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Short Communication

Liquid dispersion, gas holdup and frictional pressure drop in a packed bubble column at elevated pressures

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Abstract

The gas holdup, frictional pressure drop and liquid dispersion have been investigated in a packed bubble column at elevated pressures for the air–water system. The bubble column, which had an internal diameter of 0.15 m and which was packed with 15 mm plastic Pall rings was operated in the semibatch mode. The operating pressures ranged from 0.1 to 0.66 MPa. It was found that increasing the pressure increases both the gas holdup and the dispersion coefficient. In contradiction to the results obtained from packed bubble columns fed with a continuous net flow of liquid, a maximum point of the frictional pressure drop was observed at the transition point between bubble and pulse flow region.

Keywords: Gas holdup; Packed bubble column; Liquid dispersion; Elevated pressures

1. Introduction

Although packed bubble columns at atmospheric pressures have been the subject of many investigations, only recently there are articles focused on packed bubble columns at elevated pressures. Parameters such as the gas holdup, frictional pressure drop and mass transfer have been studied. Larachi et al. [1] and Molga and Westerterp [2] found that the gas holdup in packed bubble columns increases with increasing pressure. Larachi et al. [1] observed that increased pressures or high gas density increased the frictional pressure drop in a similar way, and argue that the primary cause is a gas density effect; a high gas density increases the momentum flow rate, ρU_G^2. They also proposed a model for estimating the pressure drop from dimensionless numbers.

The dispersion coefficient at elevated pressures in a packed bubble column has been investigated by Gelder and Westerterp [3]. They employed a small scale cocurrent upflow packed bed reactor with a diameter of 65 mm, which was packed with small glass cylinders with a diameter of 3.8 mm and a length of 4.8 mm. The superficial gas velocities in these experiments were limited to 1.5 cm/s. They observed that the liquid dispersion was independent of the pressure under these conditions.

As far as we know the pressure influence on the liquid dispersion in packed bubble columns at gas velocities higher than 1.5 cm/s has not been reported. The influence of pressure on the gas holdup and the frictional pressure drop have mainly been restricted to continuously operated packed bubble columns. The increased gas holdup at higher pressures in packed bubble columns has not been fully explained. The purpose of this study was, therefore, to further explore these areas.

2. Experimental apparatus and procedures

The high pressure experiments were performed in a steel column at 20°C, Fig. 1. The internal diameter was 0.154 m and the bubble column was filled with 15 mm plastic Pall rings to a height of 3.2 m. The perforated gas sparger, with a hole diameter of 1.5 mm, has a free area of 0.2%. The gas flow was measured by a mass flow meter at the gas outlet. A differential pressure transmitter at the lower part of the column detected the pressure drop. The column was also equipped with sensors for temperature and pressure analysis.

The gas flow range that could be investigated was restricted by limitations of the mass flow meter and the gas supply system. The lowest gas flow rate that could be measured by the mass meter was approximately 8.6 N m^3 h^{-1}. The lowest superficial gas velocity at atmospheric pressure

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Nomenclature

E_L	liquid dispersion coefficient (m^2/s)
$\Delta P/L$	frictional pressure drop per length unit (mbar/m)
U_G	superficial gas velocity (m/s)
We	Weber number
w_{ex}	expansion work (N m)
Greek letters	
ρ	gas density (kg/m^3)

was thus approximately 0.13 m/s. At a pressure of 6.6 bar, it was not possible to exceed a gas velocity of 0.07 m/s due to the low capacity of the gas supply system.

The gas holdup was measured by using an overflow technique. The bubble column was filled with water to the same level as one of the sample points. The gas was introduced and by measuring the volume of the entrained liquid, the gas holdup was calculated.

The pressure drop was obtained from the differential pressure transmitter, and by compensating for the hydrostatic pressure of the liquid the pressure drops of the flowing phases were calculated.

The liquid dispersion coefficient was measured by the liquid pool method described by Campos and Carvalho [4] and Therning and Rasmuson [5]. A tracer pulse was added to a liquid pool above the packing and due to the rapid mixing, the pool could be considered as a well-stirred fluid. Concentrated sulfuric acid was used as the tracer. Approximately 20 ml was injected to the liquid pool by a pulse of compressed air. The concentration of the tracer in the liquid pool was determined by measuring the conductivity of small samples taken from the pool.

