

RESEARCH REPORT

DYNAMICS OF TWO-PHASE FLOW IN BUBBLE COLUMN FLOTATION UNITS

by

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## ABSTRACT

The dynamics of two-phase flow in the bubbly column flotation cell is very complex, yet some knowledge of this problem is essential for efficient design and operation of the unit. A detailed study was carried out to characterize the flow of bubbles in a water-nitrogen system through holes in a constriction plate within the flow path. The results indicate that the stability of the experimental unit was sensitive to the flow rates of the gas and water, the nozzle size, and the area ratio of the holes to the area of the plates. Addition of surfactant to the water produced fine spherical bubbles but large and irregular bubbles were produced if the cell was operated under unstable conditions. Distinct flow regimes were established for each plate used in the experimental cell, and the effect of each variable on the stability of the flow regime is discussed.

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## EQUIPMENT DESCRIPTION

The schematic of the equipment used for the investigations is shown in Figure 1. Water was pumped from a 35 gallon circulating tank through a nozzle (aspirator); compressed gas (nitrogen) was passed through the aspirator where it mixed with water to form bubbles. The bubbles and water entered the upper portion of the circulating tank above the perforated plate. Six  $\frac{1}{2}$  inch inlet ports were evenly distributed along the circumference of the tank. The inlet lines were directed perpendicular to the lower constriction plate, which had nine  $\frac{1}{2}$  inch diameter holes. The lower part of the column was separated from the 40 inch separation column by the upper constriction plate. "Make-up" water was introduced just above the lower plate. The flow rate of the circulating water, make-up water, and nitrogen were independently controlled, and the upper plate and the nozzle could be replaced as necessary.

Photographs of the bubbles in the upper and lower columns were taken in order to document the type of flow and the size of the bubbles. Also monitored were the pressure-drop across the upper plate and the head-pressure above it. To help in determining the bubble size, three plastic balls, each with a diameter equal to 3.54 mm, were suspended in the upper column. These balls appeared in the photographs, along with the bubbles, and were used to calibrate the bubble sizes.

