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Scale Effects on the Hydrodynamics of Bubble Column

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Abstract

The main object of this study is to investigate the influence of the column geometric and operating variables (i.e., column diameter, superficial gas velocity and liquid viscosity) on the hydrodynamic parameter (i.e. , gas holdup, bubble dynamics and liquid phase axial dispersion coefficient). The experimental data obtained showed that the gas holdup increases linearly with superficial gas velocity at both homogeneous and heterogeneous regimes but the rate of increasing is slower at the heterogeneous one. The bubble rise velocity was found to decrease with increasing superficial gas velocity until a transition point was reached and after that the relationship was linearly increasing. It was observed that with an increase in liquid phase viscosity and increase in column diameters, a decrease in gas holdup and an increase in bubble size were obtained. It was observed that increasing axial position led to an increase in bubble diameter and a decrease in bubble rise velocity. Axial dispersion coefficient which is measured by tracer response technique was found to increase with gas superficial velocity, increases with column diameter, increases with axial position and decreases with liquid viscosity. This work also presents a theoretical analysis that is used to calculate the axial dispersion coefficient. The measured axial dispersion coefficient was generally consistent with the predictions of the well established correlations from the literature. The validity of the model was settled by comparing its predication with the objective function of the well-Known empirical correlation formulated by (Hikita and Kikukawa , 1974) .The comparison shows that the present model is statistically significant at a 95% confidence level by using goodness – of – fit test .

Also a statstical analysis was performed to get a general correlation for the gas holdup (ε_g) as a function of the parameters studied:

$$e_g = 0.15325 \; Fr^{0.29617} \; Ga^{0.09223} \; Bo^{-0.0424}$$

Where the correlation coefficient (R) was equal to (0.957) and the absolute error (3.5%).

Keywords: Scale effects, Bubble column, Hydrodynamics.

تاثير تغير قطر العمود على الخواص الهايدروديناميكيه لعمود فقاعي

الخلاصة

الدراسة الحالية تتضمن التحري عن تاثير الظروف التشغيلية والابعاد الهندسية للاعمدة (قطر العمود , السرعة السطحية للغاز وتاثير لزوجة السائل) على الخواص الهيدروديناميكية (الغاز المحتبس , ديناميكية الفقاعه ومعامل التشتت الطولي للسائل) .

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تم اجراء العمل التجريبي في ثلاثة اعمدة مختلفة الاقطار (7.5 , 15 و 30) سم وبمدى سرعة غاز سطحية يتراوح بين (1 – 10) سم/ ثا يغطي كلتا انظمة التدفق المتجانسة والاضطرابيه . ارتفاع السائل كان 100 سم عن الموزع في كل التجارب ولكل الاعمدة .
المحتوى الحجمي للغاز تم قياسه بمعدل كلي اما سلوكية الفقاعة (قطر الفقاعة وسرعة ارتفاعها) والمعاملات الطولية لتشتت السائل فقد قيست بثلاثة مواقع محورية (30 , 60 و 90) سم عن موزع الغاز . استخدمت سوائل متنوعة لتغطي مدى واسع من قيم اللزوجة وهي : الماء المقطر ,الكليسرين عند التراكيز 20% , 50% و 65% لتمثيل سلوك السوائل المعززة لاندماج الفقاعات .
من البينات التجريبية وجد بأن :

- الغاز المحتجز يزداد بزيادة سرعة الغاز السطحية وبمعدل زيادة في النظام الاضطرابي يقل عن معدل زيادتة في النظام الطباقي كما ان الغاز المحتجز اظهر نقصان بزيادة قطر العمود .
- قطر الفقاعة وسرعة ارتفاعها زادا بزيادة قطر العمود وقد اختلفت سلوكية قطر الفقاعة وسرعة ارتفاعها في النظام الطباقي عنها في النظام الاضطرابي , حيث في الاول كانا يقلان بزيادة سرعة الغاز السطحية اما علاقتهما بالنظام الاضطرابي فقد كانت طردية مع سرعة الغاز السطحية .

تضمنت الدراسة الحالية اشتقاق موديل رياضي لغرض التنبؤ بقيم معامل التشتت الطولي للسائل وتم مقارنة نتائج الموديل باستخدام طريقة جودة الموافقةGoodnes- of fit test مع احدى العلاقات التجريبية المستلة من الادبيات ((Hikita and Kikukawa (1974) ووجد ان نتائج الموديل تقترب بنسبة لا تقل عن 95% من نتائج العلاقات التجريبية . كما و تم اجراء التحليل الاحصائي للوصول الى علاقة تجريبية عامة للمحتوى الحجمي للغاز كدالة للمتغيرات المدروسة :

$$e_g = 0.15325 \ Fr^{0.29617} \ Ga^{0.09223} \ Bo^{-0.0424}$$

هذه العلاقة التجريبية اعطت معامل ارتباط (0.957) وخطأ مطلق متوسط مقداره (3.5%) .

- تاثير لزوجة السائل كان واضحا في تقليل مقدار الغاز المحتبس وزيادة سرعة الفقاعة وحجمها .
- زيادة الارتفاع المحوري عن موزع الغاز كان يؤثر ايجابيا على زيادة الغاز المحتبس وسلبيا على سرعة الفقاعة .
- المعامل الطولي لتشتت السائل كان يتناسب طرديا مع كل من (سرعة الغاز السطحية والارتفاع المحوري) وعكسيا مع زيادة لزوجة السائل .

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الكلمات المرشدة: تأثير تغير قطر العمود, العمود, الخواص الهيدروديناميكية

