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# Bubble Size Distribution In Gas-Liquid Dispersion Column

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## Abstract

The present work investigates the effect of; superficial air velocities of: 1, 3, and 6 cm/s for two types of perforated distributor on hydrodynamic characteristic in a gas-liquid dispersion column of; air-water, and air-aqueous-n-propanol solution. Bubble distribution, gas holdup, and power consumption are parameters take in consideration. Experimental work was carried out in perspex column of 8.5 cm inside diameter and 1.5 m height. Two types of bubble generator (perforated plate) were fixed at the bottom of the column; plate A (99 holes of 0.5 mm diameter and free area of 0.34%), plate B (20 holes of 1.5 mm diameter and free area of 0.62%). Photographic technique was used to measure the bubble parameters.

The experimental results were represented by two empirical correlations. The gas holdup and the Sauter mean diameter of bubbles were correlated with both the power consumption and the hole diameter of the perforate plate.

## Keywords:

**Gas-liquid dispersion column, bubble size distribution, gas holdup, and power consumption.**

## الخلاصة

العمل الحالي دراسة تأثير ، سرعة الهواء الظاهريه (1، 3، و 6 سم / ثا) ونوعين من الموزع الهواء على الخصائص الهيدروديناميكية في عمود تشتت الغاز السائل من نظامين؛ الهواء والماء، والهواء ومحلول بروبانول اعتيادي. معدل توزيع الفقاعات، وكميه الغاز المحتجز، واستهلاك الطاقة اخذت بنظر الاعتبار في هذه الدراسه. وقد أجريت تجارب العمل في العمود بقطر داخلي 8،5 سم وارتفاع 1،5 متر. وقد تم تثبيت نوعين من موزعات الهواء (لوحة مثقبة) في الجزء السفلي من العمود؛ لوحه (ا) (99 ثقب بقطر0،5 مم وكانت مساحه التثقيب تساوي 0،34 ٪)، لوحه (ب) (20 ثقب بقطر 1،5 مم وكانت مساحه التثقيب تساوي 0،62٪). تم استخدام تقنية التصوير الفوتوغرافي لقياس القيم المحدده للفقاعة. كما تم ربط النتائج العملية بمعادلات تحليلية حيث تم ربط كمية الهواء المحتجز ومعدل قطر الفقاعات بالطاقة المستهلكة وقطر موزع الهواء.

## Introduction

Bhavaraju et al. (1978) and Heijnen & Riet (1984) are the only researcher's works that take the role of sparger in the evolution of bubble characteristics. Their approach is based on the existence of two zones in the column and three bubble regimes. This study distinguishes the region near the sparger where bubble properties are determined by the bubble formation process and the region in the bulk where they are governed by bulk liquid flow. Krishna and Ellenberger (1996) illustrated that the bubble bed behavior is particularly influenced by the nature of the dispersion. Also admitted that three regimes can be distinguished depending on the gas flow rate; homogeneous, heterogeneous and slug flow regimes. The last one is only observed in small-scale columns. Bouaifi et al. (2001) studied the gas holdup, bubble size, mass transfer coefficient, axial liquid dispersion coefficient, and power consumption in stirred gas-liquid reactors and bubble columns. The liquid was tap water and the gas used for all the experiments was air. Different spargers were used such as; perforated plate, sintered glass porous plate, and perforated flexible membrane. The bubble size was measured using a photographic technique with a CCD high definition camera. It was found that the power consumption has a negative impact on the bubble size in contrarily to its impact on gas holdup, interfacial area, volumetric mass transfer coefficient, and bubble size distribution.

Gas-liquid dispersion column has been extensively used in a wide variety of chemical and biochemical processes. It is particularly used in hydrogenation, oxidation, fermentation, petroleum refining, coal liquefaction, etc., where the overall production rate is often controlled by the gas liquid interfacial mass transfer. An example of a dispersion column is the Gas-liquid dispersion column reactor. It is the type of reactor that do not only provide a significant interfacial mass transfer area but also very simple in design and no mechanical agitator is required, (Mandal et al., 2003). Breakup and coalescence of bubbles play a crucial role in a broad spectrum of multiphase flow processes, such as the evaluation of the bubble size distribution in stirred tanks and bubble columns (Delhaye and Mc Laughlim (2003)).

Mouza et al. (2005) studied the effect of the liquid properties on bubble size distribution in a bubble column equipped with two different fine porous spargers (20, 40 μm). Various liquids were used such as; water, n-butanol 0.6 wt%, n-butanol 1.5 wt%, glycerin 33.3 wt%, glycerin 50 wt%, and glycerin 66.7 wt% and atmospheric air is used as the gas phase for all experiments. Gas holdup, bubble size distribution, and mean Sauter diameter were obtained using high speed video camera.

In bubble columns two main regimes can be distinguished. The homogeneous bubbly flow regime, encountered at low gas velocities with small holes sparger, it is characterized by narrow bubble size distributions and a uniform spatial dispersion of gas hold-up. In this regime, there is no interaction between the bubbles, their motion is mostly vertical. The second regime is the heterogeneous (churn turbulent flow) regime which is observed at higher gas velocities. It is defined by a large bubble size distribution and a high concentration of large bubbles. In this regime the bubble size is governed by the coalescence–break-up equilibrium (Malysa et al., 2005, Mouza et al., 2005, Kantarci et al., 2005, and Dargar and Macchi, 2006).

The aim of the present work is to study the effect of different hydrodynamic parameters in to two systems of gas-liquid dispersion column; air-water and air-aqueous-n-propanol solution. This study mainly focused on the bubble size distribution at variety of conditions.

## Experimental Work

The experiments are conducted in a cylindrical semi batch bubble column. The column is made of perspex with an inside diameter of 0.085 m and a height of 1.5 m as shown in **Fig.1**. Two types of perforated plates are used as a multiple-orifice nozzle; plate (A) with 99 holes of 0.5mm diameter and free area of 0.34% and plate (B) with 20 holes of 1.5 mm diameter and free area of 0.62%.

Water and aqueous n-propanol solution of 0.6 wt% were presented as the liquid phase and air as the gas phase. All the experiments were conducted at ambient temperature of 25$^{o}$C and atmospheric pressure. Each experiment started by filling the column with an appropriate liquid phase up to 130 cm above the perforated plate. The gas phase was injected and distributed into the liquid phase by passing it through the perforated plate.

A high speed digital video camera is used for direct flow visualization, bubble size and gas holdup measurements. The air was passed in to the column at a superficial velocity of 1, 3, and 6 cm/s. Three pictures were taken from different angles of the column, the part above the distributor, at a recording speed of 30 pictures per second. The images were analyzed thoroughly to predict quantitative information about the bubble size distribution and the average gas holdup.

An ellipse shape was approximated for the bubbles where the major and the minor axes were computed by software. The equivalent diameter of a spherical bubble with the same volume of an ellipsoidal bubble shape was computed by Eq. (1), (Colella et al. (1999), Polli et al. (2002), and Bouaifi et al. (2001)).

$$d_{Bi} = \sqrt[3]{a^2 b} \quad (1)$$

An average number of bubbles were calculated for the three pictures in each experiment, using statistical calculations (Tse et al. (2003), and Hebrard et al. (1996)).

The most important parameter characterizing hydrodynamics behavior of a gas-liquid dispersion is the average gas holdup volume; this was calculated by Eq. (2) which it is essential for the design and the scale-up purposes (Mouza et al. 2005).

$$\varepsilon_g = \frac{H_F - H_L}{H_F} \quad (2)$$

The mean Sauter diameter, defined by Eq. (3), (Bouaifi et al. 2001):

$$d_{vs} = \frac{\sum n_i d_{Bi}^3}{\sum n_i d_{Bi}^2} \quad (3)$$

The total power consumption is related to the total gas pressure drop according to the equation (4) (Bouaifi et al. 2001):

(4)

$$\left(\frac{P_g}{V}\right)_{tot} = \frac{Q\Delta P_s}{V} = \frac{Q(\rho_l gH + \Delta P_s)}{V} = \frac{(\rho_l gH + \Delta P_s)U_g}{H}$$

In a perforated plate, the specific sparger

$$\left(\frac{P_g}{V}\right)_{tot.} = \rho_l g U_g \quad (5)$$

pressure drop can be neglected. The specific power consumption is determined equation (5):

## Results And Discussion

### Air-Water System

The bubble size distributions (BSD) are presented in **Fig. 2** for air-water system and for both perforated plates A and B. At superficial gas velocity of 1 cm/s, the photographic film was analyzed, the bubble diameter varied between 1.2 to 10.1 mm for perforated plate (A), with mean diameter of 7.037 mm and standard deviation of 2.588 mm, and 1.8 to 11.2 mm for the perforated plate (B), with mean diameter 8.522 mm and standard deviation of 2.473 mm. There is an increase in the bubble mean diameter from 7.037 to 8.522 mm with the increase in the perforated plate diameter, this because the bubble is born at larger size at the outlet of the sparger which lead to produce less number of bubbles.