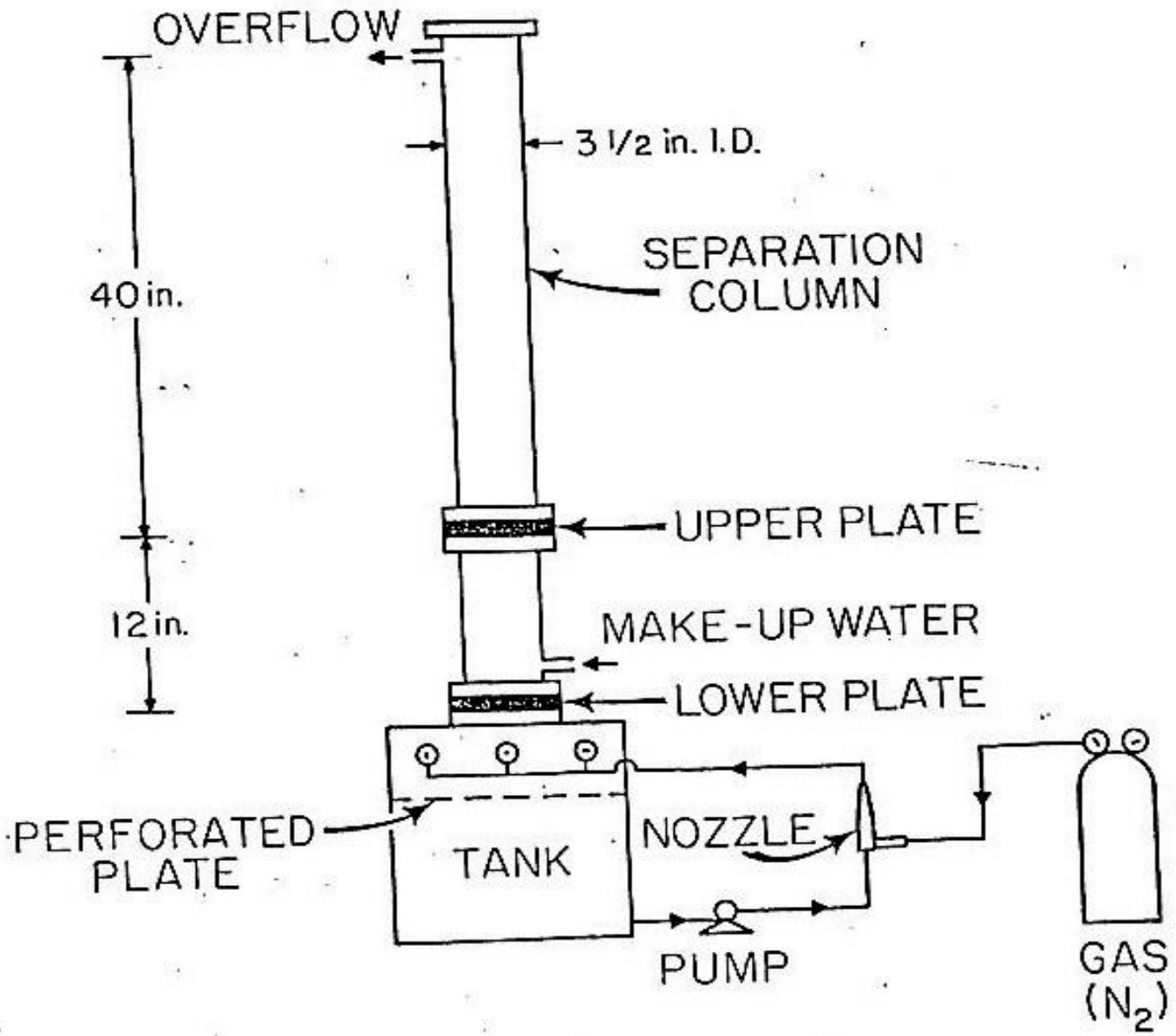


Figure 1: Experimental bubble column flotation unit.

## RESULTS AND DISCUSSION

The following results are based on the system shown in Figure 1. Some of the applicable data on the system appear in Table 1.

Table 1  
Operating Characteristics of the Bubble Column

Circulating water flow rate,  $Q_L$  = approx. 7 gpm  
Gas flow rate (variable),  $Q_g$  = 0-6 l/min  
Make-up water flow rate (variable),  $Q_L^1$  = 0-0.75 gpm  
Length of separating column,  $L$  = 3.31 ft.  
Diameter of column,  $D$  = 3.5 in.

<u>Upper Plate Number</u>	<u>Diameter of Holes, in.</u>	<u>No. of Holes</u>	<u>Hole Areal Fraction, <math>A_{H1}/A</math></u>
1	1/2	17	0.347
2	1/4	29	0.148
3	1/8	29	0.037

### Effect of Surfactant Addition

Without surfactant the sizes of the bubbles produced in the system depended strongly on the nozzle diameter and surface tension of the water for low gas flow rates. With the addition of a small amount of surfactant to the circulating and make-up water the bubble size was independent of the nozzle size, and it was much smaller than the size



of bubbles produced in the absence of surfactant. The bubble diameter before addition of surfactant was generally greater than 4 mm with elliptic or irregular shapes whereas with the surfactant the bubble size was always less than 2 mm.

Aeroflot 73 was used as the surfactant in this investigation. In accordance with industrial practice, 8 ppm (by weight) was the amount added to the water; at this concentration the surface tension is approximately 70 dynes/cm. The same concentration of surfactant was maintained in the make-up water. The measured bubble diameters, obtained from analysis of 60 photographs are summarized in Table 2.

Table 2  
Bubble Diameters after Surfactant Addition

Range of Bubble Diameters, $d_b$ (mm)	Average Diameter in the Range (mm)	Approximate Number Percentage in the Range (%)
$0.6 < d_b \leq 4.0$	$2.00 \pm 0.85$	<5
$0.1 < d_b \leq 0.06$	$0.44 \pm 0.11$	10-40
$d_b \leq 0.1$	Unresolved	>50

The results which follow are from experiments in which the surfactant was added to the water.

#### Effect of the Nozzle Size

The diameter of the nozzle affects the mass flow through the system and is therefore crucial to the efficient operation of the cell. There was no measurable flow through the water meter when the 1/4-inch diameter nozzle was used. On the other hand, a flow of approximately 7.0 gpm was obtained with the 1/2-inch diameter nozzle. The larger nozzle was therefore used throughout this investigation.

