Hydrodynamics Of Two Phase Flow For Coalescing And Non Coalescing Systems

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Abstract

This experimental study is aimed at investigating the effect of superficial gas velocity, liquid phase properties and gas distribution on gas holdup, bubble characteristics and drag coefficient in two-phase bubble column. Various liquids covering a sufficiently broad range of viscosity and surface tension values were employed, while the gas phase was atmospheric air. Aqueous glycerine solutions were used to simulate the behavior of coalescing viscous liquids whereas aqueous alcohol solutions were used to simulate the behavior of non-coalescing organic liquids. The experimental results obtained with two different types of gas distributor in the coalescence solutions and in non coalescence solutions were compared with data on standard air–water system. A computerized conductivity probe system and high speed digital camera were used for the systematic measurements of bubble size, velocity and gas hold-up. Correlations based on dimensionless groups were proposed for the prediction of gas holdup and drag coefficient in the homogeneous flow regime.

Keywords: Hydrodynamics, Two-Phase Flow, Drag Coefficient, Coalescing System, Non Coalescing System.

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الخلاصة

هذه الدراسة العملية تهدف الى بحث تأثير سرعة الغاز ٫ خواص الطور السائل وتوزيع الغاز على المحتوى الحجمي للغاز ٫ خواص الفقاعة وعلى معامل الجر في عمود فقاعة ثنائي الطور ٫ استخدمت سوائل متنوعة لتغطي مدى واسع من قيم اللزوجة والشد السطحي ٫ بينما كان الطور الغازي هو الهواء الجوي ٫ تم استخدام الكليسيرين لتمثيل سلوك السوائل اللزجة والمعززة لأنـدماج الفقاعــات بينما تم إستخدام البيوتانول لتمثيل سلوك السوائل العضوية والمثبطة لأندماج الفقاعات تم مقارنة النتــائج العملية للمحاليل المعززة لأندماج الفقاعات والمحاليل المثبطة لأندماج الفقاعات مع نظــام هــواء-مــاء القياسي تم استخدام مجس الكتروني و كاميرا رقمية عالية السرعة لقياس قطر الفقاعة٫ سرعة الفقاعة و المحتوى الحجمي للغاز ٫ اقترحت علاقات تجريبية للتنبؤ بالمحتوى الحجمي للغاز و معامل الجــر فــي نظام الجريان المتجانس ٫

Introduction

Gas-liquid contacting is one of the most important and very common operations in the chemical process industry, petrochemical industry, and mineral processing. Most commonly, it is achieved either by automation of liquid into gas in the form of drops or by bubbling (sparging) of gas into the liquid (Kulkarni and Joshi, 2005). Bubble columns are two-phase gas-liquid systems in which gas is dispersed through a distributor and bubbles rise through a liquid in vertical cylindrical columns. Bubble columns are widely used in chemical, petrochemical and biochemical and metallurgical industries (Shaikh and Al-Dahhan, 2003). Examples of such chemical and petrochemical processes are partial oxidation of ethylene to acetaldehyde, wet-water oxidation, chlorination of

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hydrocarbons, methanol synthesis, Fisher-Tropsch synthesis, and hydrogenation of organic liquids (Deckwer, 1992). In biochemical industries, bubble columns are used for single cell protein production, animal cell culture and antibiotic fermentation (Chisti, 1989).

Gas holdup is one of the important parameters for design purposes that characterize transport phenomena of bubble column systems (Lokato et al., 2002).

All studies examine gas holdup because it plays an important role in design and analysis of bubble columns (Kantarci et al., 2005). On one hand, gas holdup in two phase systems gives the volume fraction of the phases present in the reactor and hence their residence time. On the other hand, the gas holdup in conjection with the knowledge of mean bubble diameter, allows the determination of the specific interfacial area available in the dispersion for mass transfer (Bukur et al., 1987).

The behavior of the gas holdup in bubble column has been attributed to many different factors, including superficial gas velocity, liquid properties and gas distributor design.

Most published studies have shown a positive effect of the superficial gas velocity on the gas holdup (Li and Prakash, 2000; Prakash, 2001; Pandt and Doshi, 2005).

Although the systems investigated in these studies are quite different from each other, all concluded that the gas holdup increases with increasing superficial gas velocity.

The liquid phase property has an impact on bubble formation and / or coalescing tendencies and hence it is an important factor affecting gas holdup (Behkish, 2004; Kantarci et al., 2005).

Zahradink et al. (1997) studied the gas holdup in aqueous saccharose solutions in a bubble column reactor 0.15m in diameter with the distributing plate with o.5 mm holes. They reported that the gas holdup data witness an unfavorable effect of liquid viscosity on the formation of the homogeneous bubble beds.

Gas distributor type is an important parameter that can alter bubble characteristics which in turn affects gas holdup values and thus many other parameters characterizing bubble columns (Kantarci et al., 2005).

The initial bubble size and distribution at the orifice could be controlled by the distributor characteristics (Buwa and Ranade, 2002; Kantarci, 2005).

Camarasa et al. (1999), used aqueous non-coalescing solutions and water to compare the effect of porous plate, multi-orifice nozzle and perforated plate on the gas holdup. They found that bubble characteristics in water with porous plate and multi-orifice nozzle were comparable, whereas the trend was different in non-coalescing solutions. The single-orifice nozzle, on the other hand differed completely with the two other distributors.

