CHAPTER IV

AVERAGE GAS HOLD-UP

A. Fischer-Tropsch Derived Waxes

1. Reproducibility and Effect of Operating Procedure

Reproducibility of hold-ups was investigated by performing the same experiment at least twice (using the same batch of wax or fresh wax), whereas, the effect of operating procedure was investigated by conducting similar experiment in increasing and decreasing order of gas velocities (using the same batch of wax).

Figure 6 illustrates hold-up values for FT-200 wax obtained from the same batch of wax for different runs at the same operating conditions (0.051 m ID column, 1.85 mm orifice plate distributor, 265 °C, and increasing order of gas velocity). Fresh wax used in the first run, run 11-1, gave lower hold-up values than run 11-5. Run 11-5 produced large amounts of foam compared to run 11-1 or run 11-2, which barely produced foam. Also, no effect of operating procedure was observed in the absence of foam ($u_g > 0.04$ m/s) in the early runs, run 11-1 and run 11-2. During these runs (11-1–5) it was observed that the hold-ups for FT-200 wax increased after each successive run (i.e. continuous usage of the same batch of wax for several runs). This might have been caused by changes in molecular structure of FT-200 wax after prolonged heating.

Figure 7 illustrates the effect of operating procedure on the average gas hold-up for Sasol reactor wax in the 0.051 m ID column equipped with 1.85 mm orifice plate. No effect of operating procedure on gas hold-up was observed. Similar results were obtained with Mobil reactor waxes (not shown). Different results have been

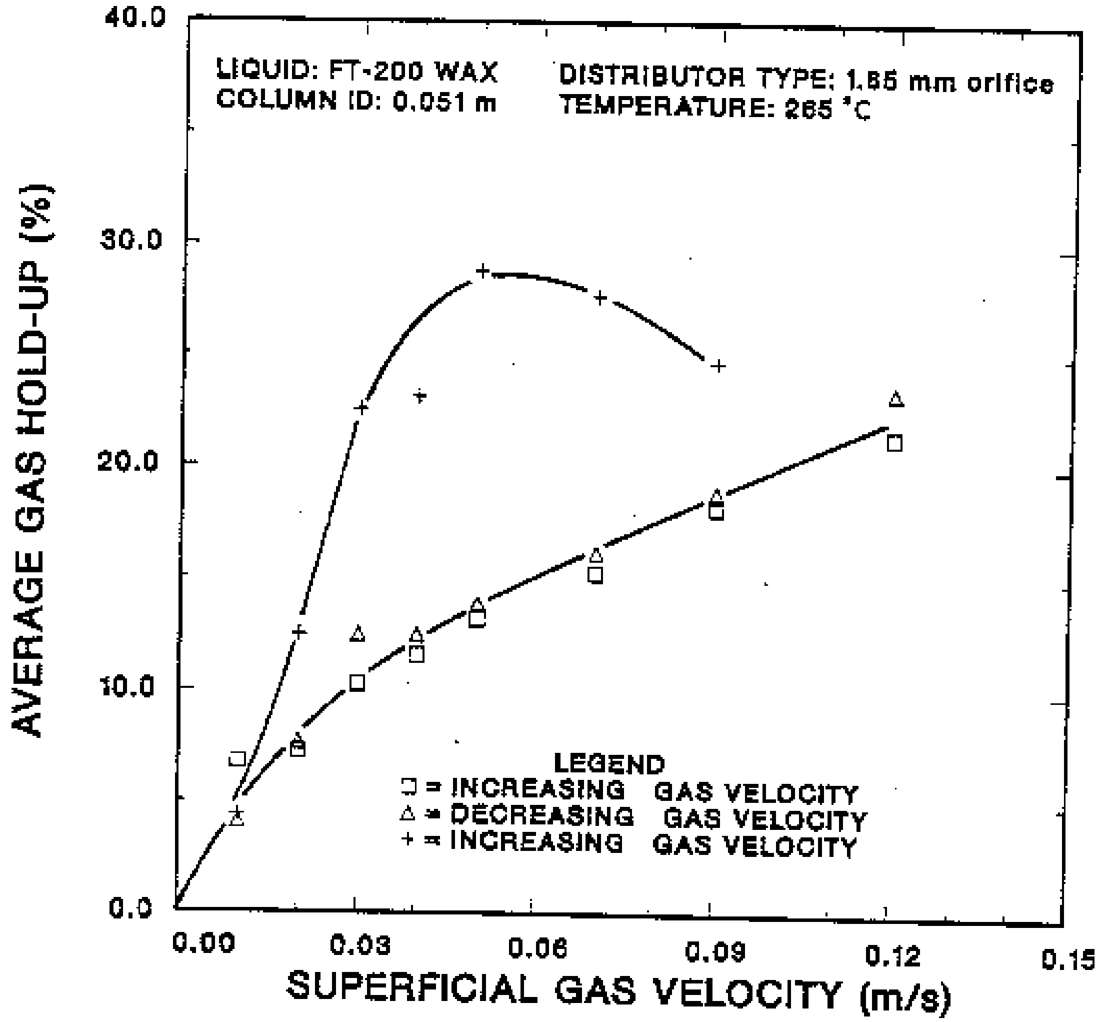

Figure 6. Effect of operating mode and superficial gas velocity on gas hold-up (□ -Run 11-1, △ -Run 11-3, + -Run 11-5).

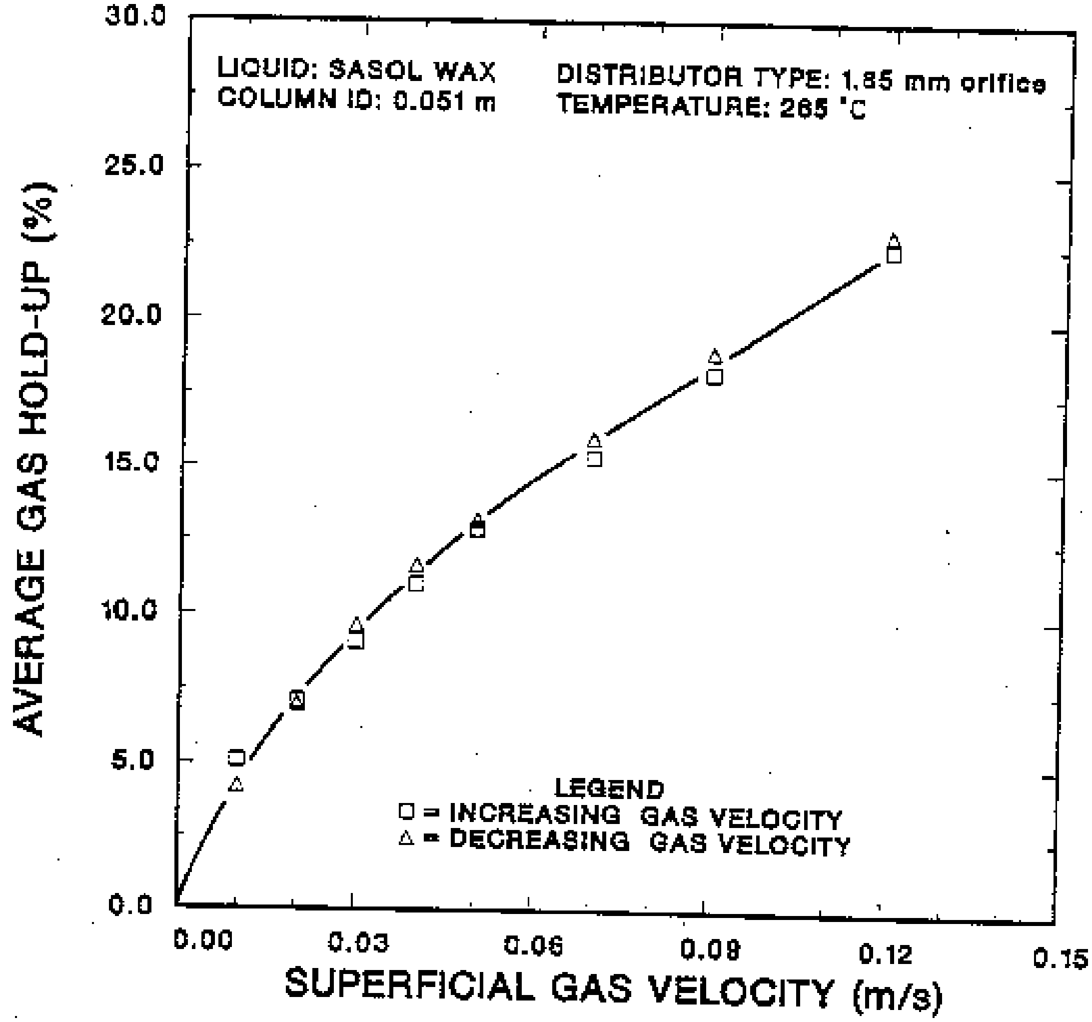

Figure 7. Effect of operating mode and superficial gas velocity on gas hold-up (□ -Run 8-1, △ -Run 8-2).

reported by Bukur *et al.* 1987, when using FT-300 wax they observed hysteresis type behavior when experiments were conducted in increasing and decreasing order of superficial gas velocity. In summary, reproducibility of hold-up data is better for the runs without foam or at high gas velocity ranges than in the presence of foam.

2. Effect of Temperature

The effect of operating temperature on gas hold-up was investigated by conducting experiments at 200 °C and at 265 °C. Most of the experiments were done in the 0.051 m ID column, and a limited number of experiments in the 0.229 m ID column. A 1.85 mm single orifice distributor plate was used for runs in the 0.051 m ID column, whereas the 5 x 1 mm, and the 19 x 1.85 mm perforated plates were used for runs in the large column. Results from these experiments can be summarized as follows:

1. For paraffin waxes, FT-200 and FT-300, runs in the 0.051 m ID column showed that, an increase in temperature was accompanied with increase in foam, and thus higher gas hold-up values.
2. In the absence of foam, hold-up values decreased slightly with decrease in temperature.

Figure 8 illustrates the effect of temperature on gas hold-up for FT-300 wax. An increase in temperature resulted in an increase in gas hold-up values. Runs conducted at 200 °C and 265 °C show a considerable increase in gas hold-up as foam was produced (u_g < 0.03 m/s) followed by decrease in gas hold-up as the flow regime changed to the slug flow. Similar results were observed with FT-200 wax for runs performed in the 0.051 m ID column at 200 and 265 °C using the

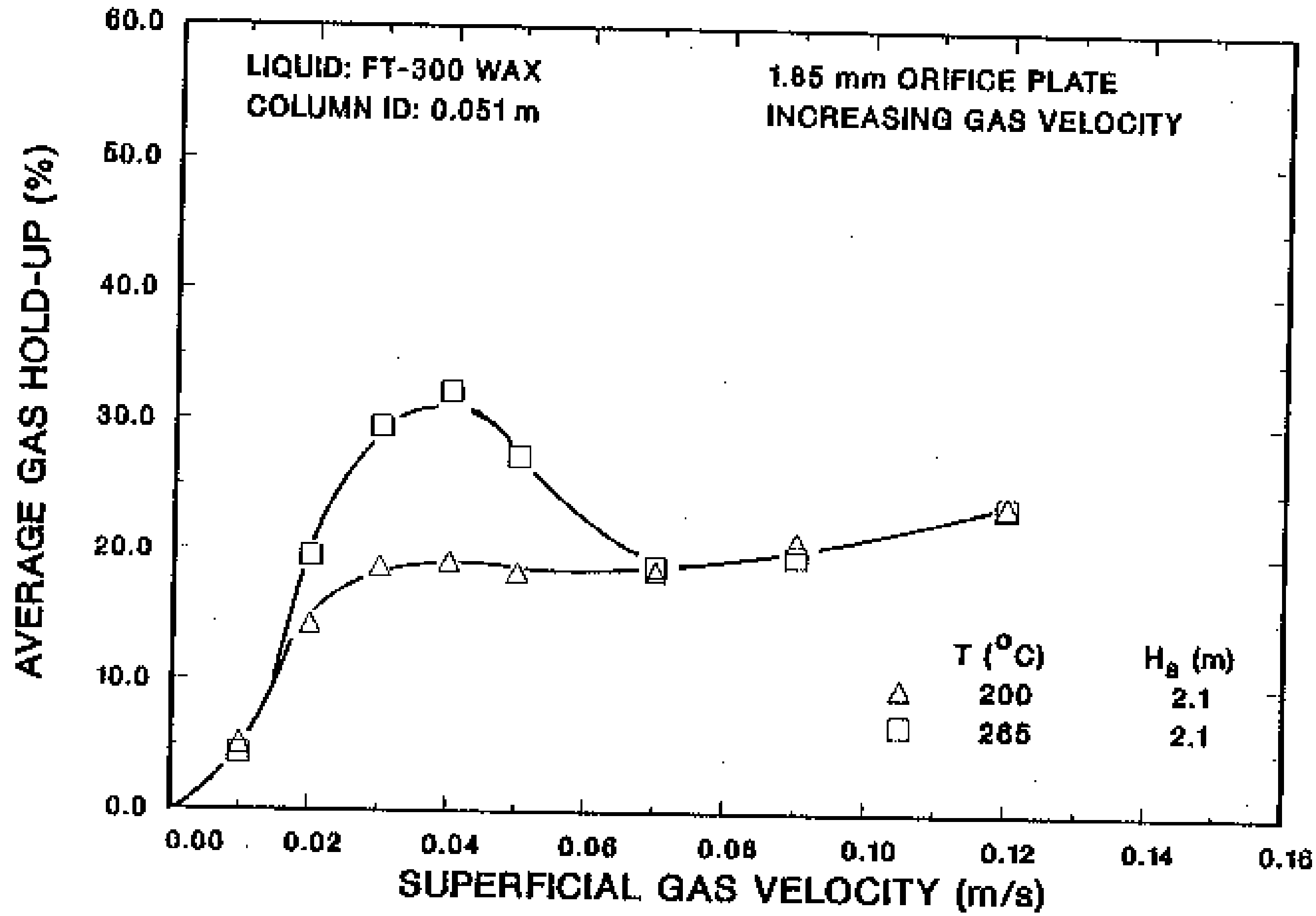

Figure 8. Effect of operating temperature and superficial gas velocity on gas hold-up.

1.85 mm orifice plate distributor. In the presence of foam hold-ups decreased with decrease in temperature and no effect of temperature on gas hold-up was observed in the absence of foam.

As reported by Bukur *et al.*, 1987 no foam (lower hold-up values) was observed for runs in the 0.051 m ID with 1.85 mm orifice plate using FT-300 wax at 160 °C and the transition to slug flow regime was not observed for the runs conducted at 280 °C in the velocity range employed (0.01-0.09 m/s).

Runs with reactor waxes (Sasol's Arge reactor wax and Mobil's reactor waxes) gave lower values of hold-up than paraffin waxes. However, these values were similar to those obtained with FT-300 wax in the absence of foam. There was a slight decrease in hold-up values as temperature decreased from 265 °C to 200 °C, and virtually no foam was produced in these runs. Results obtained with Mobil reactor wax are shown in Figure 9.

