

Hydrodynamic Characteristics of a Gas- Liquid –Solid Fluidized Bed Containing a Binary Mixture of Particles

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Abstract

The present work is an experimental study on the effect of solid loading and solid properties of both single and binary mixtures on the hydrodynamic parameters (gas holdup and bubble dynamics) of a fluidized bed bubble column. The experiments were performed in a QVF glass made column of 15 cm diameter. Wide range of solid particle diameters (0.5 to 3mm) with two different densities (i.e., 1025 and 1150 kg/m³) were investigated for the bubble effect on gas holdup and bubble dynamics using air with different gas superficial velocities (3 to 9 cm/s). A binary mixture consisting of different compositions of solid particles was prepared to be utilized in the study. It was observed that for specified operating conditions used in the experiments there is a proportional relationship between gas holdup and both superficial gas velocity and particle diameter while an inverse relationship exists between gas holdup and both solid concentration and particles density. Bubble dynamics (i.e., bubble diameter and bubble rise velocity) is looked at from a different view point, it increases with increasing solid concentration and with decreasing particles diameter.

Keywords: three phase fluidized beds, gas holdup, and bubble dynamic

دراسة الخواص الهيدروديناميكية في ابراج التميع ثلاثية الطور (غاز - سائل - صلب)

الخلاصة

ان الهدف من البحث هو دراسة الصفات الهيدروديناميكية للطبقة التميعة الثلاثية الاطوار في اعمدة التميع. ان الدراسة الحالية تضمنت تأثير تركيز المادة الصلبة وخصائصها على المتغيرات الهيدروديناميكية (معدل احتباس الغاز وديناميكية الفقاعات) في عمود الطبقة التميعة. حيث استخدم عمود اجاجي مصنوع من مادة (QVF) ويقطر (15سم) , ان الجسيمات الصلبة المستخدمة مصنوعة من مادة البولسي فنييل كلورايد ذات كثافة (1023كغم /سم³) وبقطر (0.65, 1.5, 3 ملم) والنوع الثاني من المواد البلاستيكية ذات كثافة (1150كغم/سم³) وبقطر (3, 5 ملم). استخدم الهواء كطور غازي بمعدل جريان (3 الى 9 سم/ثانية). وقد حضرت عدة خلائط ثنائية من الحبيبات الصلبة تضمنت نسب مئوية مختلفة في هذه الدراسة. وقد لوحظ بان هنالك علاقة طردية مابين معدل احتباس الغاز مع معدل سرعة الغاز وقطر الحبيبات وعلاقة عكسية بين الغاز المحتبس وكلا من تركيز وكثافة المادة الصلبة. ان ديناميكية الفقاعات (قطر الفقاعة, سرعة ارتفاع الفقاعة) سجلت من عدة نقاط مختلفة من العمود الزجاجي, حيث وجدت انها تزداد مع زيادة تركيز المادة الصلبة وتقل مع زيادة المادة الصلبة.

1. Introduction

In three-phase fluidization, the particles are fluidized by the co-current flow of liquid and gas. The three phase fluidized beds can be classified into the expanded bed and transport regimes, the solid can be introduced either continuously or batch wise ¹. Gas hold-up is dimensionless key parameter for phenomena purposes of bubble column systems ². All studies examine gas hold up because it plays an important role in design and analysis of bubble columns. In slurry columns the presence of suspended solid particles reduces the values of (ϵ_g) and their reduction by an addition of solid particles to the column is high in the transition regime and low in the heterogeneous flow regime.

Auroba-Nafaa ³ studied the effect of solid particles with different liquid-phase (alcohols and electrolytes) on gas hold-up. A dimensional analysis was used to correlate the gas hold-up with gas velocity and liquid properties. Naseer Al-Hapoby ⁴ studied the effect of solid particles and column dimensions on the gas hold-up and liquid phase mass transfer coefficient in solid suspended bubble column with draught tube and he found that the gas hold-up is not affected with column diameter and the effect of (C_s) on (ϵ_g) becomes less pronounced. In three-phase fluidized beds, the static height can be expressed as:

$$\Delta P = (r_g e_g + r_L e_L + r_s e_s) g \Delta H \quad \dots(1)$$

By proper substitutions, starting with equation (1), one can factor out the ϵ_g as:

$$e_g = \left(\frac{1}{g (r_1 f_1 + r_s f_s)} \frac{\Delta P}{\Delta H} \right) \quad \dots(2)$$

Equation (2) can be directly applied for estimation of gas hold up in a three-phase fluidized bed. The critical gas velocity for complete suspension of solid particles is the most important parameters that affect both hydrodynamic design and operation of three-phase sparged columns (slurry bubble column). Smith et al ⁵ indicated that (V_{Gc}) and minimum superficial gas velocity at which all solids are fluidized can be determined by visual observation and by pressure drop measurements.

