ESTIMATION OF GAS HOLDUP, DIAMETER AND APPARENT DENSITY OF MINERALIZED BUBBLES IN INDUSTRIAL FLOTATION COLUMNS

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ABSTRACT

Gas holdup was estimated from pressure difference measurements in two industrial flotation columns. The impact the apparent bubble density has upon gas holdup was quantified. Apparent density of the bubble-particle aggregate was evaluated as a function of the mineral drop back from the froth. At 1.5 cm/s superficial gas velocity, it was found the gas holdup can increase up to 30% by increasing the apparent bubble density.

Mean diameter of mineralized bubbles was estimated assuming the system behaves as a perfect countercurrent bubble-slurry flow. Under these conditions bubble diameter increases slightly by increasing the apparent bubble density (up to 0.15 g/mL). Furthermore, an extension of the ideal bubbly flow model was developed to consider slurry and gas recirculation in large size columns. This new approach showed that in large columns the actual mean bubble diameter can be 40-80% higher than predicted using the ideal bubbly model.

1. INTRODUCTION

Knowledge of the flow regime and gas holdup is important to estimate the particle and liquid residence time, because the achievable recovery depends strongly on these factors. Moreover, the rate of particle collection is a function of gas rate and bubble diameter, both of which affect gas holdup. Thus, the knowledge of the actual gas holdup and bubble size in the collection zone is presently considered a key aspect in the study of new control strategies for flotation columns.

Bubble column hydrodynamics has been largely studied in the field of analysis and reactor design (Shah, Y.T., 1982), particularly the case of gas-liquid in cocurrent or liquid in batch. In general, however, these works are not applicables to flotation columns for different reasons:

a) the flotation column operates in countercurrent
b) small bubbles (0.5-2.0 mm) are required, typically generated by gas spargers in the presence of frother
c) superficial gas velocities are relatively low (1-3 cm/s)
d) presence of solids, specially bubble-particles aggregates, significantly affects the hydrodynamic of the system

Consequently, it is necessary to develop new correlations to evaluate flotation columns hydrodynamic for diagnostic, design, control and optimization purposes.

In this sense, the hindered settling equations of Masliyah (1979) have been adapted (Yianatos, J.B., 1988a) to correlate mean bubble size, gas holdup and mean liquid and gas velocities in countercurrent liquid-bubble swarms. This approach has proven adequate to predict mean bubble size, from gas holdup measurements, in small diameter columns (less than 0.1m) using superficial gas velocities less than 3 cm/s, as used in industrial columns. Under these conditions, Joshi (1980) has shown that liquid recirculation does not occurs.

In flotation, solid particles partition between the liquid phase (i.e., are in suspension) and the gas phase (i.e., are attached to the bubble surface). The presence of solids will cause changes in bubble rise velocity and consequently gas holdup. This is a situation pertinent to flotation but one difficult to explore experimentally. Thus, using the same approach aforementioned, the effect of bubble loading upon gas holdup and bubble size was addressed theoretically (Yianatos, J.B., 1988a).

Apparent density and mean bubble diameter are useful to estimate bubble coverage with solids (%) and its carrying capacity, a critical parameter used to design column circuits for fine particle processing (Espinosa, R.G., 1988a, 1988b, 1989).

It is expected, however, that increasing the column diameter up to industrial sizes (e.g. 1-3m in diameter) the slurry and gas recirculation will increase, associated with larger dispersion coefficients, and probably with an increase in average bubble size and variance in bubble size distribution (larger than average bubble rise at velocities higher than the average promoting recirculation). Under these conditions the estimation of an average bubble size based upon the relative velocity between the net bubble and slurry flowrates becomes unrealistic.

In this work the estimation of the mean diameter of mineralized bubbles, in large size columns, will be addressed considering liquid recirculation and gas recirculation.

2. METHOD

2.2 Background

In gas-liquid systems in which there is a net flow of both phases, the relative

velocity U_S is defined as,

$$U_S = \frac{J_g}{\varepsilon_g} \pm \frac{J_{SL}}{(1-\varepsilon_g)} \qquad [2.1]$$

where + refers to countercurrent and - to cocurrent gas-liquid flow. All the parameters on the right-hand side are readily measured, consequently U_S can be determined.

