*Korean J. Chem. Eng.*, **29**(6), 724-730 (2012)
DOI: 10.1007/s11814-011-0242-y

# Generation of uniform small bubbles and hydrodynamic characterization of a bubble column with high pressure jet sparger

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(*Received 9 August 2011 • accepted 15 September 2011*)

**Abstract**−Systems generating uniform small bubbles are used in many mineral processing and chemical operations. We investigated the generation of smaller bubbles by using a two fluid jet system. Gas holdup results are reported in terms of the effect of superficial gas and liquid velocities in relation to the pressure in a bubble column with a water jet sparger. Experiments were conducted with hydrostatic head of 80 cm, 100 cm, and 120 cm in the bubble column. The gas velocity varied from 0.122 to 1.22 cm/s, and water flow rate from 33.3 to 333 $cm^3/s$. Experiments were conducted at pressures of 2 atms., 3 atms. 4 atms. and 5 atms., and bubble sizes were measured by a digital camera (bubble compared to a reference wire inside the bubble column). Results show that the gas holdup increases with the pressure and superficial gas velocities; and at pressures of 2, 3, 4 and 5 atms., the gas holdup increases by 8.75%, 9.166%, 10% and 10%, respectively. The maximum gas holdup of 16.4% was observed at a liquid level of 80 cm and pressure of 4 atms. Optimum conditions for generating smaller bubbles with larger gas holdup are increased liquid flow rate, low liquid level, and high gas pressure. Experimental results also indicate that the column operates in both the homogeneous and heterogeneous regimes of gas-liquid flow.

Key words: Bubble Column, Hydrodynamics, Gas Holdup, Jet Sparger, Gas-liquid System

## INTRODUCTION

A bubble column operates usually in three regimes--homogeneous (bubbly flow), heterogeneous (Churn-turbulent flow) and slug flow--and hydrodynamics is different in the three regimes. In the bubbly flow regime, there is a homogeneous distribution of small and almost identical gas bubbles. Under these conditions, the gas bubbles do not affect the liquid motion and almost no liquid mixing is observed. As the gas velocity is increased, there is more interaction among gas bubbles and both coalescence and break-up of bubbles are observed. This is the churn turbulent flow or the heterogeneous regime, where the larger gas bubbles move in a plug flow, creating liquid recirculation as well as back mixing.

The smaller gas bubbles, on the other hand, are entrained within the liquid re-circulation. Furthermore, in small diameter columns, as the gas velocity increases, gas bubbles coalesce to form slugs whose diameters can be as large as the column diameter. This regime is called the slug flow regime. Gas holdup is the volume fraction occupied by gas in the liquid phase in the reactor. The gas holdup is one of the most important parameters used to describe the performance of the bubble column reactors. The behavior of the gas holdup has been attributed to many different factors, including the physical properties of gas/liquid, column geometry, gas distributor design and the operating variables, i.e., pressure, gas velocity, water velocity. Gas holdup is directly related to overall mass transfer in a gas-liquid contactor, since increase in gas holdup leads to increase of interfacial area. Thus, the overall mass transfer for gas-liquid interface increases. Since by using jet sparger, there is a continuous bubble break-up and generation, the interfacial area increases a great deal, which results in the overall mass transfer coefficient.

Currently, there are several techniques available to measure the gas holdup, such as pressure drop measurements, electroconductivity, X-ray transmission, $\gamma$ radiation, mean resistance time distribution, optical fiber probes, particle image velocimetry and computer tomography. A considerable number of these correlations were developed at ambient conditions and they do not take into account the effect of pressure or the temperature. A number of correlations are only valid for air/aqueous solutions and do not consider the effect of gas/liquid nature. Consequently, the use of such correlations for predicting gas holdup in a typical industrial process could be risky. The hydrodynamics (gas holdup determination, bubble size measurement) depends on many variables, such as gas velocity, liquid velocity, liquid level, and gas pressure, and these variables affect it in a different manner. The effect of liquid properties and sparger characteristics on the initial bubble size distribution of a bubble column equipped with fine pore sparger was reported by Kazakis et al. [1]. It has been reported the initial bubble size distribution at different flow rates of air and water, glycerine, isobutanol and it was concluded that the homogeneous regime is most desirable and to have good initial bubble size distribution. Tabei et al. [2] reported an experimental method to measure the bubble size distribution by changing the nozzle diameter, inflow pressure and the gas velocity. The bubble size distribution and the bubble diameter are measured by the image processing technique. Shigeo et al. [3] performed experiments to generate micro bubbles by rotational porous plate, and this experiment is based on the basis of dissolution and separation of air and water. The mean diameter of micro-air-bubbles is con-

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trolled between 10 and 20 μm, and the number density between $1.3\times10^2$ and $6.6\times10^2$ number/mm$^3$. Lee et al. [4] reported the results of bubble formation and its properties under various conditions in the flotation systems.

