

Results and Discussion

Average and axial gas holdups obtained from experiments in the stainless steel columns are presented here. Axial solids concentration profiles will be discussed in Chapter IV. The discussion is divided into three main sections. In the first part, definitions and descriptions of the various flow regimes which were observed are presented. Following this, the effect of various operating conditions and column diameter on gas holdups are discussed. Finally, various correlations which may be used to predict average gas holdup in a three-phase Fischer-Tropsch bubble column reactors are presented.

Description of the Flow Field

The hydrodynamics (e.g. mixing characteristics, bubble size distribution, etc.) of a bubble column is significantly affected by the flow regime prevailing in the column. Ample evidence of this dependency is available in the literature (e.g. Shah et al., 1982) and various criteria have been proposed by different researchers to delineate the flow regimes (e.g. Taitel et al., 1981; Deckwer et al., 1980). Deckwer et al. presented a flow regime map (see Figure 2.12) which qualitatively characterizes the dependence of flow regimes on column diameter and superficial gas velocity. At low gas velocities, regardless of column diameter, the homogeneous (or homogeneous bubbling) regime exists. This regime is characterized by a uniform bubble size distribution in which there is very little interaction between neighboring bubbles. As the gas velocity increases, bubble coalescence and breakup occur. In columns less than 0.10 m in diameter, the large bubbles may fill the entire column diameter forming slugs; this is known as the slug flow regime. In larger diameter columns, large bubbles are formed without producing slugs. As these large bubbles rise through the column, there is an increase in turbulence; hence, this is called the churn-turbulent flow regime. The shaded regions in Figure 2.12

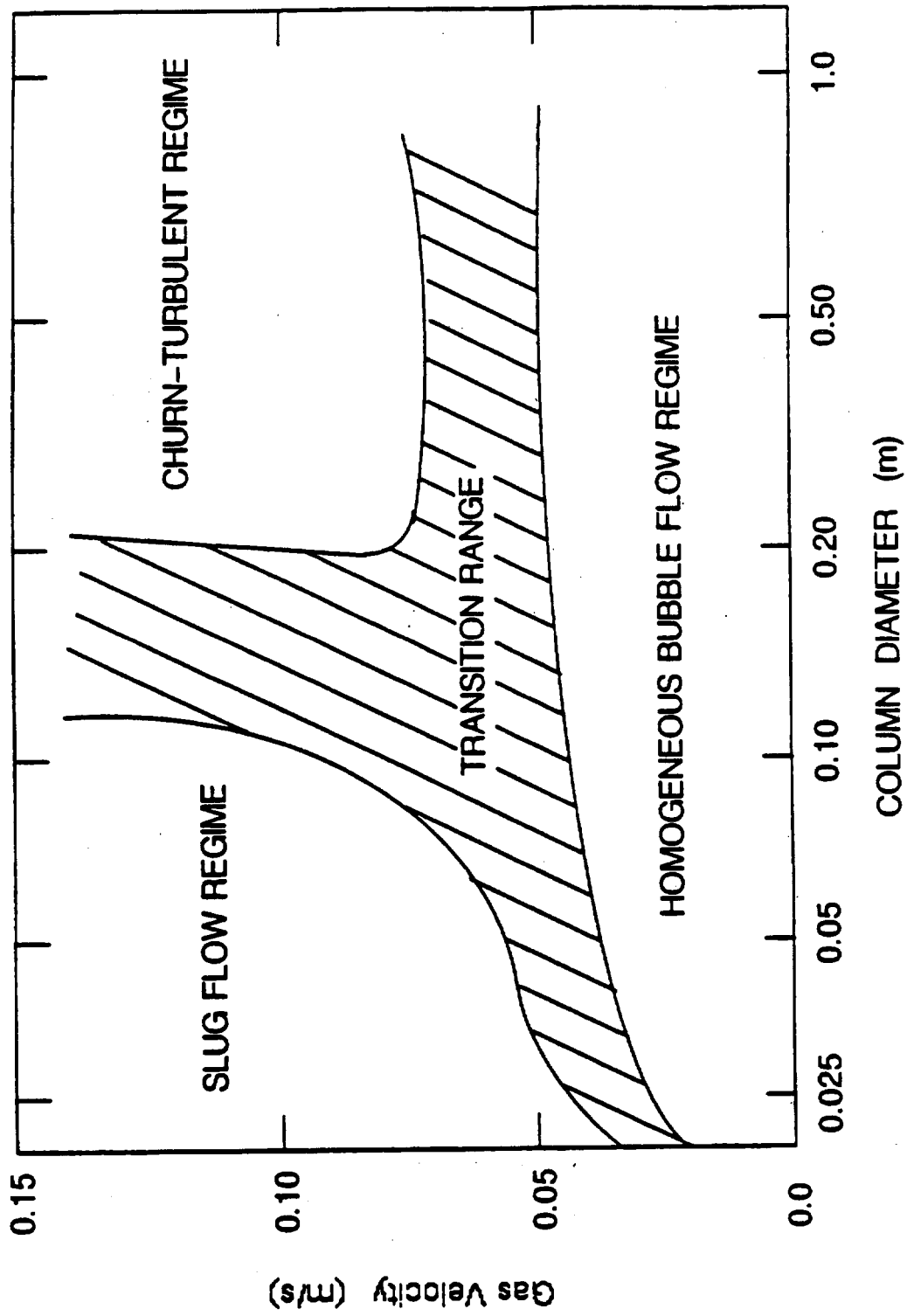


Figure 2.12. Bubble column flow regime map (adopted from Deckwer et al., 1980).

indicate the transition regions between the various flow regimes. The exact boundaries associated with the transition regions will probably vary with the system studied.

The flow regimes described above are typically associated with nonfoaming systems. For foaming systems, Shah et al. (1985) include an additional flow regime called the foaming (or foamy) regime. The foamy regime overlaps the previously described regimes and is characterized by high gas holdups and substantial recirculation of bubbles.

In our experiments, all of the flow regimes described above were observed. In the 0.05 m ID column, the homogeneous bubbly regime prevailed at superficial gas velocities less than 0.04 m/s and the slug flow regime at higher gas velocities. For experiments conducted with FT-300 wax, the foamy regime was also observed; however, with SASOL reactor wax, very little foam, if any, was present. In the 0.21 m ID column, the homogeneous bubbling regime was observed at low gas velocities ($u_g < 0.04$ m/s) and the churn-turbulent regime at higher gas velocities. The amount of foam observed in experiments with FT-300 wax in the large diameter column was significantly less than that observed under similar operating conditions in the small diameter column. As in the 0.05 m ID column, little or no foam was observed during experiments conducted with SASOL wax in the 0.21 m ID column.

Gas Holdup Results

FT-300 and SASOL wax were used for experiments in both the small (0.05 m ID) and large (0.21 m ID) diameter columns. The majority of experiments in the small diameter column were conducted with FT-300 wax, since SASOL wax was not available during the initial stages of this study. Once SASOL wax became available, some experiments were performed in order to study the effect of wax type on gas holdup and solid concentration profiles. Table 2.4 summarizes experimental conditions used in the small diameter column. An increasing order of gas velocities was employed for all

Table 2.4. Summary of Runs in the Small Stainless Steel Column

EXP. No.	WAX TYPE	T (°C)	d _p (μm)	ω _s (%)	SOLIDS TYPE	u _c (m/s)	TOS (hr)	TIME HOT (hr)
1	FT-300	265	-	-	-	0.0	0	12
2	FT-300	265	-	-	-	0.005	8	36
3	FT-300	265	-	-	-	0.02	16	60
4	FT-300	265	0 - 5	10	IRON OX	0.005	24	84
5	FT-300	265	0 - 5	10	IRON OX	0.02	32	108
6	FT-300	265	0 - 5	10	IRON OX	0.0	40	132
7	FT-300	265	0 - 5	20	IRON OX	0.005	0	12
8	FT-300	265	0 - 5	20	IRON OX	0.02	8	36
9	FT-300	265	0 - 5	20	IRON OX	0.0	16	60
10	FT-300	265	0 - 5	30	IRON OX	0.005	24	84
11	FT-300	265	0 - 5	30	IRON OX	0.02	32	108
12	FT-300	265	0 - 5	30	IRON OX	0.0	40	132
13	FT-300	265	20 - 44	10	IRON OX	0.005	0	12
14	FT-300	265	0 - 5	10	SILICA	0.005	0	12
15	FT-300	265	0 - 5	20	SILICA	0.005	8	36
16	FT-300	265	0 - 5	20	SILICA	0.02	16	60
17	FT-300	265	0 - 5	20	SILICA	0.0	24	84
18	FT-300	265	0 - 5	30	SILICA	0.005	32	108
19	FT-300	265	20 - 44	10	IRON OX	0.005	0	12
20	FT-300	265	20 - 44	10	IRON OX	0.02	8	36
21	FT-300	265	20 - 44	20	IRON OX	0.0	16	84
22	FT-300	265	20 - 44	20	SILICA	0.0	0	36
23	FT-300	265	-	-	-	0.0	0	12
24	FT-300	265	-	-	-	0.005	8	36
25	FT-300	265	20 - 44	20	IRON OX	0.0	16	60
26	FT-300	265	20 - 44	20	IRON OX	0.02	24	84
27	FT-300	265	20 - 44	20	IRON OX	0.005	32	108
28	FT-300	265	20 - 44	20	SILICA	0.0	0	12
29	SASOL	265	-	-	-	0.0	0	12
30	SASOL	265	-	-	-	0.005	8	36
31	SASOL	265	0 - 5	20	IRON OX	0.005	16	60
32	SASOL	265	20 - 44	20	IRON OX	0.0	0	12
33	SASOL	265	20 - 44	20	IRON OX	0.005	8	36
34	SASOL	265	20 - 44	20	IRON OX	0.005	12	60

Note: Horizontal lines separate batches

TOS - Time on stream

TIME HOT - Total time heated

experiments in the small diameter column, with the exception of the two batch experiments conducted with 20–44 μm silica particles (experiments 22 and 28 in Table 2.4) and the last two continuous experiments with large iron oxide particles suspended in FT-300 wax (experiments 26 and 27 in Table 2.4). For these experiments, a decreasing order of gas velocities was used. Experiments in the large diameter column were conducted once all experiments in the small diameter column were completed. SASOL wax was chosen as the primary fluid for experiments in the 0.21 m ID column since it is more representative of the reactor wax present in a slurry bubble column reactor during Fischer-Tropsch synthesis. Also, a limited number of experiments was conducted with FT-300 wax in the 0.21 m ID column. A summary of the experiments conducted in the large diameter column is presented in Table 2.5. The 19 x 2 mm perforated plate (PP) was used for majority of these experiments. With the exception of a few experiments without solids (i.e. experiments 1 – 4 in Table 2.5), all experiments in the large diameter column were performed using a decreasing order of gas velocities. The effect of slurry flow rate, solids concentration, type and size, liquid medium, temperature, distributor type, and column diameter on gas holdup is discussed below.

Effect of Slurry Velocity

Figures 2.13a and 2.13b show the effect of slurry velocity on average gas holdup for experiments conducted with FT-300 wax in the small and large diameter columns, respectively. A substantial amount of foam was produced during the batch (i.e. $u_{sl} = 0$) experiment in the 0.05 m ID column, with gas holdup values as high as 0.29 at a gas velocity of 0.04 m/s (see Figure 2.13a). Gas holdups decreased significantly for gas velocities in the range 0.04 – 0.09 m/s when the superficial slurry velocity was increased to 0.005 m/s. A further decrease in gas holdup was observed when the slurry velocity was increased to 0.02 m/s. It should be noted that at higher gas velocities,

Table 2.5. Summary of Runs in the Large Stainless Steel Column

EXP. No.	WAX TYPE	T (°C)	d _p (μm)	ω _s (%)	SOLIDS TYPE	u _r (m/s)	DIST	TOS (hr)	TIME HOT (hr)
1	SASOL	265	—	—	—	0.0	PP	0	12
2	SASOL	265	—	—	—	0.005	PP	6	36
3	SASOL	265	—	—	—	0.02	PP	12	42
4	SASOL	265	—	—	—	0.005	BC	18	78
5	SASOL	265	—	—	—	0.0	PP	0	72
6	SASOL	265	0 - 5	IRON OX	10	0.0	PP	8	96
7	SASOL	265	0 - 5	IRON OX	20	0.0	PP	16	120
8	SASOL	265	0 - 5	IRON OX	20	0.005	PP	24	124
9	SASOL	265	0 - 5	IRON OX	20	0.02	PP	32	130
10	SASOL	265	0 - 5	IRON OX	20	0.0	BC	40	154
11	SASOL	265	0 - 5	IRON OX	20	0.005	BC	48	162
12	SASOL	265	0 - 5	IRON OX	20	0.0	PP	56	186
13	SASOL	265	0 - 5	IRON OX	30	0.0	PP	64	210
14	SASOL	265	0 - 5	IRON OX	30	0.005	PP	72	234
15	SASOL	265	20 - 44	IRON OX	10	0.005	PP	0	12
16	SASOL	265	20 - 44	IRON OX	10	0.02	PP	6	18
17	SASOL	265	20 - 44	IRON OX	20	0.0	PP	12	42
18	SASOL	265	20 - 44	IRON OX	20	0.005	PP	18	48
19	SASOL	265	20 - 44	IRON OX	20	0.02	PP	24	72
20	SASOL	265	20 - 44	IRON OX	20	0.0	BC	30	120
21	SASOL	265	20 - 44	IRON OX	20	0.0	PP	36	144
22	SASOL	265	20 - 44	IRON OX	30	0.0	PP	42	150
23	SASOL	265	20 - 44	IRON OX	30	0.005	PP	48	174
24	SASOL	265	20 - 44	IRON OX	30	0.02	PP	54	180
25	SASOL	265	—	—	—	0.005	BC	0	12
26	SASOL	265	20 - 44	SILICA	20	0.0	PP	6	36
27	SASOL	265	20 - 44	SILICA	20	0.005	PP	12	42
28	SASOL	265	20 - 44	SILICA	20	0.02	PP	18	48
29	SASOL	265	20 - 44	SILICA	30	0.005	PP	24	72
30	FT-300	265	—	—	—	0.0	PP	0	12
31	FT-300	265	—	—	—	0.005	PP	6	18
32	FT-300	265	—	—	—	0.02	PP	12	24
33	FT-300	265	20 - 44	IRON OX	20	0.0	PP	18	48
34	FT-300	265	20 - 44	IRON OX	20	0.005	PP	24	54
35	FT-300	265	20 - 44	IRON OX	20	0.005	BC	30	78