Figure 2 displays the flow rate of the circulating water as a function of the gas flow rate through the 1/2-inch diameter nozzle. The data

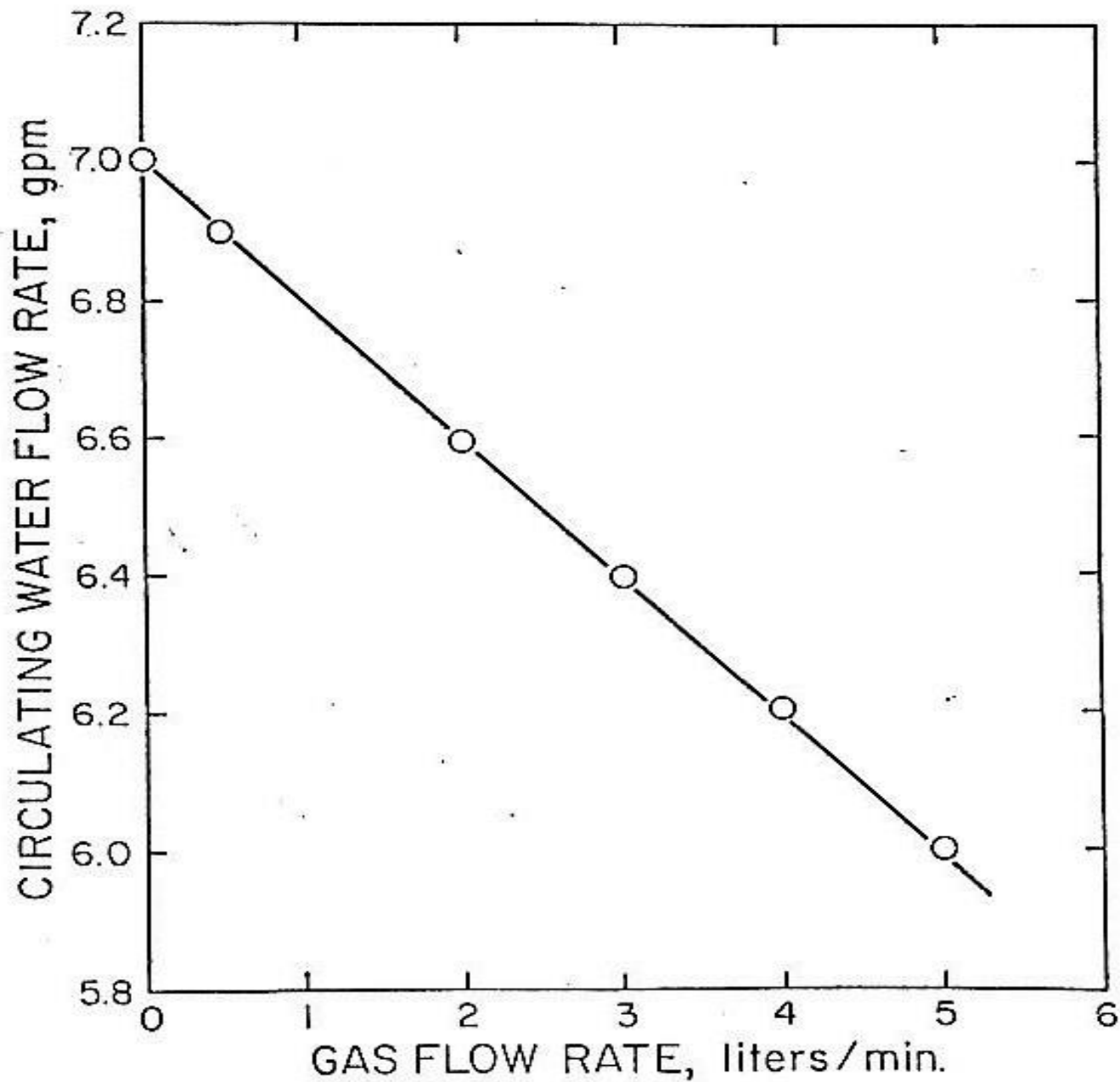


Figure 2: Circulating water flow rates and corresponding gas flow rates obtainable with the 1/2 inch diameter nozzle.



follow the equation:

$$Q_L = 7.0 - 0.2Q_g \quad (1)$$

where  $Q_L$  is the volume flow rate of water, gpm, and  $Q_g$  is the volume flow rate of gas, liters per minute. Equation (1) applies to the system when the valve controlling the circulating water and the valve controlling the gas flow are both completely open.

