Statistical Analysis of the Phase Holdup Characteristics of a Gas-Liquid-Solid Fluidized Bed

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Abstract

Experiments have been carried out to study the individual phase holdup characteristics in a cocurrent three-phase fluidized bed. An antenna type modified air sparger has been used in the gas-liquid distributor section, for uniform mixing of the fluids with the gas moving as fine bubbles to the fluidizing section. This arrangement also reduces the pressure drop encountered through a conventional distributor used for the purpose. To overcome the non-uniformity of flow through the column (i.e. the central region), a distributor plate with 20% open area has been fabricated with concentric circular punched holes of increased diameter from centre to the wall. Model equations have been developed by factorial design analysis for predicting various individual phase holdups.

Key words: Fluidization; Gas holdup; Liquid holdup; Solid holdup; Statistical design analysis; Multiphase flow

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Introduction

A three phase fluidized bed, as defined in this study, is a batch of solid particles which are fluidized by cocurrent up-flow of liquid as the continuous phase and gas as the dispersed bubble phase. Of late, the applications of three phase fluidized beds have been increasing in the chemical and biochemical processing units. Therefore, the hydrodynamic properties such as the phase holdups, bubble properties and the mixing characteristics have to be investigated in order to provide the basic information required for the design of such fluidized beds. Among the hydrodynamic properties, the most important ones for analyzing the performance of a three phase fluidized bed is the bed porosity and the individual phase holdups. Various aspects of such fluidized bed systems have been reviewed by several investigators (Baker et al. (1981); Epstein (1981); Kato et al. (1981); Muroyama and Fan (1985); Yu and Kim (1986); Fan (1989); Okamura et al. (1989); Han et al. (1990); Lee et al. (2001); Lee et al. (2004).

For chemical processes where mass transfer is the rate limiting step, it is important to estimate the gas holdup since this relates directly to the mass transfer (Fan et al. (1987); Schweitzer et al. (2001). Although gas holdup in three phase fluidized beds have received significant attention as summarized in various reviews, in most of the previous work air, water, and small glass beads has been used as the gas, liquid, and solids, respectively. This combination limits the generality and usefulness of the results. The gas holdup in such systems is often considerably lower than that for a pilot-plant or an industrial-scale unit (Safoniuk et al. (2002)).

One of the characteristics of a three-phase fluidized bed of low-density particles which distinguishes it from that of a high-density one is the axial nonhomogeneity of the holdup (i.e. volume fraction) of the phases. Nonhomogeneity of the axial phase holdup is also common in slurry bubble columns. While the behavior of a slurry bubble column has been

extensively reported in literature, only a few studies have addressed the nonhomogeneity of the phase holdups in case of three-phase fluidized bed. These studies have been primarily concerned with the freeboard behavior involving large (d_p > 0.0048 m) or heavy but small particles (Catros et al. (1985)).

The bed height and the individual phase holdups have been determined from static pressure profiles up the entire height of the column (Kim et al. (1972), (1975)).The bed height was taken as the point at which a change in the slope of the pressure profiles was observed. The bed characteristics have been studied at considerably higher values of gas velocities and over a wider range of liquid surface tension and viscosity. The local liquid holdup was directly measured by the electro conductivity technique (Muroyama and Fan (1985)). A capacitance probe technique was also employed to measure the solid and the liquid holdups (Yu and Rittman (1997)).

To obtain average gas holdups across the ebulated bed, pressure drops were measured across the bed height (Dhanuka and Stepanek (1978); Darton and Harrison (1975); Dargar and Macchi (2006)). Assuming negligible acceleration and wall friction, the measured pressure drop is related directly to the density of the individual phases by,

$$\frac{\Delta P}{\Delta H} = g(\rho_g \varepsilon_g + \rho_l \varepsilon_l + \rho_s \varepsilon_s) \qquad (1)$$

The solids holdup can be calculated based on the overall bed expansion (Jean and Fan, 1986) and the known solids loading of the bed,

$$\varepsilon_s = \frac{M_s}{\rho_s A H_e} \qquad (2)$$

Since the only phases present in the bed are the gas, liquid, and the particles,

$$\varepsilon_l = (1 - \varepsilon_s - \varepsilon_g) \qquad (3)$$

Equations (1) - (3) constitute three equations with three unknowns, and, hence, allow the overall gas holdup to be estimated.

While the bed height in equations (1) and (2) is obtained either visually or from the measured pressure drop gradient (Kim et al. (1975)), a more direct method of measuring ε_g is to simply isolate a representative portion of the test section by simultaneously shutting two quick closing valves and measuring the fraction of the isolated volume occupied by the gas (Epstein(1981). Other most promising methods of measuring the local gas holdup are electro-conductivity method reported by Bhatia and Epstein (1974), γ-ray transmission measurement by Ostergaard (1977), electroresistivity by Begovich and Watson (1978) and radioactive tracer technique by Yu and Rittman (1997).

In the present investigation, an attempt has been made to study the phase holdup characteristics of a co-current three-phase fluidized bed with a modified antenna type air sparger using liquid as the continuous phase and gas as the discontinuous phase. Spherical glass beads have been used as the solid phase. These have been done to predict phase holdups in low-to-moderate Reynolds number range and to see any improvement in gas holdup by the use of the modified antenna type air sparger. The aim of using such an air sparger is to lower the pressure drop in the distributor section that occurs in a conventional design. Statistical design approach i.e. factorial design analysis (Davies (1978)) has been applied to develop model equations for individual phase holdups. The advantage of the method is that it provides the knowledge of interacting effects of the operating variables.

Experimental system and procedure

A schematic representation of the experimental setup is shown in Fig. 1. The experimental fluidized bed consists of three sections, v.i.z., the test section, the gas-liquid distributor section, and the gas-liquid disengagement section. The test section is the main component of the fluidizer where fluidization takes place. It is a vertical cylindrical Plexiglas column of 0.1 m internal diameter and 1.88 m long. The entrained particles are retained on

the 16-mesh screen attached to the top of the column. The gas-liquid distributor is located at the bottom of the test section and is designed in such a manner that uniformly distributed liquid and gas mixture enters the test section. The distributor section made of Perspex is fructo-conical of 0.31 m in height, and has a divergence angle of 4.5^0 with one end of 0.0508 m in internal diameter and the other of 0.1 m in internal diameter. The liquid inlet of 0.0254 m in internal diameter is located centrally at the lower cross-sectional end. The higher cross-section end is fitted to the test section, with a perforated distributor plate made of G.I. sheet of 0.001 m thick, 0.12 m diameter having open area equal to 20 % of the column cross-sectional area with a 16 mesh (BSS) stainless steel screen in between. Totally 288 numbers of 0.002 m, 0.0025 m and 0.003 m holes have been drilled in triangular pitch made in 10 concentric circles of nearly 0.005 m radial gap. The size of the holes has been increased from inner to outer circle. This has been done with a view to have less pressure drop at the distributor plate and a uniform flow of the fluids into the test section. There is an antenna-type air sparger of 0.09 m diameter just below the distributor plate containing 50 number of 0.001 m holes, for generating uniform air bubbles of smaller size to flow throughout the cross-section of the column. In this section the gas and the liquid streams are merged and passed through the perforated grid. The mixing section and the grid ensured that the gas and liquid are well mixed and evenly distributed into the test section. The gas-liquid disengagement section at the top of the column is a cylindrical section of 0.026 m internal diameter and 0.034 m height, assembled to the test section with 0.08 m of the test section inside it, which allows the gas to escape and liquid to be circulated through the outlet of 0.0254 m internal diameter at the bottom of this section.

For pressure drop measurement in the bed, the pressure ports have been fitted to the manometers filled with carbon tetrachloride. Pressure ports are available at seven different levels of equal spacing including one each at the bottom and the top of the test section. This

has been made to measure the pressure drops at a particular section at three different radial positions viz. at the wall, at the center of the column and at one fourth of the diameter of the column from the wall. This arrangement enables a clear investigation of the wall effect, distribution of particle concentration and the gas holdup can be studied clearly.

The three phases viz. the solid, the liquid and the gas are glass beads, tap water and the oil free compressed air respectively. The scope of the experiment is presented in Table 1. The air-water flow was co-current and upwards. Accurately weighed amount of material was fed into the column and adjusted for a specified initial static bed height. Water was pumped to the fluidizer at a desired flow rate using water rotameter. The air was then injected into the column through the air sparger at a desired flow rate using air rotameter. Three calibrated rotameters with different ranges each for the water as well as for the air was used to for the accurately record of the flow rates. Approximately five minutes was allowed to make sure that the steady state was reached. The readings of the manometers and the expanded heights of the bed were then noted. For gas holdup measurement, the quick closing valves (9, Fig. 1) in the water and the air line were closed simultaneously. At first free board experiment with wide variation of gas and liquid flow were conducted to calculate the two phase fractional gas holdup using Eq. (4).

$$\varepsilon_g = \left(\frac{H - H_L}{H} \right) \tag{4}$$

Similarly the gas holdup was calculated for the fluidization experiment with the solid phase. The gas holdup in the three-phase region is calculated by subtracting the gas holdup in the two-phase region above the three-phase zone. The region above the expanded bed was the two-phase region. The values of minimum fluidization velocity for every run were obtained by plotting pressure drop across the bed against varying water flow rates with a constant air

flow rate. The procedure was repeated for different materials and at varying initial static bed heights.

Results and discussion

Experiments were conducted with the gas and the liquid velocities varying from 0 - 0.12 m/s and from 0 – 0.1486 m/s respectively. To ensure steady state in operation at least five minutes were allowed. The readings for bed expansion and pressure drop were then noted down. Thereafter the gas and the liquid flows were shutoff simultaneously by operating the quick closing valves and readings for the level of liquid-solid mixture were noted down. Each experiment was repeated thrice to have the accurate reading. The gas, liquid and solid holdups were calculated using Equations (2) to (4). The experimental results have been presented graphically in this section. Empirical equations have also been developed.