Note: Horizontal lines separate batches

TOS - Time on stream

TIME HOT - Total time heated

PP - Perforated plate distributor

BC - Bubble cap distributor

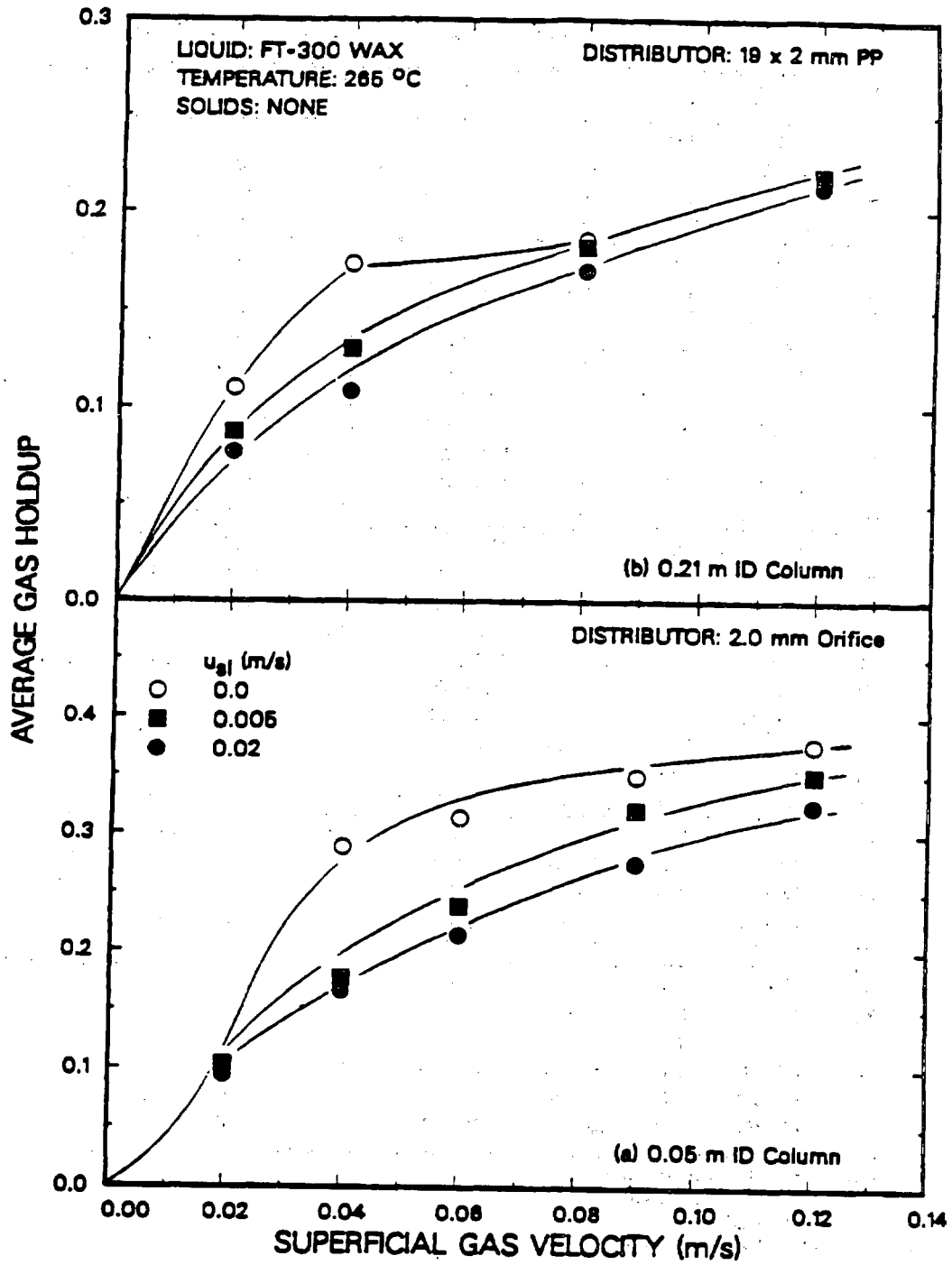


Figure 2.13. Effect of superficial slurry velocity on average gas holdup in the (a) small and (b) large diameter columns with FT-300 wax.

the difference in gas holdup between the batch experiment (i.e. $u_{s\ell}=0.0$ m/s) and the continuous experiments decreases. At a gas velocity of 0.02 m/s, the holdups from all three runs were similar (see Figure 2.13a). At this gas flow rate, the homogeneous bubbling regime exists, and one would expect holdups to be similar for all three slurry velocities.

Foam was also observed during the batch experiment in the large diameter column at a gas velocity of 0.04 m/s (see Figure 2.13b). At this gas velocity (i.e. 0.04 m/s), the amount of foam produced in the large diameter column was less than the amount of foam produced in the small diameter column (i.e. the gas holdup was 0.18 in the large diameter column as opposed to 0.29 in the small diameter column). Gas holdups during the continuous experiments at $u_g = 0.04$ m/s were lower than the gas holdups at this velocity during the batch experiment. Only a marginal decrease in gas holdup was observed when the slurry flow rate was increased from 0.005 to 0.02 m/s. At gas velocities of 0.08 and 0.12 m/s gas holdups from all three experiments were similar. At a gas velocity of 0.02 m/s, the gas holdup associated with the batch experiment was slightly higher than those from the continuous experiment. This was due to a slight increase in the gas holdup during the batch experiment in uppermost section of the column at this velocity (see Figure 2.14b).

Axial gas holdup profiles at gas velocities of 0.02, 0.04, and 0.12 m/s, from the batch experiments in the 0.05 and 0.21 m diameter columns are shown in Figures 2.14a and 2.14b, respectively. At a gas velocity of 0.02 m/s, axial gas holdup profiles in both columns are nearly uniform; however, at a gas velocity of 0.04 m/s, there is a significant increase in the gas holdup between heights of 1.5 and 2.2 m above the distributor (i.e. in the small diameter column the gas holdup increases from 0.17 to 0.64 and in the large diameter column, the gas holdup increases from 0.16 to 0.28). This increase in gas holdup indicates the presence of a foam layer at the top of the dispersion. The

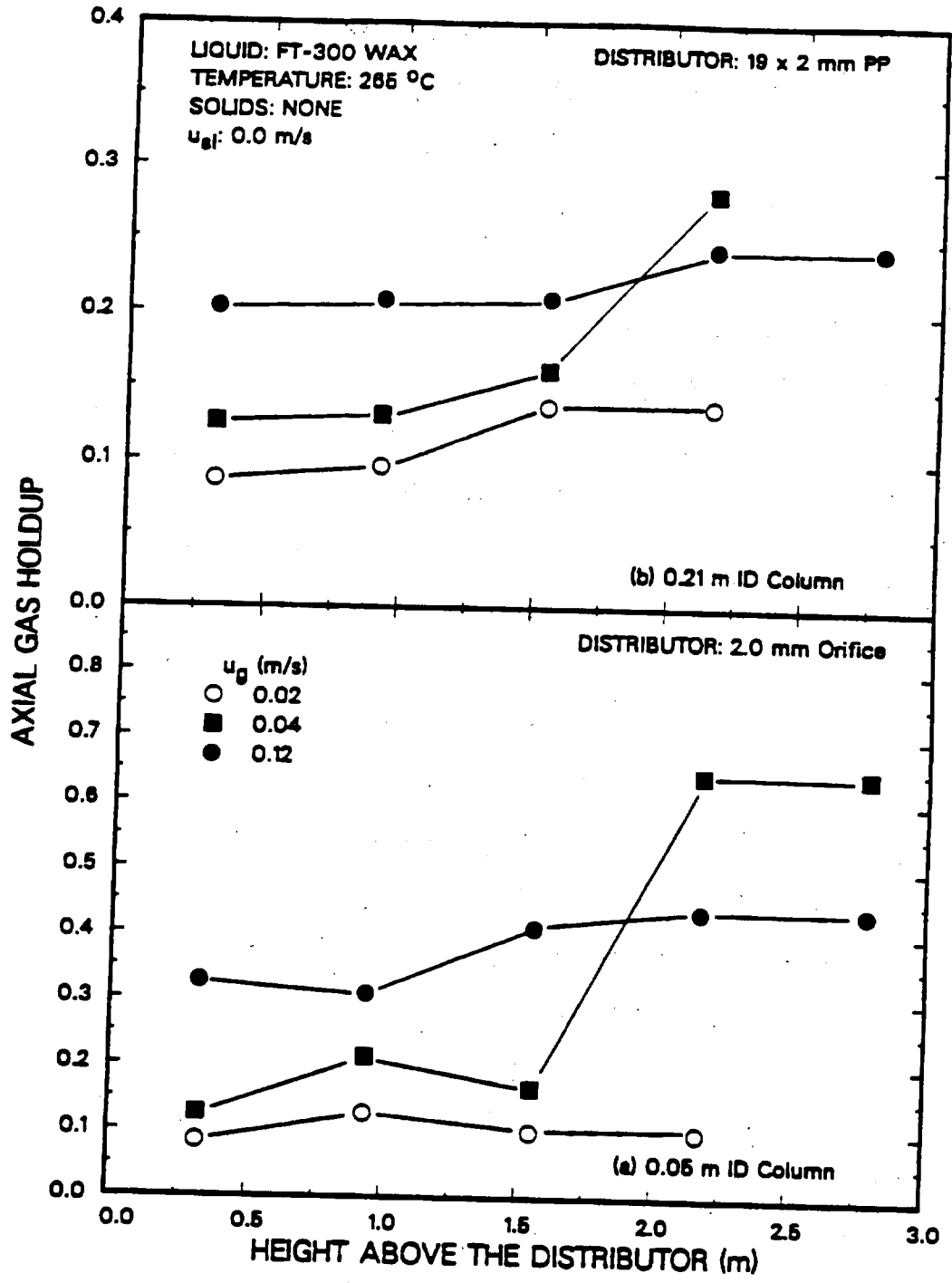


Figure 2.14. Effect of superficial gas velocity on axial gas holdup in the (a) small and (b) large diameter columns with FT-300 wax.

amount of foam present in the large diameter column at a gas velocity of 0.04 m/s was substantially less than the amount of foam present in the small diameter column at this gas velocity. The difference in the amount of foam produced in the two columns is due to differences in the flow patterns present in the two columns at this gas velocity. Liquid circulation patterns develop in the large diameter column at a gas velocity of 0.04 m/s which help break up the foam. At a gas velocity of 0.12 m/s, the gas holdup in the uppermost region of both columns was lower than that observed at a gas velocity of 0.04 m/s (see Figures 2.14a and 2.14b). Also, the gas holdup profile along the column height was fairly uniform in both columns. This indicates that the foam layer which was present in both columns at a gas velocity of 0.04 m/s had dissipated. Figure 2.15 compares axial gas holdup profiles at slurry velocities of 0.0, 0.005, and 0.02 m/s in the small diameter column. At a gas velocity of 0.02 m/s (Figure 2.15a) axial gas holdup profiles are similar for all slurry flow rates. At a gas velocity of 0.04 m/s there is a significant difference in the gas holdup profiles in the uppermost section of the column (i.e. at a height greater than 1.5 m above the distributor; see Figure 2.15b) between experiments conducted in the continuous mode of operation and the experiment conducted in the batch mode of operation. In the lower section of the column (i.e. <2.2 m above the distributor), the holdups from all three experiments are similar. This, shows that in the absence of foam, there is very little effect of liquid flow rate on gas holdup. Also, this substantiates the claim that a slight upward liquid flow rate is sufficient to dissipate the foam layer. At a gas velocity of 0.12 m/s (Figure 2.15c), we once again observe similar axial gas holdup profiles at all slurry flow rates. However, axial gas holdups are consistently lower at a slurry velocity of 0.02 m/s.

