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Fluid Dynamic in Bubble Columns with Heat Exchanger Internals

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ABSTRACT

The effects of vertical cooling internals on the gas hydrodynamics was studied in gas-liquid system (bubble columns) for column diameters, 15 and 30 cm in the absence and presence of internals (the % occluded area by internals 5, 10, and 20%). The superficial gas velocity was varied in the range 0.8-30 and 0.8-7.6 cm/s for 15 and 30 cm column diameters respectively. The effect of internals on the bubble dynamics in columns was assessed using the electroresistivity probe technique. The overall gas holdup is measured experimentally by bed expansion technique. The experimental results show that the increased in percentage coverage of cross sectional area by internals causes an increase in the overall gas holdup values, gas holdup radial profiles, bubble rise velocity, bubble frequency and reduce average bubble diameters. Correlations have been used for the estimation of the gas holdup in gas-liquid system bubble column. The overall gas holdup can be easily predicted from $\varepsilon_g = 0.00286\, U_g^{1.08} + 0.142\,\%\mathrm{int}^{-0.086} - 0.165\, r/R^{1.516}$.Comparison of the model predictions with the experimental data shows agreement with error 0.017 which ensure the reliability and confidentiality of the adopted the correlations to be used in further designation and scale-up purposes.

Keywords: Bubble columns, Overall gas holdup, Gas holdup, Internals

ديناميكية السوائل في الاعمدة الفقاعة ذات اعمدة التبادل الحراري الداخلية

الخلاصة

تمت دراسة تاثير الاعمدة الدخلية المستخدمة في عملية التبريد في الاعمدة الفقاعية على هيدروديناميكية الغاز في منظومة غاز – سائل باعمدة فقاعية ذات اقطار 15 و 30 سم بغياب ووجود الاعمدة الداخلية (بتغطية المقطع العرضي بنسب مئوية 5 ، 10 و 20% من المساحة الكلية). وقد اختلفت سرعة الغاز السطحية بين 0.8-30 و 0.8-7.6 سم/ثا لاعمدة فقاعة ذات اقطار 15 و 30 سم على التوالي. تم تقييم وقياس تاثير االاعمدة الداخلية على ديناميكية الفقاعة باستخدام تقنية المجس. تم قياس محتوى الغاز الكلي تجريبيا بتقنية تمدد الحشوة والسائل. اظهرت النتائج ان الزيادة في نسبة التغطية من مساحة المقطع العرضي بواسطة الاعمدة الداخلية يسبب زيادة في محتوى الغاز الكلي وزيادة في محتوى الغاز الشعاعي وسرعة انطلاق الفقاعة وتقليل متوسط قطر الفقاعة. يمكن التنبؤ بمحتوى الغاز الكلي من خلال المعادلة $\varepsilon_g = 0.00286\, U_g^{1.08} + 0.142\,\%\mathrm{int}^{-0.086} - 0.165\, r/R^{1.516}$
وقد استخدمت إرتباطات لتقدير محتوى الغاز في نظام غاز سائل للعمود الفقاعي. تمت مقارنة تنبوءات النموذج

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مـع البيانـات التجريبيـة واظهـرت تطابقهـا مـع نسـبة خطـا تصـل الـى 0.01 ممـا يعطـي الاعتماديـة والموثوقيـة لاستخدام الموديل في الحسابات التصميمية للاعمدة الفقاعية.

Notation

A_{tot} Total cross sectional area of the column, m^2
D Diameter of column, m
di Internal's diameter, m
do Orifice diameter, m
D_T Column diameter, m
H_0 Total liquid height in the column, m
H_d Dispersion height, m
L Height of column, m
r/R dimensionless radius coordinates
Ug Superficial gas velocity, m/s
$U_{O.A.}$ Superficial gas velocity for open area, m/s
Xv Covered volume fraction
εg Fractional gas hold-up
(-)
τ_1 Width of the pulse from the upper, s
τ_2 Transition time of the air bubble between the two tips, s
τ_3 period, s

INTRODUCTION

Bubble columns and slurry bubble columns are considered reactors of choice for a wide range of applications in the chemical, biochemical, and petrochemical industries. Many industrial applications for which bubble column reactors are preferred, such as Fischer Tropsch synthesis FT and liquid phase methanol synthesis, require high superficial gas velocities, high solids (catalyst) loading, high temperature, high pressure, and large reactor diameters and heights (Krishna and Ellenberger, 1996)[1]. To remove the heat generated by the chemical reaction, most of these applications use heat exchanging internals. However, most of the work done on bubble columns so far has not accounted for the presence of the cooling tubes (Yamashita, 1987[2], Forret et. al., 2003[3], and Larachi et al., 2006[4]). This lack can be attributed to the scrupulously protected know-how of internals design and a lack of published unified geometrical standards, coupled with the complexity imposed on laboratory scale columns by internals insertion. In the early 1990's, Saxena and his coworkers published a series of studies on bubble columns with internals [5-8]. However, these studies focused on investigating the heat transfer rather than the impact of the internals on the hydrodynamics. It is believed that the flow dynamics in the column are affected when large parts of the cross sectional area (CSA) of the reactor are obstructed by internals [9]. Even the few studies that reported experimental findings involving internal heat exchange tubes do not provide an insight into this belief as they were mostly concerned with the global parameters, with no thorough interpretation of the local parameters. De et al. (1999)[10] reported overall gas holdup based on the bed expansion method as a function of the internals. Others investigated only limited cross sectional area coverage (5%) by the internals (Chen et al., 1999)[11].

