Based on average bubble dimensions (Fig. 5) taken at 75 cm from the bottom of the bed at a gas velocity of 177 cm/s, the gas-liquid interfacial area a was calculated as a function of superficial gas velocity as:

$$a = N\hat{A}/V_{exp} \tag{21}$$

where

N = total number of bubbles in column
$\hat{A}$ = average area per bubble
V_{exp} = total column volume

and

$$N = \frac{V_{exp}\ \varepsilon_g}{\hat{V}} \tag{22}$$

where

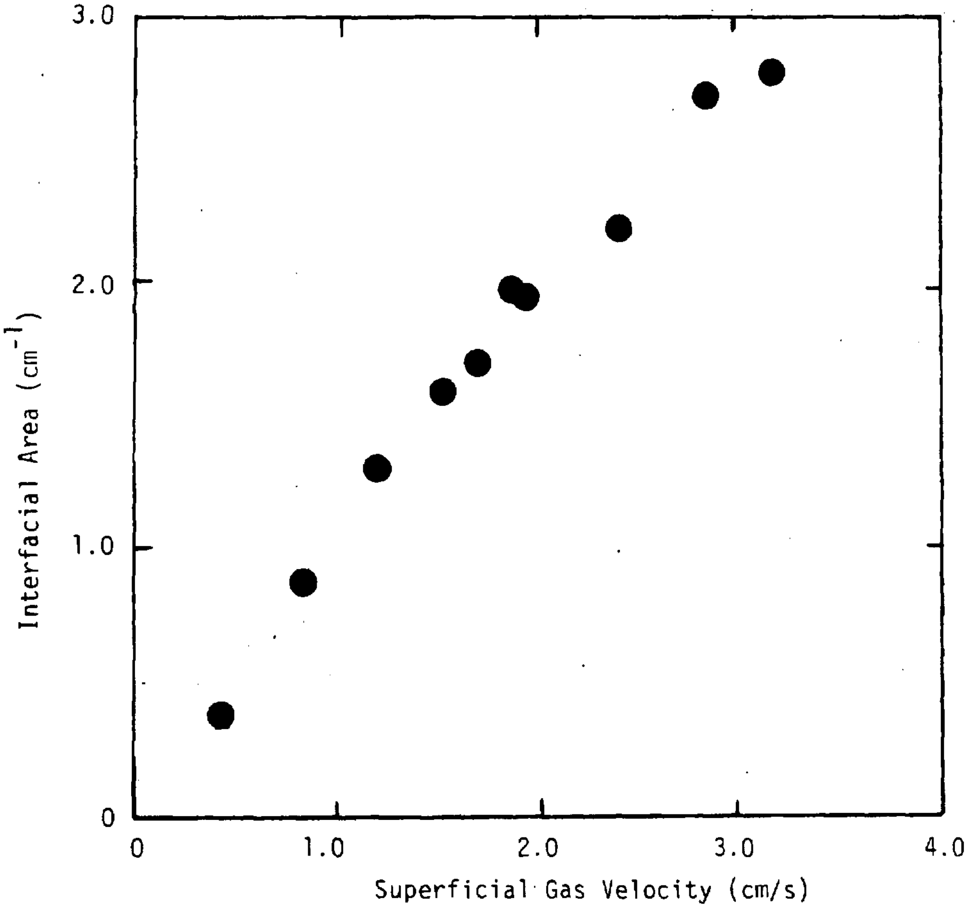
$\hat{V}$ = average volume per bubble.

A plot of gas-liquid interfacial area as a function of superficial gas velocity without solids is shown in Fig. 6. The expression:

$$a = 1.003\ U_g^{0.977} \tag{23}$$

was fitted to the data for no solids with a correlation coefficient of 0.993.

The extent of sedimentation of catalyst in the BCSR was determined from experiments in which slurry samples were taken from ports in the side of the reactor. The volume fraction of catalyst calculated for two axial positions and three superficial velocities are summarized in Table 5. The uniform catalyst concentration profile is in agreement with the findings of Dyer et al. (12). In their study, performed with nitrogen sparged through 45-to-53-μm iron oxide particles suspended in a liquid carrier of isoparaffin, a uniform catalyst concentration profile was observed through the column for a similar range of gas velocities.



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SPECIFIC GAS-LIQUID INTERFACIAL AREA IN THE ABSENCE OF SOLIDS (20-μm FRIT)

DATE	DRAWN BY	FILE NO.	FIG.
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Table 5. Catalyst sedimentation in the BCSR

U_g (cm/s)	Catalyst (volume %)	
	21.6 cm above frit	50.8 cm above frit
0.49	8.6	8.3
0.95	8.2	8.0
1.3	4.8	4.8

The reason for the lower volume fraction of catalyst at a superficial gas velocity of 1.3 cm/s cannot be adequately explained without further study. The rise velocity of a swarm of nitrogen bubbles in n-hexane was calculated from seven experiments to be 13.0 ± 0.22 cm/s.

6. DISCUSSION OF RESULTS

6.1 Experimental Data

Figure 3 shows the observed increase in gas holdup with gas velocity for the 20-μm frit with no suspended solids. The dependence on gas velocity is roughly linear.

The plot of gas holdup as a function of superficial gas velocity with suspended sand (Fig. 4) exhibits a flattening at higher gas velocities; this behavior was not seen with solids absent. The slope begins to decrease at 1.4 cm/s, close to the region where a transition in flow regime (1.5 to 1.75 cm/s) was observed.

Small particles reportedly can cause bubble coalescence. Larger coalesced bubbles decrease gas holdup [Eq. (21)] (20).

The predominant flow regime seen in mockup experiments without solids was homogeneous bubbly flow and some swirling-bubbly flow, characterized by a helical bubble path above about U_g = 1.8 cm/s. No slugging or churn-turbulence was seen. The smooth gas holdup over the range of superficial gas velocities studied (Fig. 3) is further evidence of uniform flow regimes.

With sand present at 13 wt % with a 25- to 45-μm particle-size distribution, a transition to larger bubbles with more irregular flow was observed at a gas velocity of about 1.5 to 1.75 cm/s. This change in flow regime is evidenced by the marked change in slope for the curve of Fig. 4. This transition in observed flow regimes has implications for BCSR modeling: (1) the interfacial area affects mass transfer from gas to liquid; and (2) the transition in flow regime indicates that holdup and interfacial area must be measured in the presence of solids.

Bubbles were photographed in mockup experiments in the absence of solids because the 25- to 45-μm particles darkened the slurry and made photographs impossible.