Gas holdup

Figure 2 shows the variation of fractional gas holdup with superficial liquid velocity at different values of fixed superficial gas velocity. It is seen from the figure that with increasing liquid velocity, the gas holdup decreases. However the variation of fractional gas holdup with liquid velocity is very small. It has been reported by Safoniuk et al. (2002) that the fractional gas holdup is practically unaffected by the liquid velocity except at very high liquid superficial velocities. According Breins et al. (1997) the gas holdup decreases with liquid velocity but at higher liquid velocity range it remains almost constant. Dhanuka and Stepanek (1978), Begovich and Watson (1978), Lee and Lasa (1987) have reported a slight decrease in gas holdup with liquid velocity over large a range of the later. At higher liquid velocity large number of fine bubbles are possible as the flow regime is completely distributed or dispersed, for which the gas holdup should be more. But the decrease in gas holdup with liquid velocity may possibly be due to the fact that at higher liquid velocity the

bubbles are fast driven by the liquid. The residence time of the bubbles decreases with the liquid velocity and hence the gas holdup is likely to decrease.

Figure 3 represents the variation of fractional gas holdup with superficial gas velocity, at constant liquid velocities. As seen from the figure, the fractional gas holdup increases monotonically with the gas velocity having higher value of the slope at low gas velocities. This corroborates the findings of Begovich and Watson (1978), Dhanuka and Stepanek (1978), Lee and Lasa (1987), Briens et al. (1997), Safoniuk et al. (2002), and Dargar and Macchi (2006). In the lower range of gas velocity, an increase in gas velocity results in the formation of a larger number of gas bubbles without appreciable increase in the bubble diameter. Therefore an increasing fractional gas holdup is observed. As gas velocity increases, the bubble size grows due to bubble coalescence, and relatively the gas holdup decreases. As the experiment has been conducted for the gas velocity range pertaining to the distributed bubble regime, the decrease in slope is not significant which is observed for the transformation from bubble to the slug flow regime.

In Figure 4 a peculiar behaviour of the variation of fractional gas holdup with superficial liquid velocity is seen for different particle sizes. The gas holdup decreases with liquid velocity. But the variation of gas holdup is different for different sizes. This can be divided into two ranges of liquid velocities for each particle size. In the low liquid velocity range, higher the particle size less is the fractional gas holdup. But in the higher velocity range, the value of gas holdup increases with particle size. Actually the plot presents the gas holdup for both the fixed and the fluidized bed regimes. The gas holdup is low in the fixed bed regime for higher size particle. It is a well known fact that smaller the bubble size i.e. in the distributed bubble flow regime the gas holdup is more. This phenomenon can explain the lower gas holdup for higher size particle in the low liquid velocity range. Higher the particle size higher is the liquid minimum fluidization velocity. In the fixed bed of higher size

particles, the interstitial void is large thus higher size of bubbles may be possible which produce a low value of observed gas holdup. But in the higher liquid velocity range i.e. in fluidization regime due to interaction with higher mass of particles, the bubble size may be less for particles of higher sizes due to frequent bubble breakage. Kim et al. (1975) have reported the existence of critical particle size of 0.0025 m in diameter for glass beads of same density for the air-water system, which separates the "bubble coalescing regime" from the "bubble disintegrating regime". They have reported bubble disintegrating regime for higher size particles and consequently higher gas holdup. Fan et al. (1987) have shown opposite behaviour for 0.001 m, 0.003 m, 0.004 m, 0.006 m glass beads in aqueous solution of 0.5-wt% of t-pentanol. With increase in particle size, reduced gas holdup has been reported by them.

Development of model equation

Model equation based on factorial design analysis (Davies, 1978) has been developed for the gas holdup. The method of factorial design analysis bring out the interaction effects of variables, which would not be found otherwise by conventional data analysis technique and to explicitly find out the effect of each of the variables quantitatively on the response. In this method the experiments are repeated twice or thrice at two levels of each operating conditions i.e. one at lower level (-1 level) and the other at higher level (+1 level).

The variables which affect gas holdup in fluidization are static bed height, particle size, liquid and gas velocity, sparger orifice diameter, density of gas, density of liquid and solid, viscosity of gas and liquid, surface tension of liquid and the gravitational constant. In the present investigation only four important parameters viz. static bed height, particle size, liquid velocity and gas velocity have been varied. The scope of the factors considered for factorial experimentation is presented in Table 2. Thus total numbers of experiments required

at two levels for the four variables is 16 for the gas holdup. Each experiment is repeated three times and the average of the values is reported as response value (measured gas holdup). The experiments have been conducted at other levels to test the reproducibility of the data on comparison with experimental values to those calculated from the developed model equations.

In this method the model equations are assumed to be linear with respect to the level of each of the variable and the final equation takes the general form,

$$Y = (b_0 + b_1 A + b_2 B + b_3 C + ... + b_{12} AB + b_{13} AC + ... + b_{123} ABC + ... + b_{1234} ABCD) \quad (5)$$

In equation (5), the first term is a constant, the terms with only A, B, C etc. show the main effect of different variables and the terms with AB, AC, …, ABC, ABD.., and ABCD show the interacting effect of two variable, three variable and four variables respectively.

i) Coefficients are calculated by the Yates technique;

$$b_i = \sum \frac{\alpha_i Y_i}{N} \quad (6)$$

Where b_i is the coefficient of various terms in equation (5), Y_i is the response (gas holdup), α_i is the level of the variable (either -1 or +1) and N is the total number of treatments.

ii) Calculations of the level of variables for gas holdup

A: Level for static bed height= (Static bed height – 0.272)/0.095

B: Level for particle diameter = (Particle diameter - 0.003115)/0.000935

C: Level for gas velocity = (Gas velocity – 0.06)/0.04

D: Level for liquid velocity = (Liquid velocity – 0.03925)/0.03505

The level of a variable is calculated by the formula: level of variable = [value of the variable – the average of the values of variable at minimum level (-1) and maximum level (+1)] / (magnitude of the difference of average value to the value at minimum or maximum level).

The experimental data based on factorial design and the nature of the effects has been presented for gas holdup in Table 3. In this table the column (4) has been derived from the response column (3) by summing and differencing successive pairs and the columns (5), (6), and (7) have derived from the previous one in the same way. This is done to see the effect of the variation of the operating variable on the response. The effect of the operating variable on the response calculated from column (7) has been presented in column (8). Column (9)

presents the sum of squares of the deviations from the mean. Column (10) represents the percentage contribution of each treatment combination i.e. if the variation is made in the combination how much the response is affected. It has been calculated from column (9) by dividing the total sum of squares and multiplying by 100.

The following equation has been obtained,

$$Y = 0.104729 + 0.052555C - 0.01564D - 0.00429BC) \quad (7)$$

The value of the coefficient indicates the magnitude of the effect of the variables and the sign of the coefficient gives the direction of the effect of the variable. That is a positive coefficient indicating an increasing in the value of the responses with increase in the value of the variable and a negative coefficient showing that the response decreases with increase in the value of the variable. The calculated values of gas holdup from equation (7) have been compared with experimental data taken at conditions other than those used for the development of the model equation and they have been found to agree within a standard deviation of ±10 per cent. The comparison of data for gas holdup is presented in the Figure 5. Figure 6 shows the comparison of experimental values of gas hold up with the calculated values from the correlations developed by Kato et al. (1985), Hugmark et al. (1967), Hitika et al. (1974 and 1980), Saberian et al. (1984) and Nikov et al. (1990).

Liquid holdup

Figures 7 and 8 present the variation of liquid holdup with liquid velocity at various fixed gas velocities and with gas velocity at different fixed liquid velocities respectively. It has been observed that with the increase in liquid velocity the liquid holdup increases fast and with increase in gas velocity at constant liquid velocity the liquid holdup decreases. The effect of liquid velocity and particle size on liquid holdup is shown in Figure 9. It is seen that with increase in particle size the liquid holdup decreases. The observed trends are in agreement with reported values (Bhatia and Epstein, 1974; Dhanuka and Stepank, 1978).

Development of model equation

Model equation based on factorial design analysis (Davies, 1978) has been developed for the liquid holdup. The scope of the factors considered for factorial experimentation is same as for the gas holdup and is presented in Table 2. The same variables affect the liquid holdup.

The experimental data based on factorial design, nature of the effects are presented for liquid holdup in Table 4.

The following equation has been obtained,

$$Y = 0.370493 - 0.03472B + 0.156263D - 0.02654BCD) \quad (8)$$

The calculated values of liquid holdup from equation (8) are compared with experimental data taken at conditions other than those used for development of the model equation and those have been found to agree within a standard deviation of ±10 %. The comparison of data for liquid holdup is presented in the Figure 10. The comparison of experimental values of liquid holdup with the values calculated from different correlations has been presented in Figure11. It is very interesting to note that the values are in quite good agreement with the values reported in literature.

Solid holdup

Figures 12 and 13 present the variation of solid holdup with liquid velocity at various fixed gas velocities and with gas velocity at different fixed liquid velocities respectively. It is seen that with increase in liquid and gas velocity the solid holdup decreases. The effect of liquid velocity and particle size on solid holdup is shown in Figure 14. It is seen that solid holdup increases with increase in particle size.

Conclusions

A systematic step by step detailed investigation have been carried out to study the effect of static bed height, particle size, liquid velocity and gas velocity on phase holdups in a gas-liquid-solid system. An antenna type modified air sparger has been used in the gas-liquid

distributor section, for uniform mixing of the fluids with the gas moving as fine bubbles to the fluidizing section. This arrangement also reduces the pressure drop encountered through a conventional distributor used for the purpose. To overcome the non-uniformity of flow through the column (i.e. the central region), a distributor plate with 20% open area has been fabricated with concentric circular punched holes of increased diameter from centre to the wall. Results indicate that the gas holdup increased monotonically with increasing gas velocity. At a fixed gas velocity, at low liquid velocity gas holdup decreases and remains constant with further increase in liquid velocity. In general, gas holdup decreased with increase in particle size. Liquid holdup increased steadily with increase in liquid velocity and decreased with increase in gas velocity. Liquid holdup decreases with increase in particle size. Solid holdup decreases with increase in liquid and gas velocity. Solid holdup increases with increase in particle size. Experimental study based on statistical design has been made to obtain the phase holdup of a three-phase fluidized bed. The experimental values thus obtained have been compared with those predicted by the correlations and have been found to agree well.