Results from experiments conducted with FT-300 wax in the 0.229 m ID column with 5 x 1 mm perforated plate distributor are shown in Figure 10. Runs were made at 170 °C and at 265 °C. Also shown in this figure are hold-up values obtained by Quicker and Deckwer (1981) at 170 °C using a 0.9 mm nozzle in a 0.095 m ID column. The jet velocities with the 5 x 1 mm perforated plate in this work are identical to those in the Quicker and Deckwer study. At superficial gas velocities in the range 0.01 and 0.02 m/s at 265 °C this distributor produced a substantial amount of foam which remained stable at the top of the interface. At higher superficial gas velocities, the trend was typical for FT-300 wax at the same temperature. The run at 170 °C did not produce any foam for gas velocities employed, 0.01 to 0.05 m/s. As a result, hold-up values were lower than those obtained from runs at 265 °C. These results were significantly different from those

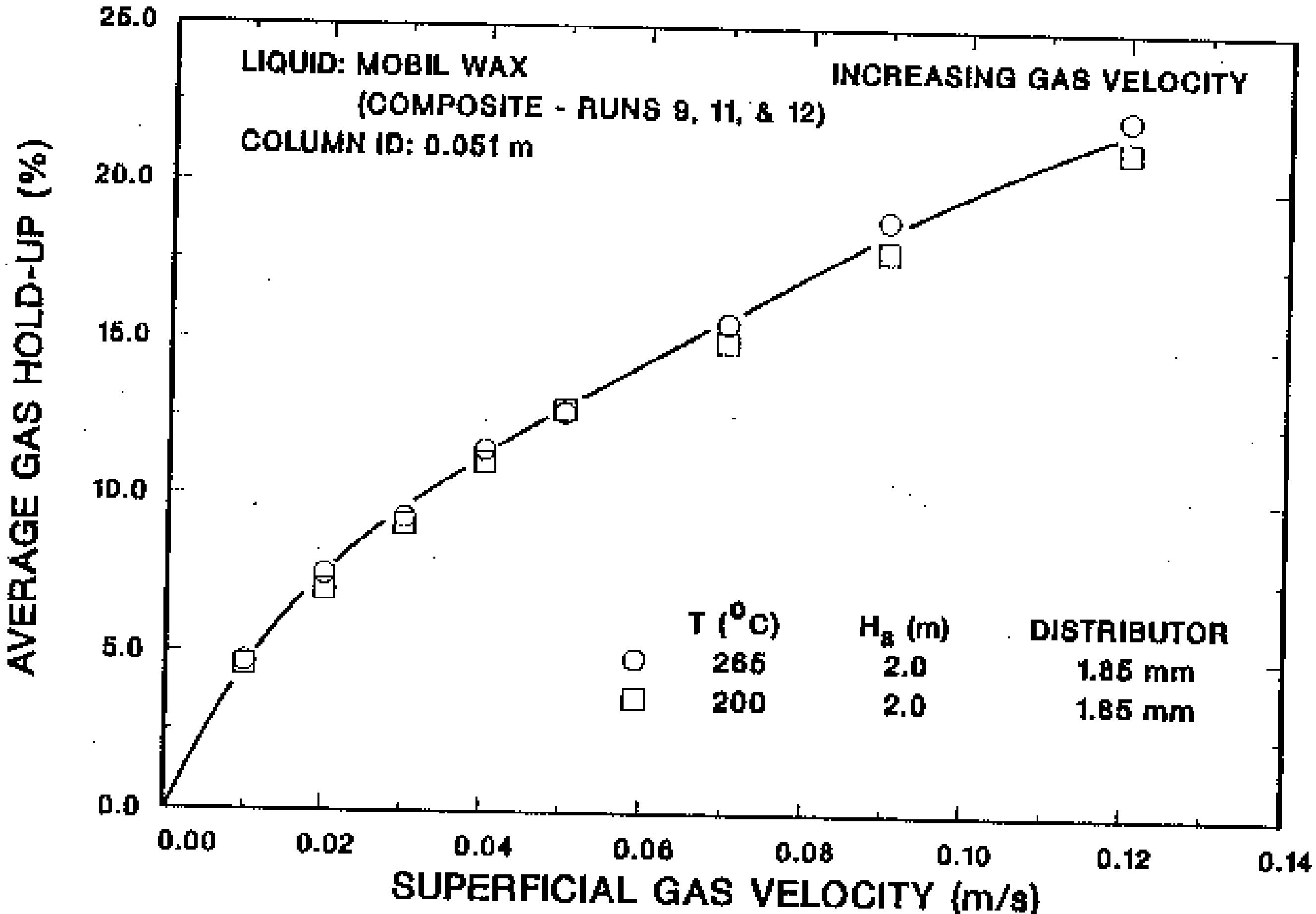

Figure 9. Effect of operating temperature and superficial gas velocity on gas hold-up (composite wax from Mobil runs CT-256-9, -11, -12; ○ -Run 9-3, □ -Run 9-2).

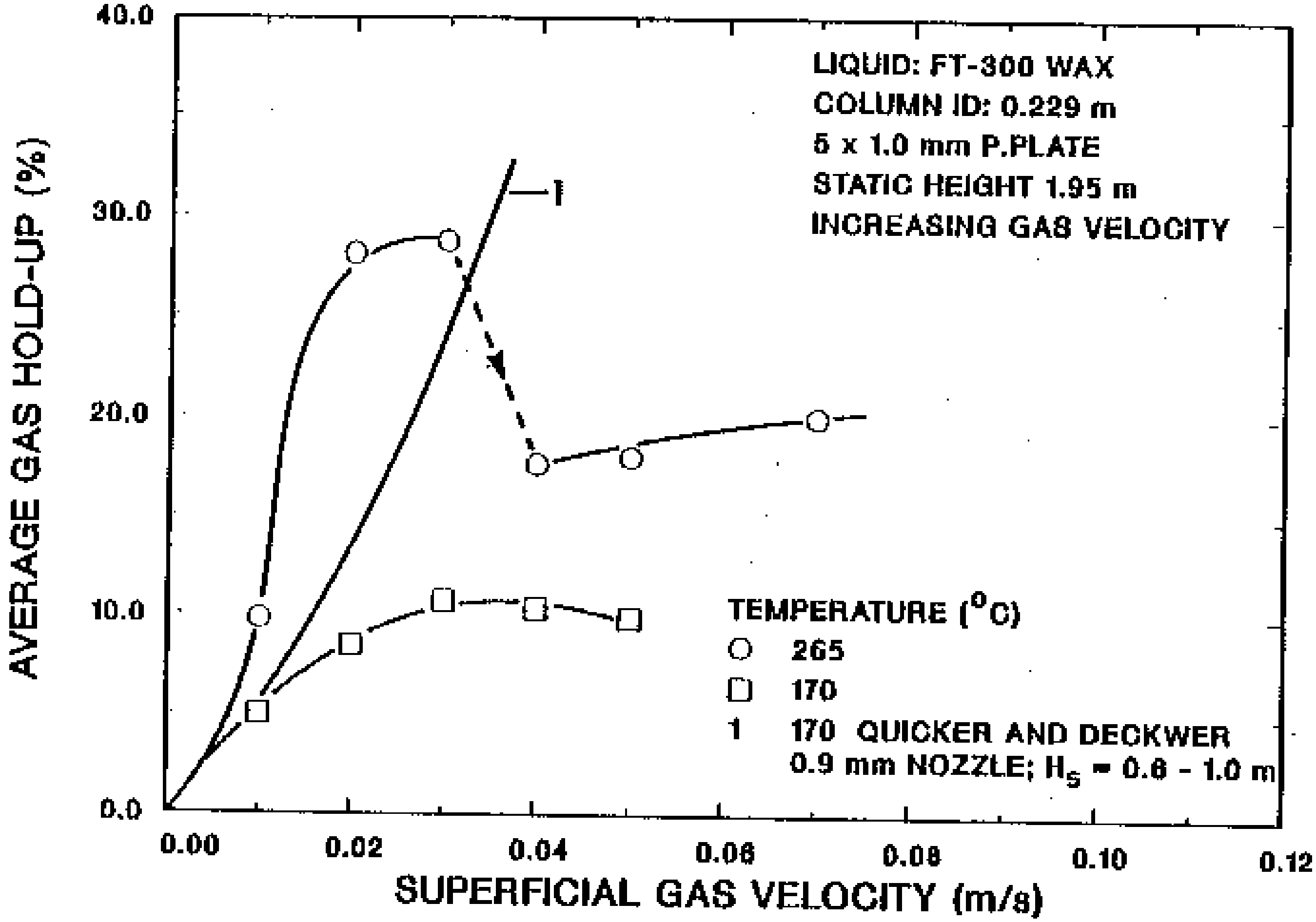

Figure 10. Effect of operating temperature and superficial gas velocity on gas hold-up and comparison with literature (○-Run 4-1, □ Run 4-2, 1 -Quickwer and Deckwer 1981).

obtained by Quicker and Deckwer under similar conditions. Their hold-up values are slightly higher than the ones obtained in this study.

Several workers have investigated the effect of temperature on gas hold-up using paraffin waxes as the liquid medium. Most of these experiments were done at low gas velocities (< 0.04 m/s), in the foamy regime. Deckwer *et al.* (1980) observed a significant decrease in gas hold-up as the temperature was increased from 180 °C to 270 °C for experiments conducted in 0.041 m ID column, and no effect of temperature was observed for runs in the 0.10 m ID column. Quicker and Deckwer (1981), while using FT-300 wax, found that hold-ups at 170 °C were higher than values at 130 °C, with both 0.9 mm nozzle and a 19 x 1.1 mm perforated plate distributor. Kuo *et al.*, 1985, found that hold-up values for runs with FT-200 wax at 138 °C were substantially lower than those at 260 °C.

In general, the temperature effect is significant in the foamy regime, however once in slug flow regime or the churn-turbulent flow regime, the hold-up values do not vary much with temperature. These results also illustrate that at sufficiently low temperatures foaming can be completely prevented. This behavior can be qualitatively explained in terms of values of liquid viscosity (Table 6). Bubble coalescence increases with liquid viscosity (i.e. as the temperature decreases), and the tiny bubbles which build up the foam at the top of the dispersion do not exist.

3. Effect of Column Diameter

Results from studies conducted in the 0.051 m ID column and 0.229 m ID column, which illustrate the effect of column diameter on gas hold-up, are shown in Figure 11. The comparison is based on runs conducted at 265 °C using 1.85 mm orifice plate distributor in the 0.051 m ID column, and 19 x 1.85 mm perforated plate in the 0.229 m ID column (The two distributors are dynamically similar, the jet velocity in the smaller column was approximately 94 % of the jet velocity in the large column), using Sasol reactor wax in the velocity range of 0.01 to 0.12 m/s. No foam was observed during these runs and no significant effect of column diameter on the gas hold-ups was observed.

Similar observations have been reported by Bukur *et al.* (1987) with FT-300 wax. In the absence of foam they observed no significant effect of column diameter on hold-up values. Similarly, Kuo *et al.*, 1985 while using FT-200 wax for runs in the 0.032 and the 0.053 m ID columns they observed no significant effect of column diameter in hold-ups. However, Deckwer *et al.* (1980) conducted experiments in 0.041 and 0.1 m ID columns at temperatures below 250 °C and at low gas velocities, 0.005 to 0.03 m/s. They reported higher hold-up values from the smaller column, this was because of the presence of foam caused by low gas velocities.

In general, the gas hold-ups are independent of column diameter in the absence of foam.

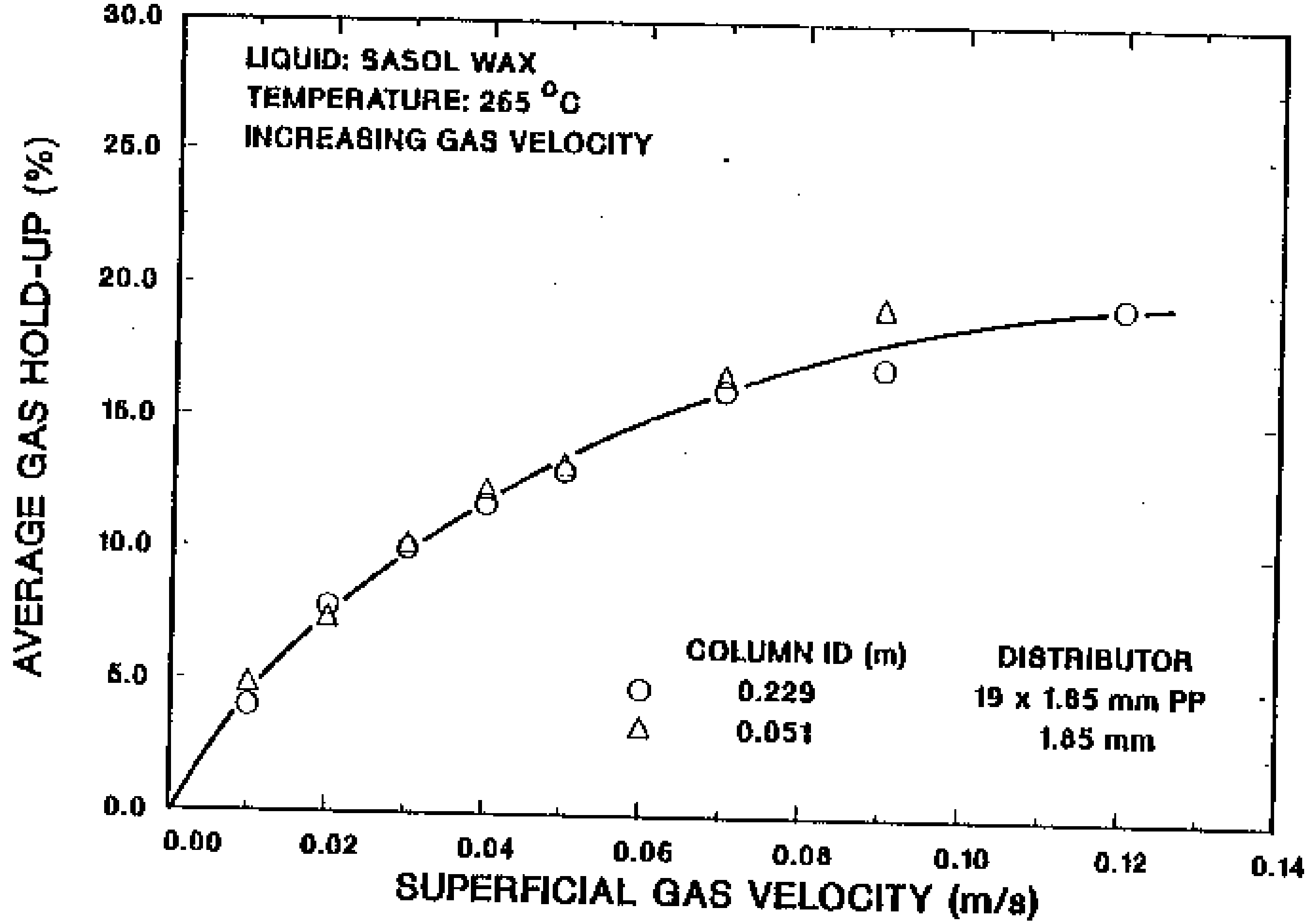

Figure 11. Effect of column diameter and superficial gas velocity on gas hold-up (○ -Run 3-2, △ -Run 8-4).

4. Effect of Distributor Type

Effect of distributor type on gas hold-up was investigated in the 0.051 m ID column. Three different distributors were used: 1 and 1.85 mm single orifice plates and a 40 μm SMP distributor. The orifice plate distributors provided jet velocities in the range of 26.0 m/s to 312 m/s for the 1 mm orifice and 7.6 m/s to 91.0 m/s for the 1.85 mm orifice for superficial gas velocities of 0.01 to 0.12 m/s.

The major highlights of these investigations are:

1. In the foamy regime the hold-up values increased with decrease in the size of the orifice diameter. The SMP distributor produced the highest hold-ups.
2. No effect of distributor type was observed for runs with reactor waxes and in the absence of foam.

Figure 12 illustrates results obtained with FT-300 wax in the 0.051 m ID column at 265 °C. All experiments produced foam at low superficial gas velocities ($< 0.05\ m/s$) followed by transition to slug flow regime at high superficial gas velocities. It was observed that the foamy regime (foaming range) increases with decrease in the orifice size (as shown in Figure 12 the transition to slug flow regime with the SMP distributor was not complete at 0.12 m/s). The SMP produced the highest amount of foam and the 1.85 mm orifice produced the least amount of foam. The differences in hold-ups in the foamy regime obtained with different distributors could be attributed to on differences in the jet velocities produced by different distributors. High jet velocities (high kinetic energy) result in large surface areas which means many small bubbles, and thus higher hold-up values. Once the transition to slug flow regime is complete, there is virtually no difference in gas hold-up values for different types of distributors. Similar results were observed with the FT-200 wax (see Figure 13).

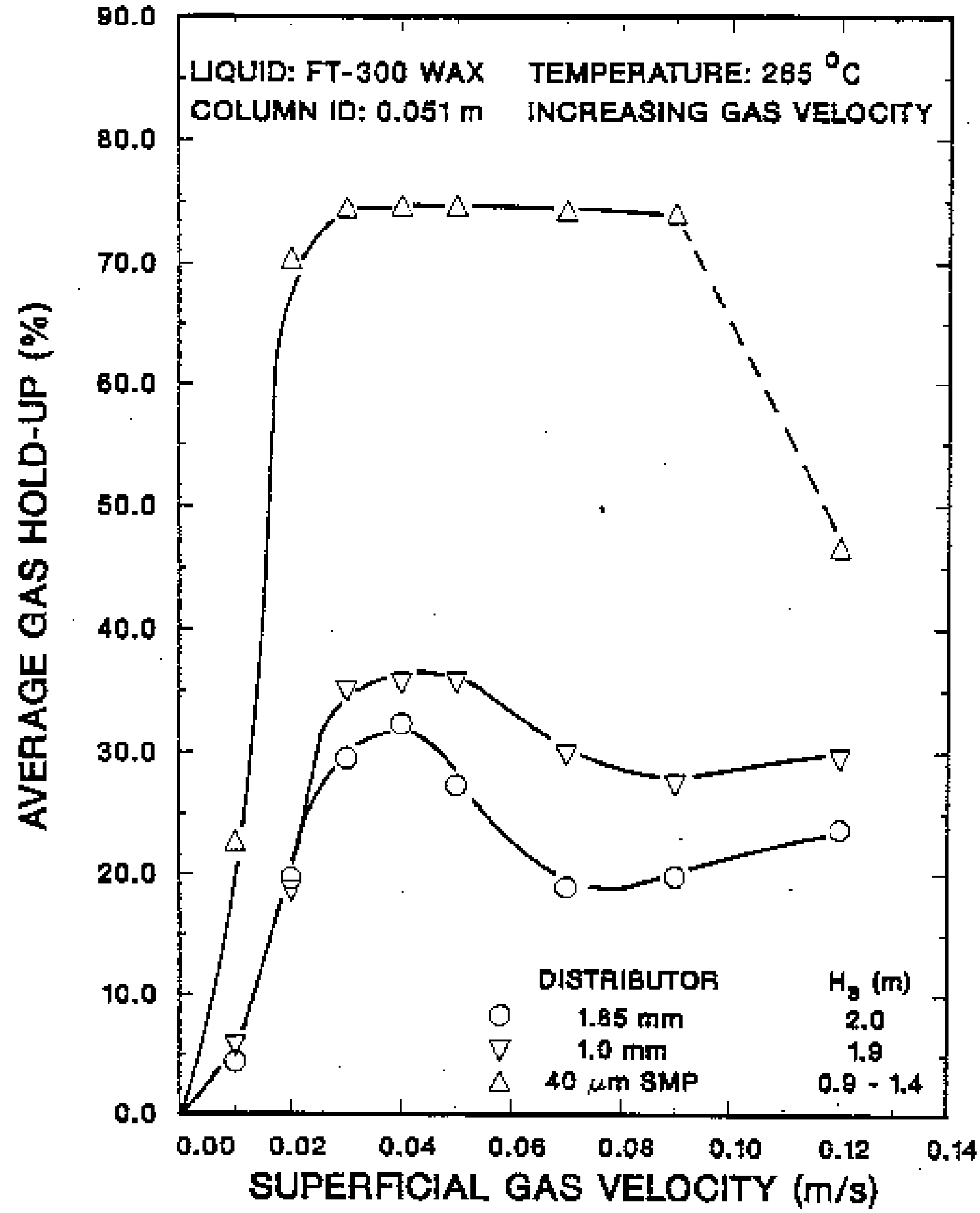

Figure 12. Effect of distributor type and superficial gas velocity on gas hold-up.