Experiments were conducted in both columns with FT-300 wax to study the effect of slurry flow rate on average gas holdup in three-phase systems. Results similar to those with FT-300 wax (no solids) were obtained (i.e. an increase in slurry flow rate

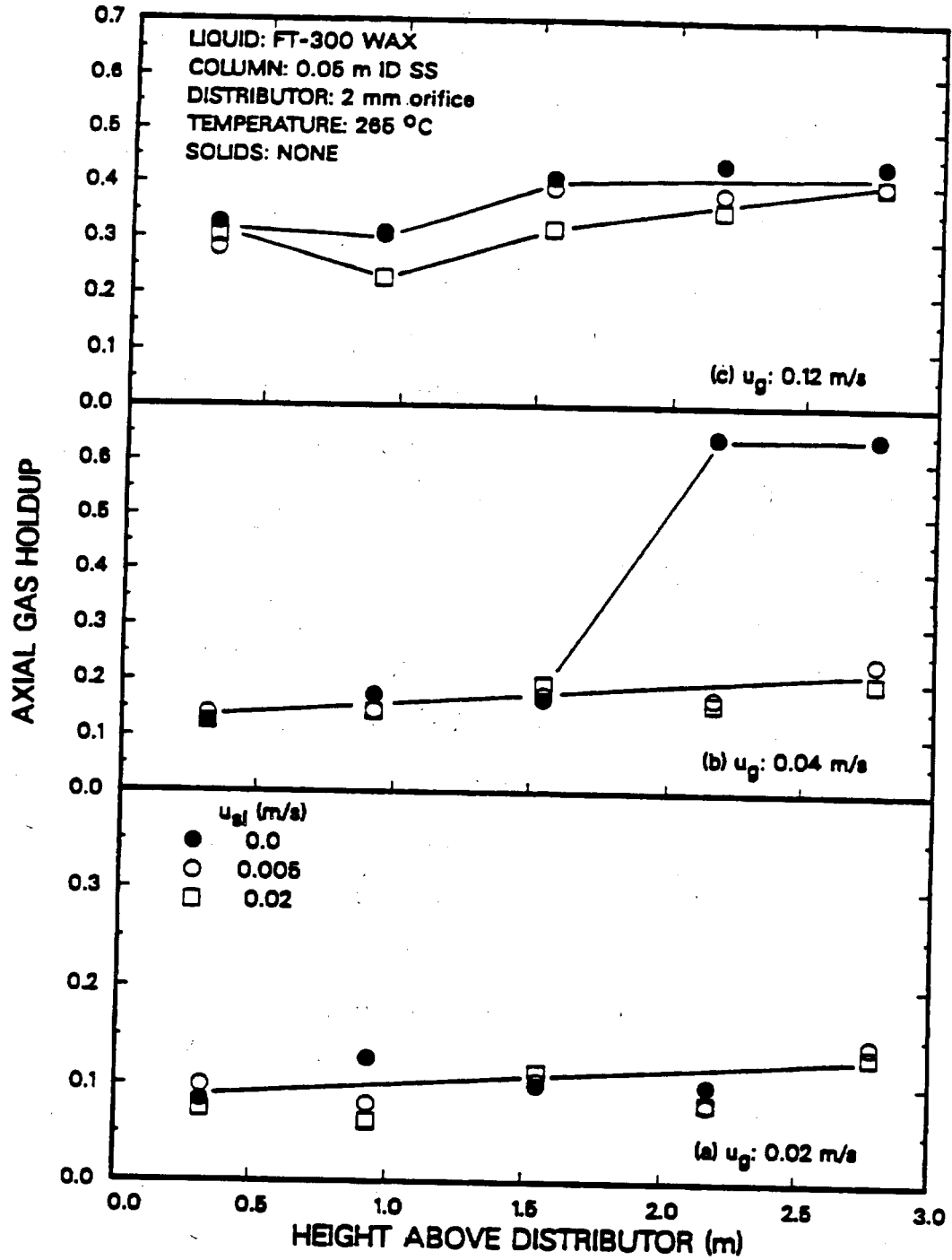


Figure 2.15. Effect of superficial slurry velocity on axial gas holdup in the small diameter column with FT-300 wax.

causes a decrease in gas holdup when foam is present). Figure 2.16 shows results for experiments in the 0.05 m ID column with 20 wt% slurries of 0 – 5 μm iron oxide (Figure 2.16a) and 0 – 5 μm silica particles (Figure 2.16b). For these systems, gas holdups from experiments conducted in the batch mode of operation were consistently higher than those obtained from experiments conducted in the continuous mode of operation. A substantial decrease in holdup was observed when the slurry velocity was increased from 0.0 to 0.005 m/s. This decrease in gas holdup with increasing slurry velocity is due to the dissipation of the foam present in batch experiments. Similar trends were observed for 10 and 30 wt% slurries of 0 – 5 μm iron oxide particles.

Results from experiments in the large diameter column, with 20 – 44 μm iron oxide particles are shown in Figure 2.17. During the batch experiment, foam was produced at a gas velocity of 0.04 m/s. Increasing the slurry velocity to 0.005 m/s decreased the gas holdup (i.e. $\epsilon_g = 0.28$ for $u_\ell = 0$ and 0.11 for $u_\ell = 0.005$) at a gas velocity of 0.04 m/s. In the absence of foam (i.e. $u_g = 0.08$ and 0.12 m/s), there is not a significant effect of slurry flow rate on gas holdup.

Thus, gas holdup decreases with increasing slurry velocity for experiments conducted with FT-300 wax (with and without solids) in the 0.05 and 0.21 m ID columns. The decrease in holdup with increasing slurry flow rate is most pronounced at gas velocities which favor the formation of foam. In the absence of foam, the effect of slurry flow rate on gas holdup is negligible.

Results from experiments with SASOL wax (no solids) in the 0.05 and 0.21 m ID columns are shown in Figures 2.18a and 2.18b, respectively. SASOL wax behaves quite differently from FT-300, i.e. it does not have a tendency to foam. An increase in slurry flow rate from 0.0 to 0.005 m/s caused a slight decrease in gas holdup in both columns (see Figures 2.18a and 2.18b). This behavior (i.e. negligible effect of $u_{s\ell}$ on ϵ_g) is consistent with that observed in experiments with FT-300 wax in the absence of foam.

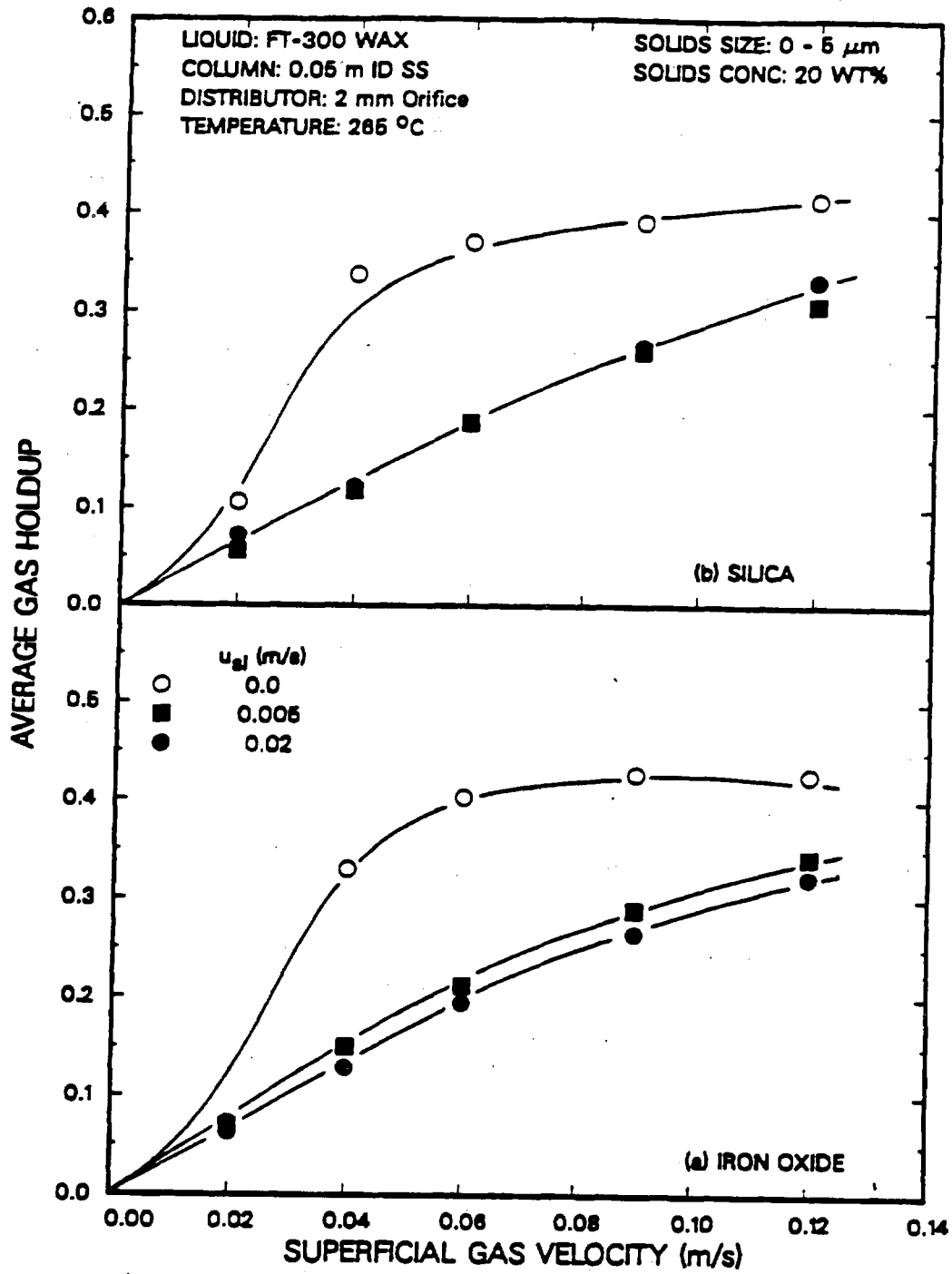


Figure 2.16. Effect of superficial slurry velocity on average gas holdup in the small diameter column with FT-300 wax in the presence of solids; (a) 0 - 5 μm iron oxide; (b) 0 - 5 μm silica.

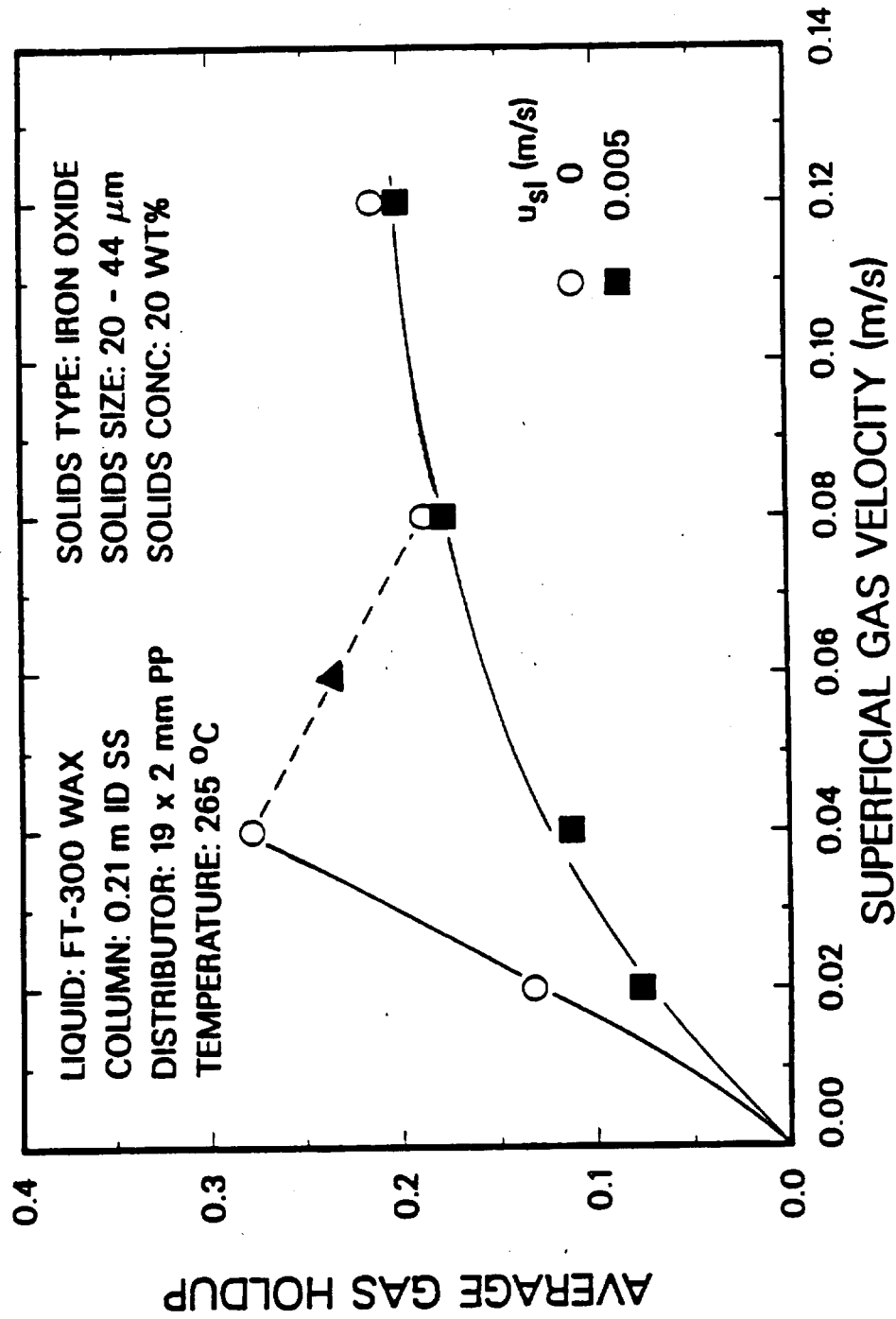


Figure 2.17. Effect of superficial slurry velocity on average gas holdup in the large diameter column with FT-300 wax (20 - 44 μm iron oxide).