In Table 2, gas velocity had little effect on bubble size, as reported by Deckwer et al. (8). Bubble size increased with position up the columns from coalescence and interaction. The increase in bubble size, because of changing gas-distributor pore diameter from 20 to 100 μm (Table 4) caused a 50% increase in bubble volume and a 30% increase in bubble area.

6.2 Comparison with Literature Data

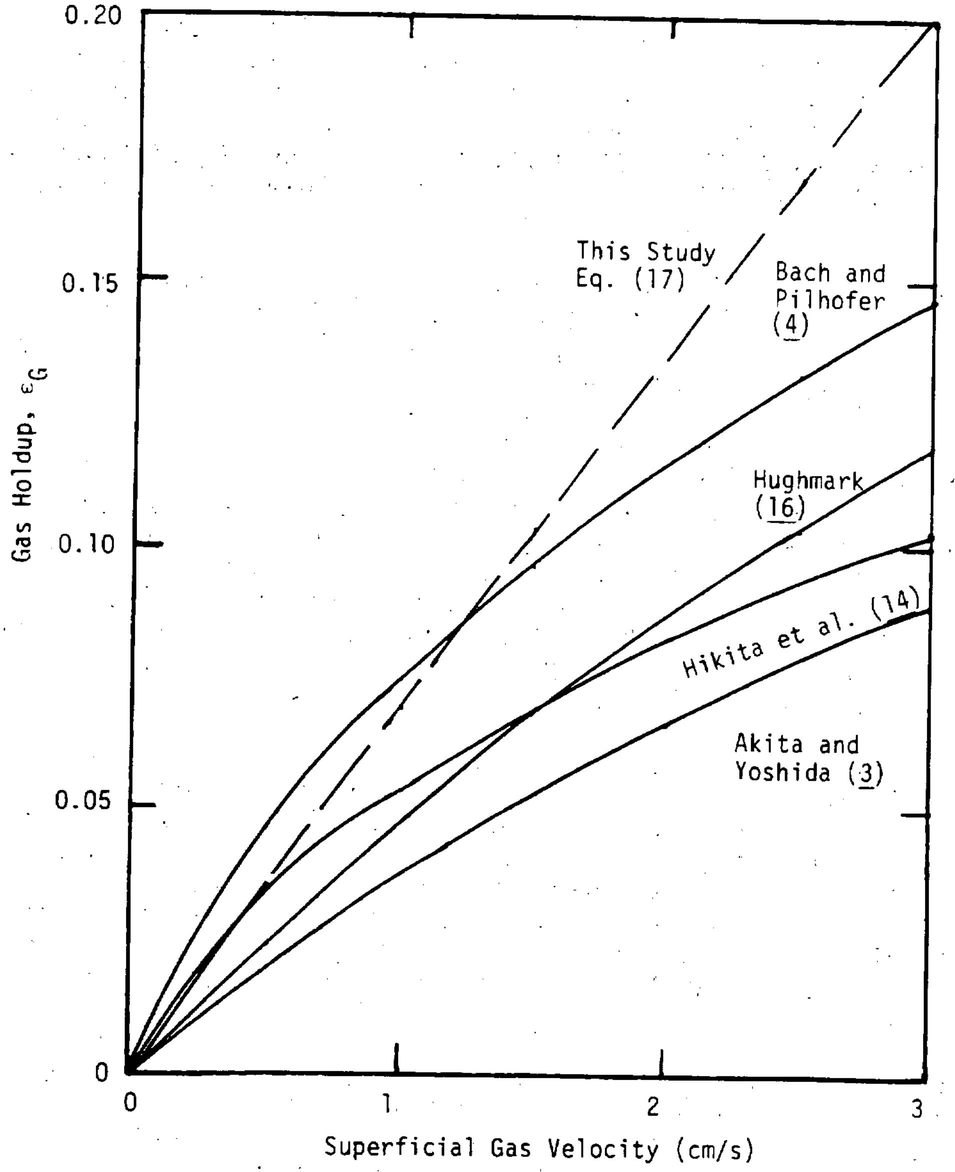
6.2.1 Gas Holdup

Gas holdup and bubble size were compared with literature correlations and values to determine their applicability to the system used in this study. All literature correlations used were based on a column diameter of 0.1 m or greater.

Our data for gas holdup with no solids were fit to a power-law expression of the form:

$$\varepsilon_g \propto U_g^{\,n} \tag{24}$$

Equation (23) is in agreement with Shah et al. (20), who report an n of 0.7 to 1.2 for bubbly flow. Empirical correlations for gas holdup in bubble-column reactors are given by several authors. The correlations of Hughmark (16), Akita and Yoshida (3), Hikita et al. (14), and Bach and Pilhofer (4) include a dependency on the surface tension, density, and viscosity of the liquid. For the properties of hexane, the gas holdup as a function of gas velocity was calculated for each correlation. Sample calculations are shown in Appendix 10.1. In Fig. 7 these predictions are compared with data from our study. For gas velocities less than 1.5 cm/s, gas holdup as predicted by Bach and Pilhofer (4) is within 6% of our data. For gas velocities greater than 1.5 cm/s, the Bach and Pilhofer correlation poorly predicts our experimental gas holdup; at 3 cm/s a 27% difference is seen. The correlations of Akita and Yoshida (3), Hughmark (16), and Hikita et al. (14) differ among themselves by only 25% at 3 cm/s, but all three fail to predict the experimental data for our study specific to the F-T synthesis. The rapid decline in the slope of the holdup curve at higher velocities for the



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GAS HOLDUP WITHOUT SOLIDS PRESENT

DATE	DRAWN BY	FILE NO.	FIG.
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Hikita et al. and the Bach and Pilhofer correlations can be explained because the exponential dependence n on gas velocity is lower (0.578 and 0.69, respectively) than in our correlation. A lower value of n qualitatively indicates a lower holdup at the same gas velocity.

