V. TASK 3 - PROCESS VARIABLE STUDIES

A. DESCRIPTION OF THE FLOW FIELD

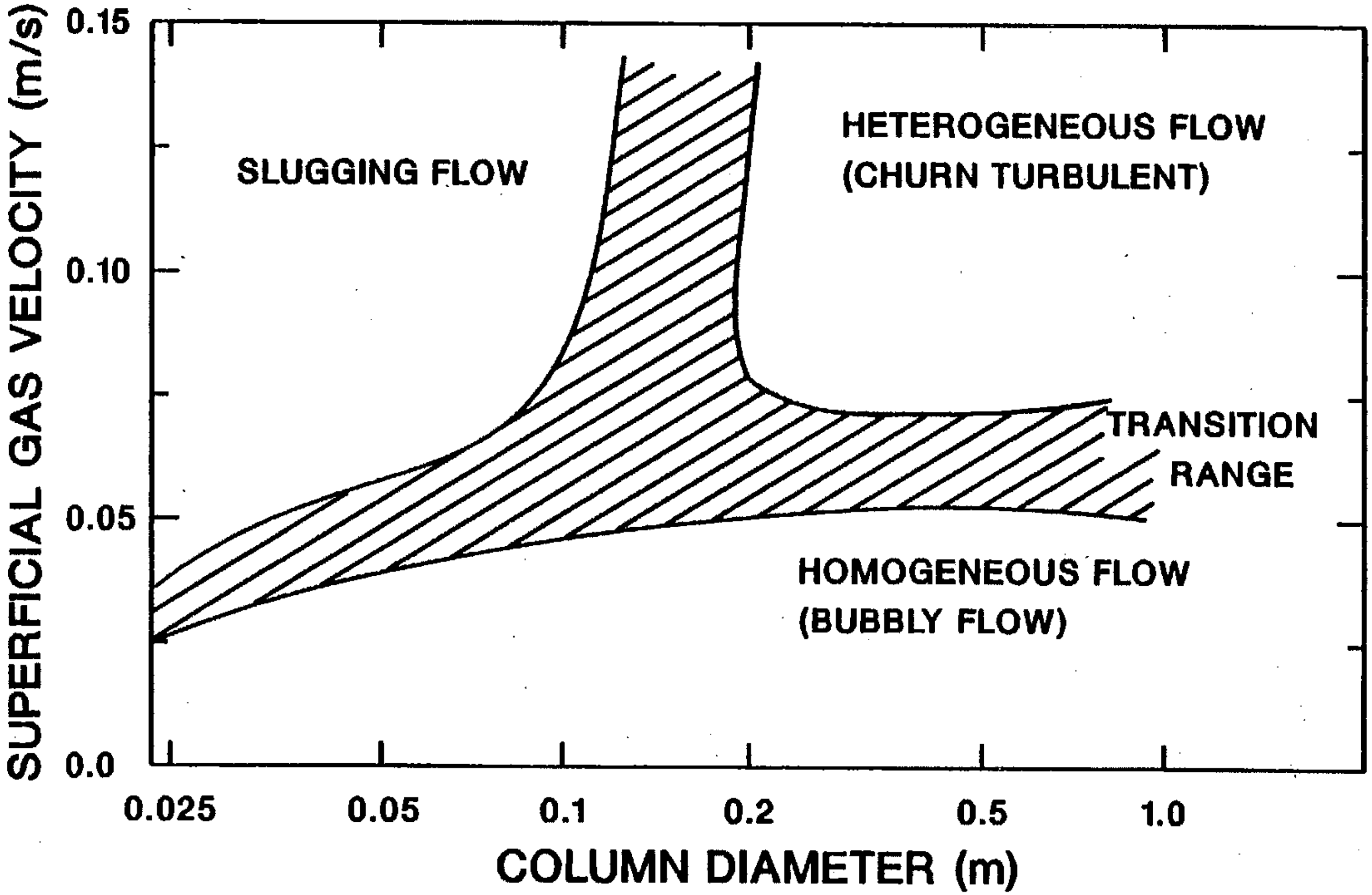
The hydrodynamics of a bubble column is significantly affected by the flow regime in which the column operates. Ample evidence of this dependency is available in literature (e.g. Shah et al, 1982) and various criteria have been proposed by different researchers to differentiate the flow regimes. Deckwer et al. (1980) presented a flow regime map (Figure V-1) which qualitatively characterizes the dependence of flow regimes on the column diameter and the superficial gas velocity. At low superficial gas velocities, regardless of column diameter, the homogeneous flow regime (or the "homogeneous bubbling" regime) exists. In this flow regime, the bubbles are uniform in size and minimal interaction between neighboring bubbles occurs. Bubble coalescence and breakup occurs as the gas velocity is increased. During this process, large bubbles may appear. In columns less than 0.10 m in diameter, the large bubbles may fill the entire column diameter forming slugs; this is the "slug flow" regime. In larger diameter columns, large bubbles are formed without producing slugs. The formations of these large bubbles is associated with an increase in turbulence; this is the "churn-turbulent" regime. The shaded regions in Figure V-1 indicate the transition regions between the various flow regimes. The exact location of the boundaries associated with the transition regions will probably depend on gas distributor design, static liquid height, operating conditions and gas and liquid media.

