GAS HOLDUP IN HIGHLY VISCOUS LIQUIDS IN GAS-LIQUID SPOUTED BEDS

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Gas holdup in highly viscous fluid in two phase spouted bed operated continuously with respect to the gas flow and batchwise with respect to the liquid was investigated using bed expansion technique. Experiments were carried out in three cylindrical spouted beds having diameters of 74 mm, 114 mm and 144 mm and height of 1000 mm under the conditions of superficial gas velocities between 0.0018 m.s^{-1} and 0.29 m.s^{-1} , liquid viscosities between 0.063 Pa.s and 0.320 Pa.s, six static bed heights of 0.12 m, 0.18 m, 0.24 m, 0.30 m, 0.36 m and 0.48 m, surface tension between 0.0248 N.m^{-1} and 0.035 N.m^{-1} and density between 906 kg.m^{-3} to 928 kg.m^{-3} using a single nozzle sparger of 10.0 mm diameter. A correlation for the gas holdup was presented, with maximum deviation of 9%. This correlation was compared with those available in the literature.

Introduction

Many chemical industries, including biotechnology, food and pharmaceutical processes, use viscous media in bubble column reactors. Gas holdup in bubble columns and spouted beds of nonviscous fluids was studied by several investigators and the effect of many parameters such as gas and liquid velocities, liquid properties and gas distributors were published (Bach and Pilhofer, 1978, Chisti and Moo-Young, 1988, Eissa and Schugerl, 1975, Kelker and Shah, 1985, Nakanoh and Yoshida, 1980, Schumpe and Deckwer, 1981, and Schugerl, 1981). On the other hands, gas holdup in spouted bed was studied by a few workers (Anabtawi *et al.*, 1991, Anabtawi and Uysal, 1992, Nishikawa *et al.*, 1985 and Nishikawa *et al.*, 1976). It was already reported by the present authors that the behavior of gas-liquid spouted beds for nonviscous fluids was similar to that of bubble columns (Anabtawi *et al.*, 1991, and Anabtawi and Uysal, 1992). It was also reported in the same papers (Anabtawi *et al.*, 1991 and Anabtawi and Uysal, 1992) that a single nozzle was more attractive economically than a complicated gas sparger. Furthermore, vigorous circulatory motion in the liquid imposed by the shearing action of the gas spout provides much better mixing than the rising bubbles in a bubble column. In the previous paper (Anabtawi *et al.*, 1991) the authors have shown that there is some similarity in the hydrodynamics between spouted beds and bubble columns for non viscous fluids. However, no attempt has yet been made to extend this similarity to highly viscous fluids.

It is thus the purpose of this study to investigate the effect of viscosity, column diameter, static bed height, surface tension, density and gas velocity on the gas holdup in two phase (air-viscous oil) spouted bed operated

continuously with respect to the gas flow and batchwise with respect to the liquid. It is aimed to correlate the gas holdup as a function of the above six variables and to compare the results with the previous correlations given for bubble columns.

1. Experimental Apparatus and Procedures

Three cylindrical columns having internal diameters of 74 mm, 114 mm and 144 mm and bed height of 1000 mm were used. As shown in **Table 1**, seven different viscous fluids, of which viscosities varied from 0.063 Pa.s to 0.320 Pa.s and of which surface tension varied from 0.0248 N.m^{-1} to 0.035 N.m^{-1} , were used. Their viscosities were determined using Ferranti Shirley Cone and Plate Viscometer and their surface tension were determined using a stalagmometer. Air was introduced from a compressor via a calibrated rotameter. The bed was filled with oil of predetermined viscosity up to a predetermined static bed height. A nozzle threaded at the column base was mounted on a centrally located pipe which was connected to the gas rotameter. The top level of the nozzle was leveled off with the base. The nozzle used was 10.0 mm in diameter. The average gas holdup was determined using expanded bed height.

$$E_g = (H_0 - H) / H_0 \quad (1)$$

The values of gas holdup calculated from Eq. (1) were also confirmed from the difference in hydrostatic head by using a piezometer. Experiments were conducted at $20 \pm 1^\circ\text{C}$.