Bubble size, bubble rise velocity, bubble size distribution and bubble velocity profile have a direct bearing on the performance of bubble columns. For this reason it is important to obtain information on bubble characteristics in the bubble column (Kantarci et al., 2005).

Camarasa et al. (1999) reported that the mean bubble size slightly increased with superficial gas velocity in the homogeneous flow regime. They also reported that the rise velocity of small bubble after an initial decrease remains constant at about 20-25 cm/s.

Prakash et al., (2001), reported that the rise velocity of small bubbles decreased with increasing superficial gas velocity, whereas the rise velocity of large bubbles increased with increasing superficial gas velocity.

Liquid properties also have a significant effect on bubble characteristics. The average bubble size

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was reported to decrease with decreasing surface tension of liquid (Kulkarni and Joshi, 2005) and increase with increasing liquid viscosity (Li and Prakash, 1997).

Many parameters control the flow of fluid phases through the bubble column. One of the most important parameters affecting the dispersed phase as the bubble rise up through the liquid phase is the drag force. Surfactants play a crucial role in the magnitude of the drag force as well as fluid properties and wall effects (Kramer, 2000).

The drag force which tends to slow the relative motion of a body is one of the most important effects of viscosity on the displacement of a body in a fluid (Karamavev, 1996).

The drag force acting on a bubble is found to be proportional to the relative velocity between the phases as follows (Clift et al., 1978):

$$f_D = C_D \frac{p}{4} d_B^2 \left(-\frac{1}{2} r_L \left(U_b - U_L\right) \left| U_b - U_L \right| \right) \quad .(1)$$

For a bubble swarm, the estimation of drag force is further complicated by the presence of other surrounding bubbles. The estimation carried out on the basis of number of bubbles (per unit volume) and the force on single bubble [given by left-hand side of Eq. (1)] gives:

$$F_D = N f_D = -e_G \, r_L \frac{3 C_D}{4 d_B} \left(U_b - U_L\right) \left| U_b - U_L \right| \quad \ldots(2)$$

The value of C_D is likely to be different for a bubble and a bubble swarm. This is because, the shape and size of a bubble in a bubble swarm is much different from that of an isolated bubble. In addition, the flow structure surrounding a bubble gets modified when it becomes part of a swarm (Vitankar et al., 2002).

Ishii and Zuber (1979), have developed a bubble drag coefficient model for multiple bubbles in an infinite medium. The authors reported that additional bubbles in the neighborhood of a single bubble will alter the single bubble drag coefficient by adding resistance to deformation of the surrounding medium and by adding direct interaction between bubble wakes.

$$C_D = \frac{2}{3} d_B \sqrt{\frac{g \, \Delta r}{s}} \left[\frac{1 + 17.6 \left[f\left(e_G\right) \right]^{6/7}}{18.67 \, f\left(e_G\right)} \right]^2 \quad \ldots (3)$$

Kendoush (2001), derived an equation for drag coefficient of spherical bubbles in terms of Reynolds number and gas holdup. The gas holdup demonstrated the existence of interaction effects.

$$C_D = \frac{48}{\mathrm{Re}\left(1 - e_G\right)^2} \quad \ldots.(4)$$

Rusche and Issa (2000), formulated a model to determine the drag coefficient in dispersed two phase system at high concentration of the dispersed phase.

In their model, they expressed the drag coefficient as the product of a correction coefficient times the drag coefficient for a single bubble.

$$C_D = \left(C_D\right)_{Single} f\left(e_G\right) \quad \ldots. (5)$$

Where $f\left(e_G\right)$ is a function takes into account the effects arising from the presence of other bubbles. They defined $f\left(e_G\right)$ as follows:

$$f\left(e_G\right) = \exp\left(3.64 \, e_G\right) + e_G^{0.864} \quad \ldots(6)$$

The authors proposed that this model is applied for bubbly flow regime.

The purpose of this work is to study the effect of superficial gas velocity, liquid phase properties and gas distributor type on gas holdup, bubble characteristics and drag coefficient.

2. Experimental equipment and measuring methods
2 .1 Apparatus

The experiments were conducted in a cylindrical semi-batch bubble column. Figure (1) shows the experimental apparatus. The column is made of QVF glass with an inside diameter of 0.10 m and a height of 2 m. Two distributors were used. The first one was porous ceramic plate distributor (PoP) of 240 μm mean pore size and 5 mm in thickness. The second one was a Perspex-made perforated plate (PfP) of 4

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mm thickness. The distributor has 88 holes each with 0.5 mm I.D. The holes were distributed on a triangular pitch of 10 mm which gives a porosity for the inlet area, β = 0.00185. Air was always used as the gas phase. Gas flow was controlled with rotameter. The superficial gas velocity ranges from 0.0063 to 0.0389 m/s spanning the homogeneous flow regime. Experiments were carried out with distilled water, aqueous solutions of glycerin and aqueous solutions of butanol at ambient temperature and pressure. Each experimental run started by first filling the column with the appropriate liquid phase up to 100 cm above the distributor. All the experiments were performed with no liquid throughput. The physical properties for the liquids used are listed in table (1).

