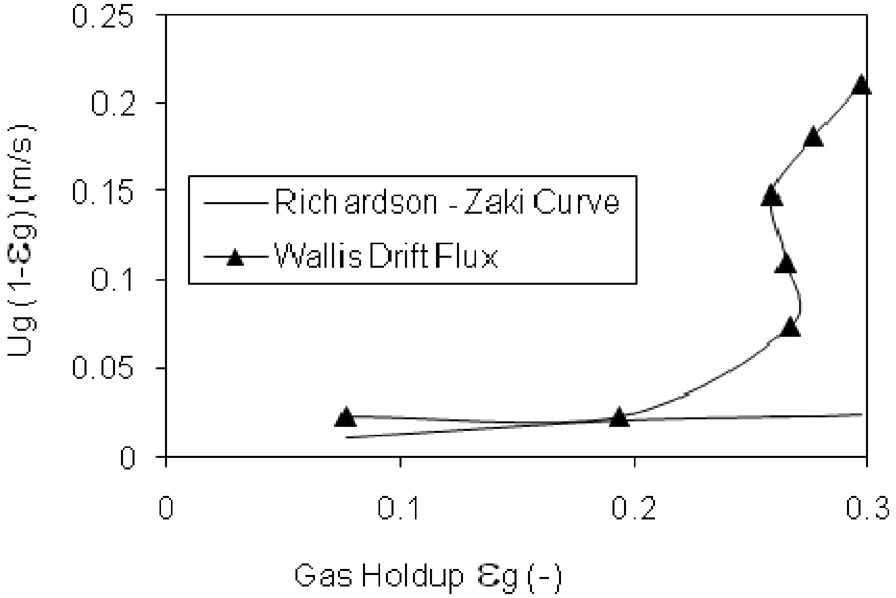

Figure (9) Wallis plot to determine transition parameters in dispersion column of 15 cm diameter for air-aqu. n-pentanol sol. (0.05 Wt%) system.

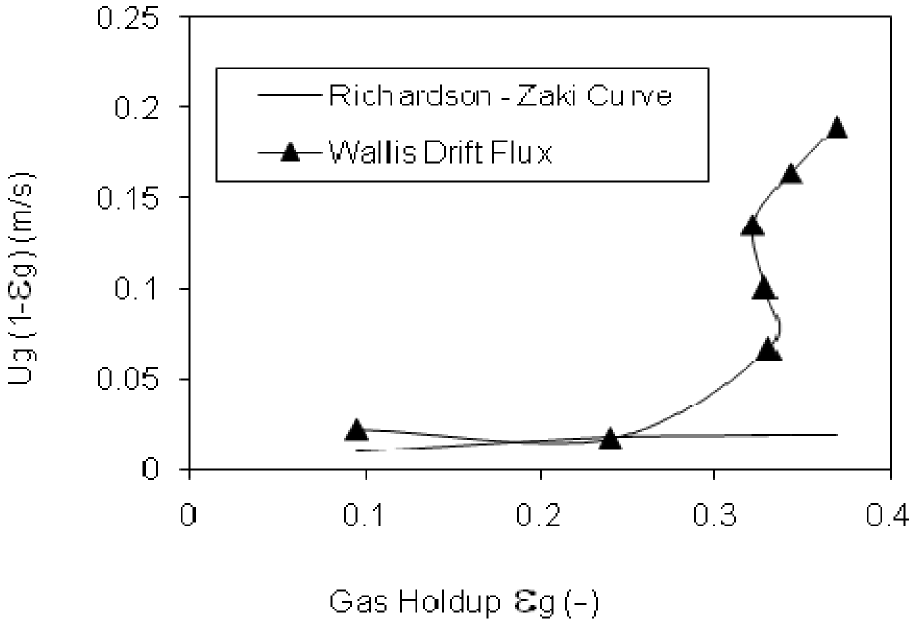

Figure (10) Wallis plot to determine transition parameters in dispersion column of 7.5 cm diameter for air-aqu. n-pentanol sol. (0.25 Wt%) system.

