Gas Holdup and liquid Phase RTD Studies in Multistage Bubble Columns

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Abstract

Installation of perforated sieve plates into a bubble column has the effect of introducing structure into an otherwise chaotic hydrodynamic behavior. In this study, we studied the effect of tray plates spacing and geometry on the overall gas holdup and liquid phase residence time distribution (RTD). The measurement carried out in bubble columns with diameter 10 cm and 20 cm with air-water system. Partition sieve plates with open areas of 15 and 30% and the tray spacing equal the column diameter (10, 20 cm) and twice the column diameters (20, 40 cm) were used in the studies. The overall gas holdup is measured experimentally by bed expansion technique and the liquid phase backmixing has been studied by measuring liquid phase RTD and analysed using one parameter dispersion model. The experimental results show that the increase in the tray spacing reduces the overall gas holdup and increase liquid phase dispersion. Also by comparing the liquid phase dispersion coefficient values with that in the conventional bubble column, it has been observed that there is reduction in the backmixing by 45-11% for tray spacing of 10 cm and 20 cm respectively in the 10 cm bubble column diameter. Correlations have been used for the estimation of the overall gas holdup and liquid phase dispersion coefficient in multistage bubble column.

Keywords: Bubble columns, multistage bubble column, overall gas holdup, liquid phase dispersion.

دراسة محتوى الغاز ودالة زمن البقاء في الاعمدة الفقاعية متعددة الطبقات

الخلاصة:

ان تركيب صواني مثقبة في العمود الفقاعي لها تاثير مشوه على السلوك الهيدروديناميكي. في هذه الدراسة، تم دراسة تاثير كل من المساحة المتاحة للجريان والتباعد بين الصواني على كل من محتوى الغاز ودالة زمن البقاء. القياسات

اجريت في اعمدة فقاعية ذات اقطار ١٠ و ٢٠ سم مع نظام ماء–هواء . تم استخدام ١٥ و ٣٠% كمساحة متاحة للجريان خلال الصواني المثقبة ، اما التباعد بين تلك الصواني فكان مساويا لقطر العمود (١٠ ، ٢٠ سم) وضعف قطر العمود (٢٠ ، ٤٠ سم) . تم قياس محتوى الغاز العام بطريقة تمدد طبقة السائل ، بينما قيس الخلط الرجوعي للطور السائل بواسطة دالة زمن البقاء وحل باستخدام نموذج عامل واحد. اظهرت النتائج التجريبية ان زيادة المسافة بين الصواني تقلل محتوى الغاز العام وتزيد من تشتت الطور السائل. وبالمقارنة بين العمود الفقاعي الاعتيادي مع العمود الفقاعي المتعدد الصواني اظهرت النتائج بان الخلط الرجوعي للطور السائل قل بنسة ١١ - ٤٥ % لمسافة تباعد بين الصواني ١٠ و ٢٠ سم للعمود الفقاعي ١٠ سم على التوالي . بالاعتماد على النتائج تم وضع علاقات رياضية لحساب محتوى الغاز العام ومعامل التشتت للطور السائل والتي يمكن من خلالها التنبؤ بمحتوى الغاز العام ومعامل التشتت للطور السائل للعمود الفقاعي ذو الصواني والاعتيادي.

الكلمات الدالة : الاعمدة الفقاعية، الاعمدة الفقاعية متعددة الصواني، محتوى الغاز العام ، معامل تشتت الطور السائل

Notation

do	Diameter of distributor/tray plate holes, mm
D_T	Column diameter, cm
$D_{ax,L}$	Liquid phase axial dispersion coefficient, cm^2/s
g	Acceleration due to gravity, cm/s^2
H_0	Total liquid height in the column, m
H_d	Dispersion height, m
H_S	Stage height (cm)
O.A.	Open area
U_g	Superficial gas velocity, cm/s
ε_g	Fractional gas hold-up

