Hydrodynamics of a Semibatch Slurry Bubble Column with a Foaming Liquid

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Slurry bubble columns are commonly used as chemical reactors in petrochemical and fermentation processes. Under the most common operating conditions, the volume fraction of the gas and liquid phases in a slurry bubble column is approximately uniform throughout the column (Smith and Ruether, 1985). On the other hand, the concentration of the solid phase in the slurry may vary with axial position if the size and density of the solid particles were sufficiently large to allow sedimentation. In the usual range of experimental conditions, the solids volume fraction is so small that solids concentration profiles do not result in gas or liquid holdup changes throughout the column. The study of the solids distribution is of relevance in the characterization of bubble column performance. In slurry reactors, the solid phase is usually a catalyst on which the chemical reaction takes place. As a consequence, a variation of the solids concentration in the column must be taken into account to determine such parameters as conversions, and heat and mass transfer rates.

Extensive experimental studies exist on the analysis of solids distribution in bubble columns. Solids concentration profiles are usually represented by means of the sedimentation-dispersion model, which was developed by Cova (1966) and by Suganuma and Yamanishi (1966). This model is based on a macroscopic mass balance of solids that takes into account the mechanisms of solids sedimentation and solids dispersion due to the convective currents in the liquid phase. Even though the theoretical basis of the sedimentation-dispersion model is still not well understood, as pointed out by Jean et al. (1989), it has proved to be a valuable tool in the analysis of experimental data (Badgujar et al., 1986; Smith et al., 1986).

The relative distribution of the phases in a bubble column depends on the prevailing flow regime. The flow regimes are qualitatively classified as bubbling flow, churn turbulent flow, slug flow, annular flow, and foaming flow. Their occurrence depends on the velocity of the phases, their physical properties, and column dimensions (Shah et al., 1982). The foaming flow regime is important when working with hydrocarbons at high temperatures and pressures (Bukur and Daly, 1987) and in fermentation processes (Stangle, 1985). This regime has not received considerable attention in the literature, since most of the experimental studies regarding bubble column performance are developed using water or other nonfoaming liquids. However, its analysis is important from a practical standpoint. For instance, foaming is an undesirable operating regime for hydroprocessing reactors, where the high gas content of the foam considerably hinders heat and mass transfer rates, which are crucial for the operation of these equipments. It is therefore relevant to consider the effect of the operating conditions on the existence of foam, as well as the performance of slurry bubble columns with foam formation.

In this work we present an experiment study of solids distribution in a semi-batch slurry bubble column in the presence of foam formation. The solids concentration profiles are analyzed by means of a modification of the sedimentation-dispersion model.

Experimental Study

The experiments were carried out in a plexiglas bubble column with an internal diameter of 29 cm. The gas distribution section is a cone with an apex angle of 60°, provided with a perforated-plate distributor located 10 cm above the cone apex. The distributor plate has 0.3-cm-dia. orifices arranged in a triangular pattern. The operating mode was continuous with respect to the gas phase and batch with respect to the slurry

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phase. Under certain operating conditions, two different regions were observed in the column: a bubbling region ($0 \le z \le H_e$), in which the bubbling or churn-turbulent flow regimes prevailed; and a foaming region ($H_e \le z \le H$), located in the upper part of the column. The height of the gas-slurry suspension was maintained at approximately 300 cm during the operation at steady state. The column was provided with seven sampling probes, which consist of tubes with an internal diameter of 0.64 cm, through which slurry samples were withdrawn and manometric pressure was measured. The probes were located at $z = 5$, 50, 100, 150, 195, 250 and 295 cm, and they had the flexibility to be placed at any radial position. The slurry samples were dried at 60°C, and their solids concentration was measured gravimetrically. Additionally, particle size distributions were measured from the solids samples.

All the experiments were conducted at atmospheric pressure and 25°C. The gas phase used was atmospheric air. The liquid phase was a solution of a commercial surfactant in kerosene at a concentration of 120 ppm (Pino et al., 1990). The physical properties of the solution were (at 25°C) $\rho = 808$ kg/m^3, $\mu = 1.6$ mPa · s, $\sigma = 20.4$ mN/m. The presence of the surfactant increased the potential of kerosene to foam, while preserving its physical properties. A polydisperse, porous solid phase was used. The cumulative particle size distribution of the solid is presented in Table 1. The mean particle size is 135 μm. The apparent density of the solid is 2,170 kg/m^3, whereas the real density is 4,660 kg/m^3. The kerosene completely wetted the solid so that, during the experiments, the pores of the solid phase were completely filled with liquid.

