SECTION 2

PROBES AND ONE-DIMENSIONAL MODELS

2.1 INTRODUCTION

This section of the report presents circulation results obtained from a laboratory scale bubble column, and demonstrates that one dimensional models meet with success in predicting circulation rate in tall columns.

2.2 LITERATURE REVIEW

The vast majority of circulation research has been performed on air-water bubble columns, but this can be extended in principle to the case of Fischer-Tropsch column provided that the fluid properties of the pulp are properly considered. Several bubble column researchers have accounted for circulation by modeling the overall holdup of gas in the column (see the reviews by Lockett and Kirkpatrick, 1975 and Shah et al., 1982 and the paper by Deckwer et al., 1974) but this approach is not general and cannot be used to infer the actual fluid velocity distribution in the vessel. For one dimensional analytic models, circulation is usually quantified in terms of the velocity distribution across the diameter at half of the column height. Usually the velocity near the center is upward while the velocity near the wall is downward although reverse circulation has been documented and more complex patterns are possible in large columns. Similar distributions in gas-liquid bubble columns have been measured or proposed by many different workers for a variety of column diameters (Rietema and Ottengraf, 1970; Hills, 1974; Rietema, 1982; Freedman and Davidson, 1969; Lamont, 1958, Steinemann and Buckholz, 1984) but little theoretical analysis is given in the literature.

Rietema and Ottengraf (1970) presented an analysis for the circulation in a Newtonian viscous liquid, while Hills (1974) examined turbulent air-water flow in a column and offered a model which used a force balance and a simple eddy viscosity model. A more detailed analysis along these lines has been presented by Miyauchi et al. (1981) but also involves simplifying assumptions about fluid shear stress which may not hold true in real column circulation. A model for circulation in Pachuca tanks (Clark, 1984) was restricted to vessels with draft tubes. Clark et al. (1987) developed a model based on simple mixing length theory, and a similar model using two mixing lengths has been offered by Michaelides and Nikitopoulos (1987). Anderson and Rice (1989) have also offered an elegant mixing length approach, while a more phenomenological analysis has been offered by Molerus and Kurtin (1986). However, there is still a need for additional accurate data on void distributions and circulation velocities in bubble columns to verify the application of these models over a broad range of column sizes and operating conditions.

2.3 EXPERIMENTAL APPARATUS AND APPROACH

A hollow cylindrical bubble column was designed to study gas-liquid circulation. It was constructed out of quarter-inch thick and eight inch internal diameter acrylic tubing. The column was composed of three attachable thirty inch sections. Each section has two, three quarter-inch flanges so that each piece could be bolted together. To prevent leaking between each section, O-rings were placed in the flange on the top section. The reason for having three sections was that it allowed for the column to be taken apart, transported, and placed together again with the least risk of possible damage to the column. Also, with three sections, the distributor plate can be changed easily. Beneath the column, a nine inch plenum of the same diameter as the column was located. To make sure that the column was perfectly horizontal, four adjustable screws are placed at the bottom of the stand. Figure 2.1 shows a schematic of the column.

Along the column walls, two resistance port holes were placed perpendicular to one another at six inch vertical intervals. The port holes are tapped with quarter-inch NPT. The two probe ports at each height allow for readings across two orthogonal diameters so that data can be taken various locations in the column to give a good evaluation of the circulation patterns.

The air needed for the project was supplied from shop source. A pressure regulator was used to control air flowrate. The air was led through a dehumidifier and then entered a Dwyer 1-10 SCFM air flowmeter. Flowrates read were for pressures at standard conditions (14.7 lb/in^2). When the flowmeter operated at higher pressure, a correction was needed to calculate the true flowrate.

From the flowmeter, the air was introduced into the plenum. Air passed through a distributor plate into the bottom of the column. The plate used was designed to given an even distribution of air, as shown in Figure 2.2.

To acquire local data, resistance probes were used. Resistance probes have been used previously (Herringe & Davis (1974) and Nassos & Bankoff (1967)) to measure the differences in resistance from the probe tip being in a bubble or immersed in liquid. These probes were used to estimate a time-average local void fraction.