Introduction

Different kinds of bubble columns are frequently used in the chemical industry to perform gas–liquid reactions. Although this kind of equipment has been extensively investigated during the last decades, the number of published articles regarding the hydrodynamics in multistage bubble columns is not as substantial. These works have considered, in particular, the influence of gas velocity, tray hole diameter, tray open area, liquid flow and tower diameter. Schugerl et al [1], Alvare and Al-Dahhan[2], Chen and Yang[3], Nishikawa et al [4], Kato et al [5], Yamada and Goto[6], Kemoun et al [7], Doshi and Pandit[8] investigated experimentally the effect of superficial gas velocity and column diameter on the overall gas holdup, the authors found that the gas holdup profile was affected by the presence of internal trays and the holdup was relatively unaffected by the liquid superficial velocity but increase

with increasing gas superficial velocity. Also they found that the tray reduce bubble coalescence and produce higher overall gas holdups. An advantage, multistage bubble column can offer compared to a bubble column without any form of internals is a considerable reduction of the backmixing. The investigations have been carried out using residence time distribution (RTD) measurements and the backmixing is usually characterised by the axial dispersion coefficient obtained from the one-dimensional axial dispersion model. According to several authors, this model generally provides a suitable representation of backmixing in multistage bubble column.[8-10] According to Shah et al.[11], it is generally believed that an increase in gas velocity increases the liquid dispersion coefficient. Published experimental studies on liquid-phase backmixing in bubble columns [12–14] have shown that the axial dispersion coefficient increases, significantly, with increasing column diameter, D_T. Alvare and Al-Dahhan[2], Sadik[15], Van-Baten and Krishna[16], Dreher and Krishna[9], Pandit and Doshi[10], studied experimentally the mixing time in sectionalized bubble column over a wide range of superficial gas velocity. The researchers [2, 15, 16, 9, 10] found that the sectionalization of bubble column increased the mixing time (reducing the liquid phase backmixing) than in conventional bubble column. Maretto and Krishna[17] have stressed the advantages of introducing staging in the liquid phase by means of partition plates and have shown that significant improvements in reactor productivity can be achieved for the Fischer–Tropsch process. Use of partition plates introduces some "structure" into an otherwise chaotic bubble column behavior. Though there is some published literature on the hydrodynamics of multi-stage bubble columns [5-17], these studies are largely restricted to operation condition (superficial gas and liquid velocities). Also, there is no systematic study on the influence of tray spacing on the hydrodynamics of multistage bubble columns [2].

The objective of this work is to investigate the effect of the tray spacing and open area on the overall gas holdup and the liquid phase backmixing characteristics in columns with varying diameters. The results of our study can be expected to be useful for scale up purposes.

Experimental

The experiments were carried out in two batch type bubble columns with internal diameters of (10, 20) cm and (160, 190) cm in height respectively. The 10 cm column was made of PVC incorporated with glass window for the purpose of visual inspection and the 20 cm column was made of glass type (QVF). The columns were open at the top; hence the pressure corresponded with ambient conditions. Both the bubble columns have then been modified to a sectionalized bubble column with four sections. The four sections are attached to each other by flanges, in each section an electric conductivity probe is installed 2 cm from the inside wall of the column, the design provide flexibility to change the height between the two trays. Figure (1) shows the experimental set up in 10 cm column diameter.
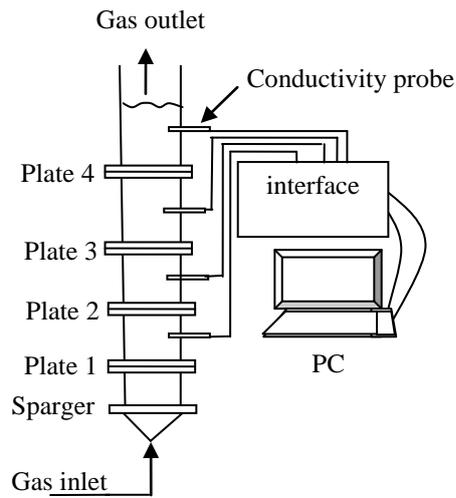
Figure (1) Multistage bubble column experimental setup

To study the effect of tray designation on gas holdup and liquid phase dispersion, three types of trays are employed as shown in Fig (2). Perforated plate sparger was used in column to distribute the gas phase. The distributor plates were made of plastic plate with holes of 2 mm diameter. Air was used as the gas phase and tap water as liquid phase. The gas was introduced at the bottom of the columns.