Hasegawa et al. [5] reported a low power micro bubble generator which consists of acryl pipe with 10 slits made at an angle of 30, 60, 90 and slit width is 0.6 mm. It was reported that the slits with angle of 60 give bubbles of 30 μm, and slits with angle of 30 and 90 give bubbles of 50 μm. Pfleger and Becker [6] reported the dynamic flow behavior in a bubble column and simulated the hydrodynamics characteristics of the bubble column. Jha et al. [7] reported the gas holdup of different types of sparger in a gas-liquid contactor with additives that gives higher gas holdup. Pollia et al. [8] reported the effect of sparger design and process parameters on the size of bubbles and the bubble size distribution. The spargers used were perforated ring spargers and perforated plate spargers, and gas holdup was found to be 1.2 to 9.0%. Tang et al. [9] reported about the time-dependent change of gas holdup in air water bubble column consisting of spider sparger and studied the effects of operating mode, sparger orientation, gas and liquid flow rate. Throat [10] reported the combined effect of the sparger height and the dispersion height. The generation of fine bubble greatly depends on the type of sparger used. Therefore, selecting a specific sparger is very important. The possible other spargers, which may also generate smaller bubbles, may be porous ceramic sparger, antenna type of sparger, rotating sparger, baffled tanks with air distributor. Jha et al. [7] reported the effect of additives and operating parameters on gas holdup for various types of sparger. Shin et al. [11] reported the various multiple effects of operating variables on the bubble properties in a three-phase slurry bubble column and presented the hydrodynamic behavior of the bubble column.

**Table 1. Operating conditions and design of experiments**
Superficial gas velocity (0.122 cm/s to 1.22 cm/s)
Liquid flow rate ($3.33\times10^{-5}$ m$^3$/s to $3.33\times10^{-4}$ m$^3$/s)
Gas pressure (1 kg/cm$^2$ to 5 kg/cm$^2$)
Liquid level in column (80 cm to 120 cm)

| Sr. No. | Jet height (cm) | Height of water in column (cm) | Gas pressure (kg/cm$^2$) | Water flow-rate (lpm) | Gas flow rate (lpm) |
|---|---|---|---|---|---|
| 1 | 30 | 80 | 2, 1, 5 | 8 | 2, 2, 20 |
| | | 100 | 2, 1, 5 | | |
| | | 120 | 2, 1, 5 | | |
| 2 | 30 | 80 | 2, 1, 5 | 10 | 2, 2, 20 |
| | | 100 | 2, 1, 5 | | |
| | | 120 | 2, 1, 5 | | |
| 3 | 30 | 80 | 2, 1, 5 | 12 | 2, 2, 20 |
| | | 100 | 2, 1, 5 | | |
| | | 120 | 2, 1, 5 | | |
| 4 | 34 | 80 | 2, 1, 5 | 8 | 2, 2, 20 |
| | | 100 | 2, 1, 5 | | |
| | | 120 | 2, 1, 5 | | |
| 5 | 34 | 80 | 2, 1, 5 | 10 | 2, 2, 20 |
| | | 100 | 2, 1, 5 | | |
| | | 120 | 2, 1, 5 | | |
| 6 | 34 | 80 | 2, 1, 5 | 12 | 2, 2, 20 |
| | | 100 | 2, 1, 5 | | |
| | | 120 | 2, 1, 5 | | |
| 7 | 40 | 80 | 2, 1, 5 | 8 | 2, 2, 20 |
| | | 100 | 2, 1, 5 | | |
| | | 120 | 2, 1, 5 | | |
| 8 | 40 | 80 | 2, 1, 5 | 10 | 2, 2, 20 |
| | | 100 | 2, 1, 5 | | |
| | | 120 | 2, 1, 5 | | |
| 9 | 40 | 80 | 2, 1, 5 | 12 | 2, 2, 20 |
| | | 100 | 2, 1, 5 | | |
| | | 120 | 2, 1, 5 | | |

Therefore, in this study an attempt has been made for uniform small bubbles by using jet type system and effect of various operating conditions on gas holdup.

## EXPERIMENTAL SETUP AND TECHNIQUE

The experimental setup, shown in Fig. 1, consists of bubble column, pump, compressor, jet sparger, rotor stator, two rotameter, two gate valve, and needle valve. The details of the jet sparger are shown in Fig. 2. The bubble column is cylindrical and made of the Perspex (methyl methacrylate) material, which is transparent with height 1.95 m and internal diameter 0.186 m. The jet sparger was placed at the top of the bubble column for facilitating the co-current flow of air and water in the column. The gas flow and water flow were measured by gas and water rotameters and controlled by needle and gate valves. A compressor was used to supply the air at required pressure for the experiment and pump to supply the water at the top of column. A bypass valve was used at the bottom of column to remove water from the bottom. The jet sparger has length of (106 cm) with internal diameter (2.54 cm) and the nozzle diameter (0.6 cm). In the second part the jet sparger was replaced by the rotor stator which is outside the bubble column and generates the bubbles out-