Krishna et al ⁶ proposed a correlation for small bubble hold up showing its dependence on solids concentration:

$$e_{df} = e_{df,0} \left(1 - \frac{0.7 f_s}{e_{df,0}} \right) \quad \dots(3)$$

dense phase gas hold up for the gas-liquid, ($\epsilon_{df,0}$), can be estimated using the correction proposed by Reilly et. al. ⁷:

$$e_{trans} = e_{df,0} = 0.59 B^{1.5} \sqrt{\frac{r_G^{0.96} S^{0.12}}{r_L}} \quad \dots(4)$$

B=3.85 For air- water system.

The above equation is applied for the gas void age at the regime transition point (ϵ_{trans}) as suggested by Krishna et al ⁸, the presence of solids and solid concentration has an impact on bubble properties. It was reported that the presence of solids led to

larger bubble size⁹. This was attributed to an increase in the apparent slurry concentration. Viswanathan et al¹⁰, Ostergaard and Micsen¹¹, indicated that for particles less than 1mm in size, the gas hold up was significantly reduced by the presence of solid particles. This was attributed to the fact that small particles promote bubble coalescence which results in higher rising velocities, while the effect of larger particles was found to be less significant, since these particles instead tend to cause break-up of the bubbles¹²

Many researchers have attempted to predict the size of bubbles, not only the variation in mean size, but also the distributions of the diameters and volumes. The mean size of the bubble population in fluidized beds increases with height above the distributor plate due to coalescence of bubbles. A new correlation for estimation of mean bubble size of bubble swarms under dispersed and fluidized operation of bubble columns employing single and multi-orifice distributors was obtained by¹³. Bubble size for beds of 2, 4 and 6mm diameter glass particles was measured using both water and octanol solution with surface tension about half that of water¹⁴. Large bubbles were observed with 2mm diameter particles, decreasing with increasing particle sizes. The octanol solution was found to stabilize much smaller bubbles than water. The expression of bubble diameter was proposed in cylindrical bubble column (Height = 0.9 m and diameter = 0.254 m) as a function of Bond, Galileo and Froude numbers as well

as the ratio of orifice diameter to the column diameter¹⁵.

$D = f(Bo, Ga, Fr, d_o/D) \dots(5)$.
Knowledge of the existing flow regime and identification of the transition between bubbly flow and churn-turbulent flow is necessary to provide a clear picture upon which modeling and design efforts for a particular process can be based. One approach that has been commonly used in identifying the prevailing regime is based on the concept of the drift flux, as introduced by¹⁶. The drift flux, j_{GL} represents the volumetric flux of gas through a surface moving at the volumetric average velocity of the dispersion, $(U_g \pm U_L/2)$, and is given by¹⁷.

$$j_{GL} = U_g (1 - \epsilon_g) \dots(6)$$

Where U_g is the superficial gas velocity of the flow regime between the gas and liquid. The aim of the present research is to investigate the effect of the solid particles on the hydrodynamic parameters (gas holdup and bubble dynamics) and to develop an empirical correlation to correlate the gas holdup with the operating variables of the fluidized bed bubble column.

2. Experimental work

The experiments were performed in QVF glass column with inner diameter of (0.15) m .The bottom of the column consists of an inverted cone section with cone angle of 45, the cone section of the column with diameter of 0.15cm it was made of QVF.The conical bottom geometry was used in order to

minimize the occurrence of dead spaces at the bottom of the column. The column was made of QVF glass, and operated in the semi-batch mode, in which the liquid is stationary and the gas flows upward. The experimental apparatus is shown schematically in Figure (1). Air was used as the gas phase. The compressed air was passed through a stabilizer then was fed to the column. The gas flow rate was adjusted with the aid of needle valves and a calibrated rotameter. Calibrated rotameter of capacity (280) lit/min was used in order to cover the operating range of the air flow rate. The range of superficial gas velocity which is used in these experiments was varied from (0.03-0.09) m/s, for $D_c = (0.15)$ m. Air was introduced into the system through a perforated plexiglass sheet of thickness 3 mm. The holes of the distributor having a circular arrangement. The geometrical characteristics of the distributor are shown in Figure (2) and listed in Table (1).

Digital camera type (OLYMPUS, C-400/ZOOM) with high resolution (4 pixels) was used in the experimental work to measure the bubble diameter; the camera was connected to the computer. The solid phase which was used in the experiment showed in tables (2) and (3).

Three concentrations of these particles (0, 5 and 10) % kg solid/kg (water + solid) were used in the experiments of this work. Electroresistivity probe is used to measure the hydrodynamic parameters which affect the design and performance of the bubble

column, these parameters are: (Local gas hold up, bubble frequency, bubble rise velocity, number of bubbles and average bubble diameter). In all experiments which applied in this work, the level of clear liquid was kept at 90 cm. The electro resistivity probe was moved in axial positions, to measure the local gas hold up in three different positions. The bubble diameter was measured by using the elector resistivity probe and was compared with the photographing method and these two methods were applied to the same column.