Therefore, there is a need for close investigation of the effects of the heat exchanging internals on the local parameters, such as local gas holdup and bubble properties, in a variety of systems at a wide range of experimental conditions.

Only few earlier studies examined global parameters in bubble columns with internals. However, Youssef et al. (2010)[12] show that the reported data is contradictory and insufficient in extracting conclusions on such systems. In this study, for the first time, insight will be presented on local bubble dynamics and liquid phase mixing behavior in a pilot plant scale unit with and without internals. This task focuses on studying the effect of vertical heat exchanger tubes in two columns of 19 and 44 cm in diameter.

(Korte, 1987[13] and Bernemann, 1989)[14] have studied heat transfer and liquid phase velocity profiles, respectively, in columns of 19 cm and 45 cm diameter with internals.

Krishna et al. (2001)[15] listed the typical conditions for an industrial Fischer-Tropsch conversion including heat removal by means of cooling tubes inserted in the reactor. The conversion process is highly exothermic, as are most processes conducted in bubble columns. However, most researchers have not studied the effect of internals as a design parameter impacting bubble column performance. Recently, Hulet et al. (2009)[16] reviewed the heat transfer studies in bubble columns and recommended that more work involving bubble columns with internals needs to be done to develop reliable models for predicting large scale unit performance. There also is no definitive guidance on the design of the internals. Kölbel and Ralek (1980)[17] in their “Notes on the Development of Large-Scale Reactors” suggested the insertion of honeycombed cross section vertical shafts inside the column, with the cooling pipes located in corners or around the shafts. They claim this design will be able to eliminate unfavorable backmixing. They, however, do not provide experimental data for such a design.

Korte (1987)[13] comprehensively studied heat transfer from horizontal and vertical tube bundles with an embedded heat transfer probe in columns of 19 and 45 cm diameter and concluded that the heat transfer coefficient is very sensitive to the bundle’s configuration and density. It was shown that even with high viscosity liquids, which promote bubble coalescence, the presence of internals may inhibit any impact (decrease) on the values of the heat transfer by enhancing the bubble break-up rate. Bernemann (1989)[14] used a flywheel anemometer and found the axial component of the liquid phase velocity to be higher in a column with internals than in a column without internals, regardless of the gas velocity used. Saxena et al. (1992)[18] investigated the effect of internal tubes in 0.305 m diameter column, blocking 1.9, 2.7 and 14.3% of the total column’s cross sectional area (CSA) with a 3 phase system (air-water-glass beads). The gas holdup was found to be higher for 37 tubes than for 7 tubes. However, they reported the overall gas holdup as a global parameter, with no mention of the resulting radial profile. Thus, the effect of internals on liquid recirculation is impossible to assess from their data. Similarly, Pradhan et al. (1993)[19] studied six different covered volume fractions (Xv) of the column ranging from 0.014 to 0.193, and their results showed that gas holdup increased with an increase of Xv (up to a maximum of 55%). Moreover, helical coil internals provided higher gas holdup than vertical tubes, a finding attributed to the fact that vertically inter-tubes gaps allowed large bubbles to escape, decreasing the gas holdup, while with helical coils, smaller gaps were present.

The goal of this study is to assess the impact of internals on bubble column hydrodynamics. This will be accomplished via extensive experimental investigations of gas holdup and bubble dynamics.