In using resistance probes, the production and maintenance of such probes are very important in receiving reliable results. The design of a resistance probe is shown in Figure 2.3: the only location on the probe that should detect a bubble or liquid is at its tip. This is an important consideration when measuring local void fraction or bubble velocities. Since the results are supposed to be local, any part of the probe except for the tip detecting bubbles or liquid would be unacceptable. To insure that the probe tip was the only place uninsulated, the probe was checked on a regular basis. If the uninsulated tip becomes too big, smaller bubbles could go by undetected and the researcher would significantly under-estimate the local void fraction. Also, the size of the needle was important. The bigger the needle, the more obtrusive the probe becomes to the overall circulation pattern and the chance that a bubble could deflect away because of its size is increased.

The manufacturing of a good resistance probe was a delicate process. First, a thin stainless steel sewing needle was bent at an angle of approximately 45°. The eye of the needle was soldered to some fine insulated wire. Next the wire was passed through a twelve inch length of 12-gauge stainless steel tubing. The tubing has an outer diameter of 0.11 inches with a wall thickness of 0.011 inches. The needle was now spray-painted to make it insulated from the tubing. With a strong epoxy, a length of the needle was glued into the inside of the tubing leaving the tip protruding. If the needle remained insulated from the tubing, the resistance probe had been manufactured successfully. If this was not achieved, the probe would not be able to detect a bubble or liquid at its tip. This problem was easily checked with a resistance measurement.

With a successful probe made, one final step was needed to complete the process. To produce a conducting tip, the needle tip was abraded with fine sandpaper. To help limit long term electro chemical effects (Galaup, 1975), the needle was re-painted and sanded regularly.

Besides estimating local void fractions, this research was intended to estimate local bubble velocities. In order to do this, a different double resistance probe was needed. This probe contained two needles (Herringe & Davis, 1976) with one directly above the other (as shown in Figure 2.4). The same steps taken to make the single probe also applied in making the double probe.

In the collection of experimental data, the resistance probe, an intermediate circuit and the data acquisition board in a Zenith computer were the main components. To help take the data and reduce it, computer programs were written with the software package Microsoft Quickbasic 3.0. The schematic of the intermediate circuit for the data acquisition system is shown in Figure 2.5.

The probe andcircuit supplied close to zero voltage to a data acquisition board when the probe tip is in a bubble because the circuit was broken between the probe tip and tubing. When the probe tip was immersed in a liquid, the circuit was completed and a voltage was read between 2.5-3.25V. This variation of 0.75 was believed to be due to the electrochemical effects caused by the use of a direct current circuit and by variations between different probe tips. Galaup (1975) discussed the use of an alternating sinusoidal current supply, which greatly reduces the erosion to the probe tip. However, for this approach to be effective, Galaup stated that the frequency of the supply voltage had to be much greater than the frequency of the phenomenon being studied. With the constant checking of the probe tip,the use of an AC circuit did not probe necessary during the present research.

In the circuit shown in Figure 2.5, there is an extra resistor of 1MΩ along the common ground line. This resistor created a greater voltage drop from when the probe was in a bubble or liquid. If this resistor was removed, the voltage of the probe in liquid read around 0.7 volts.

In theory, the signal from the probe should display a square wave with one output voltage representing a bubble and the other output voltage liquid. From viewing Figure 2.6, the trace is far from being a square wave. Due to the finite tip size and the time taken for the liquid film to drain from or reform on the tip, the signal becomes more rounded. Hence the results for a time-averaged local voidage are underestimated if a threshold voltage is not carefully chosen. A threshold voltage is a cutoff point above which the signal voltage represents a liquid and below which it represents a bubble. A newly developed protocol for identifying the best threshold voltage is discussed later in this section.

Since the probe's purpose was to detect the bubbles or liquid, a data acquisition board was needed to enact the probe, take the data, and reduce the data so that it can be analyzed. The data acquisition board used was a RTI-815-F from Analog Devices (Norwood, MA). With the compatible software language Quickbasic, the acquisition board acted as an interface between the resistance probe and the Zenith Z286 PC. This board has various analog/digital, input/output, and time related functions. For this research, the analog inputs were multi-plexed to allow for 32 single-ended and 32 pseudo-differential input channels. The board has a 12-bit analog-to-digital converter. This constitutes a conversion resolution of 4096 counts over input signals ranging from -10V to +10V (1 count ≈ 4.88 mV). The board also has the ability to amplify a low-level signal and take data at a maximum speed of 71,400 MHz. The board was operated in the Direct Memory Access (DMA) mode. When the DMA is accessed, the computer's microprocessor gives up its control to the DMA controller. By skipping over the micropressor, data can be taken rapidly and stored in Random Access Memory (RAM) until it is needed. Once all the data is taken, the microprocessor regains control of the RAM.