3. Results and Discussion

3.1 Effect of Particle properties on Transition Point

A common procedure to locate the transition point between the homogeneous and heterogeneous regimes is to apply the drift flux analysis¹⁸. The basic quantity is the drift flux, j_{GL} , which represents the gas flux through a surface moving at the average velocity of the mixture and is given by: $j_{GL} = U_{sg}(1 - \epsilon_g)$. Figure (3) shows the drift flux versus the corresponding gas holdup for the experimental data of the solid concentrations tested with $d_p = 3$ mm. The points where the change of the slope occurs are determinate and the corresponding superficial velocities (U_{sg}) are calculated. Table (4) represents the trend of a (0.5mm) and (1.5mm) particles. A general comment is that an increase in solid concentration shifts the transition to slightly lower velocities so decrease the stability of the homogeneous

regime. This behavior can be attributed to the effect of solid particles which accelerate the rate of bubble coalescence resulting in higher bubble velocity. The only exception is the solid particles of (3mm) diameter tend to increase bubbles breakage. Table (4) shows the transition between homogeneous and heterogeneous regime ($d_p=0.5\text{mm}$ and $p=1.5\text{mm}$). This behavior is in agreement with the findings of ¹⁶.

Figure (4) show the effect of particles density on transition point. The plot shows an opposition relationship between transition holdup ($\epsilon_{\text{trans.}}$) and particles density. This can be attributed to that as particles density increases, with a simultaneous increase in particle terminal velocity resulting in decrease of overall gas holdup at specified gas superficial velocity and this lowers the transition conditions. Table (5) shows the terminal velocity measured experimentally in water for different types of solid particles in agreement with ^{17, 19}.

From plots that the effect depends mainly on the percentage of the individual species.

3.2 Effect of operating parameters on Gas Holdup.

Figures (5) to (7) show the effect of superficial gas velocity on the measured local gas holdup and overall gas holdup. All figures indicate that gas holdup increases with an increase in the superficial gas velocity, although this increase shows different characteristics in the homogeneous and heterogeneous regimes.

The average gas holdup increases almost linearly with increasing

superficial gas velocity in the homogeneous regime, while this increase is less pronounced in the heterogeneous regime, because large bubbles are formed due to bubble coalescence and these large bubbles have a notable bubble-wake attraction effect. This behavior is in agreement with the findings of ²⁰. A wide range of particles diameter has been investigated to study this behavior. Figure (8) shows the measured overall gas holdup for various particle diameters, the plots indicate a proportional relationship between particles diameter and measured gas holdup. This can be attributed to the fact that rate of bubble coalescence is increased as the particles diameter decreases. This results in large bubble size which has larger bubble rise velocity than small bubbles. Gas holdup decreases as a result of bubble coalescence. This behavior is in agreement with the findings of ²¹. Figure (9) shows the measured overall gas holds up versus superficial gas velocity for the compositions of binary mixture of particles at (Ma). Analysis the plots behavior indicates that the effect of each species on the overall gas holdup depends on its percentage in the binary mixture. This analysis is of a valuable hydrodynamic aspect to the industrial reactors where different sizes of a catalyst particle a utilized. An approximate correlation can be developed to describe this behavior:

$$\epsilon_g = x_1 \epsilon_g + x_2 \epsilon_g \quad \dots(7)$$

Where x_1 and x_2 are the weight fraction of particles 1 and 2 respectively.

3.3. Effect of operating parameters on Bubble Dynamics

Figure (10) shows the effect of superficial gas velocity on bubble rise velocity size for all tested solids. From this Figure one can notice that there is a slight increase in the bubble behavior with increasing superficial gas velocity.

This increase is attributed to the fact that the increase in superficial gas velocity increases the probability of bubbles collision and coalescence resulting in greater bubble size, this in agreement with ^{22, 23}. Figure (11) shows the measured bubble diameter vs. superficial gas velocity with solid diameter for different values of (Ug) at (Cs = 10%). This Figure shows increase in the bubble rise velocity or bubble diameter with decreasing the particles diameter. The reason for this increase is that small particular sizes will increase or enhance the rate of bubble coalescence, leading to a decrease in gas holdup. This is in agreement with the work of ^{24, 25}.

Figure (12) shows the measured bubble diameter vs. superficial gas velocity at different values of binary mixture of particles, the bubble dynamics will be increased when the solid particles are mixed with the ratio of large percentage of high density with the low percentage of low density. This is in agreement with the results ²⁶. Figure (13) represents the solid holdup with superficial gas velocity, from this figure the solid holdup decreases with increase in superficial gas velocity and increases with increase in solid concentration. This is attributed to the fact that the dispersion height (H_t) is proportional

to the superficial gas velocity according to eqn. $\epsilon_s = Ws/AcH'_t \rho_s$, so for a certain solid loading any increase in dispersion height leads to a decrease in solid holdup.

3.4 correlations for gas holdup

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 (i.e., viscosity, density, surface tension).
- The column cross section.
- Particles diameters.
- Particles densities.

