5.0 Results and Discussion

The values of gas holdup reported below represent average values over the entire height of the column obtained by the method described in the previous section. Experiments to record gas holdup as a function of height using DP gauges gave inconsistent results which were discarded. Also, due to the reduction in hydrostatic head up the column, the gas superficial velocity is not constant and varies along the height. The values reported here represent arithmetic averages calculated with knowledge of the column height, slurry density, and overall holdup.

5.1 Gas Holdup

5.1.1 Two-Phase (Gas-Liquid) Flow

The variation of gas holdup with gas and liquid superficial velocity for the air-water system is shown in Figure 3. Gas holdup increases with increasing gas superficial velocity but at a declining rate. This agrees directionally with the results of nearly all other investigators.(1-28) Also, it appears that gas holdup decreases with increasing liquid superficial velocity, the most severe deviations occurring at the higher gas velocities. These results are not consistent with the findings of most other investigators who report that gas holdup is independent of liquid flow. This behavior may be due to normal experimental error or a bias in the measurement technique at higher liquid rates.

Figure 4 displays a comparison of the experimental data with that predicted by the correlation of Akita and Yoshida.(9) The experimental curve was generated by taking the average of all holdup readings at a given gas superficial velocity since Akita and Yoshida assume no dependence on liquid superficial velocity. As can be seen, there is very good agreement between the two curves.

Figure 5 displays the results of experiments to investigate the effect of surface tension variations on gas holdup. Moneteric-LF100 was added to form a 0.33 volume % solution which reduced the surface tension from approximately 70 dyne/cm to 33 dyne/cm. Gas holdup increased significantly, nearly doubling at the higher gas velocities. Again the holdup significantly decreased with increasing liquid superficial velocity. In this case, however, part of the deviation may be due to contamination of the liquid. The same liquid/surfactant mixture was used for all three runs (1.48, 2.95, and 4.43 cm/sec) and was obviously discolored by the third run. Contamination may have increased the surface tension above 33 dyne/cm, which would partially account for the separation of the curves.

5.1.2 Three-Phase (Gas-Liquid-Solid) Flow

Figures 6 through 19 present the raw data for the variations of gas holdup in three-phase systems as a function of liquid and gas superficial velocity, solids concentration and particle size, and the presence of a solids withdrawal system. Figures 6 through 9 represent the specific effects of each of the independent variables listed above while the raw experimental data are presented graphically in Figures 10 through 19.

Figure 6 shows the variation of gas holdup with solids concentration. Gas holdup decreases due to the presence of solids as can be seen by comparing the data for 0 wt.% solids with that for 5, 10, and 15 wt.%, especially at the higher gas velocities. However, the variation of gas holdup with increasing solids concentration from 5 to 15 wt.% is less severe and hardly significant. It is known(36) that the presence of solid particles below a critical particle size promotes bubble coalescence which would result in decreased gas holdup.

Figure 7 presents the effects of solids particle size on gas holdup. Gas holdup decreases with decreasing particle size which one would expect based on the work of Ostergaard and Theisen(32) and others who conclude that bed contraction is greater for accumulated beds of smaller particles. From this, one must conclude that, if bed contraction is greater, larger bubbles must be being formed which result in decreased gas holdup. A second mechanism, related to the above theory but perhaps simpler, deals with the effect of particle size on liquid viscosity. As particle size decreases, the slurry becomes more of a continuous medium and not just solid particles being moved by momentum transported to them from the liquid. The effect is to increase the viscosity of the pure liquid which increases the drag forces on rising bubbles causing them to coalesce thus reducing gas holdup. Figure 7 confirms these predictions directionally.

Figures 8 and 9 present the data for variations of gas holdup due to the presence of a solids withdrawal system. Figure 8 shows a slight increase in gas holdup due to the presence of solids withdrawal while Figure 9 shows an opposite trend. This leads us to believe that the variations in the data are caused by normal experimental error and that the presence of a solids withdrawal system with withdrawal rates as high as 15 volume % of the feed rate to the column (as was the case here for 1" tube), does not significantly affect gas holdup. Also, there were no obvious visual effects on flow patterns or gas dispersion due to the presence of a solids withdrawal system.