Nomenclature

A cross-sectional area of the column, (m^2)

b_i coefficient

d_p particle diameter, (m)

g acceleration due to gravity, (m/s^2)

H total height of test section, (m)

H_e height of expanded bed, (m)

H_l height of the liquid in the column after escape of gas, (m)

H_s initial static bed height, (m)

M_s mass of the solid in the bed, (kg)

N total number of treatments

$\frac{\Delta P}{\Delta H}$ pressure gradient in the bed, (Pa/m)

Re_l liquid Reynolds number ($\rho_l V_l d_p/\mu_l$)

Re_g modified gas Reynolds number (β_u* Re_l)

V_g gas velocity, (m/s)

V_l liquid velocity, (m/s)

Y_i response

Greek Symbols

μ phase viscosity, (Pa .s)

α_i level of the variable

$\varepsilon_g, \varepsilon_l, \varepsilon_s$ gas, liquid and solids holdups

ρ_g, ρ_l, ρ_s gas, liquid and particle density, (kg/m^3)

Subscripts

g gas phase
l liquid phase
s solid phase

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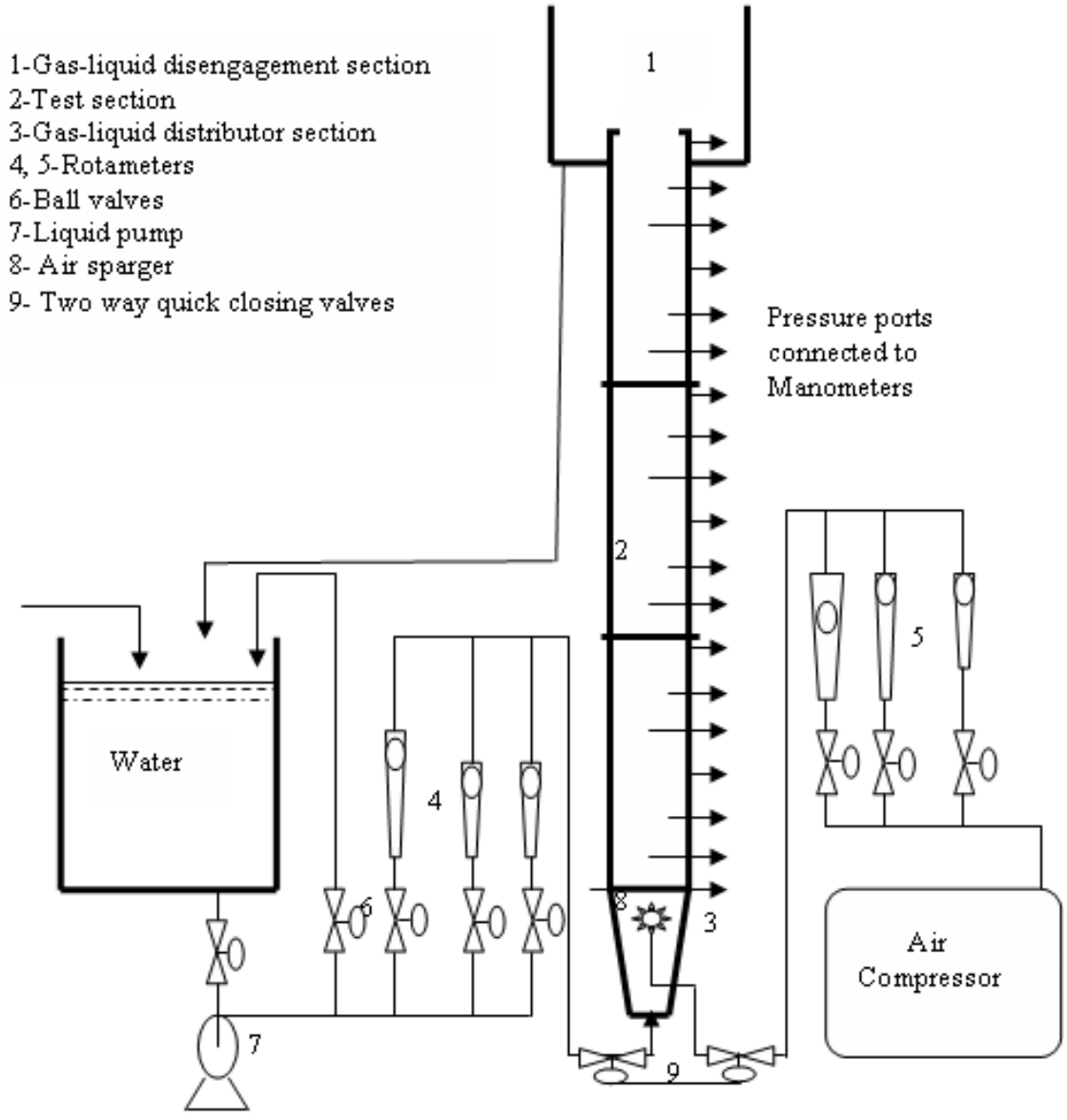

Figure 1. Schematic representation of the three-phase fluidized bed.

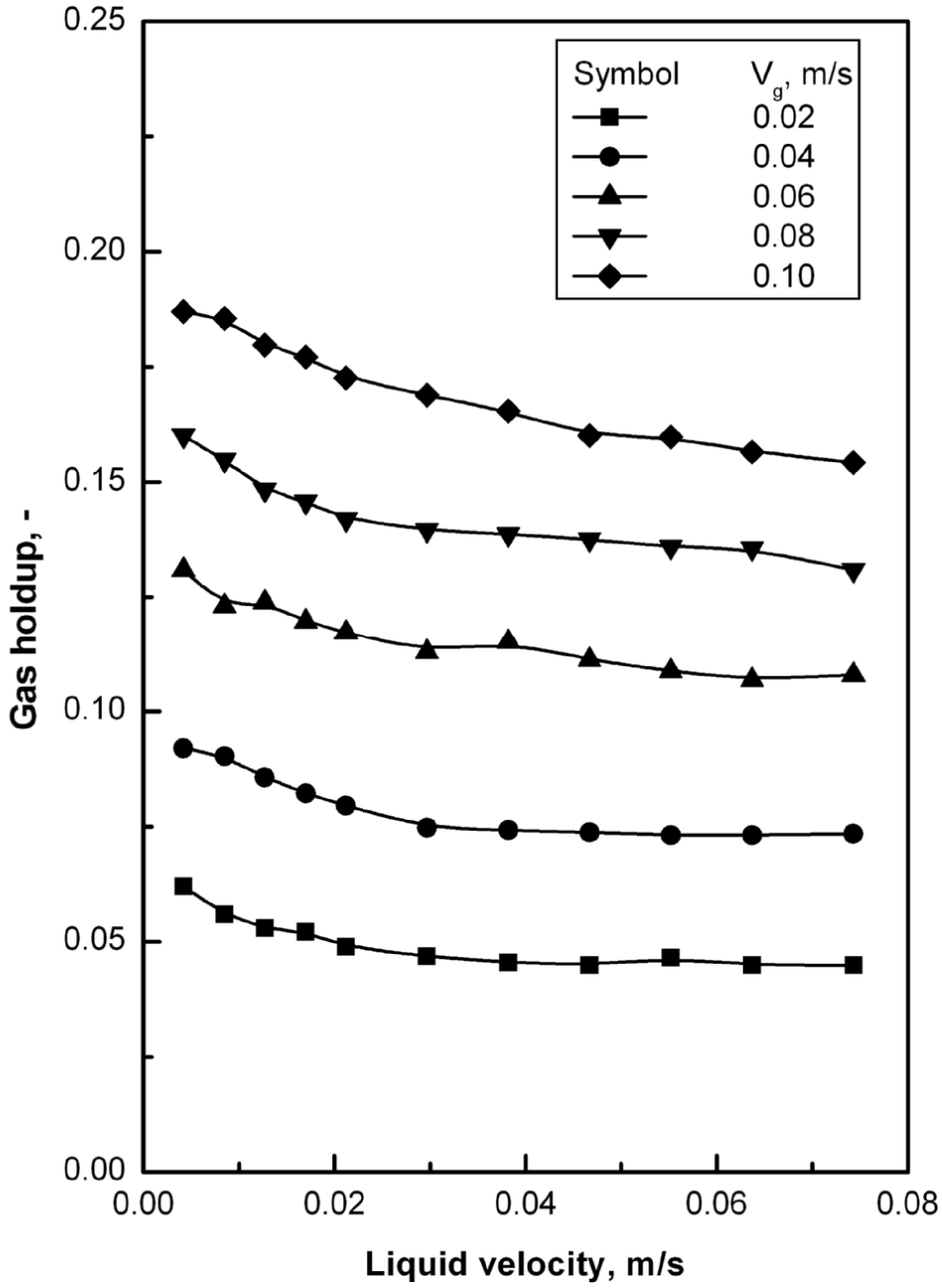

Figure 2. Variation of gas holdup with liquid velocity for different gas velocities at [H_s = 0.177 m, d_p = 0.00218 m].