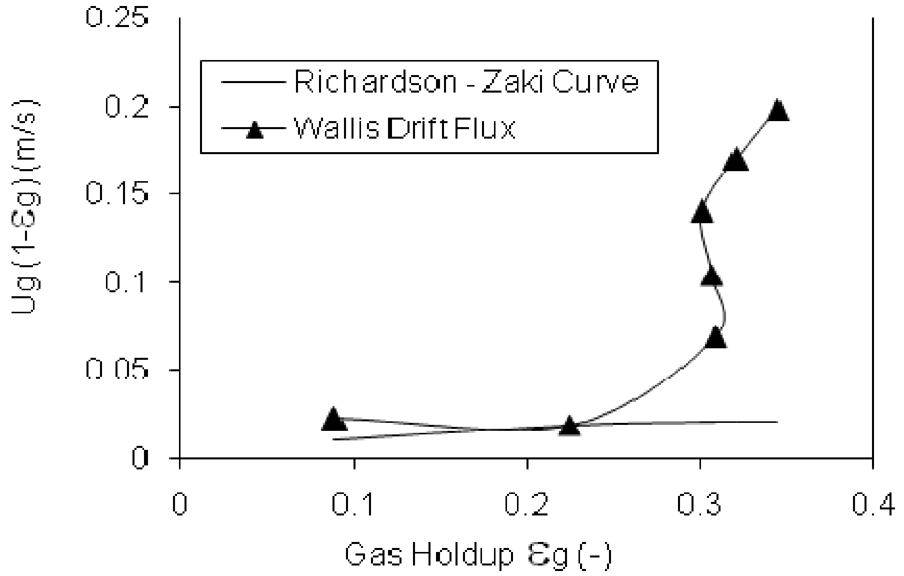

Figure (11) Wallis plot to determine transition parameters in dispersion column of 15 cm diameter for air-aqu. n-pentanol sol. (0.25 Wt%) system.

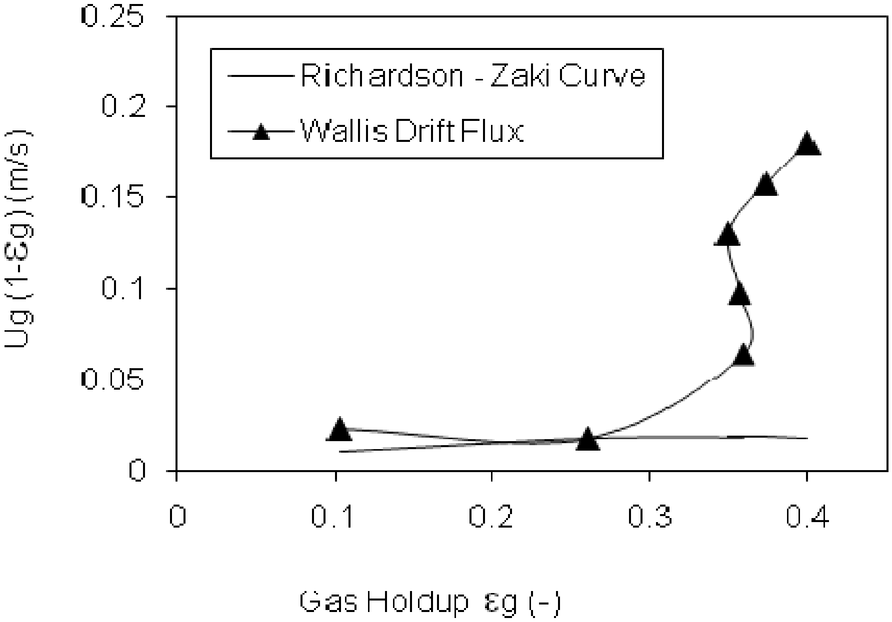

Figure (12) Wallis plot to determine transition parameters in dispersion column of 7.5 cm diameter for air-aqu. n-pentanol sol. (0.45 Wt%) system.