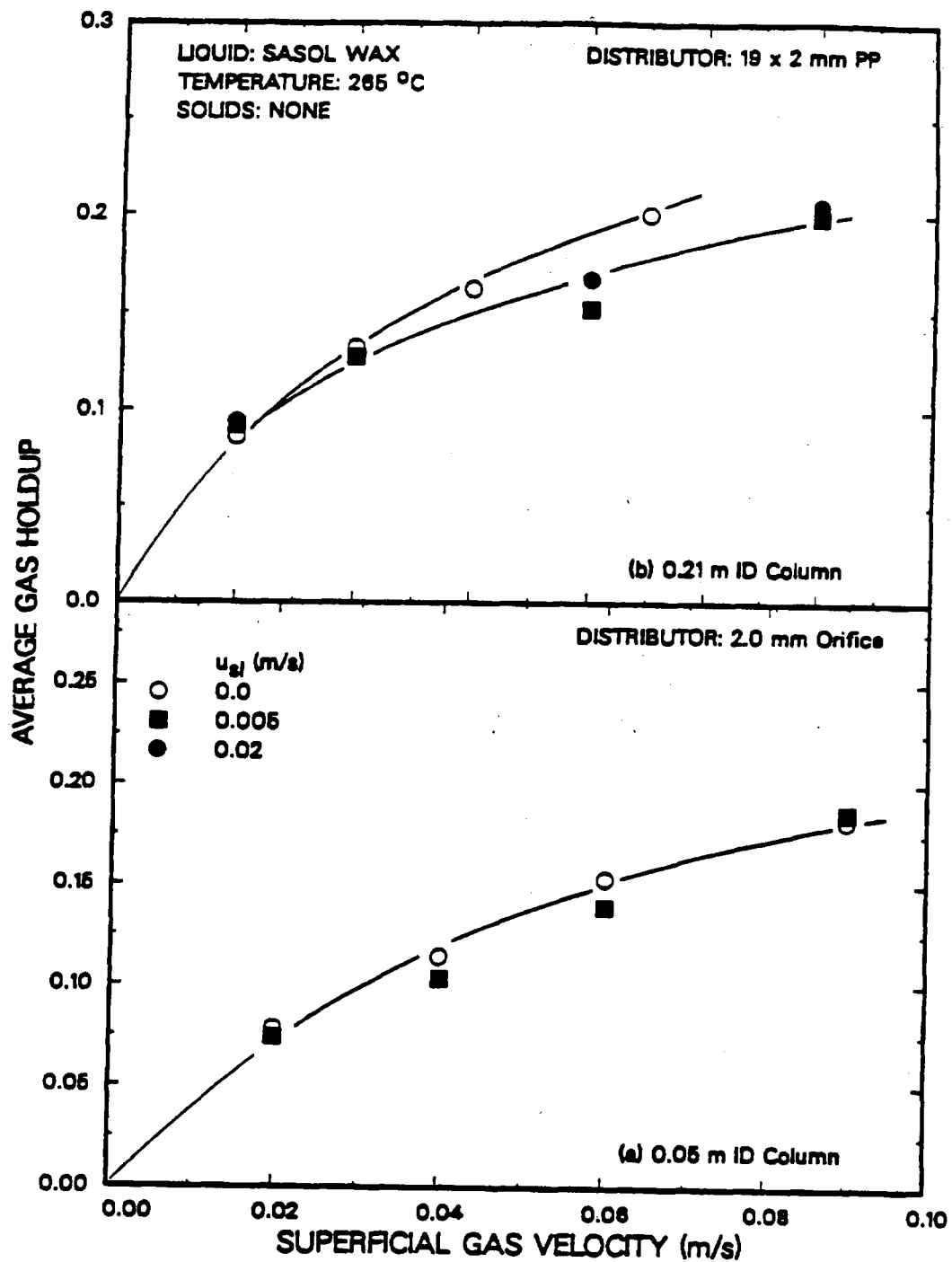


Figure 2.18. Effect of superficial slurry velocity on average gas holdup in the (a) small end (b) large diameter columns with SASOL wax.

Gas holdup results from three-phase experiments with SASOL reactor wax in the large diameter column are shown in Figure 2.19. There was no significant effect of slurry flow rate on average gas holdups for experiments with 0 – 5 μm and 20 – 44 μm iron particles (see Figures 2.19a and 2.19b, respectively). Results from the experiments conducted with 20 – 44 μm silica particles are shown in Figure 2.19c. During these experiments, the gas holdup decreased slightly with increasing slurry flow rate.

The trends observed in this study in the continuous mode of operation are in qualitative agreement with results from other studies. Studies with systems which do not foam (e.g., water – air) indicate that slurry (or liquid) velocity either has no effect on gas holdup (e.g., Akita and Yoshida, 1974; Shah et al., 1982), or decreases holdup only slightly (e.g., Kara et al., 1982; Buchholz et al., 1983; Kelkar et al., 1984; Ouyang and Tattersson, 1987). However, for systems which foam, gas holdup decreases markedly with increasing slurry velocity (e.g. Shah et al., 1985; Kelkar et al., 1983). For example, Shah et al. reported holdup values as high as 80 % with an aqueous ethanol solution at a superficial gas velocity of 0.20 m/s in the batch mode of operation; however, upon increasing the slurry flow rate to 0.0077 m/s, the gas holdup dropped to approximately 20 %.

Effect of Solids Concentration

The effect of solids concentration (iron oxide) on gas holdup in the 0.05 m ($d_p = 0 - 5 \mu\text{m}$) and 0.21 m ID ($d_p = 20 - 44 \mu\text{m}$) bubble columns with FT-300 wax as the liquid medium is shown in Figures 2.20a and 2.20b, respectively. Gas holdups in the small diameter column are highest for a solids concentration of 20 wt% at gas velocities greater than 0.02 m/s. At a solids concentration of 30 wt% the gas holdup values are lower than those for a 20 wt% slurry; however, the holdups are still higher than those with no solids present. In the large diameter column, gas holdups increased

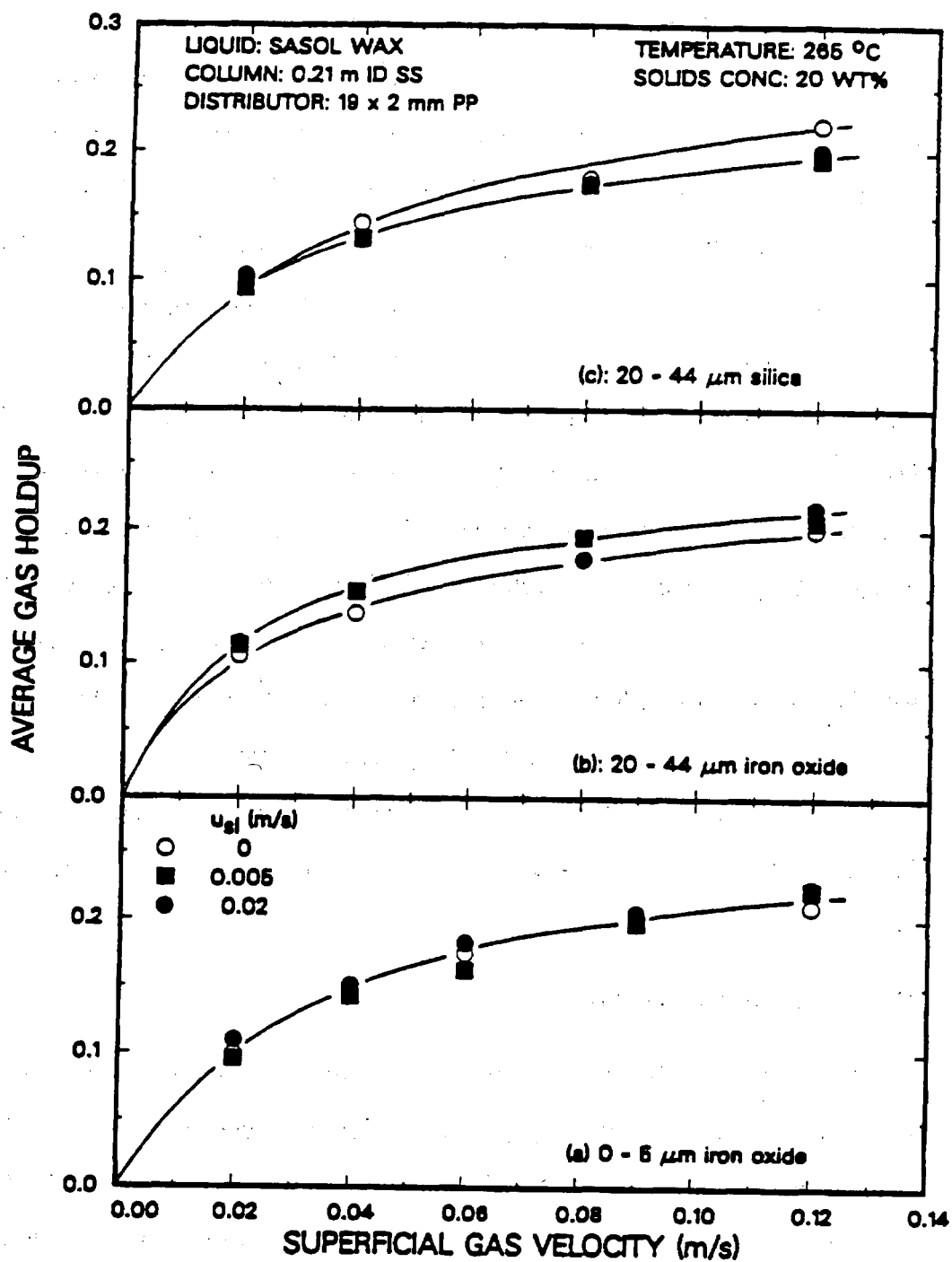


Figure 2.19. Effect of slurry velocity on average gas holdup in the large diameter column with SASOL wax ((a) 0 - 5 μm iron oxide, (b) 20 - 44 μm iron oxide, (c) 20 - 44 μm silica).

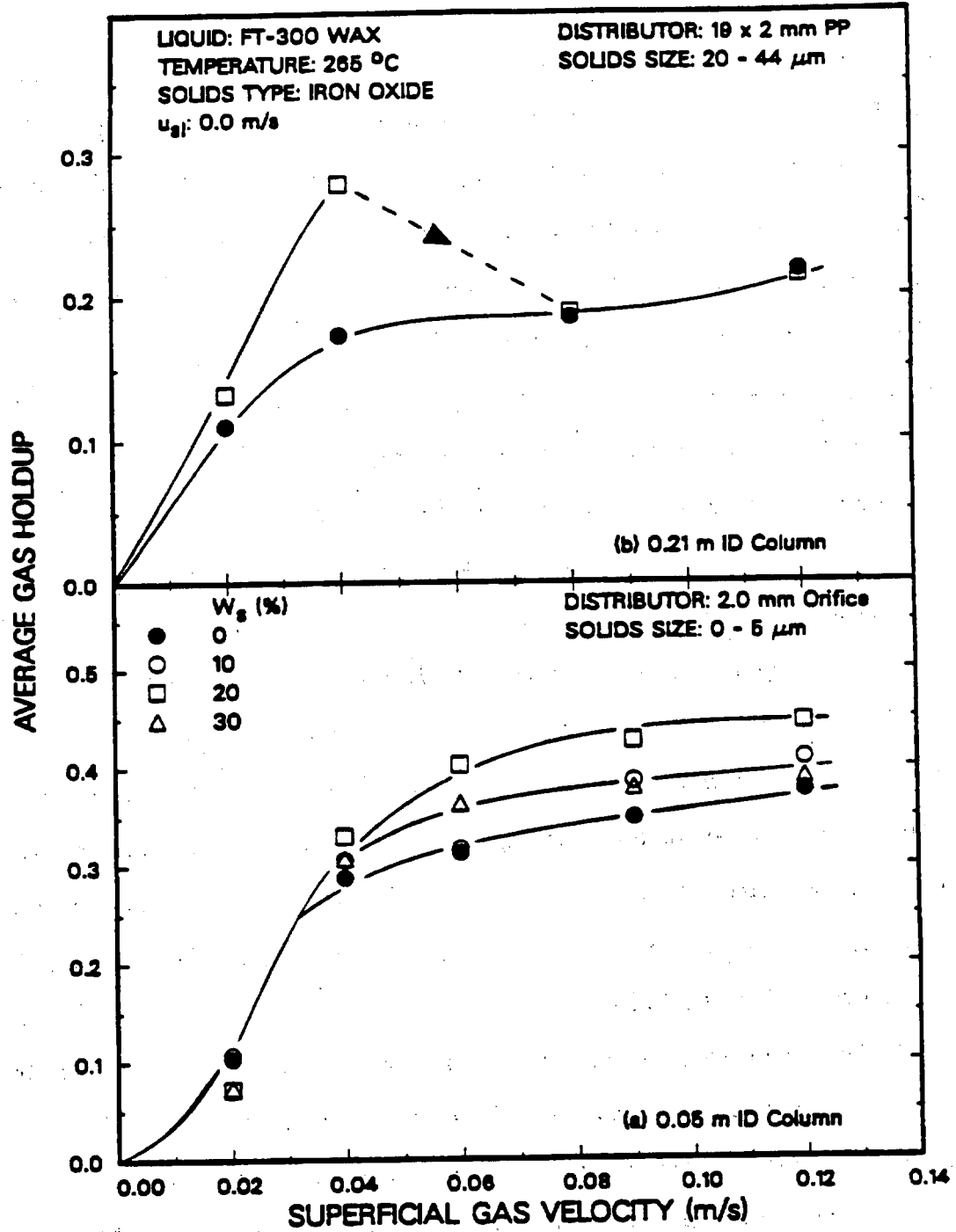


Figure 2.20. Effect of solids concentration on average gas holdup with FT-300 wax
 ((a) 0.05 m ID Column, 20 WT%, 0 - 5 μm iron oxide; (b) 0.21 m ID Column,
 20 WT%, 20-44 μm iron oxide).

at gas velocities of 0.02 and 0.04 m/s with the addition of solids, but at gas velocities of 0.08 and 0.12 m/s, there was no effect of solids concentration on gas holdup.