Similar analysis done for the both superficial gas velocities of 3 and 6 cm/s. As presented in the **Figs. 3 and 4** the mean diameters for both perforated plates (A) and (B) for the velocity of 3 cm/s are 8.527 and 8.913 mm and the corresponding standard deviations are 2.525 and 2.453 mm as respectively. Also, the mean diameters for both perforated plates for the velocity of 6 cm/s are 9.241 and 9.9806 mm and the corresponding standard deviations are 2.383 and 2.476 mm. The comparison between the bubble mean diameter for the three superficial gas velocities; 1, 3, and 6 cm/s show an increase in the bubble mean diameter from 7.037 to 9.241 mm as shown in **Fig. 5**. This lead to a conclusion that there is coalescence happening as the superficial gas velocity increases. Also, not only the holes diameter controls the size of the bubbles at the outlet of the sparger but also the gas velocity. The coalescence phenomena cause a decrease in the bubble rise velocity and decrease in the number of bubbles as shown in **Figs. 6 and 7**. As reported by Colella et al., 1999 the increase in the superficial gas velocity may lead to produce larger bubbles with lower rising velocity.

In the present work, bubbly flow regimes occur when the air velocity was between 1 to 3 cm/s and the transition regime occur when air velocity was at 6 cm/s (Barnea et al. 1980).

### Air-Water-N-Propanol Solution System

**Figure 8** shows the bubble size frequency distribution for the air-aqueous n-propanol system at 1cm/s superficial gas velocities. The bubbles diameter varied between 2.1 to 9.8 mm and 2.5 to 10.2 mm with mean diameters of 6.859 and 6.998 mm and standard deviations of 2.216 and 2.087

mm, for both perforated plates (A) and (B) respectively. It is clear from these results that the bubbles mean diameter has changed very little from 6.859 to 6.998 mm with the increase in the holes diameter in the perforated plates; this is because the addition of n-propanol to water led to inhibit the effect of the perforated holes diameter on the bubbles diameter at the outlet of the sparger. The comparison between the mean diameter resulted from water alone (7.037 mm) and from n-propanol-water system (6.859 mm), it show little change. In addition, the number of bubbles were increased with the addition of n-propanol because the addition of n-propanol to water led to increase in the breakage rate of the bubbles for a fixed velocity. This also led to increase in gas holdup as shown in **Fig. 14**. For the two higher superficial gas velocities (3, and 6 cm/s) as reported in **Figs. 9 and 10**, the mean diameters at superficial gas velocity of 3 cm/s are 6.4608 and 6.4804 mm, and the corresponding standard deviations are 2.127 and 2.508 mm for both perforated plates (A) and (B) respectively.

The mean diameters at superficial gas velocity of 6 cm/s are 4.6646 and 5.2604 mm, and the corresponding standard deviations are 1.657 and 1.846 mm for both perforated plate (A) and (B) respectively. These results show that the increasing in gas velocity led to decrease in the bubbles mean diameter from 6.859 to 4.664 mm. This also resulted in a significant increase in the number of bubbles with the increase in gas velocity as the holes diameter in the perforated plate get smaller. This is because of faster breakage rate with the increase in gas velocity due to enhancement of bubble-bubble interactions as shown in **Figs.11 and 12**. In fact, increasing the superficial gas velocity leads to smaller bubbles with lower rising velocity (Colella et al., 1999), and the coalescence occurs onto the sparger surface and continue during the movement of the bubbles through the bulk of the liquid (Mouza et al., 2005).

It is well known that the addition of few amounts of long aliphatic alcohol molecules (e.g. n-propanol) to water leads to inhibition of coalescence phenomena. This is because these molecules are composed of a hydrophobic part (carbon chain) and a hydrophilic part (polar group). Thus surface tension gradient forces are created and immobilize the gas-liquid interface so that coalescence is hindered. Aqueous alcohol solutions produce the same effect as industrial organic mixtures on the bubble coalescence and can serve as a model fluid.

The mean bubble size, Sauter mean diameter, depends on the liquid properties which may either promote (e.g. water) or inhibit (e.g. water-n-propanol mixture) coalescence of the primary bubbles formed on the sparger surface as shown in **Figs. 5 and 13**. It is generally admitted that coalescence occurs in three steps, i.e., collision, liquid film drainage and rupture. When two bubbles collide, a liquid film formed due to the small amount of liquid trapped between them. This begins to drain until it is become sufficiently thin to be ruptured due to an instability mechanism. Also bubbles coalescence is a function of the contact time between two bubbles which depends on the bubble rising velocity, bubble size and the turbulence intensity (Chaudhari and Hofmann, 1994).

Gas holdup versus superficial gas velocity is shown in **Fig. 14**, both perforated plates (A) and (B) exhibit quite similar behaviors in aqueous n-propanol solution and air/water system. The perforated plate (A) forms smaller bubbles than the perforated plate (B), as coalescence is suppressed this may preserve these small bubbles within the column leading to increase in the holdup. This may also be due to the decrease in the bubble rise velocity due to the reduction in the drag coefficient caused by the accumulation of solute molecules at the interface (Levan and Newman (1976)).

The variation of gas holdup versus the power consumption are shown in the **Figs. 15 and 16**, for air-water and air-aqueous n-propanol solution systems for the two perforated plates A and B. The increase in the gas holdup led to increase in the power consumption for both systems and for the both perforated plates A and B. This is due to increase in the gas velocity, however it can be clearly seen that the same gas hold up can be achieved with less power consumption by adding of surfactant to the water.

The variation of the bubble Sauter diameter with the total specific power consumption is shown in **Figs. 17 and 18** for both air-water and air-aqueous n-propanol solution systems for the two perforated plates A and B. The variation of Sauter mean diameter depends on the system and the kind of gas spargers used. For air-water system, the Sauter means diameter was increased with the increasing in the power consumption for both perforated plates A and B, in contrary for the air-aqueous n-propanol solution system, the Sauter mean diameter decreased with increasing power consumption for the two perforated plates

A and B. These figures show that the mean Sauter diameter decreased at less power consumption by the addition of surfactant such as n-propanol. As a conclusion, better performance of a dispersion column with less power consumption can be achieved by the addition of n-propanol to the water.