Introduction

Bubble columns are intensively utilized as mltiphase contactors and reactors in chemical, petrochemical biochemical and metallurgical industries (Kantarci et al, 2005). In all these processes gas holdup and bubble size are important design parameters, since they define the gas-liquid interfacial area available for mass transfer (Mouza et al, 2005). Thus, it is important to study the effect of geometric variables, column internals design, operating conditions, superficial gas velocity on gas holdup and bubble size distribution and hence their effect on mass transfer coefficient. The main advantages in using bubble columns compared to other multi phase contactors (stirred vessels, packed towers, trickle bed reactors) as summarized by (Shah et al., 1982; Deckwer and Schumpe, 1993): Less maintenance is necessary due to absence of moving parts. Higher values of effective in interfacial areas, heat transfer coefficients and overall mass transfer coefficients can be obtained, Solids can be handled without any erosion or plugging problems. Less floor space is occupied and bubble column reactors are less costly. Slow reactions can be carried out due to high liquid residence time. Reasonable interphase mass transfer rate Considerable backmixing in the liquid phase (continuous) and the gas phase (dispersed), high pressure drop and bubble coalescence can be isadvantageous, Most studies report that the basic factors effecting gas holdup are superficial gas velocity, column dimensions, operating temperature and pressure, gas distributor design and liquid phase properties (Kanterci et al, 2000). For both bubble columns and slurry bubble columns, gas holdup has been found to increase with increasing superficial gas velocity (Prakash and Margarities, 2001; Li and Parkash, 2000; Pino et al, 1992), although the systems investigated in these studies are quite different from each other.The effect of column diameter and height on hydrodynamics is also widely investigated in literature. (Ueyama and Miyauchi, 1979), conclude that scale-up has very little effect on the gas holdup. Their analysis yields that the gas holdup in the churn-turbulent flow slightly decreases with an increase in the column diameter. (Luo et al, 1999), report that the influence of the column height is insignificant if the height is above 1-3 m and the ratio of the column height to the diameter (aspect ratio) is larger than 5. (Krishna et al, 2001) found that the total gas holdup decreases with increasing column diameter. The reason for this scale dependency is because the strength of the liquid circulations increases with increasing scale. Such circulations accelerate the bubbles traveling upwards in the central core.The liquid phase property has an impact on bubble formation and/or coalescing tendencies and hence is an important factor affecting gas holdup (Kantarci et al, 2005). The effect of surface tension on gas hold up can be qualitatively described in that a lower surface tension gives a lower bubble

rise velocity and therefore a higher holdup (Hikita et al, 1980). Gas hold up is very dependent on the viscosity of the medium, An increase in liquid viscosity results in large bubbles
and thus higher bubble rising velocities and lower gas holdup (Akita and Yoshida, 1973, Ruzicka et al, 2003).

The influence of the sparger type is rather complex, mainly depending on fluid characteristics. The diameter of the bubbles in the column and thus the holdup is determined by the coalescence behavior of the liquid and the initial bubble size at sparger (Schugerl et al,1977). (Schumpe and Grund, 1986), worked with perforated plate and ring type gas sparger. They conclude that with ring type distributor, the total holdup was smaller.

In many industrial multiphase (gas-solid, liquid-liquid and gas-liquid-solid) contactors, a lager degree of circulation of both discrete and continuous phases occurs. This circulation causes a good degree of mixing and enhances heat and mass transfer between fluid and walls (Joshi et al. 1980, Reilly et al. 1994, and Gupta et al. 2001).The circulation of the liquid in the column is one of the major observations, which should be taken into account when calculating mass or heat transfer coefficients. This phenomenon is related to bubble size, bubble dynamic and holdup. Therefore, these factors are very important in determining the efficiency of contact in bubble columns (Whalley and Davidson 1974, Viswanathan and Rao, 1983).The main driving force, which induces the internal circulating flow of liquid, is the difference in the apparent density of gas-liquid mixtures between the central and peripheral regions of the column.

The effect of gas flow rates on bubble size and bubble rise velocity was investigated by (Akita and Yoshida, 1974; Prakash, 2001) and a decrease in bubble size with increasing gas flow rate was reported. (Buwa and Randa, 2002) have studied the effect of gas velocity and coalescence suppressing additives on bubble size distribution in a bubble column using photographic method. The others observed that when they added butanol as coalescence inhibitor into water, fine bubbles are generated even at higher gas velocity which indicates effective suppression of coalescence.

The magnitude of the wall effects depends on the ratio of the bubble diameter to the column diameter, db/DC. When the column diameter is large enough, the bubbles are free from wall effects. (Akita and Yoshida, 1974), investigated the bubble size distribution and gas holdup in various liquids and they found that the average bubble size for a given superficial gas velocity decreases with increasing column diameter. (Li and Prakash, 2001), reported that the diameter of the column has an effect on the rise velocity of large bubbles only. They discovered that as the column diameter increases, the rise velocity of large bubbles also increases. (Koide et al., 1979), measured average bubble sizes in two columns with different diameters and a higher average bubble size were obtained in the larger diameter column. (Krishna and van Baten, 2001), studied experimentally the hydrodynamics of bubble columns in 0.051 and 0.1 m diameter bubble columns with air-water system and found that the bubble rises faster in the wider column. The reason for this is the restraining effect of the walls

When bubble rise is measured, the effect of the operating conditions and physical properties of the gas-liquid systems become important and hence the evaluation of Ub for either small or large bubbles will become a function of all variables (Behkish, 2004). The average bubble size was reported to decrease with decreasing surface tension of liquid and increase with increasing liquid viscosity (Akita and Yoshida, 1974; Prakash, 1997). These results were also reported by Kulkarni and Joshi, 2005. Axial mixing, axial dispersion, and longitudinal dispersion are all terms used to describe a phenomenon that causes a distribution of residence time for a reaction mixture. Mixing in the axial

direction is produced by rising gas bubbles that carry elements of circulating fluid in bubble wakes, because bubbles rise faster than the liquid, a certain amount of liquid is carried forward faster than the bulk flow of the liquid. In a bubble column the dispersion has the effect of reducing conversion in reactors, and also influence of reaction selectivity (Lievenspiel, 1992). The experimental data of (Zhou et al, 1995) have shown that in a fine diffuser air-water bubble column and as Ug increases Dax,L increases. This result is also suggested by (Kastanek et al 1993, Deckwer 1992). It is usually assumed that the dispersion coefficient does not depend on the column height. However, studies of (Schugerl, 1967 and Deckwer et al,1973) show that dispersion coefficient may differ along the column height, decreasing from top to bottom All correlations anticipate a significant increase in Dax;L with increasing column diameter Dc, often correlated as a power-law dependence Dnc. The value of the power law index n varies between 1 and 1.5 (Krishna, 2000). The effect of gas and liquid properties on gas phase backmixing has been investigated in bubble columns (Kantak and Kelkar, 1995). Data were obtained in two 3 m tall bubble columns (of diameters 0.15 and 0.25) and by varying superficial gas velocity. Results indicate that an increase in liquid viscosity and decrease in the liquid surface tension leads to a decrease in the liquid phase backmixing. The degree of axial dispersion is also affected by vessel internals and surface-active agents that delay the coalescence.

The aim of this paper is to investigate the influence of the column geometric and operating variables (i.e., superficial gas velocity, column diameter and liquid phase properties) on the hydrodynamics parameters (i.e., gas holdup, bubble dynamics and liquid phase dispersion coefficient).

It is also to develop a model that simulates the behavior of the liquid dispersion coefficient (Dax,L) with different geometric and operating variables of the bubble column.