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 two forms:

3.5 Gas Holdup Correlation for Single State

$$e_g = 0.1788 \left(\frac{u_g^2}{gd_c} \right)^{-0.331} \left(\frac{r_l u_g^2 d_c}{S_l} \right)^{1.066} \left(\frac{r_l d_c u_g}{m_l} \right)^{-0.565} C_s^{-0.242}$$

$$\left(\frac{d_p}{d_c} \right)^{0.204} \left(\frac{r_s}{r_s - r_l} \right)^{0.334} \dots \dots \dots (8)$$

$$R = 0.96811$$

$$error = 0.0049345$$

3.6 Gas Holdup Correlation for Binary State

$$e_g = 0.057 \frac{u_g d_c F_L}{m_l}^{1.51572} c_s^{-0.38905} x_1^{0.56896} x_2^{-0.70310}$$

$$\left(\frac{d_{p1}}{d_c}\right)^{0.0750} \left(\frac{d_{p2}}{d_c}\right)^{2.4438} \dots (9)$$

$$R = 0.995641008$$

$$error = 0.000521$$

4. Conclusions

The following major conclusions are drawn from the present study:

1. Experiments show that increasing the solid concentration tends to decrease the gas holdup.
2. The visual observations and experimental results show that the superficial gas velocity looks to be the most effective parameter on the gas holdup, where the (ϵ_g) increases greatly with increasing the gas velocity .
3. The results show that there is a proportional relationship between gas holdup and particles diameter for the specified operating conditions used in the experiments.
4. It was concluded that the bubble rise velocity is increased with increasing the solid concentration.
5. From experimental results of bubble diameter which was measured in the electro resistivity probe method and also in the photographic method, a rational agreement is obtained between the measured values from the two methods.
6. The bubble rise velocity and bubble diameter increased with decreasing particles diameter.
7. For binary mixture, it was proved experimentally that the effect of each species on the hydrodynamic parameters is proportional to its

weight fraction and other corresponding properties in the mixture.

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Nomenclature

A cross sectional area, m²
 C_s Average solid concentration, kg/m³
 d_p Particle diameter, m
 d_o Hole diameter in gas distributor, m
 D_C, D Column diameter, m
 G Gravitational acceleration, m/s²
 H_f Height of beds, m
 ΔH Height difference between the transmitters, m
 ΔP Pressure drop along bed, N/m²
 U_g Superficial gas velocity, m/s
 U_l Superficial liquid velocity, m/s
 U_t Terminal velocity, m/s
 V_{Gc} Critical gas velocity, m/s
 B₀ Bonnd number, (-)
 F_r Froud number, (-)
 G_a Galileo number, (-)
 W_e Weber number, (-)

Greek symbols

ε_{df} Dense-phase (small bubble) hold up, (-)
 ε_{df,0} Dense-phase (small bubble) hold up for gas-liquid system, (-)
 ε_g Gas Hold up, (-)
 ε_{gtrans} Transition gas hold up, (-)
 ε_L Liquid hold up, (-)
 ε_s Solid hold up, (-)

ρ, ρ_L Liquid density, kg/m³
 ρ_g Gas density, kg/m³
 ρ_s solid density, kg/m³
 σ Liquid surface tension, N/m
 μ Liquid viscosity, Pa.s

Table (1) Specifications of Air Sparger.

Column Diameter Dc (cm)	No. of Holes	Hole Diameter (mm)	% Free area
15	47	2	0.836

Table (2) Physical Properties of Particles.

Particle Notation	Type of Particles	Dp (mm)	ρ_s (Kg / m ³)	Ut (cm / s)
A	PVC	3	1025	2.37
B	PVC	1.5	1025	0.529
C	PVC	0.65	1025	0.09
D	Plastic	3	1150	2.772
E	Plastic	0.5	1150	0.057

Table (3) Description of Binary Mixture of Particles.

Mixture Notation	Description	Weight Ratio 1 / 2	Diameter Ratio (large / small)	Density Ratio (heavy / light)
Ma	A & B	1:1	2	1
Mb		1:3		
Mc		3:1		
Na	A & C	1:1	4.6	1
Nb		1:3		
Nc		3:1		
Ia	A & D	1:1	1	1.122
Ib		1:3		
Ic		3:1		
Va	A & E	1:1	6	1.122

Table (4) Transition between homogeneous and heterogeneous regime($d_p = 0.5\text{mm}$ and $d_p = 1.5\text{mm}$)

Solid concentration % (w/w)	d_p, m	ϵ_{trans}	$U_{\text{trans}}, (\text{cm/s})$
0	0.5	0.333	7.2
	1.5	0.333	7.2
5	0.5	0.126	6.38
	1.5	0.17	6.92
10	0.5	0.078	5

Table (5) Terminal velocity (V_t) of solid particles.

Particle Type	Average diam. D_p (m)	Density ρ_p (g/cm^3)	Terminal Velocity (cm/s)
Pvc	3	1.025	2.37
Pvc	1.5	1.025	0.529
Pvc	0.65	1.025	0.09
Plastic	3	1.150	2.772
Plastic	0.5	1.150	0.057