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

FIGURE V-1

BUBBLE COLUMN FLOW REGIME MAP

(adopted from Deckwer et al, 1980)



"foamy" regime overlaps the previously described regimes and is characterized by the presence of a stable layer of foam on top of the dispersion. Smith, D.N et al. (1984b) have presented a procedure that makes it possible to predict the transition from the "homogeneous bubbling" regime to the "foamy" regime.

The flow fields in the 0.051 m ID and the 0.229 m ID glass columns, for the range of conditions employed in the present study, were studied visually, and with the aid of video tapes and photographs. Results from experiments conducted with the paraffin waxes (FT-200 and FT-300) and with distilled water are presented here. It was not possible to observe the flow field with reactor waxes (Sasol's Arge reactor wax and Mobil's reactor wax) due to the dark color of these waxes.

The major findings from these studies are:

- In the 0.051 m ID column, the "homogeneous bubbling" regime prevails at a superficial gas velocity of 0.01 m/s followed by a transition to the "slug flow" regime in the absence of foam. Whereas, in runs with orifice plate distributors where foam was present (e.g. with paraffin waxes), the "homogeneous bubbling" regime was followed by the "foamy" regime (for the velocity range 0.03 to 0.05 m/s in most cases), after which the "slug flow" regime prevails. Similar flow regimes were observed with the 40 μm SMP distributor, however, the "foamy" regime prevailed up to gas velocities of 0.09 m/s.
- In the 0.229 m ID column, the "homogeneous bubbling" regime occurs at gas velocities of 0.01 and 0.02 m/s followed by a transition to the "churn turbulent" flow regime in the absence of foam. However, in runs where foam was present, the "homogeneous bubbling" regime was followed

by the "foamy" regime (for the velocity range 0.03 to 0.05 m/s), after which a transition to the "churn-turbulent" flow regime occurred.

During gas hold-up measurements in the small (0.051 m ID) and large (0.229 m ID) glass columns, the flow field near the wall, at heights of approximately 0.45 m, 1.2 m and 2.1 m above the distributor, was photographed with a Canon 35 mm SLR camera and also recorded with a video camera (Hitachi, Model GP-5AU). Based on the photographs, video tapes, and visual observations recorded during the experiments, the following qualitative remarks of the flow field can be made.

A.1. <u>Small Column (0.051 m ID)</u>

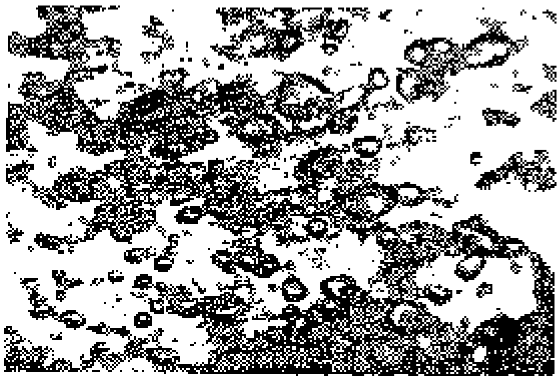
A.1.a. <u>Effect of Superficial Gas Velocity</u>

The effect of superficial gas velocity on bubbles produced in FT-300 wax at 265°C, using the 4.0 mm single orifice plate distributor, is illustrated in photographs taken at a distance of approximately 1.2 m above the distributor (Figure V-2). At a velocity of 0.02 m/s (Figure V-2a), majority of the bubbles are distributed in two size ranges; medium size bubbles (4-6 mm in diameter) and small bubbles (< 2 mm in diameter). Some large bubbles are also present (30-40 mm in diameter), however, these are not visible in Figure V-2a probably due to their tendency to remain near the center of the column. At 0.03 m/s (Figure V-2b), the density of bubbles increases, and a wide bubble size distribution is evident. At this velocity, slugs start appearing at a height of 1.2 m above the distributor (not visible in Figure V-2b). At velocities of 0.02 and 0.03 m/s the flow regime may be characterized as the transition regime between the ideal bubbly regime and the "slug flow" regime. At 0.04 m/s (Figure V-2c), the density of bubbles further increases and part of a large bubble can be seen

FIGURE V-2

EFFECT OF SUPERFICIAL GAS VELOCITY

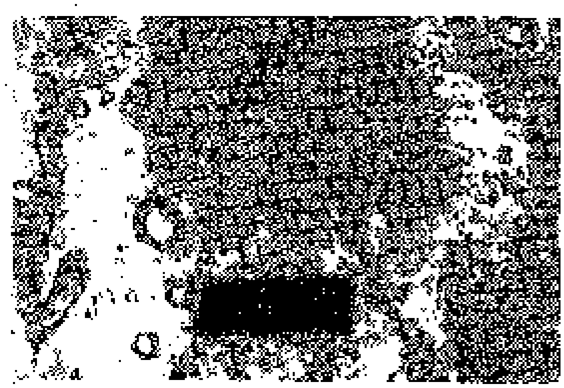
4.0 mm SINGLE ORIFICE DISTRIBUTOR



a. 0.02 m/s

b. 0.03 m/s

c. 0.04 m/s



d. 0.09 m/s

SCALE: ├──────────┤ 25.4 mm

HEIGHT = 1.2 m; T = 265 ^{o}C; d_c = 0.051 m; FT-300 WAX in the lower right hand side corner. At this gas velocity, the "slug flow" regime prevails. At 0.09 m/s (Figure V-2d), slugs are easily observed. These slugs are surrounded by fine bubbles (< 1 mm in diameter), as well as by a few larger bubbles (3-5 mm in diameter) in diameter. Similar observations were made when the 1.85 mm single orifice plate distributor was used.