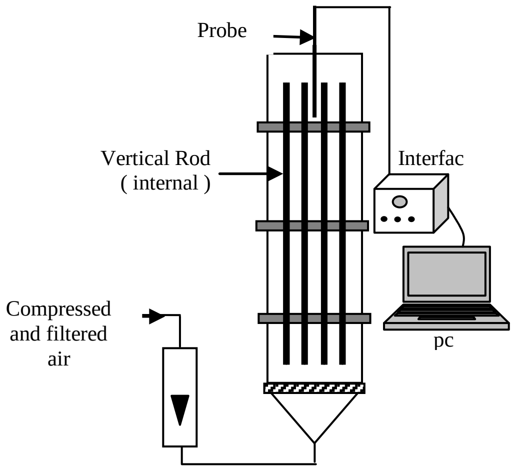


Figure (1) Schematic diagram of bubble column setup

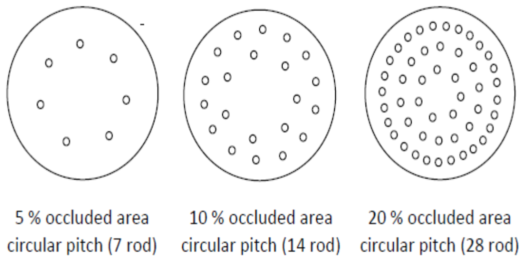


Figure (2) Configuration of internals in bubble column

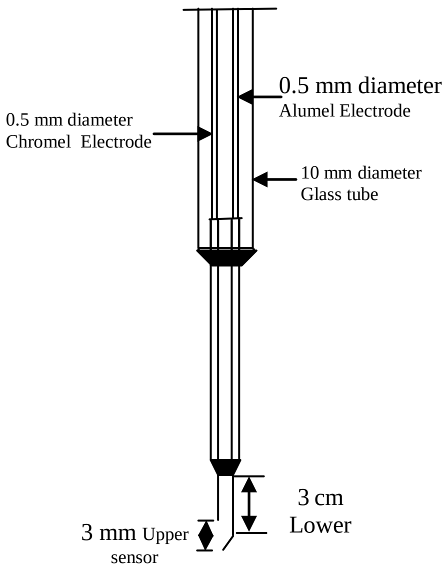


Figure (3) The electororesistivity probe

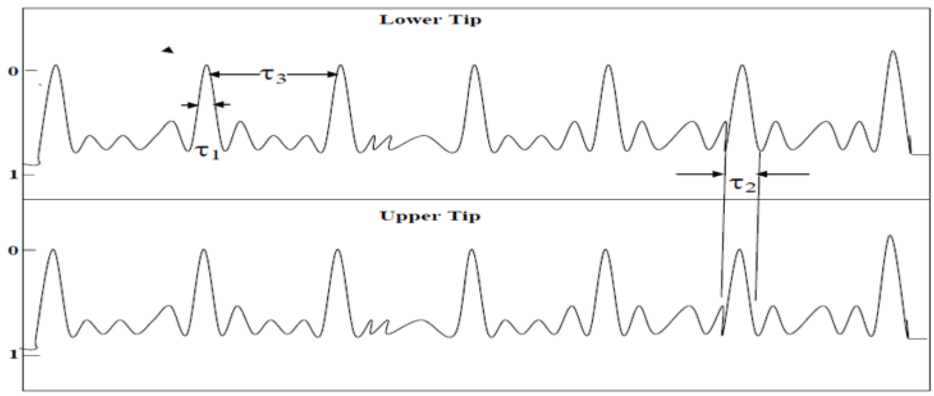


Figure (4) Signals from resistivity probe.

Results and Discussion

The overall gas holdup was measured by the change in dynamic liquid height compared to the static liquid height:[21]

$$\left(\varepsilon_g = \frac{H_d - H_o}{H_d}\right) \qquad \ldots(1)$$

Figure (5) shows the overall gas holdup as a function of superficial gas velocity with and without internals. Less significant effect was observed with internals covering 5% of the total CSA (average difference 6%). For the case where internals occupied 20% of the column's CSA, an average increase of 25% was obtained in the overall gas holdup. These findings are in line with Yamashita (1987)[2] and Bernemann (1989)[14]. Two reasons lead to the above result: first, the area available for the flow decreases with internals insertion yielding a higher 'actual' or interstitial superficial gas velocity; second, the internals effect on the bubble characteristics, as will be discussed below.

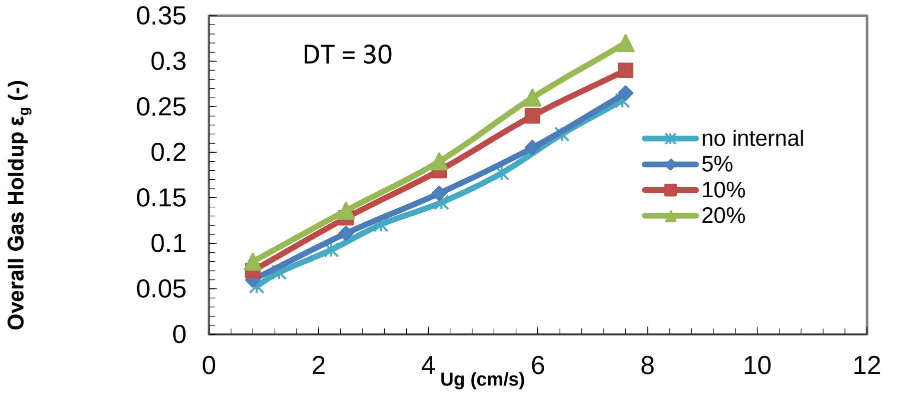


Figure. (5) Effect of internals on overall gas holdup

Figure (6) shows the local gas holdup profiles are parabolic as a function of radial position in columns without internals. It is evident from this figure that the decrease in column diameter causes an increase in gas holdup due to the increase rate of coalescence.