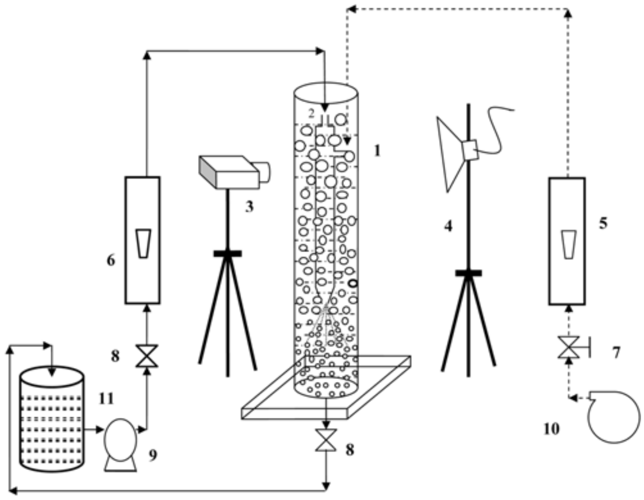
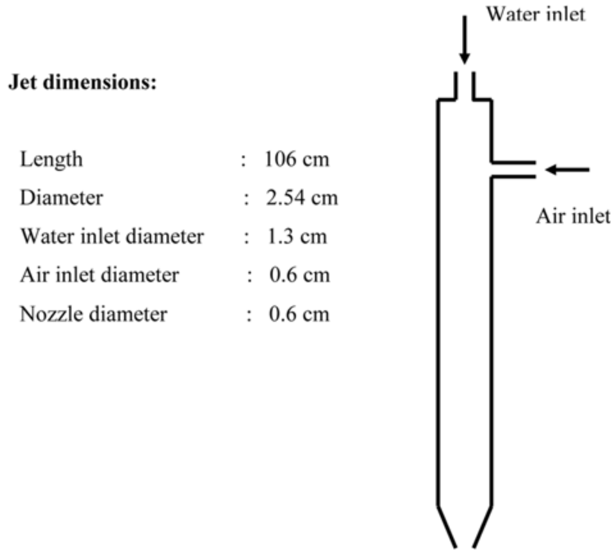


**Fig. 1. Schematic diagram of experimental setup with jet sparger.**

| | |
|---|---|
| 1. Bubble column | 7. Needle valve |
| 2. Jet sparger | 8. Gate valve |
| 3. Camera | 9. Pump |
| 4. Light source | 10. Compressor |
| 5. Gas rotameter | 11. Water tank |
| 6. Water rotameter | |



**Jet dimensions:**

| | | |
|---|---|---|
| Length | : | 106 cm |
| Diameter | : | 2.54 cm |
| Water inlet diameter | : | 1.3 cm |
| Air inlet diameter | : | 0.6 cm |
| Nozzle diameter | : | 0.6 cm |

**Fig. 2. Schematic diagram of water jet.**

side the bubble column. A digital camera was fixed on a stand close to the cylindrical column with an appropriate lighting system placed at top of column to evenly distribute the light. An iron wire suspended inside the column from top to bottom it is used as a reference to measure the bubble size by photographic method whose diameter is 1.2 mm. In actual practice compressed air after attaining the desired pressure of 2, 3, 4 and 5 kg/cm$^2$, air is allowed to pass through the bubble column. The initial height of water ($H_1$) was noted at every height, and the recirculation pump was switched on to keep the height constant. Air flow rate was controlled with a needle valve and the air dispersed through the sparger and the air flow rate was varied in between 0.122 cm/s to 1.22 cm/s for each case. Before the start of experiment, the light source was made ready for bubble size measurement. The differences in height technique were used to calculate the gas holdup as shown in Eq. (4). Each experiment was repeated 3 to 4 times to reproduce the results. During the experiment the photographs were taken to determine the bubble size by photographic method. At the end of each case we opened the bypass valve to remove the water from the bottom and maintain the water level height, and the same procedure was repeated for all cases.

### 1. Measurement of Bubble Size

To measure the bubble size the image processing technique was used. The photographs were taken with a digital camera. The camera was placed away from the column with a field view of 100×110 mm and a resolution of approximately 7.2 mega pixels. Adequate lighting facilities were provided by CFL lamps. Each lamp was mounted on a telescopic stand to allow better concentration of the lighting at the measurement location. To get a good bubble size measurement, a minimum of 80 to 100 bubbles were counted and measured with image pro plus software. Bubbles were chosen from the center of pipe and not from the near the wall of the columns as they were not going to influence the bubble size. For small and nearly spherical bubbles an equivalent bubble diameter was estimated based on the image area and the assumption of spherical shape. During bubble size measurement, we captured the images in a particular position, so hydrostatic heads remained constant.