Masliyah (1979) derived a general expression for relative particle to fluid velocity for hindered settling of spherical particles in a multispecies system. Bubble and rigid spheres in water have virtually equivalent drag coefficients up to a bubble Reynolds number (R_e) of approximately 500. Thus, for R_e less than 500, an analogous expression for bubbles can be written (Yianatos, J.B., 1988a),

$$U_S = \frac{g \cdot d_b^2 (1-\varepsilon_g)^{m-2} [\rho_a - \rho_{susp}]}{18 \mu_{SL} [1 + 0.15 Re_b^{0.687}]} \qquad [2.2]$$

where

$$Re_b = \frac{d_b \cdot U_S \cdot \rho_{SL} (1-\varepsilon_g)}{\mu_{SL}} \qquad [2.3]$$

$$\rho_a = \frac{\phi \cdot \pi \cdot d_p \cdot \rho_p}{d_b} \qquad [2.4]$$

and

$$\rho_{susp} = \rho_{SL} (1-\varepsilon_g) + \rho_a \cdot \varepsilon_g \qquad [2.5]$$

(see nomenclature for definition of symbols)

Equations [2.1] to [2.5] are adequate to describe liquid-gas countercurrent system (Yianatos, J.B., 1988a), where the following assumptions are valid.

a) small superficial gas velocities (1-3 cm/s)
b) normal distribution of bubble sizes, variance (± 20%)
c) small average bubble size (0.5-2.0 mm)
d) no liquid circulation (this is reasonable for column diameters less than 0.1 m).

2.2 Gas Holdup Measurement in Industrial Columns

Consider the column system illustrated in Figure 1. Δp can be measured using pressure transducers, differential pressure transmitters, or water manometers (Finch and Dobby, 1989). The water manometers require a slight downward flow of fresh water to prevent slurry penetration. ρ_{SL} is defined as the average slurry density and ρ_a is the apparent density of the bubble-particle aggregates between the two pressure measurement points.

Assuming the dynamic component of the pressure is negligible, the following equations can be derived in order to estimate the actual gas holdup.

water manometers,

$$\varepsilon_g = \frac{\rho_{SL} - \rho_w(1-h/L)}{\rho_{SL} - \rho_a} \qquad [2.6]$$

differential pressure transmitters,

$$\varepsilon_g = \frac{\rho_{SL} - \rho_w(\Delta P/gL)}{\rho_{SL} - \rho_a} \qquad [2.7]$$

2.3 Average Density of Bubble-Particle Aggregates in the Collection Zone of Industrial Columns

Figure 2 shows a diagram considering the interaction between the collection zone and the froth zone in a flotation column. According to Falutsu and Dobby (1989), drop back is the fraction of solids entering the froth that are rejected back into the collection zone. Here, the fractional drop back is represented by r.

The apparent density of mineralized bubbles (ρ_a) arriving at the froth zone can be related to the solids flowrate reporting to concentrate C, the drop back r, the superficial gas velocity J_g, and the column cross-sectional area A_C.

$$\rho_a = \frac{C}{(1 - r)\, J_g\, A_C} \qquad [2.8]$$

2.4 Estimation of Mean Diameter of Mineralized Bubbles in Industrial Flotation Columns

The estimation of average bubble diameter in the collection zone of a large size column needs to consider two perfomance parameters, slurry recirculation and gas recirculation.

Slurry recirculation can be accounted using the method suggested by Yianatos, J.B., (1986).When a slurry is descending countercurrent to a bubble swarm in the ideal bubbly regime, the interstitial slurry is split in two fractions (a) the flux drifted upward in the wake of the bubble, J_{SLd} and (b) the flux down ($J_{SL} + J_{SLd}$). Small bubbles, particularly those having rise velocity lower than interstitial slurry velocity, will be entrained downward.

If the superficial gas velocity increases (Jg greater than 4 cm/s), the column will reach the transition regime between the bubbly and the churn-turbulent regime (Finch and Dobby, 1989). At this point, the gas holdup becomes unstable and the flow is characterized by large bubbles rising rapidly, displacing water and small bubbles downward. In large size columns (equal or large than 0.3 m in diameter) this transition can occurs at superficial gas velocities even lower than 4 cm/s (Yianatos , J.B., 1989).