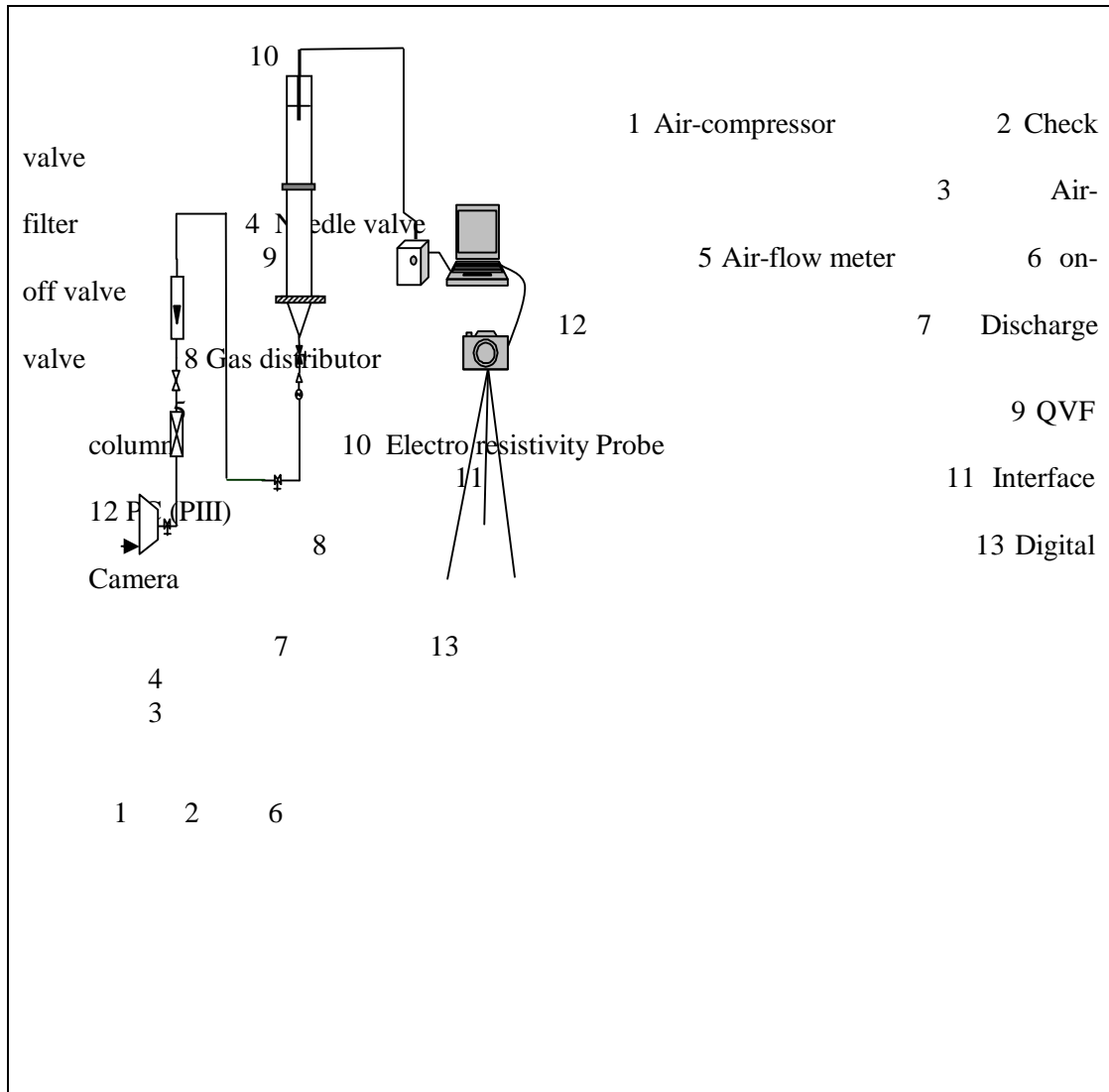


Figure (1): Schematic diagram of the experimental apparatus.

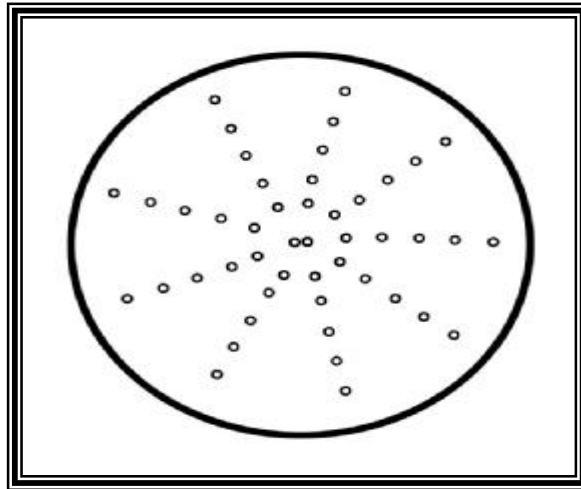


Figure (2) Shape of the gas distribution, for $D_c=15$ cm.