A.1.b. <u>Effect of Distributor Type</u>

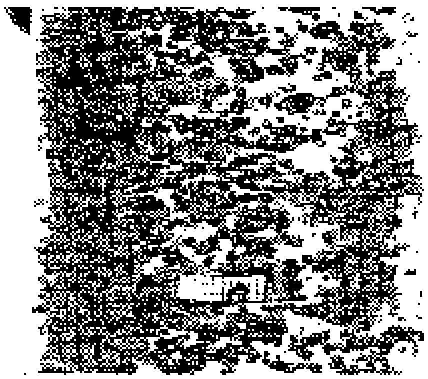
The effect of distributor type at a superficial gas velocity of 0.01 m/s, using FT-300 wax as the liquid medium at a temperature of 265 °C, is shown in Figure V-3. The bubbles produced with the 40 μm SMP distributor are smaller and more uniform than the bubbles produced using the 4.0 mm orifice plate. The effect of height above the distributor on bubble size is also shown in this figure. The bubble size distribution does not change with height for the SMP distributor (Figures V-3a and V-3c). On the other hand, the 4.0 mm single orifice distributor produces a wide bubble size distribution near the distributor (Figure V-3b). As the height increases (Figure V-3d) bubble coalescence and breakup occur and two groups of bubbles become dominant (larger bubbles 4-6 mm in diameter, and fine bubbles less than 1 mm). The vertical black lines in Figures V-3c and V-3d represent a portion of the thermocouple well (4.76 mm in diameter).

Figure V-4 compares the flow field obtained using the 1.85 mm orifice plate with that obtained using the 40 μm SMP at 0.07 m/s in the slug flow regime (foam was not present) using FT-300 wax at 265 ° C. All photographs were taken at a height of 1.2 m above the distributor. Figures V-4a and V-4b show slugs (only the bottom portion of a slug leaving the field of view can be seen in Figure V-4a), accompanied by many fine bubbles (< 1 mm

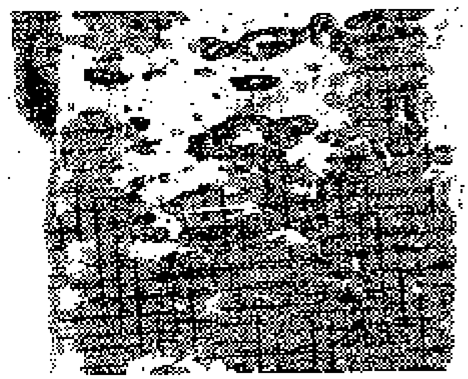
FIGURE V-3

EFFECT OF DISTRIBUTOR AND HEIGHT ABOVE THE DISTRIBUTOR

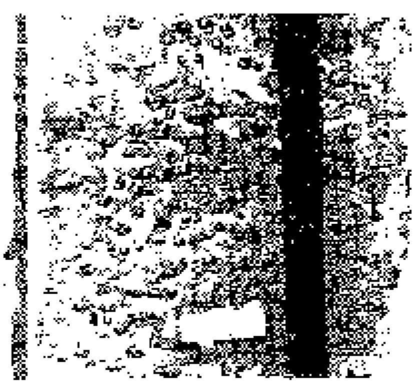
40 μm SMP | 4.0 mm



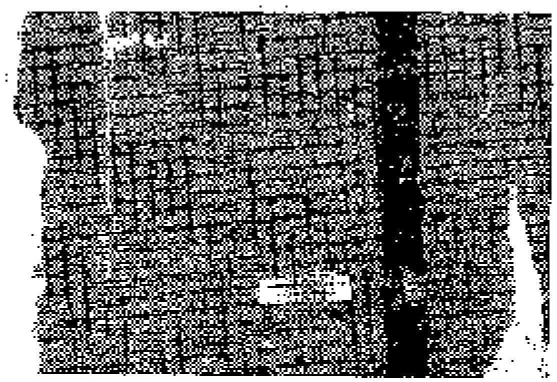
a. 0.45 m



b. 0.45 m



c. 2.1 m



d. 2.1 m

SCALE: ├──────┤ 25.4 mm

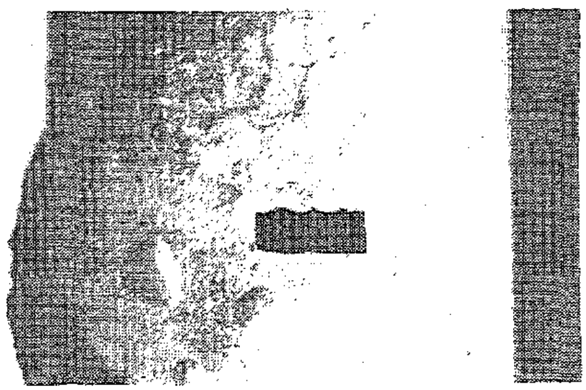
u_g = 0.01 m/s; T = 265 ^{o}C; d_c = 0.051 m; FT-300 WAX