Each experiment was carried out by means of the following procedure. First, a load solids concentration was specified. The column was then loaded with the appropriate amounts of liquid and solid to reach the specified proportions. The superficial velocity of the gas was then set at the desired value. The total amount of slurry in operation was such that a suspension height of approximately 300 cm was obtained.

The achievement of the steady state was verified by performing experiments under a wide range of operating conditions, in which solids samples were taken at different axial positions every 30 minutes. It was observed that, in the first two to three hours of operation, the solids concentration changed in the following fashion. In the lower part of the column, the concentration diminished continuously, whereas in the upper part it increased constantly. This indicates that the solids were not completely suspended at this stage. After three hours of operation, the solids concentration at each sampling probe location reached a steady state characterized by oscillations that sometimes had an amplitude of about 10% of the measured concentration. These oscillations were not a product of experimental error, since a positive fluctuation of one sampling probe coincided with a negative one at a neighboring probe. This behavior is caused by the state of turbulence in suspension and the fact that the measured concentrations are point values. To minimize the effect of these fluctuations and to allow enough time to reach stable conditions, the steady-state solids concentrations reported here were made to correspond to arithmetic averages of the values of the three samples taken every 15 minutes after six hours of operation.

Table 1. Particle Size Distribution

Size Range, μm	%
0–50	20
50–150	22
150–250	34
>250	24

The global gas holdup (ϵ_g) was determined by the bed expansion method as the ratio of the gas volume, measured after complete disengagement of the gas phase at the end of the experiment, to the total volume of gas-slurry suspension during operation. The average solids concentration in the slurry ($\overline{C}_s$) was calculated by numerically integrating the measured point concentrations over the column length. Note that the average solids concentration is not necessarily equal to the load concentration, since part of the loaded solid might settle.

It was determined experimentally that the solids concentration did not change with radial position in the column. This was done by locating the sampling probes, which were designed to be movable, at several radial positions, drawing samples and measuring their concentration. In all the cases, the changes observed in the concentration were well within experimental error.

In the foaming regime, the gas holdup of two-phase bubble columns might exhibit hysteresis with respect to the gas superficial velocity. This behavior was reported by Bukur and Daly (1987). However, for the air-kerosene system at ambient conditions, Pino et al. (1990) did not observe such behavior. In addition, the suspension of solids in three-phase nonfoaming systems might also present hysteresis with respect to the gas flow rate, which was established by Heck and Onken (1987). Therefore, experiments were conducted in this work to determine if the hydrodynamics of the system under study was affected by the start-up procedure regarding the setting of the gas velocity. The variations of gas holdup and solids concentration profiles in those experiments were within experimental error, indicating that no hysteresis existed.

Sedimentation-Dispersion Model

In this work the sedimentation-dispersion model is applied to the case in which two different regions of solids mixing can be distinguished in the bubble column. Our analysis is based on the approach by Smith and Ruether (1985); the problem was formulated by taking into account that bubbling and foaming regions might be characterized by different parameters. Under steady-state conditions and with no net flow of slurry (semibatch operation), a mass balance of solid particles in the ith particle size range yields:

$$\frac{d}{dz}\left(E_{sib}\frac{dC_{si}}{dz}\right) + \frac{d}{dz}(\psi_{lb}U_{pib}C_{si}) = 0 \qquad i = 1, \ldots N \qquad 0 \le z < H_e \qquad (1)$$

$$\frac{d}{dz}\left(E_{sif}\frac{dC_{si}}{dz}\right) + \frac{d}{dz}(\psi_{lf}U_{pif}C_{si}) = 0 \qquad i = 1, \ldots N \qquad H_e < z \le H \qquad (2)$$

where

C_{si} = solids concentration of the ith particle size range
E_{si} = solids dispersion coefficient

ψ_l = volume fraction of interparticle liquid
U_{pi} = particle sedimentation velocity
z = axial position
H_e = height of the interface between foaming and bubbling regions
H = total gas-liquid-solid suspension height
b, f = bubbling and foaming regions

In establishing Eqs. 1 and 2, we have followed the recommendations put forth by Smith et al. (1986) and Badgujar et al. (1986) regarding the use of independent mass balances for narrow particle size ranges. We have considered that the solid can be divided into N particle size fractions, each of which has a characteristic value of solids dispersion coefficient and particle sedimentation velocity.