*Tray # 3 :1.8 cm ,
tray hole diameter,
30. % open area*

*Tray # 1 : 0.75 cm
tray hole diameter,
30. % open area*

*Tray # 2 : 0.75 cm
tray hole diameter,
15. % open area*
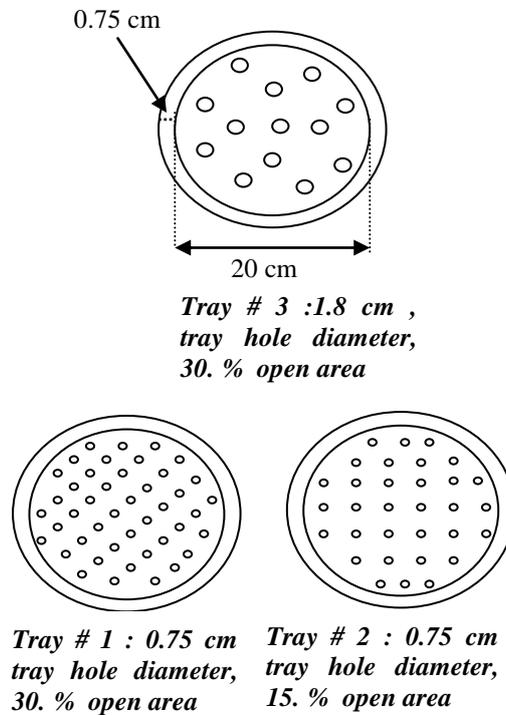
Figure (2) Tray design

The overall gas holdup was determined in the range of superficial gas velocities from 0.6 to 8 cm/s corresponding to volumetric flow rate equal to 5 to 60 liter per hour. For attaining high level of reliability, each experiment has been repeated three times and average results are considered. Residence time distribution (RTD) of the liquid phase was measured using different amounts of saturated solution of NaCl as a tracer. Different volumes of tracer were used to obtain the optimal amount of tracer that corresponds to optimal signal within the operating range of conductivity cell. This optimal amount of a saturated solution of NaCl was found equal to 4 wt %. The conductivity probes used in this work was manufactured by Philips Company, dimensions 1cm in diameter and 15 cm long. They simply consist of two electrodes, approximately 3 mm apart, and encapsulated in plastic tubing. The probes were properly calibrated by measuring their responses to solutions of different known tracer concentrations. The signals from the electrodes were transmitted to conductance meter (of Philips type), of range 100 μs to 1000 ms which provide a reading in units of conductance. The meters were connected with an interface to a personal computer. Tracer was injected as a pulse input. Local changes in tracer concentration were displayed and saved continuously on PC. Four electric conductivity probes were placed 2 cm away from the inside wall, located at different heights as shown in Fig. (3), each of them was connected to PC via interface circuit. The distance from the injection to the measuring points, L_1, L_2, L_3, L_4 and H_d are given in Table (1).
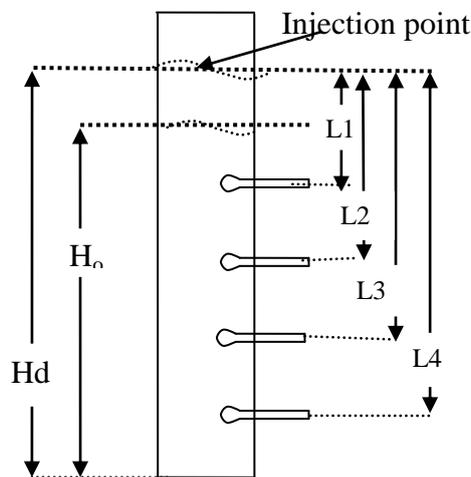
Figure (3) Distances to the measuring points in the column.