FIGURE V-4

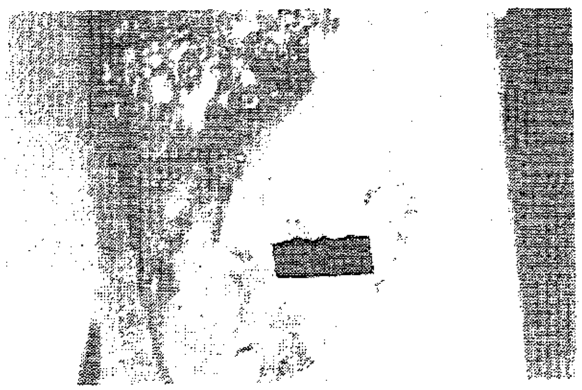
EFFECT OF DISTRIBUTOR

SLUG FLOW REGIME

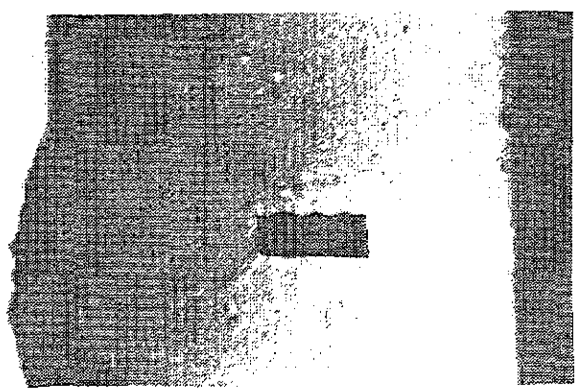
40 µm SMP | 1.85 mm



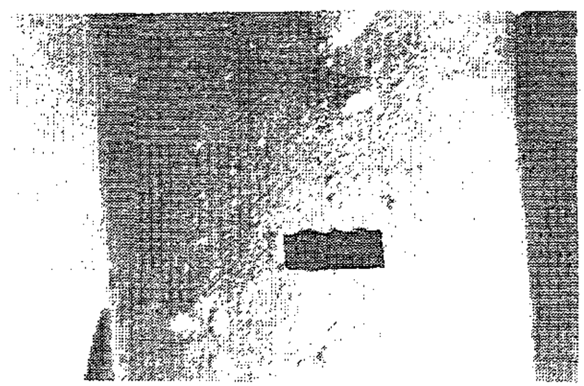
a. slug present



b. slug present



c. absence of slug



d. absence of slug

SCALE: |————| 25.4 mm

u_g = 0.07 m/s; HEIGHT = 1.2 m; T = 265 °C;
d_c = 0.051 m; FT-300 WAX

in diameter), produced when the SMP and the 1.85 mm orifice plate distributor, respectively, were used. There was no noticeable difference in the slugs formed in the two cases. Figures V-4c and V-4d are at the same height and velocity as Figures V-4a and V-4b, however, they show the flow field in the absence of slugs. Once again, there is no obvious difference in the bubbles produced by the two different distributors in the slug flow regime, when foam is not present.

Figure V-5 shows foam produced by the 40 μm SMP and the 1.85 mm orifice plate distributor at 265 °C with FT-300 wax at a velocity of 0.03 m/s. For experiments conducted with the SMP distributor in the "foamy" regime, photos were taken only at a height of 1.2 m above the distributor since foam usually filled the entire column and there was not a noticeable difference between the foam at the bottom and the top of the gas-liquid dispersion. Figure V-5a shows foam produced by the SMP distributor at a height of 1.2 m above the distributor. For experiments conducted with the 1.85 mm orifice plate distributor, foam usually appeared only at the top of the column. Figure V-5b shows foam produced by the 1.85 mm orifice plate distributor at a height of 2.1 m above the distributor. Figures V-5a and V-5b also show that the average size of bubbles produced by the two different distributors is similar and consists of bubbles less than 1 mm in diameter. The foam associated with the SMP distributor is composed of bubbles of a uniform size, whereas, foam produced with the 1.85 mm orifice plate distributor consists of a wider range of bubble sizes.

A.1.c. Effect of Height above the Distributor

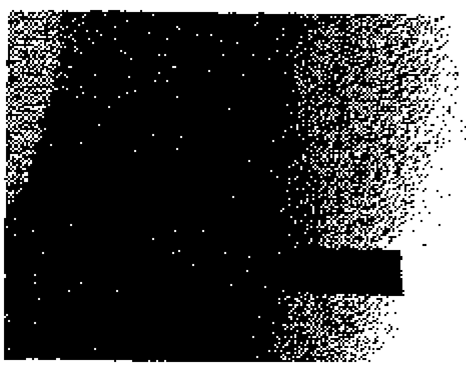
Figure V-6 shows the effect of height above the distributor on bubbles formed, when the 1.85 mm orifice plate distributor was used, at velocities