Equations 1 and 2 can be integrated using the fact that there is no net flow of solids at any cross section in the column (Smith et al., 1986) to obtain

$$C_{si} = A_{i\alpha} e^{-Bo_{i\alpha}(z/H)} \qquad \alpha = b, e \tag{3}$$

where *Bo* is the Bodenstein number, defined by

$$Bo = \frac{\psi_l U_p H}{E_s} \tag{4}$$

The constants $A_{i\alpha}$ must be determined either from the concentration at any point inside each region or from the average concentration within each region. Note that the formulation presented allows the occurrence of a discontinuity in the solids concentration at the bubbling region-foam interface ($z = H_e$). The total concentration of solids at any point in the column can be calculated as the sum of the concentrations of all the particle ranges.

The model conformed by Eq. 3 simply represents the application of the sedimentation-dispersion model in a bubble column with two different mixing zones. As pointed out by Jean et al. (1989), there is controversy on the deduction and physical meaning of the parameters involved in the sedimentation-dispersion model for semibatch operation. This indicates that Eq. 3 must be considered a result of empirical considerations, in which the Bodenstein numbers represent adjustable parameters. Further theoretical work must be performed to establish a rigorous basis for the sedimentation-dispersion model.

Results and Discussion

Figure 1 shows the effect of the presence of solids on the gas holdup. At the lowest gas velocity, the solids content does not affect appreciably the gas holdup in the range of concentrations considered. At intermediate and high gas velocities, an increase in solids concentration results in a decrease in gas holdup. The decrease of gas holdup with solids concentration is consistent with the trend observed in nonfoaming systems and the particle size range considered in this work (Kara et al., 1982; Badgujar et al., 1986).

Changes in gas holdup with solids concentration are attributed to the effect of the solid particles on the coalescence of the gas bubbles. Kato et al. (1972) observed that the solid particles promote bubble coalescence, which results in lower bubble residence time and hence lower gas holdup. This fact has been confirmed experimentally in more recent works (Kojima and Asano, 1981; Badgujar et al., 1986). Kojima and Asano (1981) and O'Dowd et al. (1987) measured bubble sizes in the presence of solids, finding that the mean bubble size increased as the solids concentration increased. Note that, when small particles are used (<10 μm), the effect of the presence of solids in bubble coalescence is reversed: the solid particles accumulate at the gas-liquid interface, thus inhibiting bubble coalescence and increasing the gas holdup. This behavior has been reported by Sada et al. (1986) and Capuder and Koloini (1984). Figure 1 shows that the coalescence mechanism is improved in the system considered. It should be noted that in this case the presence of solids does not inhibit the formation of foam, causing only a change in its structure. Even though it is well known that certain types of solids, even at low concentrations, can inhibit foam formation (Frye and Berg, 1989), it was not the case for the system studied here. Morooka et al. (1986) also report the presence of foam in slurry bubble columns in continuous operation when a surfactant was added to water.

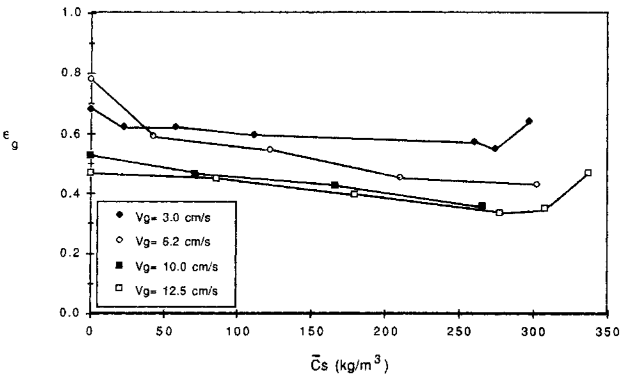

Figure 1. Gas holdup.

For each experiment, it was determined if the two regions (bubbling and foaming) were present either by visual observation or, when the opaqueness of the suspension did not allow it, by noticing whether there was a sharp change in the solid concentration profile and the pressure profile. These sharp changes, which are considered as discontinuities in the profiles predicted by the model, indicated a difference between the two regions in their ability to retain solids. When only one region was present, Eq. 3 was used to fit single values of A_i and Bo_i for the whole column ($0 \leq z \leq H$). Note that A_i represents the concentration at $z = 0$. Four particle size ranges were considered ($N = 4$): 0–50 μm, 50–150 μm, 150–250 μm, and 250–300 μm.