2.2 Data Acquisition Methodology
2.2.1 Digital Photograph

The digital camera (Olympus, C-4000/Zoom) with high resolution (4 Pixels) was used for bubble size and gas holdup measurements. Pictures were taken after air is injected and steady state is established. The difference in liquid level gives a measure of the average gas holdup, thus:

$$e_G = \frac{H_D - H_L}{H_D} \qquad \text{.......(7)}$$

Where H_D is the height of gas-liquid dispersion and H_L is the height of clear liquid. Each run was repeated three times and the gas holdup values were averaged (relative error less than 5 %).

2.2.2 Computerized Conductivity Probe System (CCPS)

The hydrodynamic parameters of the bubble column (the local gas holdup, the rise velocities and sizes of bubbles) have been studied with the help of conductivity probe detector (Luo, 1993, Mohammed, 1997, Suker, 2004). The measurement principle of conductivity probe technique utilizes the difference in electrical conductivity between the liquid and gas phases. Details of this system are shown in figure (2).

A series of experiments were conducted and each experiment was repeated three times to reduce errors of human and devices, the absolute average error between each three repeated experiments was in the range (3- 5) %.

3. Results and Discussion
3.1 Gas Holdup
Influence of Superficial Gas Velocity

Figure (3) shows the effect of superficial gas velocity on gas holdup for all liquids used. This figure indicates that the gas holdup increases with increasing superficial gas velocity. This increase is attributed to the fact that in the homogeneous flow regime, the bubbles rise almost vertically and lift up a considerable amount of liquid to the top of the column. The liquid thus carried up must return down, as there is zero net liquid flow in the column. The liquid counter-current delays the bubble rise, hence increasing the gas holdup. It can also be seen from figure (3) for liquid of higher viscosity value (70% Glycerine solution), the effect of U_G is less pronounced at high gas flow rates (U_G > 0.02). This indicated that the transition from bubbly flow to churn-turbulent flow occurs around U_G = 0.02 m/s. These results are in agreement with the findings of many investigators (Molina et al., 1999; Ruzicka et al., 2001a; Shuhaib, 2003).

Influence of Liquid Properties
i. Liquid Viscosity

Figure (4) shows the gas holdup as function of liquid viscosity. From this figure one can notice that the gas holdup increases with increasing viscosity up to μ_L < 3. This behavior can be explained on the basis of the hindered gas bubble motion in the viscous liquids, in which at relatively low viscosities, the drag forces are not large enough to cause bubble coalescence. These moderate forces contribute to reduce the bubble rise velocity and hence higher gas holdup. This explanation was supported also by other investigators (Snape et al., 1995; Ruzicka et al., 2003).

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For $\mu_L \geq 3$; the experimental data displayed in figure (4) witness a considerable reduction of the gas holdup as a result of increasing liquid viscosity. The negative effect of viscosity can be ascribed to the existence of drag forces promoting bubble coalescence in the distributor region. Therefore, the gas holdup was decreased as a result of presence large population of big and fast bubbles with short retention time in the column.

This result is in agreement with the observation of the previous investigators (Kantak et al., 1995; Mohammed, 1997; Suker, 2004).

ii. Presence of Surface active agents

It is well-known that addition of minute quantities of aliphatic alcohol in water leads to inhibition of coalescence phenomena. This is because alcohol acts as a surfactant in water which hinders bubble coalescence by accumulating at the gas-liquid interface and orienting their hydrophilic group into the liquid film surrounding the gas bubble and thus creating repulsive electric forces when two bubbles come close to each other. As coalescence is suppressed, the small bubbles are preserved within the column and the gas holdup reaches steeply high values as can be seen from figure (3) that the gas holdup of aqueous alcohol solutions is greater than other liquids. This increase in gas holdup may also be due to a decrease in bubble rise velocity due to the increasing of the drag coefficient caused by the accumulation of alcohol molecules at the interface.

Similar findings have been reported in some of previous studies with dilute alcohol in water (Bukur and Patel, 1989; Zahardnik et al., 1997; Camarasa et al., 1999).

Alcohol concentration is another variable that seems to affect the gas holdup in a bubble column. Figure (5) shows the effect of butanol concentration on gas holdup. This figure shows that as the concentration of Butanol increases, so does the gas holdup. This trend was

also seen by (Shuhaib, 2003; Mouza et al., 2005). This increase is attributed to the fact that if there is a higher concentration of alcohol, there will be a higher concentration of hydrophilic molecules which increases the degree of coalescence restraining and yields small bubbles having a long retention time in the column which leads to higher gas holdup.

Influence of Gas Distributor

Figures (6-8) summarize the data of gas holdup versus superficial gas velocity obtained using the two different types of gas distributors for each liquid used. These figures indicate that the values of gas holdup are higher with porous plate than with the perforated plate. This result may be due to the porous distributor generates a uniform size of bubbles and distributes the gas uniformly at the bottom of the liquid pool and bubbles formed at the distributor zone rise almost vertically which give an enhancement of gas holdup. This is in agreement with the observation of previous investigators (Zaharadrik et al., 1997; Camarasa et al., 1999).

3.2 Bubble Characteristics
3.2.1 Bubble Size
Influence of Superficial Gas Velocity

Figure (9) shows the effect of superficial gas velocity on bubble size for all liquids used. From this figure one can notice that there is a slight increase in the bubble size with increasing superficial gas velocity. This increase is attributed to the fact that the increase in superficial gas velocity increases the probability of bubbles collision and coalescence resulting in greater bubble size. This result is in agreement with these of previous investigators (Camarasa et al., 1999; Ruzicka et al., 2001b; Ribeiro and Lage, 2004).