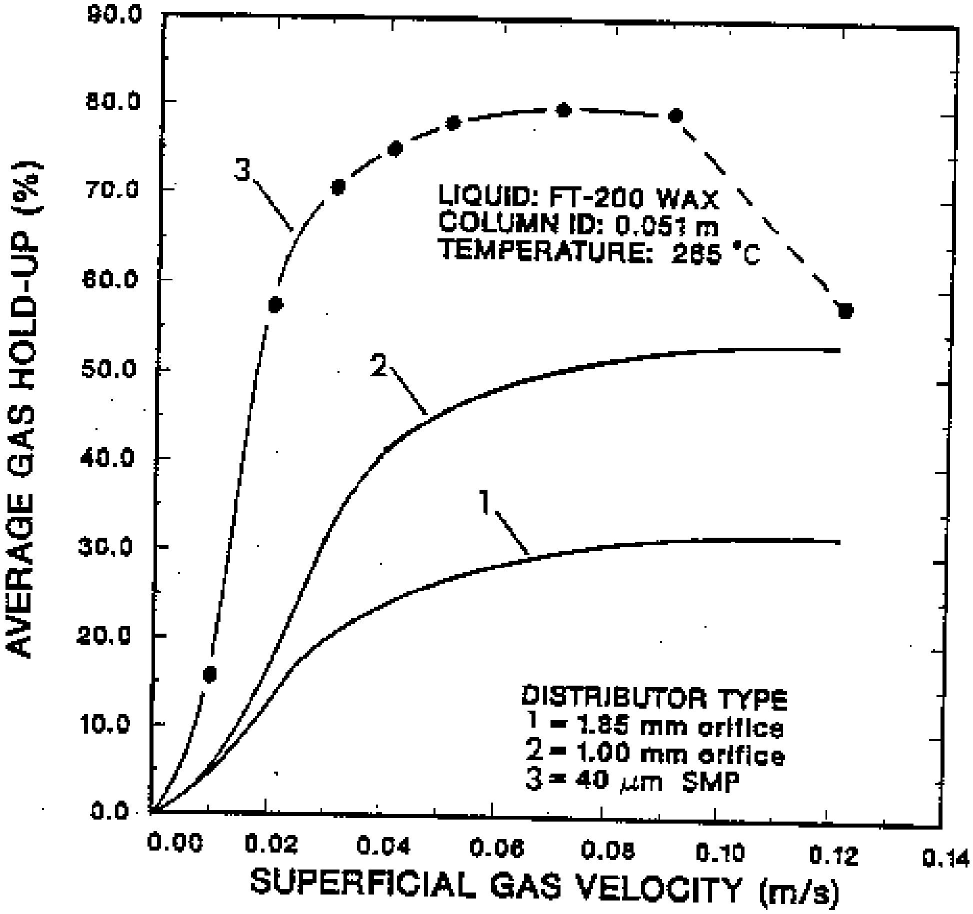

Figure 13. Effect of distributor type on gas hold-up (1 -Average of Runs 11-3, 11-5, 18-1, and 18-2; 2 -Average of Runs 17-1 and 17-2; 3 -Run 20-1).

Similar observations were reported by Kuo *et al.*, 1985 in their experiments with FT-200 wax, using three different types of SMP distributors, 15, 60 and 100 μm; and three different types of orifice plates, 0.25, 0.39, and 0.57 mm. They observed that hold-ups were highest with 15 μm SMP distributor and lowest with 0.57 mm orifice plate distributor. Their studies were carried out at low gas velocities ($<$ 0.04 m/s), and they had high hold-up values up to 75 % due to foaming.

Figure 14 illustrates the hold-ups obtained with Mobil reactor wax in the 0.051 m ID. No significant effect of distributor type was observed. Similar results were obtained with Sasol reactor waxes.

In summary, effect of distributor type is very significant in the runs where foam is produced, and hold-up values increase with decrease in the size of the orifice.

B. Pure Liquids

The bubble columns were operated with liquids other than molten waxes to investigate the effect of the liquid medium on hydrodynamics of bubble columns. A range of the operating variables used in this study is presented in Table 4. A total of seven runs were performed using pure liquids (distilled water and n-butanol). Two runs were done in the 0.051 m ID column using n-butanol, one with 1.85 mm orifice plate distributor and the other one with the 40 μm SMP distributor. Three runs were made with distilled water, in the 0.051 m ID column using the 1.85 mm orifice plate and the 40 μm SMP. Two runs with distilled water were performed in the 0.229 m ID column equipped with a 19 x 1.85 mm and a 5 x 1 mm perforated plate distributor. Runs in the small column were performed at superficial gas velocities in the range of 0.01 to 0.12 m/s; whereas, for runs in the larger diameter column the superficial gas velocities ranged from 0.01 to 0.07 m/s

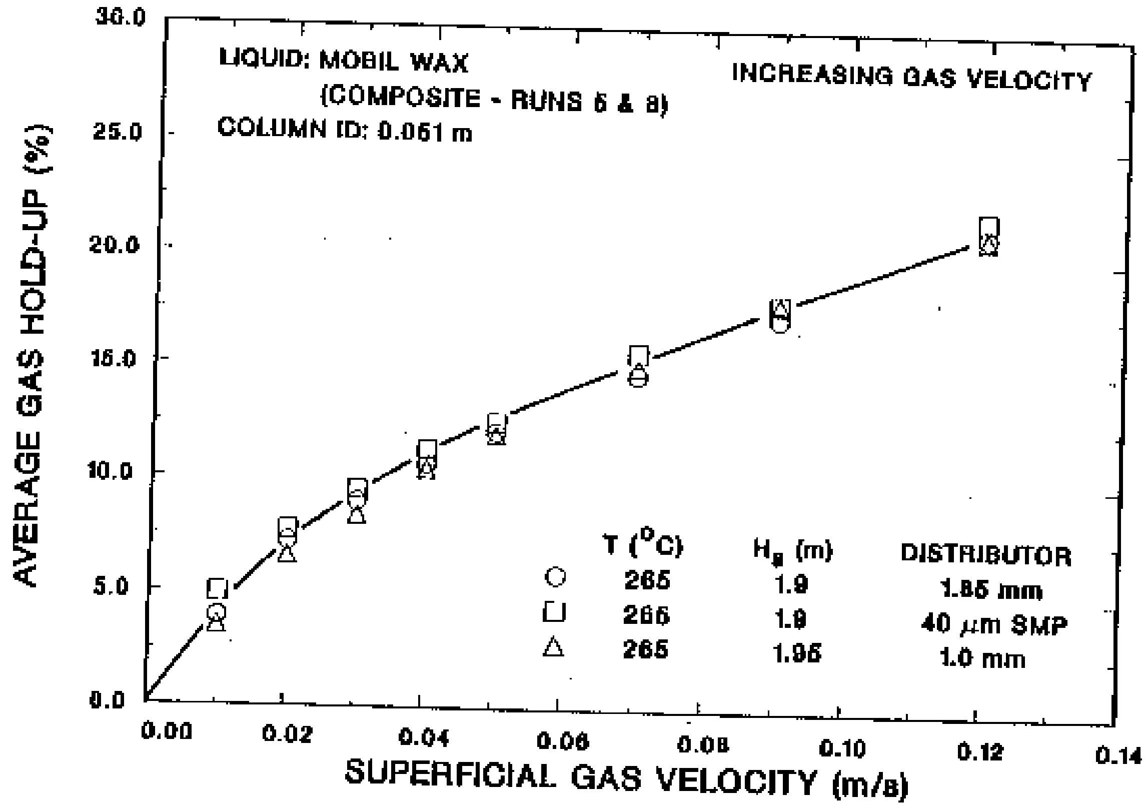

Figure 14. Effect of distributor type and superficial gas velocity on gas hold-up (composite wax from Mobil runs CT 256-5 and 8).

for the 5 x 1 mm perforated distributor plate and from 0.01 to 0.09 m/s for the 19 x 1.85 mm perforated distributor plate. It was not possible to use at superficial gas velocities higher than specified above due to a high pressure drop across the distributors.

1. Effect of Start-up Procedure

Figure 15 shows the effect of operating procedure on gas hold-up for distilled water in the 0.051 m ID column using the 1.85 mm orifice plate distributor. No difference in hold-ups was observed for runs conducted in the order of increasing or decreasing superficial gas velocities. In both cases long slugs were observed at high gas velocities (> 0.05 m/s).

2. Effect of Column Diameter

Figure 16 compares the average gas hold-ups from the 0.051 m ID column and the 0.229 m ID column for distilled water. 1.85 mm orifice plate distributor was used for the small column and 19 x 1.85 mm perforated plate for the large column. These two distributors produce the same jet velocity in the small and the large columns respectively. The gas hold-ups in the large column were lower than those obtained in the small column. This may be due to the existence of different flow regimes in the two columns. Slugs were observed in the small column even at relatively low gas velocities; whereas in the large column, no slugs were seen at all but a more violent motion and downward movement of fluid along the wall (churn-turbulent flow) was observed. Bubbles near the wall showed very complex motions. They moved up around and down along the wall, with a downward movement being more pronounced at higher gas velocities.

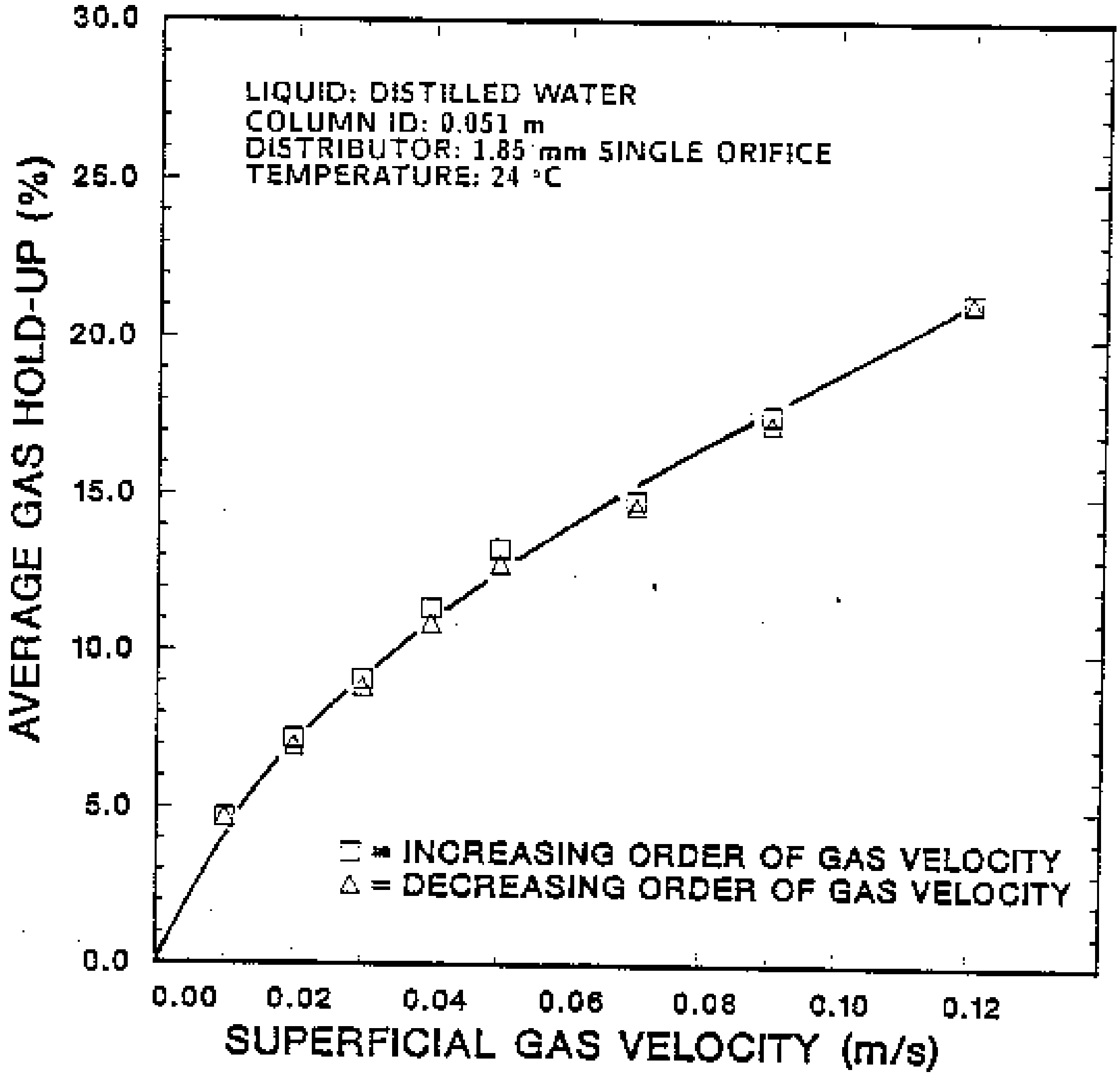

Figure 15. Effect of start-up procedure and superficial gas velocity on gas hold-up (□ -Run W-1, △ -Run W-2).

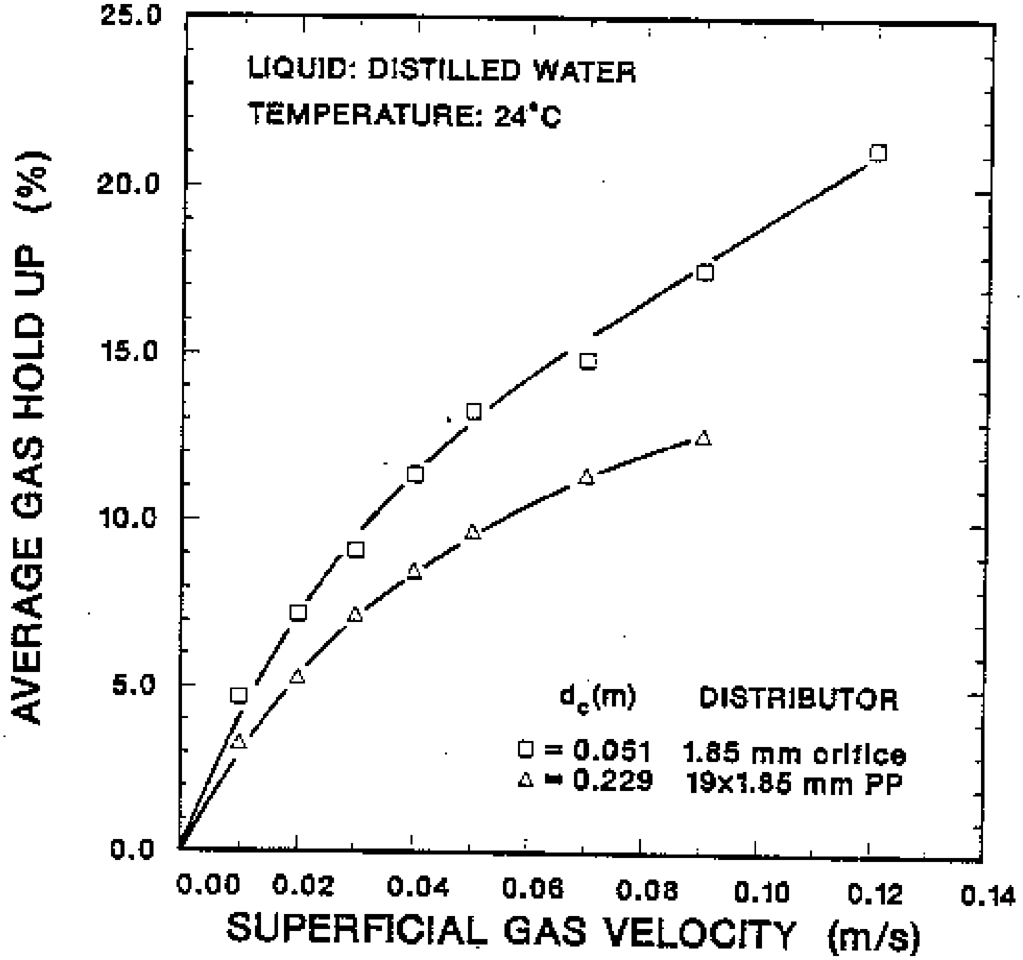

Figure 16. Effect of column diameter and superficial gas velocity on gas hold-up (□ -Run W-1, △ -Run W-4).