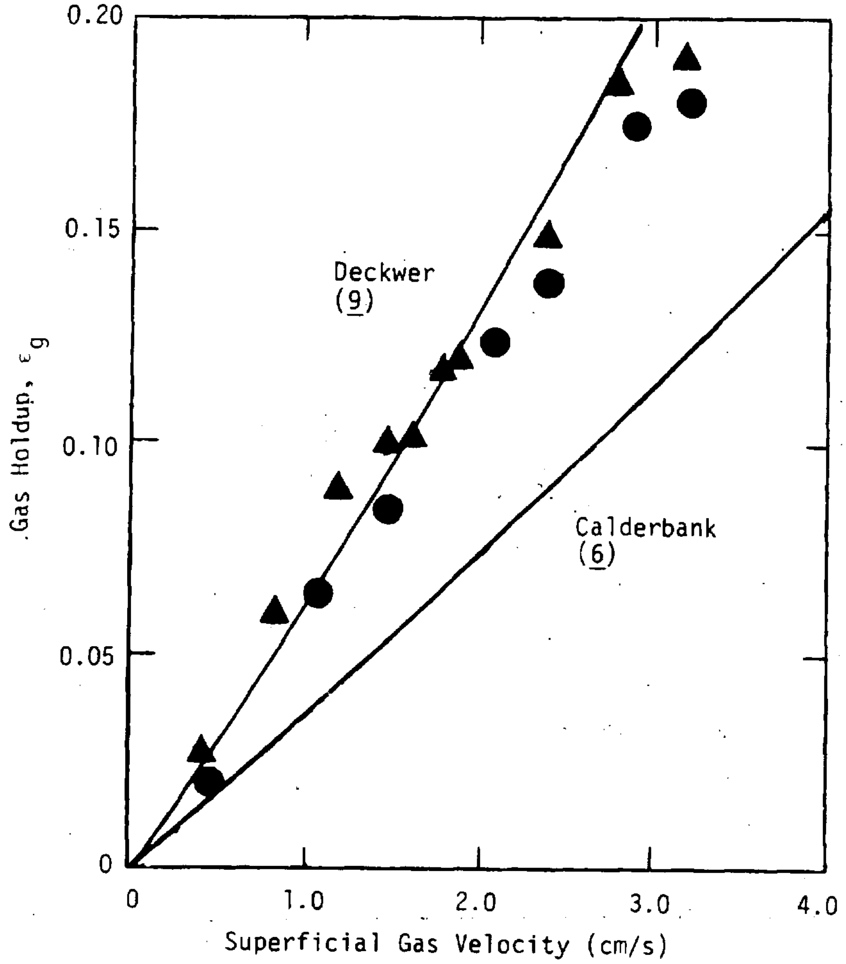
The discrepancy between literature data and our data can be partially explained by studying the ranges of parameters suggested for each correlation. The column diameter for our study was only 5.08 cm, which is smaller than the 10 cm recommended for all the general correlations. Also, rheological properties of the liquid (surface tension, viscosity, and density) are slightly lower than the recommended range for the literature correlations.

Deckwer et al. (9) and Calderbank et al. (6) studied the hydrodynamics of Fischer-Tropsch reactor at elevated temperatures for a paraffin with similar physical properties to the hexane (simulated n-octacosane) in our study. A comparison of our data with that of Deckwer et al. and Calderbank et al. is shown in Fig. 8. Calderbank et al. (6) reported that gas holdup was virtually linear with gas velocity; however, it was 40% lower than that measured in our study. Their work was done with a ball-and-cone sparger. Agreement between our data and the data of Deckwer et al. is very good, within 10% at all velocities; the data of Deckwer et al. was obtained with a 10-cm bubble column and a 75-μm frit. This suggests that liquid properties (surface tension, density, and viscosity) are the important factors for the inability of the correlations of Akita and Yoshida (2), Hughmark (16), and Hikita et al. (14) to accurately predict gas holdup in our system.

As shown in Fig. 9 the gas holdup with solids is nearly the same as that without solids for gas velocities below 1.4 cm/s. This observation was also made by Adlington and Thompson (1), who reported that the presence of solids had little effect on gas holdup below gas velocities of 1.5 cm/s. Above a gas superficial velocity of 1.5 cm/s, a transition of flow regime accompanies a coalescence of bubbles caused by the presence of solids. The result is that the gas holdup as a function of velocity decreases sharply. Similar results were reported by Imafuker et al. (17).

For gas holdup with solids present, empirical correlations from Kato et al. (18), Begovich and Watson (5), and Deckwer et al. (9) were compared with data from our study. In Fig. 10, a comparison of these three empirical correlations with our data is shown. The sharp decrease in slope at higher gas velocities was not predicted by any of the correlations. The Deckwer et al. correlation, the only correlation specific for a Fischer-Tropsch system, agreed well with our data up to a gas velocity of 1.5 cm/s. The correlation of Kato et al. agrees up to a gas velocity of about 1 cm/s.

The discrepancies may be caused by the different particle sizes used to develop the correlations. Deckwer et al. (9) used a particle with an average size less than 5 μ. Because of the small particle



Data From Our Work

▲ 20-μm Frit

● 100-μm Frit

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COMPARISON WITH CORRELATIONS FOR GAS HOLDUP WITHOUT SOLIDS PRESENT

DATE	DRAWN BY	FILE NO.	FIG.
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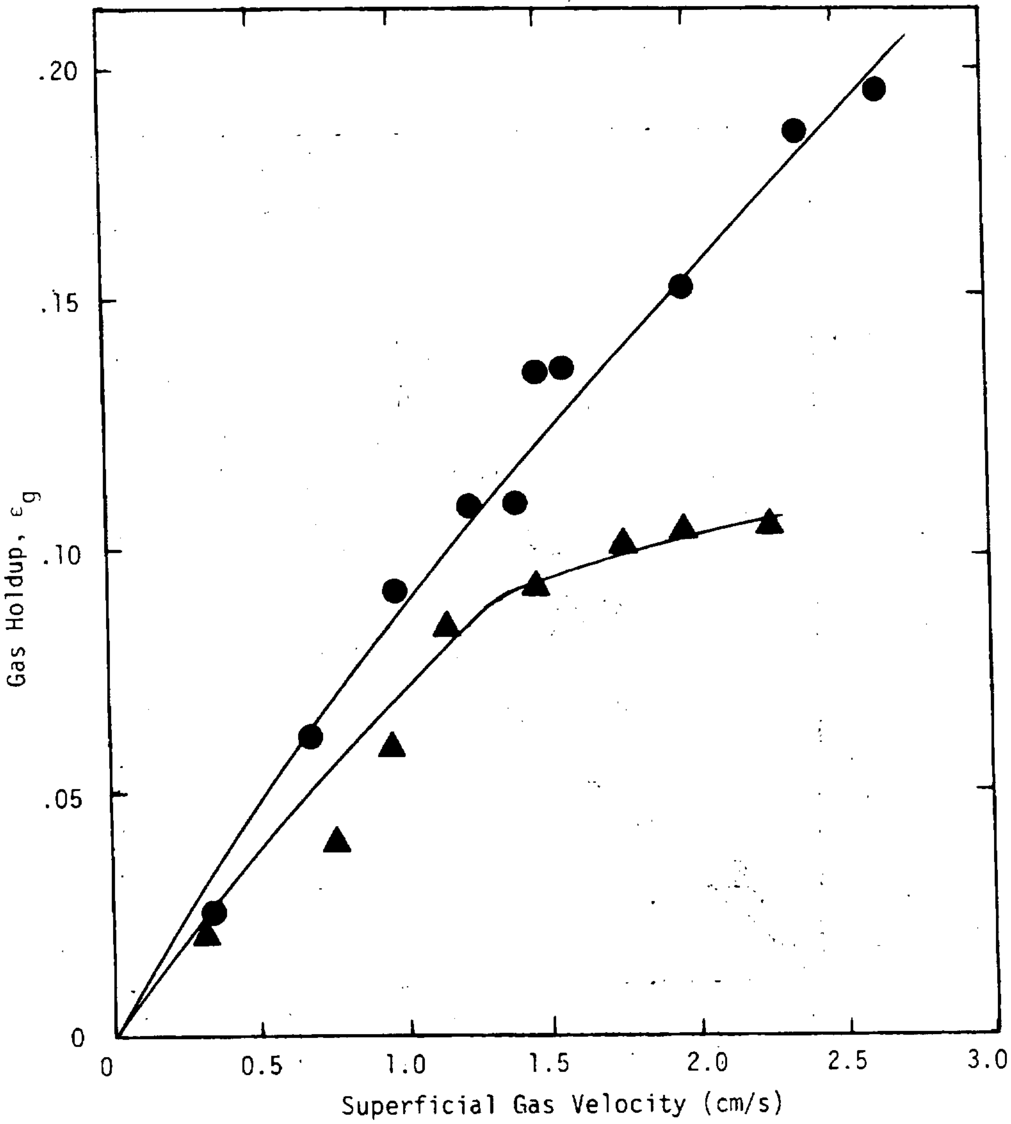

