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A Hydrodynamic Study in a Sieve Plate Sectionalized Bubble Column

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Abstract

The sectionalization of conventional bubble columns to tray bubble column by perforated trays has been used in chemical, biochemical, and petroleum processes as an effective way to improve the gas-liquid contacting efficiency, and reduce liquid backmixing. In this study, an experimental semi-batch tray bubble column setup has been built. Column 0.15 m inside diameter and total height of 2.20 m is sectionalized into four stages using three perforated plates to investigate the effect of tray geometry, superficial gas velocities and liquid phase physical properties on overall gas holdup. The overall gas holdup is measured experimentally by bed expansion technique. For studying the effect of physical properties of the liquid phase, two different gas and liquid systems are used (air-water and air-methanol solution).Methanol solution was used as the liquid phase to simulate the hydrodynamic behavior of the high gas holdup systems. Remarkable increases of up to 80% in the overall gas holdup have been observed in tray column as compared to conventional bubble column when this liquid system was used. Experimental results of tray bubble column shows significant increase the overall gas holdup in comparison with conventional bubble column. Correlations have been used for the estimation of the fractional gas holdup in bubble column with and without tray. Comparison of the model predictions with the experimental data and with the published data of other authors shows fine agreement which ensure the reliability and confidentiality of the adopted the correlations to be used in further designation.

Keywords: Bubble columns, Tray bubble column, overall gas holdup

دراسة السلوك الهيدروديناميكي للعمود الفقاعي ذو الصوني المثقبة

الخلاصة

يستخدام العمود الفقاعي متعدد الصواني في العمليات الكيمياوية والبايوكيمياوية وعمليات النفط كوسيلة فعالة لزيادة كفاءة الاتصال لطوري السائل والغاز ولتقليل الخلط الرجوعي المحوري (axial backmixing) للطور السائل يستخدام العمود الفقاعي متعدد الصواني في العمليات الكيمياوية والبايوكيمياوية وعمليات النفط كوسيلة فعالة لزيادة كفاءة الاتصال لطوري السائل والغاز ولتقليل الخلط الرجوعي المحوري (axial backmixing) للطور السائل .
تم نصب عمود فقاعي متعدد الصواني تجريبيا" بقطر 0.15 متر وبارتفاع كلي 2.20 متر حيث قسم هذا العمود الى اربع مقاطع باستخدام ثلاثة صفائح مثقبة لدراسة تاثير كل من هندسة الصينية، سرعة الغاز والخواص الفيزياوية للطور السائل. تم قياس محتوى الغاز العام (overall gas holdup) بطريقة تمدد الحشوة. لدراسة تأثير الخواص الفيزياوية للطور السائل تم استخدام نظامي من غاز-سائل مختلفة حيث استخدم في الاول نظام ماء –هواء والثاني هواء-محلول الميثانول, استخدم محلول الميثانول كطور سائل لمحاكاة السلوك الهيدروديناميكي للانظمة ذات محتوى غاز (gas holdup) عالي , ولقد لوحظ ارتفاع ملحوظ في محتوى الغاز العام في العمود الفقاعي

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متعدد الصـواني يصـل الـى 80% بالمقارنـة مـع الاعمـدة الفقاعيـة التقليديـة . بينـت نتـائج العمـود الفقـاعي متعـدد الصـواني زيـادة ملحوظـة فـي محتـوى الغـاز العـام مقارنـة مـع العمـود الفقـاعي الاعتيادي. بالاعتماد على النتائج تم وضع علاقات رياضية لحساب محتوى الغاز العام والتي يمكن من خلالها التنبؤ بمحتوى الغـاز العـام فـي كل مـن العمـود الفقـاعي ذو الصـواني والاعتيـادي . كمـا اظهـرت النتـائج لهـذا الموديـل تطـابق جيـد مـع النتـائج التجريبيـة والادبيـات المنشـورة ممـا يعطـي الاعتمادية والموثوقية لاستخدام الموديل في الحسابات التصميمية للاعمدة الفقاعية .