## Empirical Correlations

The experimental results are represented by empirical correlations using a computer program named Statistical. The experimental correlations relating the gas holdup and Sauter mean diameter to the specific power consumption and Perforated plate hole diameters for the both systems. These are:

- **For Air-Water System**

The correlation for Gas holdup;

$$\varepsilon_g = -0.011012 + 0.00101\left(\frac{\rho_g}{V}\right) - 15.349\, d_H - 1*10^{-6}\left(\frac{\rho_g}{V}\right)^2 + 0.0655653\, d_H^2 - 0.036932\left(\frac{\rho_g}{V}\right) d_H \quad (6)$$

Correlation coefficient = 0.917
Average error = 10.6%
Standard deviation = 0.0139
The correlation for Sauter mean diameter of bubbles;

$$d_{vs} = 6.2526 + 0.006361\left(\frac{\rho_g}{V}\right) + 1108.939\, d_H - 1*10^{-6}\left(\frac{\rho_g}{V}\right)^2 + 2.3182\, d_H^2 - 1.1529\left(\frac{\rho_g}{V}\right) d_H \quad (7)$$

Correlation coefficient = 0.962
Average error = 2.13%
Standard deviation = 0.202

- **For Air-Aqueous N-propanol Solution System**

The correlation for Gas holdup;

$$\varepsilon_g = 0.00103 + 0.001164\left(\frac{\rho_g}{V}\right) - 4.6511\, d_H - 1*10^{-6}\left(\frac{\rho_g}{V}\right)^2 + 0.075572\, d_H^2 - 0.064265\left(\frac{\rho_g}{V}\right) d_H \quad (8)$$

Correlation coefficient = 0.97
Average error = 8.15%
Standard deviation = 0.0153
The correlation for Sauter mean diameter of bubbles;

$$d_{vs}\, 7.08193 + 0.001019\left(\frac{\rho_g}{V}\right) - 104.189\, d_H - 1*10^{-6}\left(\frac{\rho_g}{V}\right)^2 - 0.12599\, d_H^2 + 0.97587\left(\frac{\rho_g}{V}\right) d_H \quad (9)$$

Correlation coefficient = 0.996
Average error = 0.93%
Standard deviation = 0.0621

The term $(P_g/V)^2$ in Eqns. (6,7,8 and 9) can be neglected because the effect of this term is very small.

**Figure 19** and **Fig. 20** show the relation between the experimental and the predicted gas holdup and Sauter mean diameter respectively. The results good agreements with a maximum error around 10%.

The present experimental data is compared with the correlations predicted by Bach & Pilhofer 1978 and Hikita et al. 1980. In general, the experimental data were found to deviate considerably from proposed empirical models as shown in **Figs. 21 and 22**. The predicted values of gas holdup for the air-water system showed a deviation from our experimental data of 23% and 38% for the two plates respectively. Similar results have been predicted for the air-aqueous n-propanol sol. (0.6 wt %), the deviation were 26% and 54% for both plates respectively. The deviation in the correlations that estimate the gas holdup as published by Bach and Pilhofer (1978) was may be due to the difference in conditions; where $D_c$>0.1 m and $H_L$>1.2m, same reason for the data predicted by the correlations by Hikita el a. (1980), where $U_g$=0.042-0.38 m/s, $D_c$=0.1m and $H_L$=0.65m.

**Figures 23 and 24** show the comparison between the correlations prediction by Akita & Yoshida (1974) and Bouaifi el a. (2001) and the experimental data from this research regards the Sauter mean diameter values. For air-water system the deviation were around 22% and 51% for both plated respectively. For air-aqueous n-propanol solution (0.6 wt%), the deviation were little smaller around 13% and 29% for both plated respectively, as shown in figures (23 and 24). This deviation in Sauter mean diameter estimated by the correlations of Akita and Yoshida (1974 ) may be due to the condition used of $D_c$ up to 0.3 m, $U_g$ up to 0.07 m/s and single-orifice sparger. The correlations conditions for the study published by Bouaifi et al. (2001) were $U_g$=0.0025-0.04 m/s, $D_c$=0.15-0.2m and $H_L$=2m.

## Conclusions

It was found that the type of the liquid phase is the main factor that affects the bubble size distribution and the gas holdup. Power consumption is decreased with the addition of surfactant (n-propanol) compared to water alone at the same output. The values of Sauter mean diameter increased due to increase in the superficial air velocity for air-water system, in contrary to air-aqueous n-propanol solution. Perforated plate A gave a lower bubble diameter and a higher gas holdup compare to perforated plate B.

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## Notation

a= major axis of ellipsoidal bubble, mm
b= minor axis of ellipsoidal bubble, mm
$d_{Bi}$ = diameter of bubble of size i, mm
$d_H$= hole diameter of perforate plate, mm
$d_{vs}$ = sauter mean diameter of bubbles, mm
$D_c$=diameter of column, m
g = acceleration of gravity, $m/s^2$
$H_L$ = clear liquid height, mm
$H_F$ = aerated liquid height, mm
$n_i$ = number of bubbles of size i
$\Delta P$ = gas pressure drop, $N/m^2$
$\Delta P_s$ = sparger pressure drop, $N/m^2$
$P_g$ = power consumption in aerated liquid, W
Q = gas flow rate, $cm^3/s$
$U_g$ = superficial gas velocity, cm/s
V = column liquid volume, $mm^3$
Wt = weight percent of n-propanol in water, %

## Greek Symbols

$\varepsilon_g$ = gas holdup
$\rho$ = liquid density, $kg/m^3$

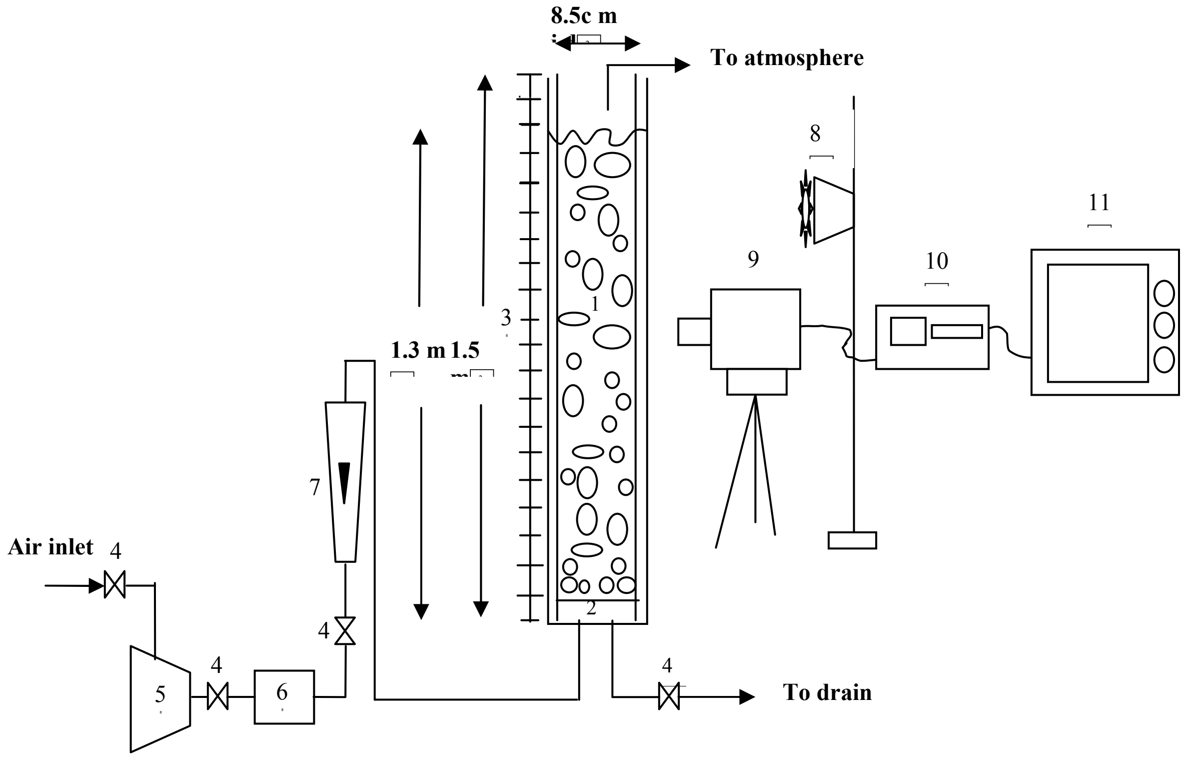


Fig.(1): Experimental set-up: (1) test column: (2) perforate plate: (3) Scale: (4) regulating valves: (5)compressor: (6) air filter:(7) rotameter: (8) electric flash: (9) digital camera: (10) video tape recorder: (11)screen.