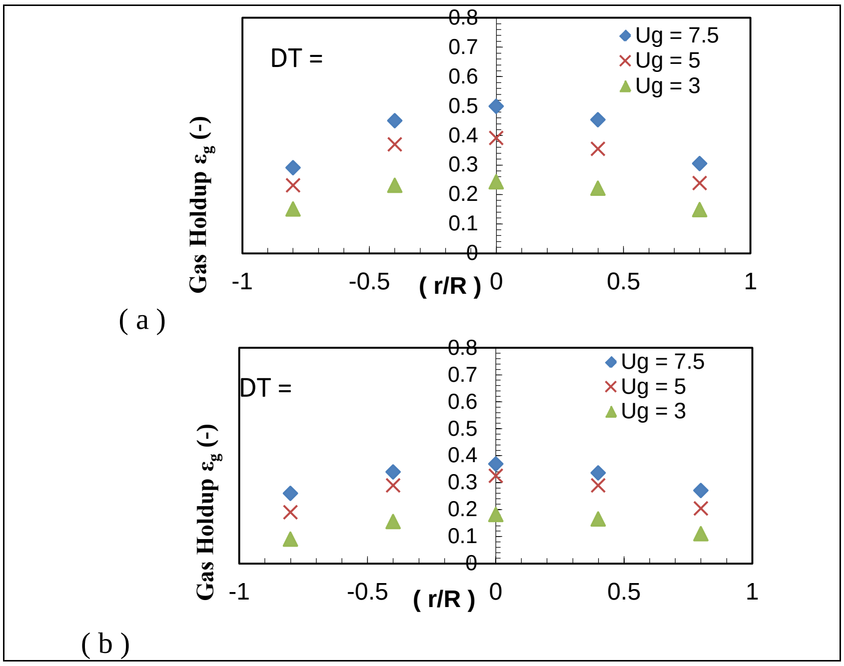


Figure. (6) Radial local gas holdup in bubble column without internal

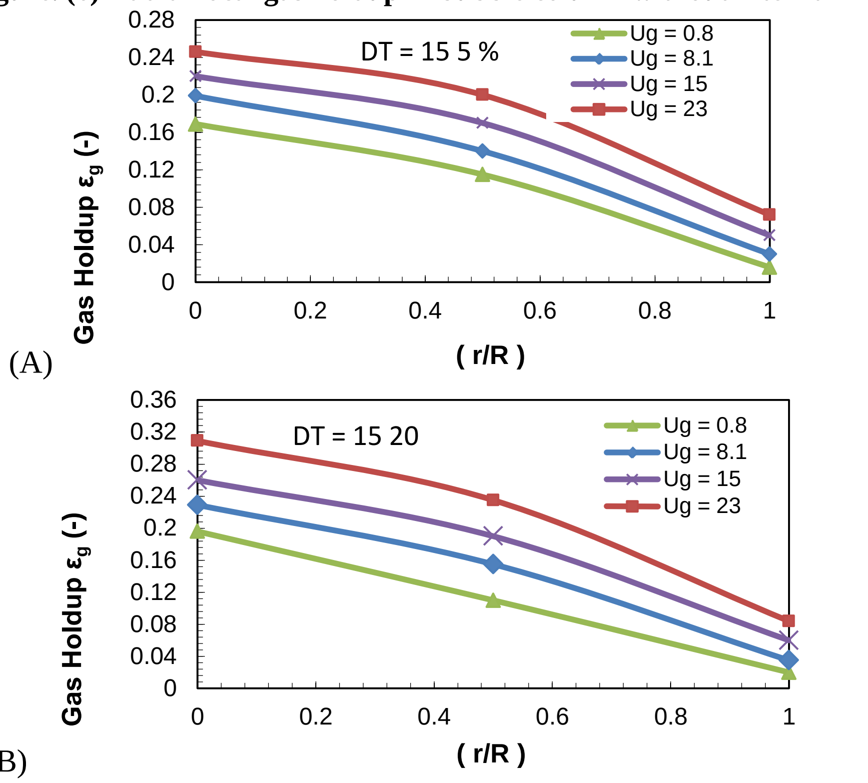


Figure. (7) Radial gas holdup profiles at different superficial gas velocities a) 5% b) 20% internals

Figure (7) presents the radial gas holdup profiles with internals covering 5% of the column's CSA at 0.8, 8.1, 15, and 23 cm/s. It is obvious that these internals do not impact the shape of the radial distributions considering typical trends observed in columns without internals.

Similar trends were observed for 20% covered CSA. However, it is noteworthy that the full radial profile could not be obtained in the case of 20% internals at low superficial gas velocities. It is common at low velocities to have a maldistribution of the gas flow through the sparger holes, with some inactive zones, if the sparger was not designed for low velocities as in our case (Degaleesan, 1997[20] and Pandit and Doshi, 2005)[21]. In such cases, bubble swarms flow upwards from the various active bubbling zones on the distributor, which have been found to shift circumferentially. Earlier studies in empty columns showed that the recovery from the above mentioned maldistribution, yielding a radially well-distributed gas plume, occurred at higher axial locations or at higher gas velocities. Visual observations from the current study showed that the presence of dense vertical internal structures (20% covered CSA) prevented the full development of the flow at such a low superficial gas velocity (8.1 cm/s and 0.8 cm/s). The internals trap the maldistributed gas flow and prevent the bubbles from dispersing radially as the gas flows upwards. As a consequence, at certain radial locations the probe did not encounter bubbles, and hence no measurement was recorded. This observation highlights the importance of sparger design for the desired range of gas velocity to ensure gas uniformity at the sparger region, especially when internals are present. Another solution is to extend the column to have a larger L/D ratio.

Figure (8) shows the effect of internals on the gas holdup radial profile for the 15 cm bubble column diameter at a superficial gas velocity of 23 cm/s, calculated based on the empty column's cross sectional area (CSA). Similar to trends seen with the overall gas holdup, an increase in the local values of gas holdup occurred when 5%, 10%, and 20% of the column's CSA was covered. Chen et al. (1999)[11] reached analogous conclusions using Computed tomography. However, when the internals covered 10% of the CSA, a significant increase in the gas holdup was observed. For example, at r/R=0, the gas holdup increased from 0.193 to 0.276, an increase of ~43% that can be explained as follows. In columns without internals, it is natural to find large bubbles due to coalescence at the column's core region, while the physical presence of internals impedes such bubble coalescence and rather enhances the break-up rate of the bubbles. The bubbles are forced to a maximum size dictated by the tube pitch. Bubbles of small size rise with lower velocities that extend the residence time of the gas phase in the system; hence, they elevate the gas holdup.