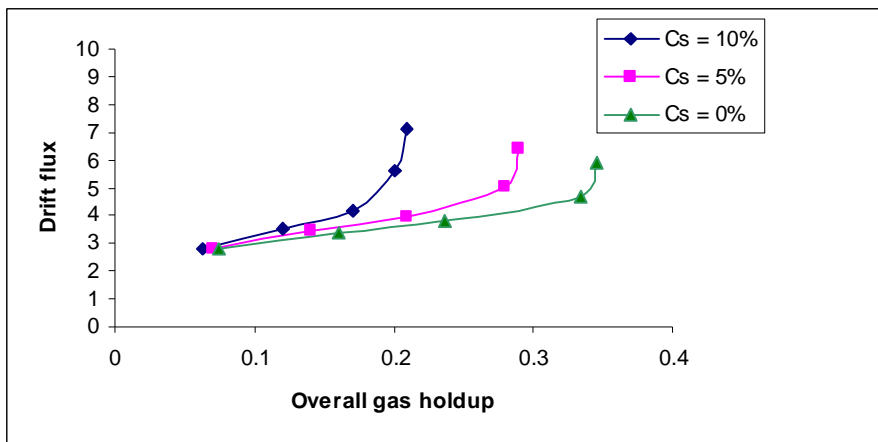


Figure (3) Drift Flux vs. Overall gas holdup for $\rho_s=1025$ kg/m³, different values of solid concentration (C_s) and ($d_p=3$ mm) .

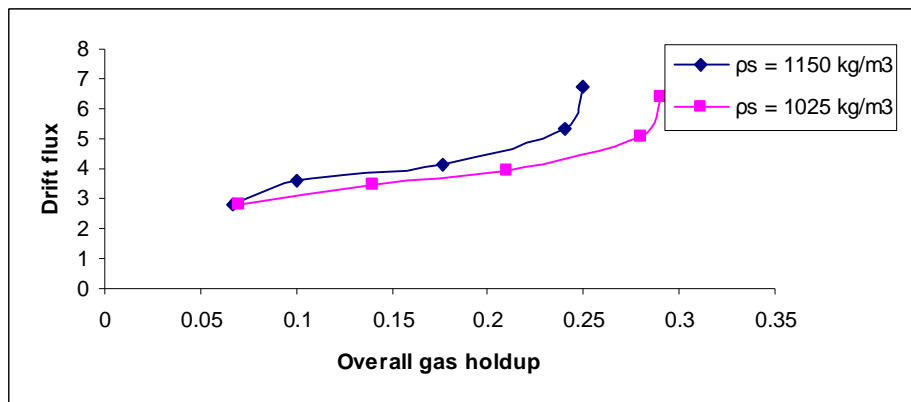


Figure (4) Drift flux vs. overall gas holdup for different densities of particles, $d_p=3\text{mm}$ at $C_s=5\%$.

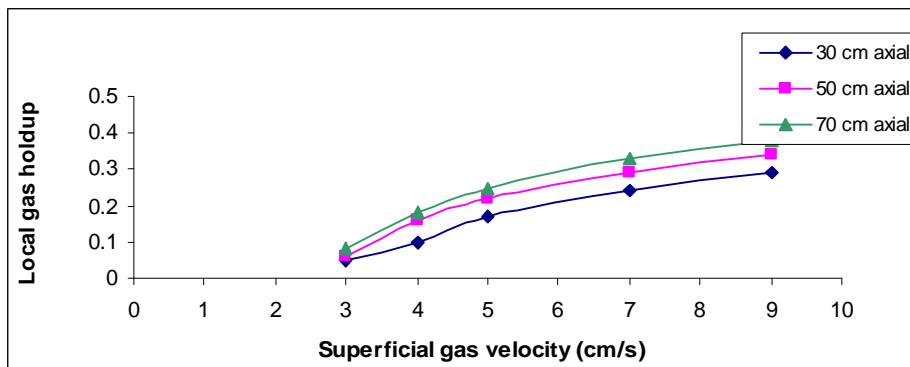


Figure (5): Local gas holdup vs. superficial gas velocity for different axial position for $\rho_s=1025\text{ kg/m}^3$, $d_p=3\text{mm}$ at $C_s=5\%$.

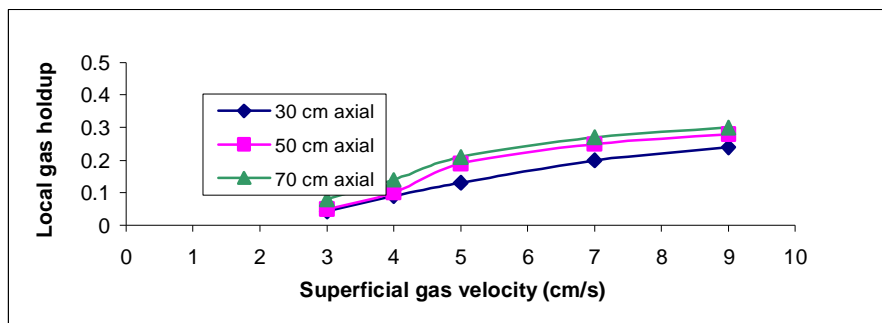


Figure (6): Local gas holdup vs. superficial gas velocity for different axial position for $\rho_s = 1150 \text{ kg/m}^3, dp=3 \text{ mm}$ at $C_s=5\%$.