3. Effect of Distributor Type

Figure 17 (a) and (b) shows the average gas hold-ups for n-butanol and distilled water in the 0.051 m ID column and 0.229 m ID columns, respectively. The 1.85 mm orifice plate and the SMP distributors were used in the 0.051 m ID column, whereas the 19 x 1.85 mm perforated plate and the the 5 x 1 mm perforated plate were used for the large column. No effect of distributor type on gas hold-up was observed for runs in the 0.051 m ID column. Slightly higher hold-ups were obtained for the 19 x 1.85 mm perforated plate than for 5 x 1 mm perforated plate. This might be due to higher jet velocities for the 5 x 1 mm perforated plate than the 19 x 1.85 mm perforated plate. Similar observation were obtained with FT derived waxes. In the absence of foam the gas hold-up was found to be independent of the type of the distributor.

In summary, with pure liquids there is no significant effect of distributor type on gas hold-up.

4. Effect of Liquid Medium

The major highlights of this investigation are as follows:

1. Both liquids, distilled water and n-butanol, are coalescing mediums.
2. No foam was observed in the course of experiments in the range of gas velocities employed.
3. At high gas velocities, the slug flow regime was observed for runs in the small column with all types of distributors. It was observed that n-butanol is less coalescing than distilled water. Consequently, at low gas velocities (< 0.02 m/s) fewer small bubbles were observed for the distilled water/nitrogen system compared to the n-butanol/nitrogen system. These small bubbles

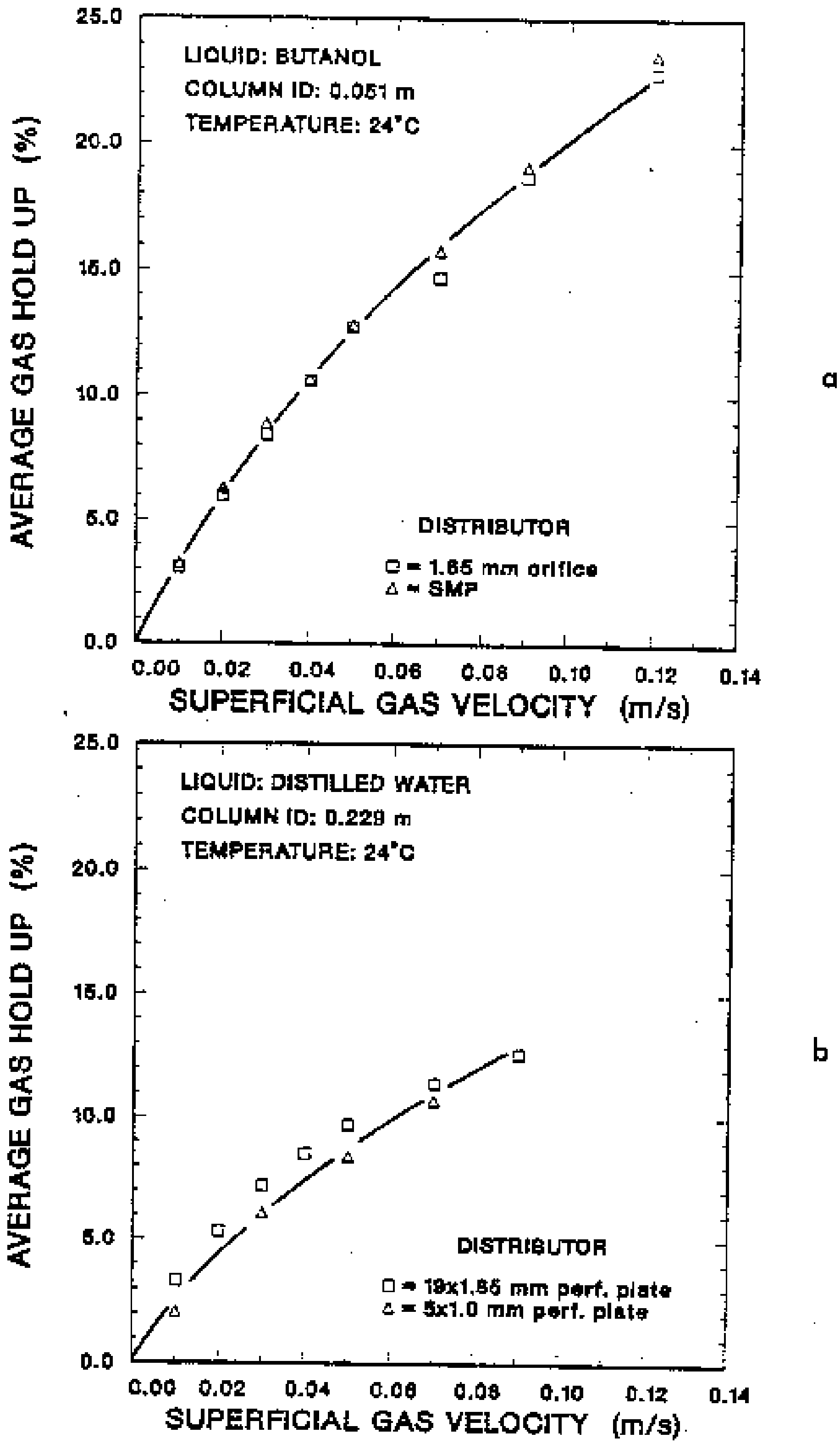

Figure 17. Effect of distributor type and superficial gas velocity on gas hold-up for pure liquids.

usually coalesce to form larger bubbles and slugs before disengaging. Since the coalescence rate for the butanol/nitrogen system was not as high as that for distilled water, no slugs were observed in the disengagement zone in the former case. As the superficial gas velocity was increased, large bubbles and slugs were observed just above the distributor for the distilled water/nitrogen system. Long slugs ($\sim$ 0.2 m) were frequently seen at high gas velocity ($>$ 0.09 m/s) at height about 1.2 m above the distributor, and only a few small bubbles were observed. On the other hand, in the butanol-nitrogen system no slugs were observed just above the distributor even at high gas velocity (0.12 m/s). At high gas velocities, short slugs ($\sim$ 0.07 m) and a large number of small bubbles were seen rising very rapidly at height about 1.2 m above the distributor.

4. No slugs were observed in the large column for the range of gas velocities used.

Figure 18 compares the hold-ups for distilled water, n-butanol, Sasol reactor wax (at 265 °C), and Mobil reactor wax (at 265 °C) obtained from the 0.051 m ID column using the 1.85 mm orifice plate distributor. Only a small difference could be observed despite significant difference in their physical properties: for example (distilled water and n-butanol), the surface tension differs by a factor of 3, the viscosity by a factor of 2.9, and the density by a factor of 1.2. This shows that, the average gas hold-up values for non-foamy liquid mediums are independent of their physical properties: the surface tension, the density, and the viscosity. Similar observations have been reported by Bach and Pilhofer (1978) in their studies with ethylene glycol and octanol.

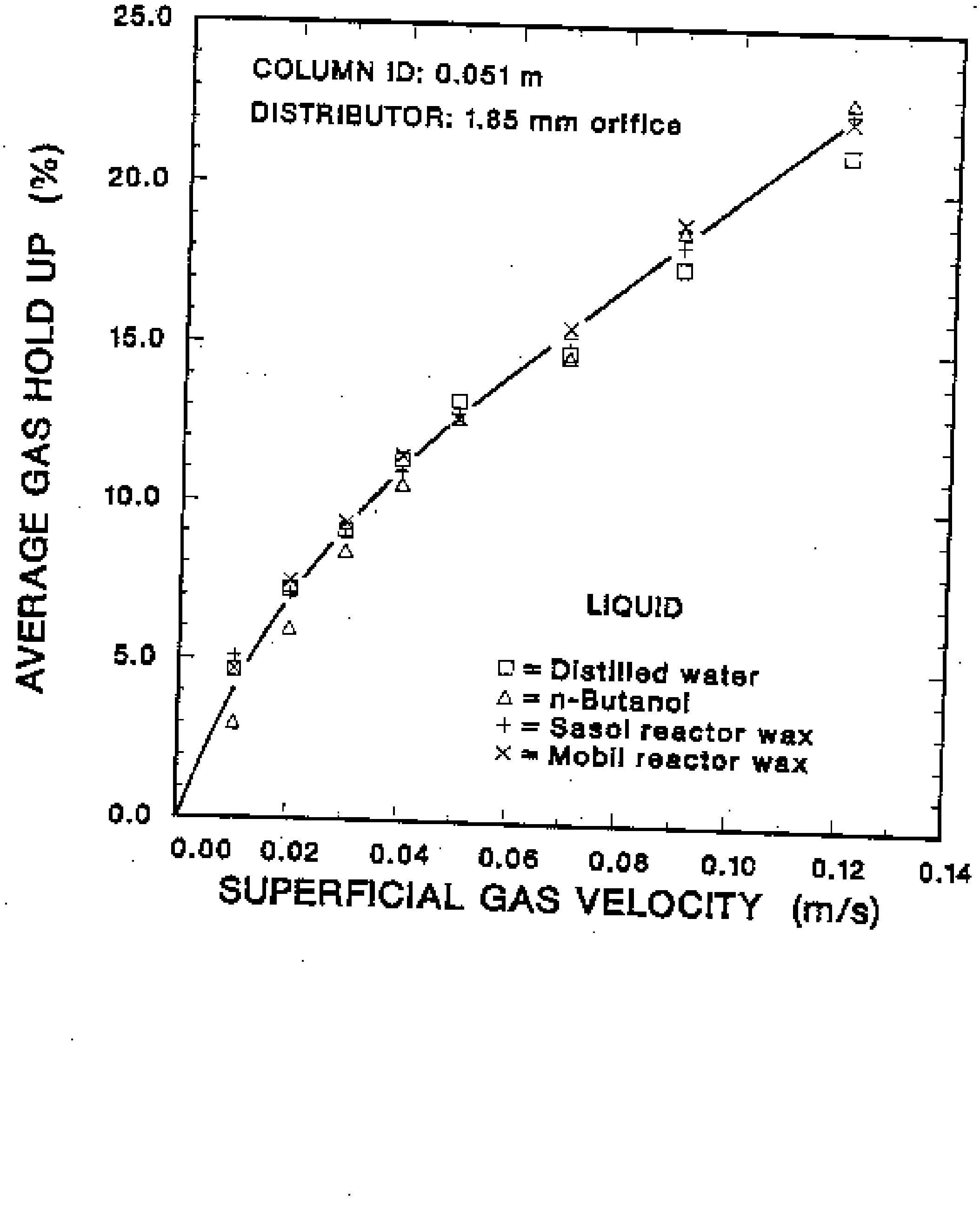

Figure 18. Comparison of average gas hold-ups for non-foamy mediums (□ - Run W-1, △ -Run B-1, + -Run 8-1, × -Run 9-3).

C. Aqueous Solutions of n-Butanol

1. Effect of n-Butanol Concentration

The presence of alcohols inhibits coalescing behavior of distilled water. It has been observed by Hikita and Kikukawa (1974); Schugerl *et al.* (1977); and Kelkar *et al.* (1983)) that in the presence of alcohols the bubbles are smaller and more rigid, and have lower rising velocities, resulting in higher gas hold-ups. Also, it has been observed that gas hold-up increases with an increase in the alcohol chain length. Similar trends were observed in both columns, therefore only results from the 0.051 m are discussed below.

Figure 19 shows the average gas hold-ups in the 0.051 m ID column using different concentrations of butanol in distilled water, 0.0 %, 0.5 %, 1.0 %, and 100 % by wt., using the 1.85 mm orifice plate distributor. Gas hold-up increased with increasing concentration of butanol in water (the same trend was observed with the SMP distributor). These low concentrations of alcohol in distilled water act like impurities (surfactants), and hence hinder the coalescence nature of distilled water. The resulting small bubbles are rigid, have high residence time, and accumulate at the interface building a stable cellular foam which causes the average gas hold-up to increase. Increasing the alcohol concentration increases the number of small bubbles, therefore giving rise to the gas hold-up values. Relating butanol concentration to surface tension of the mixture, i.e. increasing butanol concentration lowers the surface tension of water and vice versa, reveals that, for non-pure liquids (mixtures) gas hold-ups increase with a decrease in surface tension up to a certain critical concentration, where the gas hold-ups will start decreasing as the surface tension approaches that of the other pure liquid.

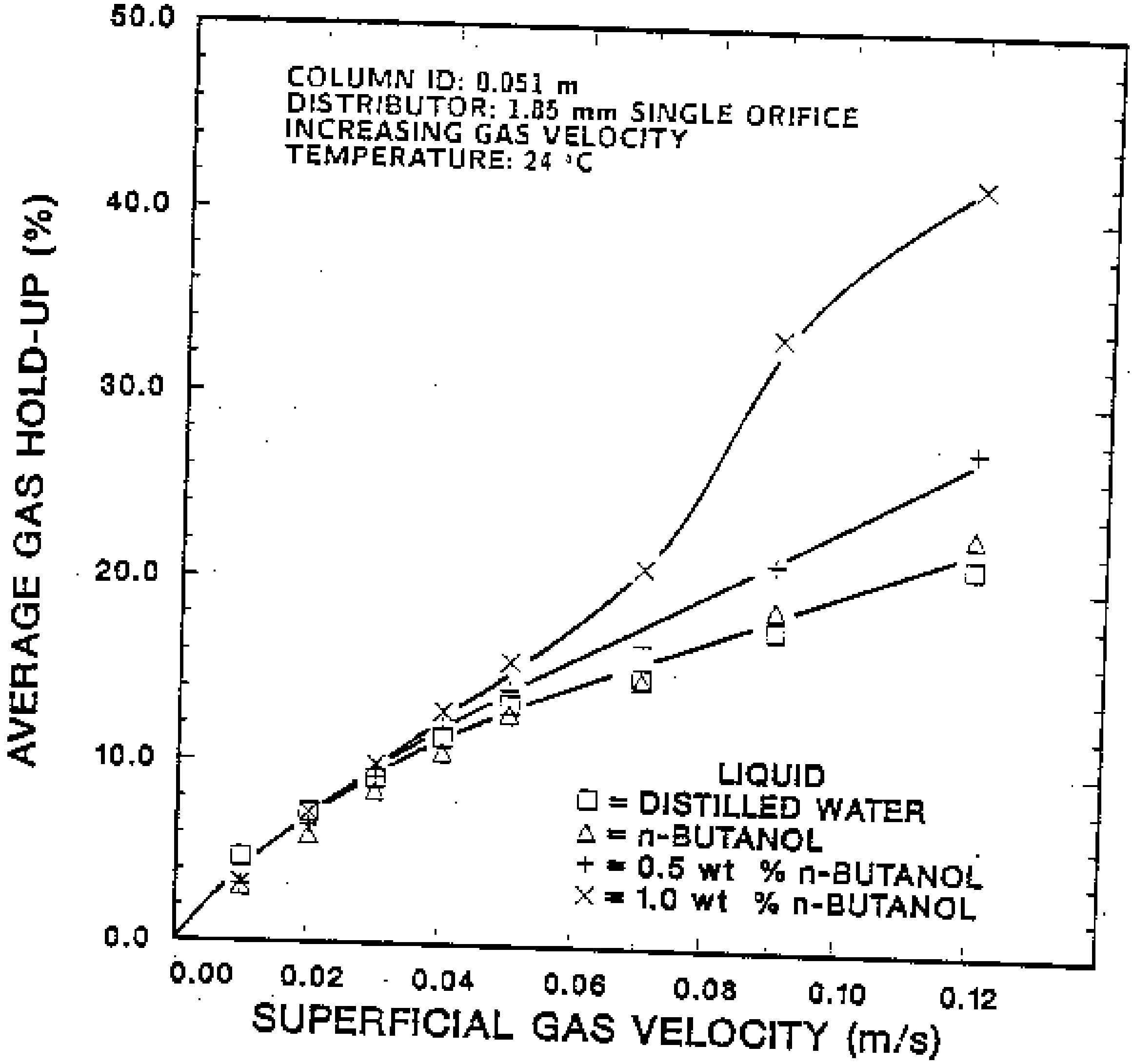

Figure 19. Effect of butanol concentration and superficial gas velocity on gas hold-up (□ -Run W-1, △ -Run B-1, + -Run B-7, × -Run B-3).