The process of taking data involved three subroutines from the RTI board library. They were called the Initialize, Scan, and Check routines. The Initialize routine reads the hardware configuration data from the disk. It clears all previously defined logical channel definitions and makes sure the DMA buffer allocated. If either is not achieved, an error code is returned. Before the data acquisition begins, the Initialize routine must be executed. The next routine implemented was SCAN. This routine reads a specified number of analog inputs into DMA buffer from multiple channels. It goes to the channel specified and then loops continuously over the 32 input channels until the number data points specified is reached. To allow for all 32 input channels to be used, and AC1585-1 Screw Termination Panel was added to the board. This extension is displayed in Figure 2.7. Only two input channels are directly connected to the probes. However, the other channels are linked to the two main channels to allow for the probe to take readings on all 32 channels. The last routine used was the CHECK routine. The CHECK routine tests for the completion of the SCAN and COLLECT operations.

In estimating the global void fraction or the overall gas hold-up, the mixture expansion was measured. As Hills (1974) and Molerus (1985) discussed, this theory compares the volume of an unaerated liquid phase to a new aerated volume of a gas-liquid mixture. Since the column used has a constant cross-sectional area, the global void fraction was estimated by the comparisons of the heights before and after aeration. The equation for the global void fraction is

$$\bar{\epsilon} = \frac{H_m - H_L}{H_m}$$

where

H_m = height of two-phase gas-liquid mixture

H_L = height of single-phase liquid before aeration

$\bar{\epsilon}$ = global void fraction

A problem with the mixture expansion is estimating the height of the column once the air is introduced. As Molerus (1985) observed, at high flowrates, a foam region appears at the top of the mixture. The foam was not considered when estimating the height, H_m, in the column. From observation, there are not any circulation patterns occurring in this region. Also, the mixture density in this foal was considerably less than the average density of the gas and liquid in the bulk of the column. It was for these two reasons that the foam region was disregarded. In this research, the mixture expansion was used solely as a comparison tool to verify resistance probe data. This comparison provided a check on the reliability of the resistance probes, by comparing global holdup measured in the column.

In estimating the local void fraction, the method used to determine the threshold voltage was very important. If the threshold voltage was not chosen wisely, the local void fraction would be underestimated or overestimated. Previous workers have generally used a Schmitt trigger to perform this function, but in the present work it was implemented with software. A program was written to collect the voltage from the probe at a large number of discrete times (generally 1000). Each voltage was then examined to see whether a bubble or liquid was present at the probe at that time, and a time-averaged gas void fraction was computed. To establish a cutoff voltage, the probe was operated at a fixed point with constant two phase flow conditions in the column. During preliminary work time-averaged void fraction was computed using tentative threshold voltages varying from 0 to 3V, and a voltage of 1.625V was selected as a good threshold voltage in the preliminary research since this lay on the "plateau" of a plot of measured void fraction against threshold voltage.

Subsequent analysis of high-speed traces of the probe voltage signal has demonstrated that this primitive thresholding was unsatisfactory. Also, comparison of increase in column height, with the local measured void fraction integrated throughout the column volume has shown that the probe with primitive thresholding may underestimate void fraction by as much as 40%. The trace in figure 2.6, showing voltage versus time for a probe in the 8-inch diameter column, demonstrates that the probe signal is certainly not a square wave. Brief intersections with bubbles lead to a small voltage drop, which may not be detected by the primitive thresholding, and more significant intersections still show a finite rate of voltage drop and rise. The investigators have concluded from these traces and from cumulative frequency plots of measured voltage (see figures 2.8 and 2.9)that a better threshold is a voltage which is very slightly lower than the typical voltage when the tip is in water. A final criterion chosen for the threshold was 0.025V less than the voltage at the 50th percentile on the cumulative frequency plot of voltage, this percentile being an excellent estimate of the probe voltage in water. Since measured void fractions are always less than 50%, this approach proves to be reliable and quite objective. The new thresholding criterion has led to an improvement in void fraction measurement: the void fraction measured by the probes is then less than 10% lower then the void fraction implied by column expansion.