الكلمات الدالة : الاعمدة الفقاعية ، العمود الفقاعي ذو الصواني ، محتوى الغاز

Notations

do Diameter of distributor/tray plate holes, m
D_T Column diameter, m
g Acceleration due to gravity, m/s^2
H_0 Total liquid height in the column, m
H_d Dispersion height, m
u velocity, m/s
ε_g Fractional gas hold-up
μ_L Dynamic viscosity of liquid, cp
ρ_L Density of the liquid phase, kg/m^3
σ_L Surface tension of the liquid, N/m
Fr Froude number $\left(\frac{u^2}{D_T\ g}\right)$
Mo Morton number $\left(\frac{\mu_L^4\ g}{\rho_L\ \sigma_L^3}\right)$

Introduction

The addition of trays to conventional bubble columns helps to further improve the intensity of interfacial transport and to reduce the axial dispersion of the gas and liquid phase, which is needed in some industrial processes.[1-4] The operating mode, flow arrangement, and plate internals have a strong effect on the performance of these reactors, as well as on the extent of axial backmixing reduction. The columns can be operated in a semi-batch or continuous mode. [5-6]

Tray bubble columns (TBC) have been applied in biotechnology, where low backmixing is required to achieve high substrate conversion, for instance, [2] analyzed their performance as biological fermentors in aerated slurry system (e.g. continuous single-cell protein production). Other chemical processes that have benefited from the unique hydrodynamic and mixing characteristics of TBC include ozonation of drinking and wastewater[7], and Fischer-Tropsch synthesis of paraffins from syngas by use of a slurry catalyst.[8] The Visbreaking of petroleum residues, a petroleum refining process, is a recent and very important application of tray bubble columns.[9]

Overall gas holdup ε_g is an important parameter in the design and scale-up of bubble columns.[1] The effects of design and scale-up variables, and of the operating conditions on gas holdup should be properly characterized for reliable design and scale-up of the tray bubble columns. In these columns, the gas volumetric fraction mainly depends on the superficial velocity of the dispersed and continuous phases, physical properties of the gas and liquid phase, column dimensions (diameter, total height, and stage height), geometric design of the tray (hole diameter, and total open area), flow operation arrangement, and type of gas sparger (single or multi nozzle and perforated plates and others). While some authors have conducted experimental studies in tray bubble column reactors [2,10-12]. Only [3,4] developed a correlation (not take in account the effect of physical properties of liquid phase) for the estimation of the overall gas holdup in counter-current columns as a function of the most of the factors listed above.

The average bubble size in the column is set by the balance between coalescence and external breakup force. Coalescence is significantly influenced by the physical properties of the liquid phase, whereas the breakup phenomenon is mainly due to disturbances at the interface caused by external factors. Therefore the use of non coalescing liquid system helps to control the bubble size growth, which in turn increases the overall gas holdup.

Schugerl[2], Alvare[3], Chen[11], Nishikawa[12], Kato[13], Yamada[14], Kemoun[15], Doshi[16] investigated experimentally the effect of stage height 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.

Alvare[3], Sadik[4], Van-Baten[5], Dreher[6], Pandit[17], studied experimentally the mixing time in sectionalized bubble column over a wide range of superficial gas velocity. The researcher found that the sectionalization of bubble column increased the mixing time (reducing the liquid phase backmixing) than in conventional bubble column.

The objective of this work is to investigate the effect of the gas superficial velocity on overall gas holdup both in conventional and tray bubble column also investigate the effect of the liquid phase physical properties on the overall gas holdup via tested two different liquid system tap water and aqueous solution (20 % tap water 80 % methanol) this system mimics the physical properties of the high gas holdup systems [9].