Due to the limitations of the gas flow, some gas holdup measurements at atmospheric conditions were performed in a glass column with the internal diameter of 0.20 m. Visual analysis was also possible in this column.

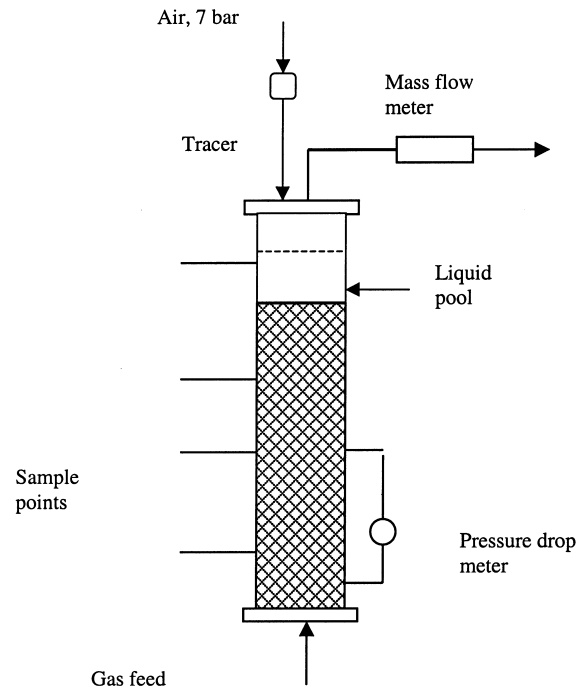

Fig. 1. Experimental setup for measurements in the steel column, diameter 0.15 m.

3. Results

3.1. Gas holdup

Experimental data at elevated pressures are compared with gas holdup data at atmospheric pressure in Fig. 2. It is worth noting that the data for atmospheric conditions at higher gas velocities are taken from the experiments using both the steel and glass columns. For lower gas velocities, i.e. below 0.13 m/s, the gas holdup data at atmospheric pressure are obtained from the glass column.

As expected, the measured gas holdup depends on the pressure. The gas holdup increases with increasing pressure. These results are consistent with the previous observations by Larachi et al. [1], Molga and Westerterp [2]. The same trend has also been found in empty bubble columns [6,7].

3.2. Liquid dispersion

Due to the flow restrictions, the dispersion measurements were performed at a superficial gas velocity of 0.135 ± 0.008 m/s. At this gas velocity, it was possible to study the pressures ranging from 0.1 to 0.56 MPa. The measurements were made in the pulsation flow regime.

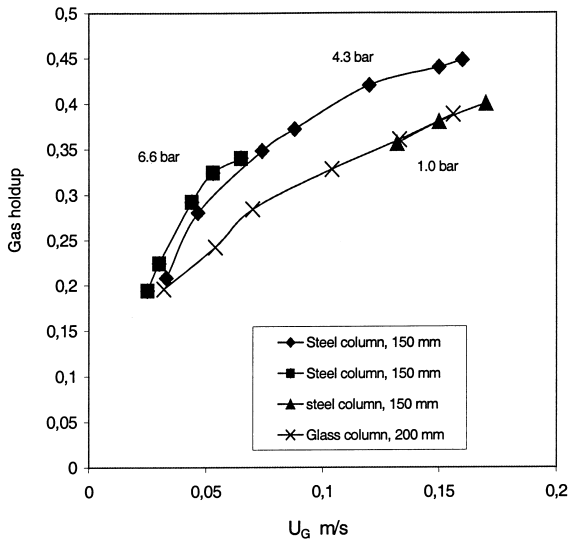

Fig. 2. The gas holdup as a function of the superficial gas velocity at 1.0, 4.3 and 6.6 bar.