Gas recirculation will be explored by assuming that a percentage of the total gas flowrate was recicled. Thus, defining R as the fraction of J_g drifted downward, the actual superficial gas velocity of the bubbles rising in the column will be $J_g(1+R)$. For simplicity, it was also assumed that the bubbles move downward at the same interstitial velocity of the slurry, considering the total downward flux of slurry ($J_{SL}+J_{SLd}$).

3. EXPERIMENTAL DATA AND ANALYSIS

Figure 3 shows data on gas holdup versus superficial gas velocity, from two different plants using large size flotation columns. Data on differential pressure were collected either from water manometer or differential pressure transmitters. The gas holdup estimation was done assuming drop back equal to zero. This Figure shows that varying the superficial gas velocity from 0.5 to 3.0 (cm/s), the gas holdup increased from 8% to 20%.

Figure 4 shows the impact the fractional drop back (r) has upon the apparent bubble density ρ_a, at J_g=1.5 (cm/s) and concentrate carrying capacity 2.7 (g/min/cm^2), taken from column B. Here, it must be noticed that the maximun drop back is limited by the bubble surface coverage with mineral. For instance, considering the size and density of particles in column B, and assuming a maximun

bubble coverage $\emptyset<50\%$ (G.J. Jameson, personal communication), the maximun drop back will be around 80-90%. Thus, the expected apparent bubble density should be less than 0.4 (g/mL). The following analysis will be limited to this range.

Figure 5 shows the estimated gas holdup versus apparent bubble density, for a constant pressure difference reading and J_g=1.5 (cm/s). In this case, a change in apparent bubble density from 0 to 0.27 (g/mL), r = 89%, implies an increase from 15% to 20% in gas holdup. In large size columns, a drop back of 80-90%.can be expected. Thus, the effect of the corresponding increase in apparent bubble density is significant and should be taken into account.

Figure 6 shows the effect of slurry recirculation upon the estimated mean bubble diameter. For the ideal case of no slurry recirculation, the bubble size increases slightly by increasing the apparent bubble density. The same effect is more significant if slurry recirculation is considered. For the range of interest, the increase in bubble diameter due to this effect varied between 30-45%.

Figure 7 shows the effect of slurry recirculation upon the estimated mean bubble diameter. Gas recirculation is represented as the fraction (R) of the gas rate drifted downward by the slurry. The effect of R is particularly significant for low apparent bubble densities (less than 0.15 g/mL), and decreases by increasing the bubble density. Physically, at small apparent bubble densities, R can not be larger than 0.1, because the fraction of the total gas holdup occupied by the recicled gas approachs 50%. At larger apparent bubble densities, it is possible to reach values of R greater than 0.1.

Figure 8 shows the effect of superficial gas velocity upon mean bubble diameter. This effect is significant for the whole range of apparent bubble density. For instance, a change from 1 to 2 (cm/s) in superficial gas velocity will increase the mean bubble diameter in 30% approximately.

4. DISCUSSION

4.1 Estimation of the R value in a Gas-Liquid System

A rough estimation of R, using cumulative bubble frequency curves (% undersize), measured by photographs (Pal and Masliyah, 1989; Dobby, G.S., 1988) in columns of diameter equal or less to 0.1 m, showed the gas recirculation was less than 5%. This value, however, should increase for larger column diameters, and for highly loaded bubbles in flotation columns.

4.2 Estimation of the Average Density of Mineralized Bubbles

From industrial data on concentrate mass flowrates C (g/s) and superficial gas velocities J_g (cm/s), the minimum apparent bubble density can be stated. If the assumption of zero drop back (100% froth zone recovery) was true, the apparent bubble density would be small and does not affect bubble size significantly. However, Falutsu and Dobby (1989) measured drop back of 20-60% in a laboratory column; Yianatos, J.B., (1988b) estimated 5-50% drop back, from measurements of grade and percentage solid profiles in the froth zone of two industrial columns (0.46 and 0.91m, in diameter). It is expected in large size columns, 2-3m in diameter, the drop back can be as high as 80-90%. Thus, bubble loading needs to be considered in bubble size estimation, as well as the increase in gas holdup may have to be considered in slurry residence time calculations, and/or to account for changes in the kinetics of the collection zone.