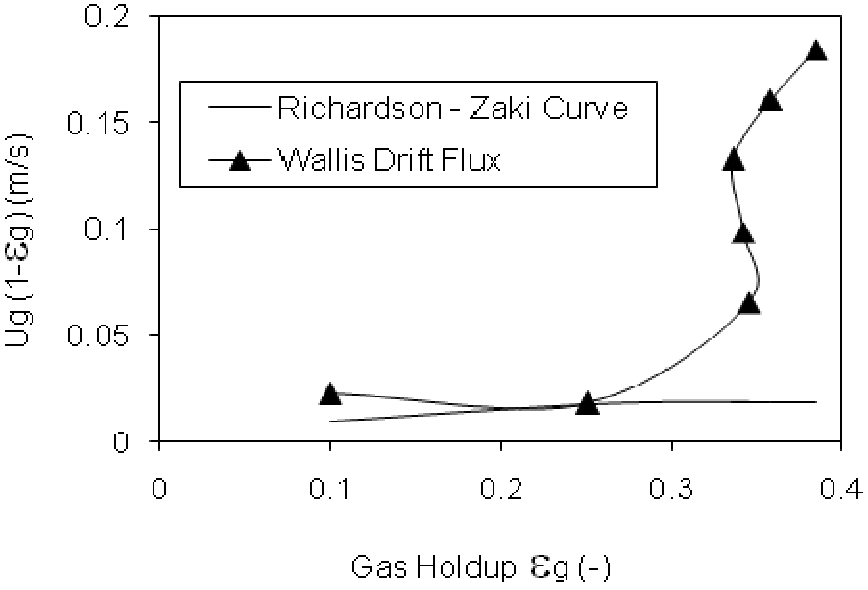

Figure (13) Wallis plot to determine transition parameters in dispersion column of 15 cm diameter for air-aqu. n-pentanol sol. (0.45 Wt%) system.

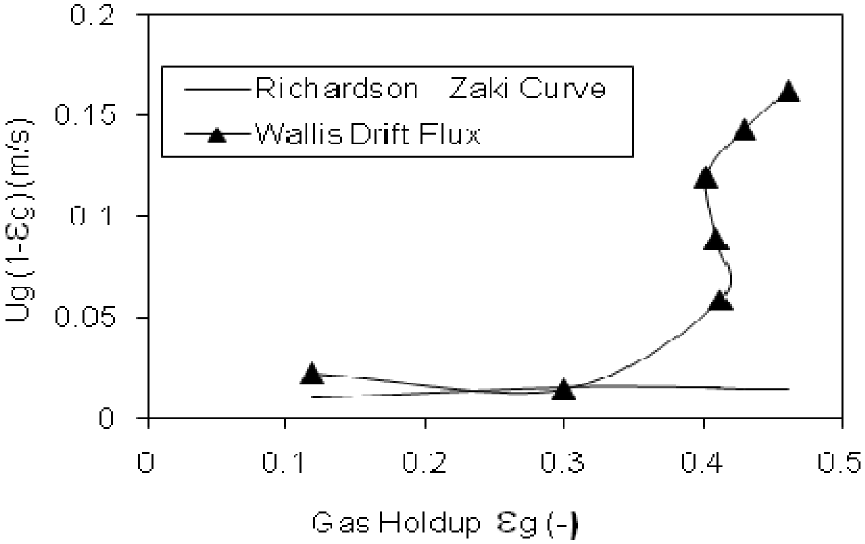

Figure (14) Wallis plot to determine transition parameters in dispersion column of 7.5 cm diameter for air-aqu. n-pentanol sol. (0.7 Wt%) system.