Voidage profiles at various heights and flowrates could now be measured with a reliable method of estimating the threshold voltage. For the experimental analysis, voidage profiles were developed at three heights of one, two, and three feet of water each subsequently aerated with 4.6, 7.3, and 10.4 CFM of air. To show the circulation development, the probe was inserted at various heights in the column. To obtain an accurate time average over a long time period, ten runs of 1200 readings at 62.5 points per second were taken. To check the consistencies of the probes, a sample standard deviation for small sets of experimental data was calculated using the equation:

$$\sigma = \sum_{i=1}^{N} \sqrt{\frac{(\varepsilon_{ave} - \varepsilon(r))^2}{N-1}}$$

where σ = sample standard deviation

N = number of experimental tests

ε_{ave} = average of experimental tests

The probe tip was placed an inch from the far column wall and moved away from the wall in one inch increments until the tip was an inch from the probe port opening in the near side wall. At the same time, a second profile was developed perpendicular to the other profile at the same height. This gives a more 3-dimensional impression of the circulation process, and it also serves as a check on the probes. Instead of one local void fraction, there are two local void fractions (which should be quite similar) at each radius. The results should be similar because the column was level, air was introduced evenly through the distributor plate, and the circulation should be symmetrical. If the results from the two probes varied too much, it was found that one of the probes was not functioning properly. In this instance, the faulty probe was removed and replaced.

In estimating the bubble velocity in the bubble column, two different approaches were taken. With each method, the technique had to be able to estimate bubble velocities ranging from -20 to 50 in/s. This range was found by adding the expected bubble slip velocity (Serizawa et al, 1974a) to the expected circulation velocities found using one-dimensional theory and the measured void profile. The first approach used a cross-correlation technique to estimate an overall bubble velocity, while the other method measured individual bubble velocities. In both techniques, the results were not very reliable. However, in the center of the column, the results were more acceptable.

Bubble velocities were determined in a circulating system (initially two feet of water), at 6", 12", 18", and 24" above the distributor plate, and at air flowrates of 4.6, 7.3, and 10.4 CFM. From these results, a liquid velocity profile could be compared with the one dimensional force balance approach. The distance between the lower and upper probe tip was 3/8". Velocity data was taken at a sampling rate of 2000Hz (1000 Hz per probe tip) for eight seconds.

The cross-correlation technique (Herringe & Davis, 1974b and Serizawa et al, 1974) searches for a time delay between probe tips by multiplying the signal from the lower probe by the signal of the upper probe a moment of time, Δt, later, and then determining the Δt for which this product is a maximum.

The signals of the two probes are multiplied according to the following equation:

$$F(\Delta t) = \sum_{i=1}^{T} V_L(t)V_U(t+\Delta)$$

where $F(\Delta t)$ = sum of multiplied signals at a specified time delay

$V_L(t)$ = signal of lower probe

$V_U(t+\Delta t)$ = signal of upper probe

To illustrate this point Figure 2.10 shows an actual experimental traces of the signals from the two probe tips and Figure 2.11 displays the cross-correlation technique determining the time delay between probe tips. With the time delay known, the actual velocity can now be calculated by the equation

$$V_B = \frac{\Delta x}{\Delta t_A}$$

where V_B = bubble velocity

Δx = probe tip separation

Δt_A = actual time delay

To relate liquid and bubble velocity,

$$V_B = V_L + V_b$$

where V_B = bubble velocity in circulation relative to column

V_L = liquid velocity

V_b = rise velocity of a single bubble in quiescent fluid

The rise velocity of a single bubble can be (Harmathy, 1960) calculated by the equation:

$$V_b = 1.53\left[\frac{\sigma g \Delta\rho}{2\rho_L}\right]^{1/4}$$

where σ = surface tension between air and water

g = gravity

$\Delta\rho$ = difference in density between air and water

ρ_L = liquid density

This equation applies for bubble sizes ranging from 2-30 mm which were the approximate size of the bubbles seen in the column. In this way liquid velocities could be inferred from probe measurements.