Influence of Liquid Properties
i. Liquid Viscosity

Figure (10) shows the effect of liquid viscosity on bubble size. It can be

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seen from this figure that for liquids of low viscosity ($\mu_L < 3$), the bubble sizes are independent of the liquid viscosity while at higher viscosities ($\mu_L \geq 3$) an increase of liquid viscosity causes an increase in bubble sizes. This behavior is attributed to the fact that the increase in the viscosity of liquid means the increase in the magnitude of viscous forces exerted during formation which promotes the coalescence on or above the distributor. These results are in agreement with the results of previous investigators (Jamialahmadi et al., 2001; Kulkarni and Joshi, 2005).

ii. Surface Tension

Figure (11) shows the effect of surface tension on bubble size. It can be seen from this figure that the bubble size increases with increasing surface tension of liquid. This behavior is attributed to the fact that the increase in liquid surface tension helps a bubble to adhere to the edge of orifice, delaying the detachment process and as a result, the bubble size increases. This result is in agreement with the result of previous investigators (Idogawa et al., 1987; Hsu et al., 2000).

Influence of Gas Distributor Type

Figures (12-14) summarize the data of bubble size versus superficial gas velocity using the two different types of gas distributor for each liquid used.

From these figures one can notice that the bubble size with porous plate and perforated plate distributors present similar trends in water and in aqueous glycerine solutions but exhibit very different behaviors in aqueous butanol solutions. Consequently, it appears that the coalescing media (water and aqueous glycerine solutions) and non-coalescing media (aqueous butanol solutions) exhibit very different behaviors whose origin can be found in bubble formation process due to distributor type and coalescence phenomena. When bubbles are generated in water and in aqueous glycerine solutions, the bubbles coalesce markedly on or above the distributor, and as a result a similar bubble size was observed by using the two types of gas distributor. On the other hand, when the bubbles are generated in a solution of surface active substances (alcohol), bubble coalescence is almost completely hindered, and as a result the bubble size obtained with porous plate distributor is smaller than that produced by perforated plate distributor. Therefore, the effect of gas distributor is enhanced in non-coalescing media. These results are in agreement with the observations of Camarsa et al., (1999).

3.2.2 Bubble Rise Velocity
Influence of superficial gas velocity and gas holdup

Figure (15) show the effect of the superficial gas velocity on the bubble rise velocity for all liquids and for both distributor types used. From this figure one can notice that as the superficial gas velocity increases, the bubble rise velocity decreases. The same behavior can be shown in figure (16) which represents the effect of gas holdup on bubble rise velocity, i.e., the bubble rise velocity decreases with increasing gas holdup.

This decrease is attributed to the fact that in the homogeneous flow regime, the bubble rises almost vertically at a velocity lower than the terminal velocity due to the hindrance effect. This hindrance effect arising from each bubble in the swarm tends to avoid each other. This avoidance can be expressed as (hindering) of the rise velocity. The hindrance progressively reduces the bubble rise velocity with increasing gas holdup. This result was also reported by other investigators (Camarasa et al., 1999; Li and Parakash, 2000;; Sangani 2002; Ruzicka, 2003).

3.3 Drag Coefficient
Influence of Liquid properties on Drag Coefficient

Figure (17) show the effect of glycerine concentration on the drag coefficient. This figure indicates that the drag coefficient increases with increasing

glycerine concentration. This result is explained as that at higher concentrations of glycerine viscous forces tend to be predominating. The dominance of viscosity means that the shear stress effects dominate the drag force. This result has been found by Dharwadker et al. (1987) and Abd-alKareem (1999).

On the other hand, the addition of surface-active substances to air-water system would be expected to cause considerable alteration in the flow behavior where these substances cause an increase in drag coefficient as can be seen from Figure (18).

Influence of Gas Holdup and Reynolds Number

Figures (19) to (21) show the combined effects of gas holdup and Reynolds number on the drag coefficient for the air bubbles flow in different liquids. From these figures, it is clear that the drag coefficient decreases with increasing Reynolds number because the increase in Reynolds number meaning that the inertial force is increased relative to the viscous force in the direction of reducing the drag force. This result was in agreement with the observations of Mohammed, (1997).

The gas holdup contributes significantly to the drag coefficient in the multi bubbles system. It can also be seen from these figures that the drag coefficient increases with increasing gas holdup. This behavior can be explained as that the increase in gas flow rate increases the gas holdup. At low gas rates, the bubble ascended individually and the number of bubbles per unit volume was small. At higher gas flow rates, the concentration of bubbles increased with the bubbles rising in close proximity to each other. The smaller the distance between the bubbles, the higher drag on bubbles. This result was in agreement with Lane (2006) and also with Ishii and Zuber (1979) who approved that through Equation (3) and with Rusche and Issa (2000) through Equation (5).

4. Empirical Correlations
4.1 Gas Holdup Correlation

An attempt was made to formulate a correlation that would permit the prediction of gas holdup, a variable that greatly affects the bubble column operation. From the present work and the careful inspection of the experimental results (from various investigators) it can be concluded that the gas holdup value is the result of the interaction of several parameters as follows:

- The superficial gas velocity.
- The physical properties of liquid phase (i.e., viscosity, density, surface tension).
- The column cross section.
- The distributor cross section.