2. Effect of Start-up Procedure

Figure 20 shows the effect of the operating procedure on gas hold-up in the 0.051 m ID column equipped with 1.85 mm orifice plate distributor for the 1.0 wt % butanol solution. No effect of operating procedure on gas hold-up was observed.

Due to the foaming nature of this solution, it was expected that the gas hold-ups would be lower when the experiments are performed in decreasing order of gas velocities, analogous to runs with paraffin waxes. However, no changes in foaming trend were observed, therefore similar hold-ups were observed in both cases.

3. Effect of Column Diameter

Figure 21 shows hold-up values for two sets of distributors in the large and small columns using the 1.0 wt % n-butanol solution. The 19 x 1.85 mm perforated plate and the 1.85 mm orifice plate distributors produce the same jet velocities in the 0.299 m and 0.051 m ID columns, respectively. Likewise, the 19 x 1.0 mm perforated plate and the 1.0 mm orifice plate distributors produce the same jet velocities. The 19 x 1.85 mm perforated plate distributor resulted in higher gas hold-ups in the large column than the 1.85 mm orifice plate in the small column. However, at high superficial gas velocities (> 0.09 m/s) the hold-ups were the same. On the other hand, at high gas velocities, the 1.0 mm single orifice distributor in the small column produced higher gas hold-ups than those produced by the 19 x 1.0 mm in the large column. Higher hold-ups in the large column at low gas velocities might be attributed to the nature of flow regime being different from that of the small column. The presence of slugs in the small column tends to disperse the small bubbles and break the accumulated foam at the interface as they burst on top. Whereas, for the large column small bubbles do not disengage

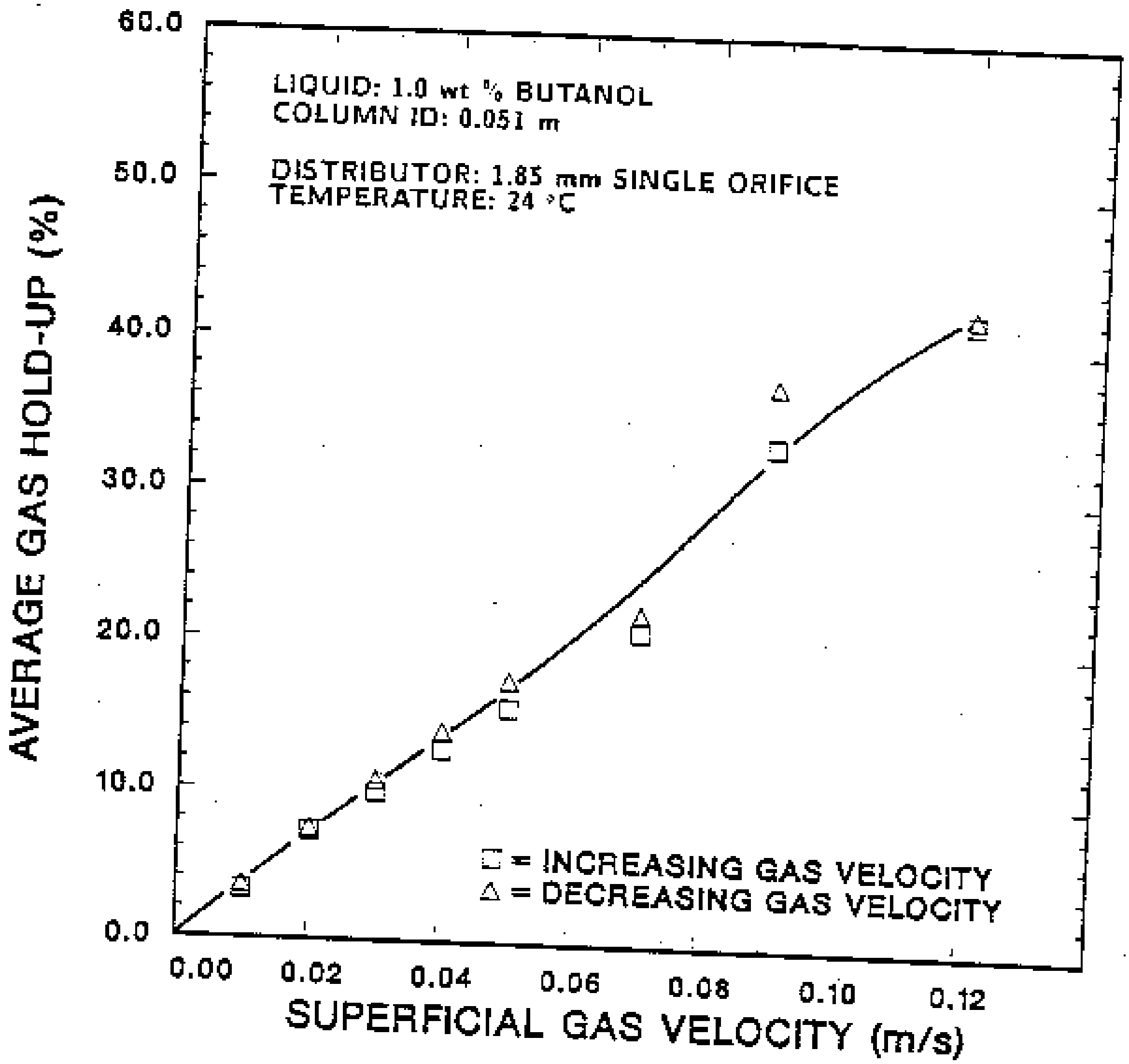

Figure 20. Effect of start-up procedure and superficial gas velocity on gas hold-up (□ -Run B-3, △ -Run B-4).

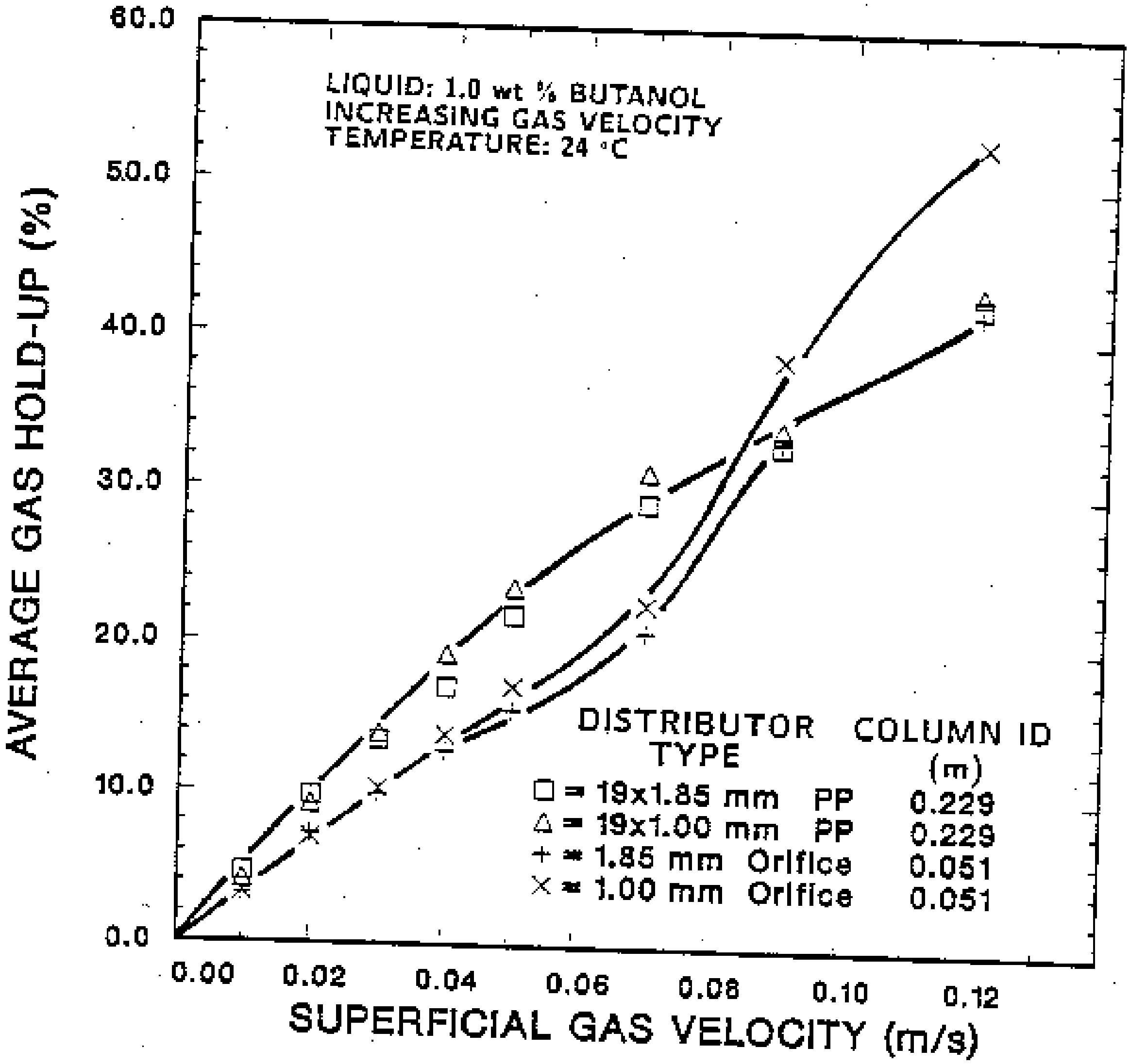

Figure 21. Effect of column diameter and superficial gas velocity on gas hold-up (□ -Run B-16, △ -Run B-17, + -Run B-3, × -Run B-6).

easily, instead, they follow the liquid circulation in the column, staying longer in the column before they disengage. This process results in higher gas hold-up values for the large column at lower gas velocities.

4. Effect of Distributor Type

Figure 22 shows the average gas hold-up for runs with 0.5 wt % butanol solution in 0.051 m ID column equipped with 1.85 mm orifice plate and SMP distributors. From these runs it was observed that gas hold-ups for the SMP distributor were slightly higher than those from the 1.85 mm orifice plate distributor. Small amounts of foam were observed for both distributors, with that for the SMP distributor being slightly higher (APPENDIX C. Run B-7 and B-8). Also, the SMP distributor produced more small bubbles (< 1 mm) than the 1.85 mm orifice plate distributor. These tiny bubbles were non-coalescing at low gas velocities (< 0.04 m/s). So no slugs were seen at low gas velocity. Whereas with the 1.85 mm orifice plate distributor slugs were seen at gas velocities as low as 0.02 m/s.

Figure 23 shows the gas hold-ups for runs in the small column using a 1.0 % butanol solution for three different distributors; SMP, 1.0 mm orifice, and 1.85 mm orifice plate distributor. The SMP distributor produced large amounts of foam at low superficial gas velocities (< 0.05 m/s) resulting in higher gas hold-ups than the orifice plate distributors. At high gas velocities (> 0.09 m/s) large amounts of foam were observed for all three distributors (see APPENDIX C. Runs B-3, B-5, and B-6). The 1.0 mm orifice plate distributor produced the largest amount of foam followed by the 1.85 mm orifice plate and the SMP distributor. Visually, it was observed that SMP distributor produced more tiny bubbles than the orifice plate distributors. The concentration of these small bubbles increased with increasing

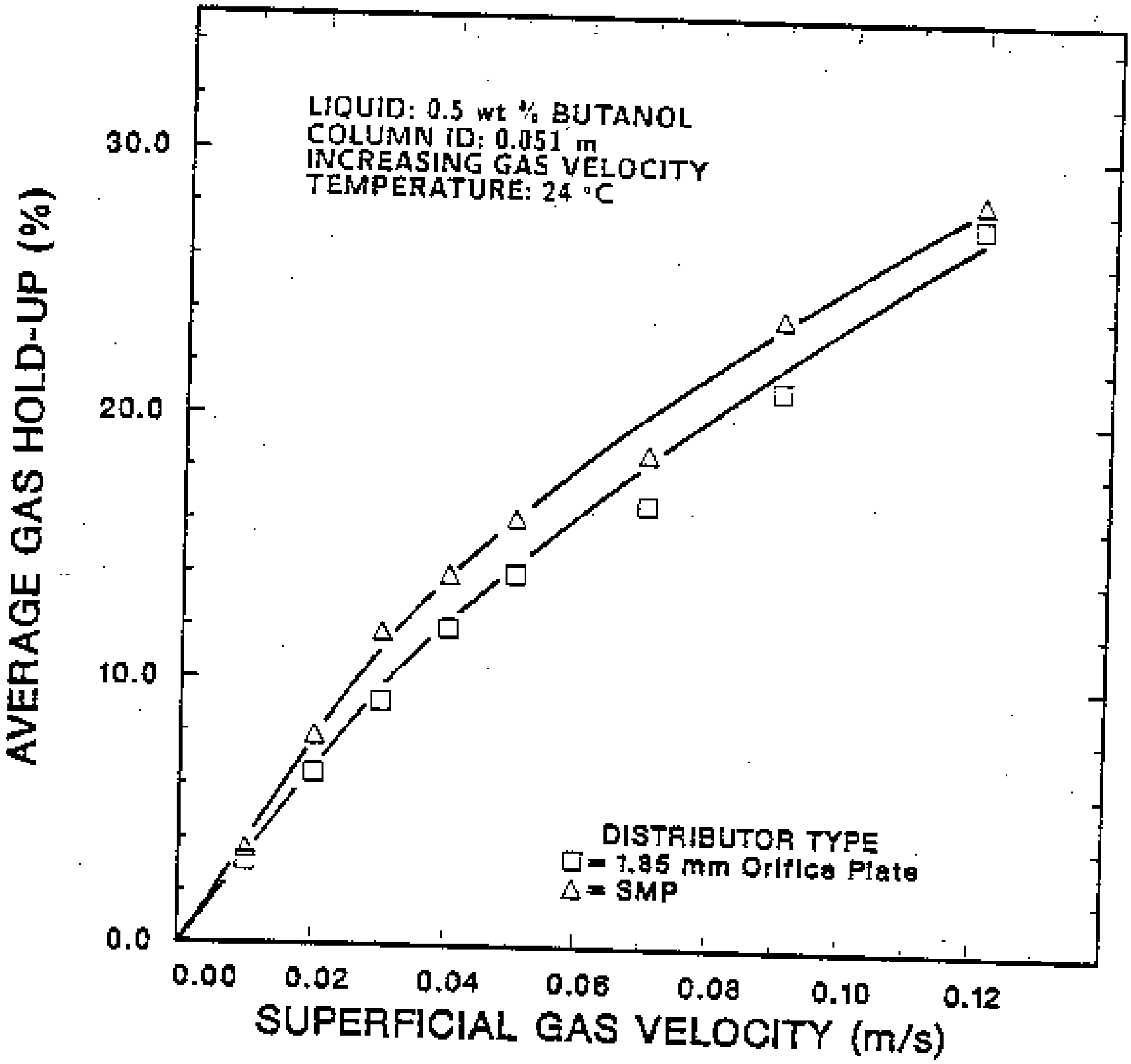

Figure 22. Effect of distributor type and superficial gas velocity on gas hold-up (□ -Run B-7, △ -Run B-8).