Loaded bubbles will exhibit a larger bubble diameter compared with unloaded bubbles which can be allowed for similar conditions in the bubbly flow model.

Another aspect to be considered is that small bubbles have larger residence times and become more loaded than larger ones. This effect will also benefit recirculation of small bubbles.

4.3 Comments on the Use of Microbubbles at Industrial Scale

Unloaded single microbubbles (0.1-0.2 mm) have terminal rise velocities 1-2 cm/s (Clift, R., 1978). Because of the hinder effect of the bubble swarm, as well as the high loading of the bubble-particle aggregates (small bubbles have larger residence time), the actual rise velocity of bubbles in the swarm can be less than a half (i.e. 0.5-1.0 cm/s). Now, flotation columns at industrial scale operate at 1.0-2.0 cm/s interstitial downward velocity of slurry. Thus, the small bubbles will have a net downward velocity and will report to tailings. The problem is minor for fine particles with low density (e.g. fine coal), which causes less increase in the apparent bubble density. A way to operate the column with microbubbles would be to decrease the feed volumetric flowrate and, to maintain the column capacity the feed % solids should be increased. However, there is a maximun because the consequent increase in slurry density and viscosity have opposing effects and probably will produce a net decrease on the rise velocity of bubbles. It seems, that unless the improvement the microbubbles produce in collection kinetics and carrying capacity be significantly large, the capacity of the column will decrease.

4.4 Static Observation of Bubble Size Distribution

Only static bubble size distributions has been observed from photographs of the bubbles zone in two-phase systems. Using this direct measurement, or pressure measurements (the case of industrial flotation columns), a static mean bubble size can be estimated. This average bubble size, however, does not correspond to the

mean bubble size of the total gas flowrate arriving at the froth. Larger bubbles rising at higher interstitial velocities contribute with a minor frecuency in a static observation. Otherwise, this kind of measurement will always underestimate the actual average bubble diameter of the gas flowrate.

5. CONCLUSIONS

- Estimated gas holdup from two industrial flotation columns, assuming no drop back (r = 0), varied from 5% to 20%, for superficial gas velocities 0.5-3.0 cm/s. At J_{g}=1.5 cm/s and considering an expected drop back (r = 0.9), the estimated gas holdup increased by 30%.

- The increase in mineral drop back, up to r = 0.6, slightly increases the apparent bubble density. Higher drop backs from 0.6 to 0.9 result in a sharp increase in apparent bubble density and gas holdup.

- The estimated mean bubble diameter increased slightly by increasing the apparent bubble density up to 0.15 (g/mL). For higher apparent bubble densities (drop backs 0.8-0.95) the estimated bubble size increased significantly.

- The effect of slurry recirculation increased in 25-30% the estimated mean bubble diameter, at J_g = 1.5 cm/s, with respect to the estimation using the ideal countercurrent model.

- The effect of gas recirculation (R) on estimated bubble diameter was significant. At low apparent bubble densities (ρ_a < 0.1 g/mL), variations of R from 0 to a maximum of 0.1 increased the bubble diameter by 30-43%. At higher apparent

bubble densities the maximum R value can be larger, but the impact on mean bubble diameter decreases.

- In summary, corrections for slurry recirculation and gas recirculation can increase the estimation of mean bubble diameter by 40-80%, if compared with predictions from the ideal countercurrent bubble-slurry model.

- A static estimation of the mean bubble diameter, from both photographs and pressure difference measurements, will always underestimate the actual average bubble size of the gas flowrate arriving at the froth.

ACKNOWLEDGEMENT

Funding for column flotation research from FONDECYT-Chile (project #190/89) and Santa María University (project #89/27) is acknowledge. Discussion with R. Espinosa-Gomez is also gratefully acknowledge. The assistance provided by Juan Godoy, who typed this manuscript and prepared the diagrams, is greatly appreciated.