Experimental Apparatus and Procedure

1. Experimental Procedure

A schematic diagram of the experimental apparatus used in this work is shown in the figure (1).The heart of the apparatus is three columns of different diameters (7.5, 15, and 30) cm. Detailed description of the experimental setup can be found in (Farah, 2008).

2. Experimental procedures

In all the experiments the height of liquid in the column was kept constant at 100 cm. The physical properties and operating conditions are listed in tables (1) and (2). Detailed description of the procedure followed during the hydrodynamics experiments can be found in (Farah, 2008).A wide range of superficial feed gas velocity as well as concentration of the coalescing agent was investigated to study their effects on the hydrodynamics of the bubble column. Tracer experiments with delta function pulse input to the upper part of the column are used to estimate the liquid axial dispersion coefficient.

Theory

1. Average gas holdup

The average gas holdup which represents the fractional of the total gas-liquid system that is occupied by the gas and was measured using equation (1):

$$e_g = \frac{H_d - H_o}{H_d} \qquad \ldots\ldots(1)$$

2. Bubble Dynamics

Bubble populations, their holdup contributions and rise velocities have significant importance on altering the hydrodynamics, as well as heat and mass transfer coefficient in a bubble column. Bubble diameters are estimated high speed digital camera type (OLYMPUS, C-400/ZOOM) using While bubble rise velocity was calculated using the well-known Mendelson equation with scale factor for bubbles smaller than 17mm:

$$V_b^0 = \sqrt{\frac{2s}{r_L d_b} + \frac{g\, d_b}{2}}(SF) \qquad \ldots(2)$$

$$SF = \left[1 - \left(\frac{d_b}{D_C}\right)^2\right]^{\frac{3}{2}} \qquad \ldots(3)$$

3. Center line liquid velocity (VL(0))

The upwardely directed axial component of the liquid velocity at the center of the column VL(0) is considered as a mesure of the strength of the liquid circulation velocity for bubble columns ((Krishna et al., 2000).

Center line liquid velocity is estimated by using the well-known Riquart, (1981) Eq. (4).

$$V_L(0) = 0.21\sqrt{D_C g}\left(\frac{U_g{}^3}{u_L g}\right)^{1/8} \qquad \ldots(4)$$

Krishna et al., 2000) proved experimentally that Riquart correlation works equally well for water and high viscous liquids.

4. Liquid axial dispersion coefficient, Dax,L

For the present work a mathematical model is formulated to predict the radial and axial dispersion coefficients through the bubble column following the subsequent steps:

Set the principal assumption

(Unsteady state operation;The flow mode is co-current upflow ;Physical properties are constant throughout the column;The radial convective motion is neglected in comparing with the axial one).

Set a differential mass balance

A mass balance for the tracer in liquid phase is made over a cylindrical shell of volume (2πrΔrΔh) (Farah, 2008) the following partial differential equation obtained:

$$\frac{\partial C_L}{\partial t}=-V_{r,L}\frac{\partial C_L}{\partial r}+D_{r,L}\frac{\partial^2 C_L}{\partial r^2}-V_{ax,L}\frac{\partial C_L}{\partial h}+$$

$$D_{ax,L}\frac{\partial^2 C_L}{\partial h^2}+\frac{1}{r}D_{r,L}\frac{\partial C_L}{\partial r} \qquad ....(5)$$

The dimensionless form of equation (5) is:

$$\frac{\partial C_T}{\partial q}=\frac{\partial^2 C_T}{\partial y^2}-\frac{V_{ax,L}L}{D_{ax,L}}\frac{\partial C_T}{\partial y}+\frac{1}{x}\frac{\partial C_T}{\partial x}+\frac{\partial^2 C_T}{\partial x^2} \qquad ..... (6)$$

For a batch of liquid in a bubble column, there is no superimposed liquid flow and, hence, Vax,L= 0, the last equation becomes:

$$\frac{\partial C_T}{\partial q}=\frac{\partial^2 C_T}{\partial y^2}+\frac{1}{x}\frac{\partial C_T}{\partial x}+\frac{\partial^2 C_T}{\partial x^2} \qquad ...(7)$$

By using the B.c and Bessel function the solution is:

$$C_T=\sum_{n=1}^{\infty}\frac{J_0(\upsilon_n x)}{J_0^2(\upsilon_n b)}e^{-(\upsilon_n^2 q)}\left(1+2\sum_{m=1}^{\infty}\cos(m p y)\,e^{-(m^2 p^2 q)}\right) \qquad .... (8)$$

Note that when the CT in Eq. (4 - 2) is radially invariant (i.e. Dr,L=∞), υn,β and x become zero and J0 (υnβ) = J0(υnx)=1. In this case Eq. (4 - 2) reduces to:

$$C_T=1+2\sum_{m=1}^{\infty}\cos(m p y)\,e^{-(m^2 p^2 q)} \qquad ..... (9)$$

Results and Discussion

1. Gas Holdup

1.1 Effect of Superficial Gas Velocity and Column Diameter

It is observed in figure (2) a, b & c that, when the superficial gas velocity increased the gas holdup in the bubble column increases too, for water and all Glycerin concentrations. Therefore, the figure shows that the gas holdup is mainly dependent on the superficial gas velocity and liquid concentrations. In the churn-turbulent regime, as the superficial gas velocity increases the overall holdup increases due to the large bubble holdup increase. The contribution of small bubbles to overall holdup is constant and equal to the transition holdup. In bubbly flow, small bubble holdup is not constant but changes significantly as the superficial velocity is changed. While the gas holdup is found to decrease slightly with increasing column diameter, see figure (2) a, b, c & d. This decrease in gas holdup evident in both the homogeneous and heterogeneous flow regimes is due to increased liquid recirculation with increasing column diameter, due to these strong circulations, the bubbles will be accelerated. This acceleration effect causes a reduction in gas holdup with increasing column diameter. This result is in agreement with the observation of many investigators (Mouza et. al., 2005, Krishna and van Baten, 2002Al-Banna, 2005, Krishna et al, 2001).

1.2 Effect of Liquid Viscosity

It can be noted in figures (3) a,b & c that gas hold up decreases with increasing viscosity for the range above (3mPa.s) while gas hold up increases for the range less than (3mPa.s). This results confirms the abnormal behavior of Glycerin solution at viscosity less than (3mPa.s), a phenomenon which has been reported by many investigators of the field (Ruzicka, 2003; Krishna and Van Baten, 2001).

Also, figure (3) shows a strong influence of Glycerin concentration on gas holdup values. Thus, as the concentration of Glycerin solution is increased, the mean gas holdup value decreases in the bubble column, or in other words, it was found that the gas holdup decreases with increasing liquid viscosity. The viscosity range covered by the present work was (1 to 22 mPa.s). Therefore, the decrease in gas holdup values may be attributed to:

1-Increasing of the system viscosity.