Table (1) Constructional detail about the RTD experiments

Operating condition	Column diameter	
	$D_T = 10$ cm	$D_T = 20$ cm
Liquid height H_0 /cm	131	135
Distance to the measuring point / cm	$L_1 = 2.8$ $L_2 = 44$ $L_3 = 82$ $L_4 = 112.8$	$L_1 = 2.5$ $L_2 = 45$ $L_3 = 100$ $L_4 = 115$

Time for each experiment was about 10 min to reach final concentration in the column. The constructive details of the RTD experiments, in the two bubble columns, are specified inTable (1). Fig. (4) shows typical transient tracer concentrations from the 10 cm column, operated at 4.7 cm/s superficial gas velocity. These signals were fitted using the analytic solution to the diffusion equation [18].
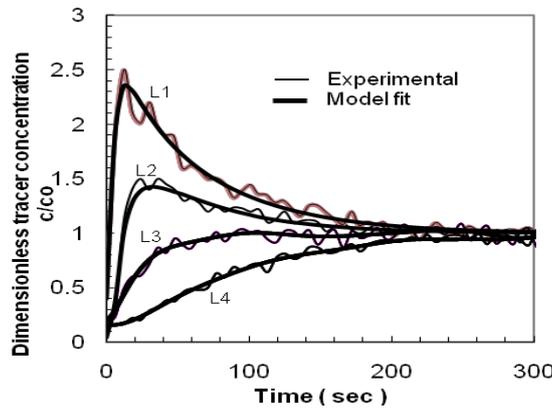
Figure (4) Normalised liquid-phase tracer concentration measurements

Results and Discussion

For the estimation of the overall gas holdup, according to bed expansion technique, the overall gas holdup is determined by measuring the heights of the dispersed phase at 161-183 cm that corresponds to initial and dynamic liquid heights respectively. According to these two heights, the overall gas holdup is calculated using $\left(\varepsilon_g = \dfrac{H_d - H_o}{H_o} \right)$.

Figure (5) and (6) show the overall gas holdup versus the superficial gas velocity, for 10 cm and 20 cm bubble column diameters respectively, for different tray open area and tray spacing, from the figures we seen that the overall gas holdup significant increase when the tray spacing decrease, due to the redistribution of the gas phase by the trays which help to re-adjust the bubble size and reduce the bubble coalescence and break-up. Also, the competition

between the gas and the liquid phases to move across the trays enhance the overall staging effect of the gas in the column. in addition to the formation of gas pockets below each sectionalizing plate which are proportionally related to Ug, even though, these gas pockets are not in dispersed form, but still they contributes their existence to the observed increase in H_d, (higher ε_g). It seems from Fig (5) and (6), that smaller tray open area promotes higher energy dissipation rate which counter the increase in overall gas holdup due to energy dissipation effect. The overall gas holdup in the multistage bubble column is represented as a function of the variables studied in this work

$$\left| \varepsilon_g = f\left(U_g\,,d_o\,,H_S\,,OA\,,g\,\right)\right|$$

that can be expressed in the dimensionless form

$$\left[\varepsilon_g = k\left(\frac{U_g^2}{g\,d_o}\right)^a \left(\frac{d_o}{H_S}\right)^b OA^c \right]$$
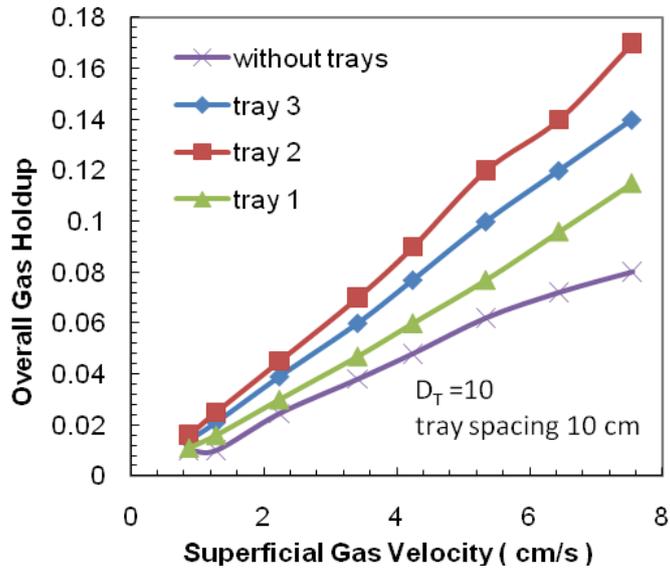
(a)
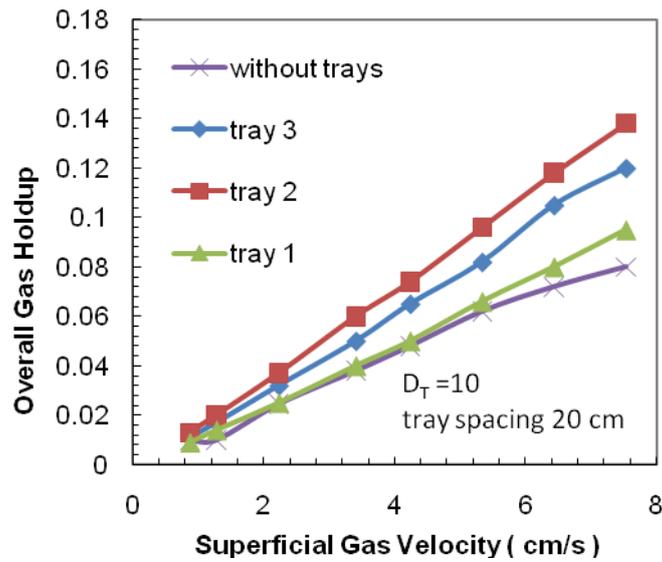
(b)