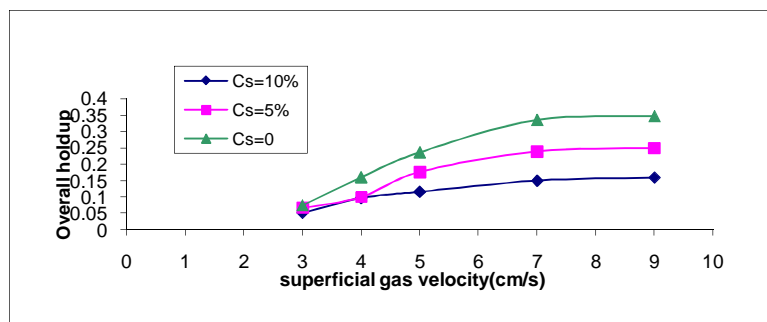


Figure (7): Overall gas holdup vs. superficial gas velocity for different C_s for $\rho_s = 1150 \text{ kg/m}^3$ at $dp=3 \text{ mm}$.

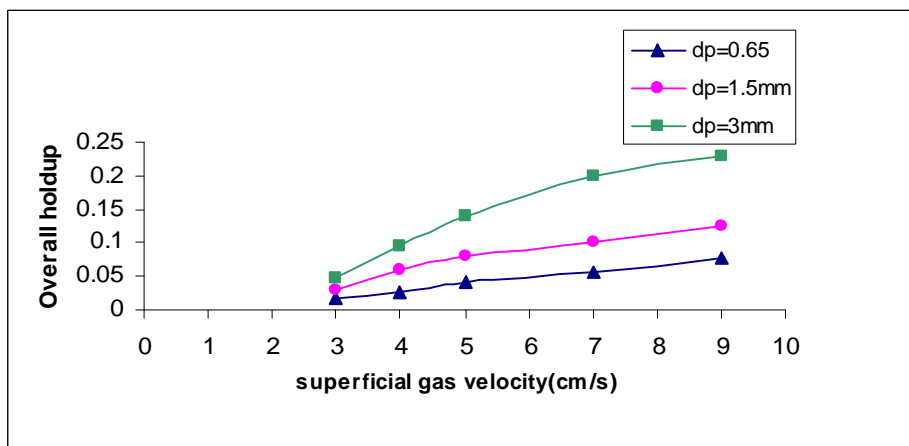


Figure (8): Overall gas holdup vs. superficial gas velocity for different Particles diameter and $C_s=10\%$ at $\rho_s = 1025 \text{ kg/m}^3$.

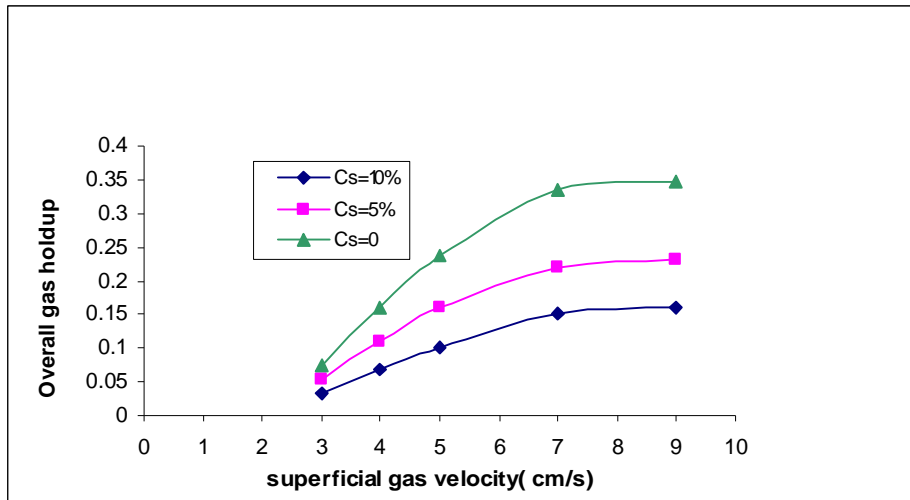


Figure (9): Overall gas holdup vs. superficial gas velocity for different Cs and binary mixture of particles at (Ma).

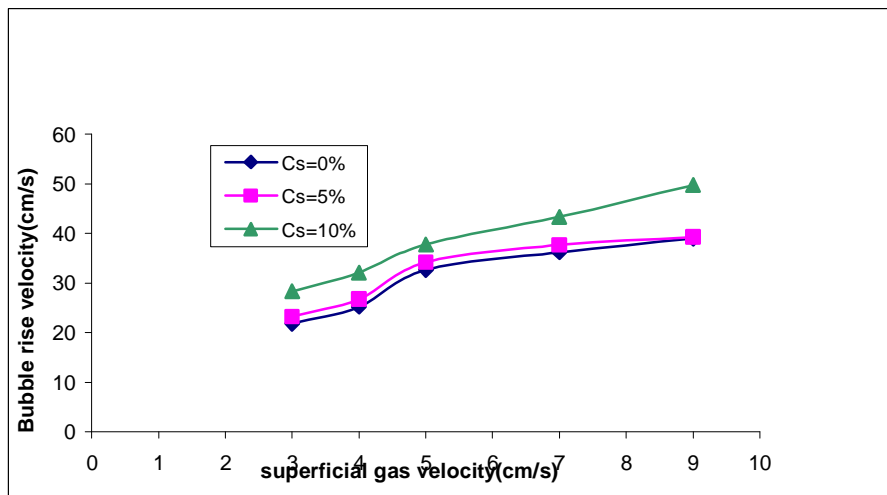


Figure (10): Bubble rise velocity vs. superficial gas velocity for $\rho_s=1025 \text{ kg/m}^3$, $d_p=3\text{mm}$ at different values of Cs and axial position at 30cm.