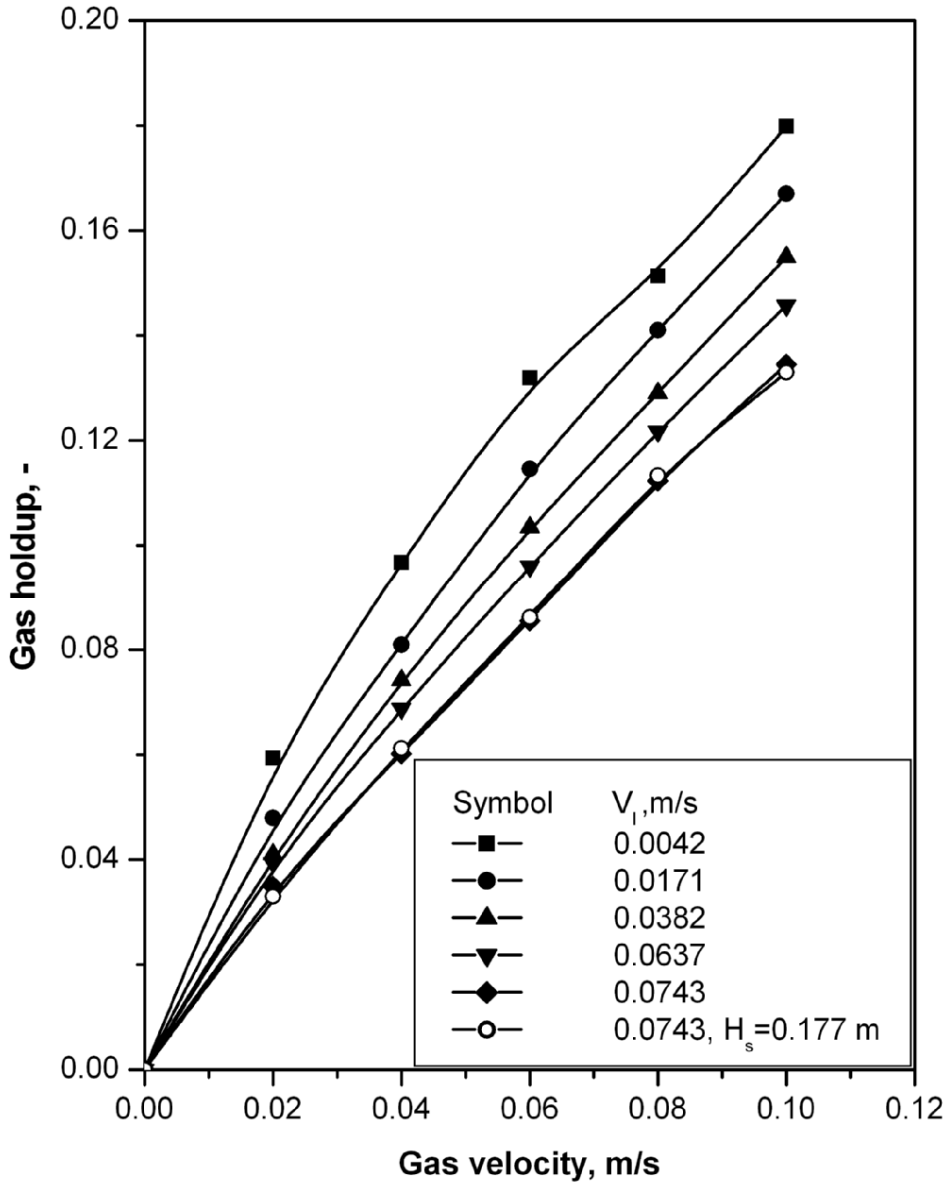

Figure 3. Variation of gas holdup with gas velocity for different liquid velocities at [H_s = 0.367 m, d_p = 0.00218 m].

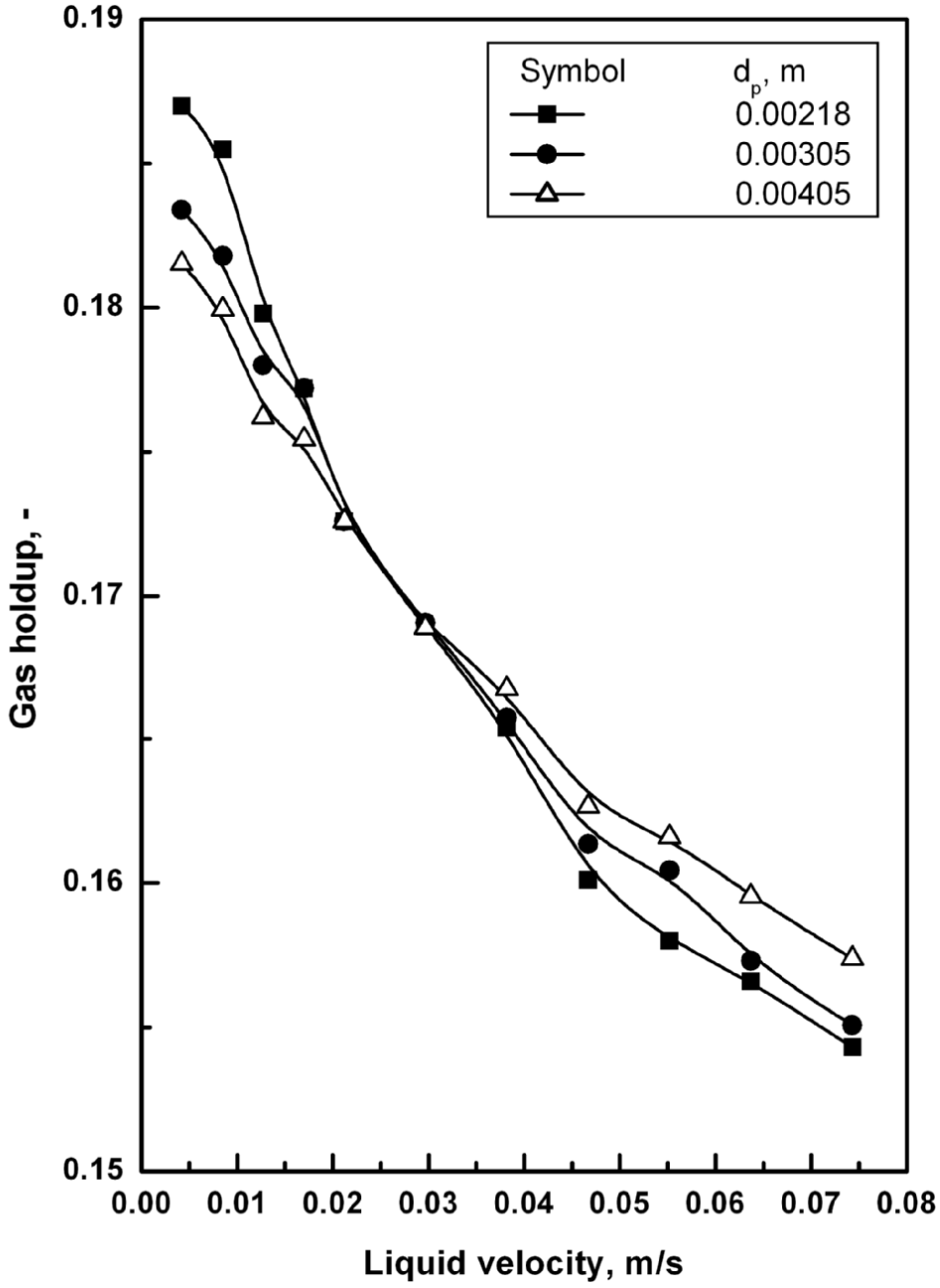

Figure 4. Variation of gas holdup with liquid velocity for different particle sizes at [H_s = 0.367 m, V_g = 0. 10 m/s].

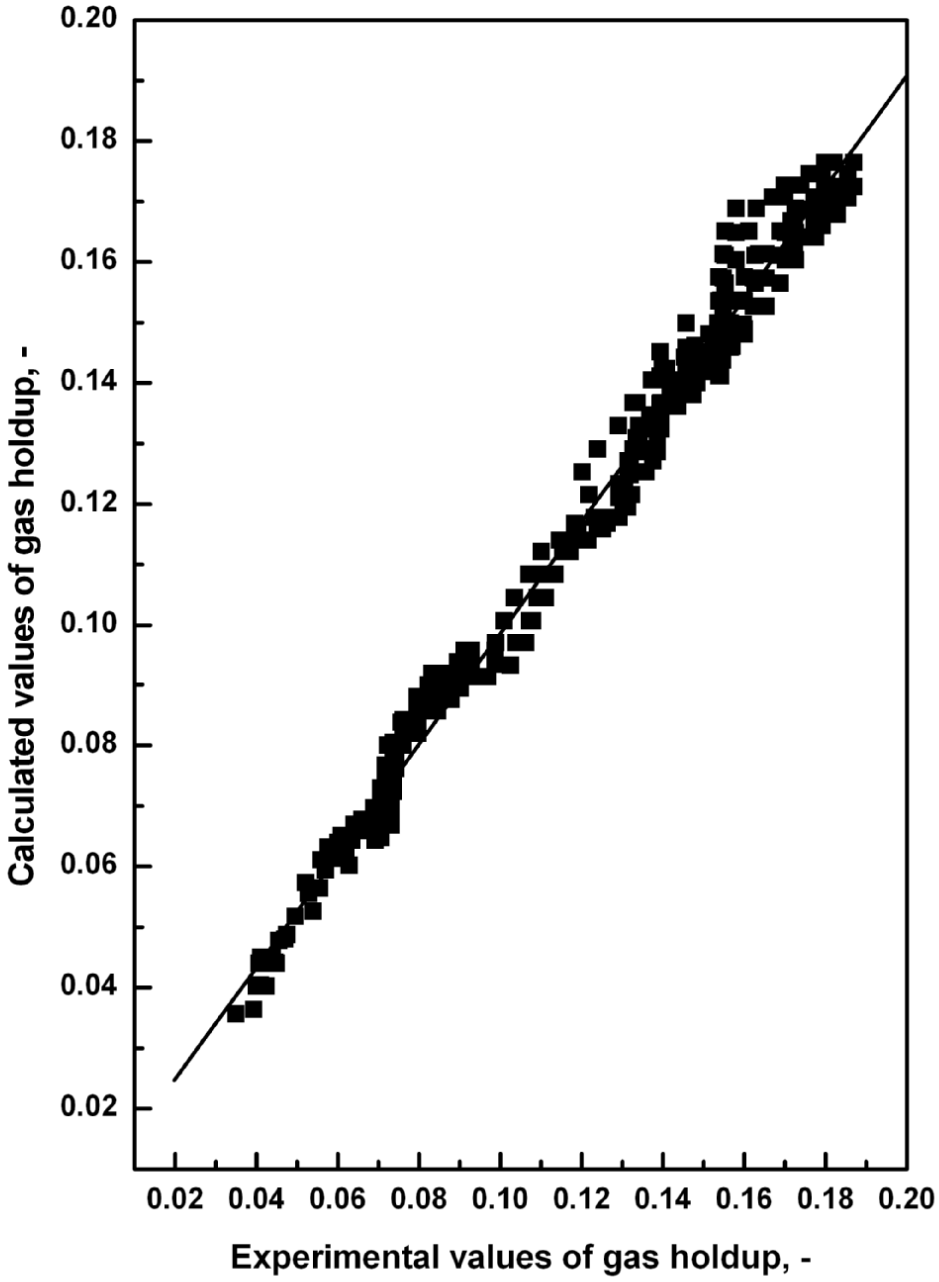

Figure 5. Comparison of experimental values of gas holdup with those calculated from factorial design equation (7).