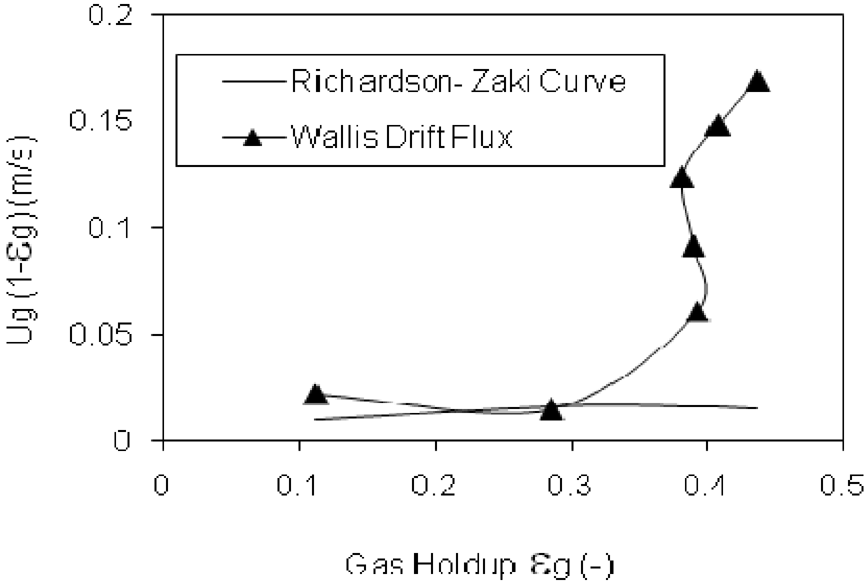

Figure (15) Wallis plot to determine transition parameters in dispersion column of 15c m diameter for air-aqu. n-pentanol sol. (0.7 Wt%) system.

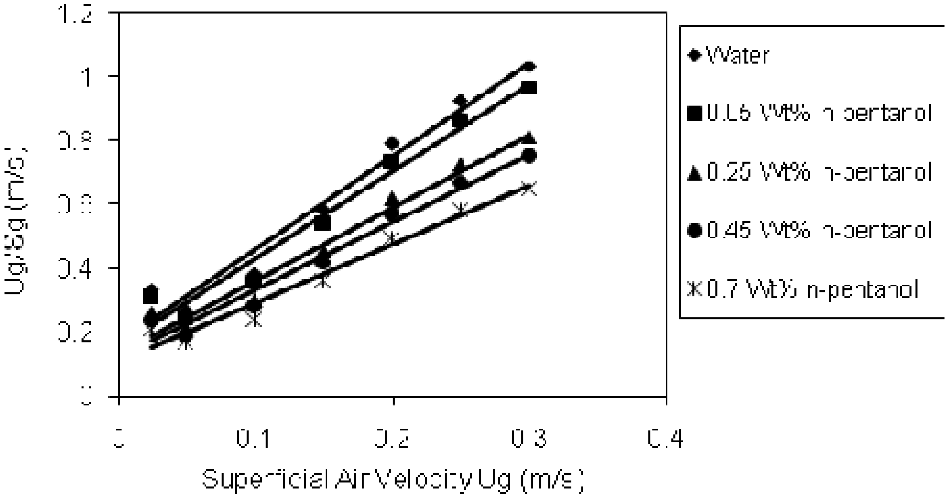

Figure (16) Zuber and Findlay drift flux plot to determine bubble rise velocity in dispersion column of 7.5 cm.