2. Results and Discussion

2.1 Gas-liquid flow pattern

The movement of the bubbles in spouted beds used

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Table 1 Liquid-phase physical properties at 200°C

Liquid	Viscosity (Pa·s)	Sur.Tension [N·m ⁻¹]	Density [kg·m ⁻³]	Colour
Light Oil	0.063	0.0350	906	Yellowish
Machine Oil	0.133	0.0307	914	Light Yellow
Lubricant Oil	0.194	0.0298	916	Blackish
Engine oil (1)	0.230	0.0289	918	Blackish
Engine oil (2)	0.279	0.0278	920	Greenish
Engine oil (3)	0.294	0.0254	923	Brownish
Engine oil (4)	0.320	0.0248	928	Dark Brown

Fig. 1 A sketch of observed flow pattern as a function of superficial velocity

can be characterized into three types of liquid-gas flow patterns depending on the operating conditions as shown in Fig. 1.

Type a. At very low gas flow rates, small and nearly uniform bubbles were observed in all seven viscous liquids used, **Fig. 1 a**.

Type b. For large gas flow rates, larger bubbles were observed mainly in the annular section, whereas near the interface between the spout and the annulus there were small bubbles mainly due to the large shear force acting on their surface, **Fig. 1 b**.

Type c. Further increase in the gas flow rates resulted in further coalescence of smaller bubbles to form larger bubbles in the annulus, **Fig. 1 c**.

For the small column of 0.074 m diameter the transition from type a to type b flow patterns occurred when $0.0100 \text{ m.s}^{-1} < U_g < 0.0186 \text{ m.s}^{-1}$, for bed height of 0.12 m $0.0159 \text{ m.s}^{-1} < U_g < 0.0279 \text{ m.s}^{-1}$, for bed height of 0.48 m and the transition from type b to type c flow patterns for the same column diameter occurred when $U_g > 0.0186 \text{ m.s}^{-1}$, for bed height of 0.12 m and $U_g > 0.0279 \text{ m.s}^{-1}$, for bed height of 0.48 m.

However, for the large column of 0.144m diameter the transition from type a to type b occurred when $0.0018 \text{ m.s}^{-1} < U_g < 0.0029 \text{ m.s}^{-1}$, for bed height of 0.12 m and $0.0025 \text{ m.s}^{-1} < U_g < 0.0038 \text{ m.s}^{-1}$, for bed height of 0.48 m, and transition from type b to type c flow patterns for the same column diameter occurred when $U_g > 0.0029 \text{ m.s}^{-1}$, for bed height of 0.12 m and $U_g > 0.0038 \text{ m.s}^{-1}$, for bed

Fig. 2 Comparison of present data on gas holdup in spouted bed with previous data in bubble columns for gas holdup, $D_c = 0.144 \text{ m}$, $U_g = 0.12 \text{ (m/s)}$, $H = 0.24 \text{ m}$, and temperature of 200°C

height of 0.48 m. Small bubbles were observed to circulate steadily from the annulus to the spout. The rate of circulation was decreasing with increasing of fluid viscosity. It was also observed that at large gas flow rates large bubbles, > 10 mm, in the annulus were unable to join the spout but finally these large bubbles entered in the annulus and reached the surface of the bed to disintegrate. The liquid phase were turbid due to the presence of a large number of very small entrapped bubbles. This is similar to the observations reported in bubble columns (Kim *et al.*, 1972 and Moo-Young and Kawase, 1987) and those reported in spouted beds (Anabtawi *et al.*, 1991 and Nishikawa *et al.*, 1985). A foam layer of about 20 mm height was observed to be formed on the surface of the fluid, which lasted for a few minutes after the gas flow to the spouting line was suddenly stopped.

3. Comparison of Spouted Bed with Bubble Column

Figure 2 shows that the correlations proposed by Akita and Yoshida (1973), Hikita and Kikukawa (1974) Hikita *et al.* (1980) and Mersmann (1978) do not agree with the present experimental data. The correlation of Hikita *et al.* (1980) provides the closest prediction for the present data of E_g for a given gas velocity, but still overestimated the experimental holdup by about 13%. The correlation of Hikita and Kikukawa (1974) however, overestimated the present data by 68 %.