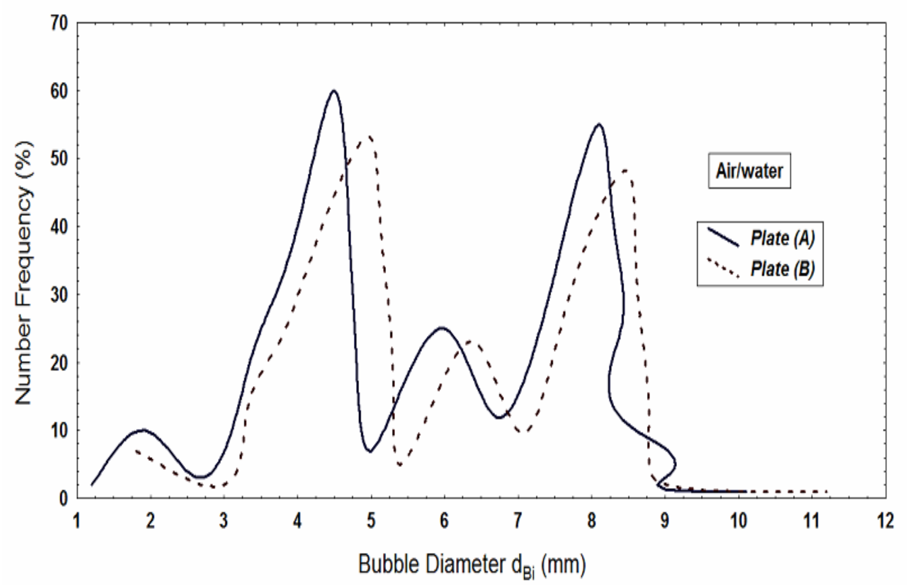


***Fig.2: Effect of hole diameter on BSD at ($U_g$= 1 cm/s) .***

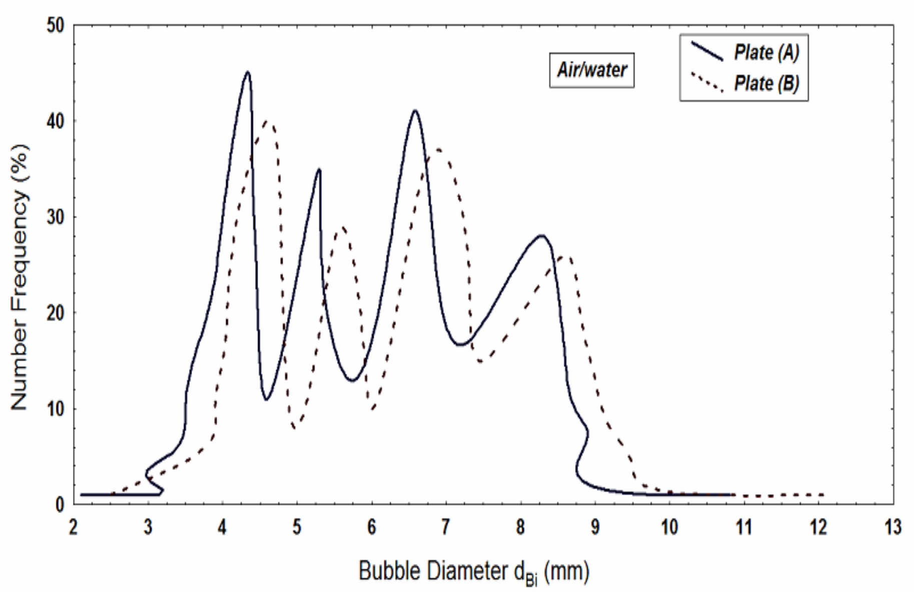


***Fig.3: Effect of hole diameter on BSD at ($U_g$= 3cm/s) .***

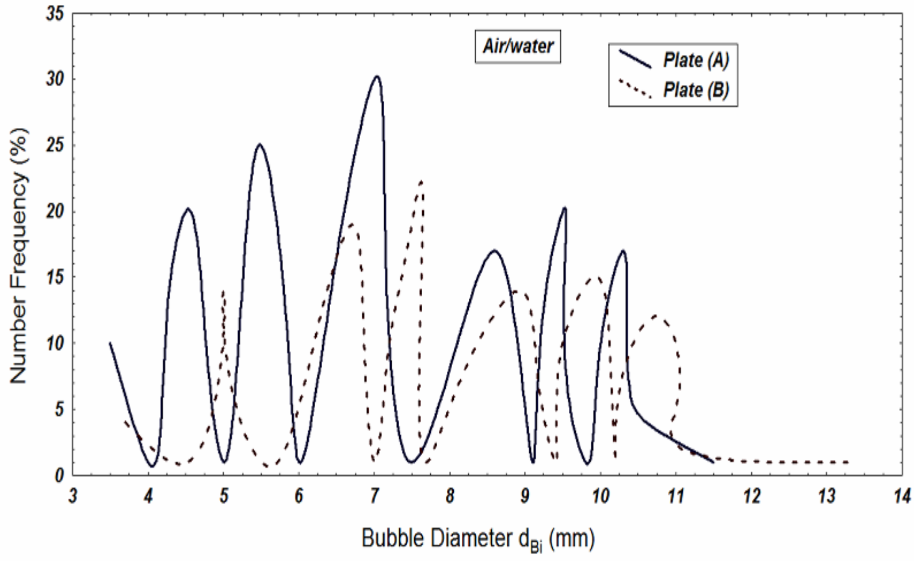


**Fig.4: Effect of hole diameter on BSD at ($U_g$= 6 cm/s) .**

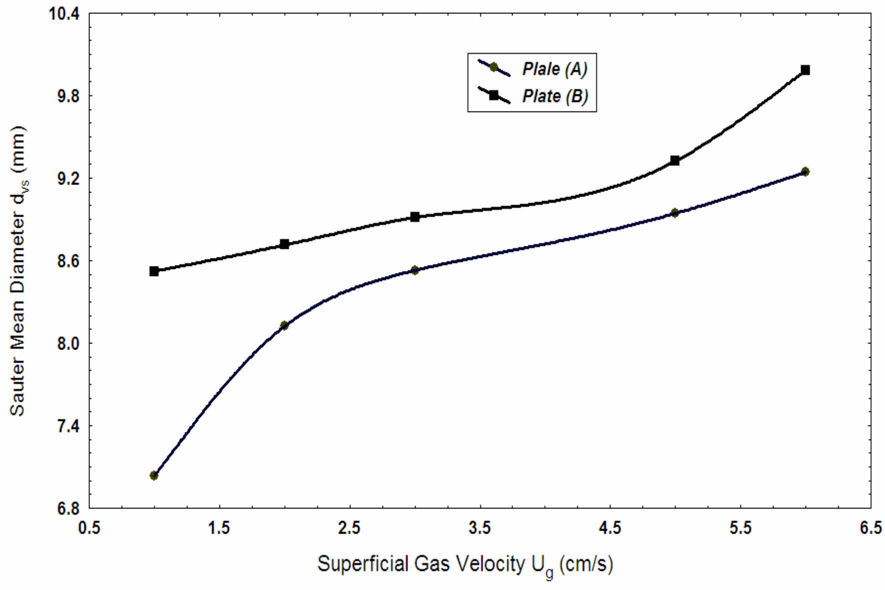


**Fig.5: Evolution of $d_{vs}$ with $U_g$ for air-water system.**

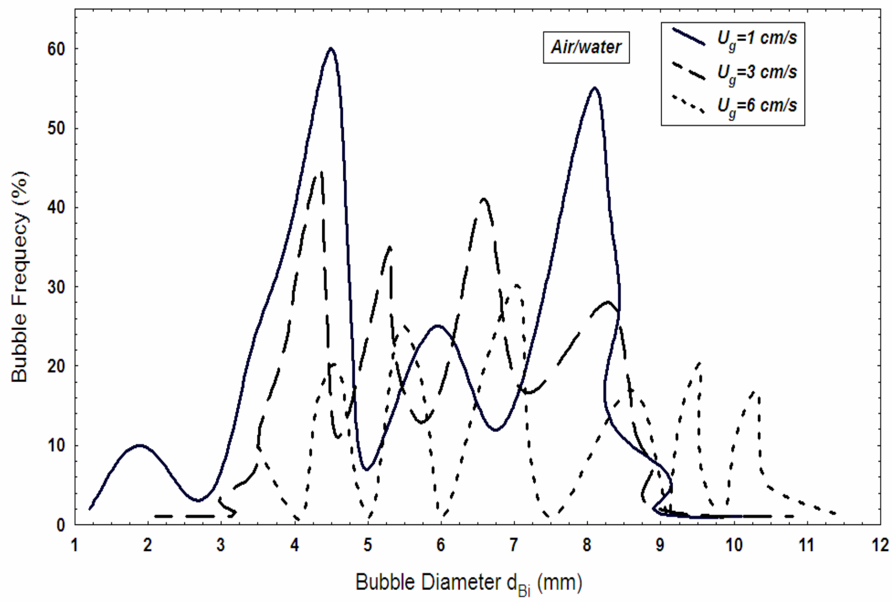