Figure (5) Overall gas holdup in 10 cm multistage bubble column with tray spacing equal to, (a) 10 cm (b) 20 cm
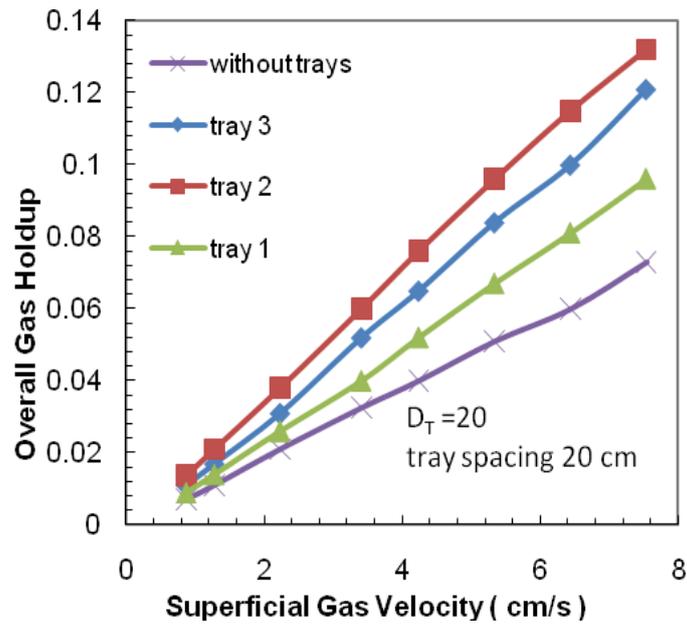
(a)
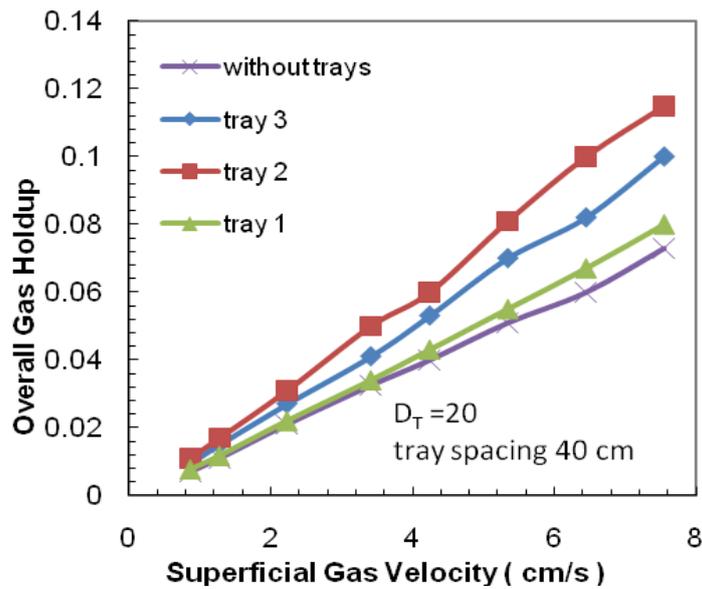
(b)