2-Formation of large bubbles with fast rising velocity.

On the other hand, there is a tendency towards bubble coalescing behavior as the liquid viscosity is increased; therefore it is expected to obtain lower values of the gas holdup as the Glycerin liquid concentration increases (viscosity increasing). Such a behavior of high viscosity liquids in bubble column is in agreement with most previous investigations (Godbole, 1982, Walter and Blanch, 1983, and Mohammed, 1997, Ruzicka et al;2003, Krishna and van Baten, 2001).

2. Bubble Diameter

2.1 Effect of Superficial Gas Velocity, Column Diameter, and Liquid Viscosity

Figures (4) a,b & c, show the effect of superficial gas velocity, Column Diameter, and Liquid Viscosity on bubble size for water and all Glycerin concentration. From these figures, one can notice that the bubble size increases with increasing superficial gas velocity, Column Diameter, and Liquid Viscosity. It indicates that for all Glycerin concentrations, and as the air flow rate starts to increase, the density of the small bubbles generated is increased gradually, with slow rate of collisions and coalescence resulting in small increase in bubble diameter. As transition point reached, the coalescence rate increased with higher rate of large bubble production, this production rate continues over the domain of the heterogeneous regime. These results are in agreement with those of (Mouza et al, 2005; Marrucci, 1967; Onno Kramer, 2000,; Koide et al, 1979).

2.1 Effect of Axial Position

Figures (5) a,b & c, show the effect of axial position of liquid in the column on bubble diameter (d_b). It indicates that, the bubble diameter decreases with increasing height of liquid. This can be attributed to that, when the bubble rises up through the liquid, due to the collisions with neighboring bubbles, phenomenon of brakeup occur which results bubbles with small diameter, this phenomenon increases as the superficial velocity of the gas increased. These results are in agreement with (Lockett and Kirkportick, 1975; Kolbel et al., 1972 and Krishna 2000).

3. Bubble Rise Velocity

3.1 Effect of Superficial Gas velocity, Column Diameter and Liquid Viscosity

Figures (6) a,b & c, show the effect of superficial gas velocity on bubble rise velocity at different Glycerin concentrations and axial positions for each column diameter. It can be seen that the small bubble rise velocity decreases gradually as the gas velocity is increased, then passes a minimum and finally converges on a more constant value leading to continuously increases in large bubble rise velocity. It also indicate that as the liquid concentrations (i.e.; liquid viscosity) increases the rise velocity of small bubbles at the bubbly flow region decreases due to the drag effect of viscous liquid while at the

heterogeneous region the effect of the viscosity is to enhance coalescence and the formation of large bubbles resulting in higher bubble rise velocity.
This is in agreement with the findings of (Mouza et al; 2005, Krishna 2000).

3.2 Effect of Axial Position

Figure (7) a,b & c, show the effect of axial position on bubble rise velocity for each column diameter, from figure one can notice that the higher bubble rise velocity is obtained near the gas sparger and decreased gradually as the liquid
level increased. This is can be attributed that Near the sparger, large bubbles are formed due the effect of higher liquid viscosity, so higher bubble rise velocity is monitored near the sparger, and as the bubble rises up it undergoes a breakup phenomena, smaller bubbles formed and consequently, the bubble rise velocity decreases. This is in agreement with finding of (Shumpe and Grund, 1986; Camarasa, et al., 1999; Li and Parakash, 2000; Krishna, 2000; Ruzicka, 2003).

3.3 Effect of Bubble Diameter

Figures (8) a,b & c, show the effect of bubble diameter on bubble rise velocity at different Glycerin concentrations and axial position for each column diameter. It can be seen that as the bubble diameter starts to increase because of gradual increasing of gas flow rate, the rise velocity of the bubbles decreases due to the increasing drag forces between small bubbles formed indicating a region of bubbly regime. A minimum value of bubble rise velocity is reached after which it begins to increase due to the formation of large bubbles indicating the onset of the heterogeneous regime. This minimum value is gradually decreased as the column diameter increases and also as the liquid concentration increases.This is in agreement with (Miyahara et al, 1983; Schumpe and Grund, 1986).

4. Center Line Velocity (VL(0))

4.1 Effect of Superficial Gas velocity, Column Diameter and Liquid Viscosity

Figures (9) a, b & c, show the effect of superficial gas velocity, Column Diameter, and Liquid Viscosity on center line velocity, figure (9) indicates that, the center line liquid velocity increases with increasing superficial gas velocity for all other geometric and operating variables. This can be attributed to the increasing of generating rate of bubbles which are affected by two drag forces, first the interfacial drag between the bubbles and second the column wall effect which is minimum at the center line.
Consequently there is a proportional relationship between superficial gas velocity and center line liquid velocity while it is decreases with increasing liquid viscosity due to gradual increasing of viscous forces which retard the bubble motion through the column and due to increasing in bubble diameter. This is in agreement with the findings of (Riquart,1981; Joshi,1980; Wilkinson et al,1992; Krishna, 2000).

5. Axial Liquid Dispersion in Bubble Column (Dax,L)

5.1 Effect of Superficial Gas Velocity, Column Diameter and Liquid Viscosity

Figure (10) a,b & c, show effect of superficial gas velocity, Column Diameter, and Liquid Viscosity on axial dispersion coefficient (Dax,L), From these figures one can notice, that the increment in the axial dispersion coefficient (Dax,L) is slightly with increasing superficial gas velocity in the homogenous flow regime for different Glycerin concentrations and then the rate of increasing becomes faster, this is a mark for the beginning of the churn-turbulent flow regime where the coalescence of bubbles takes place to produce the first fast rising 'large' bubble. The explanation for this increase in axial liquid phase dispersion coefficient in the churn-turbulent flow regime is that, in the churn-turbulent flow regime the gas – liquid flow has a higher gas bubble concentration than that at lower superficial gas velocity. Since the liquid envelopes the gas bubbles, it will be entrained and dragged upwards and also part of gas – liquid dispersion will flow downwards and consequently cause an increase in the liquid phase dispersion coefficient (Deckwer, 1992), in addition, the larger bubbles in the churn-turbulent flow regime undergo more frequent breakup and coalescence and this too increased the axial dispersion coefficient relative to the situation in the homogenous flow regime. This result is in agreement with that of (Camacho et al., 2004). Also, It can be seen that, Dax,L increase in the 30 cm column diameter is more clearly than that in the (15 and 7.5) cm column diameters. This trend of (Dax,L) is due to the increase in liquid recirculation with increasing column diameter resulting in an increase in the back mixing. This result is in agreement with that of (Krishna et al., 2000).Another explanation for this increase in (Dax,L) is that the decrease in column diameter causes an increase in the gas hold-up which reduces the liquid circulation velocity leading to decrease in (Dax,L). This result is in agreement with the findings of (Pandit and Joshi, 1982). While one can notice, that as the liquid viscosity increases the axial liquid dispersion coefficient (Dax,L) decreases because of gradual increase in bubble diameter due to the formation of large bubbles by coalescence tendency leading to decrease in (Dax,L). This is in agreement with the results of (Hikita and Kikukawa, 1974; Riquarts, 1981; Bernemann, 1989; Kantak and kelkar, 1995).