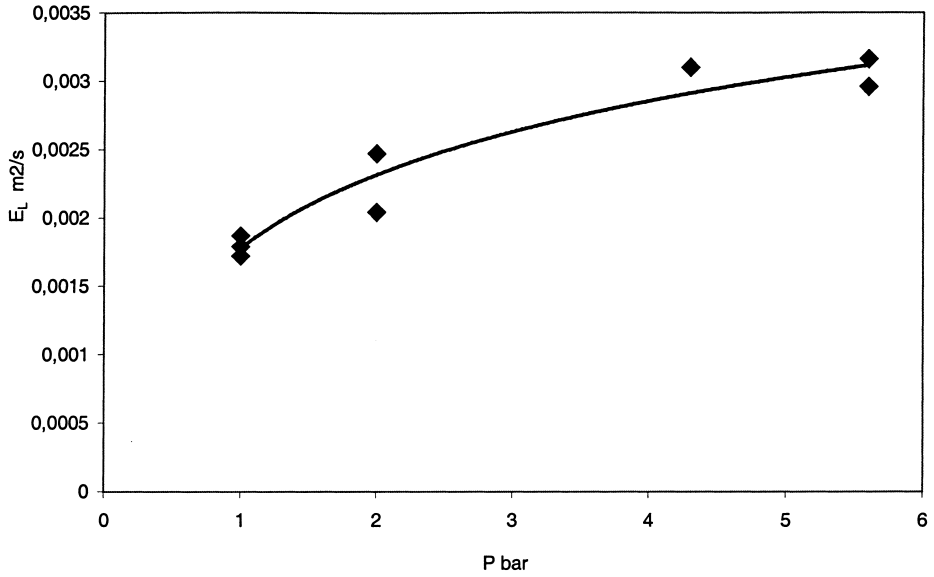

Fig. 3. The dispersion coefficient versus the pressure at $U_G = 0.135$ m/s.

As shown in Fig. 3, the dispersion coefficient increases with increasing pressure. This is in contrast with the results obtained by Gelder and Westerterp [3], where no pressure dependence of the liquid dispersion coefficient was observed. However, there are some experimental differences between the present studies and the work of Gelder and Westerterp. Both the gas velocities and flow regimes differ. The study by Gelder was performed at considerably lower superficial gas velocities, 1.5 cm/s, in the bubble flow regime. The results in Fig. 3 are in agreement with the results for an empty bubble column obtained by Wilkinson et al. [8]. Wilkinson explained this behavior by the fact that the smaller bubble size reduces the dispersion in the radial direction, which is due to the fact that larger bubbles increase the turbulence in the system.

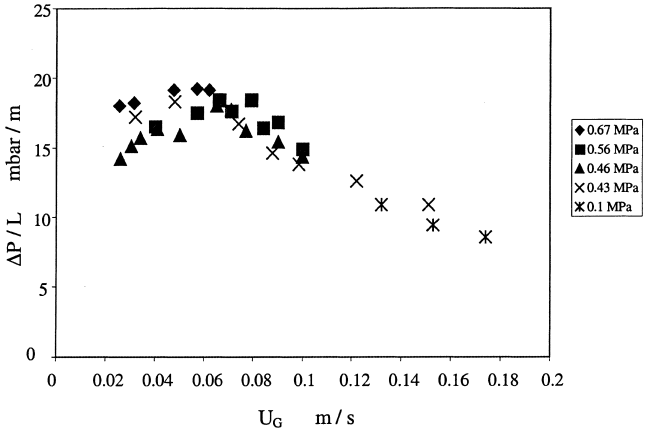

Fig. 4. The frictional pressure drop $\Delta P/L$ as a function of the superficial gas velocity at different pressures.

3.3. Frictional pressure drop

The frictional pressure drops are presented in Fig. 4. In accordance with the earlier works by Larachi et al. [1], an increase in the pressure results in an increase in the frictional pressure drop. However, two measurements performed at 0.43 MPa deviate from this behavior. The reasons for these deviations are not known.

As expected, and in line with the general fluid dynamic theory, the frictional pressure drop initially increased with the superficial gas velocity. However, at a gas velocity of approximately 0.06 m/s, the magnitude of the frictional pressure drops suddenly decreases, and surprisingly continues to decrease when the gas velocity is further increased. This behavior does not follow the general trend found in packed bubble columns with a liquid flow co-current or counter-current through the packed bed [1,9]. However, Achwal and Stepanek [10] achieved a frictional pressure drop profile similar to that presented in Fig. 4. Achwal and Stepanek performed their investigation in a semibatch bubble column packed with 6 mm solid ceramic cylinders.

4. Discussion

The bubble size in a packed bubble column can depend on the initial bubble size at the distributor and on the coalescence and breakup in the bed. Coalescence as well as bubble breakup is probably impaired in a packed bed, however, because (1) the bubbles are too small to be affected by the Rayleigh–Taylor instabilities [11]; (2) the packing prevents turbulent eddies of the size that could break up the bubbles; (3) visual observations in this work indicate that the shearing action of the packing does not produce small bubbles at the wall in a glass column at atmospheric pressure.