Figure 2.21 shows axial gas holdup profiles at gas velocities of 0.02, 0.04, and 0.12 m/s for the four experiments conducted in the batch mode of operation with 0 – 5 μm iron oxide particles in the small diameter column. At a gas velocity of 0.02 m/s (Figure 2.21a), there was no consistent effect of solids concentration. However, at gas velocities of 0.04 and 0.12 m/s (Figures 2.21b and 2.21c, respectively), a definite trend exists in the uppermost sections of the column (i.e. above a height of 1.5 m above the distributor). The holdup in the presence of solids is consistently higher than that in the absence of solids. Also, the holdup increases with increasing concentration of solids up to a concentration of 20 wt %. Upon increasing the concentration of solids further (i.e. to 30 wt%), the holdup in the uppermost section of the column decreases.

Experiments were also conducted in the batch mode of operation with 20 wt% slurries of 20 – 44 μm iron oxide particles and 0 – 5 μm silica particles in the small diameter column. Average gas holdups from these experiments together with the experiment conducted without solids is shown in Figure 2.22. Once again, the gas holdup increased with the addition of both large iron oxide particles (Figure 2.22a) and small silica particles (Figure 2.22b).

As described below, the opposite trends were reported in the literature for the effect of solids concentration on gas holdup. In some studies, it was observed that gas holdup decreases with the addition of solids. This decrease in gas holdup was usually attributed to an increase in the slurry viscosity. Other investigators have found that when relatively small particles or low density particles are used, the addition of solids may cause the gas holdup to increase. In general, it was claimed that the increase in gas holdup is due to poor wettability of the solids.

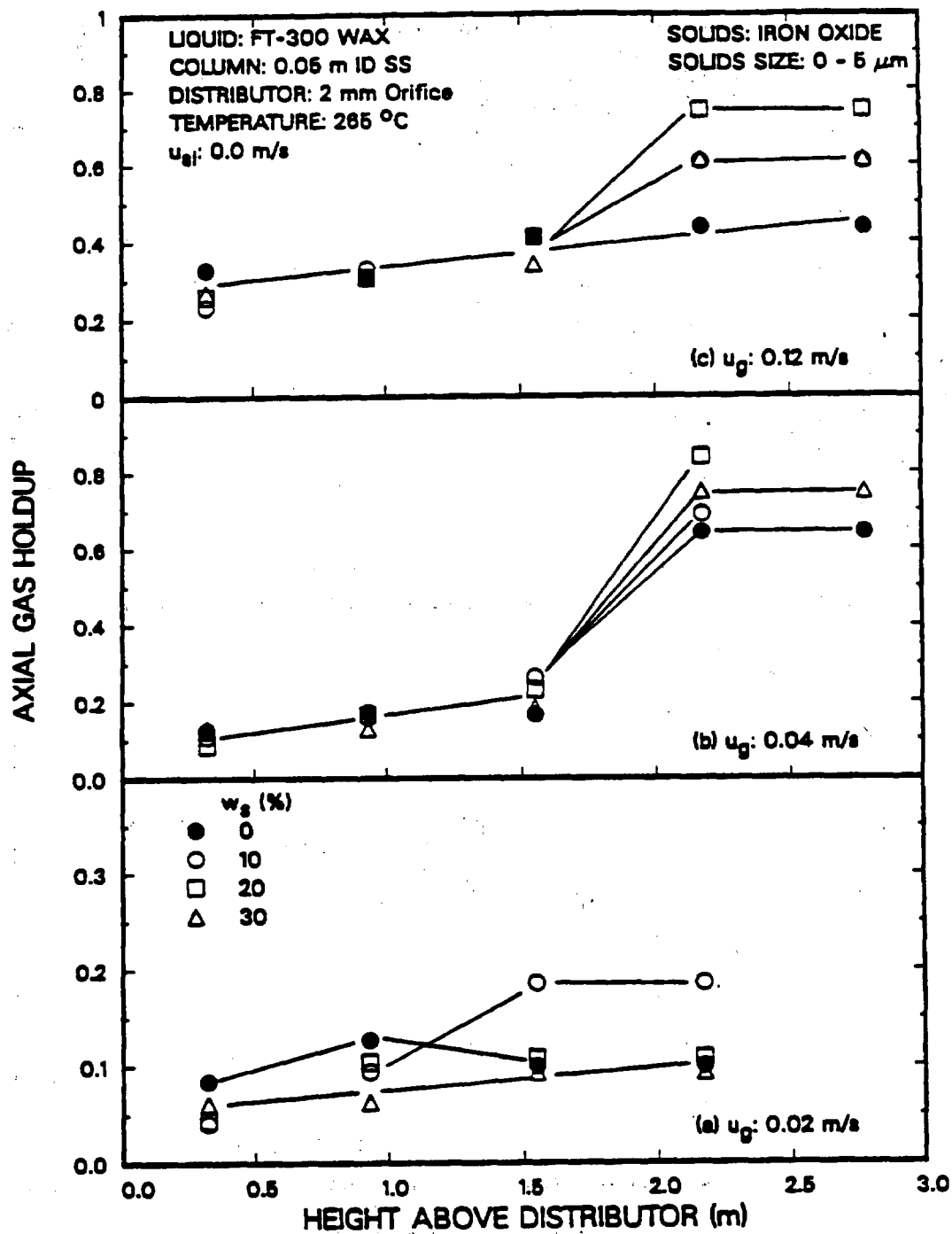


Figure 2.21. Effect of solids concentration and superficial gas velocity on axial gas holdup in the 0.06 m ID column with FT-300 wax (0 - 5 μm iron oxide particles; (a) $u_g = 0.02$ m/s; (b) $u_g = 0.04$ m/s; (c) $u_g = 0.12$ m/s).

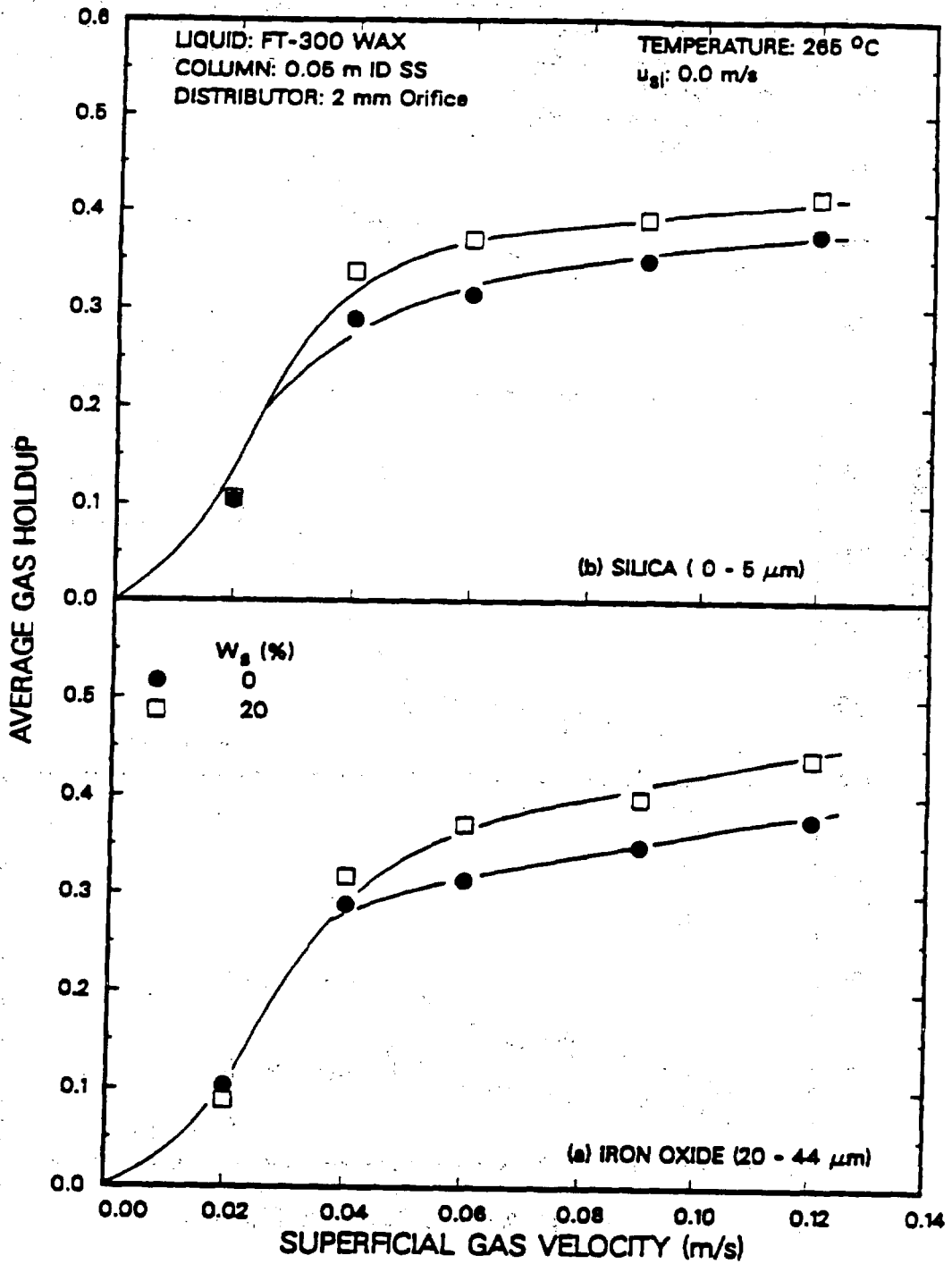


Figure 2.22. Effect of solids concentration on average gas holdup in the 0.05 m ID column with FT-300 wax ((a) 20 - 44 μ m iron oxide; (b) 0 - 5 μ m silica)

Deckwer et al. (1980) studied the effect of solids concentration (up to 16 wt%) in a paraffin wax/ Al_2O_3 / nitrogen system. The solids were 0 – 5 μm in diameter. Their results, limited to low gas flow rates ($u_g < 0.04$ m/s), showed that the addition of solids reduces gas holdup slightly ($\Delta\epsilon_g = 0.01$ to 0.02). However, they did not observe any specific trend in terms of the effect of solids concentration in the range 5.5 to 16 wt% on gas holdup. Ying et al. (1980) and Kato et al. (1972) also reported a decrease in gas holdup with increasing solids concentration. Kara et al. (1982) used various coal/water slurries with coal particles ranging from 10 to 70 μm in diameter, and solids loadings up to 44 wt%. In general, they observed a decrease in gas holdup with increasing solids concentration. However, with 10 μm particles, they observed a slight increase in gas holdup values relative to experiments conducted without solids. They postulated that the observed increase in gas holdup might be due to poor wettability. Results obtained from several other investigators show that the addition of solids increases gas holdup. Sada et al. (1986) examined the effect of fine particles (Al_2O_3 and CaCO_3) in both an electrolyte solution and in distilled water. Solids concentrations up to 1 wt% were used. Results from their study indicate that gas holdup decreases with the addition of solid particles ($d_p > 50$ μm). However, for particles less than 10 μm in diameter, in low concentrations, the gas holdup increases. They attributed this increase in gas holdup to the bubble coalescence hindering action of fine solids dispersed in the liquid film around the bubbles. They also observed, that the increase in gas holdup was more pronounced for systems which produce very fine bubbles. The effect of solids concentration and type was also studied by Sauer and Hempel (1987). They observed an increase in gas holdup with increasing solids concentrations (up to 13 wt%) for particles with densities less than 1300 kg/m^3 and superficial gas velocities in the range 0.01 to 0.04 m/s. They explained their results by using the qualitative model of Rabiger (1985). According to Rabiger, there exists an optimum ratio between the particle diameter

and microscale of turbulence which depends on density, particle shape and structure of liquid turbulence. Upon reaching the optimum ratio, the turbulence associated with the three-phase system is greater than that with the two-phase system, and as a result, smaller bubbles are produced and this gives rise to higher gas holdups. This increase in turbulence is only possible up to certain values of gas holdups and solids concentrations because the distances between bubbles and particles become very small in the swarm. Thus, on exceeding certain values, the turbulence subsides, resulting in larger bubbles and consequently lower holdups.