5.2 Effect of Axial Position

Figure (11) a, b & c, show the effect of the axial position (Z) from the sparger on the axial liquid dispersion coefficient (Dax,L). It can be seen that, the axial liquid dispersion coefficient (Dax,L) increases with increase in the axial position (Z). This increase in (Dax,L) is due to a decrease in bubble diameter which leads to increase in the liquid circulation velocity, then increase in the axial liquid dispersion coefficient (Dax,L). These results are in agreement with those of (Pandit and Joshi, 1982 and Krishna et al.,2000).

6. Empirical Correlations (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.
- 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:

$$e_g = d_\circ Fr^{d_1}\, Ga^{d_2}\, Bo^{d_3} \qquad (10)$$

The constants (d_0) and the powers (d_1, d2 and d_3) were estimated by using the simplex method with the aid of a computer program. The values of the constants and the powers of the above equation were illustrated in table (3) above. Then by substituting the values in the above table in equation (5-5), the recommended correlation will be:

$$e_g = 0.15325\, Fr^{0.29617}\, Ga^{0.09223}\, Bo^{-0.0424} \quad ..... (11)$$

This correlation gives:
Correlation coefficient (R) = 0.95783
Error = 0.03539

7. Validity of the Present Developed Model

To settle the validity of a model, it must be compared with another model which was proven to be reliable. The present model is compared with the correlation of Hikita and Kikukawa, 1974, equation (12) using different experimental operating conditions. Comparison shows that the mathematical model is statistically significant at a 95 % confidence level.

$$D_{axL} = \left(0.15 + 0.69 Ug^{0.77}\right) D_T^{1.25} \left(\frac{10^{-3}}{m_L}\right)^{0.12} \qquad (12)$$

Figures (12) a, & b show the experimental results of liquid axial dispersion coefficient (Dax,L) predicted by above equation and presented model for both Air-water and Air-65% glycerin. These Figures are used as bases of calculation for the model validity.

Conclusions

In this work, the gas hold-up, the bubble characteristics and axial liquid dispersion are investigated for coalescing systems (air-water and air-aqueous glycerin solutions). This study has led to the following conclusions:

- The gas holdup increases with increasing superficial gas velocity.
- The gas holdup and its critical value (εtrans) decrease with increasing liquid viscosity for μL=3-22 mPa.s. On the other hand the measurements also indicate that there is a narrow viscosity range μL < 3 mPa.s where the gas holdup increases with increasing liquid viscosity.
- Increasing column diameter, D_C, leads to decrease in the gas holdup and increase in the bubble size.
- The bubble size increases with increasing liquid viscosity and slightly increases with increasing superficial gas velocity.
- The bubble rise velocity was found to decrease as the superficial gas velocity increases then passes a minimum and finally converges at a more constant value. The bubble rises faster in the wider column.
- It has been observed that, the axial liquid dispersion coefficient (Dax,L) increases with an increase in both superficial gas velocity and column diameter.

- It has been observed that, the axial liquid dispersion coefficient (Dax,L) increases when the bubbles rise up through the liquid (i.e., increase height of axial probe location).
- The axial dispersion coefficient values are estimated using the complete dispersion model is generally consistent with the predictions of the existing correlations.

All the experiments were performed with no liquid throughput. The physical properties for the liquids used are listed in table (1).

Nomenclature

CL Tracer concentration inside the column (kg/m3)
Dax,L Axial liquid phase dispersion coefficient (m2/s)
Dr,L Radial liquid phase dispersion coefficient (m2/s)
Dc Column diameter (m)
db Bubble diameter (m)
G Acceleration due to gravity (m/s2)

H_d Final liquid height with gas (m)
$H_\circ$ Initial liquid height without gas (m)
R Radial position inside the column (m)
Ug Superficial gas velocity (m/s)
Vax,L The axial velocity of the liquid (m/s)
Vr,L The radial velocity in the liquid (m/s)
Vb° Single bubble rise velocity (m/s)
VL(0) Center line liquid circulation velocity (m/s)

Z Axial position (m)

Dimensionless Groups

Bo Bond number, $gD_c^2 r_l / s_l$
Fr Froude number, $U_g / (gD_c)^{1/2}$
Ga Galilei number, gD_c^3 / u_l^2

Greek Symbols

εg Gas holdup (dimensionless)
εtrans Gas holdup at transition regime (dimensionless)
μl Liquid viscosity (mPa.s)
ρg Gas density (kg/m3)
σl Liquid surface tension (mN/m)
u_l Kinematics viscosity (m2/s)
Θ Dimensionless time ($D_{ax,L}.t/L^2$)

Acknowledgements

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Table (1) Physical Properties of the Liquids at 25 °C (Perry, 1997)

Liquid Phase	Concentration (wt %)	Density (kg/m^3)	Viscosity (mPa.s)	Surface tension (mN/m)
Distilled Water	0	998	1	72
Glycerin	20	1050	2	68.7
Glycerin	50	1126	8.2	68
Glycerin	65	1162.5	22	65.8

Table (2) Column dimensions and selected operating conditions

Ug (Air), cm/s	1-10
Pressure = atm	1
Liquid mode	Batch
Temperature, °C	25
Initial Liquid Height, H_o cm	100
Volume of tracer for each run, ml	960 (for 30 cm diameter column), 240 (for 15 cm diameter column) and 60 (for 7.5 cm diameter column) of (6 wt %) saturated NaCl solution was prepared.