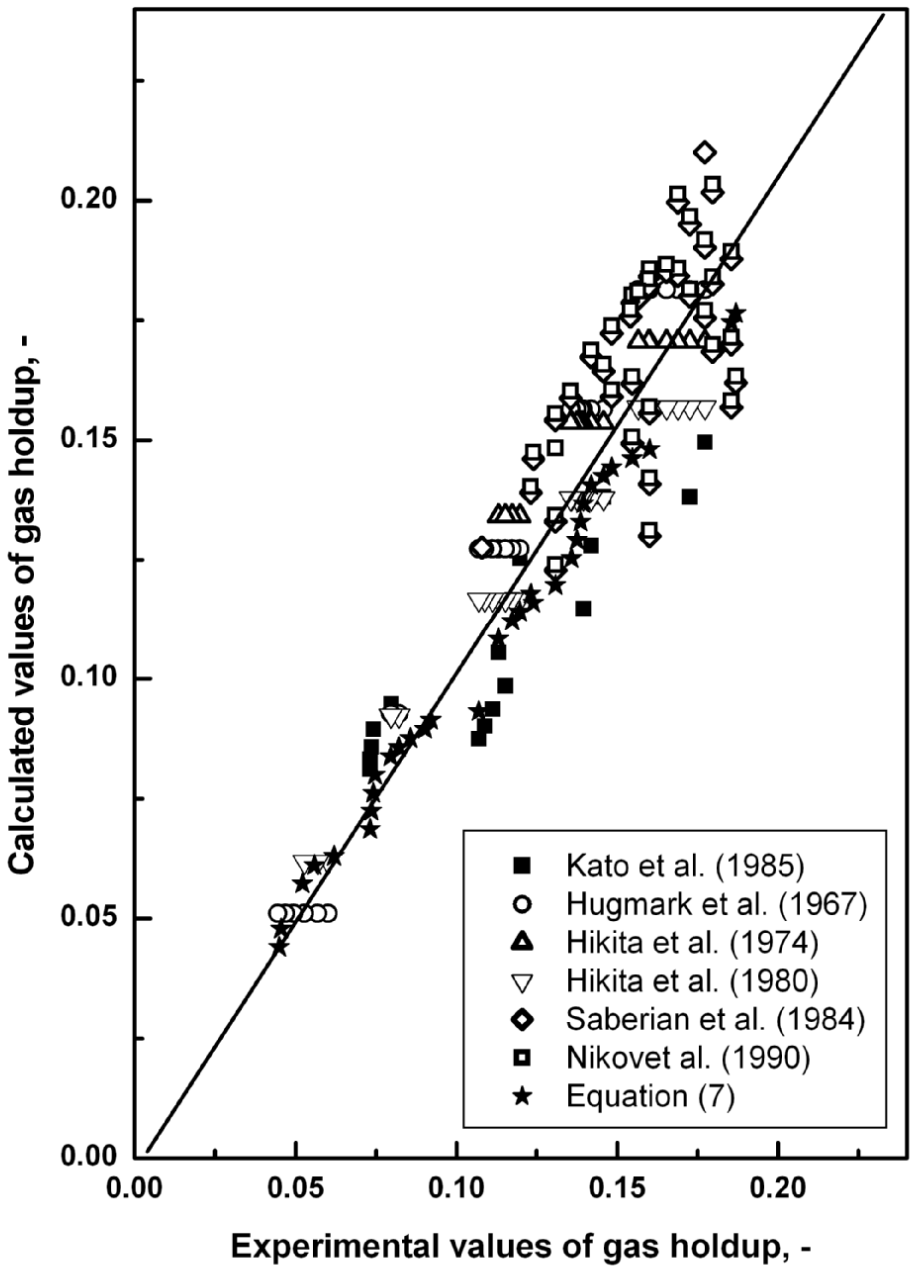

Figure 6. Comparison of experimental values of gas holdup with those calculated from reported values in the literature.

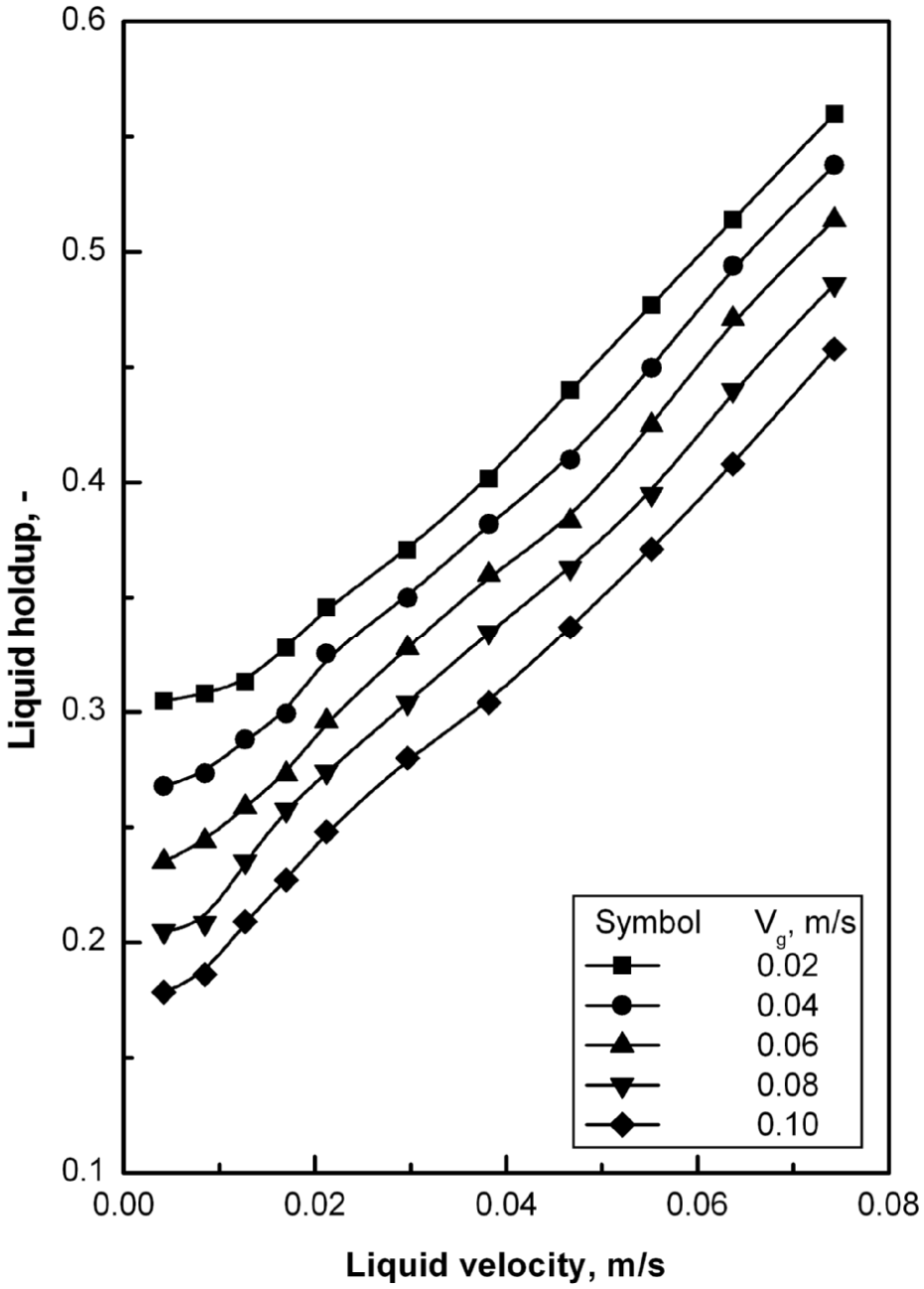

Figure 7. Effect of liquid velocity on liquid holdup for different gas velocity at [H_s = 0.267, d_p = 0.00218 m].

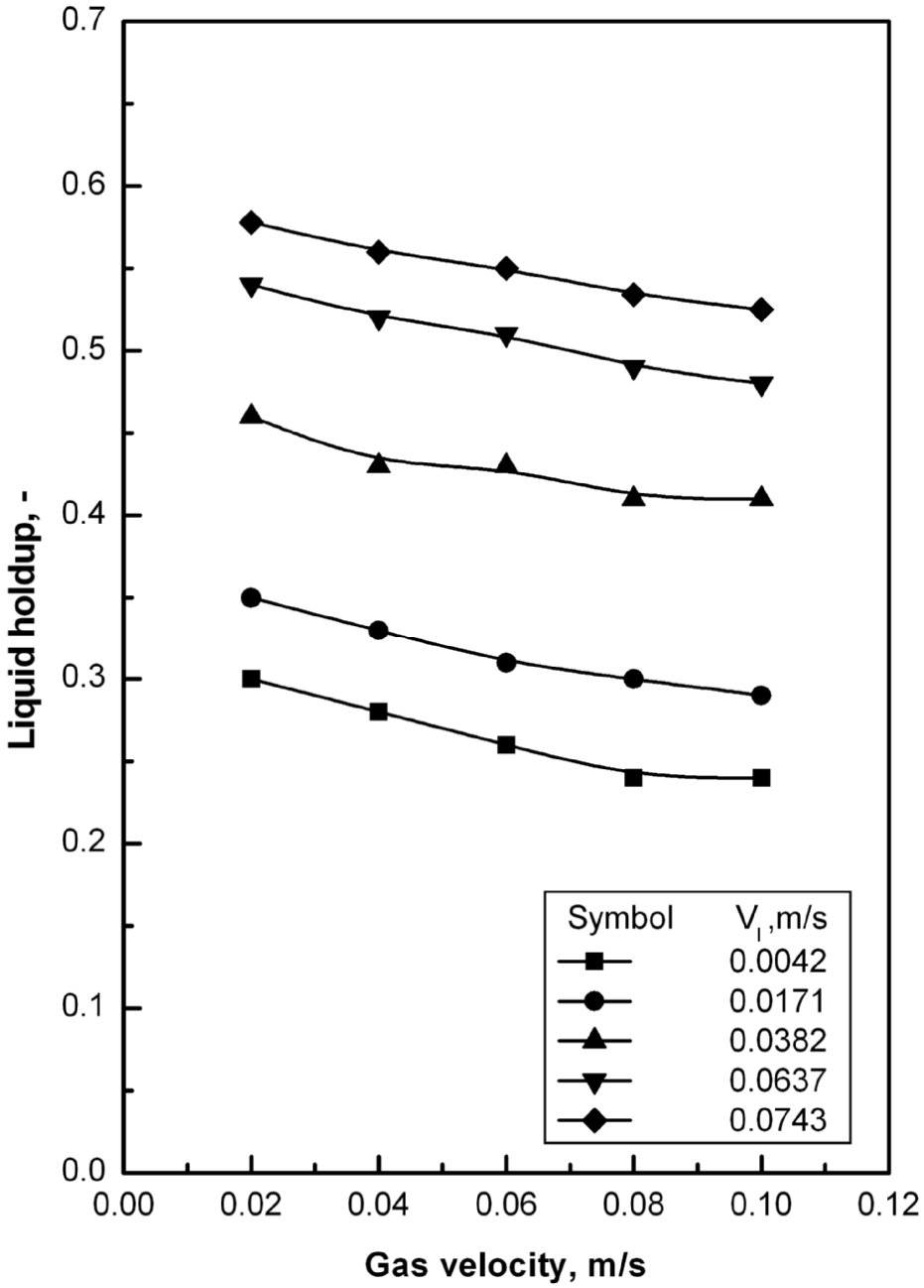

Figure 8. Effect of gas velocity on liquid holdup for different liquid velocity at [H_s = 0.367 m, d_p = 0.00218 m].