#### Gas and Circulating Water Flow Rates

When the flow of the circulating water was decreased below a critical value by partially closing the outlet (discharge) valve at the pump, the gas in the inlet lines to the tank (Figure 1) developed "slugs". In turn, these slugs caused surges of gas pockets under the upper constriction plate. When this happened, irregularly shaped and large bubbles were observed above the upper plate.

In Figure 3, the gas momentum flux is plotted against the make-up water momentum flux at various values of the circulating water flow rate. At a specific flow rate of the circulating water, the region above the curve defines the condition when the gas between the constriction plates flows as large, irregularly shaped bubbles whereas in the region below the curve the bubbles maintain their sphericity and small size.

#### Gas and Make-up Water Flow Rates

The circulating water did not flow through the upper constriction plate into the separation column; hence, make-up water was introduced into the system above the lower constriction plate (Figure 1). Data collected at various gas and water flow rates were used in computing the momentum flux of each phase.

To determine the density of the gas below the upper plate, the gas pressure was calculated by the equation:

$$P_g = P_o + \bar{\rho}gh + \frac{2\sigma}{r_i} \quad (2)$$

where  $P_o$  = atmospheric pressure  
 $\bar{\rho}$  = density of the two-phase fluid in the column,  
 $h$  = height of the column,  
 $r_i$  = radius of the bubbles, and  
 $\sigma$  = surface tension.