Table (3) Estimated values of the constant and the powers of equation (5-5)

$d_{\circ}$	0.15325
d_1	0.29617
d_2	0.09223
d_3	-0.0424

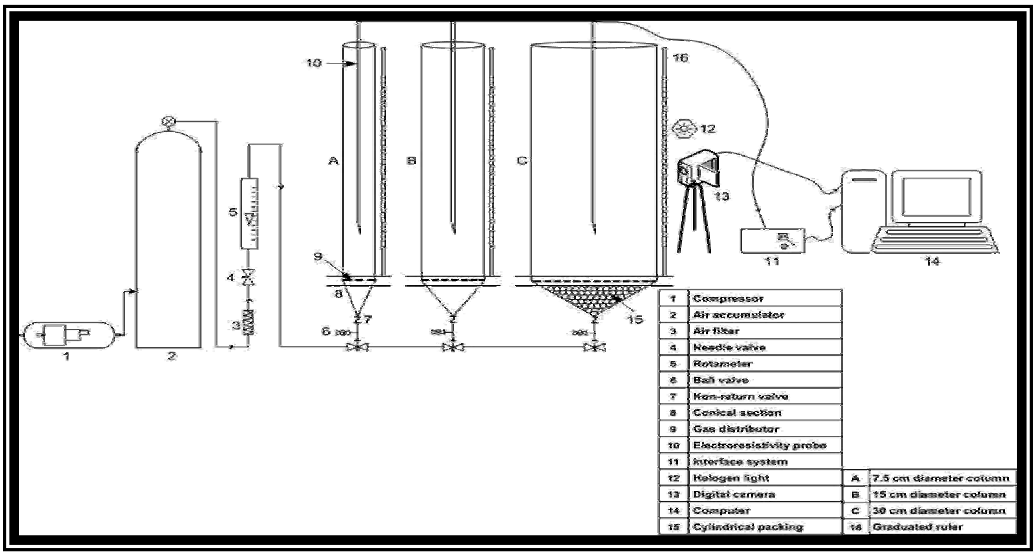
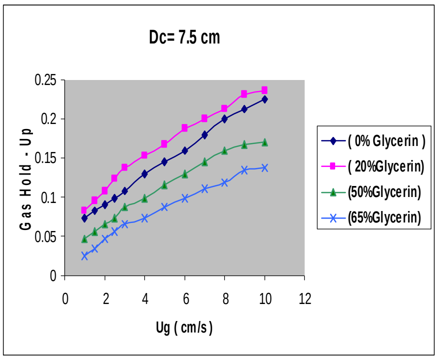


Figure (1) Schematic diagram of experimental setup



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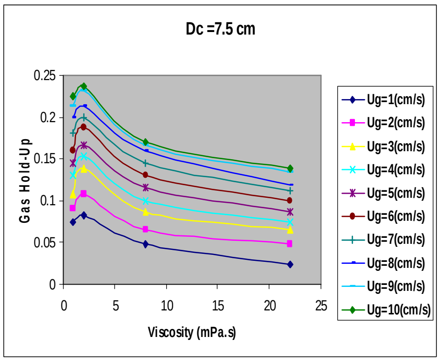

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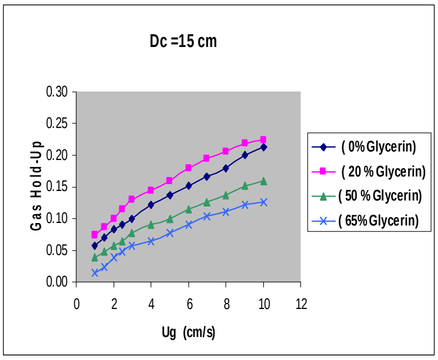

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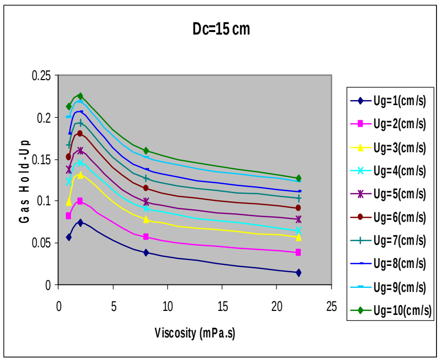

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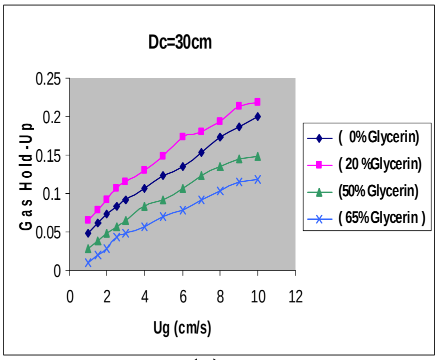

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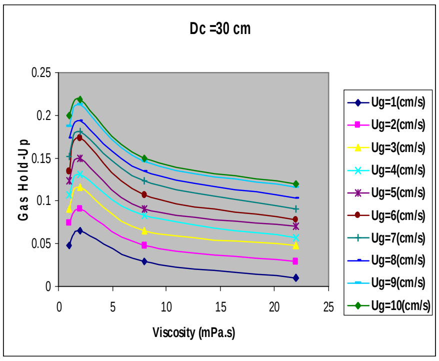

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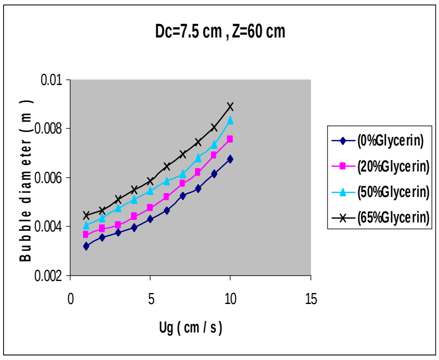
Fig (2) Effect of superficial gas velocity on gas holdup

Fig (3) Effect of liquid viscosity on gas holdup



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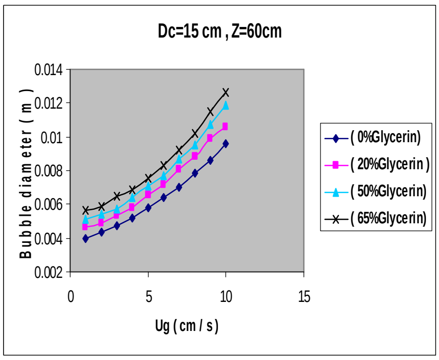

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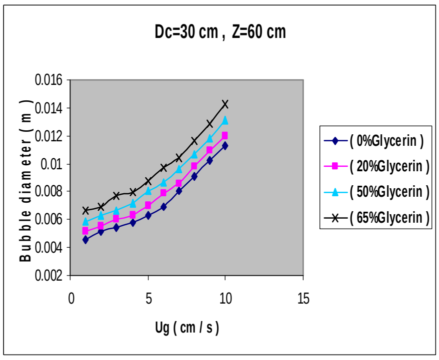