The increase in gas holdup with the addition of solids which we observed during experiments conducted in the batch mode of operation with FT-300 wax may be attributed to poor solids wettability in the region of high gas holdup (i.e. at heights greater than 1.5 m above the distributor). Bhatia et al. (1972) have shown that non-wettable particles cause an increase in bed expansion in a three-phase fluidized bed. They attributed the increase in bed expansion to solid particles adhering to the surface of the large fast rising gas bubbles and being carried upward through the column. In our case, we have relatively high density particles ($\rho_s = 2650$ and 5100 kg/m^3) and very small, slow rising gas bubbles (see Chapter V). Thus, when particles adhere to the surface of these small bubbles, they not only reduce coalescence, but they also reduce the effective rise velocity of the gas bubble, which results in a longer residence time. This in turn causes an increase in the gas holdup. In the lower portion of the column (i.e. below the foam layer), gas holdups are substantially lower than they are in upper portion of the column (see Figure 2.21). Figure 2.23 shows average gas holdups, excluding foam (i.e. neglecting axial gas holdups at heights of 2.2 and 2.8 m above the distributor when calculating the average gas holdup), for experiments conducted with small iron oxide particles in the 0.05 m ID column. As can be seen, there is a slight decrease in gas holdup with increasing solids concentration when the foam is neglected.

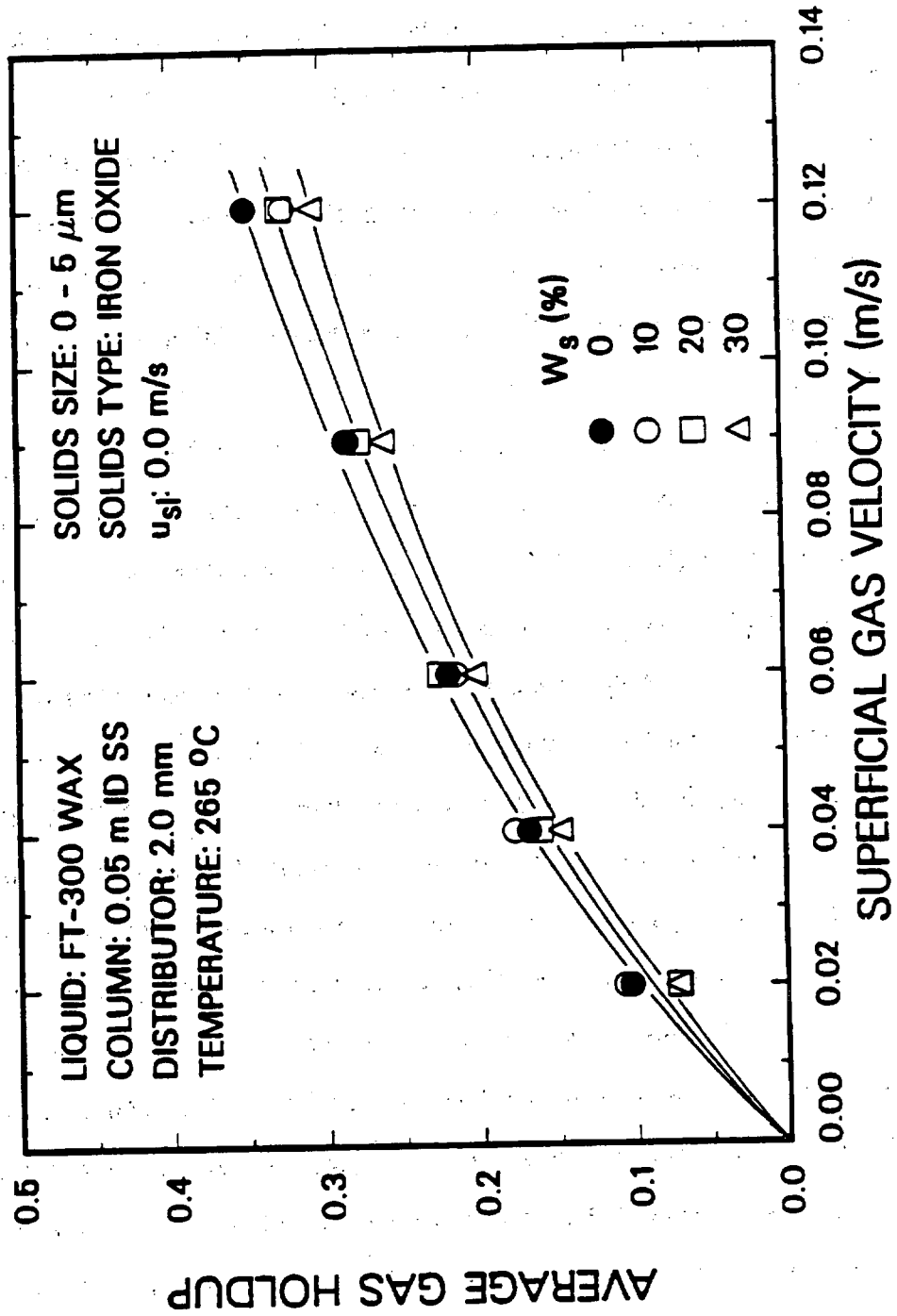


Figure 2.23. Effect of solids concentration on average gas holdup neglecting foam (0 - 5 μm iron oxide).

This decrease in gas holdup with increasing solids concentration may be attributed to an increase in the apparent viscosity of the slurry. It has been shown that an increase in slurry viscosity produces larger bubbles which in turn reduces the gas holdup (Bukur et al., 1987a). Thus, the variation in the effect of solids concentration on gas holdup may be due to: (1) poor wettability of solids, and (2) an increase in the slurry viscosity with the addition of solids. The former causes the gas holdup to increase, while the latter causes the gas holdup to decrease. These competing phenomena might be responsible for the maximum in gas holdup observed with the 20 wt% slurry of small iron oxide particles.

Some experiments were also conducted with FT-300 wax in the continuous mode of operation to determine the effect of solids concentration on average gas holdup. Figures 2.24a and 2.24b show results from experiments conducted with iron oxide particles (0 - 5 μm) in the small diameter column using slurry velocities of 0.005 and 0.02 m/s, respectively. The average gas holdup decreased with increasing solids concentration for experiments conducted in the continuous mode of operation. Thus, it appears that a small upward liquid flow is sufficient to disperse the fine bubbles at the top of the dispersion, and as a result, the adhesion of the solid particles to the liquid film of the bubbles comprising the foam no longer has a significant effect on the gas holdup. The decrease in gas holdup is due solely to the increase in slurry viscosity associated with the addition of solids. Similar results were observed for experiments with small silica particles in the 0.05 m ID column and with large iron oxide particles in the 0.21 m ID column at a slurry velocity of 0.005 m/s (see Figures 2.25a and 2.25b, respectively).

Gas holdups from batch experiments with SASOL reactor wax in the 0.05 m ID column with 20 - 44 μm iron oxide particles and in the 0.21 m ID column with both 20 - 44 and 0 - 5 μm iron oxide particles are shown in Figure 2.26. The trends were qualitatively similar to those observed in experiments with FT-300 wax in the presence

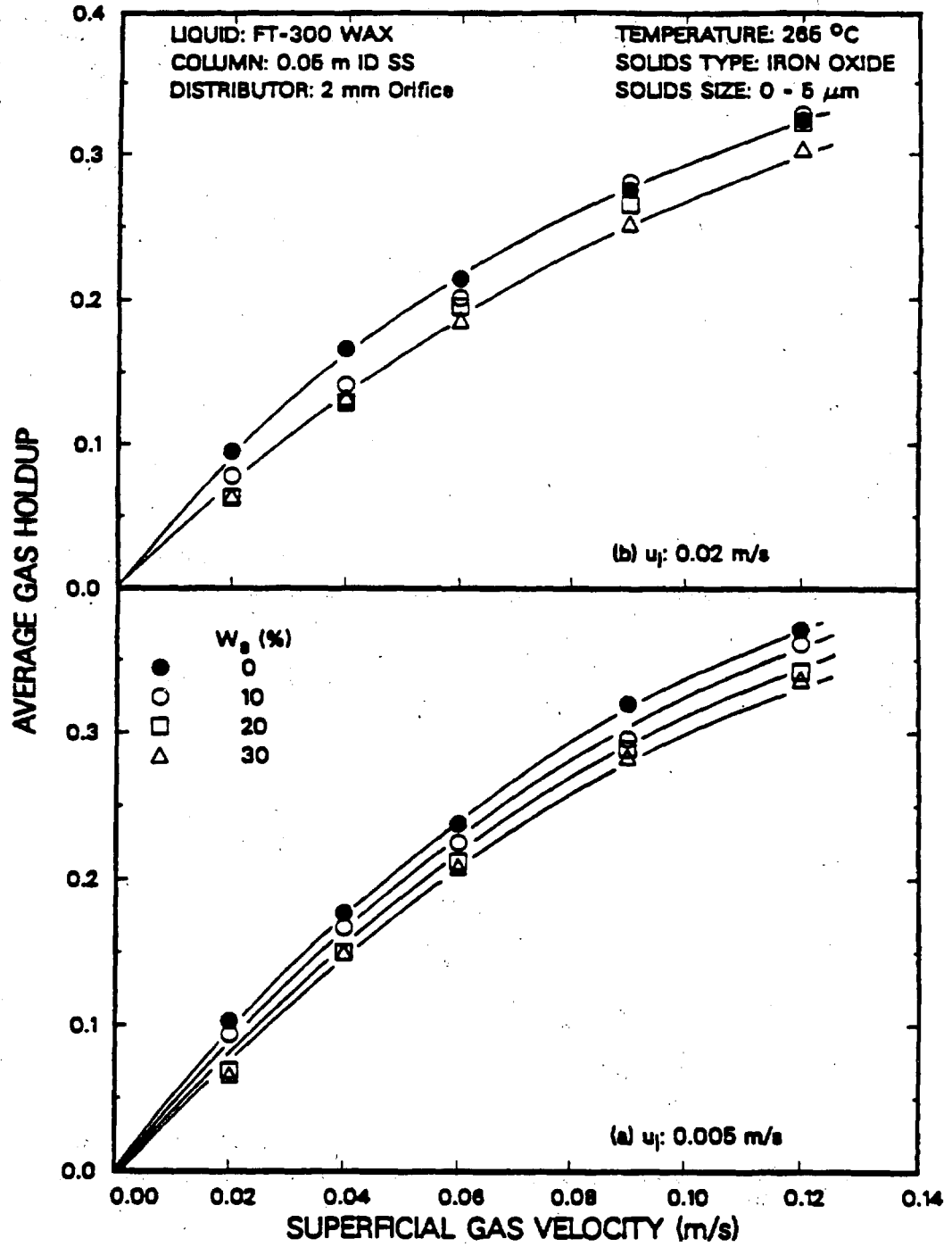


Figure 2.24. Effect of solids concentration on average gas holdup in the continuous mode of operation with FT-300 wax (0 - 5 μm iron oxide; (a) $u_{g1} = 0.005$ m/s; (b) $u_{g1} = 0.02$ m/s).

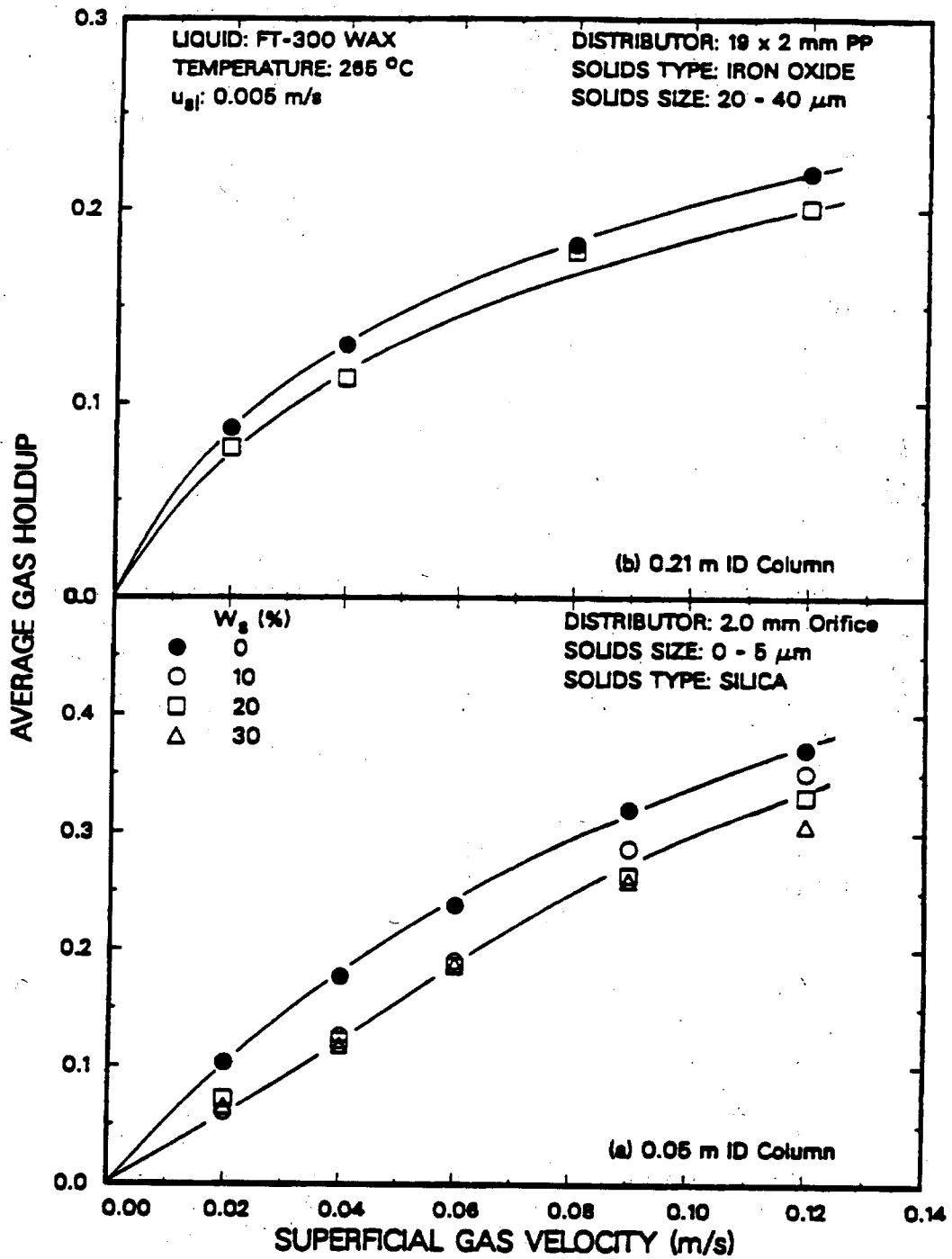


Figure 2.25. Effect of solids concentration on average gas holdup with FT-300 wax ((a) 0.05 m ID column, 0 - 5 μm silica; (b) 0.21 m ID column, 20 - 44 μm iron oxide).