NOMENCLATURE

A_c	column cross-sectional area, cm^2
C	solids reporting to concentrate, g/s
d_b	mean bubble diameter, cm
d_p	particle size, μm
g	gravitational acceleration, cm/s^2
h	height of water level in manometer, cm
J_g	superficial gas velocity, cm/s

J_{SL} superficial slurry or liquid velocity , cm/s

J_{SLd} superficial velocity of liquid or slurry drifted by bubble swarm, cm/s

L distance between pressure taps on a column, cm

m parameter in eq. [2.2]

ΔP pressure difference, $g/cm/s^2$

R fraction of gas rate drifted downward

r fractional drop back

U_S relative velocity between bubbles and slurry, cm/s

W solids arriving at the froth, g/s

Greek Symbols

ε_g fractional gas holdup

ϕ fractional bubble coverage with minerals

μ_{SL} slurry or liquid viscosity, g/cm/s

π pi number

ρ_a apparent bubble density, or density of the bubble-particle aggregate, g/mL

ρ_p particle density, g/mL

ρ_{Susp} suspension density inside the column, g/mL

ρ_{SL} slurry or liquid density, g/mL

ρ_w water density, g/mL

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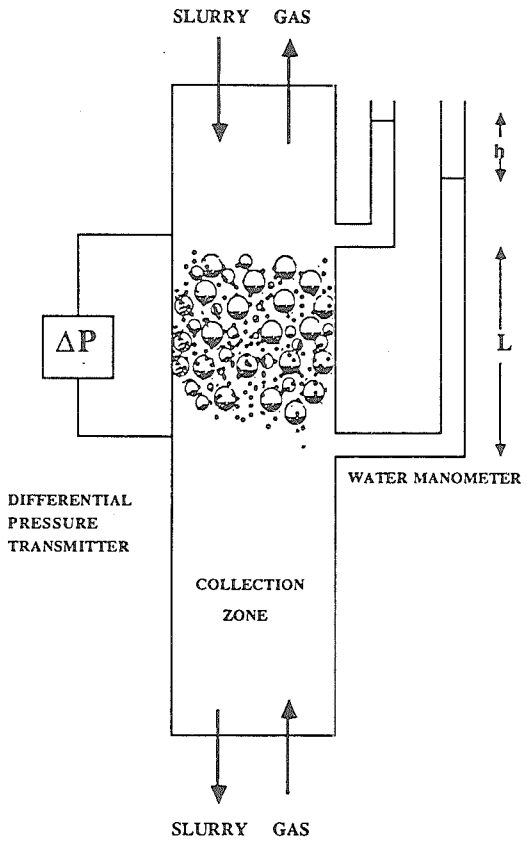

Figure 1. Pressure measurements in flotation columns.

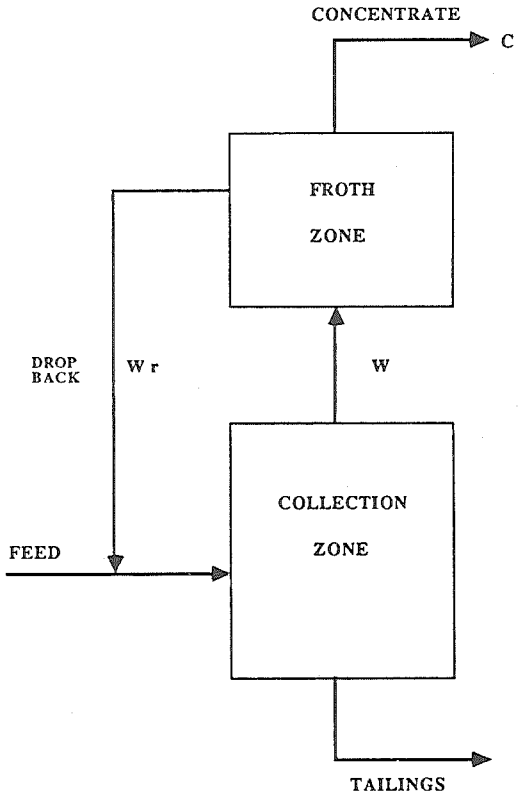

Figure 2. Interaction between collection and froth zones in flotation columns.