In order to formulate a generalized correlation that would incorporate the relative effect of all the above parameters, dimensional analysis using Buckingham's π-theorem was performed. The resulting expression then has the form:

$$e_G = 0.048703 Fr^{0.530755} Ga^{0.133047} Bo^{0.253508} \left(\frac{Do}{Dc}\right)^{-0.070889}$$

This correlation gives:
Correlation coefficient (R) = 0.97471
Final Value = 0.05269
Proportion of variance accounted for = 0.95007.

4.2 Drag Coefficient Correlation

From the experimental results, it can be concluded that the drag coefficient value is the result of interaction of several parameters, the most important of which are:

- The gas holdup.
- The bubble characteristic (bubble diameter and bubble rise velocity).
- The physical properties of the liquid phase (i. e., surface tension, viscosity and density)

In order to formulate a generalized correlation that would incorporate the relative effect of all the above factors, dimensional analysis using Buckingham's π-theorem was performed.

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The resulting expression then has the form:

$$C_D = 1.826129 \; e_G{}^{0.067566} \; \mathrm{Re}^{-0.033534} \; Fr_b{}^{-0.864212}$$

This correlation gives:

Correlation coefficient (R) = 0.98734
Final Value = 0.97483
Proportion of variance accounted for = 0.69339.

5. Conclusions

In this paper, the gas hold-up, the bubble characteristics, and the drag coefficient were investigated for coalescing systems (air-water and air-aqueous glycerin solutions) and non-coalescing systems (air-aqueous butanol solutions). This study led to the following conclusions:

- The gas holdup increases with superficial gas velocity.
- The gas holdup decreases with liquid viscosity for μ_L = 3-22 mPa.s. On the other hand the measurements also indicate that there is a narrow viscosity range $\mu_L < 3$ mPa.s where the gas holdup increases with liquid viscosity.
- The presence of surface active agents in water causes higher values of gas holdup.
- The effect of gas distributor type is shown to be much higher in non-coalescing media.
- The bubble size increases with liquid viscosity, slightly increases with superficial gas velocity, and decreases with surface tension.
- The drag coefficient of a bubble in swarm decreases with Reynolds number and increases with gas holdup, glycerine concentration and butanol concentration.
- The higher drag coefficient values were reported in alcohol solutions.

Acknowledgements

Nomenclature

C_D	Drag coefficient (-)
d_B	Bubble diameter (m)
D_C	Column diameter (m)
f_D	Drag force on a single bubble (N)
F_D	Drag Force on a bubble swarm (N)
g	Gravitational acceleration (m/s^2)
H_D	The height of the gas-liquid dispersion (m)
H_L	The height of clear liquid (m)
N	Number of bubbles (-)
U_b	Bubble rise velocity (m/s)
U_L	Liquid phase velocity (m/s)
U_G	Superficial gas velocity (m/s)

Greek Letters

e_G	Gas holdup (-)
m_L	Viscosity of liquid phase (kg/m.s)
ρ_L	Density of liquid phase (kg / m^3)
$\Delta\rho$	Density Difference between liquid and gas phases, (ρ_L-ρ_G) (kg/m^3)
σ	Surface tension of the liquid (N/m)

Dimensionless Groups

Bo	Bond number,	$\dfrac{r_L \, gD_C^2}{s_L}$
Fr	Gas Froude number,	$\dfrac{U_G{}^2}{gDc}$
Fr$_b$	Bubble Froude number,	$\dfrac{U_b^2}{gd_B}$
Ga	Galileo number,	$\dfrac{r_L^2 \, gD_C^3}{m_L^2}$
Re	Reynolds number,	$\dfrac{r_L U_b \, d_B}{m_L}$

Abbreviations

But   Butanol
CCPS   Computerized Conductivity

Probe System
Gly Glycerine
PoP Porous Plate distributor
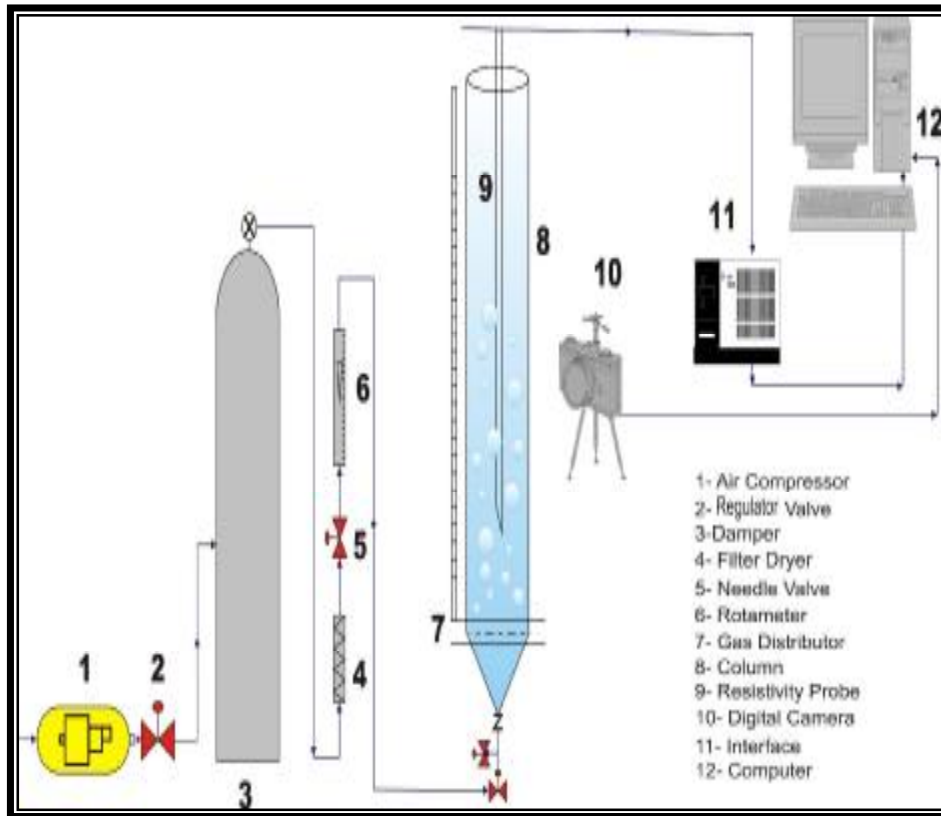PfP Perforated Plate distributor