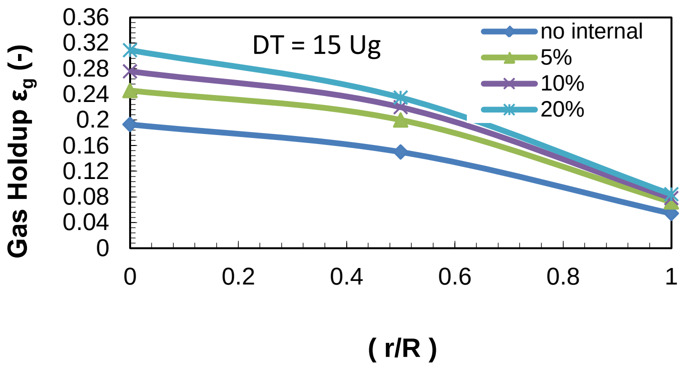


Figure. (8) Effect of internals on local gas holdup at Ug=23cm/s

Figure (9) and (10) show the radial profile of the number of the bubble with a superficial gas velocity for the bubble column with and without internals.
From Fig. (10), one can see that the more internals cover the column's CSA, the more bubble is generated. Furthermore, the increases in bubble frequency and interfacial area are due to rapid bubble breakup and coalescence, as will be explained later.

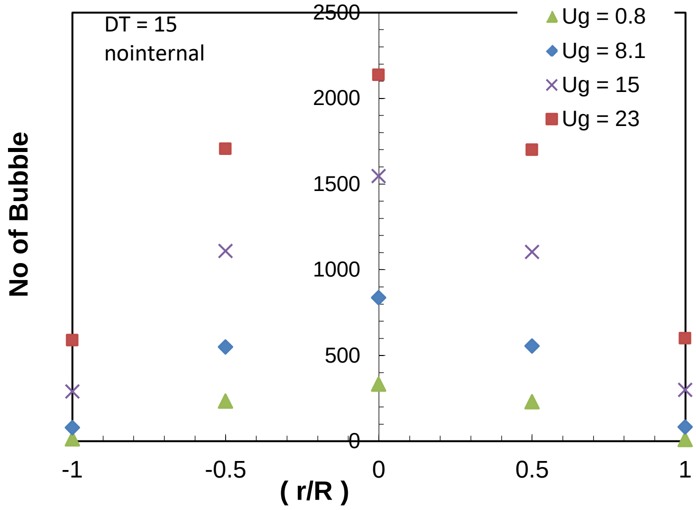


Figure. (9) Radial profile of the No. of bubble at different superficial gas velocities (no internals)

It was found that a greater number of bubbles existed at the column's center than in the region near the wall, which is similar to the findings of Xue et al. (2008)[22]. This difference is due to enhanced rates of breakup and coalescence among bubbles in the central region of the column in the churn turbulent flow regime, which was confirmed by the bubble frequency measured by the probe. An increase in bubble frequency leads to an increase in number of bubbles (specific interfacial area). The same trend was observed and explained by Youssef and Al-Dahhan (2009)[23] for the case of empty bubble columns. At low velocity, small bubbles uniformly distribute across the column in low numbers, which causes low local gas holdup both in the center and wall region of the column. With an increase in superficial gas velocity, bubbles, including the newly coalesced large bubbles from coalescence that move towards the center of the column, move in greater numbers, causing an increase in gas holdup. Most small bubbles still stay in the wall region and move across the probe at a relatively low frequency. Hence, the gas holdup, the number of bubbles, and the bubble frequency in the center all become larger than those in the wall region (see Fig. 11).