Figure (6) Overall gas holdup in 20 cm multistage bubble column with tray spacing equal to, (a) 20 cm (b) 40 cm

In order to find the coefficients k, a, b and c a nonlinear regression technique via Statistica software is used. The experimental data for a multistage bubble column are regressed and the following relationship is determined with correlation coefficient of $R^2 = 0.998$:

$$\left[\varepsilon_g = 2.361 \left(\frac{U_g^2}{g\, d_o} \right)^{0.54} \left(\frac{d_o}{H_S} \right)^{0.268} OA^{-0.21} \right] \tag{1}$$

Good agreement between the experimental overall gas holdups and the estimated values from the empirical expressions has been obtained Fig. (7).
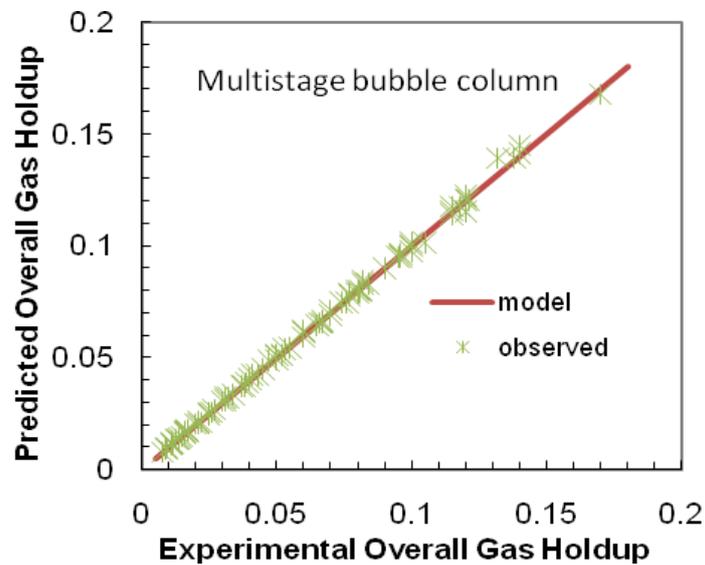
Figure (7) Comparison between the experimental and prediction correlation data of this work

We first measured the axial dispersion coefficients in the two columns without partition plates. The interpretation of the data is identical to that in our earlier publications [12,14,18] and the results are shown in Fig. (8). It can be seen that the values of the axial dispersion coefficient, $D_{ax,L}$, increase with increasing superficial gas velocity and with increasing column diameter, liquid-phase turbulence, induced mainly by the movement of bubbles and the existence of large-scale liquid internal circulation, are the main causes of liquid mixing in bubble columns, the presence of a large-scale liquid circulation cell in bubble columns, with liquid ascending at the central region and descending at the wall region. This liquid internal circulation is mainly driven by non-uniform radial gas distribution in the column. In homogeneous bubbly flow regime, there is no pronounced large-scale liquid circulation in the column and the liquid phase turbulence induced by rising bubbles is the main reason for liquid mixing. The scale of turbulence in homogeneous bubbly flow regime depends on the bubble size, as the gas velocity increases, the bubble size increases thus the bubble-induced turbulence increases which result in a rapid increase in the axial dispersion coefficient, as shown in Fig. (8). In churn-turbulent flow regime, both the convective liquid circulation and the liquid turbulent fluctuations play important roles in determining the mixing behavior of the liquid phase which causes liquid phase dispersion.This is in reasonably good agreement with the vast amount of literature available in this area and the values agree reasonably well with the recently developed correlation [9,12,14].
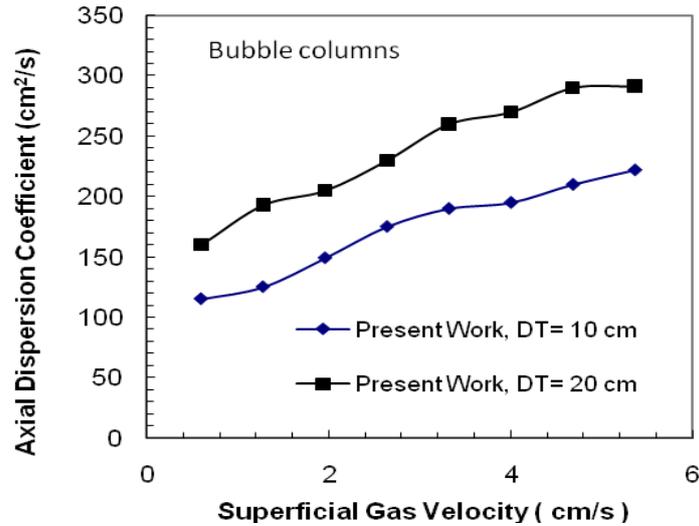
Figure (8) Axial Dispersion Coefficient in Conventional Bubble Columns