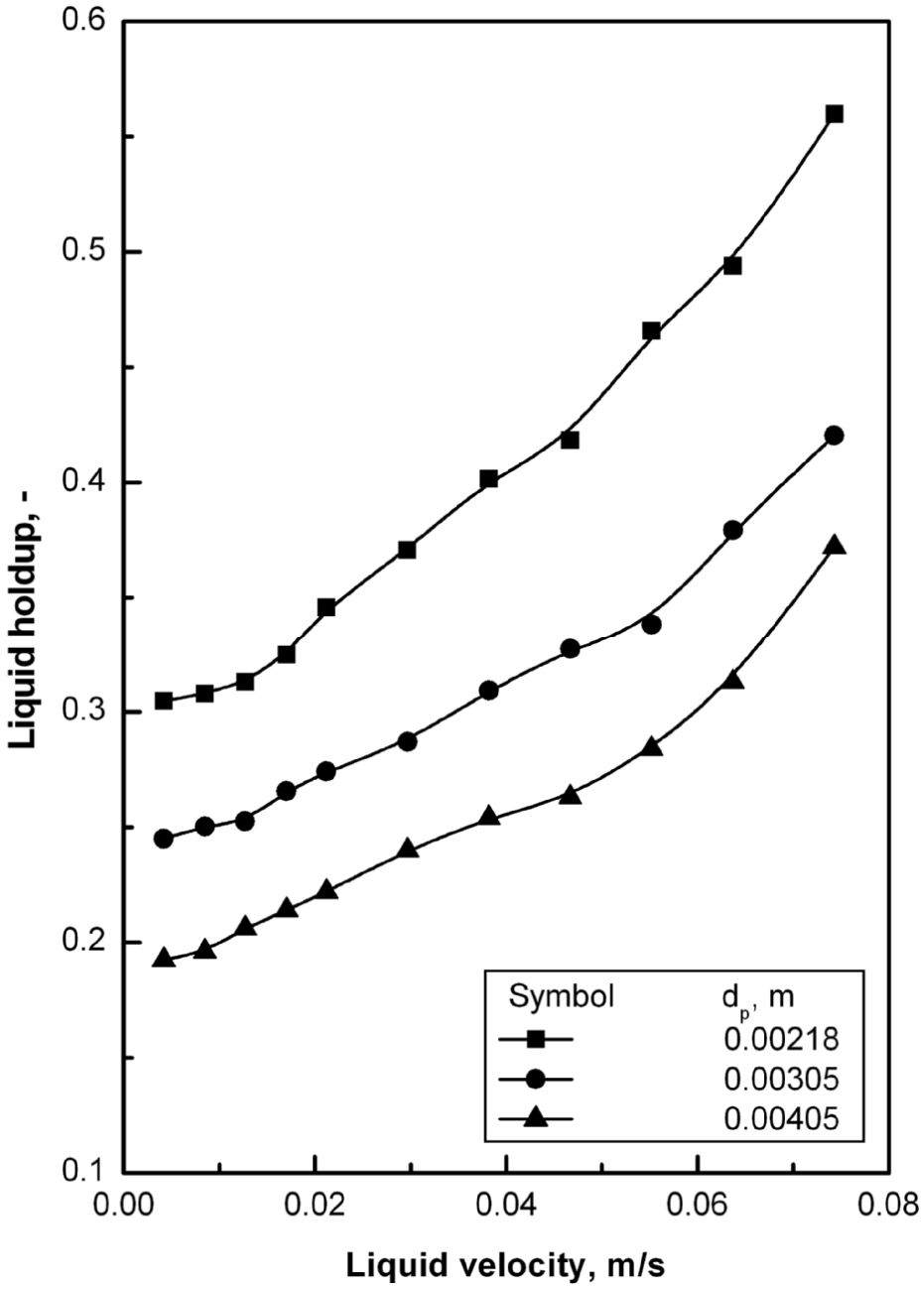

Figure 9. Effect of liquid velocity on liquid holdup for different particle size at [V_g = 0.02 m/s, H_s = 0.267 m].

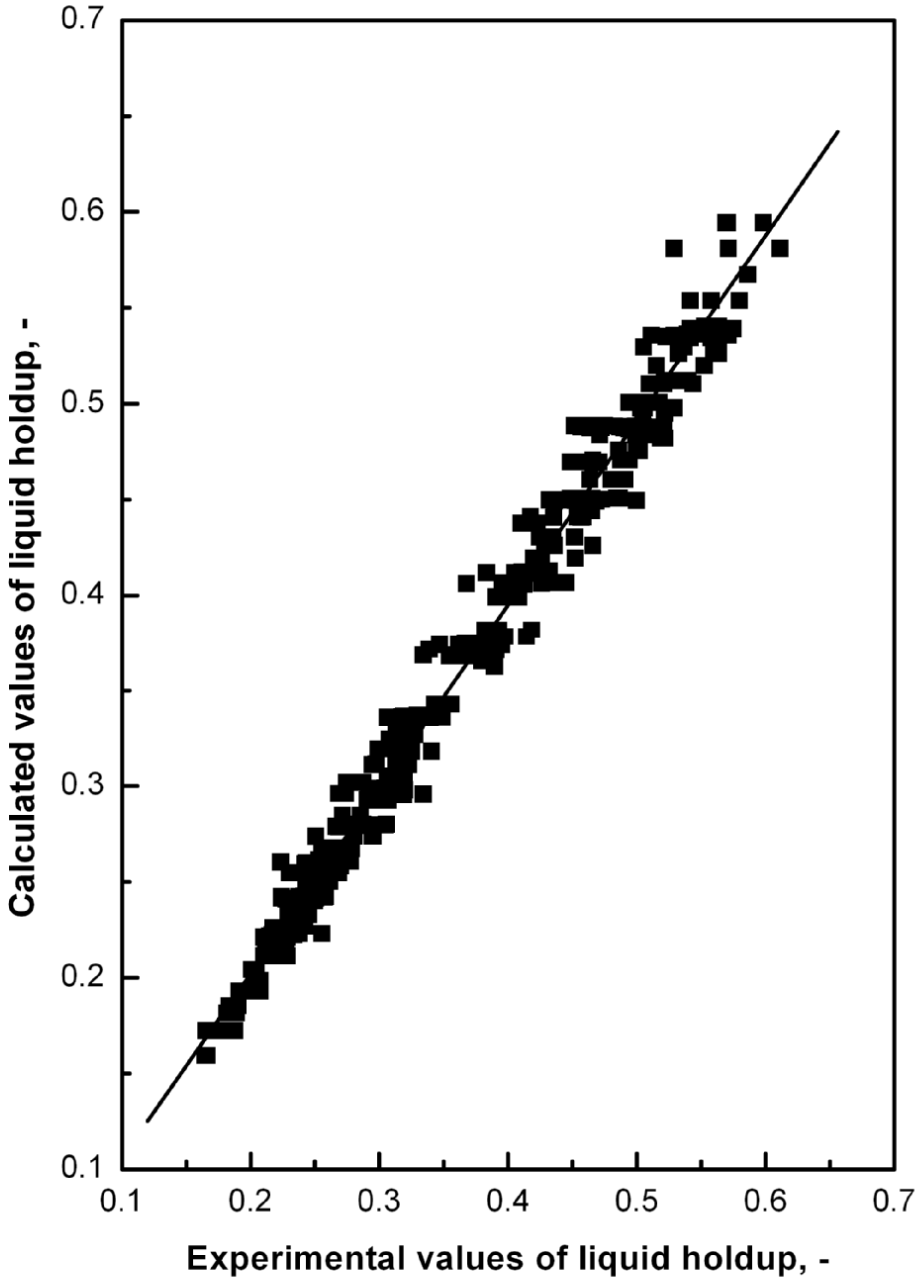

Figure 10. Comparison of experimental values of liquid holdup with those calculated from factorial design equation (8).