4. Correlation of Gas Holdup

Because of lack of capability of the previous correlations to explain the present data of E_g within a fair accuracy, the values of E_g were correlated empirically using a multiple regression technique over the following ranges of experimental variables:

Fig. 3 Effect of viscosity on gas holdup

Fig. 4 Effect of column diameter on gas holdup

0.0248 N.m ⁻¹	< σ <	0.0350 N.m ⁻¹
906 kg.m ⁻³	< ρ _L <	928 kg.m ⁻³
0.063 Pa.s	< μ <	0.320 Pa.s
74 mm	< D _c <	144 mm
120 mm	< H <	480 mm
0.0018 m s ⁻¹	< U _g <	0.29 m s ⁻¹

The following correlation was obtained with a correlation coefficient of 0.96 and an average standard error of 3.8%

$$E_g = 0.239 Fr^{0.653} (\sigma / U_g \mu)^{0.09} (Bo)^{-0.430} (\rho_L / \rho_g)^{0.481} \quad (2)$$

where Bo is Bond number which is the ratio of Weber number to Froude number (We/Fr^2) and is defined as the ratio of gravitational forces to surface forces. The maximum deviation of the experimental data from the predictions of this correlation was 9%. Eq. (2) was tested on the data produced by Anabtawi *et al.* (1991) for air-water system using bidimensional spouted bed. It was found to explain the data with an average deviation of 13 %. This deviation

Fig. 5 Effect of superficial gas velocity on gas holdup

could be due to the effect of column geometry on the gas holdup. Some typical experimental results are shown in Figs. 3-6. Solid lines in these figures correspond to the predictions from Eq. (2).

Effect of viscosity on gas holdup is shown in Fig. 3. Eq. (2) indicates that the power of μ is -0.089. This exponent of μ was qualitatively in good agreement with those reported by other investigators (Godbole *et al.*, 1982, Godbole *et al.*, 1984, Hikita *et al.*, 1980 and Hikita and Kikukawa, 1974) for bubble columns, being -0.058, -0.19, -0.053 and -0.05, respectively.

Effect of column diameter on gas holdup is shown in Fig. 4. Gas holdup was found to decrease with increasing column diameter as reported by other investigators (Godbole *et al.*, 1984, Haque *et al.*, 1986, Kato and Nishiwaki, 1972, and Moo-Young and Kawase, 1987) for bubble columns. In smaller diameter columns where slugs are formed, the slugs of gas rise with a smaller bubble rise velocity because of the retardation effect of the wall, in comparison to the fast rising large bubbles in larger diameter columns. This could be the reason for lower values of gas holdup obtained in highly viscous liquids using larger diameter columns. Eq. (2) gives the power of D_c as -1.02. This exponent of D_c was qualitatively in agreement with the result reported by Godbole *et al.* (1982), Haque *et al.*, (1986) and Moo-Young and Kawase (1987) for bubble columns and they have reported powers of -0.50, -0.15 and -0.21 respectively.

Effect of superficial gas velocity on gas holdup is shown in Fig. 5. The gas holdup was found to increase with increasing gas velocity as it was reported by Anabtawi *et al.* (1991) who used air-water system in a two dimensional spouted bed, and by others who used air-water system in cylindrical spouted beds (Nishikawa *et al.*, 1985 and Nishikawa *et al.*, 1976). This was also similar to those results reported in bubble columns (Botton *et al.*, 1978, Godbole *et al.*, 1984, Hikita *et al.*, 1980, Wachi *et al.*, 1987 and Yamashita, 1985).

Fig. 6 Effect of bed height on gas holdup

The increase in the gas holdup with gas velocity in spouted beds is naturally expected because as the gas velocity increases, large numbers of small bubbles, especially in the annular region away from the interface between spout and the annulus, start to coalesce resulting in the formation of larger bubbles. These large bubbles with the presence of noncoalesced small bubbles form a mixture of small and large bubbles that are responsible for further expansion of the bed surface and therefore a higher value of gas holdup. The presence of a mixture of small bubbles with large bubbles are the characteristic of the churn turbulent regime in bubble columns (Shah *et al.*, 1982). This can also be considered almost the case for churn turbulent in a spouted bed too. In the present work the gas holdup was found to be proportional to about 0.563 power of superficial gas velocity. The power was in excellent agreement to that proposed by Anabtawi *et al.* (1991) for nonviscous fluid in spouted beds being equal to 0.58. This was also in an excellent agreement with Hikita *et al.* (1980), Godbole *et al.* (1984) and Haque *et al.* (1986) who used viscous fluids in bubble columns and reported powers of 0.578, 0.6 and 0.6 respectively. It was also in very good agreement with Ueyama and Miyauchi (1979), Hikita and Kikukawa (1974) and Godbole *et al.* (1982) who also used viscous fluid in bubble columns and reported powers of 0.50, 0.47 and 0.476 respectively.