Figures 10 through 19 are a graphic representation of the raw data, part of which was used to develop Figures 6 through 9. Figure 13 represents a rerun of the data presented in Figure 12 which shows a large variation of holdup with superficial slurry velocity. Figure 13 is much more consistent with other data.

5.2 Solids Accumulation

Figures 20 through 30 show the results of the experiments to characterize the extent of solids accumulation as a function of gas and slurry superficial velocity. As previously stated, sampling taps were located in each flange, their height being measured from the joint of the column's conical end with the 3" feed line.

Figures 20, 21, and 22 show the solids concentration gradients at slurry superficial velocities of 1.48, 2.95, and 4.43 cm/sec for gas superficial velocities of 1.03 (Figure 20), 5.4 (Figure 21), and 9 cm/sec (Figure 22). In each case the concentration gradient flattens with increasing slurry superficial velocity which agrees well with the results of other investigators. It is well established that the extent of bed expansion increases with increasing slurry/liquid velocity. Concerning the effect of gas velocity, an inspection of the vertical axis indicates a significant increase in solids holdup between gas velocities of 1 and 5.4 cm/sec at the lower most sampling point. Apparently at some velocity between 1 and 5.4 cm/sec, the gas velocity reaches a point where the forces causing the bed to contract are overcome by the forces causing expansion and the bed expands. Thus, accumulated solids that normally would be fluidized below the first sampling tap are pushed upward and the solids concentration at the first tap increases. The data show that the concentration at the top sample tap does not seem to vary much with changes in gas superficial velocity, probably due to the fact that solids holdup there is relatively low and a ebullient bed is not formed.

Figures 23 through 30 represent solids concentration gradients for superficial slurry velocities of 0.91 and 1.5 cm/sec at gas superficial velocities of 0.47, 1, 2, 2.2, 3.6, 5.5, 7.25, and 9 cm/sec. Similar behavior concerning apparent bed expansion that was observed in Figures 20 through 22 appears between Figures 23 and 24. At a gas superficial velocity of 0.47 cm/sec, the solids concentration is significantly lower than at a superficial velocity of 1 cm/sec at the bottom sampling tap. This leads us to conclude that for accumulated solid beds with a mean particle diameter somewhere around 125 microns, the critical gas velocity where the forces causing bed expansion overwhelm those causing contraction is approximately 1 cm/sec.

Comparison of Figures 25 and 26 for gas velocities of 2 and 2.2 cm/sec shows good agreement between the data as one would hope to see. This adds confidence to conclusions and shows that the sampling technique was sound.

Further inspection of Figures 23 through 30 shows that as gas velocity increases the curves shift to the right adding further support to the conclusion that the effect of gas velocity is significant in three-phase beds of accumulated particles. The shift is more noticeable for the 0.910 cm/sec slurry superficial velocity curves than for the flatter profiles typical of higher slurry velocities.

5.3 Backmixing

As mentioned earlier, qualitative tests were performed to develop an understanding of the degree of backmixing in tall two-phase columns. With normal gas flow but no liquid flow, methylorange dye was injected in (a) the top and (b) the middle of the transparent column. The dispersion and progression of the dye through the column was observed and recorded with color photographs at fixed intervals. Figures 31 (A-C) demonstrate that with top injection the dye required approximately two minutes to reach the bottom of the column. Figures 32 (A-C) demonstrate that with middle injection, migration upwards was rapid following the gas flow, as expected, but dispersion downwards due to backmixing still proceeded slowly; the dye initially reached the bottom in 40 seconds but backmixing was only complete after two minutes. Close observation indicated that radial dispersion of the dye was nearly instantaneous but appeared to concentrate in distinct zones or "cells". These "cells" migrated while continuing to backmix well within each fixed volume. Both experiments led to the preliminary conclusion that the column as a whole is not well backmixed but the "cells" do remain well mixed. Quantitative work to support this has been planned but not carried out.