FIGURE V-5

EFFECT OF DISTRIBUTOR

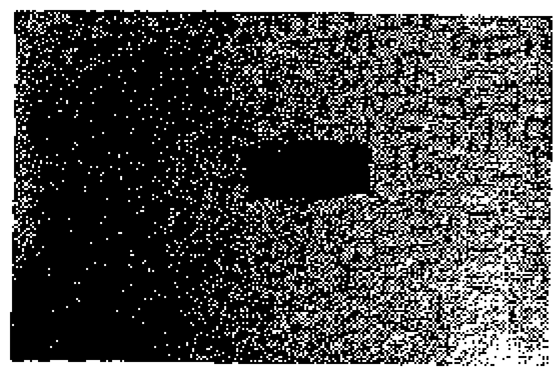
FOAMY REGIME

40 μm SMP



a. 1.2 m

1.85 mm



b. 2.1 m

SCALE: ├──────┤ 25.4 mm

u_g = 0.03 m/s; T = 265 ^oC; d_c = 0.051 m; FT-300 WAX of 0.03 and 0.07 m/s, and at heights of 0.45 and 2.1 m above the distributor. All photographs were taken using FT-300 wax as the liquid medium at a temperature of 265 °C. At a velocity of 0.03 m/s there is a considerable difference in the bubbles produced near the distributor and at the top of the dispersion (Figures V-6a and V-6c, respectively). The bubble size distribution near the distributor is wide, with large bubbles (10-20 mm in diameter), intermediate size bubbles (2-6 mm in diameter), and small bubbles (< 1 mm in diameter) being present. However, at a height of 2.1 m above the distributor, the distribution is narrower, with a greater concentration of small bubbles (< 1 mm in diameter) and relatively few large bubbles. At 0.07 m/s (Figures V-6b and V-6d), there are essentially no medium size or large bubbles present at 2.1 m above the distributor (except for slugs, which are not visible in the Figure). Whereas, at a height of 0.45 m above the distributor, the bubble size distribution is significantly wider than at 2.1 m. At this height large bubbles, nearly filling the entire column cross-section, were often observed.

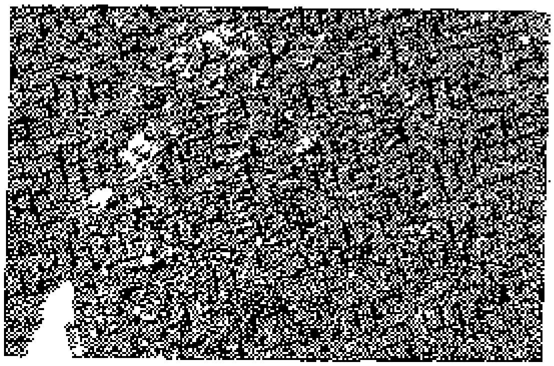
A.1.d. Slug Frequency

For majority of the experiments conducted with an orifice plate distributor, the slug frequency, regardless of liquid medium, goes through a local maximum followed by a local minimum, after which it increases gradually with gas velocity. The slug frequency was measured at approximately 0.3 m below the top of the expanded level. Figure V-7 shows the slug frequency as a function of superficial gas velocity for paraffin waxes (FT-300 and FT-200) and distilled water. Accurate measurements of the slug frequency for Sasol and Mobil reactor waxes could not be made due to the dark nature of the waxes. As can be