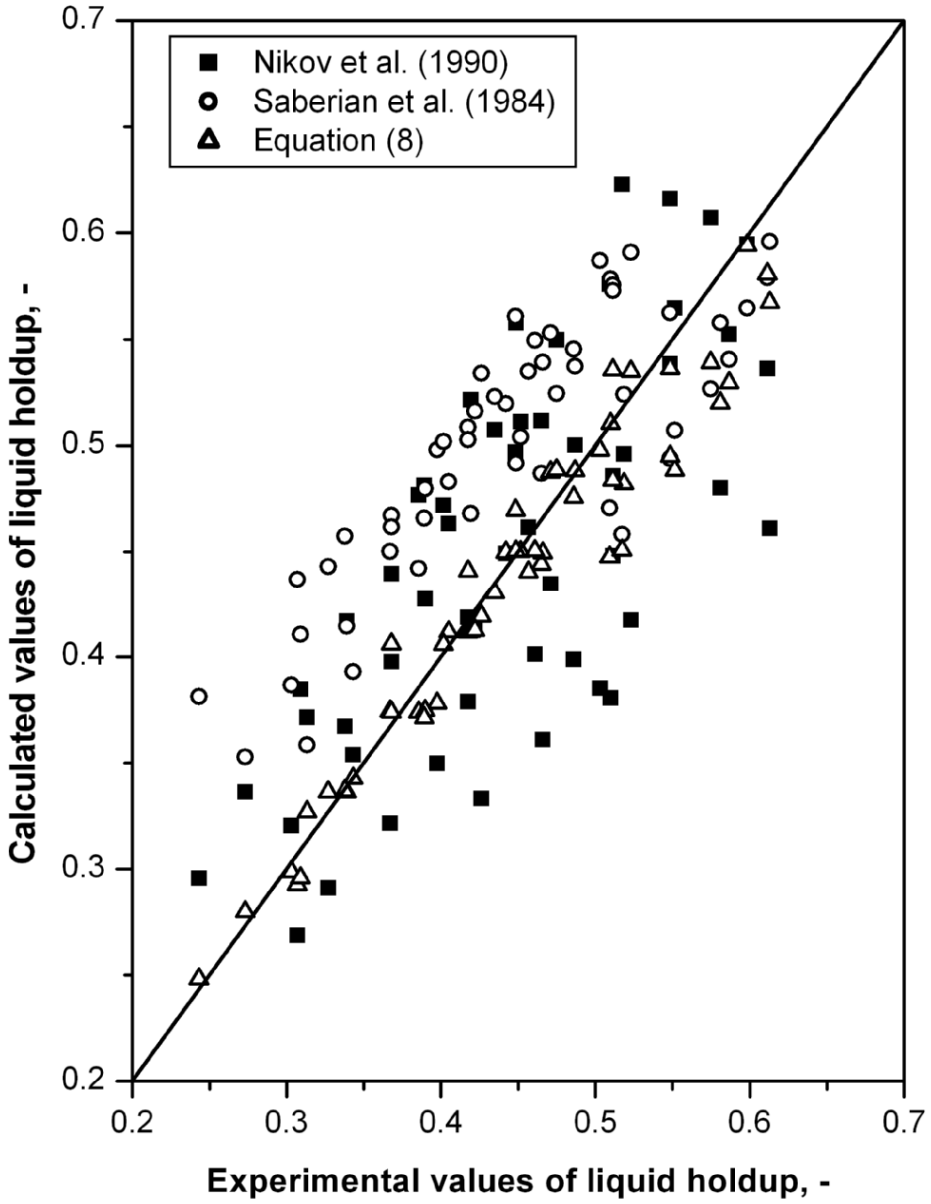

Figure 11. Comparison of experimental values of liquid holdup with those calculated from Nikov et al. (1990) and Saberian et al. (1984).

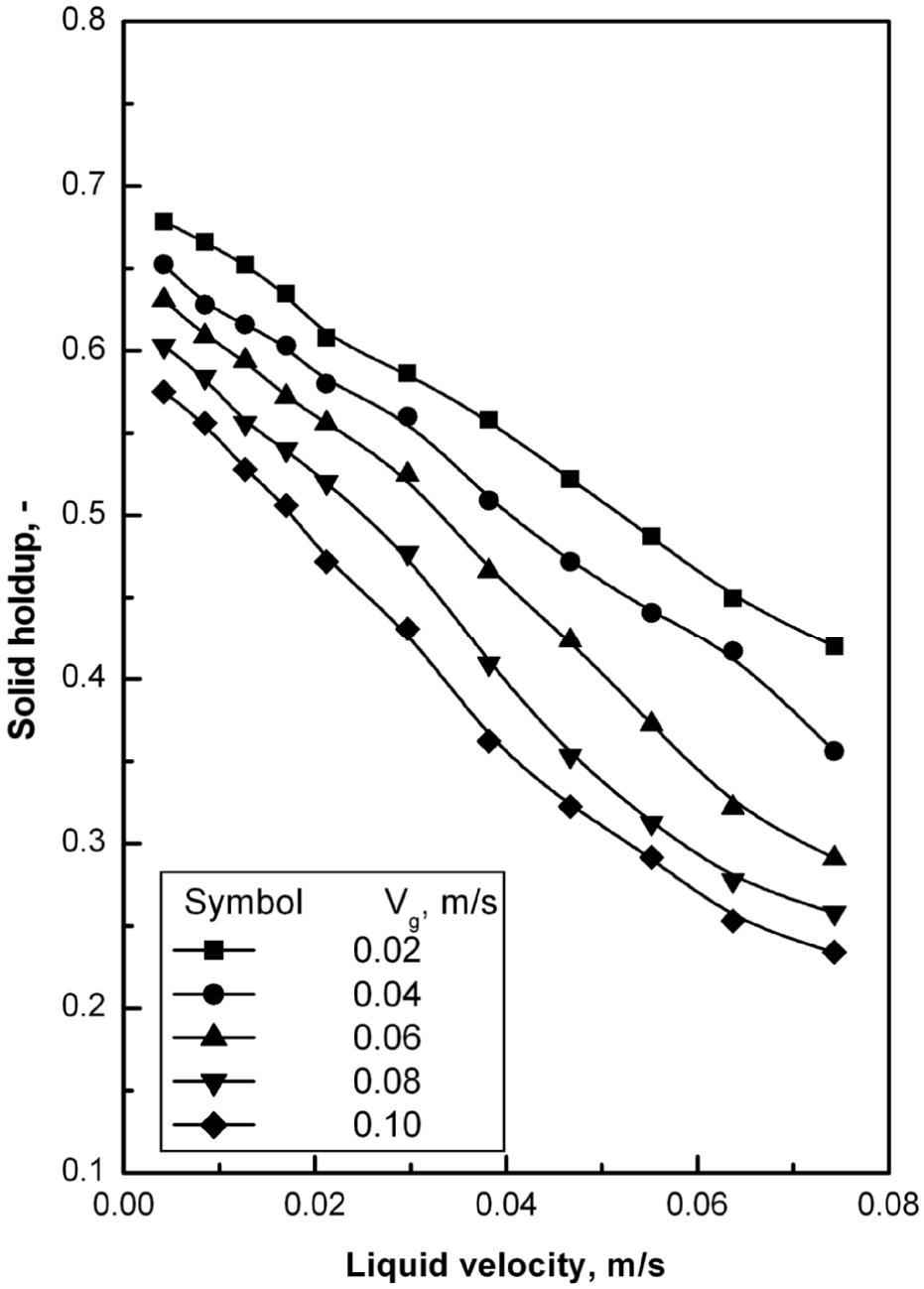

Figure 12. Effect of liquid velocity on solid holdup for different gas velocity at [H_s = 0.177 m, d_p = 0.00218 m].

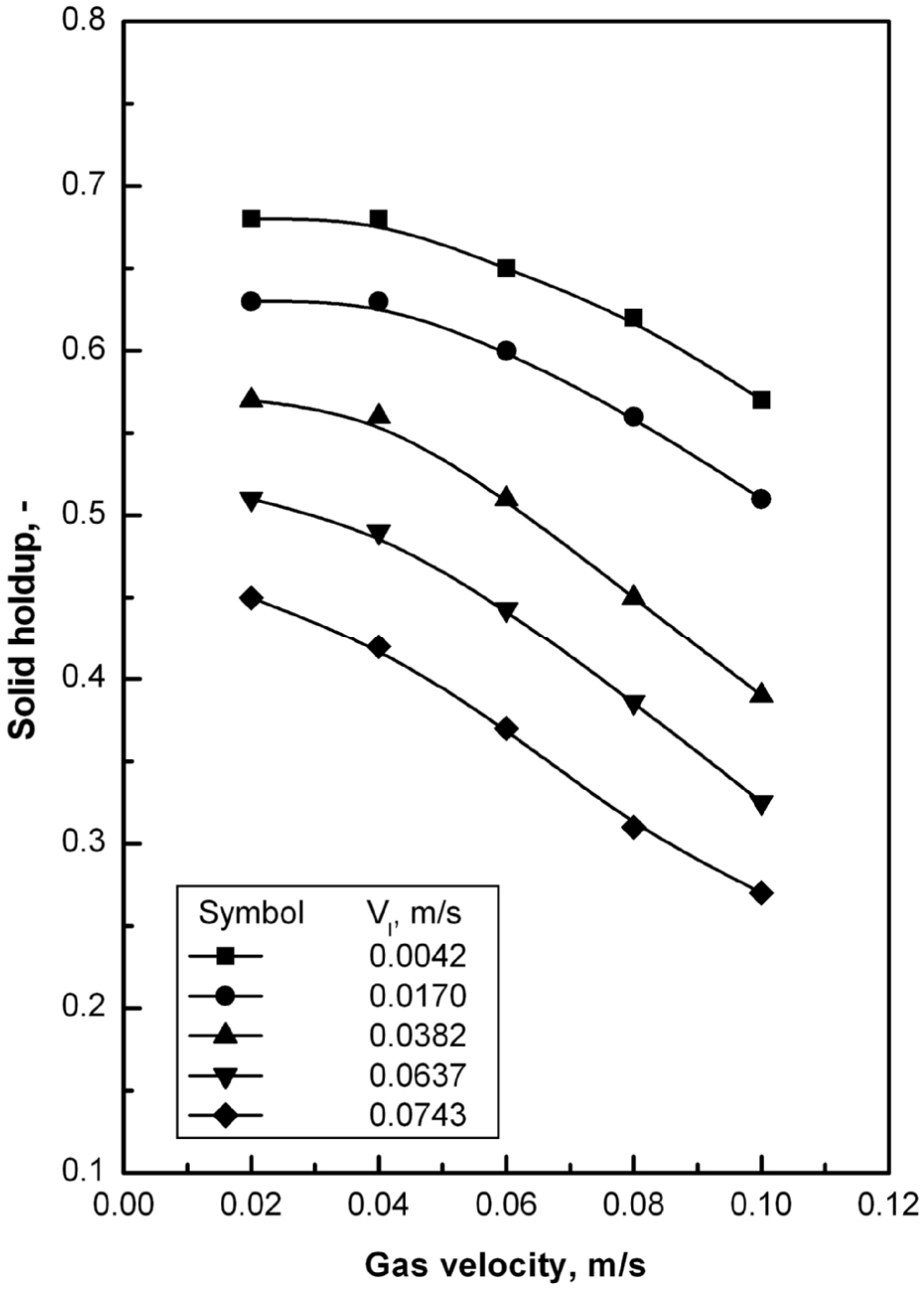

Figure 13. Effect of gas velocity on solid holdup for different liquid velocity at [H_s = 0.367 m, d_p = 0.00218 m].