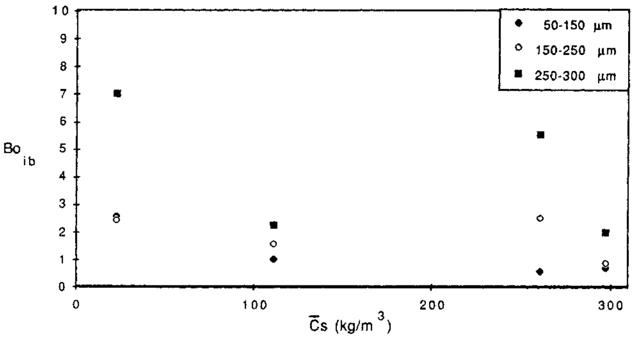

Figure 2. Bodenstein numbers for the bubbling region, V_g = 3.0 cm/s.

Table 2. Values of the Parameter Bo_{if}

V_g cm/s	$\overline{C}_s$ kg/m^3	H_e cm	Bo_{if} 0–50 μm	50–150 μm	150–250 μm	250–300 μm
3.3	22.7	113	0.35	0.99	3.20	*
3.0	111.0	123	3.52	—	0.032	*
2.8	260.5	125	4.02	2.60	*	*
3.6	297.3	108	1.97	0.98	*	*
6.6	42.6	105	6.00	3.48	0.62	2.05

*No appreciable amount of this fraction was obtained.

These ranges were narrow enough to obtain the values of the sedimentation-dispersion parameters that fitted the experimental data. When two regions were present, the values of A_{ib}, Bo_{ib}, A_{if}, and Bo_{if} were fitted to experimental data by applying Eq. 3 to the two regions.

Bubble and foaming regions coexisted in the column at low gas superficial velocities (below 4 cm/s), and at gas velocities up to 6 cm/s only for low average solids concentration (below 50 kg/m^3). The values of the parameter Bo_{ib} are presented in Figure 2 as a function of the average solids concentration in the column for a gas superficial velocity of 3.0 cm/s. The Bodenstein number is not reported for the particle size range 0–50 μm, since the solids concentration in this range was approximately uniform indicating that $Bo_i = 0$ for this range. Figure 2 shows that, as the particle diameter increases, the values of the Bodenstein number increase. This trend results from the larger sedimentation velocities of the coarser particles. The changes of the sedimentation-dispersion coefficient with average solids concentration are somewhat erratic in Figure 2, although for the 50–150 μm range, a continuous decrease of Bo_{ib} with an increase in average solids concentration is observed.

The values of the Bodenstein number corresponding to the foaming region, Bo_{if}, are reported in Table 2. The results do not exhibit definite trends. It is worth mentioning that these coefficients, which are the slopes of curves in semilog plots of the solids concentration vs. axial position, are very sensitive to experimental error. The most interesting aspect of the results in Table 2 is that the Bodenstein numbers corresponding to the foaming region are generally of the same order of magnitude as those of the bubbling region. Sedimentation in a foam occurs through the liquid films. Accordingly, one would expect lower sedimentation velocities in the foaming region. The fact that the ratio of sedimentation velocity to dispersion coefficient is of the same order of magnitude in both regions suggests that the solids dispersion coefficient is also lower in the foam than in the bubble region. This agrees with visual observation that the recirculation of the liquid phase in the foam is of lower magnitude than in the bubbling region.

The values of the Bodenstein number for intermediate and high gas superficial velocities are presented in Figures 3a and 3b. In this case, only one region was distinguished in the column except for the lowest solids concentration in Figure 3a. The results indicate that the Bodenstein number decreases with the average solids concentration. This decrease, however, is generally of low magnitude, from which it can be concluded that Bo_{ib} can be considered approximately independent of average solids concentrations.

From the results of Figure 3 it is evident that the Bodenstein number increases with particle size, as expected: larger particles

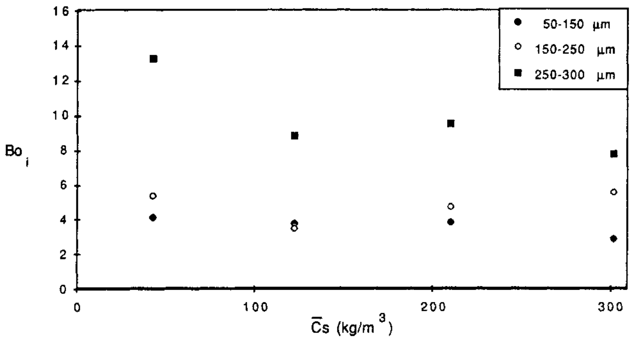

Figure 3a. Bodenstein numbers, $V_g = 6.1$ cm/s.