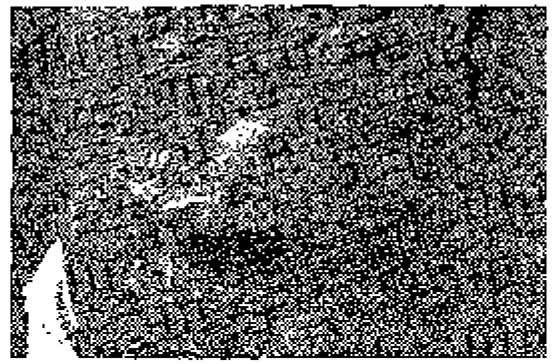
FIGURE V-6

EFFECT OF HEIGHT ABOVE THE DISTRIBUTOR AND SUPERFICIAL GAS VELOCITY

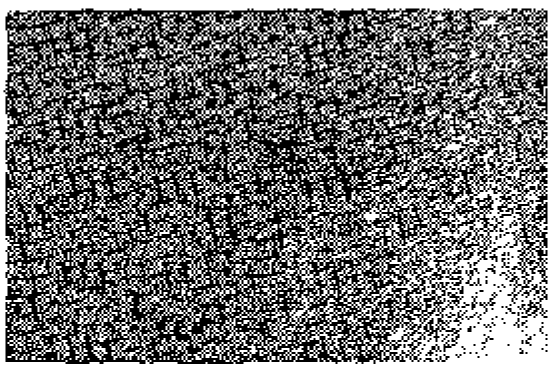
1.85 mm SINGLE ORIFICE DISTRIBUTOR



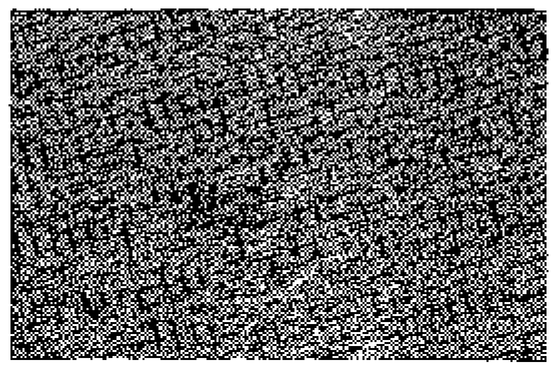
a. 0.03 m/s; 0.45 m



b. 0.07 m/s; 0.45 m



c. 0.03 m/s; 2.1 m



d. 0.07 m/s; 2.1 m

SCALE: ⊢——⊣ 25.4 mm; Figures a and c

SCALE: ⊢——⊣ 25.4 mm; Figures b and d

T = 265 °C; d_c = 0.051 m; FT-300 WAX

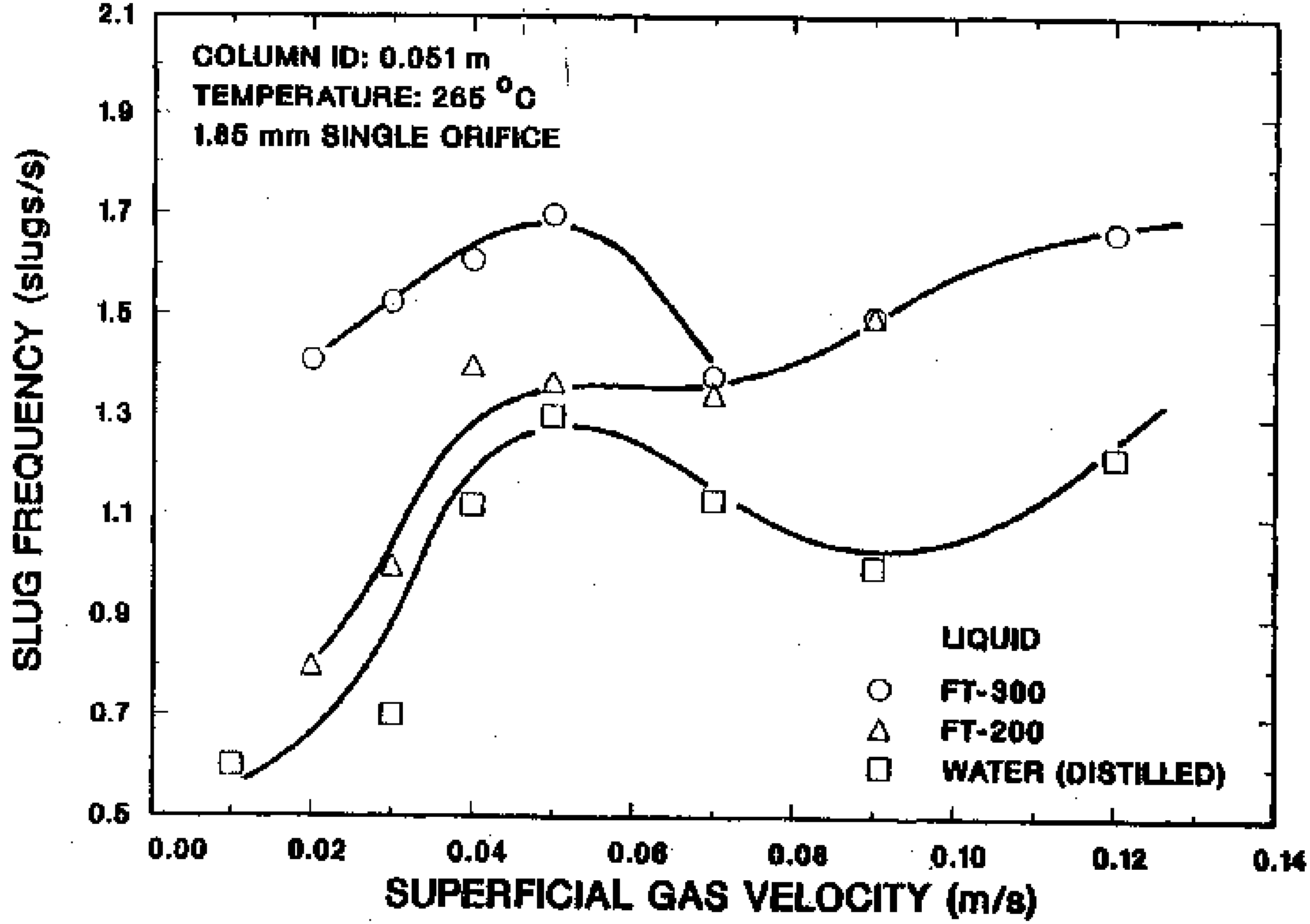


Figure V-7. Effect of superficial gas velocity and liquid medium on slug frequency (measurements made at 0.3 m below the top of the expanded level) (Run 3-2) seen from Figure V-7, the slug frequency for each medium goes through a local maximum followed by a local minimum. Similar results were obtained by Ohki and Inoue (1970) in an air-tap water system. This type of behavior can be explained as follows. Initially, the number of slugs increases until the slug frequency reaches a maximum. At this point, the slugs begin to interact with one another, becoming longer; hence, the frequency of the observed slugs decreases. This decrease in frequency with increasing gas velocity continues till a maximum stable slug size is reached. This corresponds to the local minimum value of the slug frequency. Since slugs do not appear to grow in length beyond this point, a further increase in the gas flow rate causes the slug frequency to increase. For all three liquid mediums a maximum slug frequency occurred between 0.04 and 0.05 m/s. For FT-300 and FT-200 waxes, the minimum occurred at 0.07 m/s while with water the minimum occurred at 0.09 m/s. The slug frequencies associated with water at all velocities were less than those of either waxes. This is probably due to the fact that significantly longer slugs were formed in the experiments with water than in the experiments with wax. For velocities less than 0.07 m/s, the slug frequency of FT-200 was less than that of FT-300. This is probably due to the fact that FT-200 produces fewer large bubbles (i.e. fewer and smaller slugs); hence, the slug frequency is smaller.