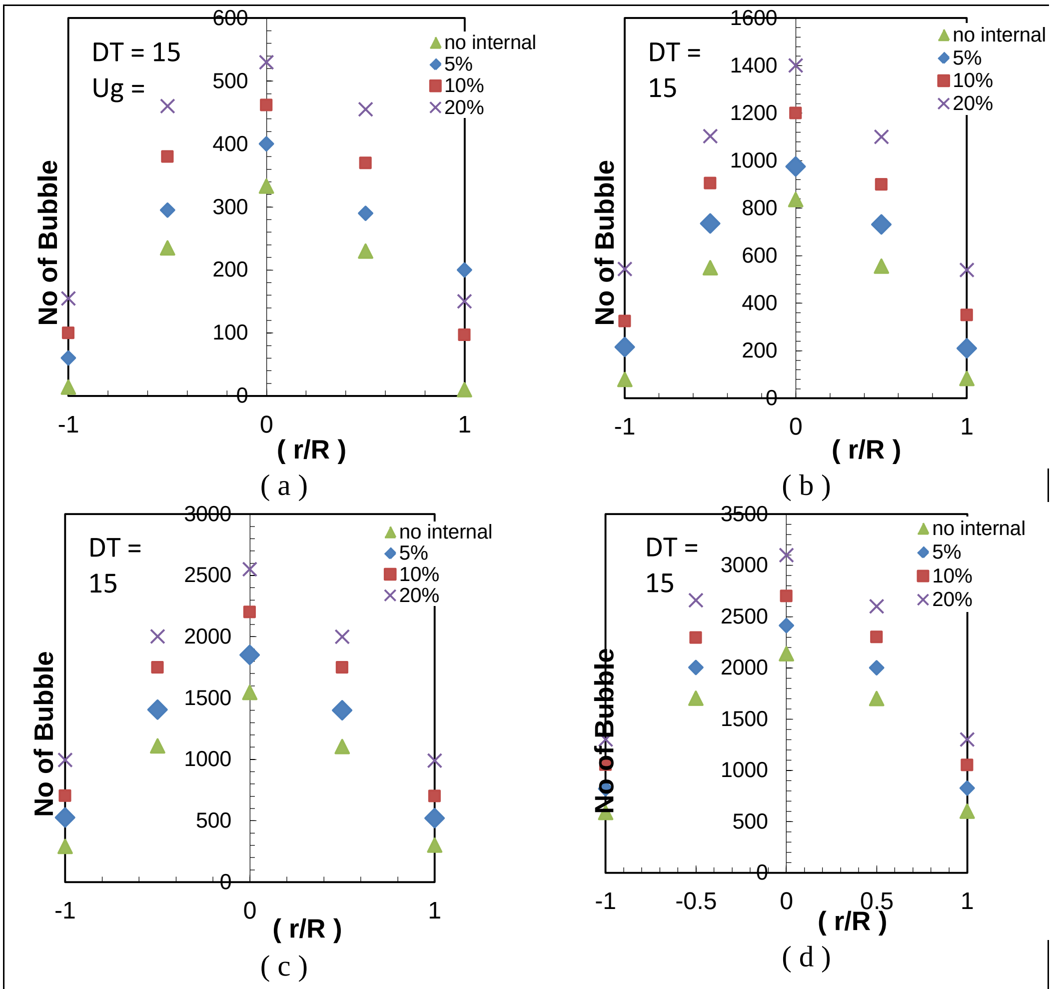


Figure. (10) Effect of internals on the No. of bubble a) Ug=0.8 b) Ug=8.1 c) Ug=15 d) Ug = 23 cm/s

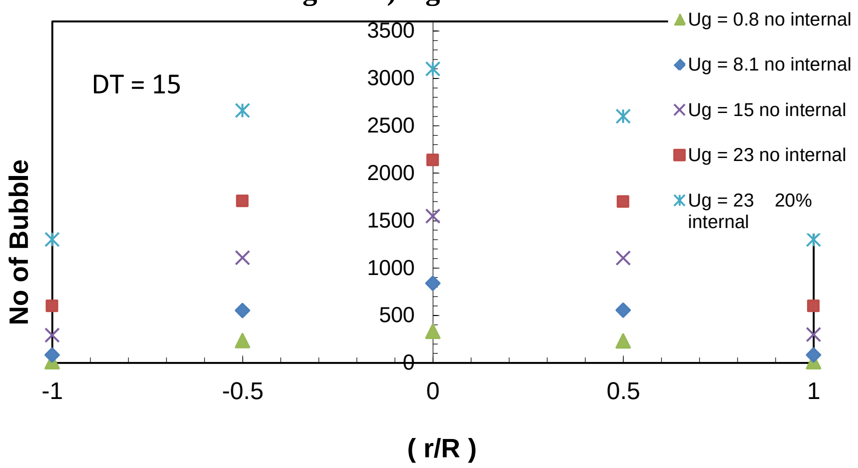
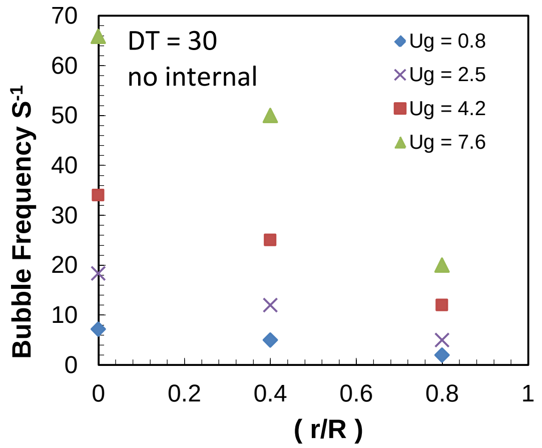


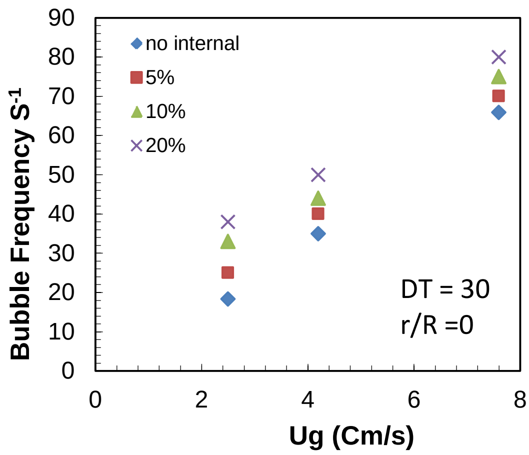
Figure. (11) Bubble passage frequency as a function of radial position at various conditions

Bubble frequency can be defined as the number of bubbles that hit the central tip of the probe per second. Since the bubble frequency, gas holdup, and specific interfacial area are interwoven parameters, one can confidently expect an increase in both gas holdup and interfacial area with an increase in bubble frequency. Accordingly, the bubble frequency typically exhibits parabolic profiles as shown in Fig. (12 b). It is clear from the figure that the bubble frequency increases with superficial gas velocity.