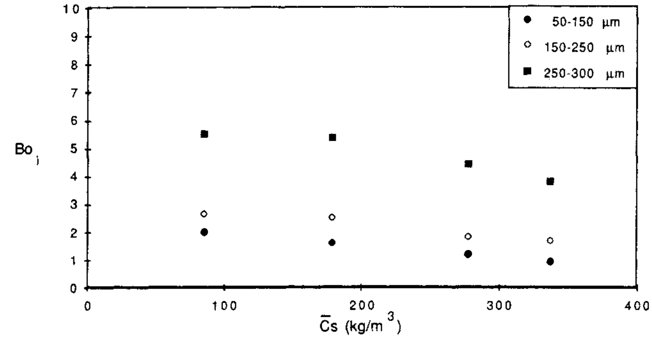

Figure 3b. Bodenstein numbers, $V_g = 12.5$ cm/s.

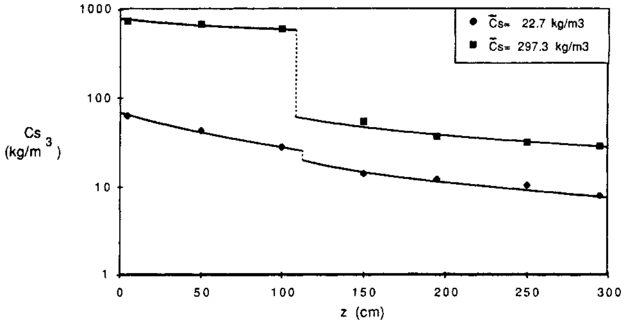

Figure 4a. Application of the sedimentation-dispersion model, $V_g = 3.0$ cm/s.

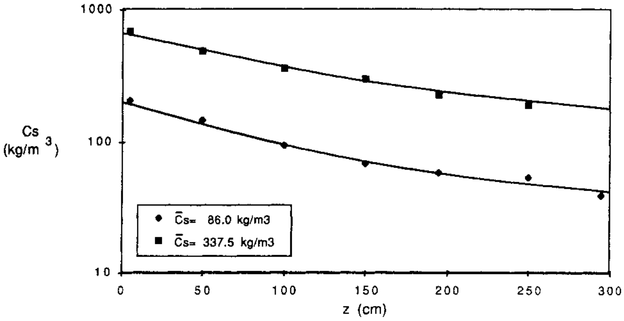

Figure 4b. Application of the sedimentation-dispersion model, $V_g = 12.5$ cm/s.

tend to have larger sedimentation velocities and lower dispersion coefficients. Comparing the results corresponding to the intermediate and high gas velocities, the value of the Bodenstein number decreases with an increase in gas superficial velocity. This is consistent with the previous results; for instance, in the correlations by Smith et al. (1986), which predict sedimentation velocities and solids dispersion coefficients, the Bodenstein number exhibits a relation with the gas superficial velocity which is approximately $Bo_{ib} \sim V_g^{-0.25}$.

Figures 4a and 4b illustrate how this model fits the experimental data on total solids concentration. In these curves, the solid lines represent the results predicted by the model. In Figure 4a, corresponding to low gas velocities, the discontinuity in the solids concentration between bubbling and foaming regions is clearly distinguished. The magnitude of this discontinuity increases with average solids concentration. At high gas velocities (Figure 4b), the results clearly indicate the existence of a homogeneous flow pattern in the column since no discontinuities are observed. It is interesting to mention that the total solid concentration cannot be adjusted in terms of a global Bodenstein number, since this would require the semilog plots of total concentration vs. axial position to be a straight line which is not the case. This indicates the necessity of finding sedimentation-dispersion coefficients for each particle size range, as it was performed in this work.

Notation

Bo = Bodenstein number, defined by Eq. 3
C_s = solids concentration
$\overline{C}_s$ = average solids concentration
E_s = solids dispersion coefficient
H = height of the gas-slurry suspension
H_e = height of the bubbling region–foaming region interface
N = number of particle size ranges
U_p = particle sedimentation velocity
V_g = superficial gas velocity
z = vertical coordinate

Greek letters

ϵ_g = global gas holdup
μ = viscosity
ρ = density
ψ_l = volume fraction of interparticle liquid
σ = surface tension

Indices

b = bubbling region
f = foaming region
i = refers to ith particle size range

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