Figure V-8 shows the slug frequency as a function of gas velocity for FT-300, FT-200, and water for experiments conducted with the 40 μm SMP distributor. For FT-300 and FT-200 waxes, the slug frequency increases with an increase in gas velocity and levels off (FT-300 - 2.0 slugs/s; FT-200 - 1.2 slugs/s). This is probably caused by the large

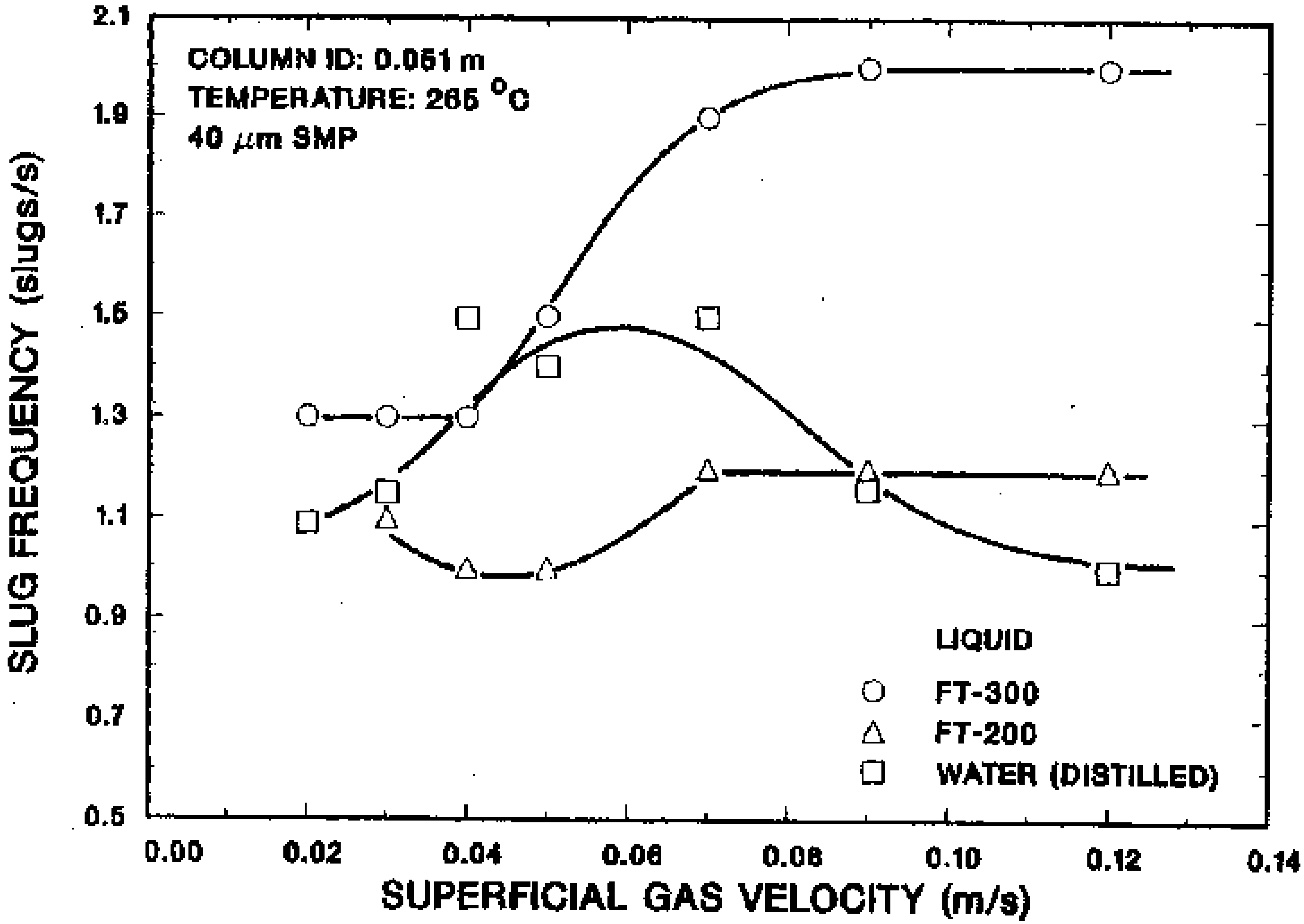


Figure V-8. Effect of superficial gas velocity and liquid medium on slug frequency (measurements made at 0.3 m below the top of the expanded level) amounts of foam present which prevent significant bubble interaction. On the other hand, the slug frequency did go through a maximum (1.5 slugs/s) between 0.04 and 0.07 m/s for the experiment conducted with distilled water (i.e. no foam present). As seen with the 1.85 mm distributor, the slug frequency associated with FT-200 was significantly less than that of FT-300.

A.2. Large Columns (0.229-0.241 m ID)

The major difference between the flow regimes present in the 0.051 m ID column and those present in the large columns (0.229-0.241 m ID) is the absence of slugs in the latter. In the absence of foam, the "churn-turbulent" flow regime prevails in the large columns for velocities of 0.02 m/s and higher. Observations made during experiments conducted with FT-300 wax at 265°C using a 19X1.85 mm perforated plate distributor are discussed here. At a gas velocity of 0.01 m/s and a height of 0.3 m above the distributor, small bubbles (1.0 - 5.0 mm in diameter) and fine bubbles (less than 1 mm) were present. Occasionally, larger bubbles (10.0 - 20.0 mm) appeared. The fraction of fine bubbles increases with column height. As the velocity was increased, local circulation patterns are observed in the column with the small and fine bubbles moving downwards near the wall of the column. At a velocity of 0.03 m/s, large bubbles, approximately 50.0 mm in diameter, were seen bursting at the top of the dispersion. At velocities of 0.09 and 0.12 m/s the fraction of large bubbles (50.0 mm in diameter) increased, and swirling patterns were observed in the liquid. The flow regime at 0.01 m/s may be characterized as the ideal bubbly flow regime and at higher velocities as the "churn-turbulent" flow regime. During runs when foam was produced, the ideal bubbly flow regime was followed by the "foamy" regime. This regime usually prevailed over the velocity range 0.02-0.05 m/s. Beyond this point a transition to the "churn-turbulent" flow regime took place. The amount of foam produced during runs in the 0.229 m ID columns was lower than that produced in the 0.051 m ID column with the orifice plate distributor.