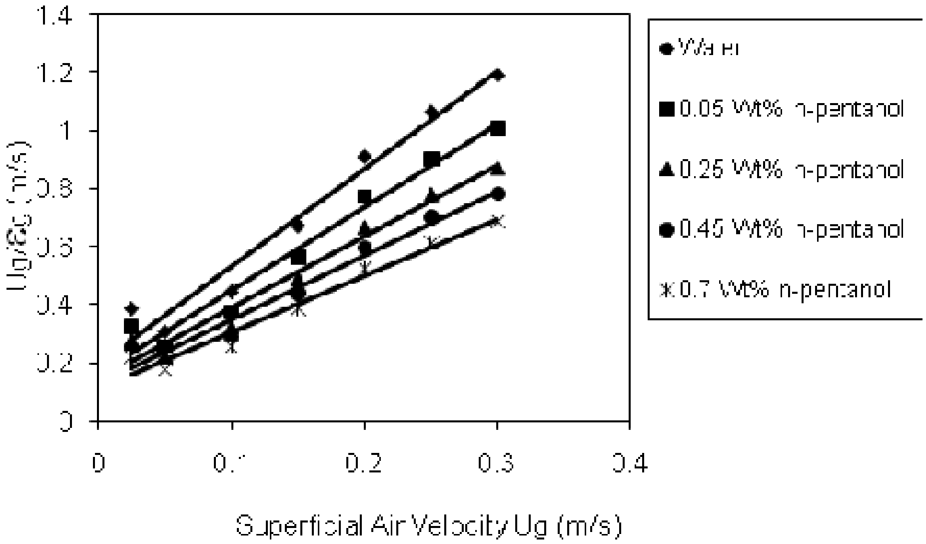

Figure (17) Zuber and Findlay drift flux plot to determine bubble rise velocity in dispersion column of 15 cm.

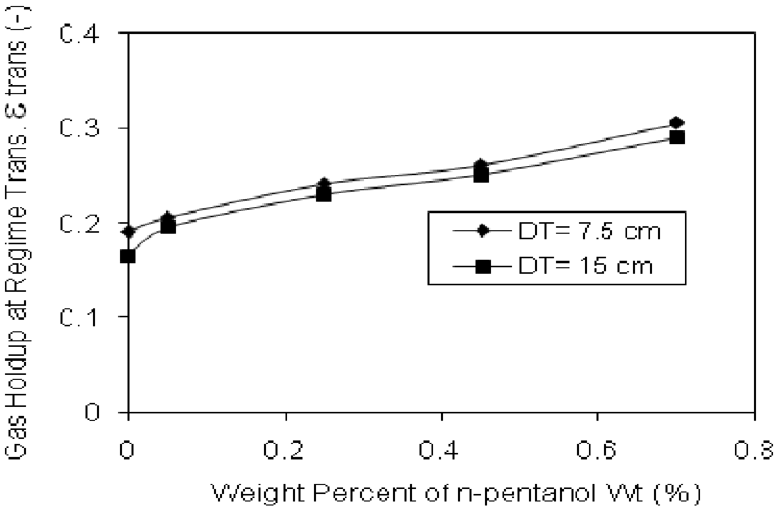

Figure (18) Variation of gas hold-up at regime transition with weight percent of n-pentanol at different dispersion columns.

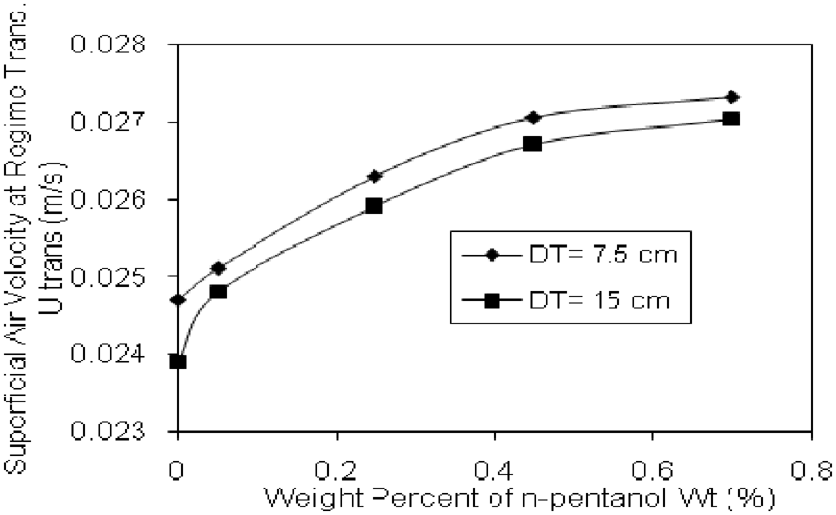

Figure (19) Variation of superficial air velocity at regime transition with weight percent of n-pentanol at different dispersion columns.