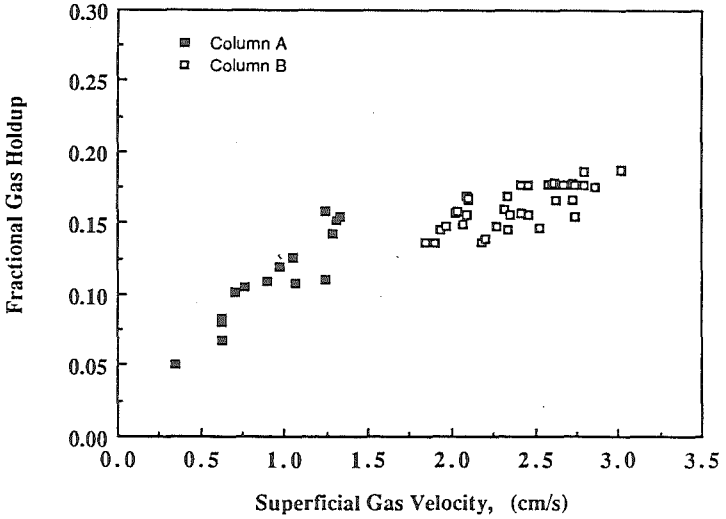

Figure 3. Gas holdup versus superficial gas velocity in two large size column.
(assuming drop back, r = 0)

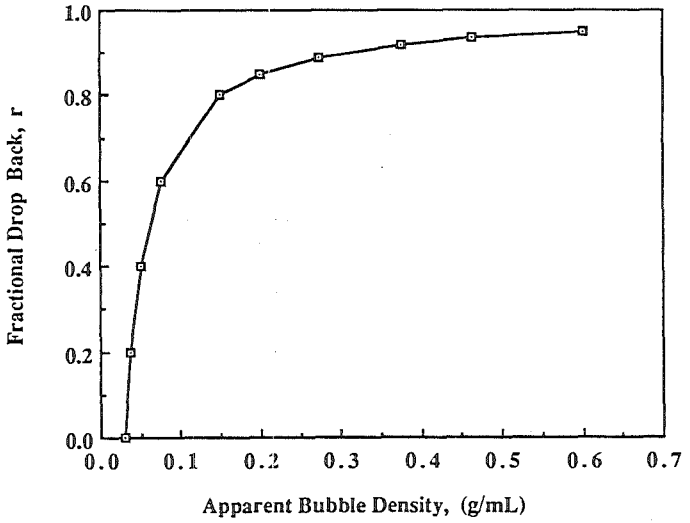

Figure 4. Fractional drop back versus density of bubble-particle aggregate.
(concentrate carrying capacity = 2.7 g/min/cm^2, J_g = 1.5 cm/s)

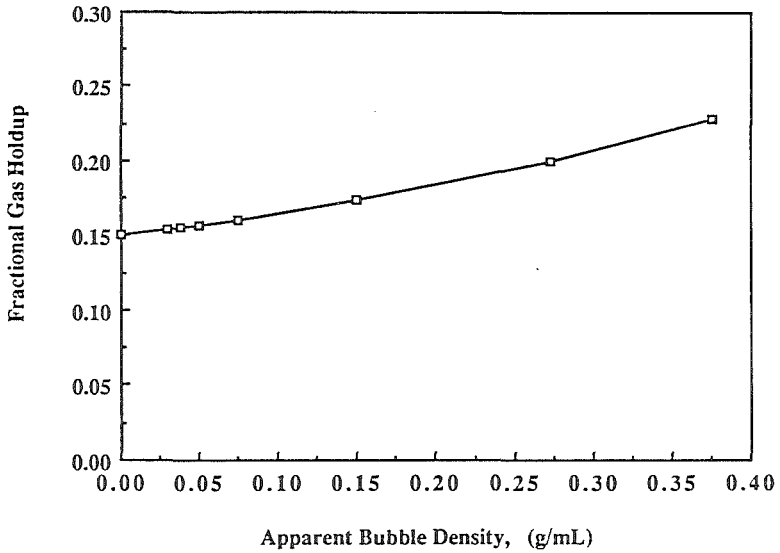

Figure 5. Gas Holdup versus apparent bubble density.
(J_g= 1.5 cm/s, $\Delta P/gL$ = 0.935 g/mL)