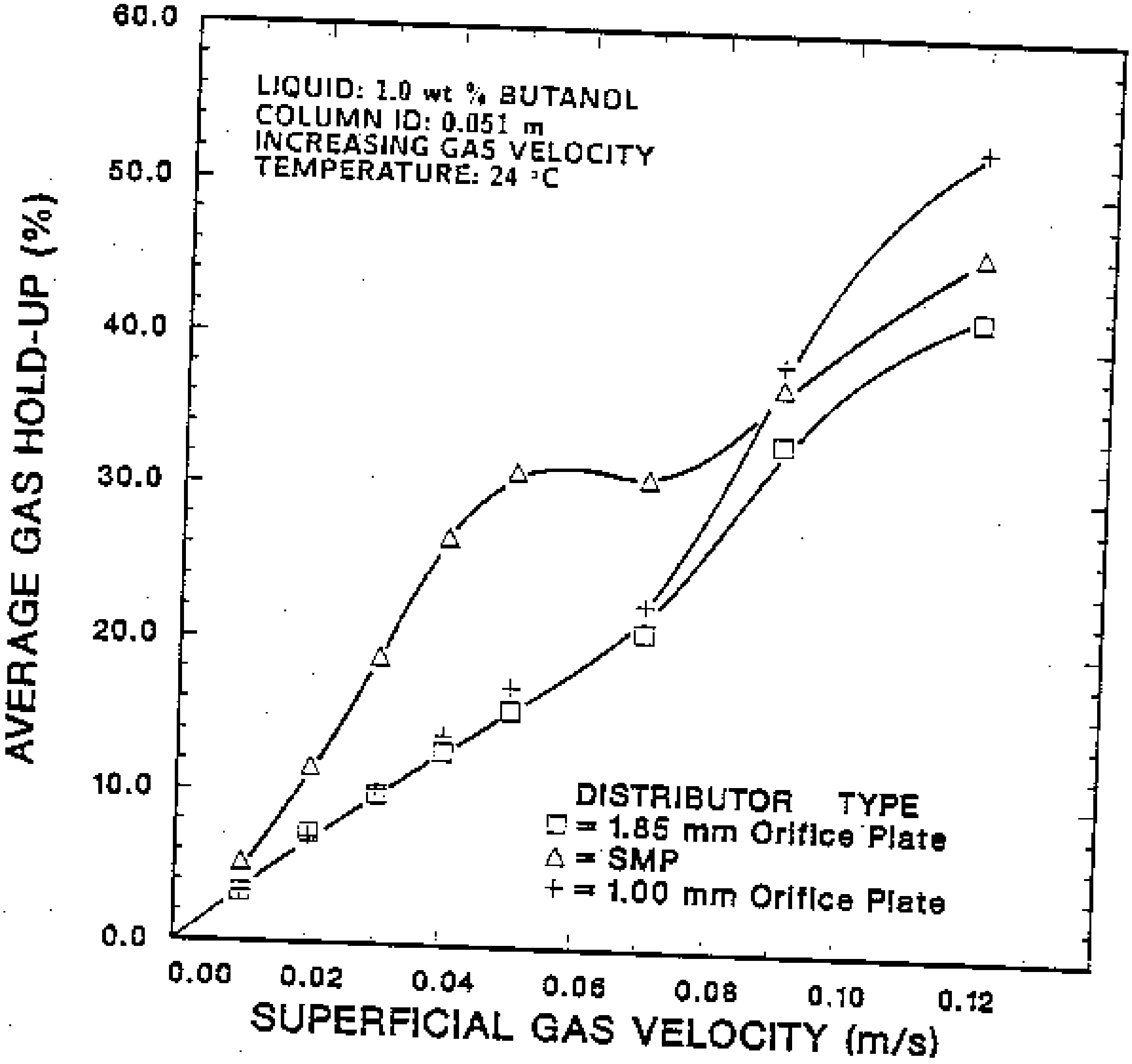

Figure 23. Effect of distributor type and superficial gas velocity on gas hold-up (□ -Run B-3, △ -Run B-5, + -Run B-6).

concentration of alcohol. The coalescence of bubbles was more pronounced for the orifice plates than the SMP (slugs were seen at low gas velocities, such as 0.02 m/s for the 1.85 mm orifice plate distributor and about 0.03 m/s when SMP distributor was used). Moreover, the velocity at which the slugs first appeared increased with an increase in butanol concentration. (i.e., for 1.0 % butanol solution slugs appeared at superficial gas velocity of 0.05 m/s and at 0.03 m/s for 0.5 % butanol solution while using 1.85 mm orifice plate distributor).

Higher gas hold-ups for the 1.0 mm orifice plate distributor at higher gas velocities (> 0.09 m/s) can be attributed to the higher jet velocities for this distributor as compared to the 1.85 mm orifice plate distributor. The high jet velocity produced many tiny bubbles which accumulated on top of the dispersion as a stable foam. This phenomenon resulted in the high gas hold-up values.

Figure 24 shows the effect of the type of distributors on gas hold-ups for 1.0 wt % butanol solution in 0.229 m ID column using the 19 x 1 mm and the 19 x 1.85 mm perforated plate distributors. No effect of distributor type on gas hold-up was observed in these runs. The flow of gas in the column looked similar for both distributors. No slugs were observed at all and the amount foam increased with increase in gas velocity (APPENDIX C. Run B-16 and Run B-17). There were many small bubbles (< 1 mm) produced by both distributors, which were seen moving up and down near the wall as the large bubbles moved in zig zag path near the center of the column.

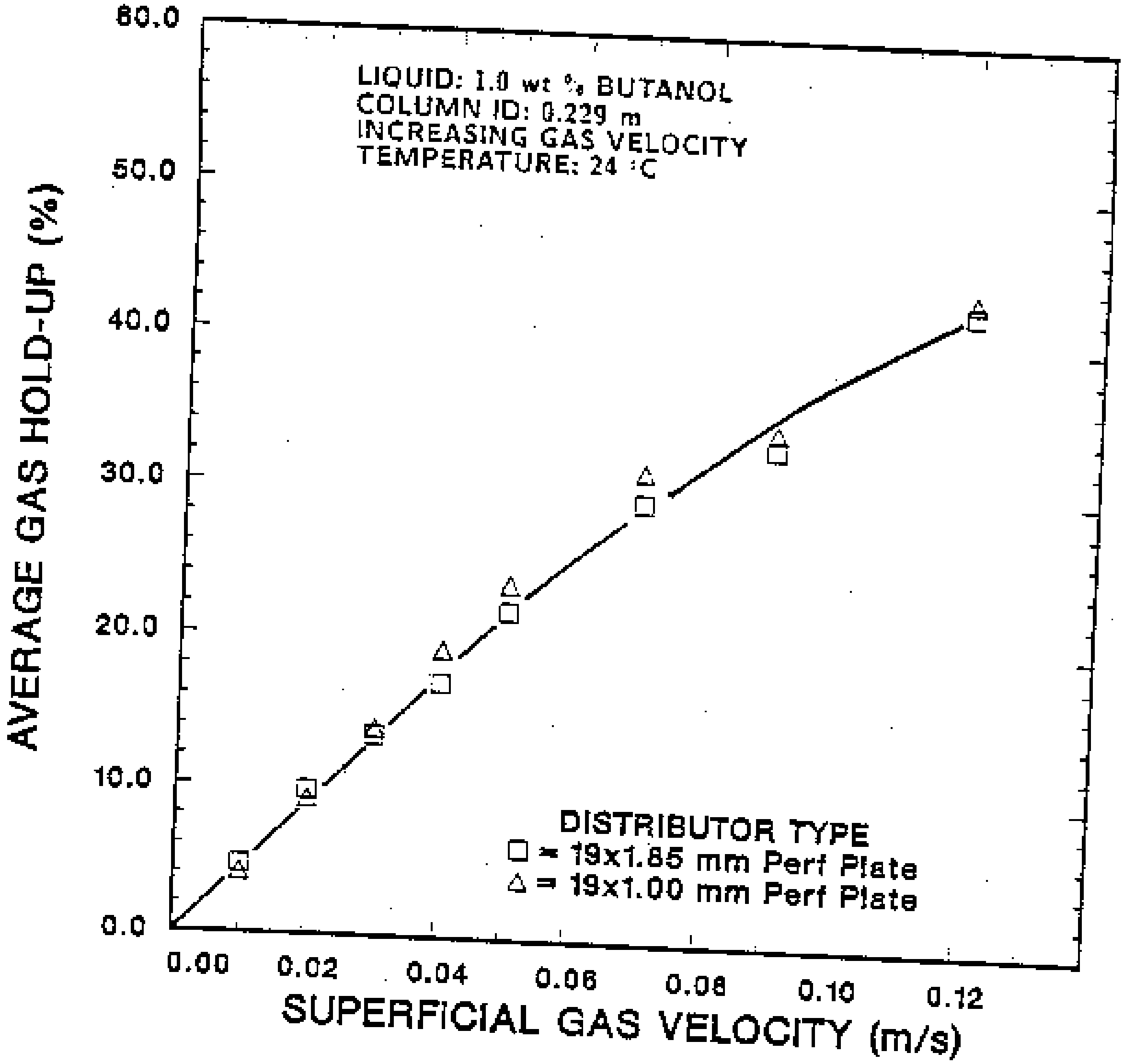

Figure 24. Effect of distributor type and superficial gas velocity on gas hold-up (□ -Run B-16, △ -Run B-17).

5. Comparison With Other Foaming Mediums

Figure 25 presents hold-ups obtained with 1.0 wt % n-butanol solution in the 0.051 m ID column using 1.85 mm orifice plate and those obtained with FT-200 wax at 265 °C in the 0.051 m ID column equipped with the same gas distributor. Shown together with this are the literature values obtained from Posarac and Tekic (1987) while using 1.0 wt % butanol solution in the 0.1 m ID column with 4 mm single sparger.

Hold-ups obtained from the alcohol solutions show similar trend (continuous increse in hold-up with u_g) and close values, whereas hold-up values from the FT-200 wax show a flat profile (ϵ_g=30 %) at high superficial gas velocities. This illustrates that, different systems have different foaming capacity which depends on the physical properties of the foaming medium.

D. Aqueous Solutions of n-Butanol With CMC

1. Effect of CMC Concentration

The effect of CMC concentration on gas-hold-up was investigated by adding two different concentrations (0.1 and 0.5 wt %) of CMC in the foaming mixture (aqueous solution of 1.0 wt % n-butanol). Experiments were performed in the 0.051 m ID column and the 0.229 m ID column. SMP, 1 mm orifice plate, and 1.85 mm orifice plate were used for the small column, whereas the 19 x 1 mm perforated plate and the 19 x 1.85 mm perforated plate were used for the large column. Figures 26, 27, and 28 illustrate some of the results obtained using these solutions.

Visually, the 0.1 wt % CMC solution produced more tiny bubbles than aqueous butanol without the addition of CMC, but the coalescencing nature of the bubbles

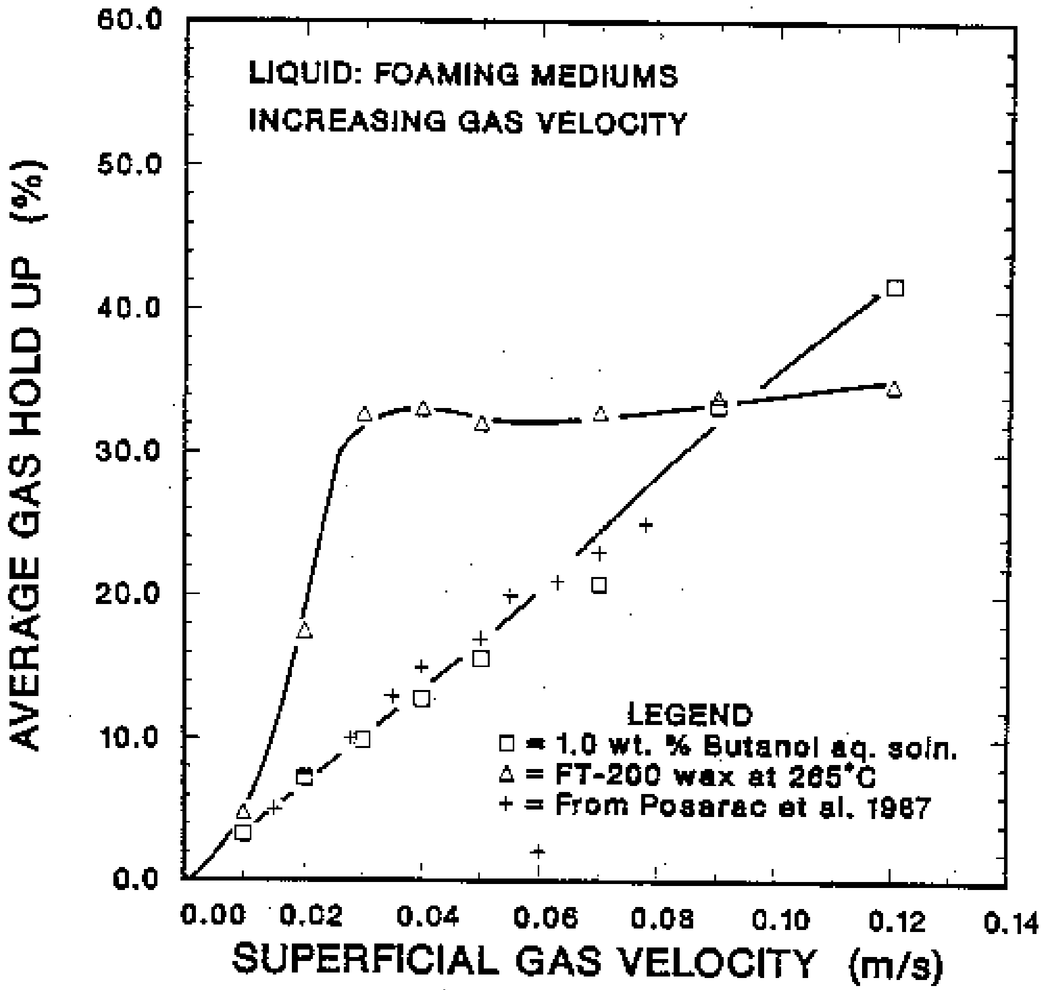

Figure 25. Comparison of gas hold-ups for foaming liquids (□ -Run B-3, △ -Run 18-1, + From Posarac *et al.* 1987 using 1.0 wt. % aq. butanol soln.)

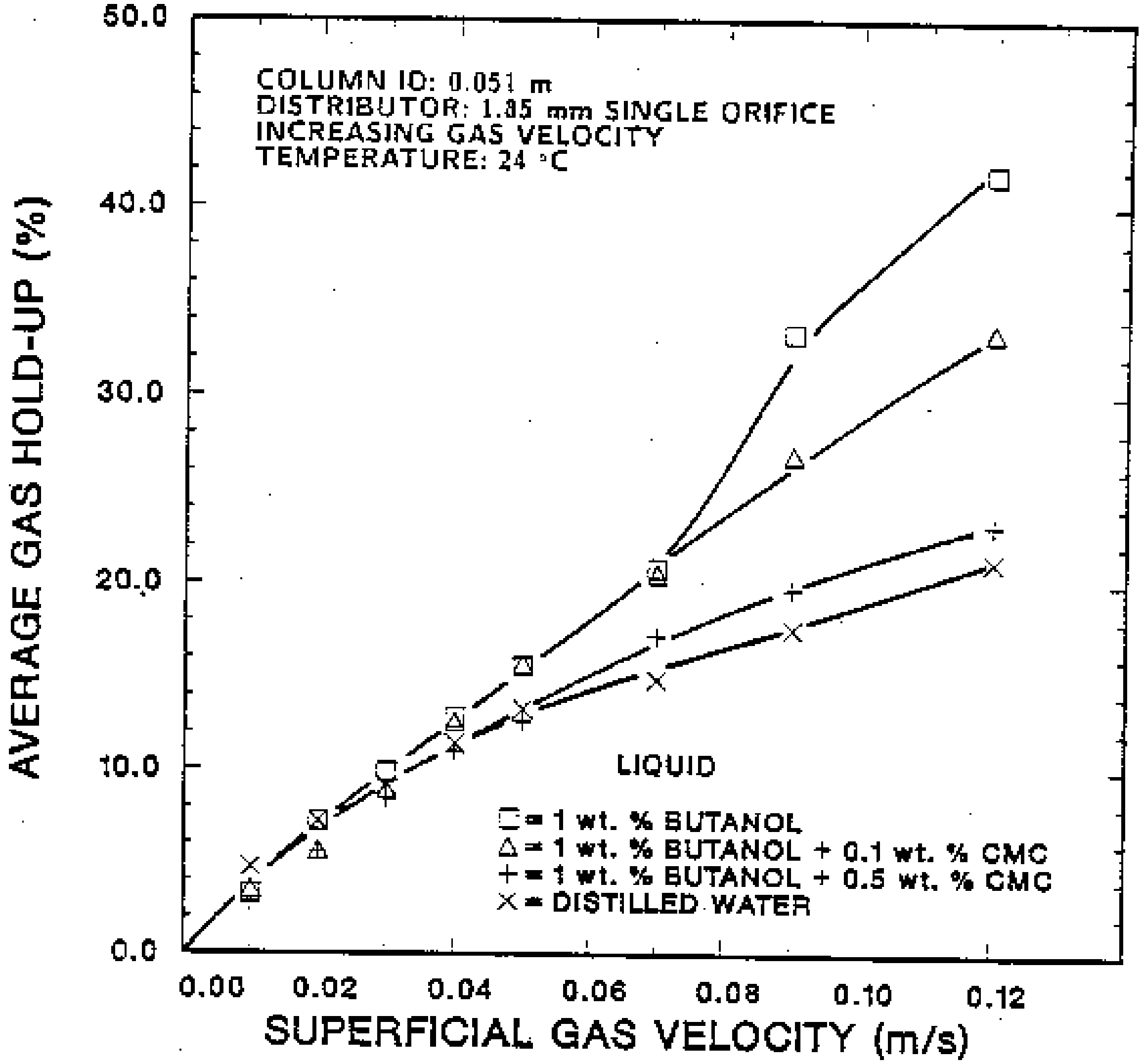

Figure 26. Effect of CMC concentration and superficial gas velocity on gas hold-up (□ -Run B-3, Δ -Run B-10, + -Run B-13, × -Run W-1).