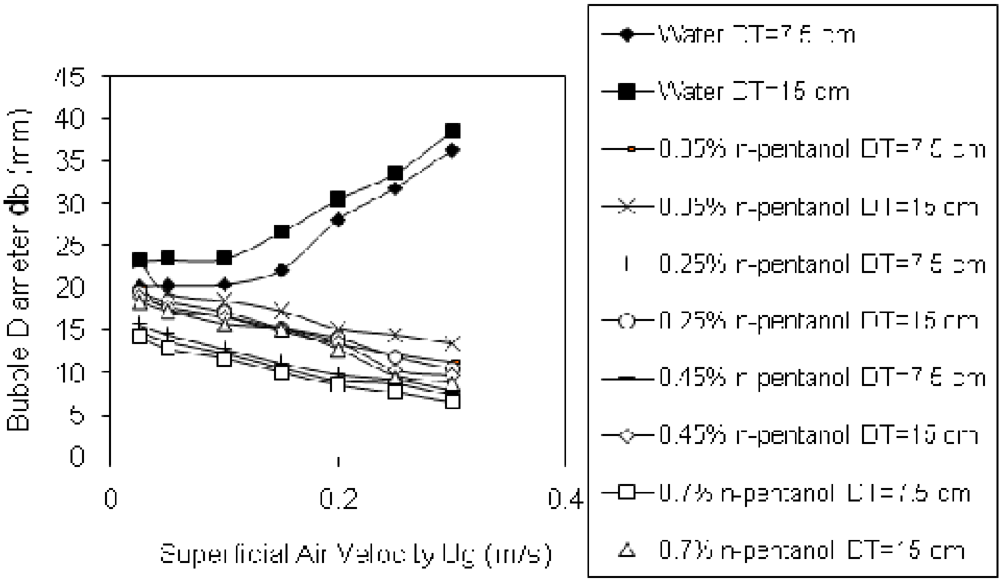

Figure (20) Influence of type of liquid, weight percent of n-pentanol and column diameter on bubble diameter in two dispersion columns.