Experimental

A batch tray partitioned bubble column setup is erected as schematically shown in Fig. (1). The column consists of four intermediate sections of 15 cm ID and 45 cm height and a bottom (plenum) section of 40 cm height, all made of PVC. To erect a four-stage setup unit, three trays are mounted. To study the effect of tray designation on gas holdup, three types of trays are employed as shown in Fig (2). Their design was chosen in such a way that it would permit the independent study of the tray hole diameter and the tray open area. 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.

Two phase liquid phase systems have been selected tap water and solution mixture (20% tap water and 80% methanol by volume). Their physical properties are listed in table (1). Filtered and compressed air was used as the gas phase.

The overall gas holdup was determined in the range of superficial gas velocities from 1 to 12 cm/s. All experiments are performed at atmospheric pressure and room temperature. For attaining high level of reliability, each experiment has been repeated three times and average results are considered.

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 175-210 cm that corresponds to initial and dynamic liquid heights respectively. According to these two heights, the overall gas holdup is calculated by using $\left(\varepsilon_g = \frac{H_d - H_o}{H_o}\right)$. Figure (3) shows the overall gas holdup versus the superficial gas velocity, Ug, of air-water and air-methanol solution systems, respectively, in a single stage bubble column and tray bubble column of different tray types. In mentioned figures, two different regions are recognized. At low superficial gas velocity region (Ug < 4-5 cm/s)[4], which is known as bubbly flow regime, almost a linear relationship between superficial gas velocity and gas holdup is established. Seemingly, tray types shows little influence on gas holdup, as the holes diameter is larger than the average bubble size diameter, that lead to easy swift of gas bubbles through the holes tray. At higher gas velocity, the gas-liquid flow induces more turbulence where hydrodynamic properties of the system are radically changed, in this flow regime, which is known as churn-turbulent flow regime, bubbles induces a wide distribution of sizes, shapes, and rise velocities, where almost no longer linear relationship between gas holdup and superficial gas velocity exists. It is in this turbulent region where the introduction of perforated trays inside the column increasingly affects the overall gas holdup in comparison with single stage bubble column. The redistribution of the gas phase by trays helps 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, which subsequently increases their residence time.

In studying the effect of tray geometry on overall gas holdup especially in turbulent regime, Fig (3) clarify the existence of a significant increase in the fractional gas hold-up as a result of sectionalization due to rebreakage of the bubbles, which reduces the average bubble size, and in return increases the fractional gas hold-up, 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 Hd, (higher ε_g). It seems from Fig (3), that tray type #3 (30 % O. A., do = 1.8 cm) show lower overall gas holdup than tray type #2 (15 % O. A., do = 0.75 cm), and type #1 (30 % O. A., do = 0.75 cm). In non-coalescing gas-liquid system, the bubble size at each tray is maintained along the stage itself, which clarify the importance of the tray holes diameter for controlling the diameter of the bubble at each tray, whereas in a coalescing medium, the tray hole diameter does not have such a strong effect but still its importance is greater than tray open area. In turbulent regime, it seems that smaller tray open area promotes higher energy dissipation rate but still for trays of equal hole diameters and higher open areas, a larger number of bubbles is formed (i.e., more gas-liquid interfacial area), which counter the increase in overall gas holdup due to energy dissipation effect. This gave a good explanation of what actually happened between tray type #1 (30 % O. A., do = 0.75 cm and 120 holes) which gave always slightly higher overall gas holdup than tray type # 2 (15 % O. A., do = 0.75 cm and 60 holes). These findings are in good agreement with that of Sadik[4].

It seems that the nature and surface tension of liquid phase are largely affecting column hydrodynamic behavior. In this work, it is remarkable to see that the overall gas holdup as high as 80% can be reached when methanol solution is used. Fig. (4) shows the comparison of the result obtained with the air-water and the air methanol systems in the single stage and multistage bubble columns.