For ellipsoidal bubbles the major and minor axis of the image were measured. The third dimension was calculated assuming that the bubbles were symmetric around the minor axis. The bubble diameter was calculated by assuming a sphere of volume equal to the volume of the ellipsoid bubble. In the present bubble generating systems the majority of the bubbles are ellipsoidal. The bubble diameter is therefore calculated from Eq. (1).

$$d_v=(d_1^2 d_2)^{1/3} \tag{1}$$

$d_1$=major axis length (mm)
$d_2$=minor axis length (mm)
$d_v$=Bubble diameter (mm)

The number average bubble diameter, $d_b$

$$d_b=\sum_{i=1}^{N_b}\frac{d_{v1}}{N_b} \tag{2}$$

Using the ratio of the sum total of volume to that of surface area of the measured droplets, therefore, the Sauter mean diameter is called "volume-surface mean diameter," and is commonly abbreviated as "$d_{32}$" or "SMD". The mean volume surface diameter or Sauter mean bubble diameter, $d_{32}$ found from in the range of 0.5 to 3.0 mm is given by

$$d_{32}=\frac{\sum_{i=1}^{N_b} d_{vi}^3}{\sum_{i=1}^{N_b} d_{vi}^2} \tag{3}$$

### 2. Determination of Gas Holdup

$$\%\ \text{gas holdup}\ (\varepsilon_G)=\frac{H_2-H_3}{H_1} \tag{4}$$

$H_1$=Initial water at time 0 min
$H_2$=Initial water+air+water after 2 min
$H_3$=Initial water+water after 2 min

## RESULTS AND DISCUSSION

Experiments were conducted to determine the gas holdup and bubble size distribution in the bubble column using a water jet sparger at different superficial gas velocities and liquid velocities. The superficial gas velocity varied from 0.122 cm/s to 1.22 cm/s by using a high pressure jet sparger. The water flow rate varied from $3.33\times10^{-5}$ m$^3$/s to $33.3\times10^{-5}$ m$^3$/s and gas pressure varied from 1.0 to 5.0 kg/cm$^2$, whereas the jet height was fixed at 34 cm by carrying out the experiment at different jet heights; it was found that jet height has marginal effect on gas holdup. In this study a detailed investigation has been carried out on the effect of superficial gas velocity at various liquid height and pressure on gas holdup.

### 1. Effect of Gas Pressure on Gas Holdup at Constant Liquid Flow Rate and Constant Liquid Level

As shown in Fig. 3 at a liquid flow rate of $Q_L\times10^6$=130 m$^3$/s and liquid level 80 cm, the gas holdup increases with increase in superficial gas velocity. In this figure the straight lines indicate the homogeneous regime at the start and then the heterogeneous regime. It can be seen that gas holdup in homogeneous regime is more than

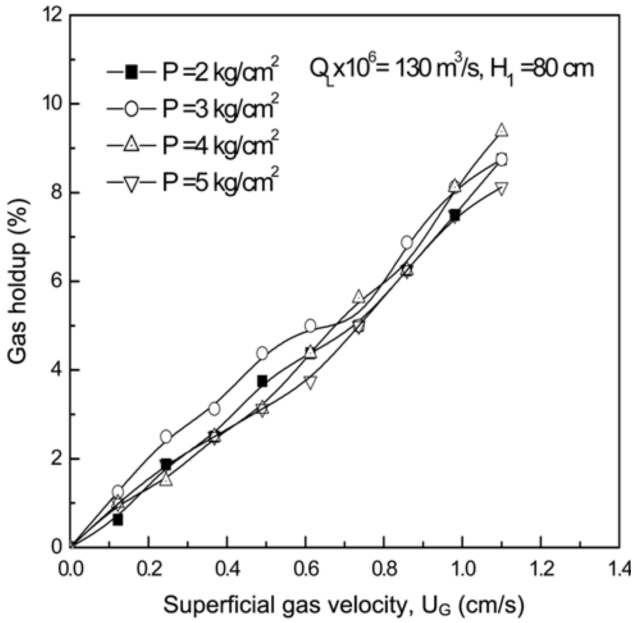


**Fig. 3. Effect of superficial gas velocity on gas holdup at various pressure and $Q_L\times10^6=130\ m^3/s$, $H_1=80$ cm.**

heterogeneous regime. Although the homogeneous regime is preferred, however both homogeneous and heterogeneous regime of bubble swarm was observed in the column. At relatively lower pressures the bubbles generated from the water jet sparger are fine, discrete, and uniform in size. Bubbles liquid after generation and travel down some extent and again move up to the top, due to which bubbles have more residence time; these bubbles have some effect of wall that will hinder their velocity due to which the gas holdup is maximum. However, at a pressure of 5.0 kg/cm$^2$ as more amount of gas is injected in the column the number of bubbles is greater and there is a maximum possibility of collision, which leads to coalescence due to which the size of bubbles increases and the rise velocity also increases and the residence time inside is minimum. As a result gas holdup is minimum at the pressure 5 kg/cm$^2$. It has been observed that at the pressures of 2, 3, 4 and 5 kg/cm$^2$ the gas holdup values are 10, 10.6, 10 and 8.75%, respectively. A similar profile has been observed for the liquid flow rate of $Q_L\times10^6=130\ m^3/s$ and liquid height of 100 cm as shown in Fig. 4. The gas holdup is increased somewhat at pressure 3 kg/cm$^2$ in comparison with at pressure of 2 kg/cm$^2$, then it decreased at 5 kg/cm$^2$. The behavior of gas holdup is same as that of at Liquid height of 80 cm. Gas holdup values at the pressure of 2, 3, 4 and 5 kg/cm$^2$ are 11, 11.3, 11 and 10%, respectively. It has been observed that the gas holdup is more at the 100 cm liquid level than 80 cm. This may be because the upward distance moved by the suspension is increased in 100 cm.