Effect of bed height on the gas holdup is shown in Fig. 6. It was found that gas holdup to decrease with increasing bed height, as reported by Anabtawi *et al.* (1991) and Anabtawi and Uysal (1992) for nonviscous fluids. This can probably be explained as follows; for a certain increase in gas flow rate in similar beds at different bed heights, if the number of bubbles generated are the same in both beds, then according to Eq. (1) the gas holdup E_g will be higher in the shorter bed. Eq. (2) predicts a power of -0.43. This is close to the value of -0.288 reported by Anabtawi *et al.*, (1991) in air-water two dimensional spouted bed and it was also close to the value of -0.234 reported by Anabtawi and Uysal (1992) in three phase two

dimensional spouted bed. Gas holdup was found to increase with increasing both surface tension and liquid density as was reported in bubble column (Shah *et al.*, 1982) but their effects were less significant.

Conclusions

The effect of fluid viscosity, column diameter, gas velocity, surface tension, density and static bed height on gas holdup in spouted beds were studied, using three different column diameters and seven different viscous fluids. Gas holdup was found to increase with increasing gas velocity, surface tension, density and to decrease with increasing static bed height, liquid viscosity and column diameter of the bed. These findings suggested qualitative similarity in the performance between spouted beds and bubble columns for viscous liquids.

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Nomenclature

Bo	= Bond number, $\rho_L g H D_c / \sigma$	
D_c	= column diameter	[m]
E_g	= gas holdup	
F_r	= Froude number, $U_g / (D_c g)^{0.5}$	
g	= acceleration due to gravity	[m.s ⁻²]
H	= clear liquid height	[m]
H_o	= aerated liquid height	[m]
U_g	= superficial gas velocity	[m/s]
We	= Weber number, $U_g^2 H \rho / \sigma$	
μ	= liquid viscosity	[Pa.s]
ρ_g	= gas density	[kg.m ⁻³]
ρ_L	= liquid density	[kg.m ⁻³]
σ	= surface tension	[N.m ⁻¹]

Literature Cited

- Akita, K. and F. Yoshida; "Gas Holdup and Volumetric Mass Transfer Coefficient in Bubble Columns," *Ind. Eng. Chem. Proc. Des. Dev.*, **12**, 76-80 (1973)
- Anabtawi, M. Z., B. Z. Uysal, R.Y. Jumah and N. Abdel-Jalil; "Gas Holdup in a Bi-Dimensional Two Phase Spouted Bed," *Chem. Eng. J.*, **47**, 135-139 (1991)
- Anabtawi, M. Z. and B. Z. Uysal; "Gas Holdup in a Bi-Dimensional Three Phase Spouted Bed," *Chem. Eng. J.*, **50**, 143-147 (1992)
- Bach, H. F. and T. Pilhofer; "Variation of Gas Holdup in Bubble Columns with Physical Properties of Liquids and Operating Parameters of Columns," *Ger. Chem. Eng. J.*, **1**, 270-275 (1978)
- Botton, R., D. Cosserrat and J.C. Charpentier; "Influence of Column Diameter and High Gas Throughputs on the Operation of a Bubble Column," *Chem. Eng. J.*, **16**, 107-115 (1978)
- Chisti, M. Y. and M. Moo-Young; "Gas Holdup in Pneumatic Reactors," *Chem. Eng. J.*, **38**, 149-152 (1988)
- Eissa, S. H. and K. Schugerl; "Holdup and Backmixing Investigations in Cocurrent and Countercurrent Bubble Columns," *Chem. Eng. Sci.*, **30**, 1251-1256 (1975)
- Godbole, S. P., M. F. Honath and Y. T. Shah; "Holdup Structure in Highly Viscous Newtonian and Non-Newtonian Liquids in Bubble Columns," *Chem. Eng. Commun.*, **16**, 119-134 (1982)
- Godbole, S.P., A. Schumpe, Y. T. Shah and N. L. Carr; "Hydrodynamics and Mass Transfer in Non-Newtonian Solutions in a Bubble