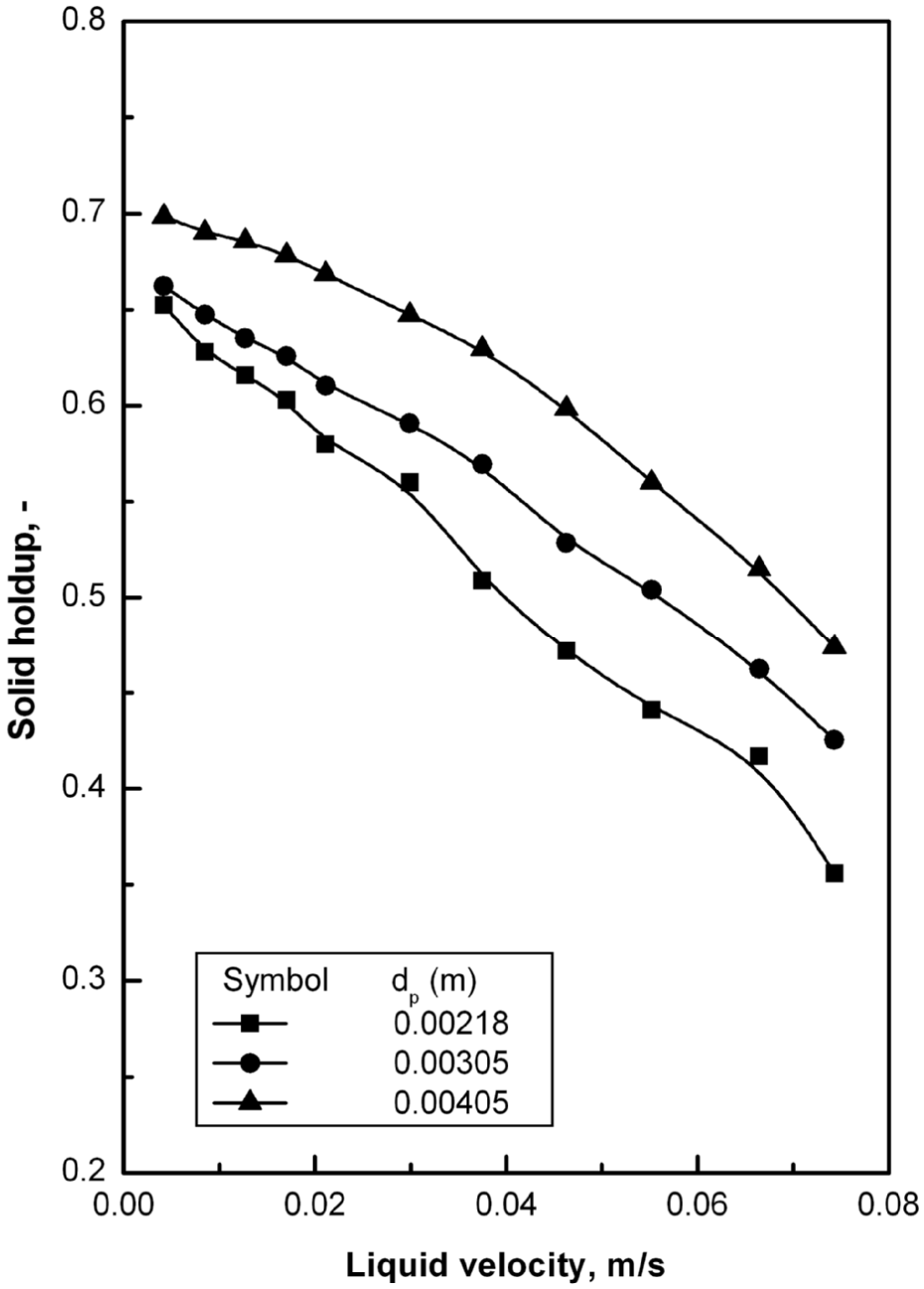

Figure 14. Effect of liquid velocity on liquid holdup for different particle size at [V_g = 0.04 m/s, H_s = 0.367 m].

Table 1
Scope of the experiment

A. Properties of bed materials				
Particle notation	**Materials**	**Mesh size (BSS)**	**d_p (m)**	**ρ_p (kg/m^3)**
P1	Glass beads	-7+8	0.00218	2,216
P2	Glass beads	-5+6	0.00305	2,253
P3	Glass beads	-4+5	0.00405	2,270
Initial static bed height (m)		0.177	0.267	0.367
B. Properties of fluidizing medium			**ρ (kg/m^3)**	**μ (Pa.s)**
Air at 25^{0}C			1.187	0.0000181
Water at 25^{0}C			997.15	0.000891
C. Properties of manometric fluid			**ρ (kg/m^3)**	**μ (Pa.s)**
Mercury			13,574	0.001526
Carbon tetra-chloride (CCl_4)			1,000	0.000942

Table 2
Scope of the factors for hydrodynamics for gas and liquid holdup

Sl. No.	**Name of the variable**	**variable (General symbol)**	**Factorial design symbol**	**Min. level (-1)**	**Max. level (+1)**	**Magnitude of variables**
1	Static bed height (m)	H_s	A	0.177	0.367	0.177,0.267,0.367
2	Particle dia. (m)	d_p	B	0.00218	0.00405	0.00218,0.00305,0.00405
3	Gas velocity (m/s)	V_g	C	0.02	0.10	0.02,0.04,0.06,0.08,0.10
4	Liquid velocity (m/s)	V_l	D	0.0042	0.0743	0.0042,0.0085,0.0127,0.0170, 0.0212,0.0297,0.0382,0.0467, 0.0552,0.0637,0.0743

Table 3

The effects of parameters on gas holdup as per factorial design analysis

Sl. No.	Treat-ment comb-ination	Experi mental gas holdup	1	2	3	4	Effect (4)/8	Sum of squares $(4)^2/16$	Perc-entage contri-bution
1	1	0.0620	0.1213	0.2628	0.9629	1.6757			
2	a	0.0593	0.1415	0.7002	0.7127	-0.0338	-0.0042	1.12E-06	0.15
3	b	0.0720	0.3668	0.1546	-0.0141	-0.0563	-0.0070	3.09E-06	0.40
4	ab	0.0695	0.3334	0.5581	-0.0197	0.0268	0.0034	7.02E-07	0.09
5	c	0.1870	0.0843	-0.0052	-0.0131	0.8409	0.1051	0.000691	90.26*
6	ac	0.1798	0.0703	-0.0090	-0.0431	-0.0129	-0.0016	1.63E-07	0.02
7	bc	0.1676	0.2936	-0.0053	0.0055	-0.0687	-0.0086	4.61E-06	0.60
8	abc	0.1658	0.2645	-0.0144	0.0213	0.0147	0.0018	2.12E-07	0.03
9	d	0.0449	-0.0027	0.0202	0.4374	-0.2502	-0.0313	6.11E-05	7.99*
10	ad	0.0394	-0.0025	-0.0334	0.4035	-0.0055	-0.0007	3E-08	0.00
11	bd	0.0350	-0.0072	-0.0140	-0.0038	-0.0300	-0.0037	8.79E-07	0.11
12	abd	0.0353	-0.0018	-0.0291	-0.0091	0.0157	0.0020	2.42E-07	0.03
13	cd	0.1543	-0.0056	0.0002	-0.0536	-0.0339	-0.0042	1.12E-06	0.15
14	acd	0.1394	0.0003	0.0054	-0.0151	-0.0053	-0.0007	2.73E-08	0.00
15	bcd	0.1320	-0.0149	0.0059	0.0052	0.0385	0.0048	1.45E-06	0.19
16	abcd	0.1325	0.0005	0.0154	0.0095	0.0043	0.0005	1.79E-08	0.00
							Total sum of squares = 0.000765		

* Significant variable

Note: The variables C and D are most significant. The interaction CD is significant. The interaction BC is included in the equation (7) to improve accuracy even though it is not significant.

Table 4

The effects of parameters on liquid holdup as per factorial design analysis

Sl. No.	Treat-ment comb-ination	Experi mental liquid holdup	1	2	3	4	Effect (4)/8	Sum of squares $(4)^2/16$	Perc-entage contri-bution
1	1	0.2855	0.6017	0.9736	1.7138	5.9279			
2	a	0.3162	0.3719	0.7403	4.2141	0.0523	0.0065	2.67E-06	0.04
3	b	0.1856	0.3562	2.1387	0.0737	-0.5555	-0.0694	0.000301	4.46
4	ab	0.1863	0.3841	2.0753	-0.0214	-0.0431	-0.0054	1.81E-06	0.03
5	c	0.1605	1.1160	0.0314	-0.2018	-0.2967	-0.0371	8.6E-05	1.27
6	ac	0.1957	1.0227	0.0423	-0.3537	-0.0247	-0.0031	5.95E-07	0.01
7	bc	0.1885	1.1678	0.0071	-0.0581	0.0907	0.0113	8.03E-06	0.12
8	abc	0.1956	0.9075	-0.0285	0.0150	0.0459	0.0057	2.06E-06	0.03
9	d	0.5526	0.0307	-0.2298	-0.2333	2.5002	0.3125	0.006105	90.41
10	ad	0.5634	0.0007	0.0279	-0.0634	-0.0951	-0.0119	8.83E-06	0.13
11	bd	0.5132	0.0352	-0.0933	0.0109	-0.1518	-0.0190	2.25E-05	0.33
12	abd	0.5095	0.0071	-0.2603	-0.0356	0.0731	0.0091	5.22E-06	0.08
13	cd	0.5984	0.0108	-0.0300	0.2577	0.1699	0.0212	2.82E-05	0.42
14	acd	0.5694	-0.0037	-0.0281	-0.1670	-0.0465	-0.0058	2.11E-06	0.03
15	bcd	0.4535	-0.0290	-0.0145	0.0019	-0.4247	-0.0531	0.000176	2.61
16	abcd	0.4540	0.0005	0.0295	0.0440	0.0421	0.0053	1.73E-06	0.03
							Total sum of squares = 0.006752		

* Significant variable

Note: The variables D and B are most significant. The interaction BCD is included in the equation (8) to improve accuracy even though it is not significant.