Typical fits of the RTD curves measured at four locations are shown in Fig. (4) for the 10 cm diameter column. Similar excellent fits of the RTD curves were obtained for a whole range of gas velocities for all the two columns studied. Figure (9) shows the results of the axial dispersion coefficients in multistage bubble column, from fitted RTD curves as described above for different tray open area and spacing, it is seen that D_{axL} increases slightly with increasing superficial gas velocity as compared   with empty bubble column, also it is seen that as we decrease the percentage free area of the perforated plates the flow resistance to the gas phase in the direction of the flow increases so the gas gets redistributed in the radial direction at each of these plates. This uniform distribution of the dispersed phase minimizes the density gradient effects, which results in the reduction in the liquid recirculation. The reduction in the liquid circulation velocities ultimately results in lower back mixing. Experiments have been carried out at tray spacing of 10 cm, i.e. tray spacing equal to the diameter of the column and twice the column diameter i.e., 20 cm. By comparing the liquid phase dispersion coefficient values with that in the simple bubble column, it has been observed that there is reduction in the backmixing by 45-11% for tray spacing of 10 cm and 20 cm respectively. The experimental results show that the liquid phase dispersion for 20 cm diameter column is 0.83-1.1 time more than 10 cm diameter column in the case 20 cm tray spacing and multistage bubble column, while equal to 1.3-1.54 for the conventional bubble column.
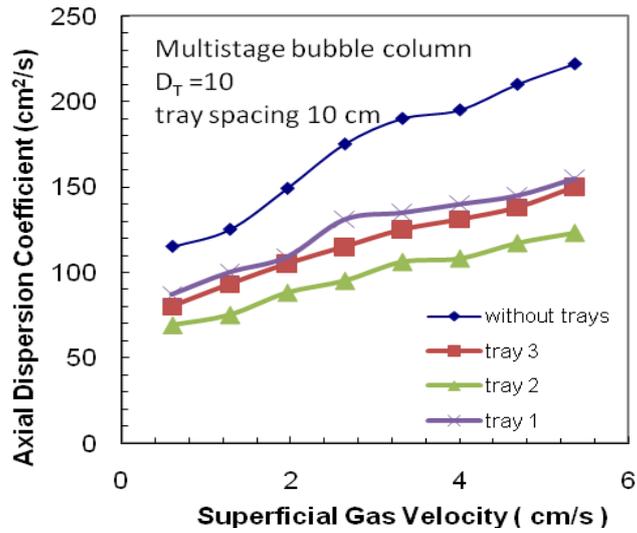
(a)
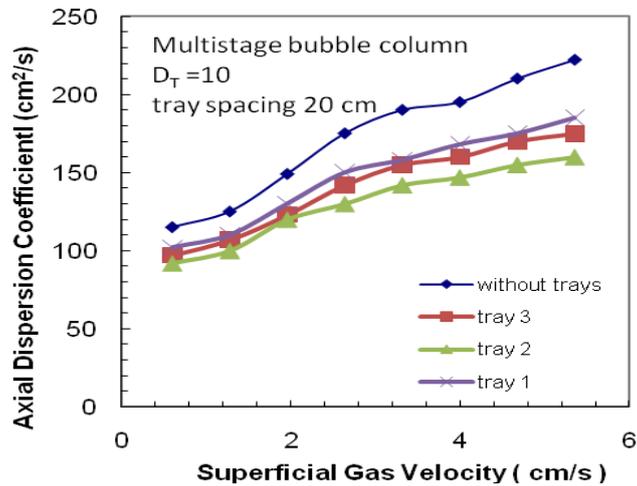
(b)