Fig. 5 represents the effect of superficial gas velocity on gas holdup at various pressures. It can be seen that the gas holdup at $H_1=80$ cm is maximum at P=3 kg/cm$^2$ but is decreased at P=4 kg/cm$^2$ and gas holdup at P=4 kg/cm$^2$ is much less (12%) than at P=3 kg/cm$^2$ (16%). However at $H_1=100$ cm it is almost same as that at P=4 kg/cm$^2$. This may be because at $H_1=120$ cm gas holdup is more at 4 kg/cm$^2$ than at P=3 kg/cm$^2$ since the residence time provided by 120 cm height is more than 100 cm and 80 cm of liquid height. It has been observed that with increase in pressure, the gas hold-up increases and this is due to higher ejection force by jet. Fig. 6 shows a typical plot to show the effect of superficial gas velocity on gas holdup at various height of the jet. It has been observed that at pressure 2, 3 and 4 kg/cm$^2$ gas holdup is maximum at the 80 cm than 100 cm and 120 cm, because as the liquid level increases, recirculation inside the bubble column increases, so the recirculation accelerates the bubble rise velocity due to which the residence time inside the column is minimum. As a result the gas holdup is less at

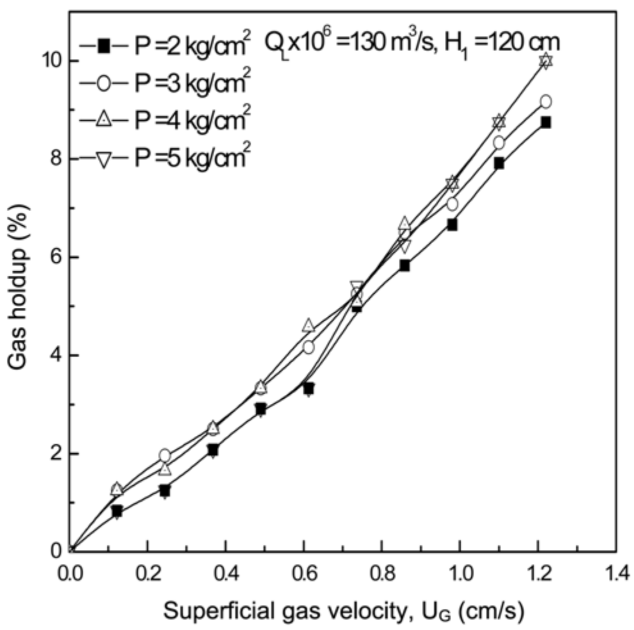


**Fig. 4. Effect of superficial gas velocity on gas holdup at various pressure and $Q_L\times10^6=130\ m^3/s$, $H_1=120$ cm.**