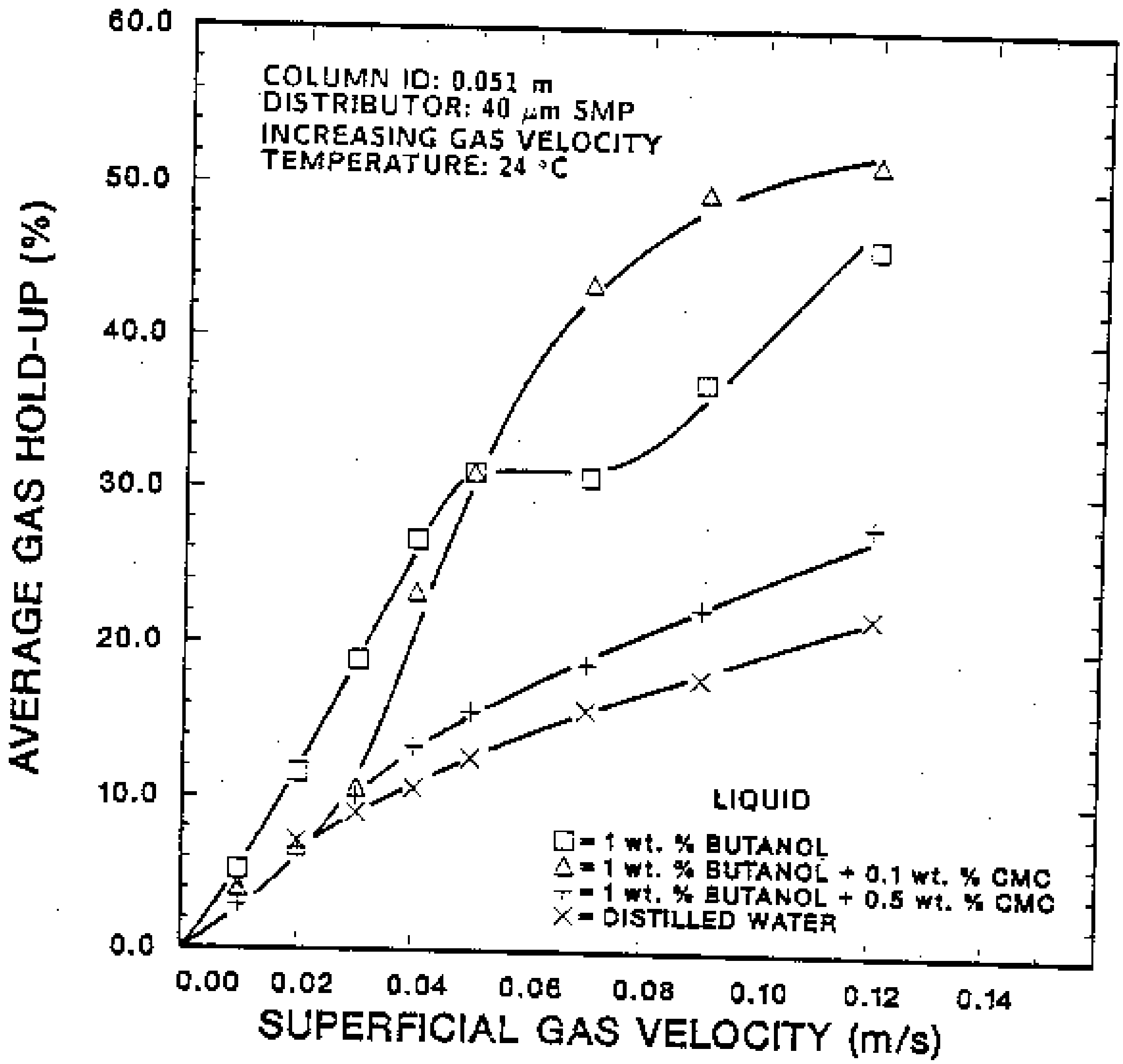

Figure 27. Effect of CMC concentration and superficial gas velocity on gas hold-up (□ -Run B-5, △ -Run B-9, + -Run B-14, × -Run W-3).

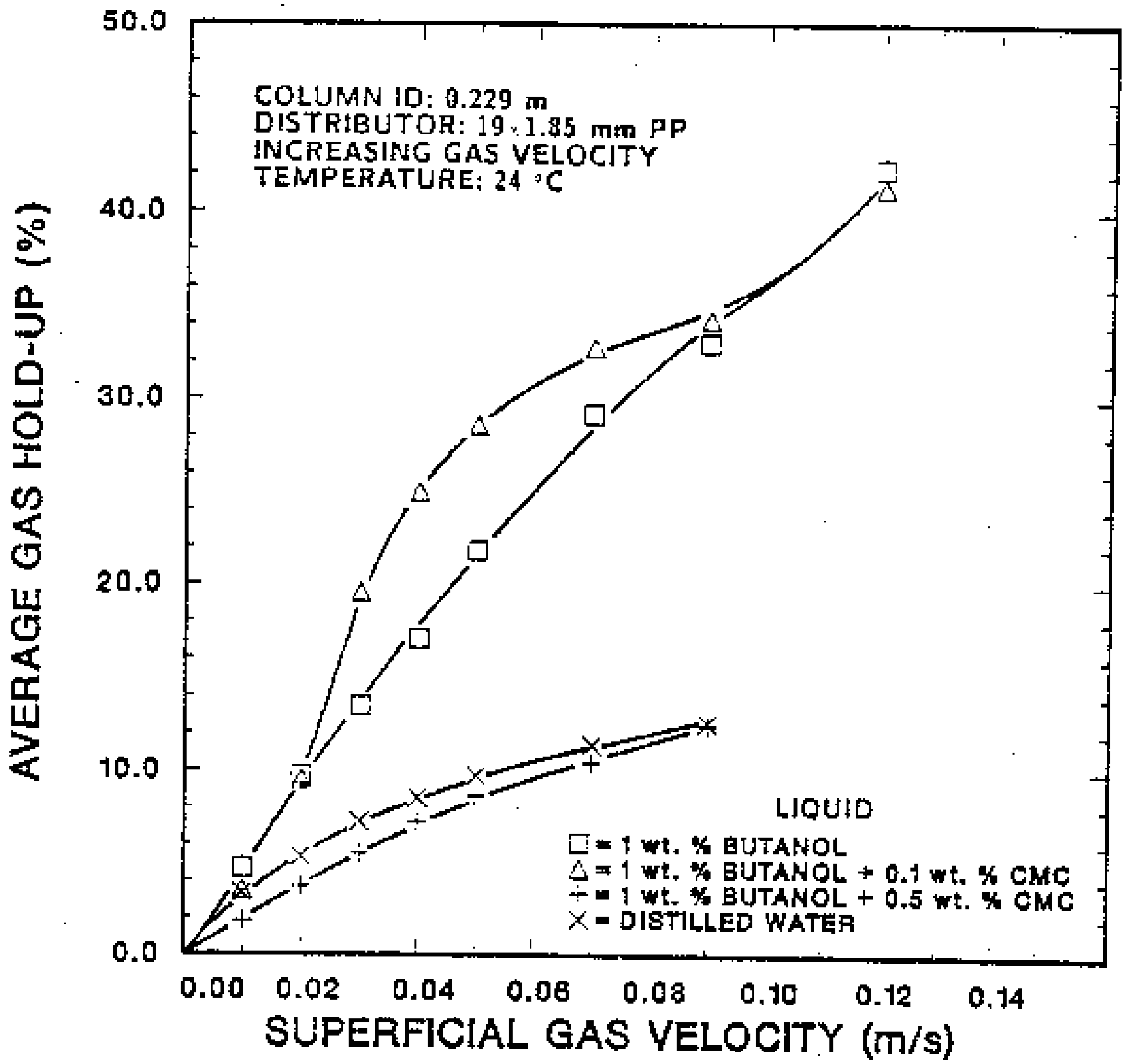

Figure 28. Effect of CMC concentration and superficial gas velocity on gas hold-up (□ -Run B-16, △ -Run B-19, + -Run B-20, × -Run W-4).

appeared to be the same. The tiny bubbles rose very slowly due to the increased viscosity of the mixture (higher drag friction on the bubbles), moreover it was observed that the bubbles were more rigid and they had a tendency of clustering together and behaving like a single bubble. The cluster of bubbles accumulated at the interface (gas-liquid) as foam, resulting in unexpected large amounts of foam and hence, higher gas hold-ups (sometimes higher than those from n-butanol solution), see Figures 27 and 28. For the 0.5 wt. % CMC mixture, average gas hold-up values were close to those of pure liquids (see Figures 26–28). The coalescence of bubbles was high. Slugs and large bubbles were seen at low gas velocities just above the distributor for the small column. The number of tiny bubbles was very large and the column looked white due to the presence of many tiny bubbles in the solution. It took more than 10 hours for all free bubbles to disengage, while some tiny bubbles remained clinging on the walls of the column. No foam was observed in any runs using this high concentration of CMC.

2. Effect of Column Diameter

Figure 29 shows the effect of column diameter on gas hold-up for aqueous solution containing 1.0 wt % n-butanol with 0.1 wt % CMC. Hold-ups obtained from the 0.229 m ID column using 19 x 1.85 mm perforated plate were consistently higher than those obtained from the 0.051 m ID column using 1.85 mm orifice plate. However, increasing the concentration of the CMC to 0.5 wt % the trend was reversed (the hold-ups from the small column were higher than those from the large column), see Figure 30. At this high concentration of CMC no foam was observed in either column.

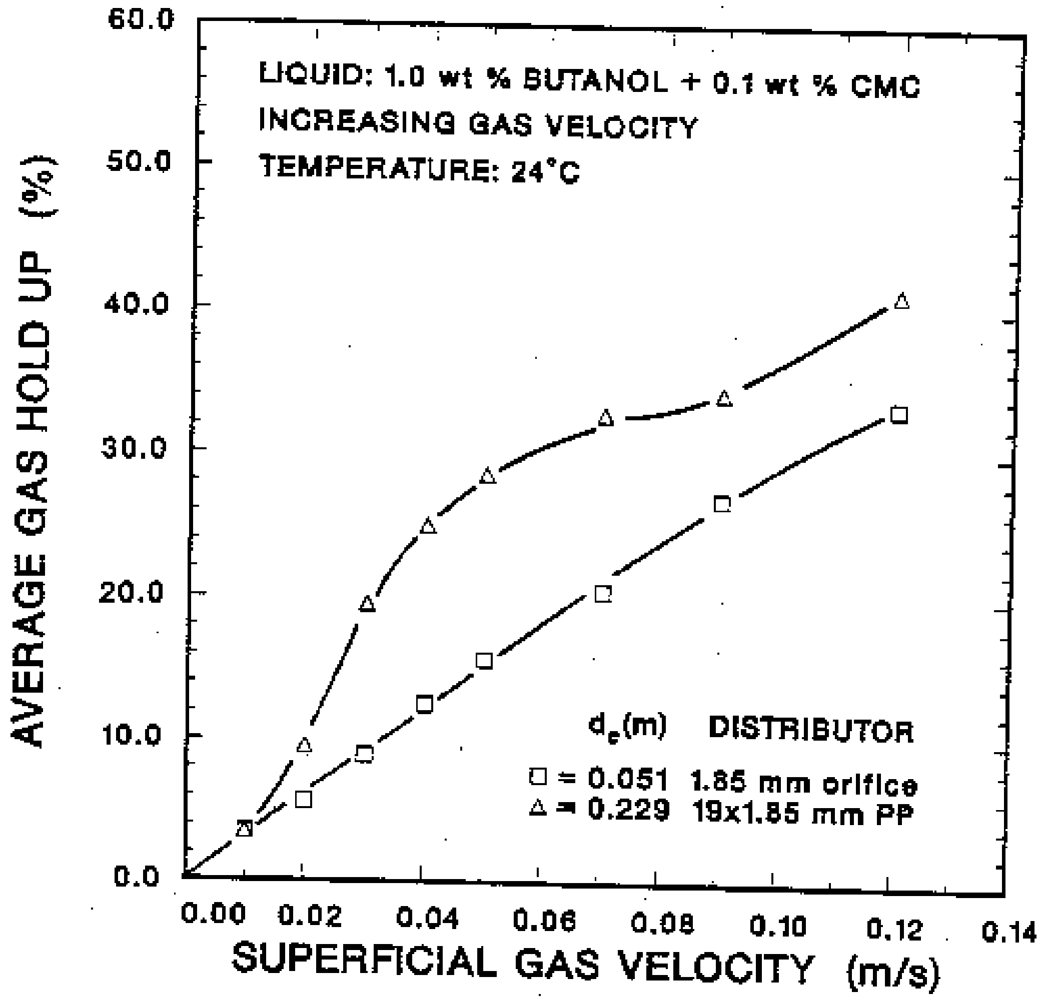

Figure 29. Effect of column diameter and superficial gas velocity on gas hold-up (□ -Run B-10, △ -Run B-19).

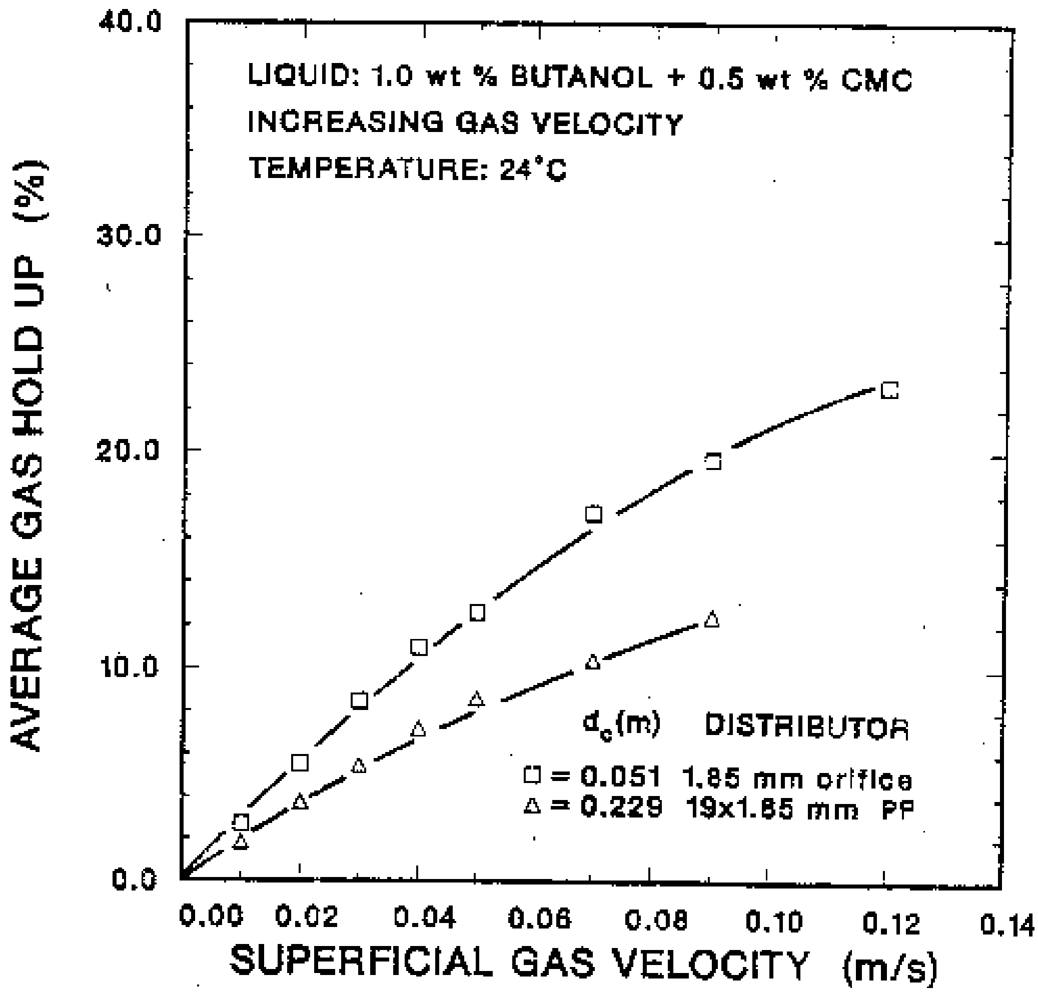

Figure 30. Effect of column diameter and superficial gas velocity on gas hold-up (□ -Run B-13, △ -Run B-20).

Comparing to paraffin waxes, in the presence of foam small column gave higher hold-ups and similar values of hold-ups were obtained in the absence of foam. However, these new observations with aqueous solutions tend to contradict this observation, which can not be explained qualitatively, it seems to be the combined effects of column diameter and viscosity on gas hold-ups. Similar observations were observed when 1 mm distributor plate was used.

3. Effects of Distributor Type

Figure 31 shows the effect of distributor type on gas hold-ups for aqueous mixture containing 1.0 wt. % n-butanol and 0.1 wt % CMC in the 0.051 m ID column. At low superficial gas velocity (< 0.03) small amount of foam was observed for all distributors (SMP, 1 mm orifice and 1.85 mm orifice) and the hold-ups showed small difference. However, at high gas velocities (> 0.05 m/s) the SMP distributor produced higher gas hold-up values than the orifice plate distributors. Also, it was observed that the gas hold-up values for the orifice plate distributors decreased with increasing orifice diameter. This trend was similar to what was observed with paraffin waxes in the presence of foam.

It is well established that the diameter of bubbles in the column and thus gas hold-up are determined by the coalescence behavior of the liquid and the initial bubble size at the distributor. For foamy systems the rate of coalescence of bubbles is very low, thus the initial bubble size (size at the distributor hole) tends to persist. The non-coalescence of these bubbles and the slow rise velocities for the small bubbles results in higher hold-up values for the SMP distributor (small initial bubble size) than the hold-ups from the orifice plate distributors.