*Fig.6: Effect of superficial gas velocity on BSD for (plate A).*

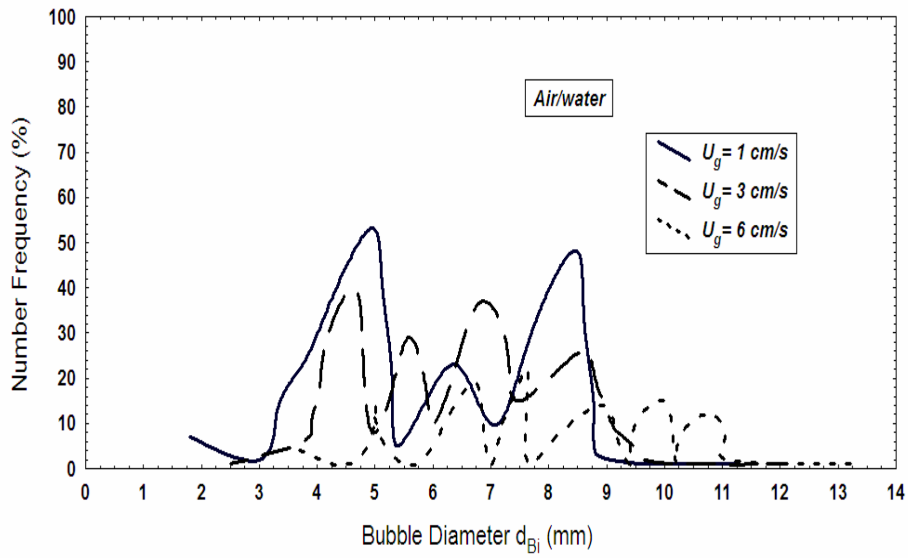


*Fig.7: Effect of superficial gas velocity on BSD for (plate B).*

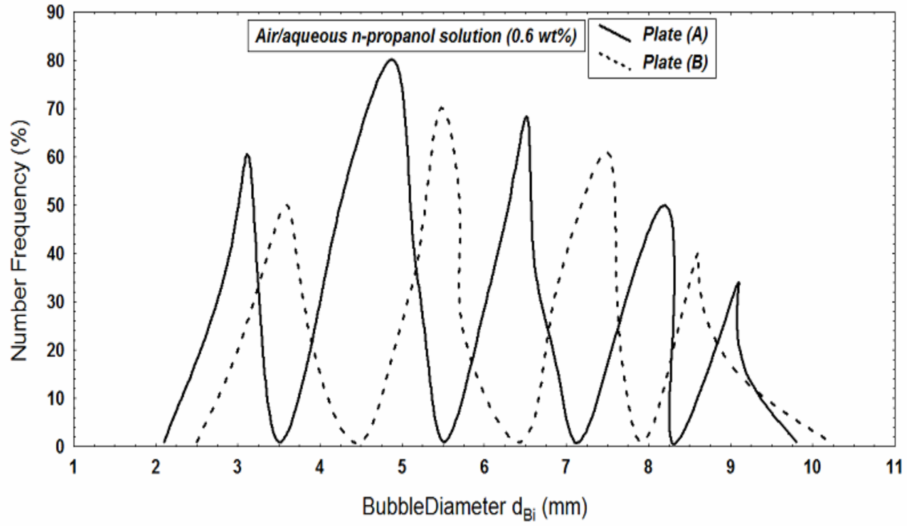


***Fig.8: Effect of hole diameter on BSD at ($U_g$= 1cm/s) .***

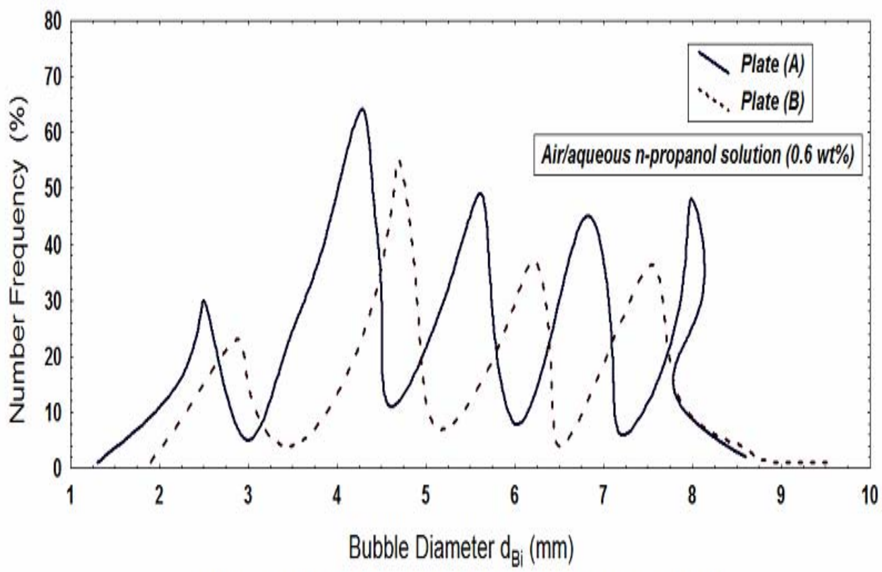


***Fig.9: Effect of hole diameter on BSD at ($U_g$= 3 cm/s) .***

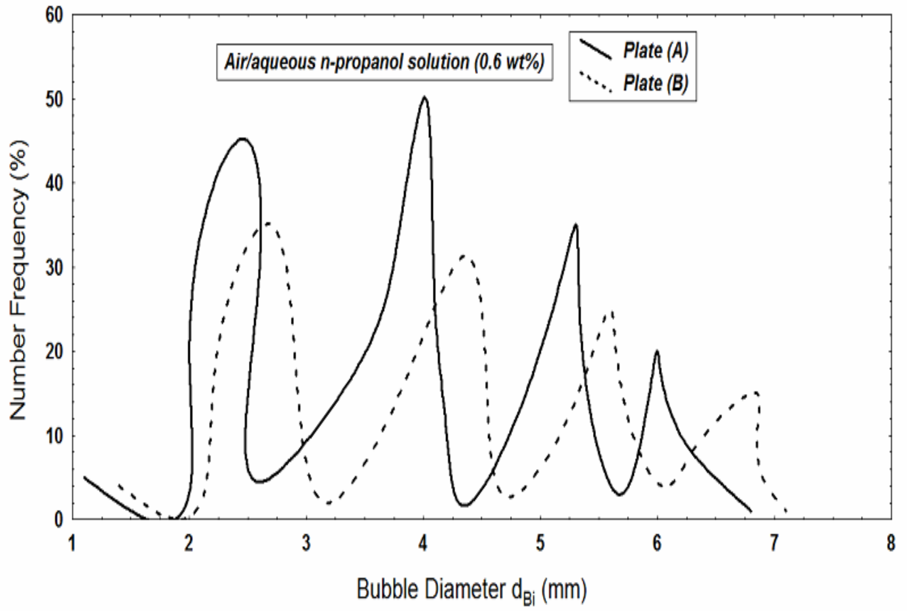


***Fig.10: Effect of hole diameter on BSD at ($U_g$=6 cm/s) .***

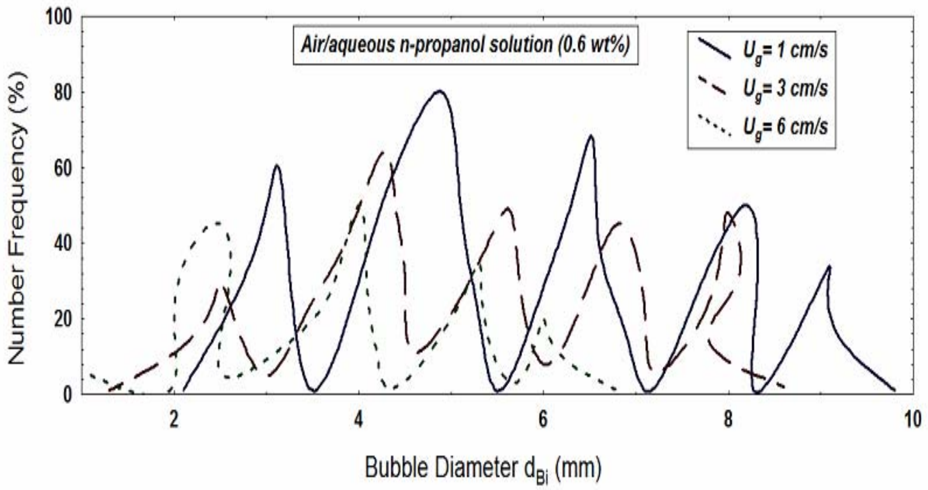