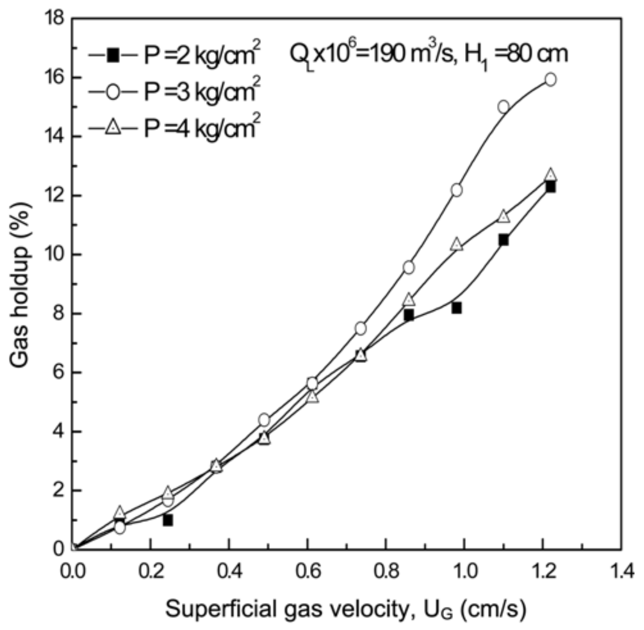


**Fig. 5. Effect of superficial gas velocity on gas holdup at $Q_L\times10^6=190\ m^3/s$, $H_1=80$ cm.**

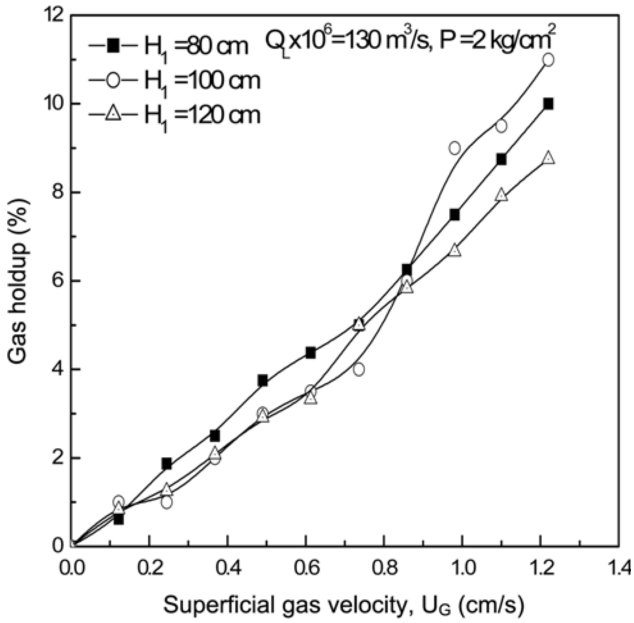


**Fig. 6. Effect of superficial gas velocity on gas holdup at $Q_L\times10^6$= 130 m$^3$/s, P=2 kg/cm$^2$.**

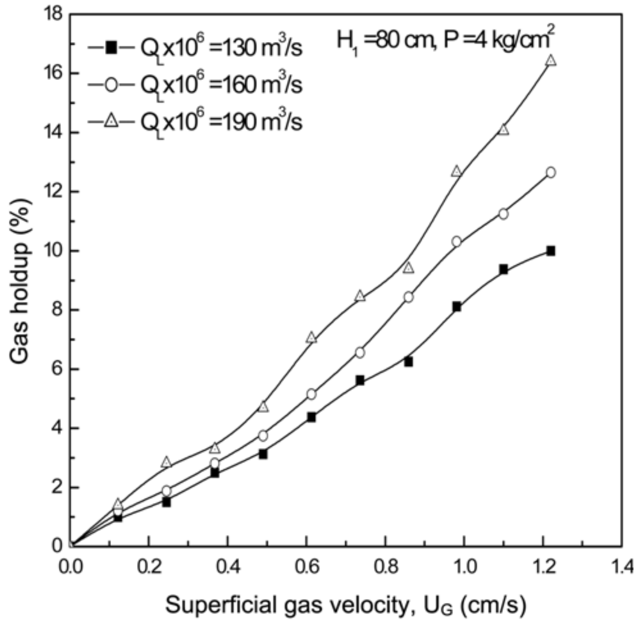


**Fig. 8. Effect of superficial gas velocity on gas holdup at different liquid flow rate and $H_1$=80 cm, P=4 kg/cm$^2$.**

100 cm than 120 cm. However, at high pressure of 5 kg/cm$^2$ gas holdup is more at the height of 120 cm than 80 cm and 100 cm because of greater liquid height aided by the increased pressure, i.e., more amount of gas present in the system. From the experimental findings it has been observed that at pressure 2, 3 and 4 kg/cm$^2$ the heterogeneous bubble regime occurred, when liquid level was 100 cm and transition from homogeneous to heterogeneous regime started at superficial gas velocities in between 0.6 cm/s-0.8 cm/s. Therefore, at high liquid level above 100 cm heterogeneous regime is dominant and as a result gas holdup is less at liquid level 120 cm. In addition, at the liquid level of 120 cm and 100 cm liquid recirculation is maximum, so it accelerates the bubble rise velocity; thus the residence time of bubbles inside the column is less and that's the reason for gas holdup being less at the 120 cm. It has been also observed that for the liquid flow rate $Q_L\times10^6$=130 m$^3$/s and $Q_L\times10^6$= 160 m$^3$/s (as shown in Fig. 7) at pressure of 2, 3, 4 and 5 kg/cm$^2$ the liquid level affects the gas holdup in the same way as for the liquid flow rate of $Q_L\times10^6$=130 m$^3$/s.

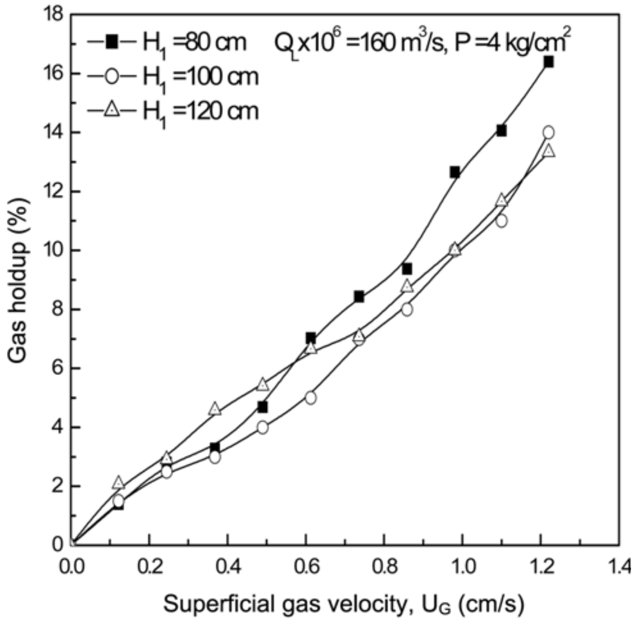


**Fig. 7. Effect of superficial gas velocity on gas holdup at $Q_L\times10^6$= 160 m$^3$/s, P=4 kg/cm$^2$.**

### 2. Effect of Superficial Gas Velocity on Gas Holdup at Various Liquid Flow Rates at Constant Liquid Level and Constant Gas Pressure