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EFFECT OF SOLIDS ON GAS HOLDUP
FOR A 20-μm FRIT

DATE	DRAWN BY	FILE NO.	FIG.
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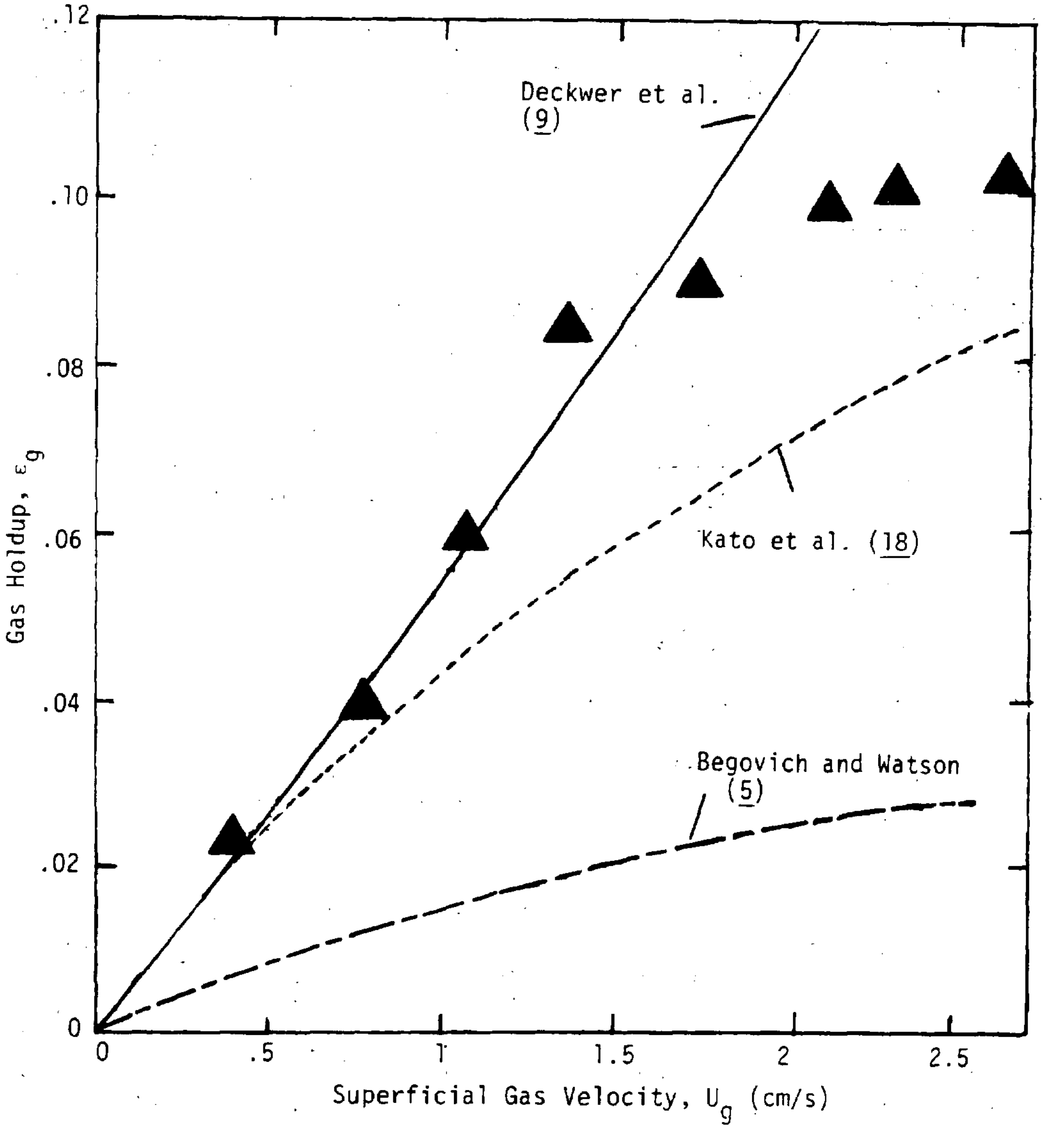

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COMPARISON WITH CORRELATIONS FOR
GAS HOLDUP WITH SOLIDS PRESENT

DATE	DRAWN BY	FILE NO.	FIG.
08/31/82	DPW	CEPS-X-362	10

size, the slurry was likely pseudohomogenous and was unaffected by the transition in flow regime at about 1.5 cm/s. Begovich and Watson (5) and Kato et al. (18) used particles about 1 mm in diameter, which were much larger than those in our study. The larger particles probably caused bubbles to break, increasing holdup. No decrease in slope of gas holdup as a function of gas velocity is seen at 1.5 cm/s. The sharp transition in flow regimes at a superficial velocity of about 1.5 to 1.75 cm/s was eliminated by these larger particles. Further study on the effect of particle size and concentration needs to be conducted.