The overall gas holdup in the tray bubble column is represented as a function of the variables studied in this work $\left[\varepsilon_g = f\left(U_g, d_o, OA, g, \rho_L, \mu_L, \sigma_L\right)\right]$ that can be expressed in the form of Froude and Morton dimensionless number $\left[\varepsilon_g = f\left(Fr_g, Mo, OA\right) = k\, Fr_g^{\,a}\, Mo^{b}\, OA^{c}\right]$

In order to find the coefficients k, a, and b a nonlinear regression technique via Statistica software is used. The experimental data for a tray bubble column are regressed and the following relationship is determined with correlation coefficient of R^2 = 0.962:

$$\varepsilon_g = 0.471 \left[\frac{U_g}{\sqrt{g\, d_0}}\right]^{0.839} \left[\frac{\mu_L^4\, g}{\rho_L\, \sigma_L^3}\right]^{0.067} O.A.^{0.123}$$

The range over which the dimensionless group are applicable are varied as follows:

Frg=0.024 - 0.495 , Mo = 2.633×10-19 – 1.972×10-11 , O.A. = 0.15-0.3

The following sets of variables are considered to correlate the key factors to overall gas holdup in semi-batch conventional bubble columns. $\left[\varepsilon_g = f\left(U_g, \rho_L, \mu_L, \sigma_L\right)\right]$. Further, it can be assumed that the following power law relationship holds. $\varepsilon_g = k\, U_g^a\, \rho_L^b\, \mu_L^c\, \sigma_L^d$. Once more in order to find the coefficients k, a, b, c, and d a nonlinear regression technique via Statistica software is used and the following regressed relationship is determined with correlation coefficient of R^2 = 0.992:

$$\varepsilon_g = 0.277 U_g^{0.819}\, \rho_L^{0.086}\, \mu_L^{0.246}\, \sigma_L^{-0.098}$$

The ranges over which parameters vary are: Ug = 1 – 12 cm/s, ρ_L= 0.81 – 0.997 g/cm3, μ_L= 0.00535 – 0.0001 g/cm.s, σ_L= 36.9 – 72dyn/cm.

Good agreement between the experimental overall gas holdups and the estimated values from the empirical expressions has been obtained Fig. (5).

Figure (6) shows the overall gas holdups obtained in this work versus the values predicted with available literatures correlation.

Conclusions

The main results presented in this work are:

- Trays partitioned significantly increase the overall gas holdup in tray bubble column in comparison with conventional bubble column. Also this increase in gas holdup is found strongly dependent on the type of gas-liquid system. Furthermore, tray hole diameter is the key parameter, whereas tray open area shows insignificant effect on overall gas holdup.
- Increases up to 80% in the overall gas holdup have been observed in tray column as compared to the single column when methanol solution used as liquid system.
- The following empirical expression account for the effect of the studied parameters on the overall gas holdup in tray bubble column

$$\varepsilon_g = 0.471\left[\frac{U_g}{\sqrt{g\,d_0}}\right]^{0.839}\left[\frac{\mu_L^4\,g}{\rho_L\,\sigma_L^3}\right]^{0.067} O.A^{0.123}$$

and for the conventional bubble column.

$$\varepsilon_g = 0.277U_g^{0.819}\,\rho_L^{\;0.086}\,\mu_L^{\;0.246}\,\sigma_L^{\;-0.098}$$

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Table (1) Physical properties of liquid system used in this work

	Density g/cm^3	Viscosity g/cm.s	Surface tension dyn/cm
Tap water	0.997	10^{-4}	72
20%Tap water + 80% methanol	0.810	0.00535	36.9