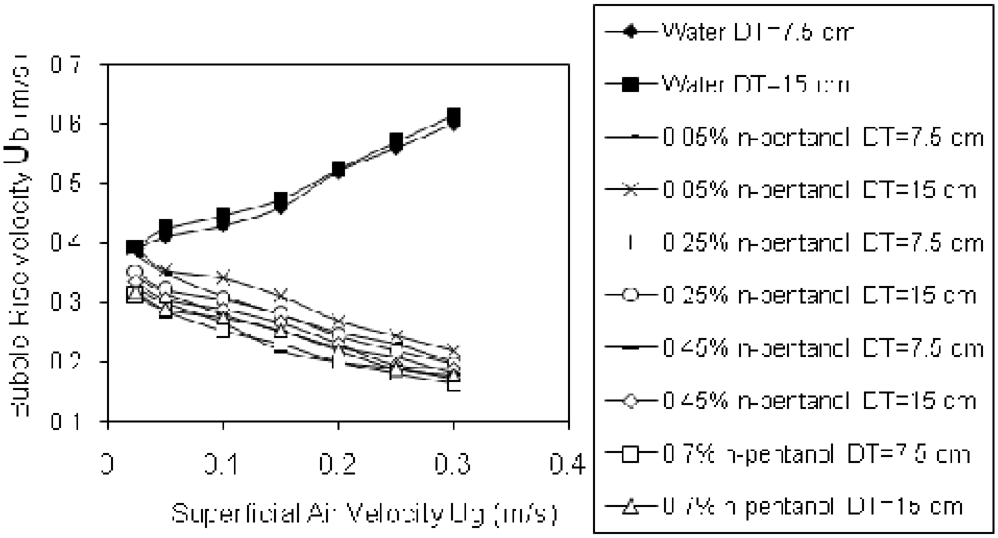

Figure (21) Influence of type of liquid, weight percent of n-pentanol and column diameter on bubble rise velocity in two dispersion columns.

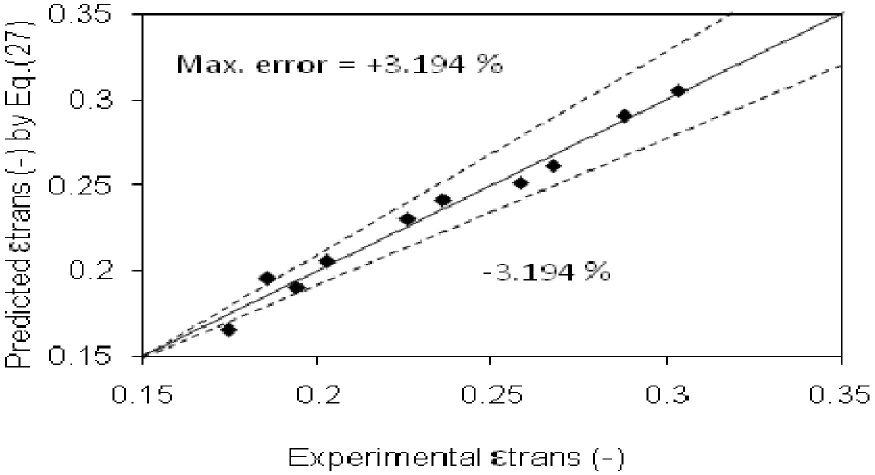

Figure (22) Comparison between experimental and predicted ε_{trans} values at transition regime in two dispersion columns.

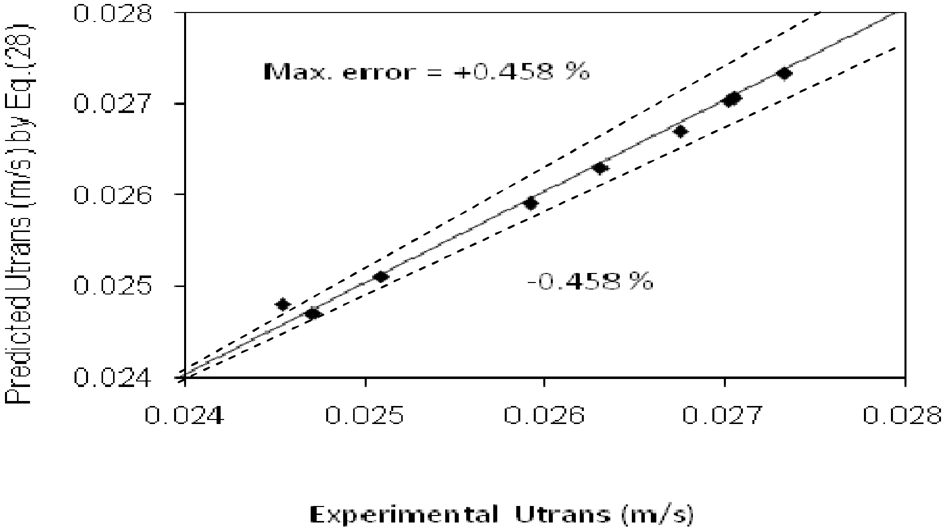

Figure (23) Comparison between experimental and predicted U_{trans} values at transition regime in two dispersion columns.