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Table (1): Physical Properties of the Liquids at 25 ^{o}C (Mouza et al., 2005).

et Liquid	Concentration (wt %)	Density (kg/m^3)	Viscosity (mPa. s)	Surface tension (mN/m)
Distilled water	—	998	1	72
Glycerine	10	1020	1.5	71
Glycerine	30	1081	3.5	70
Glycerine	50	1126	8.2	68
Glycerine	70	1173	22.5	67
n-Butanol	0.6	994	0.9	60
n-Butanol	1.5	991	0.9	48

1- Air Compressor
2- Regulator Valve
3-Damper
4- Filter Dryer
5- Needle Valve
6- Rotameter
7- Gas Distributor
8- Column
9- Resistivity Probe
10- Digital Camera
11- Interface
12- Computer

Figure(1):Schematic Diagram Of The Experimental Setup.
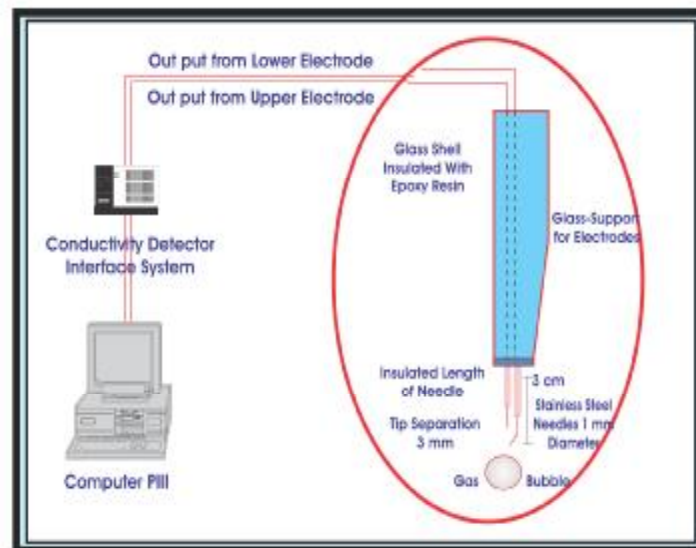
Figure (2) : Schematic diagram of the conductivity bubble detector system with probe details..

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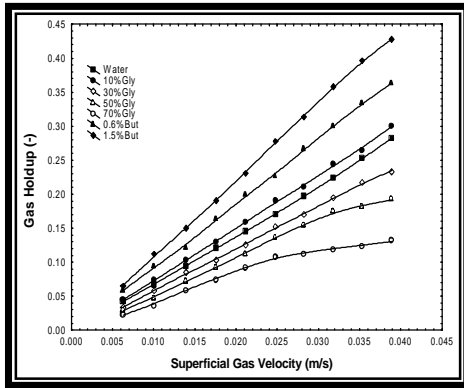
Figure (3): Gas Holdup Versus Superficial Gas Velocity (Porous Distrributor)
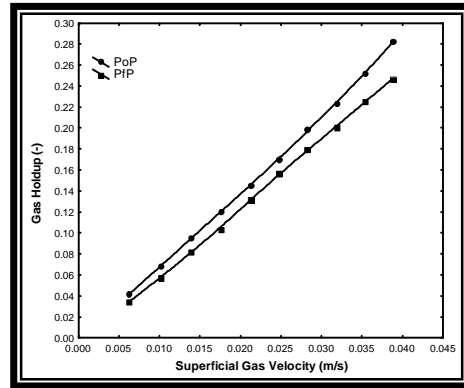
Figure (6): Effect of Gas Distributor Type on Gas Holdup for Air-Water System
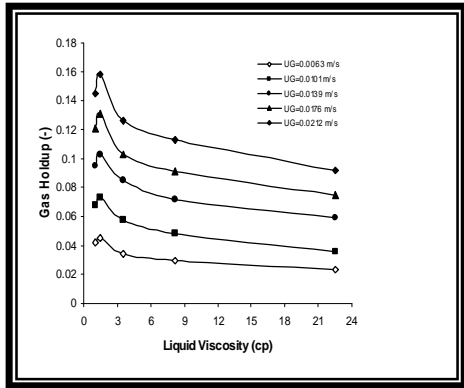
Figure (4): Gas Holdup Versus Liquid Viscosity for Air-Glycerine Solutions (Porous Distributor)
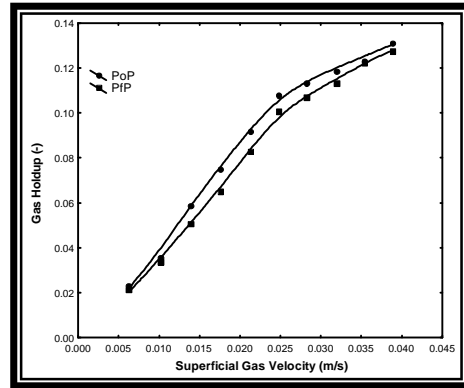
Figure (7): Effect of Gas Distributor Type on Gas Holdup for Air-70% Glycerine Solution
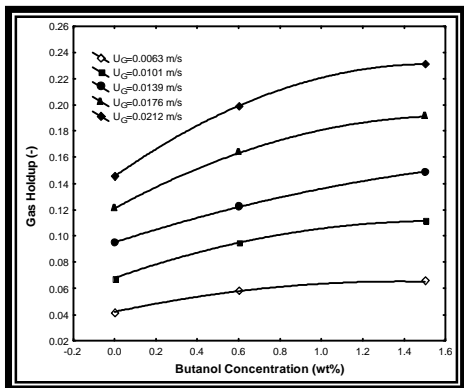