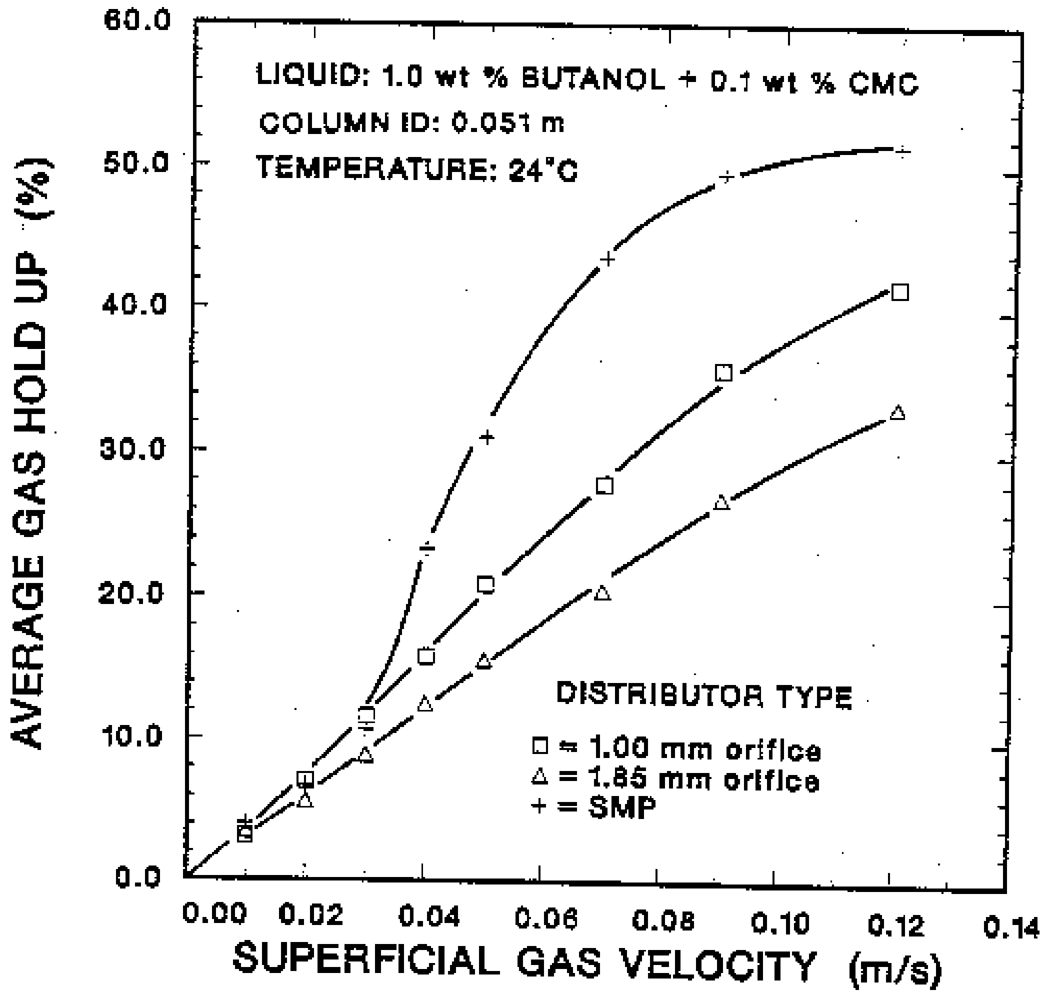

Figure 31. Effect of distributor type and superficial gas velocity on gas hold-up (□ -Run B-12, △ -Run B-10, + -Run B-9).

Figure 32 shows the effect of the distributor type on gas hold-up for an aqueous mixture containing 1.0 wt. % butanol and 0.5 wt. % CMC in the 0.051 m ID column. The mixture was very thick and looked milky due to the presence of many tiny bubbles. At gas velocities lower than 0.07 m/s, the SMP distributor gave slightly higher hold-ups than the orifice plates, whereas no difference in hold-ups was observed for the orifice plate distributors. In the fully developed slug flow regime ($u_g > 0.07$ m/s), 1 mm orifice plate distributor gave higher hold-ups than either SMP or 1.85 mm orifice plate distributor. This observation was similar to that observed with paraffin waxes using the same distributor.

In summary, these results confirm the previous findings with paraffin waxes, that in the bubbly flow regime the gas hold-up decreases with increase in orifice size, i.e., SMP produces higher hold-ups than orifice plates.

4. Effect of Viscosity on Gas Hold-up

To analyze the effect of liquid viscosity on gas hold-up, the average gas hold-ups at different superficial gas velocities were plotted against the apparent viscosity of the liquid on the log-log scale. Results from different distributors (SMP, 1 mm and 1.85 mm orifice plates) and column diameters (0.051 m and 0.229 m) were very much alike, therefore only results obtained with 1.85 mm distributor plate are discussed here.

Figures 33 and 34 illustrate results obtained from the 0.051 m ID column and the 0.229 m ID columns, respectively. The gas hold-ups showed a maximum when aqueous solution containing 1 wt % n-butanol with 0.1 wt % CMC was used (μ_a of about 1 to 1.5 mPa.s). Similar results with a maximum value of hold-up have been reported by Bach and Pilhofer (1978) and by Kelkar and Shah (1985), they

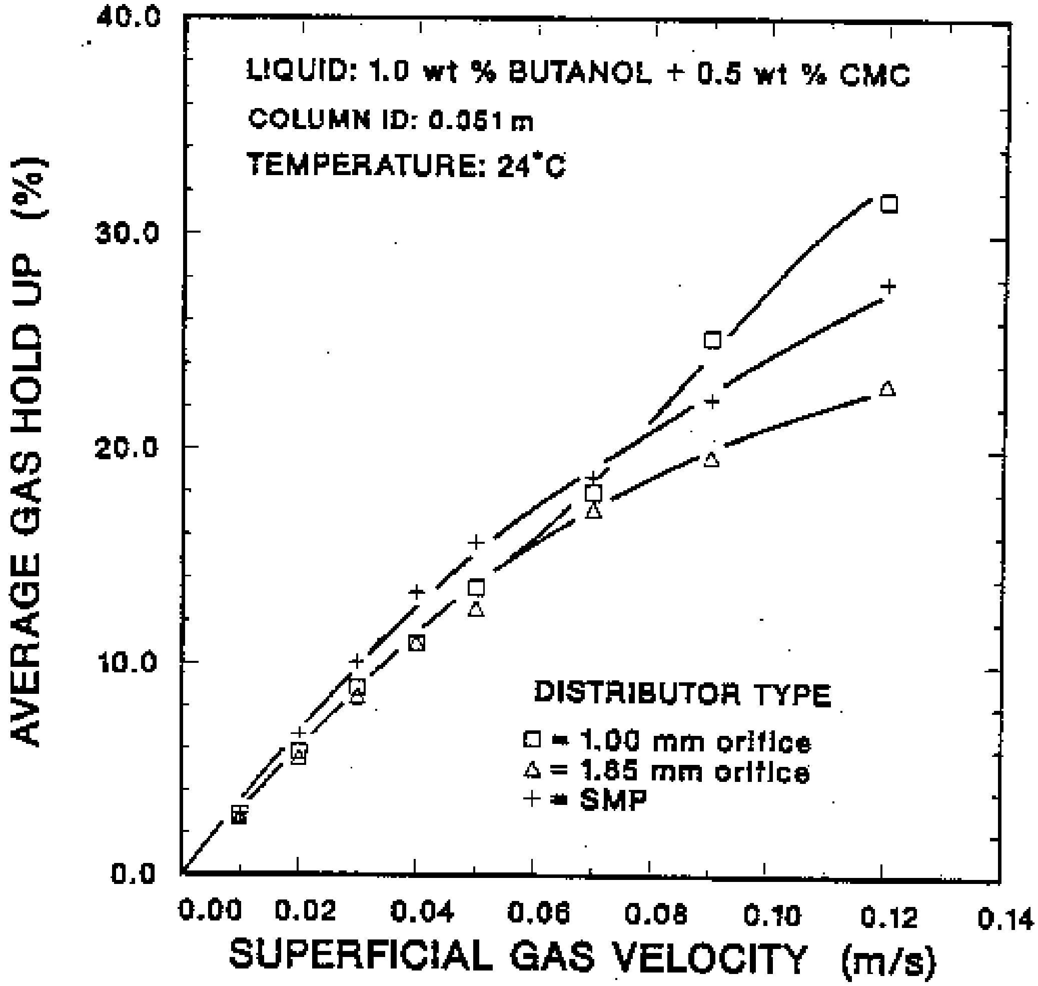

Figure 32. Effect of distributor type and superficial gas velocity on gas hold-up (□ -Run B-15, △ -Run B-13, + -Run B-14).

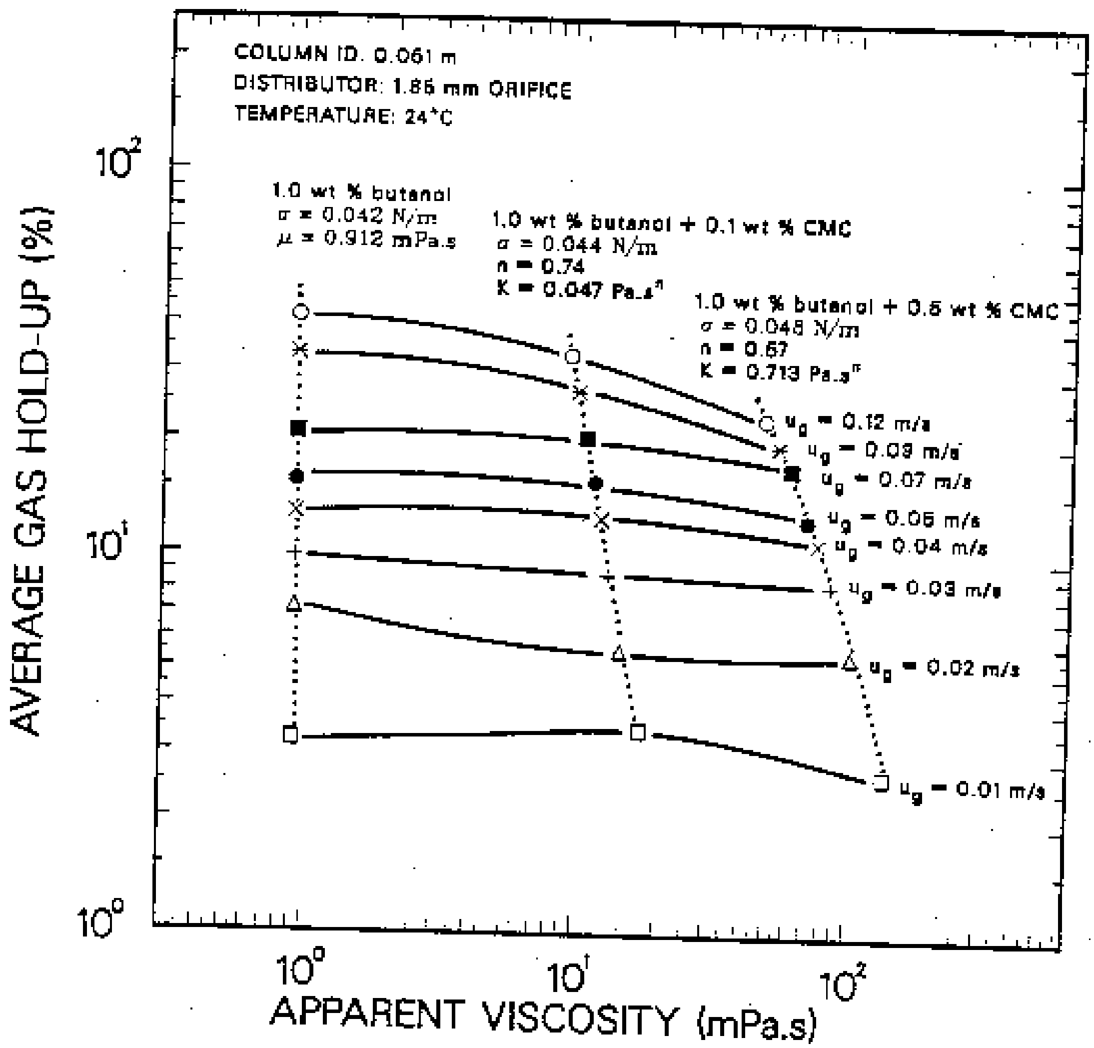

Figure 33. Effect of liquid viscosity and superficial gas velocity on gas hold-up.

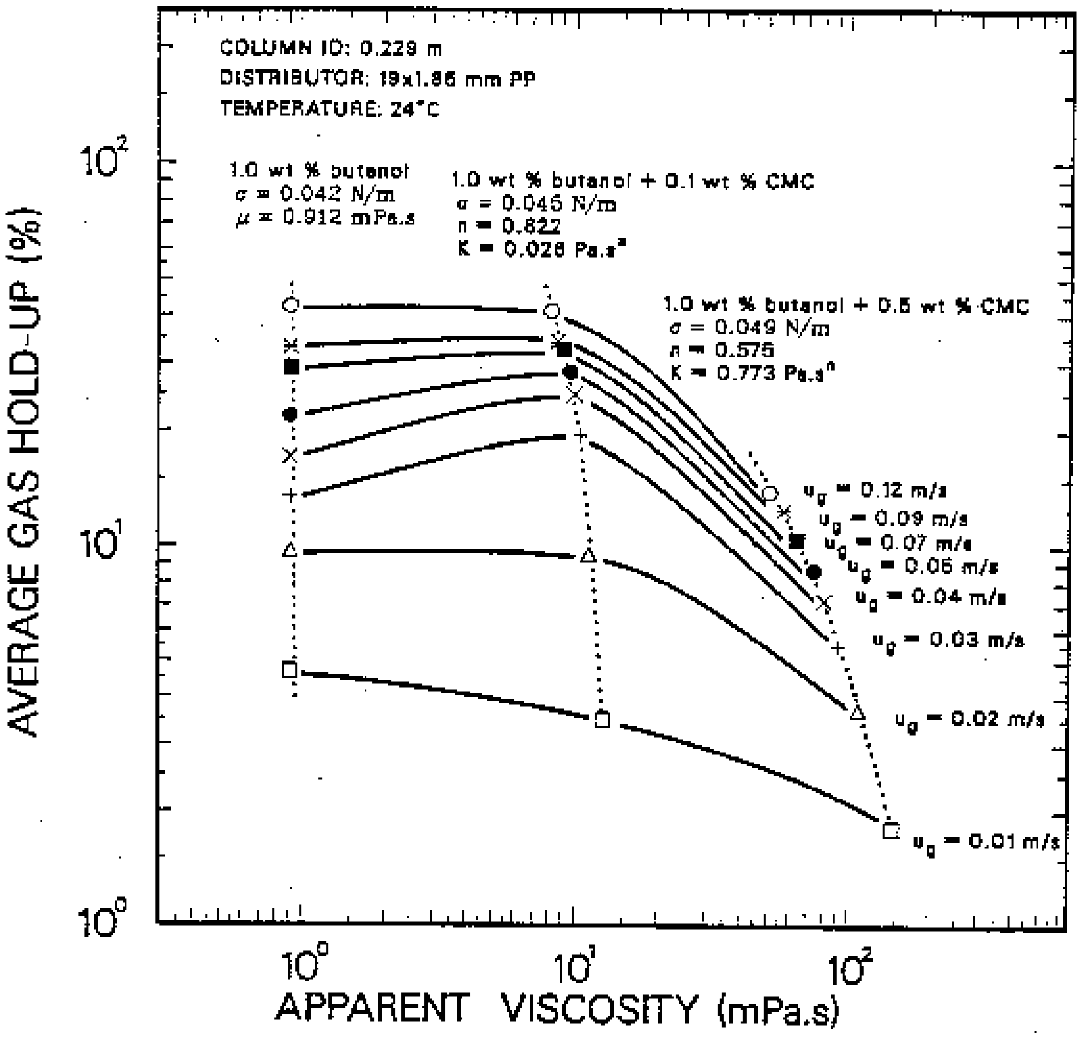

Figure 34. Effect of liquid viscosity and superficial gas velocity on gas hold-up.

observed maximum hold-ups at μ_a of about 3 mPa.s. Due to limited data of μ_a in this study, it is not possible to draw the conclusion that maximum hold-up occurs at μ_a of about 1 mPa.s. Furthermore, it was observed that the local maximum gets more steeper as the superficial gas velocity increased. It was also observed that, there is a strong viscosity dependence on gas hold-up for the large column in the churn-turbulent regime (u_g > 0.02 m/s), this is illustrated by high steepness of the lines in Figure 34 than those obtained from the 0.051 m ID column, Figure 33.

In summary, there seems to be a value of μ_a where hold-ups tend to be at maximum values, then decrease as the viscosity of the liquid is increased. These observations are in agreement with those reported by Eissa and Schugerl (1975) and by Kelkar and Shah (1985) while using highly viscous non-Newtonian solutions of CMC.