To test the cross-correlation approach, an attempt to measure a single bubble's velocity was made. Quarter-inch nominal diameter tubing was attached to the air supply. The tubing was placed through a probe port in the column and the end of the tubing was located at the center of the column. Next, the double resistance probe was inserted above the tubing so that bubbles from the tubing could impact the probe. Air was then introduced into the column at such a low flowrate that individual bubbles rose from the tubing periodically. As the isolated bubbles approached the probe, the data acquisition program was started and the probe took data. A trace of two bubbles impacting the dual probe is displayed in Figure 2.12. The cross-correlation program estimated a bubble velocity of 10.2 in/s. These results coincide with the single bubble theory, and it also demonstrates the accuracy and ability of the cross-correlation technique to measure the rise velocity of a single bubble.

Implementing the cross-correlation technique was accomplished through the use of computer software. The technique was broken into two programs with one taking and storing the data while the other program retrieved the data and reduced it. The first program, RAWDATA, was identical to the data taking process for the local void fraction with the only exception being the sampling rate. The CORRELATION program began with retrieving the stored data and separating the data into the lower and upper probe arrays. Another program was also written that could measure individual bubble velocities (termed the "window" method). Serizawa et al, (1974) used a similar approach called the "Multi-channel Technique". They took down the time a bubble hit the lower and upper probe and with the separation between the probes known, the velocity of that individual bubble during circulation could be calculated. In this case the RAWDATA program was used again for the data taking process. Also, the technique used to determine a threshold voltage of each probe was implemented in the program REDUCTION to determine the precise time a bubble hit and left the two probes. This data was stored in data files and reduced later in the WINDOW program.

The WINDOW program takes the time a bubble impacts the lower probe and searches for the same bubble to hit the upper probe within a specified time frame or "window frame". This window frame was based on the expected bubble velocity found from one dimensional theory. From the predicted velocity the window frame was opened up to look at times representing 50% before and after the expected bubble velocity. After a bubble impacts the lower probe, several scenarios are possible. Serizawa et al, (1974) noted (a.) the bubble does not hit the second probe within the time span, (b.) the bubble deflects and misses the probe, and (c.) another bubble reaches the upper probe before the first bubble arrives. See figure 2.13. There are two other possibilities that could affect this technique. One possibility is if a bubble hits the lower probe away from the center, the bubble could deflect and hit the upper probe centrally. This would cause an overestimation in the bubble velocity. The other possibility was just the opposite. In this case, a bubble could hit the lower probe at its center and deflect to where the bubble would impact the upper probe at its side. This case would cause an underestimation of the bubble velocity. Figure 2.13 displays all the possibilities leading to velocity malestimation.

In the WINDOW program when a bubble was found at the upper probe within the window frame, the following equation was executed:

$$\text{mult} = \frac{[S_L - S_U] + [E_L - E_U]}{2}$$

where mult = time delay for individual bubble

S_L = starting time of bubble on lower probe

S_U = starting time of bubble on upper probe

E_L = ending time of bubble on lower probe

E_U = ending time of bubble on upper probe

To make sure that the bubble on the upper probe was not computed with another bubble on the lower probe, a string condition was placed on it to disallow the bubble from further computations. When there was not a bubble on the upper probe within the time frame, a new starting time for a bubble on the lower probe was found and the process repeated itself. While Serizawa et al, (1974) only used the starting times, the ending times on the probes were used in this research to help compensate for the under and overestimations demonstrated in Figure 2.13. All the time delays for the individual bubbles were totaled and averaged to find the actual time delay between the probe tips.

2.4 EXPERIMENTAL RESULTS

The results found for the local void fraction were reliable. In comparison with the expansion of the mixture upon aeration; the local void fraction was underestimated by only 8-15% as shown in Table 2.1. With this small error, the threshold technique described above was taken to be reliable, since some underestimation might be expected due to deflection of bubbles from the probe.

Void fraction profiles were measured across the column diameter for the following conditions: at 1, 2 and 3 feet of unaerated water in the column, at