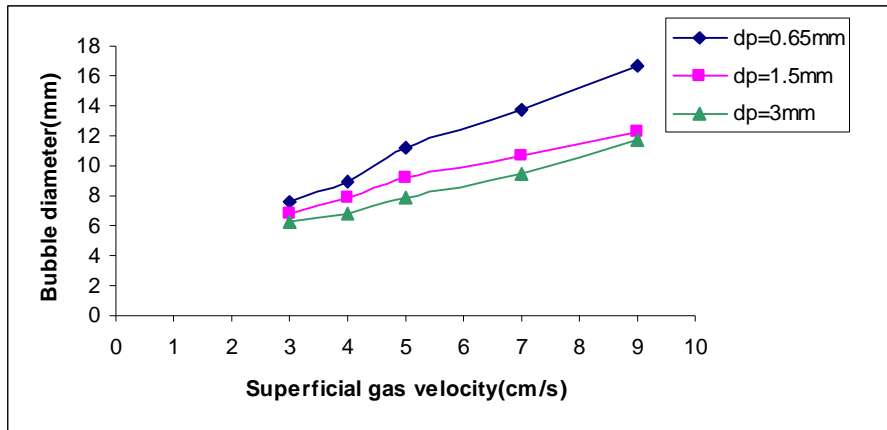


Figure (11): Bubble diameter vs. superficial gas velocity for different values of particles diameter and $C_s=10\%$ at $\rho_s=1025\text{ kg/m}^3$.

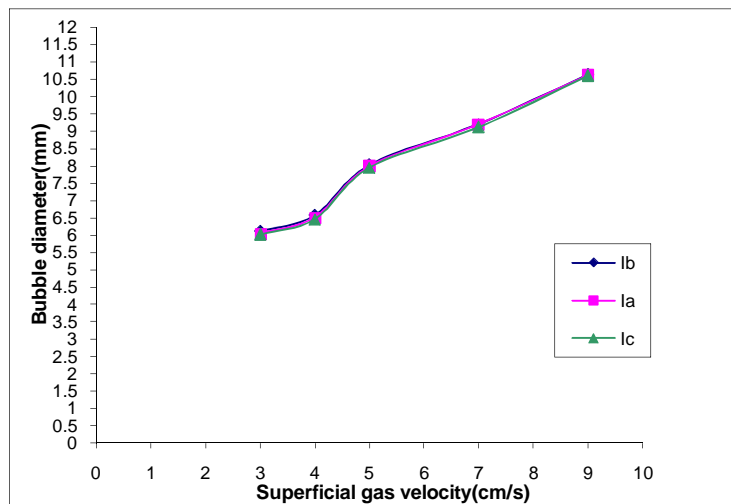


Figure (12): Bubble diameter vs. superficial gas velocity for binary mixture of particles for the same diameter ($d_p=3\text{mm}$) at $C_s=5\%$.

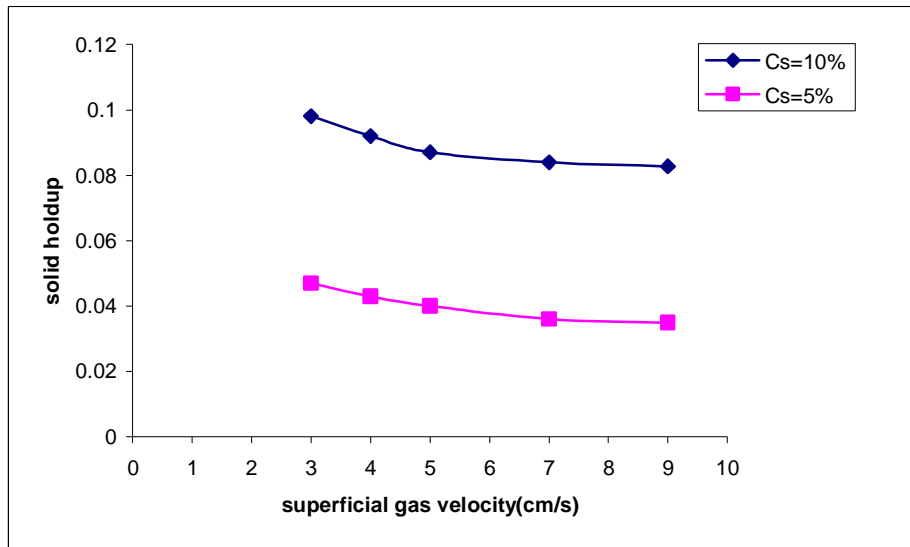


Figure (13): Solid holdup vs. superficial gas velocity for $\rho_s=1025 \text{ kg/m}^3$, different values of C_s and d_p at $d_p=3\text{mm}$.