Figure (12 a) shows that the insertion of internals increases the bubble frequency due to rapid bubble breakup and coalescence, as explained before.



(a)



(b)

Figure. (12) a) Bubble frequency as a function of radial position for empty bubble column b) bubble column with internals

Figure (13) indicated that the bubble rise velocity will be increases with more internals cover the column's CSA at different values of superficial gas velocity. The reason of this increase in the bubble rise velocity is that, the insertion of internals increases the small bubble sizes will be increases of enhanced coalescence, in addition the rise velocity of the bubbles near the wall was less than at the center due to the effect of both the balance of forces and wall that bring a reduction in their velocity.

From Fig. (14) we have seen that bubble diameter decrease by insertion the internals due to breakup and coalescence as explain before.

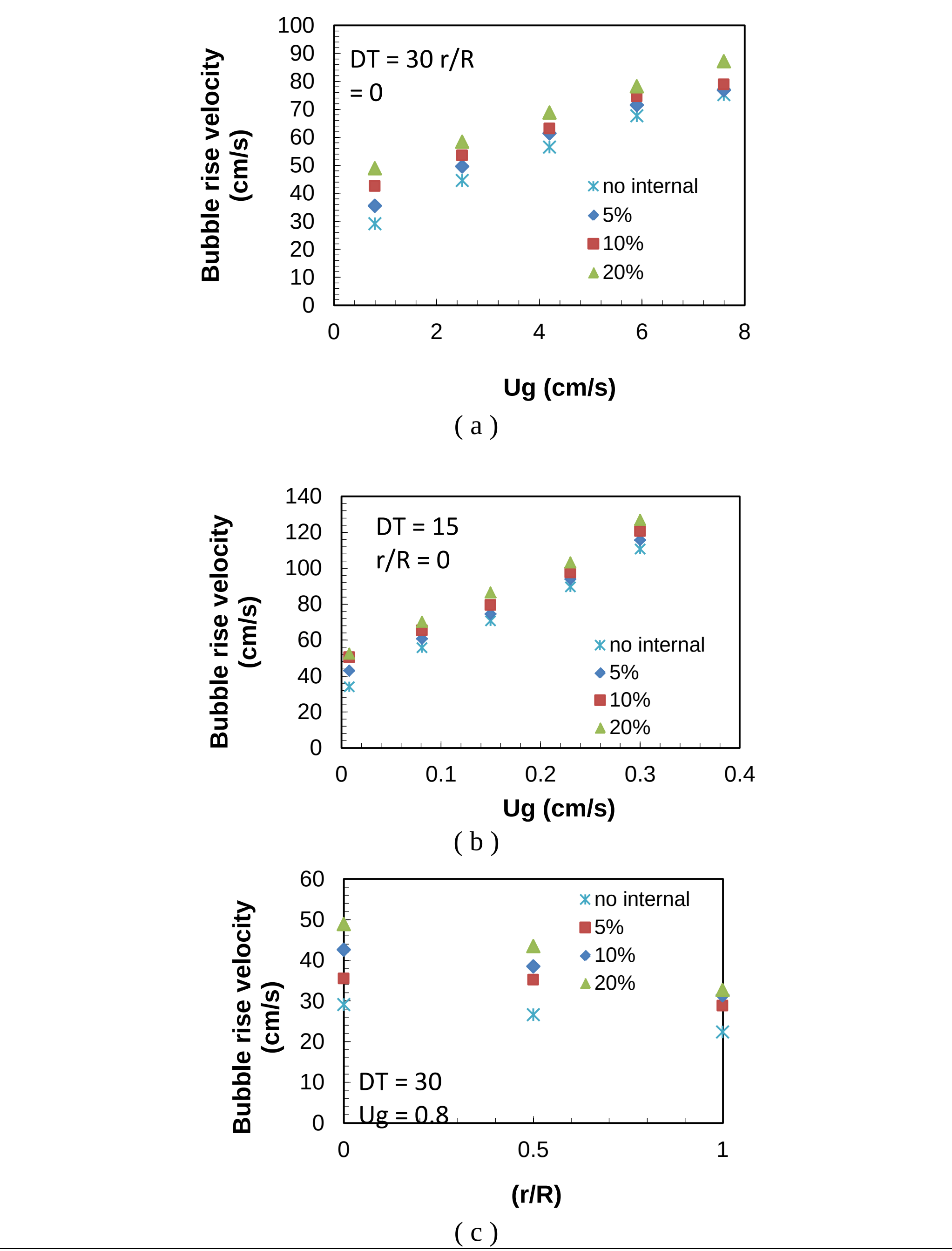


Figure. (13) Bubble rise velocity as a function of a) superficial gas velocity DT=30 b) superficial gas velocity DT=15 b) radial position in bubble columns.