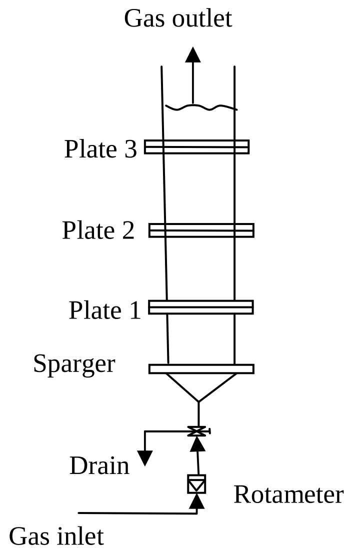


Figure (1) Tray bubble column experimental setup

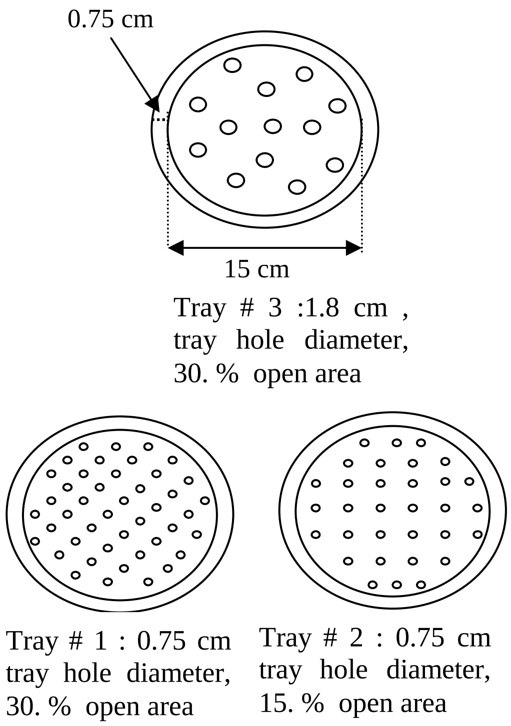
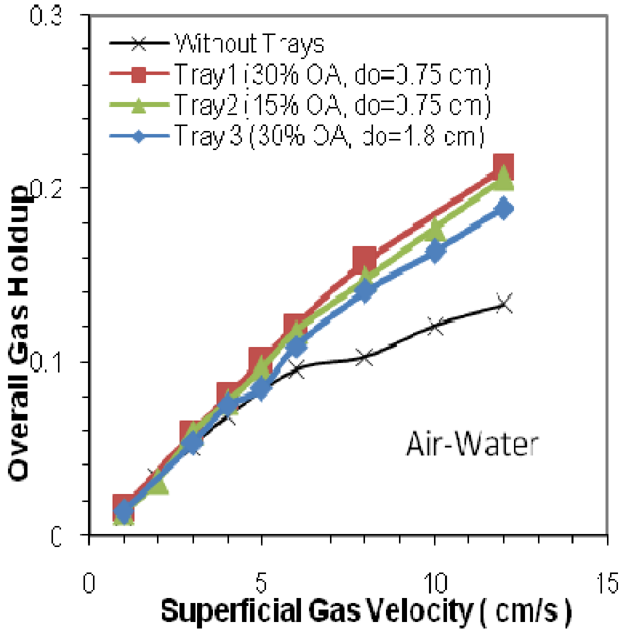
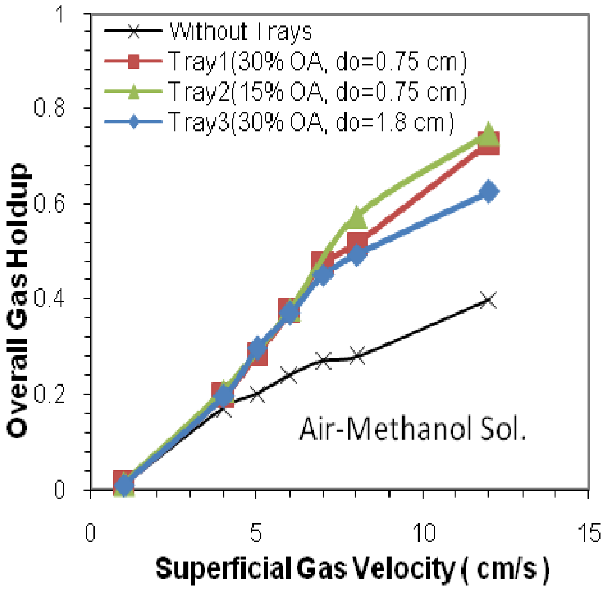