6.2.2 Gas-Bubble Size

In Table 6, the volume-equivalent bubble diameter from this study is compared with that taken from literature data.

Table 6. Gas-bubble size

Source	Bubble diameter (cm)
Our study	0.28 to 0.31
Akita and Yoshida (2)	0.43 to 0.55
Deckwer et al. (9, 10)	0.07
Dyer et al. (12)	0.27 to 0.35

The range of diameters shown represent the largest variance at the velocities studied (0.47 to 3.04 cm/s). The data from our study falls within the range of the data reported by Dryer et al. They performed their experiments with an isoparaffin which is similar to n-octacosane. The prediction of Akita and Yoshida gives a slightly larger bubble size than any of the experimental values. It is likely that the low value reported by Deckwer et al. is because of the presence of surface-active species (such as aldehydes and acids) in the molten wax, which could affect bubble-size (15).

The equivalent diameters listed in Table 2 for various gas velocities indicate that bubble diameter is unaffected by increasing gas velocity. This agrees with observations made by Deckwer et al. (9). The mild influence of gas-sparger pore size shown in Table 4 on bubble size is also in agreement with Deckwer et al. (8). On the other hand, Akita and Yoshida (2) observed that gas-bubble size was independent of orifice size. However, because their study was performed with a single-orifice sparger, the applicability of their observation to our study, performed with a fritted gas distributor, is questionable.

6.2.3 Interfacial Area

Gas-liquid interfacial area for Fischer-Tropsch systems as a function of superficial gas velocity is compared with literature correlations in Fig. 11. The correlation for Deckwer et al. (9) was regressed from reported data. They used 4.1- and 10-cm-ID bubble columns, with nitrogen sparged through a 75-μm-pore gas distributor into a paraffin wax that contained up to 15 wt % solids at 503 K. The plot of this correlation (Fig. 11) shows much greater specific interfacial areas than those for our study. This is because the bubble reported by Deckwer et al. was 0.7-mm diameter, considerably smaller than that determined in our study of about 3 mm. The data of Calderbank et al. (6) agree closely with our data up to a gas velocity of about 1.3 cm/s, even though they used a ball-and-cone gas sparger.

6.3 Reactor Modeling

From the mockup study, the following conclusions can be drawn for the range of gas velocities 0 to 3 cm/s:

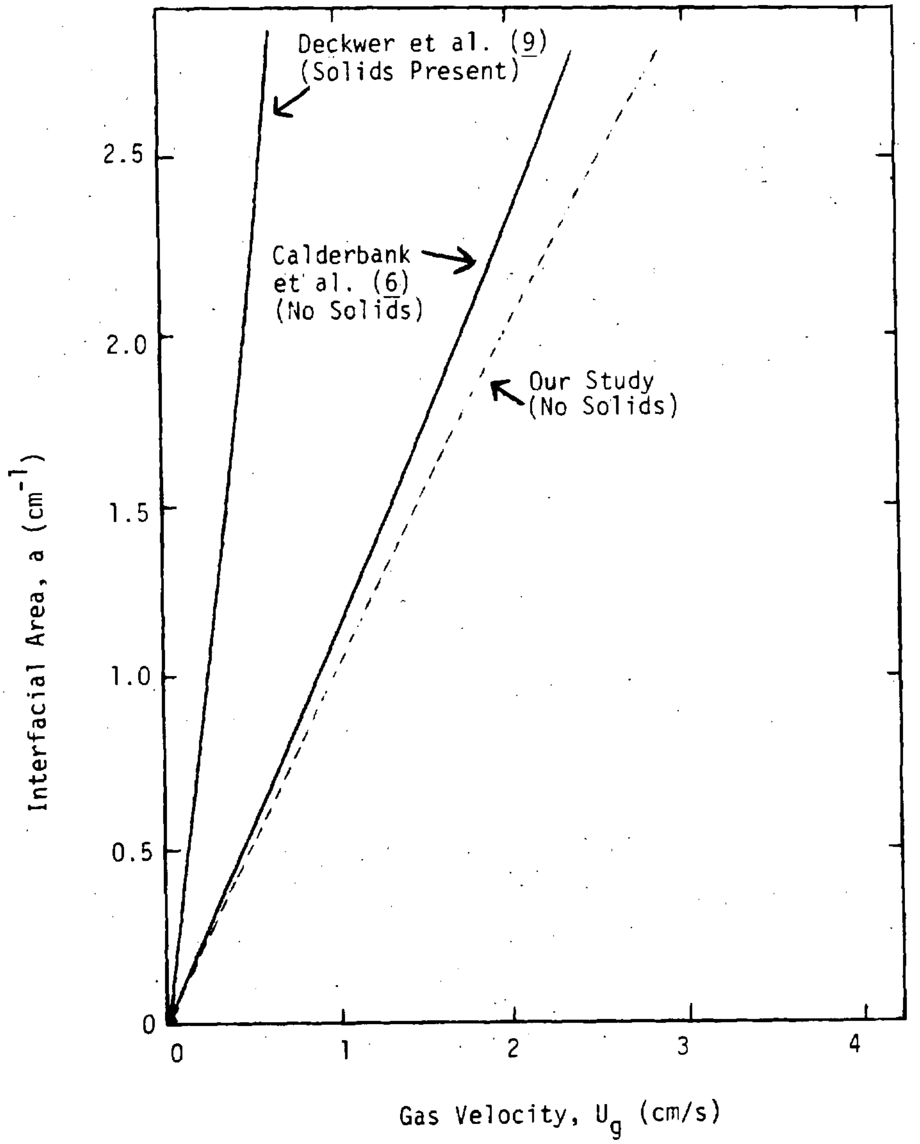
1. The catalyst is well dispersed. This was verified by the sedimentation experiments in which no axial concentration gradient of catalyst was seen.

2. The gas travels through the liquid in plug flow. At gas velocities of about 1.5 cm/s, with solids present, a transition in flow regime was observed, from bubbly flow to semiturbulent. However, semiturbulent flow was judged not to cause significant gas-phase mixing. Generally the assumption of the liquid phase as well-mixed is made (10) for columns with low L/D ratios. This assumption can be verified by performing experiments in which a dye or solute tracer is used to determine the extent of backmixing in the liquid phase.

7. CONCLUSIONS

1. With no solid particles suspended, gas holdup was a linear function of superficial gas velocity.

2. With 13 wt %, 25- to 45-μm sand particles, a transition in flow regime from homogeneous bubbly to semiturbulent flow was observed between gas velocities of 1.5 to 1.75 cm/s.