***Fig.11: Effect of superficial gas velocity on BSD for (plate A) .***

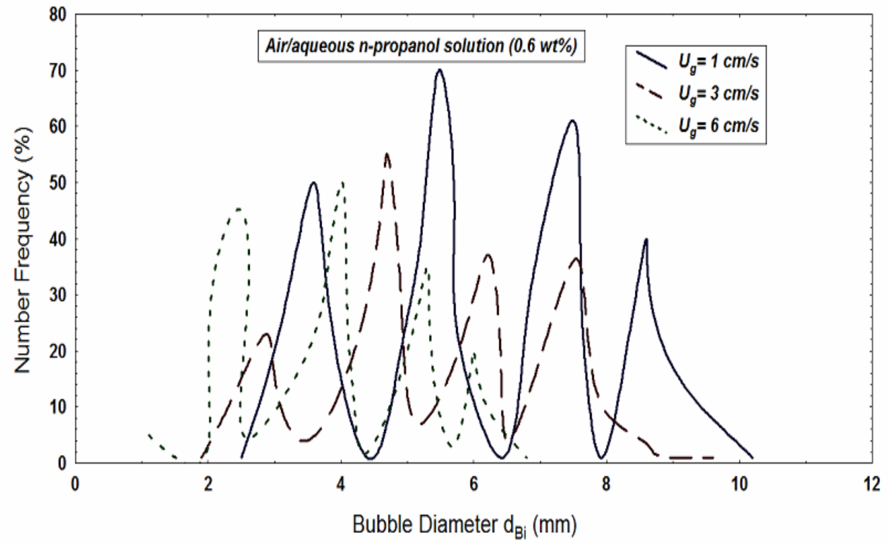


***Fig.12: Effect of superficial gas velocity on BSD for (plate B) .***

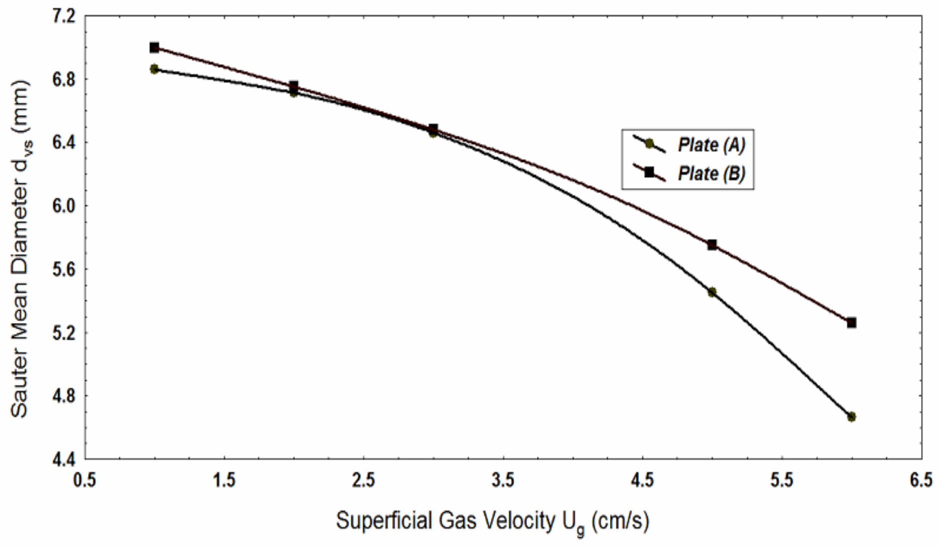


***Fig.13: Evolution of $d_{vs}$ with $U_g$ for air/aqueous n-propanol sol. system.***

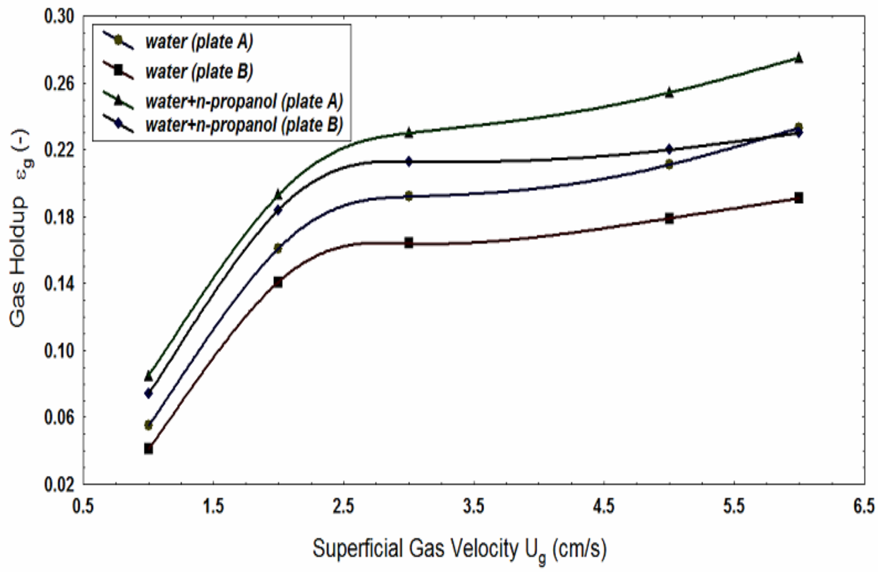


**Fig.14: Gas holdup as a function of superficial gas velocity.**

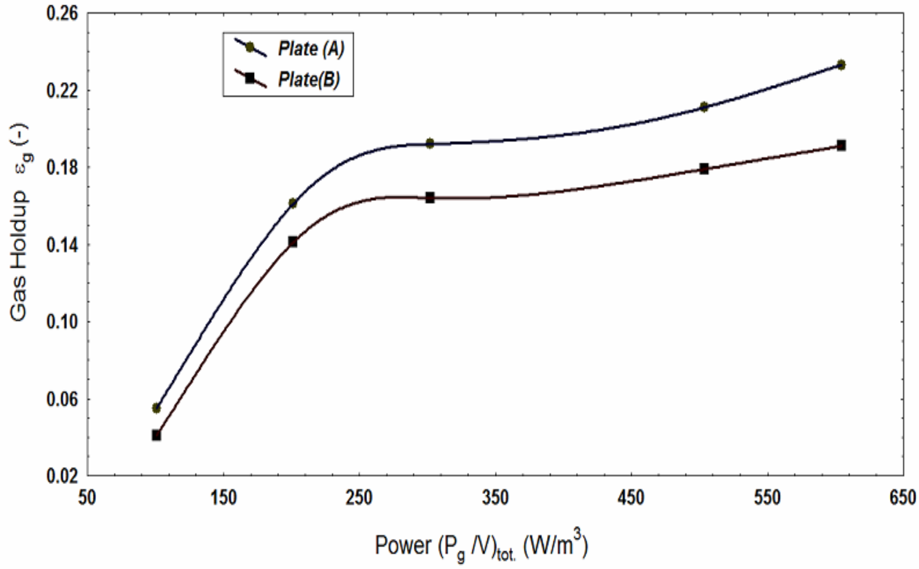