Figure (2) Tray design

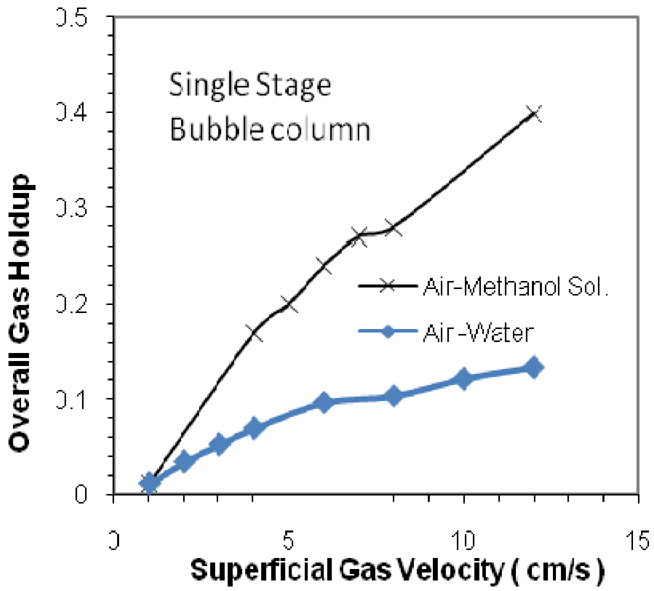


(a)

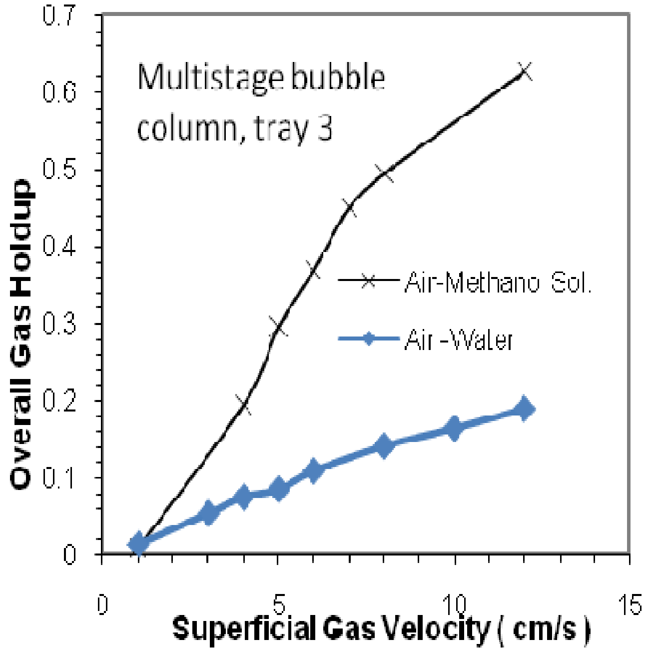


(b)

Figure (3) Comparison of the overall gas holdup between the bubble column with and without trays, (a) air water system (b) air methanol solution system

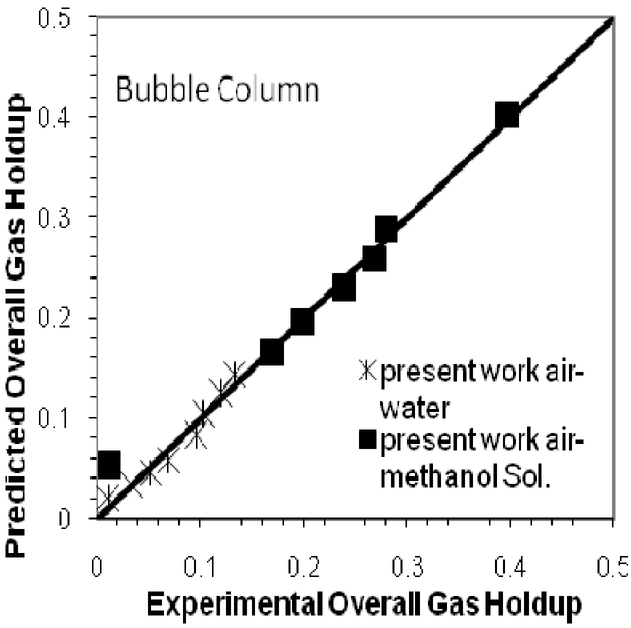


(a)