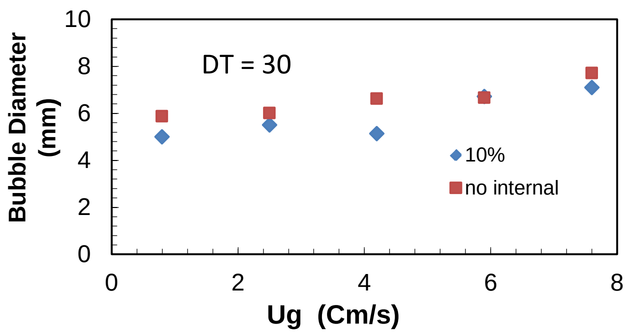


Figure. (14) Bubble Diameter as a function of superficial gas velocity

Figure (15) shows the effect of superficial gas velocity for open area on overall gas holdup at different internals arrangements.

The superficial gas velocity for open area (UO.A.) can be defined as the volumetric flow rate of the gas divided by only the free CSA of the column (i.e., the total CSA minus the area obstructed by the rods). As a matter of fact, utilizing the superficial gas velocity for open area can be useful to better evaluate the factors affecting the overall gas holdup.

The superficial gas velocity for open area can be calculated from the following simple equation:

$$A_{tot} \times U_g = (1\text{-fraction covered CSA}) \times A_{tot} \times U_{O.A.}$$

The Figure shows similar profiles to those illustrated in Fig. (5). It is obvious that the small differences between the gas holdup profiles with internals covering 5% and the case of no internals disappear. Also the small differences between the gas holdup profiles with internals covering 10% to 20% disappear (the gas holdup increases as a result of the internals' impact on bubble characteristics. In addition, the increase in the actual gas velocity in the column due to the decrease in available flow surface area causes another boost in the gas holdup values). Lower gas holdup values are observed for the case of no internals. The results are in agreement with earlier work by Bernemann (1989)[14] and Youssef and Al-Dahhan (2009)[23].

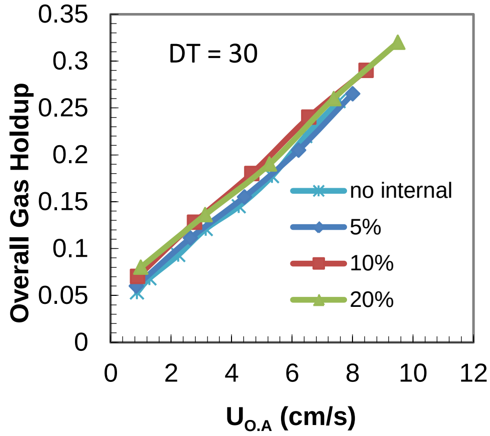


Figure. (15) Effect of superficial gas velocity for open area on overall gas holdup at different internals arrangements.

The gas holdup is represented as a function of the variables studied in this work $\varepsilon_g = f\left(U_g\ ,\ \%\,\text{int}\ ,\ r/R\right)$. Further, it can be assumed that the following relationship holds. $\varepsilon_g = k\,U_g^a\ + k1\ \ \%\,\text{int}^b + K2\ \ r/R^c$. Once more in order to find the coefficients k, k1, k2, a, b, and c a nonlinear regression technique via Statistica software is used and the following regressed relationship is determined with correlation coefficient of R2 = 0.97:

$$\varepsilon_g = 0.00286\,U_g^{1.08} + 0.142\,\%\,\text{int}^{-0.086} - 0.165\,r/R^{1.516}$$

The ranges over which parameters vary are: Ug = 0.8 – 23 cm/s, %internal = 5% – 20%, r/R = 0 – 1.

Good agreement between the experimental overall gas holdups and the estimated values from the empirical expressions has been obtained with error 0.017 Fig. (16).

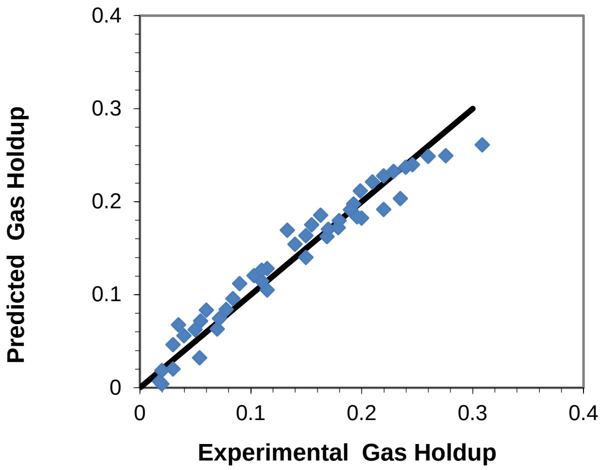


Figure. (16) Comparison between the experimental and prediction correlation data of this work

CONCLUSIONS

The main results presented in this work are:

- Increased density internals (i.e. increased percentage coverage of cross sectional area (CSA) by internals) causes an increase in the overall gas holdup values.
- The gas holdup increases in presence of internals, but that such increase is low percentage occluded open area (5%).
- The increase in the superficial gas velocity was found to increase radial gas holdup in the Center of the column and a decrease near the wall. The same trend was observed in the presence of internals.
- The presence of internals increase bubble rise velocity.
- The presence of internals decreases the bubbles diameters.
- The increase in the superficial gas velocity was found to increase the bubble frequency in the center of column and a decrease near the wall. The same trend was observed in the presence of internals.

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