Figure (5): Gas Holdup Versus Butanol Concentration (wt%) (Porous Distributor)
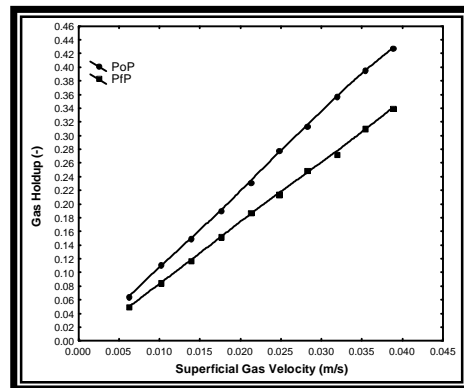
Figure (8): Effect of Gas Distributor Type on Gas Holdup for Air-1.5% Butanol Solution

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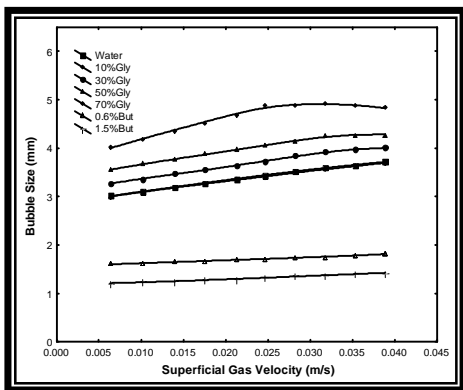
**Figure (9): Bubble Size Versus Superficial
Gas Velocity (Porous Distributor)**
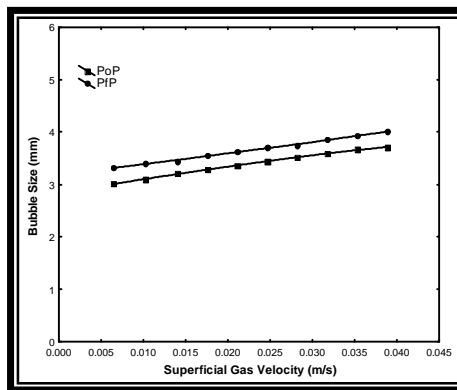
**Figure (12): Effect of Gas Distributor Type
on Bubble Size for Air-Water System**
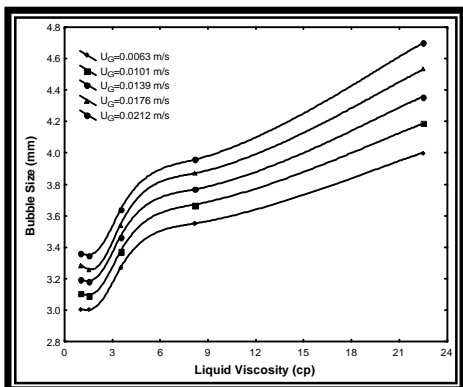
**Figure (10): Bubble Size Versus Liquid
Viscosity for Air-Glycerine Solutions
(Porous Distributor)**
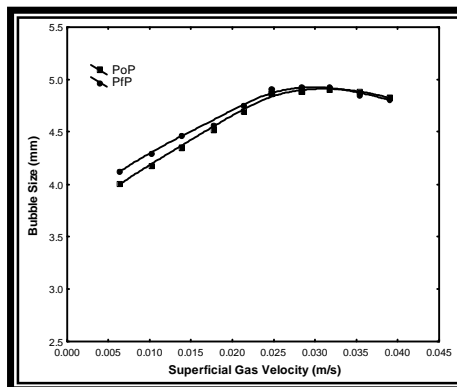
**Figure (13): Effect of Gas Distributor Type on
Bubble Size for Air-70% Glycerine Solution**
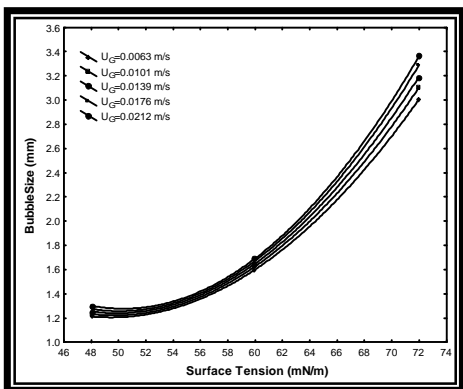
**Figure (11): Bubble Size Versus Surface
tension for Air-Butanol Solutions
(Porous Distributor)**
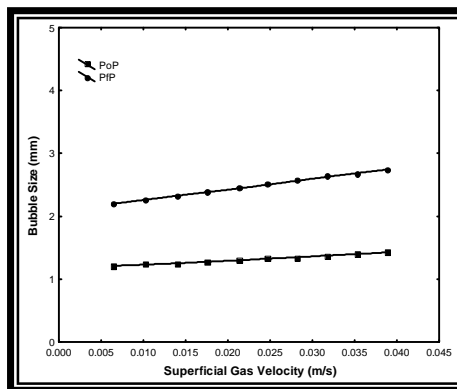
**Figure (14): Effect of Gas Distributor Type
on Bubble Size for Air-1.5% Butanol
Solution**