**Fig.15: Gas holdup vs. power consum. for air-water system.**

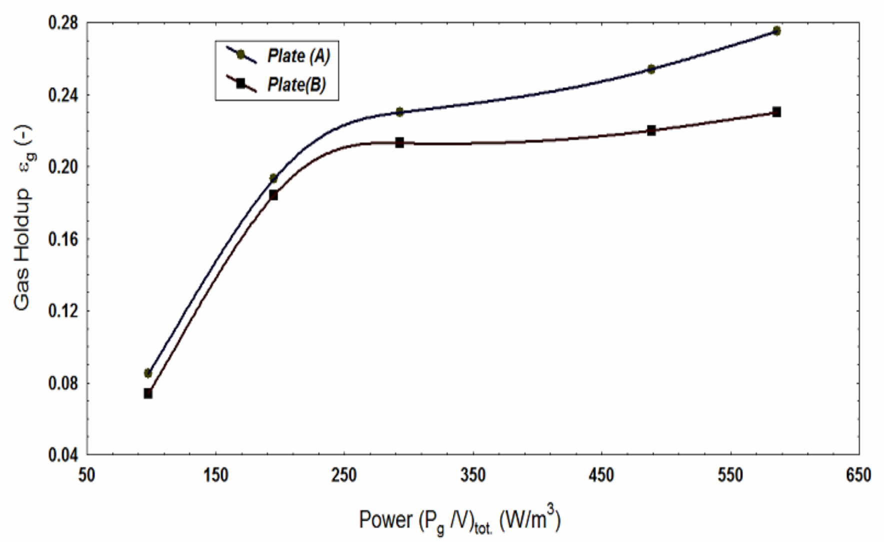


**Fig.16: Gas holdup vs. power consum. for air-aqu. n-propanol sol. system.**

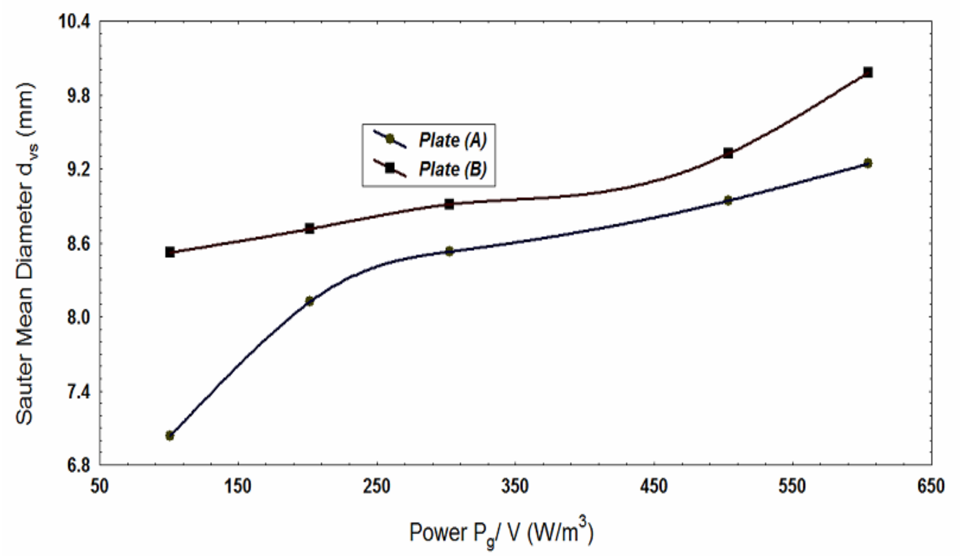


**Fig.17: $d_{vs}$ vs. power consum. for air-water system.**

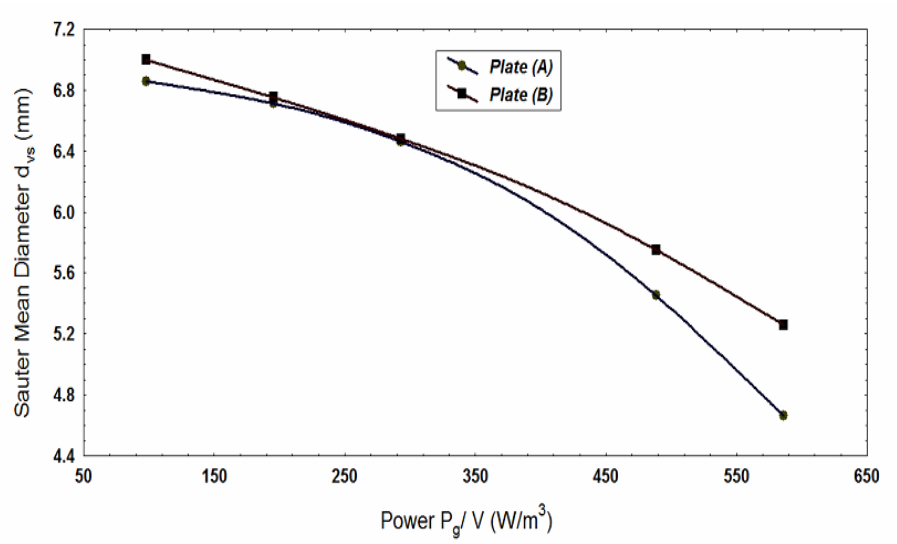


Fig.18: $d_{vs}$ vs. power consum. for air-aqu.n-propanol sol. system.

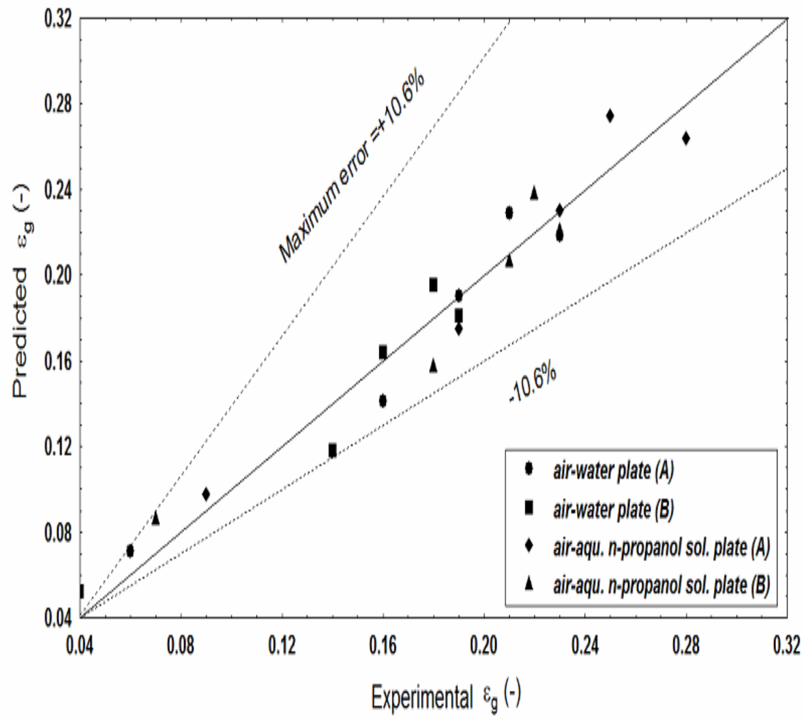


Fig.19: Comparsion between exp. and pred. gas holdup values Eqn.(6&8).