Figure (9) Experimental Axial Dispersion Coefficient with Different Trays and in Spacing (a) 10 cm (b) 20 cm

The axial dispersion coefficient in the multistage bubble column is represented as a function of the variables studied in this work $\left[D_{ax,L} = f \left(U_g , d_o , H_S , OA \right) \right]$ that can be expressed in the dimensionless form

$$\left[D_{ax,L} = k \, U_g^a \left(\frac{d_o^{\,2}}{H_S} \right)^b OA^c \right]$$

In order to find the coefficients k, a, b and c a nonlinear regression technique via Statistica software is used. The experimental data for a multistage bubble column are regressed and the following relationship is determined with correlation coefficient of $R^2 = 0.90$:

$$\left[D_{ax,L} = 29.972\, U_g^{0.294} \left(\frac{d_o^{\,2}}{H_S} \right)^{-0.105} OA^{0.275} \right] \qquad (2)$$

Agreement between the experimental axial dispersion coefficients and the estimated values from the empirical expressions has been obtained Fig.(10). Figure (11) shows the experimental axial dispersion coefficient and the values predicted from the model obtained in this work with available literatures experimental and correlation at specified tray spacing (constant tray spacing).
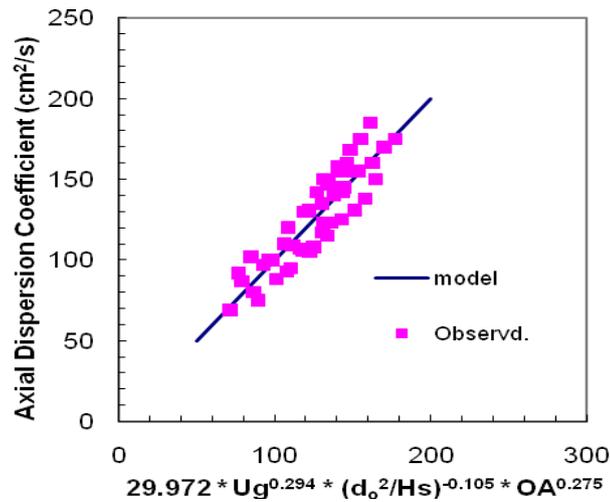
Figure (10) Comparison between the experimental and prediction correlation data of this work
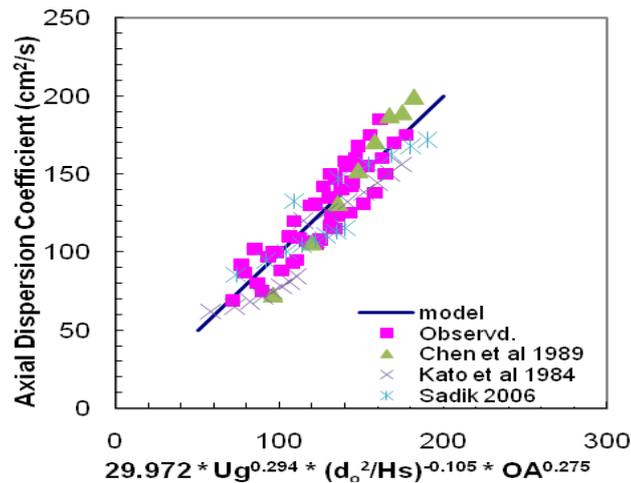
Figure (11) Comparison between the experimental and prediction correlation data of this work and of the published literatures at specified tray spacing

Conclusions

The main results presented in this work are:

- Trays partitioned significantly increase the overall gas holdup in multistage bubble column in comparison with conventional bubble column. Also this increase in gas holdup is found strongly dependent on the tray spacing.
- Liquid phase dispersion for 20 cm diameter column is 1.3-1.54 times more than 10 cm diameter column in the case of conventional bubble column.
- Liquid phase dispersion for 20 cm diameter column is 0.83-1.1 time more than 10 cm diameter column in the case 20 cm tray spacing and multistage bubble column.
- The empirical expression account for the effect of the studied parameters on the overall gas holdup Eq. (1) and axial dispersion in multistage bubble column Eq. (2).

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