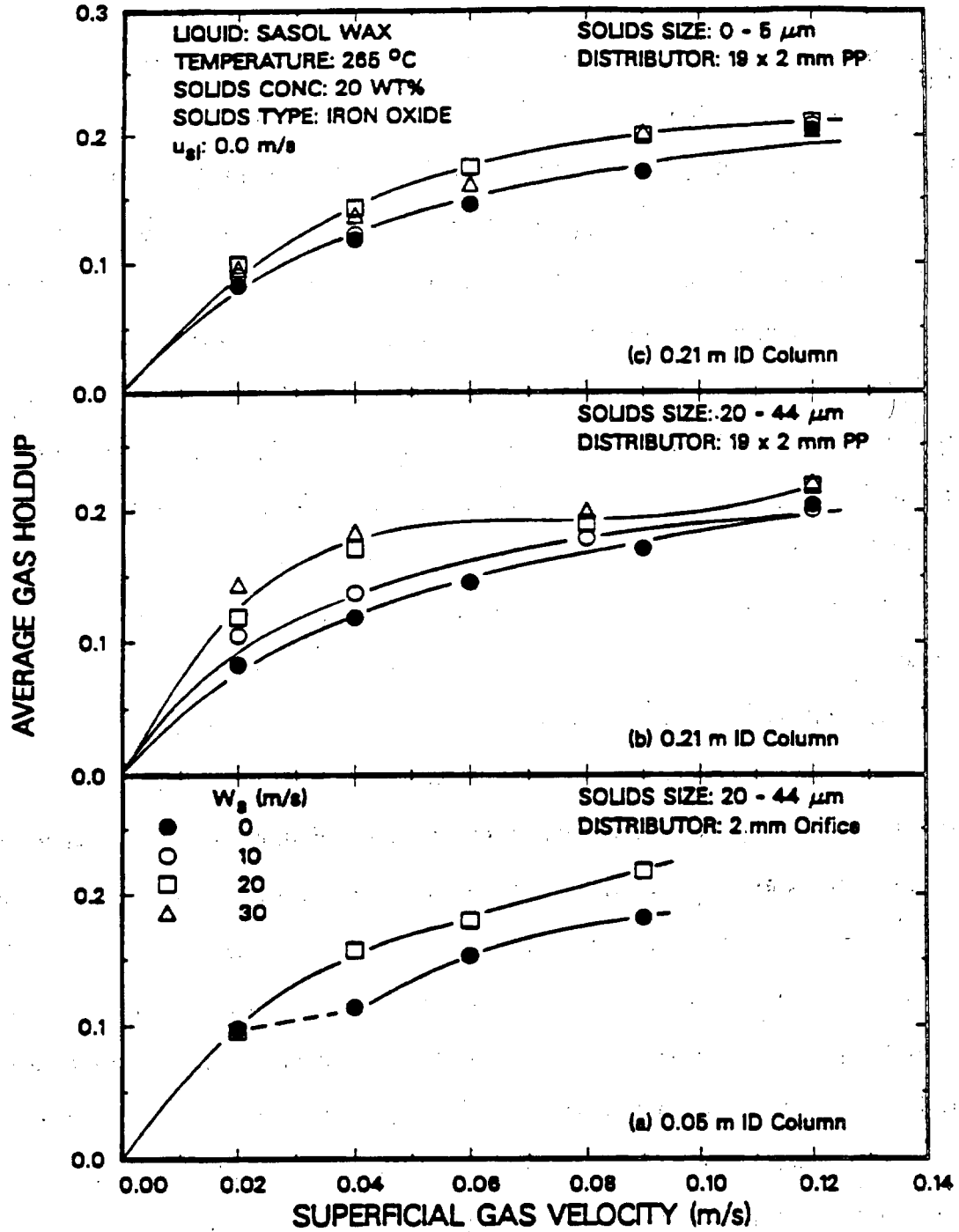


Figure 2.26. Effect of solids concentration on average gas holdup with SASOL wax ((a) 0.05 m ID column, 20 - 44 μm iron oxide, (b) 0.21 m ID column, 20 - 44 μm iron oxide, (c) 0.21 m ID column, 0 - 5 μm iron oxide).

of solids (i.e. the addition of solids caused an increase in gas holdup). These results were somewhat surprising since SASOL wax does not produce foam. Since we observed a decrease in gas holdup with the addition of solids in the absence of foam with FT-300 wax (see Figures 2.23 and 2.24), we expected gas holdups with SASOL reactor wax to decrease with increasing solids concentration. However, the solids used in this study may be less wettable in SASOL wax as compared to FT-300 wax, and as a result the holdups increased. One indication of this is the fact that the holdup in the uppermost section of the small diameter column increased by 50 to 70 % (relative) with the addition of large iron oxide particles for the experiment with SASOL wax, but increased only by 30 to 50 % (relative) for the experiment conducted with FT-300 wax.

Experiments were also conducted with SASOL wax in the continuous mode of operation. The addition of solids increased the gas holdup for experiments in both the small and large diameter columns. Figure 2.27a shows results from experiments conducted with small iron oxide particles in the 0.05 m ID column. Results from experiments conducted with various concentrations of large iron oxide particles and various concentrations of small iron oxide particles are shown in Figures 2.27b and 2.27c respectively. Gas holdups increased with increasing solids concentration. Holdup values from experiments in the large diameter column approached the same value at superficial gas velocities greater than 0.08 m/s. A similar trend was observed during batch experiments in the large diameter column (see Figures 2.26b and 2.26c).

Similar results were observed for experiments conducted with silica particles in the large diameter column; however, the increase in gas holdup with increasing solids concentration was less pronounced. The convergence of gas holdup values at high gas velocities for various slurry concentrations in the large diameter column is due to an increase in turbulence. Turbulence is greater in the large diameter column than the small diameter column (i.e. the flow patterns present in the large diameter column are

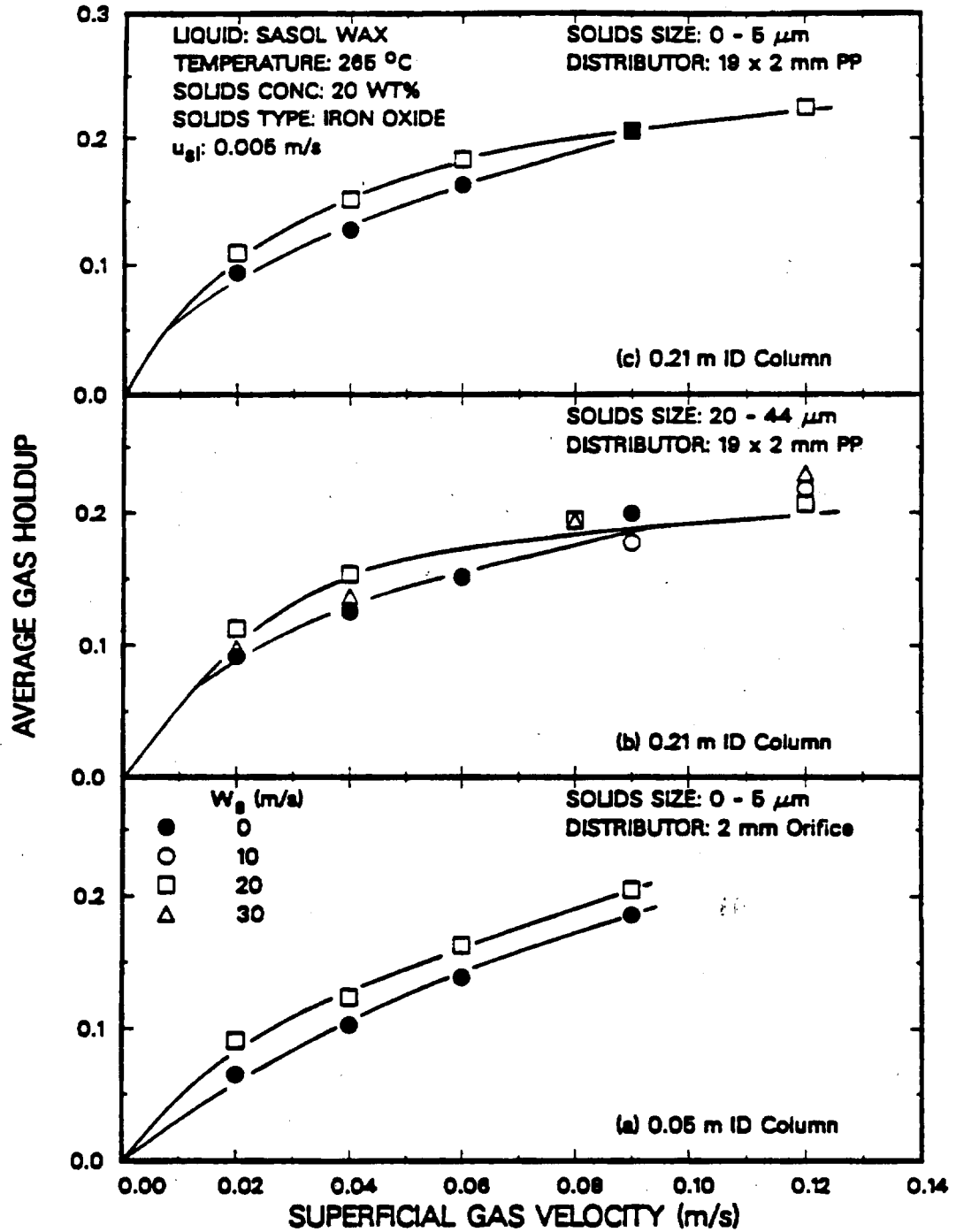


Figure 2.27. Effect of solids concentration on average gas holdup with SASOL wax in the continuous mode of operation ((a) 0.05 m ID column, 20 - 44 μm iron oxide, (b) 0.21 m ID column, 20 - 44 μm iron oxide, (c) 0.21 m ID column, 0 - 5 μm iron oxide).

much more chaotic). Therefore, at high superficial gas velocities, any particles which may adhere to the surface of gas bubbles are likely to be stripped away, and as a result, gas holdups in the presence of solids become similar to those in the absence of solids.

Thus, the addition of solids increases gas holdup for experiments conducted in the batch mode of operation with both FT-300 and SASOL reactor wax. However, in the continuous mode of operation, addition of solids to FT-300 wax causes a slight decrease in the gas holdup; whereas, addition of solids to SASOL wax causes a slight increase in the gas holdup. The differences in the behavior of the two waxes might be due to differences in the wettability of the particles with respect to each wax type.

Effect of Solids Type and Size

The effect of solids type and size for batch experiments with FT-300 wax in the small diameter column are shown in Figure 2.28. The highest holdups were obtained in experiments with small iron oxide particles. Gas holdups from experiments with large iron oxide particles and small silica particles were similar. An increase in gas holdup with increasing particle size has been observed in some earlier studies (Kim et al., 1977, Shah et al., 1982). A possible explanation for this is that the particles are breaking up the bubbles as they rise through the column, thus producing smaller bubbles and consequently higher gas holdups. Kim et al. showed that when solids have sufficient kinetic energy, they can cause bubble breakage which results in an increase in gas holdup. Using a balance between the surface tension forces of the bubble, and the force exerted by the particle, their proposed criterion for bubble breakage is:

$$We = \frac{\rho_p u_f^2 d_p}{\sigma_l} > 3 \quad (2.28)$$

For the system in our study, the Weber number, We , has a maximum value of 1.5 and is obtained for large iron oxide particles suspended in FT-300 wax at $u_g=0.12$ m/s.