Figs. 8-12 show the effect of superficial gas velocity on gas holdup at different pressures and liquid flow rates. It has been found that there is an effect of jet height inside the bubble column, and as the jet height from top increases, the generation of bubbles and its uniform distribution after a certain optimum height decreases. It has been observed that at three heights 80 cm, 100 cm, 120 cm the gas holdup is increased with increase in liquid flow rate at pressures 3, 4 and 5 kg/cm$^2$. This may be because with increase in water flow rate the bubbles along with water go deep inside below jet in water. Thus residence time inside is maximum and the bubbles moving to top feel the resistance by jet of water and the residence time in bubble column is increased at higher liquid flow rates. However, gas holdup is decreased at higher liquid flow rate ($Q_L\times10^6$=160 m$^3$/s) at the gas pressure 2 kg/cm$^2$ at liquid level 80, 100 and 120 cm, respectively, because the gas pumped at 2 kg/cm$^2$ is less so the bubbles produced are not fine. As reported in the literature, the gas holdup is more in the homogeneous regime than in heterogeneous regime, but after homogeneous regime gas holdup decreases somewhat and then increases after some time. With an increase in liquid flow rate the hold-up increases, because as the liquid flow rate increases, the relative velocity increases and bubbles are regenerated by breaking

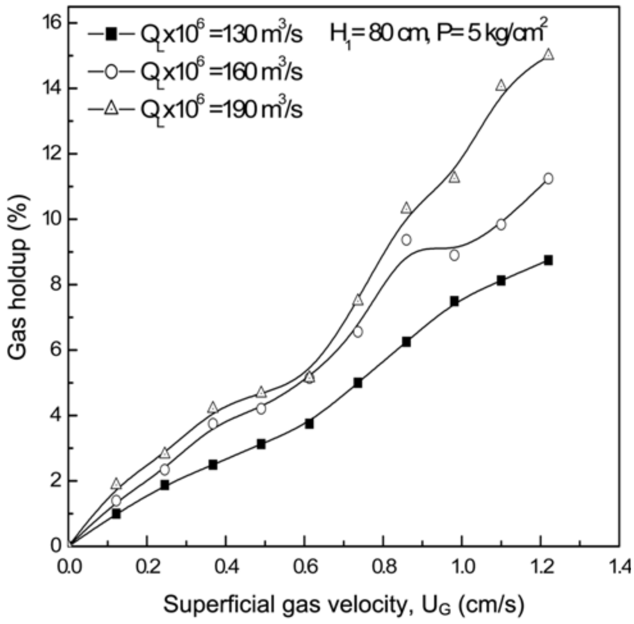


**Fig. 9. Effect of superficial gas velocity on gas holdup at different liquid flow rate and $H_1$=80 cm, P=5 kg/cm$^2$.**

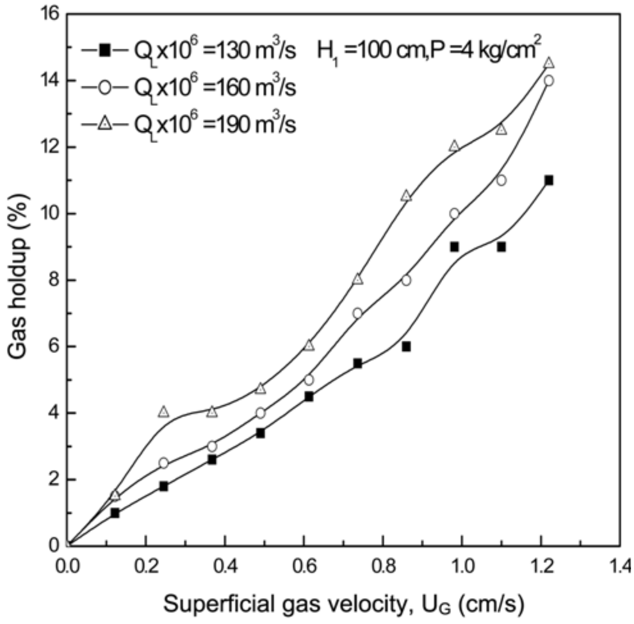


**Fig. 10. Effect of superficial gas velocity on gas holdup at $H_1$=100 cm, P=4 kg/cm$^2$.**

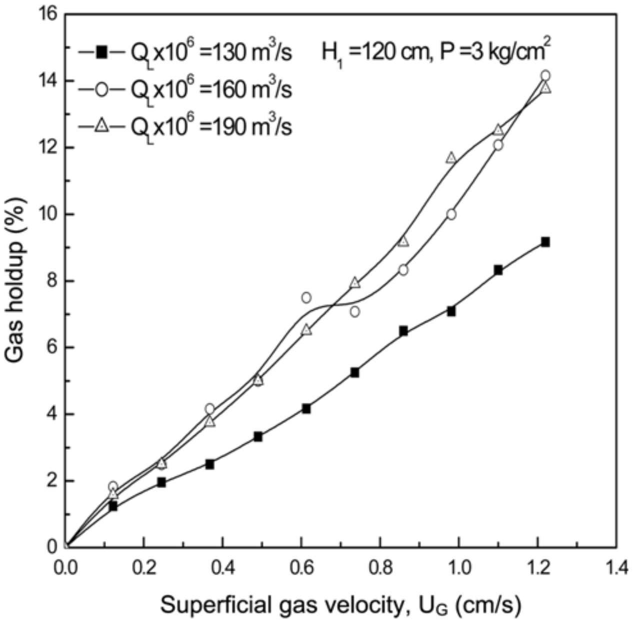


**Fig. 11. Effect of superficial gas velocity on gas holdup at different liquid flow rate and $H_1$=120 cm, P=3 kg/cm$^2$.**