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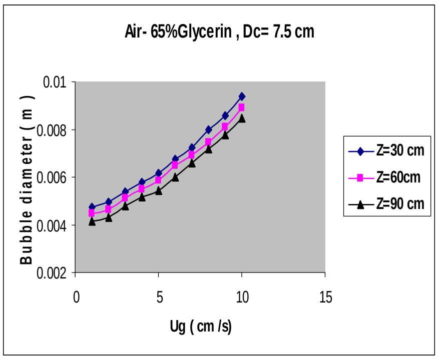
Fig (4) Effect of superficial gas velocity, column diameter & liquid viscosity on bubble diameter



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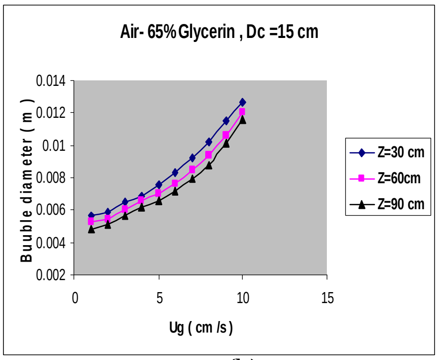

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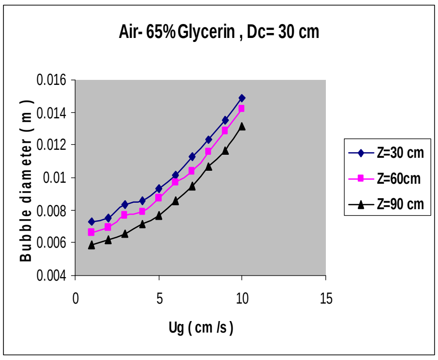

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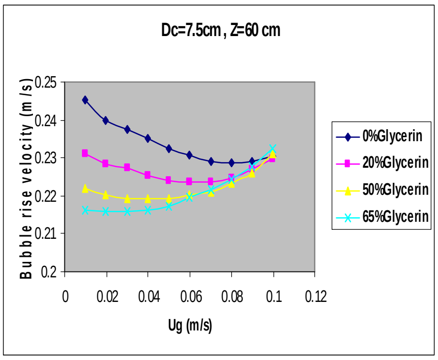
Fig (5) Effect of axial position on bubble diameter



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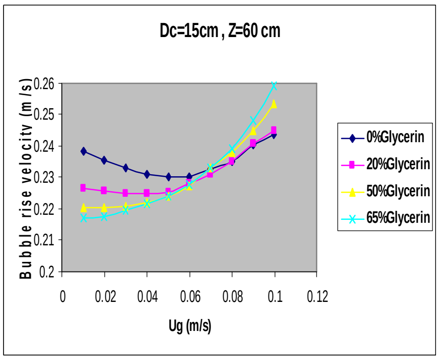

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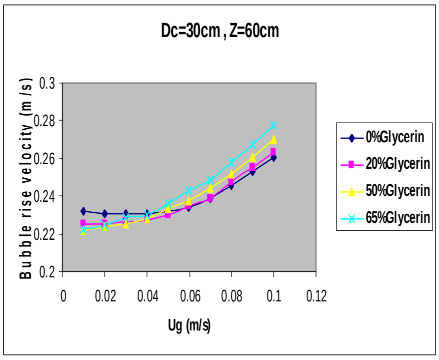

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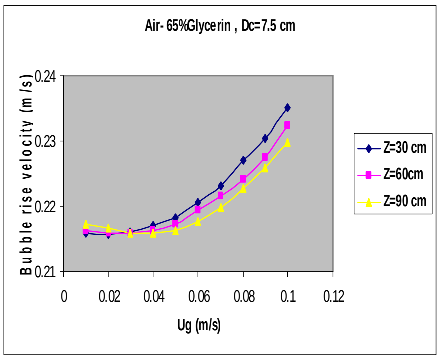
Fig (6) Effect of superficial gas velocity, column diameter & liquid viscosity on bubble rise velocity



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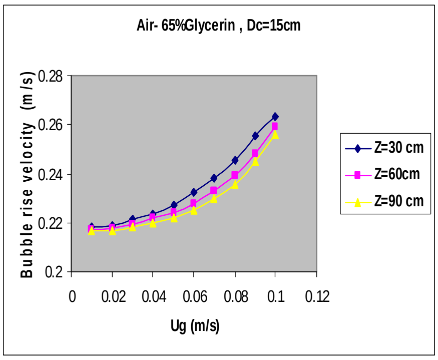

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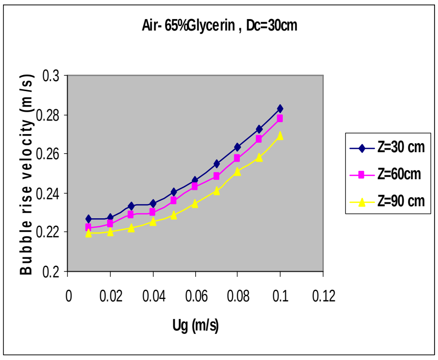

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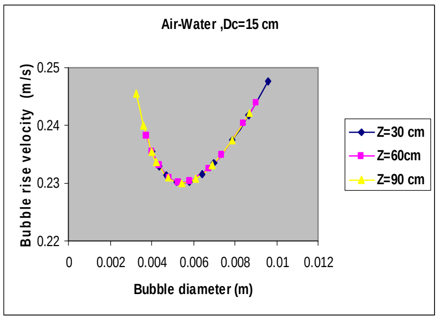
Fig (7) Effect of axial position on bubble rise velocity



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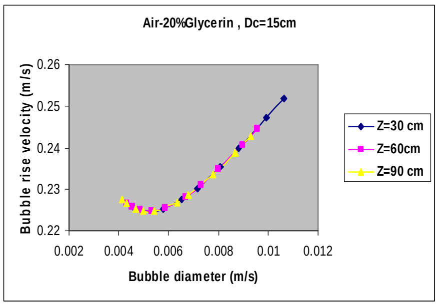

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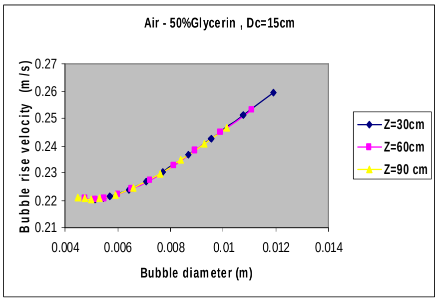