4.1. Gas holdup

In empty bubble columns, the increase in gas holdup at elevated pressures depends on the decrease in the mean bubble size [7,11–13]. It is, therefore, expected that the increased gas holdup at elevated pressures in a packed bubble column is also a result of a reduction in the mean bubble size. This is in agreement with the increased frictional pressure drop at higher pressures observed by Larachi et al. [1]. Both Larachi et al. and Wilkinson noted the importance of the gas density in determining the bubble size. Despite these similarities, the physical explanations for the reduction in bubble size may differ between bubble columns with and without packing.

As discussed above, the formation process in the region just above the gas sparger may mainly determine the size of the bubbles. In this region, the bubble breakup and the coalescence rate are probably higher than in the rest of the bed, i.e. farther away from the sparger. This implies that the mechanism that controls the pressure effect on the bubble size reduction occurs in the sparger region.

In this work, the sparger design assures that $We > 2$, i.e. the bubble formation occurs in the jetting regime [11]. In a packed bubble column, the continuous jet stream is not broken up in a free liquid, rather it can be assumed that the impact against the packing reduces the free length of the jet stream. The packing splits up the continuous jet into smaller fractions and individual bubbles are eventually formed. This mechanism excludes single bubble formation and bubble growth at the orifice; a mechanism that otherwise could be affected by the gas density and the pressure [11]. Since the momentum flow ρu^2 increases with increasing pressure, it can be assumed that the gas–liquid dissipation and the gas–packing dissipation also increase as well as the distributor pressure drop. This energy transfer from the gas may, according to Bernoulli's equation, reduce the pressure inside the gas bubble available for expansion work. The expansion work necessary for a 'new-born' spherical bubble to increase the volume by dV can simply be expressed by

$$\mathrm{d}w_{\mathrm{ex}} = \Delta P \, \mathrm{d}V \tag{1}$$

where ΔP is the difference between the gas pressure inside the bubble and the pressure outside (in the liquid phase) and w_{ex} the expansion work. This means that the pressure difference ΔP is reduced at higher pressures. Thus, the bubble cannot expand to a size larger than would be possible at a lower pressure and a higher ΔP.

4.2. Liquid dispersion

As seen in Fig. 3, the dispersion coefficient increases with increasing pressure. This further supports the theory that smaller bubbles are formed in the bed at higher pressures. This observation is also in agreement with the results for an empty bubble column recorded by Wilkinson et al. [8]. Wilkinson explained this behavior by the fact that the smaller bubble size reduces the dispersion in the radial direction due to the fact that larger bubbles increase the turbulence in the system.

4.3. Frictional pressure drop

The frictional pressure drop is caused by energy dissipation between the three phases, namely gas–liquid, gas–packing and liquid–packing phases. The frictional pressure losses caused by the interaction between the packing and the gas phase are expected to be more or less negligible due to a high degree of wetting of the packing.

It is worth noting that the maximum pressure drop occurs at the transition point between bubble and pulsation flow (Fig. 4). Visual observations by Therning and Rasmuson [5] at atmospheric pressure reveal that a transition point exists at a superficial gas velocity of approximately 0.06–0.07 m/s. It is, therefore, most likely that the negative gradient of $\Delta P/L$, as shown in Fig. 4, in some way is a consequence of the pulsation flow regime. It is expected that the larger bubble fragments formed and the channeling phenomena that may occur in the pulsation flow regime reduce the frictional pressure drop gradient. Larger bubbles decrease the interfacial gas–liquid area and the gas–liquid interfacial drag. These phenomena are, however, valid for both semibatch and continuously operated packed bubble columns and can obviously not explain the different behavior in the pulsation flow regime. The large difference between the two methods of bubble column operation is in the liquid feed, and as a consequence of this, the influence of the liquid feed also has to be of high significance. Previous experiments have shown that an increase in the superficial liquid velocity at a given gas velocity will increase the frictional pressure drop [14].

5. Conclusions

It can be concluded that both the gas holdup and the liquid dispersion coefficient increase at increasing pressures in a packed bubble column. It is also observed that the frictional pressure drop increases when the gas velocity increases in the bubble flow regime. In the pulsation flow regime, the frictional pressure drop $\Delta P/L$ decreases when the gas velocity is increased and a maximum point occurs in the transition region.

Acknowledgements

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