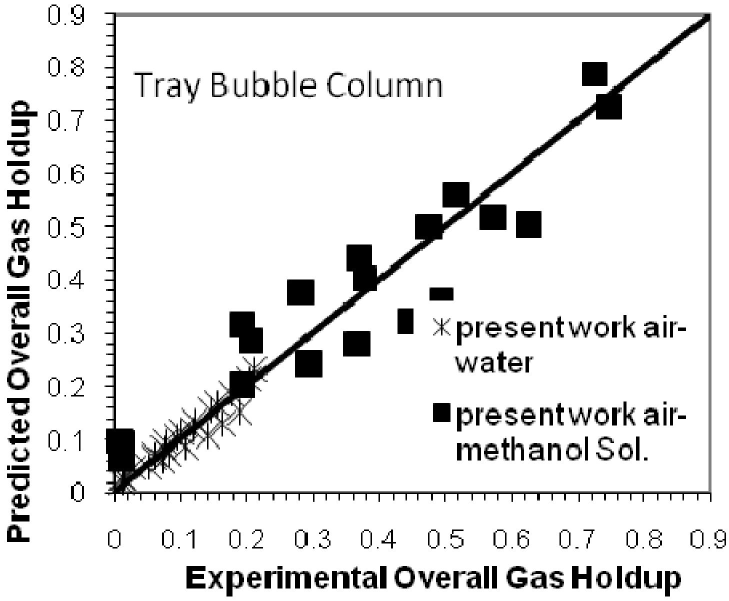


(b)

Figure (4) Comparison of the overall gas holdup between the bubble column with and without trays, (a) air water system (b) air methanol solution system



(a)



(b)

Figure (5) Comparison between the experimental and prediction correlation data of this work in (a) bubble column (b) tray bubble column

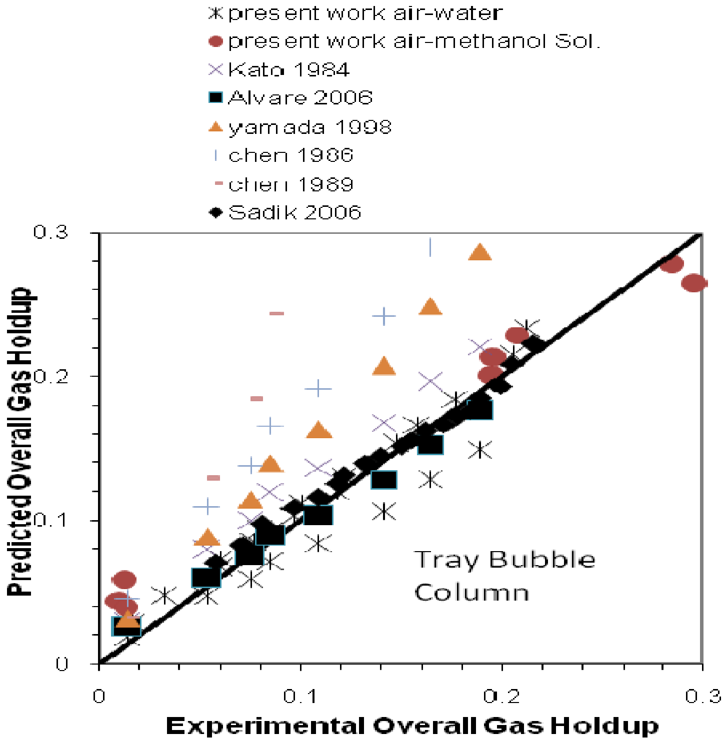


Figure (6) Comparison between the experimental and prediction correlation data of this work and predictions of the published correlations