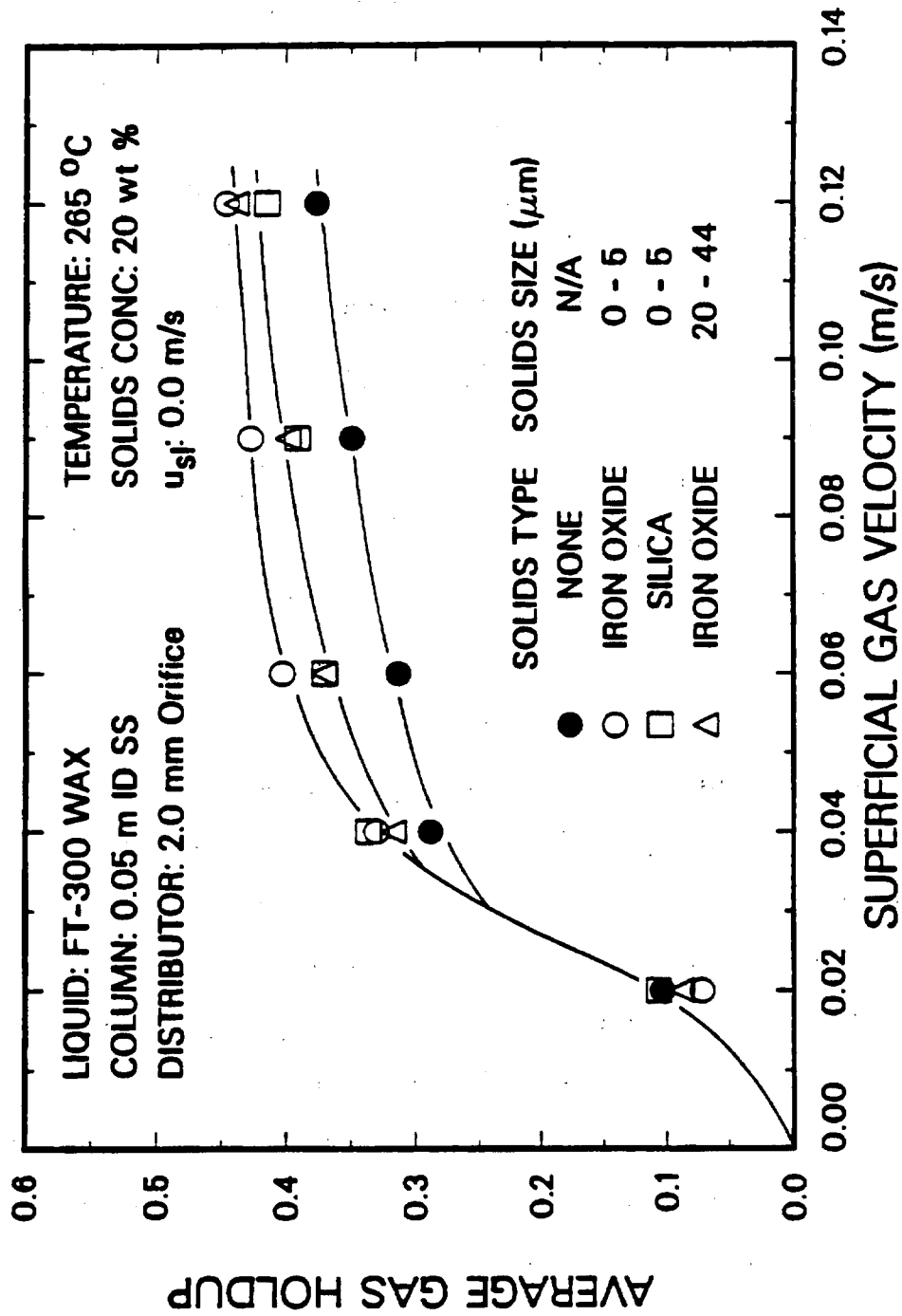


Figure 2.28. Effect of solids type and size on average gas holdup in the 0.05 m ID column with FT-300 wax.

Thus, we can assume that with our particles, no bubble breakage is occurring due to the presence of solids.

One possible explanation for the decrease in gas holdup with increasing particle size that was observed, might be due to the non-uniformity in the axial solids distribution of large particles. For the experiment conducted with small iron oxide particles, the solids concentration remains axially uniform (≈ 20 wt%); however, in experiments with large iron oxide particles, the solids concentration at the bottom of the column ranged from 30 to 35 wt% (see the Figure on page 208). This increase in solids concentration at the bottom of the column results in a higher apparent slurry viscosity near the orifice plate. As a result, larger bubbles may be formed in the region near the distributor which results in lower gas holdups.

Figure 2.29 shows results for experiments conducted in the batch mode of operation with 30 wt % small iron oxide, 20 wt% small silica, and 20 wt% large iron oxide slurries. The gas holdups from all three runs are similar. All three experiments had similar volume concentrations of solids near the distributor (i.e. ≈ 0.045). These results indicate that the volume concentration of solids near the distributor may be important in determining the gas holdup. Similar results were observed for experiments conducted in the continuous mode of operation with small iron oxide and silica particles.

The effect of solids type and size for experiments with 20 wt% slurries (SASOL wax) in the large diameter column is shown in Figures 2.30a and 2.30b for experiments conducted in the batch and continuous modes of operation, respectively. Gas holdups were similar for batch experiments with small iron oxide particles and large iron oxide and silica particles. In the continuous mode of operation, there is no discernible effect of either solids type or size on gas holdup.

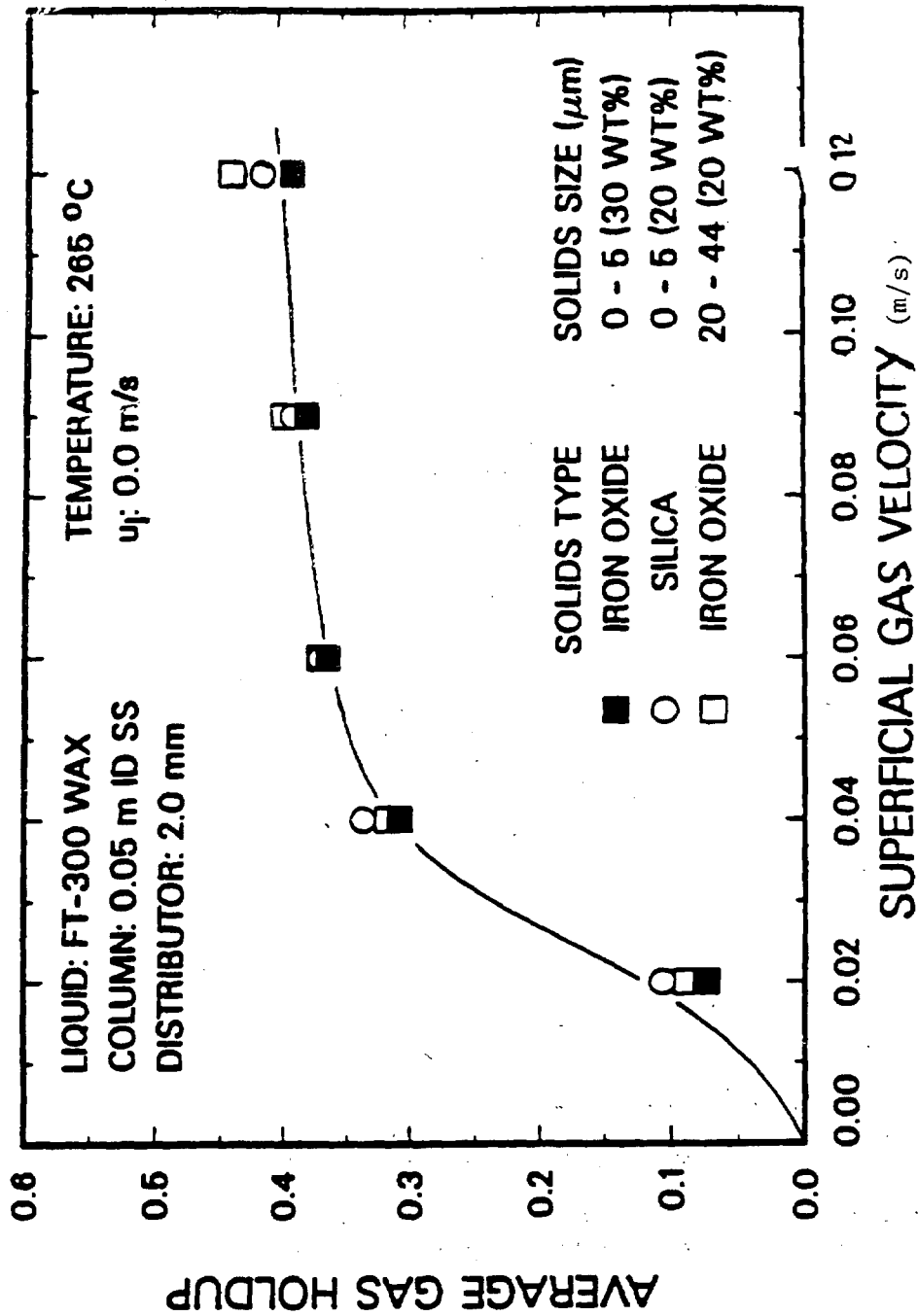


Fig. 2.29 Effect of solids type and size on average gas holdup in the 0.05 m ID column with FT-300 wax (volume fraction of solids at the distributor = 0.045).

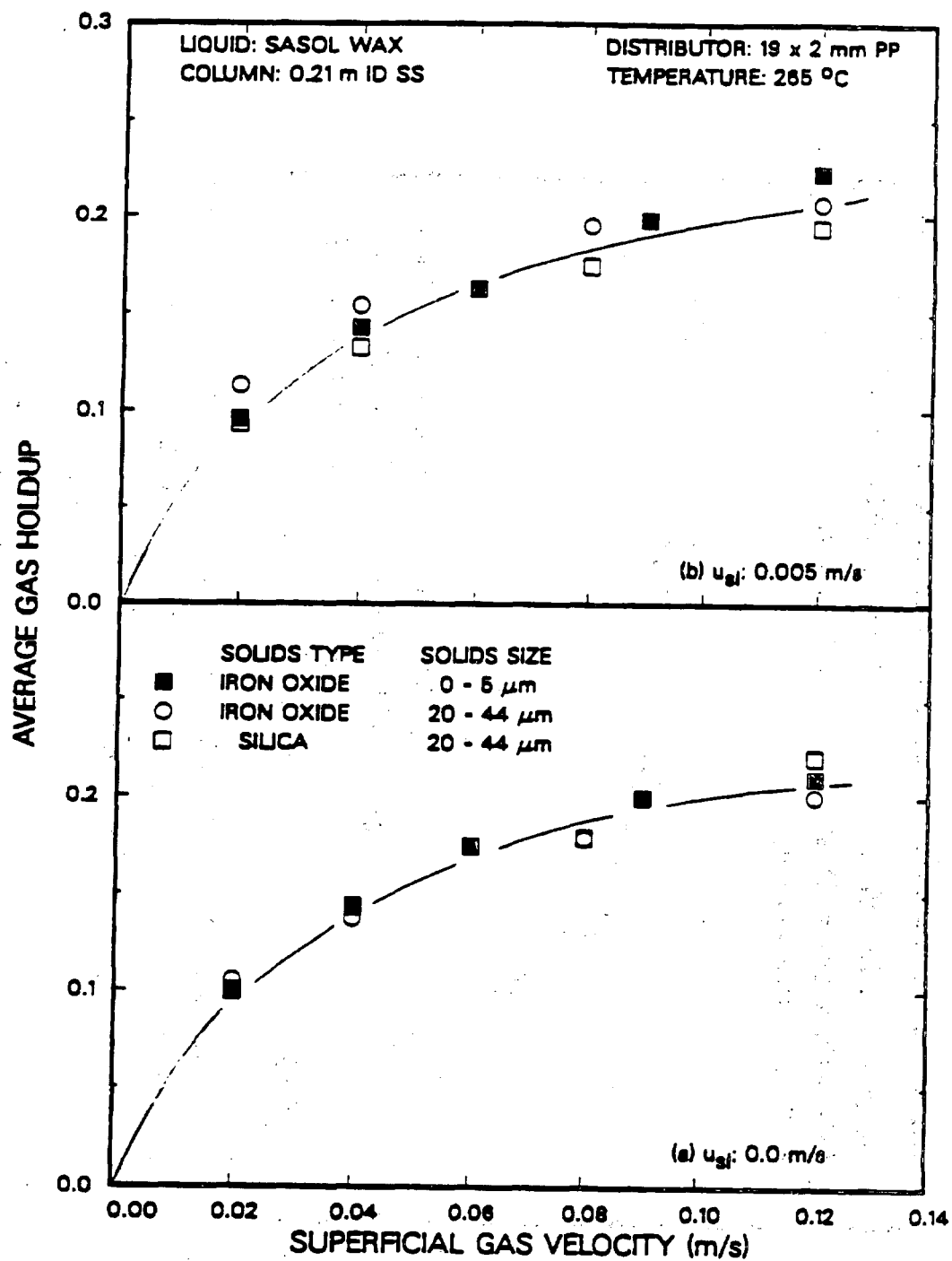


Figure 2.30. Effect of solids type and size on average gas holdup in the 0.21 m ID column with SASOL wax ((a) $u_{gj} = 0.0 \text{ m/s}$; (b) $u_{gj} = 0.005 \text{ m/s}$).