- Column," *AIChE J.*, **30**, 213-220 (1984)
- Haque, M.W., K.D. Nigam and J.B. Joshi; "Hydrodynamics and Mixing in Highly Viscous Pseudo-Plastic Non-Newtonian Solutions in Bubble Columns," *Chem. Eng. Sci.*, **41**, 2321-2331 (1986)
- Hikita, H., S. Asai, K. Tanigawa, K. Segawa and M. Kito; "Gas Holdup in Bubble Columns," *Chem. Eng. J.*, **20**, 59-67 (1980)
- Hikita, H. and H. Kikukawa; "Liquid Phase Mixing in Bubble Columns," *J. Chem. Eng. Japan.*, **8**, 191-195 (1974)
- Kato, Y. and A. Nishiwaki; "Longitudinal Dispersion Coefficient of a Liquid in a Bubble Column," *Int. Chem. Eng.*, **12**, 182-187 (1972)
- Kelkar, B. G. and Y. T. Shah; "Gas Holdup and Backmixing in Bubble Column with Polymer Solutions," *AIChE J.*, **31**, 700-702 (1985)
- Kim, S. D., C. G. Baker. and M.A. Bergougnou; "Holdup and Axial Mixing Characteristics of Two Phase and Three Phase Fluidized Beds," *Can. J. Chem. Eng.*, **50**, 695-701 (1972)
- Mersmann, A.; "Design and Scale-Up of Bubble and Spray Columns," *Ger. Chem. Eng.*, **1**, 1-6 (1978)
- Moo-Young, M. and Y. Kawase; "Gas Hold-Up and Mass Transfer in a Bubble Column with Viscoelastic Fluids," *Can. J. Chem. Eng.*, **65**, 113-118 (1987)
- Nakanoh, M. and F. Yoshida; "Gas Absorption by Newtonian and Non-Newtonian Liquids in a Bubble Column," *Ind. Eng. Chem. Proc. Des. Dev.*, **19**, 190-195 (1980)
- Nishikawa, M., K. Shiino, T. Kayama, S. Nishioka and K. Hashimoto; "Gas Absorption in a Multi-Stage Gas-Liquid Spouted Vessel," *J. Chem. Eng. Japan.*, **18**, 496-501 (1985)
- Nishikawa, M., Y. Yonezawa, T. Kayama, K. Koyama and S. Nagata; "Studies on Gas Holdup in Gas-Liquid Spouted Vessel," *J. Chem. Eng. Japan.*, **9**, 214-219 (1976)
- Schumpe, A. and W.D. Deckwer; "Determination of Interfacial Area in Non Newtonian Gas-Liquid Flow," Paper Presented at the 72nd ACS conference Atlanta, March 30-2 April 2 (1981)
- Schugerl, K.; "Oxygen Transfer into Highly Viscous Media," *Adv. Biochem. Eng.*, **19**, 71-174 (1981)
- Shah, Y. T., B. G. Kelkar, S. P. Godbole and W. D. Deckwer; "Design Parameters Estimations for Bubble Column Reactors," *AIChE J.*, **28**, 353-379 (1982)
- Ueyama, K. and T. Miyauchi; "Properties of Recirculating Turbulent Two Phase Flow in Gas Bubble Column," *AIChE J.*, **25**, 258-266 (1979)
- Wachi, S., H. Morikawa. and K. Ueyama; "Gas Holdup and Axial Dispersion in Gas-Liquid Concurrent Bubble Column," *J. Chem. Eng. Japan.*, **20**, 309-316 (1987)
- Yamashita, F.; "Effect of Liquid Depth, Column Inclination and Baffle Plates on Gas Holdup in Bubble Columns", *J. Chem. Eng. Japan.*, **18**, 349-353 (1985)