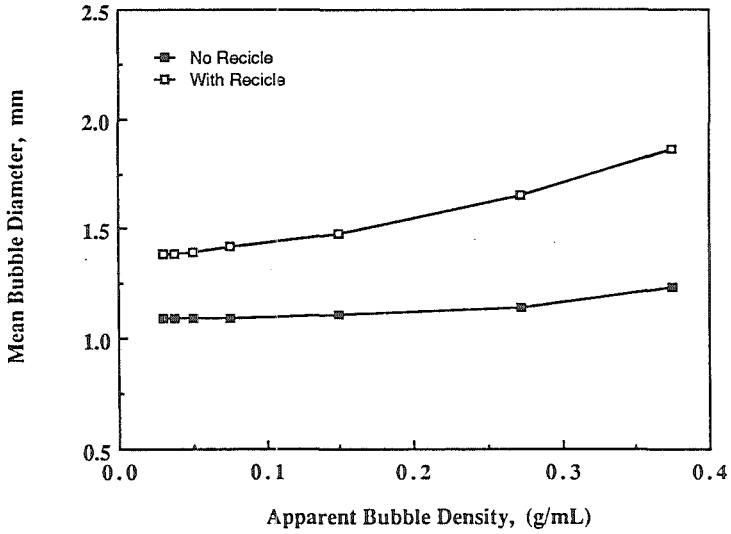

Figure 6. Effect of Slurry Recirculation.
(J_g = 1.5 cm/s, J_{SL} = 1.0 cm/s, $\Delta P/gL$ = 0.935 g/mL, R=0)

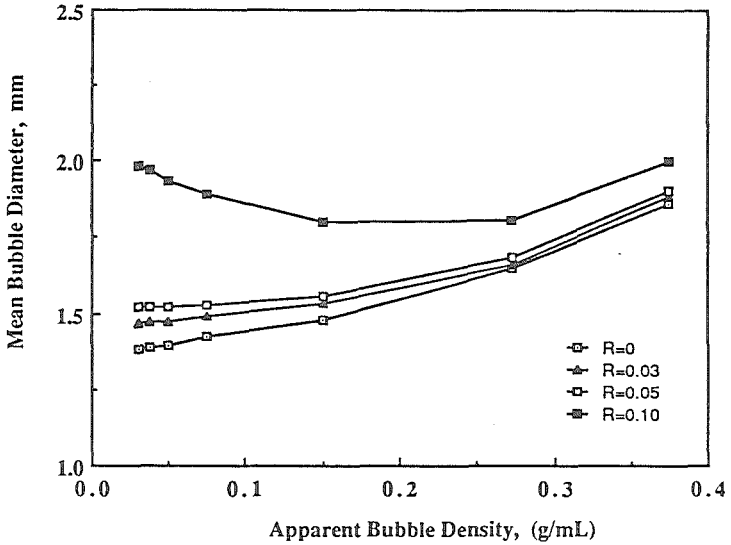

Figure 7. Effect of gas recirculation.
(J_g = 1.5 cm/s, J_{sL} = 1 cm/s, $\Delta P/gL$ = 0.935 g/mL)

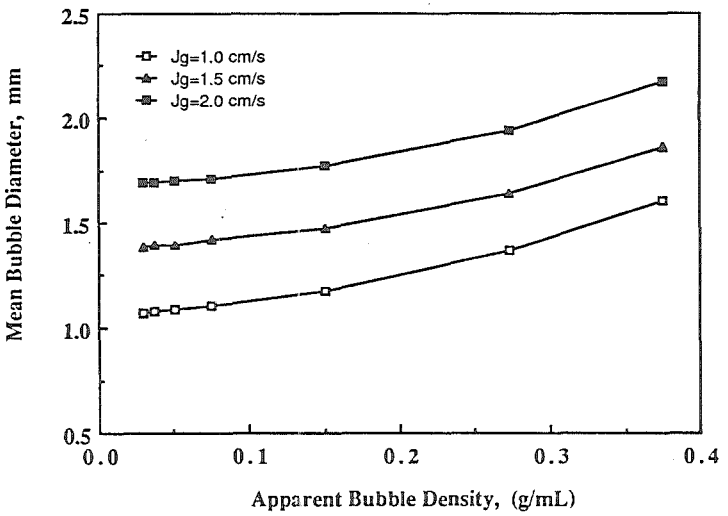

Figure 8. Effect of gas velocity.
($_{R=0}$)