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EXPERIMENTAL DATA FROM F-T SYSTEMS
FOR INTERFACILA GAS AREA

DATE	DRAWN BY	FILE NO.	FIG.
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3. General gas-holdup correlations are not applicable to Fischer-Tropsch systems.

4. Gas-bubble size is affected by distributor pore size and axial position. Bubble area increased 32% upon increasing frit size from 20 to 100 μm. At a gas velocity of 1.8 cm/s, gas-bubble size increased throughout the column, suggesting coalescence.

8. RECOMMENDATIONS

1. Measure the mass-transfer resistance k_La for a Fischer-Tropsch system in the presence of solids. This can be done in a dynamic study with a soluble gas.

2. Perform gas-holdup studies to determine the effect of particle size and density on gas holdup and flow regime.

3. Examine liquid backmixing to determine the extent of dispersion in the liquid phase. Several experiments in this area have been performed by past Practice School groups; their results should prove helpful.

4. Improve the design of the reactor by: (a) decreasing the length of transfer lines between the reactor and the product traps; (b) pressure-testing the reactor to eliminate leaks; and (c) repairing the on-line gas chromotograph so that rapid compositional analysis of the off-gas is possible.

9. ACKNOWLEDGMENTS

We thank Bob Wham for his help in getting the BCSR working, and Harvey Stenger at MIT and Jim Attrill at ORNL for analyzing the gas samples. We also thank Jack Watson and Bill Rodgers for helpful discussions.

10. APPENDIX

10.1 Sample Calculations

10.1.1 Gas Holdup

The gas holdup ε_g in the expanded column with no solids present is given by Eq. (15). For an expanded column height H_{exp} of 105.7 cm and an unexpanded (stagnant) height H_0 of 91.6 cm, the gas holdup is:

$$\varepsilon_g = \frac{105.7 \text{ cm} - 91.6 \text{ cm}}{105.7 \text{ cm}} = 0.133$$

10.1.2 Volume and Area of Ellipsoidal Bubble

The volume of an ellipsoid is given by Eq. (18). At a superficial gas velocity of 1.77 cm/s and a position 75 cm from the gas distributor, the major axis a' and minor axis b were measured as 0.2 and 0.12 cm, respectively. The volume of the ellipsoid is:

$$\hat{V} = \frac{4}{3} (\pi) \ (0.2 \text{ cm})^2 \ (0.12 \text{ cm}) = 0.0201 \text{ cm}^3$$

The eccentricity ε of an ellipsoid is given by Eq. (19); and for the same dimensions, the eccentricity is:

$$\varepsilon = \frac{\sqrt{(0.2 \text{ cm})^2 - (0.12 \text{ cm})^2}}{0.2 \text{ cm}} = 0.80$$

The area of an ellipsoid is given by Eq. (19) and equals:

$$\hat{A} = 2\pi \ (0.2)^2 + \frac{\pi}{3} \ (0.12)^2 \ \ln\left(\frac{1 + 0.80}{1 - 0.80}\right) = 0.255 \text{ cm}^2$$

10.1.3 Gas-Liquid Interfacial Area

Interfacial area can be calculated from Eq. (21). The volume of gas in a bubbling bed V_G can be found from the gas holdup and the expanded bed height as:

$$V_G = \varepsilon_G V_{exp} \tag{25}$$

where the expanded bed volume V_{exp} can be calculated from:

$$V_{exp} = \frac{\pi}{4} D_C^2 H_{exp}$$

The number of bubbles in the column can be calculated from Eq. (22). For a gas holdup ε_g of 0.135 and an expanded bed height H_{exp} of 106 cm, the volume of expanded bed is:

$$V_{exp} = 106 \text{ cm} \frac{\pi}{4} (5.08 \text{ cm})^2 = 2140 \text{ cm}^3$$

The number of bubbles is

$$N_B = \frac{(0.135)\ (2140 \text{ cm}^3)}{0.0201 \text{ cm}^3} = 14{,}400 \text{ bubbles}$$

and interfacial area is

$$a = \frac{(14{,}400 \text{ bubbles } (0.255 \text{ cm}^2)}{2140 \text{ cm}^3} = 1.69 \text{ cm}^{-1}$$

10.1.4 Correlations for Gas Holdup Without Solids

Gas holdup was calculated from four different correlations for no solids. Parameters used for calculating holdup with these correlations are listed in Table 7.

Gas holdup calculated with Eq. (7) from Hikita et al. (14) at a gas velocity of 0.01 m/s is:

Table 7. Parameters used in sample calculations

Liquid properties

$\rho_L = 660 \text{ kg/m}^3$

$\mu_L = 3.1 \times 10^{-4} \text{ kg/m-s}$

$\nu_L = 4.70 \times 10^{-7} \text{ m}^2\text{/s}$

$\sigma = 1.84 \times 10^{-2} \text{ kg/s}^2$

Gas Properties

$\rho_g = 1.07 \text{ kg/m}^3$

$\mu_L = 1.7 \times 10^{-5} \text{ kg/m-s}$

Miscellaneous

$D_C = 0.0508 \text{ m}$

$g = 9.8 \text{ m/s}^2$

$d_p = 37 \times 10^{-6} \text{ m}$

$$\varepsilon_g = 0.672\left[\frac{(0.01 \text{ m/s})(3.1 \times 10^{-4} \text{ kg/m-s})}{1.84 \times 10^{-2} \text{ kg/s}}\right]^{0.578}$$

$$\left[\frac{(3.1 \times 10^{-4} \text{ kg/m-s})^4(9.8 \text{ m/s})}{660 \text{ kg/m}^3(1.84 \times 10^{-2} \text{ kg/s})^3}\right]^{-0.131} \times \left(\frac{1.07 \text{ kg/m}^3}{660 \text{ kg/m}^3}\right)^{0.062}$$

$$\times \left(\frac{0.017 \text{ cp}}{0.31 \text{ cp}}\right)^{0.107} = 0.0543$$

The Bach-Pilhofer (4) correlation [Eq. (8)] yields a gas holdup as a function of gas velocity of:

$$\frac{\varepsilon_g}{1 - \varepsilon_g} = 0.115\left[\frac{U_g{}^3}{(4.70 \times 10^{-7} \text{ m}^2\text{/s})(9.80 \text{ m/s}^2)\dfrac{(660 - 1.07 \text{ kg/m}^3)}{660 \text{ kg/m}^3}}\right]^{0.23}$$

$$\frac{\varepsilon_g}{1 - \varepsilon_g} = 1.9425\ U_g^{0.69}$$

For a superficial gas velocity U_g of 0.01 m/s, the gas holdup is:

$$\varepsilon_g = \frac{1.9425\ (0.01\ \text{m/s})^{0.69}}{1 + 1.9425\ (0.01)^{0.69}} = 0.0749$$