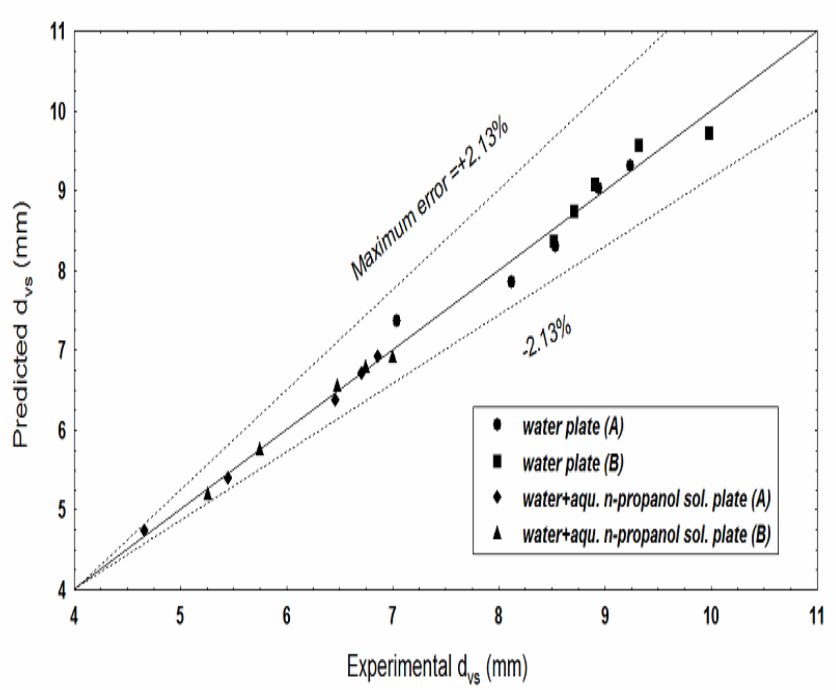


**Fig.20: comparsion between exp. and pred. sauter mean dia. values Eqn.(7&9).**

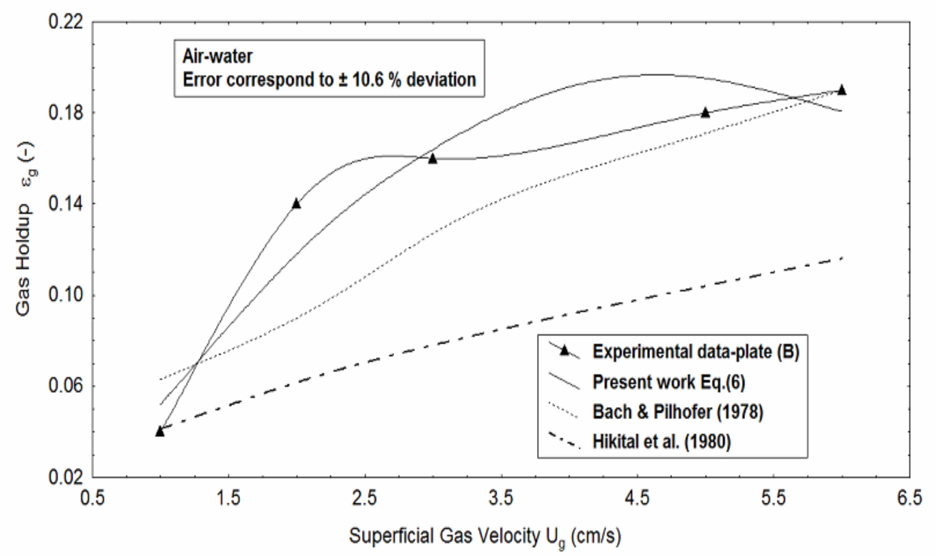


**Fig.21: Comparison of the exp.data with others authors work.**

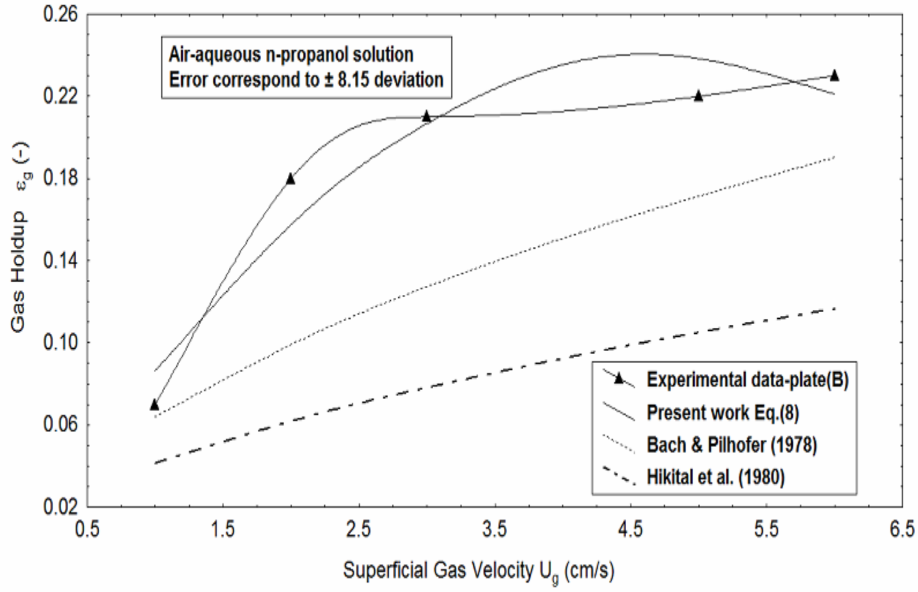


***Fig.22: Comparison of the exp.data with others authors work.***

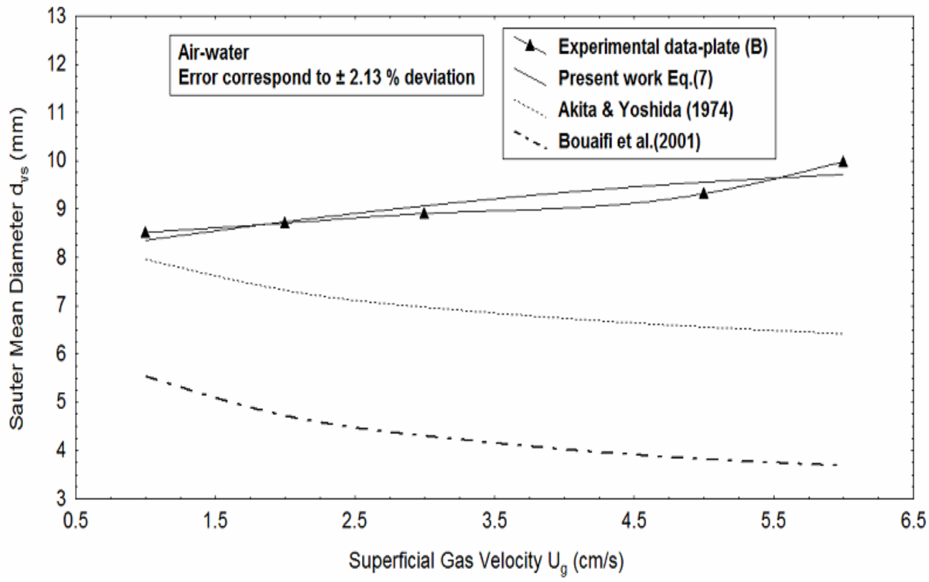


***Fig.23: Comparison of the exp.data with others authors work.***

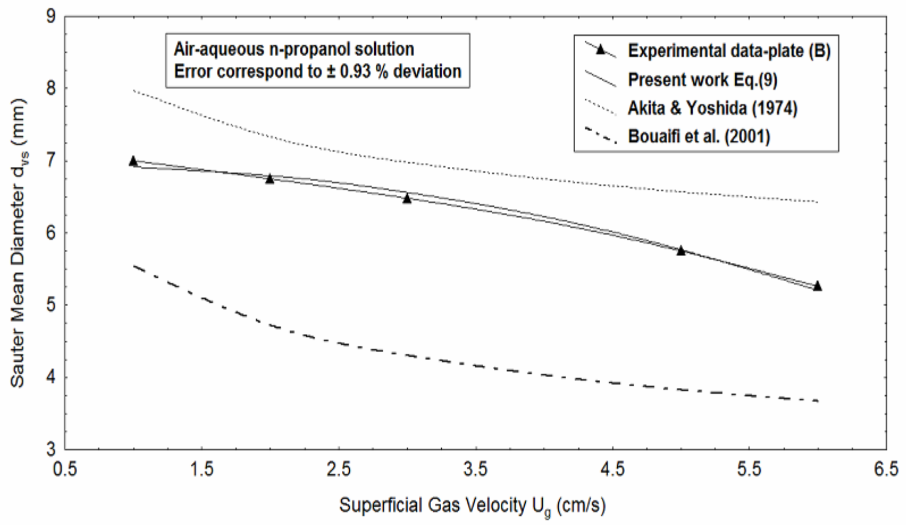


***Fig.24: Comparison of the exp.data with others authors work.***