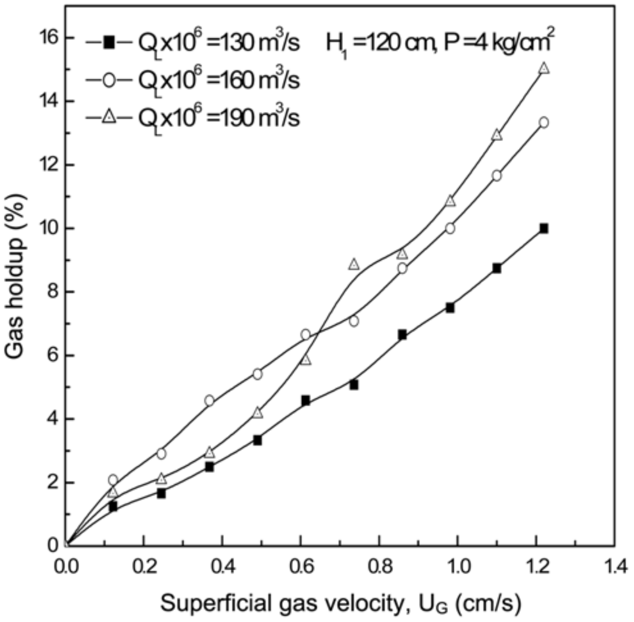


**Fig. 12. Effect of superficial gas velocity on gas holdup at different liquid flow rate and $H_1$=120 cm, P=4 kg/cm$^2$.**

and re-breaking mechanism. The jet produced by high velocity water penetrates inside the water phase with dispersed air within it, where due to the buoyancies gas bubbles travel in countercurrent direction. Thus, as the number of bubbles increases with smaller diameter, the gas hold-up significantly increases. In Figs. 8-12 it is observed that the heterogeneous regime occurred at $Q_L\times10^6$=190 m$^3$/s at the superficial velocity in between 0.5 cm/s-0.7 cm/s except at pressure 2 kg/cm$^2$, but at gas pressure 2 kg/cm$^2$ the heterogeneous regime starts at $Q_L\times10^6$=190 m$^3$/s. At the liquid flow rate of $Q_L\times10^6$=190 m$^3$/s for the gas pressure 3, 4 and 5 kg/cm$^2$, the column is operating in the heterogeneous regime from the start at all liquid levels so the gas holdup is increasing with increase in liquid flow rate. The maximum gas holdup 16.4% occurs at liquid level 80 cm, gas pressure 4 kg/cm$^2$ at $Q_L\times10$=190 m$^3$/s. The uniform bubble size generated was affirmed from the size distribution of bubbles measured by a high speed digital camera.

## CONCLUSION

The generation of uniform and small bubbles finds many applications in the chemical and mineral process industries. A bubble column with jet type sparger was designed and fabricated to produce smaller bubbles in the range of 1 to 3 mm in size under the pressure of 2.0 to 5.0 kg/cm$^2$. Experiments were carried out to determine the gas holdup in the cylindrical bubble column with jet sparger and bubble size distribution by Image-pro-Plus photographic method. Results indicate that the gas holdup increases with increase in superficial gas velocity under various operating conditions such as liquid level and pressure. At high liquid level above 100 cm heterogeneous regime is more dominant than that of heterogeneous regime; as a result gas holdup is less at higher liquid level. It is interesting to note that gas holdup values at a pressure of 2, 3, 4 and 5 kg/cm$^2$ are 11, 11.3, 11, 10%, respectively. It is found that the gas holdup is increased at the 100 cm liquid level than 80 cm because the upward distance move is increased in 100 cm. It can be concluded that the optimum conditions for generating smaller bubbles with higher gas holdup are higher liquid flow rate, low liquid level, high gas pressure. Experimental results also indicate that the column operates in both homogeneous and heterogeneous regime of gas-liquid flow. Results indicate that a maximum gas holdup of 16.4% was achieved at a liquid level of 80 cm, gas pressure 4 kg/cm$^2$ and liquid flow rate, $Q_L \times 10^6 = 190$ m$^3$/s. Thus, the outcome of the present research may be in mineral beneficiation flotation column and aerated reactors in both chemical and biological processes.

## ACKNOWLEDGEMENTS

Authors thankfully acknowledge the financial support granted by M/S Tata Steel, Jamshedpur, India for conducting this project work (Sanction No: IITKGP/MBG).

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