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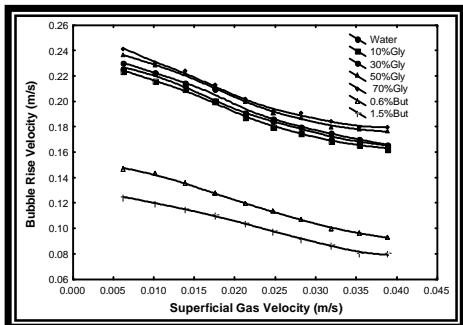
**Figure (15): Bubble Rise Velocity Versus
Superficial Gas Velocity (Porous Distributor)**

**Figure (16): Bubble Rise Velocity Versus
Gas Holdup (Porous Distributor)**

**Figure (17): Effect of Glycerine Concentration
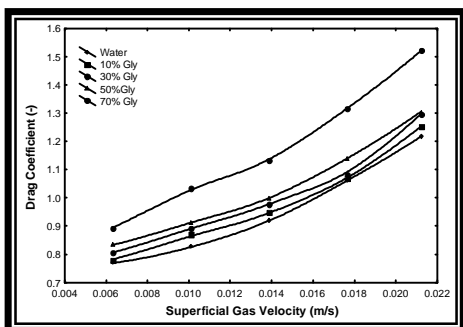on Drag Coefficient (Porous Distributor)**

**Figure (18): Effect of Butanol
Concentration on Drag Coefficient
(Porous Distributor)**
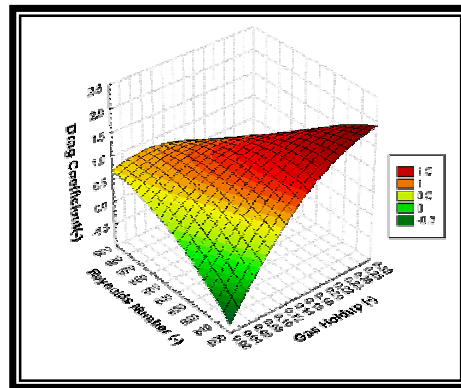
**Figure (19): Effects of Gas Holdup and Reynolds
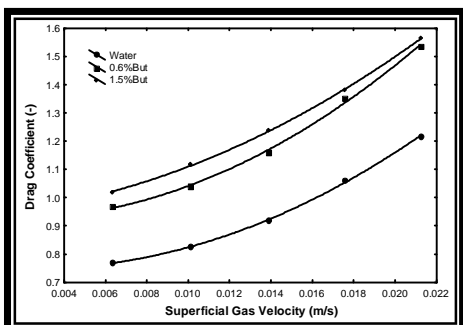Number on Drag Coefficient for Air-Water
System**
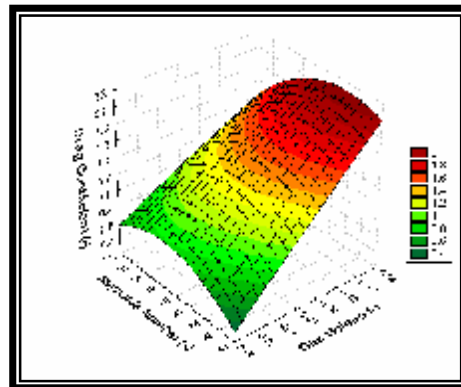
**Figure (20): Effects of Gas Holdup and Reynolds
Number on Drag Coefficient for Air-70% Glycerine**
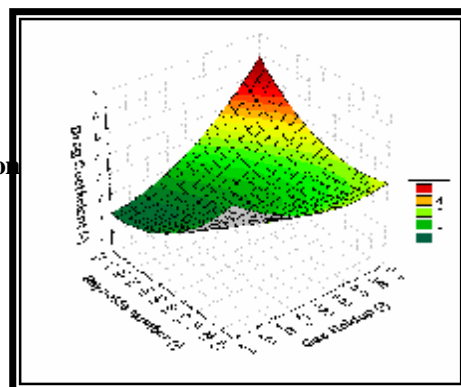
**Figure (21): Effects of Gas Holdup and
Reynolds Number on Drag Coefficient for
Air-1.5% Butanol**

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