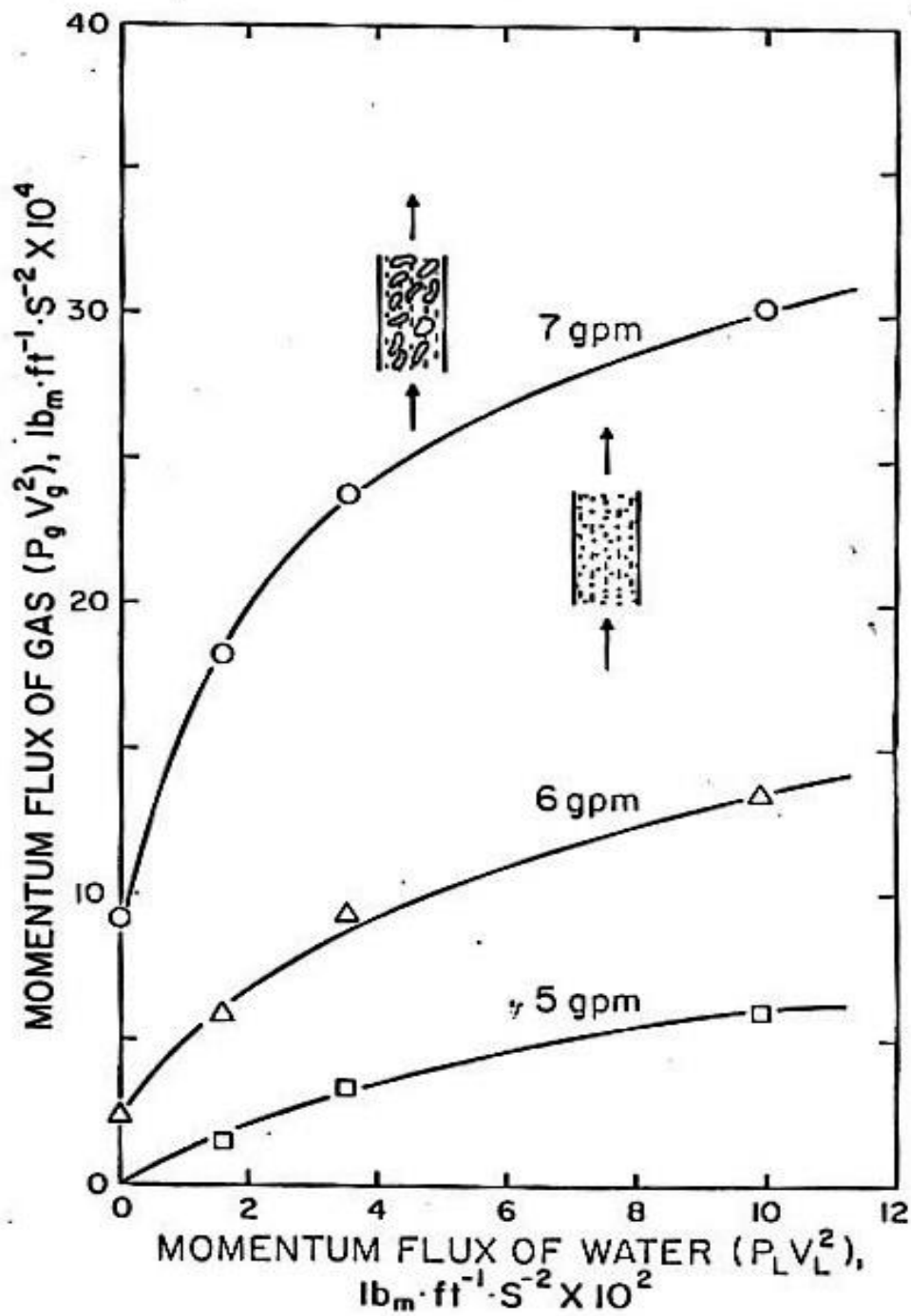


Figure 3: Flow regimes for plate 1. The numbers on the curves refer to the flow rate of the circulating water.