For the Hughmark (16) correlation given in Eq. (9), gas holdup can be calculated as a function of gas velocity:

$$\varepsilon_g = \frac{1}{2 + 0.35/U_g[(660\ \text{kg/m}^3)(1.84 \times 10^{-2}\ \text{kg/s}^2)/72]^{1/3}}$$

$$= \frac{1}{2 + [0.19338/U_g]}$$

For a superficial gas velocity U_g of 0.01 m/s, the gas holdup is:

$$\varepsilon_g = \frac{1}{2 + [0.19339/0.01\ \text{m/s}]} = 0.0469$$

From Akita and Yoshida's (3) correlation of Eq. (6), gas holdup as a function of gas velocity is:

$$\frac{\varepsilon_g}{(1 - \varepsilon_g)^4} = 0.2\left(\frac{9.8\ \text{m/s}^2\ 0.0508\ \text{m}^2\ 660\ \text{kg/m}^3}{1.84 \times 10^{-2}\ \text{kg/s}^2}\right)^{1/8}$$

$$\times \left[\frac{(9.8\ \text{m/s}^2)(0.0508\ \text{m}^3)}{(4.70 \times 10^{-7}\ \text{m}^2/\text{s})^2}\right]^{1/8} \frac{U_g}{\sqrt{9.8\ \text{m/s}^2\ (0.0508\ \text{m})}}$$

$$= 4.3247\ U_g$$

This is a fourth-order polynomial in gas holdup and can be solved if U_g is specified. For a superficial gas velocity of 0.01 m/s, gas holdup is:

$$\varepsilon_g = 0.0372$$

10.1.5 Correlations for Gas Holdup with Solids

Gas holdup with solids was calculated from three correlations. From Begovich and Watson (5) [Eq. (10)] gas holdup as a function of gas velocity is:

$$\varepsilon_g = 1.612\ (37 \times 10^{-6}\ \mathrm{m})^{0.168}\ (0.0508\ \mathrm{m})^{-0.125}\ U_g^{0.72}$$

$$= 0.4213\ U_g^{0.72}$$

For a gas velocity U_g of 0.01 m/s, gas holdup is:

$$\varepsilon_g = 0.4213\ (0.01\ \mathrm{m/s})^{0.72} = 0.0153$$

From Deckwer et al. (9), gas holdup with solids can be expressed as in Eq. (11). For a gas velocity of 1.0 cm/s, the gas holdup is

$$\varepsilon_g = 0.053\ (1.0)^{1.1} = 0.053$$

10.1.6 Correlations for Bubble Size

From Akita and Yoshida (2), bubble size can be expressed as Eq. (12). With the values in Table 7, effective bubble diameter d_{eff} as a function of gas velocity is:

$$d_{eff} = 26\ (0.0508\ \mathrm{m}) \left[\frac{(9.8\ \mathrm{m/s^2})(0.0508\ \mathrm{m})^2\ 660\ \mathrm{kg/m^3}}{(1.84 \times 10^{-2})}\right]^{-0.5}$$

$$\times \left[\frac{(9.8\ \mathrm{m/s^2})(0.0508\ \mathrm{m})^3}{(4.70 \times 10^{-7}\ \mathrm{m^2/s})^2}\right]^{-0.12} \left(\frac{U_g}{\sqrt{9.8\ \mathrm{m/s^2}\ (0.0508\ \mathrm{m})}}\right)^{-0.12}$$

$$= 0.0028314\ U_g^{-0.12}$$

For a gas velocity of 0.01 m/s, the effective bubble diameter is:

$$d_{eff} = 0.0028314\ \mathrm{m}\ (0.01)^{-0.12} = 0.00492\ \mathrm{m}$$

10.1.7 Correlations for Interfacial Area

Interfacial area can be estimated by Eq. (13), according to Akita and Yoshida (2). From parameters in Table 7, interfacial area a as a function of gas holdup ε_g is:

$$a = 1/3\ (0.0508\ \mathrm{m}) \left[\frac{(9.8\ \mathrm{m/s^2})(0.0508\ \mathrm{m})^2(660\ \mathrm{kg/m^3})}{1.84 \times 10^{-2}\ \mathrm{kg/s^2}}\right]^{0.5}$$

$$\times \left[\frac{(9.8\ \mathrm{m/s^2})(0.0508\ \mathrm{m})^3}{(4.70 \times 10^{-7}\ \mathrm{m^2/s})^2}\right]^{0.1} \varepsilon_g^{1.13}$$

$$= 1872\ \varepsilon_g^{1.13}$$

For a superficial gas velocity of 0.01 m/s, gas holdup from the Akita-Yoshida correlation [Eq. (6)] is 0.0372. Interfacial area is thus:

$$a = 1872\ (0.0372)^{1.13} = 45.4\ \mathrm{m}^{-1}$$

10.2 Original Data

Table 8 shows gas holdup as a function of gas superficial velocity for different-size frits, with and without solids.

Table 8. Gas holdup as a function of gas superficial velocity

U_g (cm/s)	H_0 (cm)	H_{exp} (cm)
	20-μm frit; no solids present	
0.411	91.0	93.4
0.822	90.7	96.5
1.19	90.0	98.9
1.51	91.8	102.9
1.69	91.0	103.1
1.87	91.3	105.6
1.93	91.6	105.7
2.38	88.6	104.6
2.83	87.0	106.8
3.18	86.7	107.3
	100-μm frit; no solids present	
0.485	83.7	85.5
0.929	91.1	93.2
1.094	95.2	101.9
1.472	95.1	103.9
2.089	94.9	108.4
2.393	94.1	109.2
2.878	94.5	114.5
3.223	92.9	113.3
	20-μm frit; 13 wt % sand (25 to 45 mm)	
0.403	86.0	88.0
0.773	85.7	89.3
1.07	85.3	90.7
1.37	84.5	92.3
1.76	85.7	94.1
2.14	85.5	94.8
2.34	85.0	95.3
2.71	84.2	95.4

10.3 Error Analysis

10.3.1 Gas Holdup

Error in calculating the gas holdup for any experiment comes from two sources: (1) measurement of the gas flow rate; and (2) measurement of expanded-bed height. Error in the measurement of gas flow rate resulted from the use of a timer to record flow through a wet-test meter. For ten experiments, a standard deviation 2.0 ± 0.07 L/min resulted which corresponds to a superficial velocity of 1.65 ± 0.07 cm/s.