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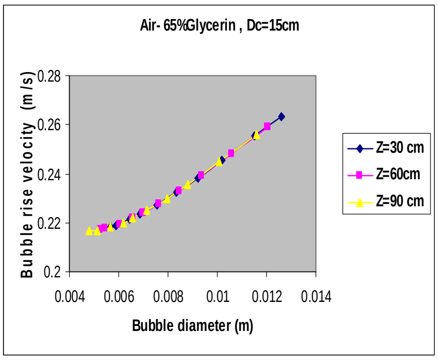
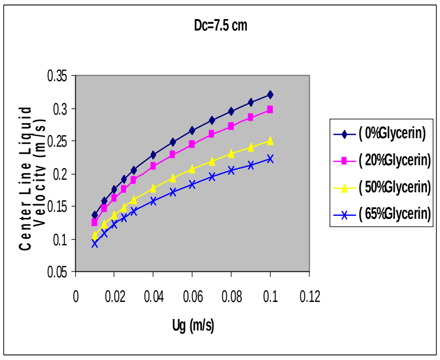


(d)

Fig(8) Effect of bubble diameter on bubble rise velocity



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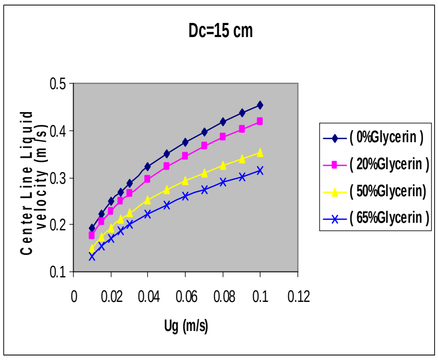

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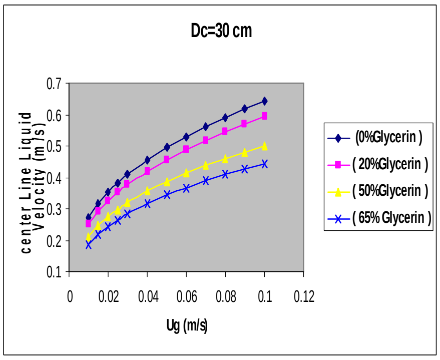

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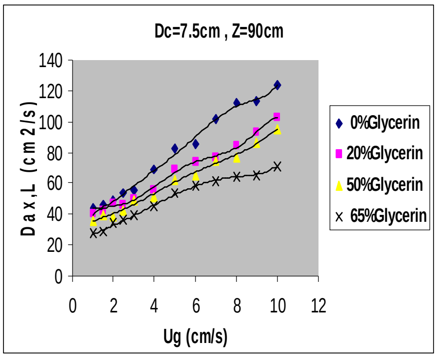
Fig (9) Effect of superficial gas velocity & liquid viscosity on $V_L(0)$



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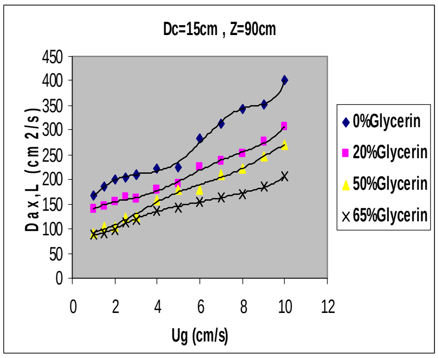

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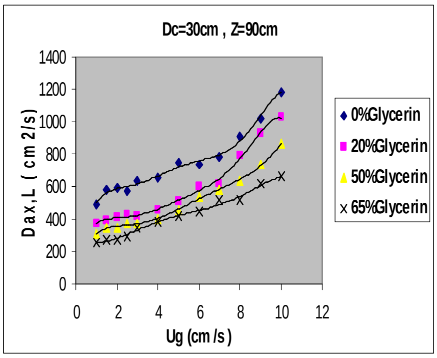

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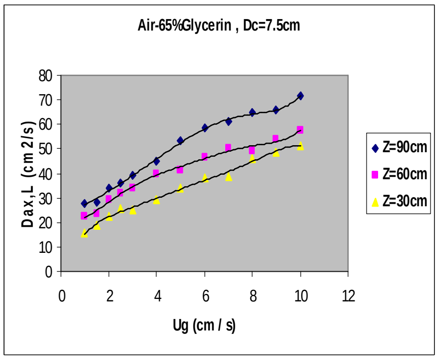
Fig (10) Effect of superficial gas velocity, column diameter and liquid viscosity on (DaxL)



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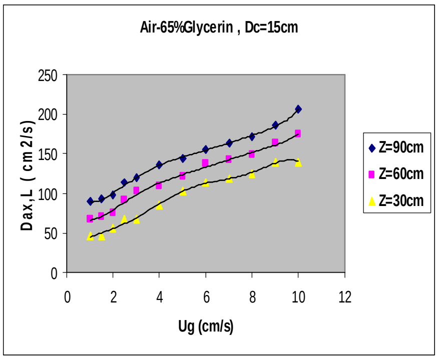

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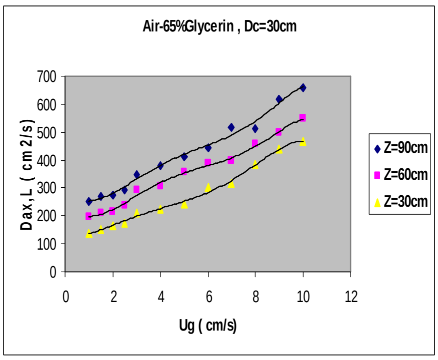

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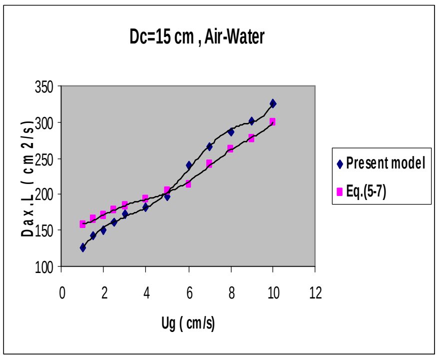
Fig(11) Effect of axial position on (D_{axL})



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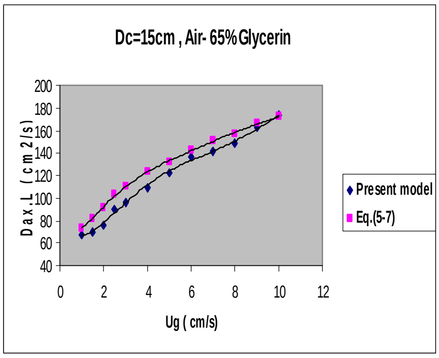

(b)

Fig (12) Comparison between the present model and Hikita and Kikuawa, 1974 correlation