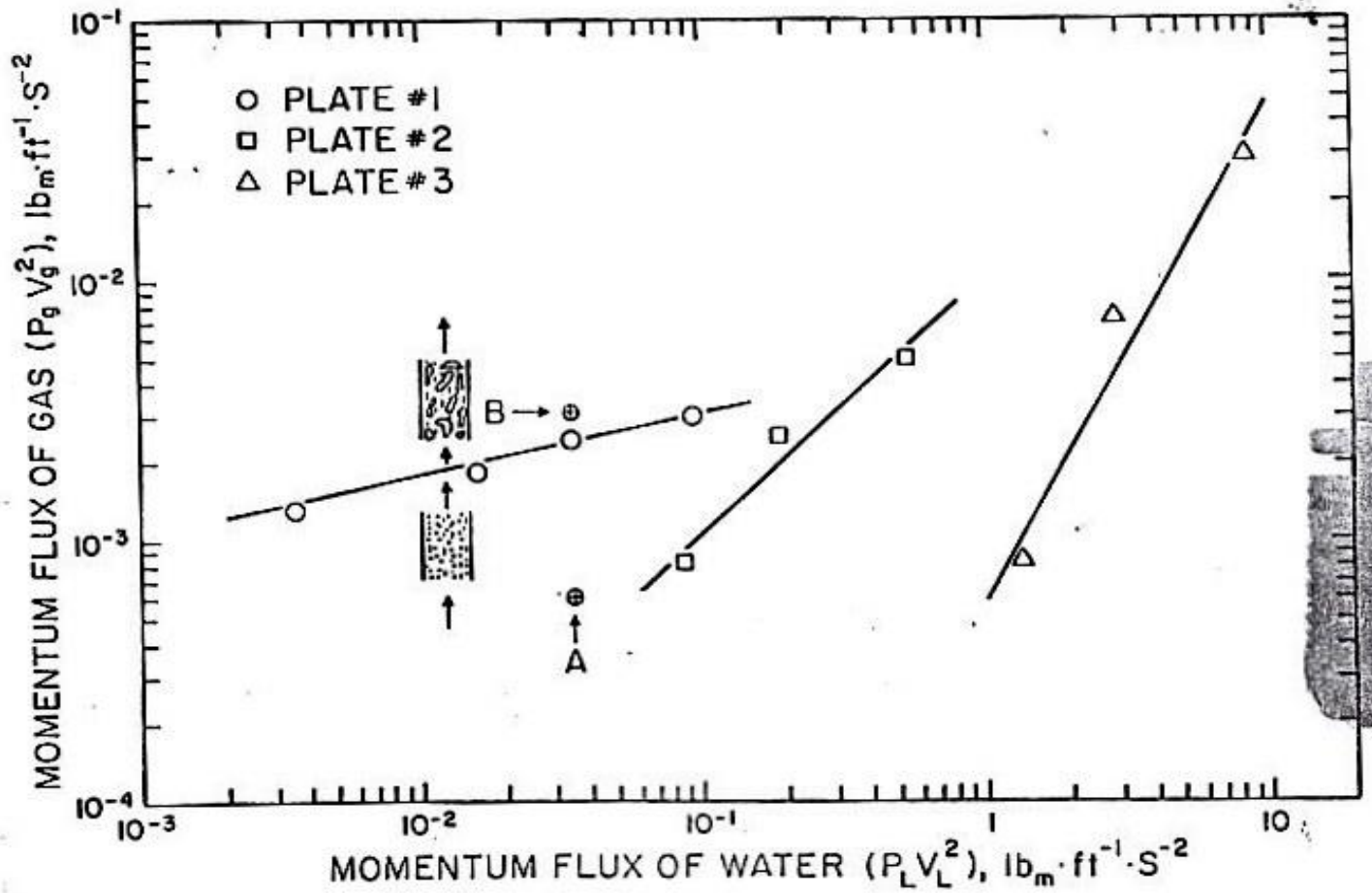


Figure 4: Flow regimes for plate 1, 2, and 3 at 7 gpm circulating water flow rate.



where  $E_g$  = gas momentum flux ( $lb_m/ft \cdot s^2$ ),

$E_L$  = water momentum flux ( $lb_m/ft \cdot s^2$ ), and

$\alpha$  and  $\beta$  are constants.

A least square analysis of the data of Figure 4 gives the results tabulated in Table 3.

Table 3  
Values of the Constants for Equation 6

Plate Number	Diameter of holes, in.	$\alpha$	$\beta$
1	1/2	$5.35 \times 10^{-3}$	0.25
2	1/4	$1.04 \times 10^{-2}$	0.99
3	1/8	$5.31 \times 10^{-4}$	1.94

At this point it was decided to compare the data obtained for two plates at various make-up water flow rates and at two circulating water flow rates. Earlier in Figure 3, it was observed that a dramatic change occurred when the circulating water was varied; hence, similar data were collected for plate No. 2. Figure 5 displays the results for plates 1 and 2 at circulating water flow rates of 7 and 6 gallons per minute. It is seen that the relationship described by Equation 6 holds for each plate at both flow rates. More interestingly, an analysis of these lines revealed that for a given plate, the slope of the lines, at both flow rates, are the same while the intercepts vary as shown in Table 4. The constant slope ( $\beta$ ) for each plate might be due to the influence of the hole size on the flow through the plate; however, more tests are needed to confirm such influence. The intercept ( $\alpha$ ) is shown to vary with the circulating water flow rates. No conclusive relationship can be established for the slopes and intercepts of the above results on the basis of the limited experiments conducted, nevertheless the results indicate the complexity of the system and the potential of such relationship in enhancing the mathematical description of the system.