10.3.2 Gas-Liquid Interfacial Error

The primary error in calculating the gas-liquid interfacial area results from the estimation of average bubble size. Error in the gas holdup measurement propagates to the specific area calculation. Variance in the bubble size is introduced from three sources: (1) random variation because of distribution of bubble size; (2) approximation of an irregular bubble by a regular ellipsoid; and (3) coalesence through the column. The error of bubble irregularity and size distribution is accounted for in the error shown in Tables 2, 3, and 4.

10.3.3 Catalyst Sedimentation

The primary error in measuring the volume percentage of catalyst in slurry samples taken from the reactor resulted from incomplete centrifugation of the sample. Solidification of the slurry in the centrifuge (melting point of n-octacosane, 338 K) prevented centrifugation for longer than 5 min. Rather than a sharp boundary between catalyst solids and carrier supernatant, a diffuse zone of about 0.1 ml was seen. The error introduced from this reading error of ±0.1 ml amounted to about 0.8 vol % catalyst.

10.4 Location of Original Data

Data for experiments run on the mockup and BCSR can be found in ORNL databook A-9913-G, pp. 30-65. Complete calculations are on file at the MIT School of Chemical Engineering Practice.

10.5 Nomenclature

a	Gas-liquid interfacial area, cm^{-1}
a'	Ellipsoid semi-major axis, mm
A	Average area per bubble, cm^2
b	Ellipsoid semi-minor axis, mm
d_{eff}	Effective bubble diameter, m
d_p	Particle diameter, m

D_C	Column diameter, m
g	Gravitational acceleration, m/s^2
ΔH	Heat of reaction, kJ/mol
H_{exp}	Expanded bed height, m
H_o	Unexpanded bed height, m
k_L	Gas-liquid mass-transfer coefficient, cm/s
n	Exponent in power-law expression
N	Total number of bubbles in column
U_g	Superficial gas velocity, m/s
V_{exp}	Expanded bed volume, cm^3
V_G	Volume of gas in expanded bed, cm^3
$\hat{V}$	Average volume per bubble, cm^3
ε_g	Gas holdup
ε	Ellipsoid eccentricity
ρ_g	Gas density, kg/m^3
ρ_L	Liquid density, kg/m^3
σ	Surface tension, N/m
ν_L	Liquid kinematic viscosity, m^2/s
μ_g	Gas viscosity, kg/m-s
μ_L	Liquid viscosity, kg/m-s

10.6 References

1. Adlington, D. and E. Thompson, in Proceedings of the 3rd European Symposium on Chemical Reaction Engineering, Pergamon Press, Oxford, p. 203, 1965.

2. Akita, K. and F. Yoshida, "Bubble Size, Interfacial Area and Liquid-Phase Mass Transfer Coefficient in Bubble Columns," I&EC Proc. Des. Dev., 13, 84 (1974).

3. Akita, K. and F. Yoshida, "Gas Holdup and Volumetric Mass Transfer Coefficient in Bubble Columns," I&EC Proc. Des. Dev., 12, 76 (1973).

4. Bach, H. F. and T. Pilhofer, "Variation of Gas Holdup in Bubble Columns with Physical Properties of Liquids and Operating Parameters of Columns," Germ. Chem. Eng., 1, 270 (1978).

5. Begovich, J. M. and J. S. Watson, "Hydrodynamic Characteristics of Three-Phase Fluidized Beds," Fluidization, Proc. 2nd Eng. Foundation Conf., J. F. Davidson and D. L. Keairns, eds., 190 (1978).

6. Calderbank P. H., F. Evans, R. Farley, G. Jepson, and A. Poll, "Rate Processes in the Catalyst-Slurry Fischer-Tropsch Reaction," Catalysis in Practice, London: Insti. Chem. Engrs., 1963.

7. Chemical Rubber Company Handbook, E. R. Weast, ed., Chemical Rubber Company Press, Cleveland, Ohio, 60th Edition, 1980.

8. Deckwer W.-D., L. Adler, and A. Zaidi, "A Comprehensive Study on CO_2 Interphase Mass Transfer in Vertical Co-Current and Counter Current Gas Liquid Flow," Can. J. Chem. Eng., 56 (1978).

9. Deckwer, W.-D., Y. Louisi, A. Zaidi, and M. Ralek, "Hydrodynamic Properties of the Fischer-Tropsch Slurry Process," I&EC Proc. Des. Dev., 19, 1980.

10. Deckwer, W.-D., Y. Serpemen, M. Ralek, and B. Schmidt, "On the Importance of Mass Transfer in the Fischer-Tropsch Reaction," Chem. Eng. Sci., 36, 765 (1981).

11. Deckwer, W.-D., Y. Serpemen, M. Ralek, and B. Schmidt, "Modeling the Fischer-Tropsch Synthesis in the Slurry Phase," I&EC Proc. Des. Dev., 21 (1982).

12. Dyer, P. N., R. Pierantozzi, B. W. Brian, and J. V. Bauer, "Catalyst and Reactor Development for a Liquid Phase Fischer-Tropsch Process," Quarterly Technical Progress Report for Period, 1 July 1981-30 September 1981, Air Products and Chemicals, Inc., October 1981.

13. Hall, K. R., Selected Values of Properties of Hydrocarbons and Related Compounds," Thermodynamics Research Center, Chem. Eng. Div. of Texas Exp. Station, Texas A&M, 1982.

14. Hikita, H., S. Asai, K. Tanigawa, K. Segawa, and M. Kitao, "Gas Holdup in Bubble Columns," Chem. Eng. J., 20, 59 (1980).

15. Huff, G. A., personal communication, MIT, August 30, 1982.

16. Hughmark, G. A., "Holdup and Mass Transfer in Bubble Columns," I&EC Proc. Des. Dev., 6, 218 (1967).

17. Imafuku, K., T.-Y. Wang, K. Koide, and H. Kubota, "The Behavior of Suspended Solid Particles in the Bubble Column" J. Chem. Eng. Japan, 1, 2 (1968).

18. Kato, Y., A. Nishiwaki, T. Fukuda, and S. Tanaka, "The Behavior of Suspended Solid Particles and Liquid in Bubble Columns," J. Chem. Eng. Japan, 5, 2 (1972).

19. Satterfield, C. N., G. A. Huff, Jr., and J. P. Longwell, "Product Distribution from Iron Catalysts in Fischer-Tropsch Slurry Reactors," I&EC Proc. Des. Dev., 21, 465 (1982).

20. Shah, Y. T., B. G. Kelkar, S. P. Godbole, and W.-D. Deckwer, "Design Parameter Estimation for Bubble Column Reactors" AICHE J. 28, 353 (1982).