A viewing port was constructed which enabled us to take photographs of bubbles at approximately 0.03 m from the center of the stainless steel column, at a height of 1.45 m. At a velocity of 0.01 m/s, it is expected that the bubble size at the center of the column would be approximately the same as that near the wall since the ideal bubbly regime prevails. However, at higher velocities, it is expected that larger bubbles would be present near the center of the column. Figure V-9 shows photographs obtained at 0.01 and 0.07 m/s in the large glass column (at the wall) and in the large stainless steel column (at the center). At 0.01 m/s it appears that bubbles observed at the wall are slightly larger than those observed at the center (Figures V-9a and V-9b). However, at 0.07 m/s the bubbles at the wall are smaller than those near the center (Figures V-9c and V-9d).

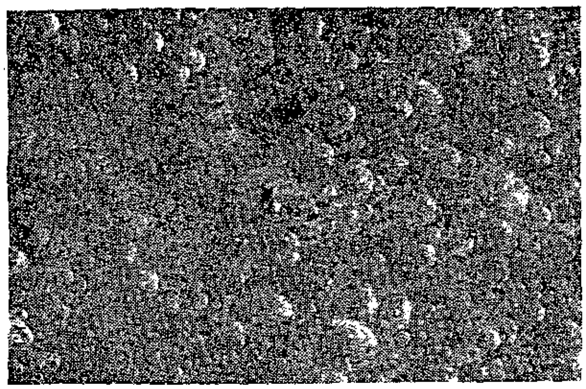
Since we were limited to observations at the wall of the column and at the top of the liquid level, no significant differences were seen for the other distributors employed in our study or with Sasol's Arge reactor wax. On the other hand, our experiments conducted with distilled water showed a significant increase in the fraction of large bubbles (50 mm in diameter) and essentially no bubbles less than 5 mm in diameter.

FIGURE V-9

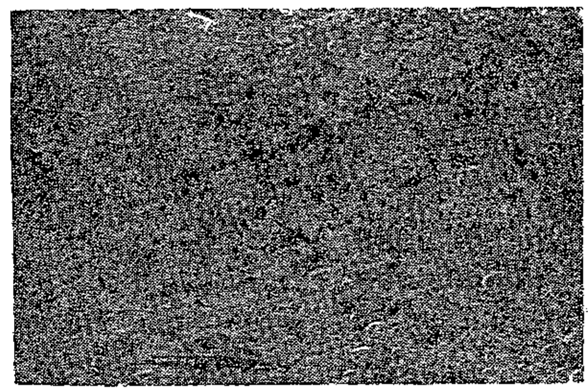
EFFECT OF RADIAL DISTANCE

0.229 m ID Glass
height = 1.2 m

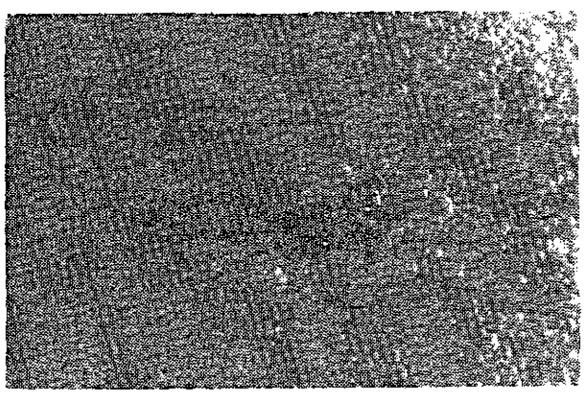
0.241 m ID SS
height = 1.45 m



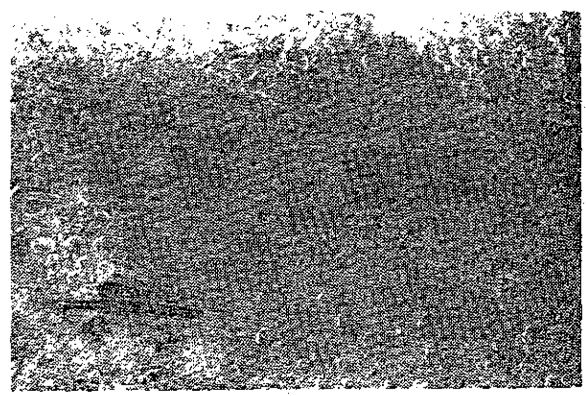
a. 0.01 m/s; at wall



b. 0.01 m/s; 0.03 m from center



c. 0.07 m/s; at wall



d. 0.07 m/s; 0.03 m from center

SCALE: ——— 25.4 mm; Figures a, b, & d

SCALE: ——— 25.4 mm; Figure c

T = 265 °C; FT-300 WAX