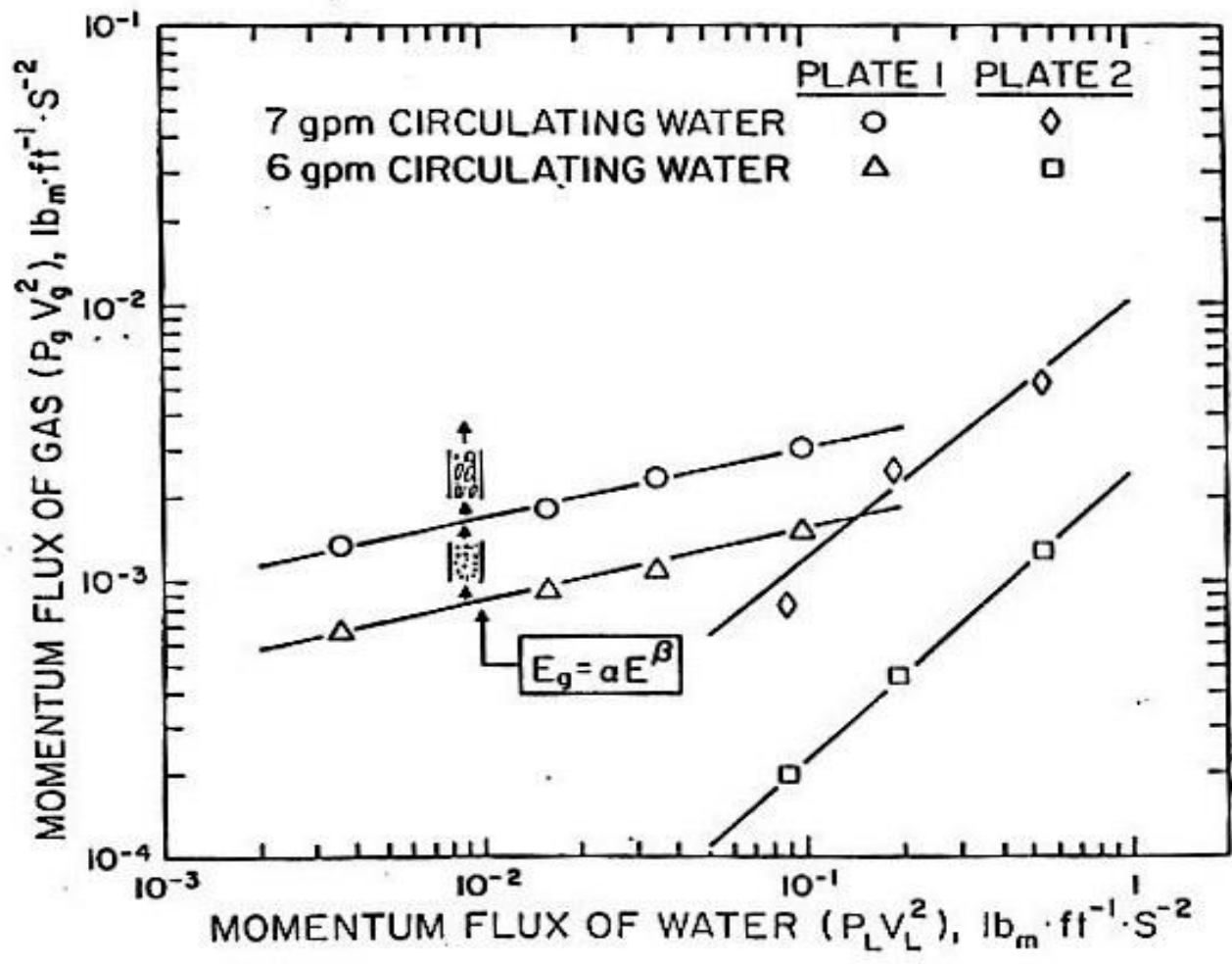


Figure 5: Flow regime for plates 1 and 2 at circulating water flow rates of 7 and 6 gallons per minute.

Table 4  
Values of Constants for Lines in Figure 5

Plate Number	Diameter of holes, in.	Constants at Circulating Water Flow Rates			
		7gpm		6gpm	
		$\alpha$	$\beta$	$\alpha$	$\beta$
1	1/2	$5.35 \times 10^{-3}$	0.25	$2.70 \times 10^{-3}$	0.25
2	1/4	$1.04 \times 10^{-2}$	0.99	$2.43 \times 10^{-3}$	1.03

### Constriction Plate Holes

The size of the bubbles above the upper constriction plate was affected by the diameter of the holes in the plate when there was a gas pocket formation below the plate. Large elliptic bubbles were produced whenever the gas pocket was observed. It is known that the efficiency of the column flotation cell is influenced by the size and shape of the bubbles within the separation column and such efficiency is increased by fine spherical bubbles which provide large surface area for particulate adsorption. On the other hand, large and non-spherical bubbles are less efficient due to their instabilities and small surface area; hence, their production is detrimental to the efficient operation of the cell.

Since the large and irregular bubbles were observed inspite of the presence of the surfactant, it was decided to compare the measured bubble diameters with those predicted by the following equation, under low gas flow rates to determine any dependence on hole size:

$$\left(\frac{\pi}{6}\right)d^3(\rho_f - \rho_g)g = 2\pi r\sigma \quad (7)$$

where  $d$  = diameter of bubbles  
 $\rho_f$  = liquid density  
 $\rho_g$  = gas density  
 $r_h$  = radius of hole  
 $g$  = acceleration due to gravity  
 $\sigma$  = surface tension of liquid



When appropriate values were substituted into the equation, the results shown in Table 5 were obtained.

Table 5  
Comparison of Measured and Predicted Bubble Size for  
Different Plates Under Gas Pocket Formation Conditions

Diameter (d)	Plate 1	Plate 2	Plate 3
Measured (mm)	6.57	4.56	3.29
Predicted (mm)	9.68	6.90	5.22
$\frac{\text{Measured}}{\text{Predicted}}$ ( $\frac{\text{mm}}{\text{mm}}$ )	0.68	0.66	0.63

The measured values are smaller than the predicted values but decrease with the diameter of the holes as in the predicted diameters. The ratio of the measured diameters over the predicted diameters is approximately the same for each plate and this indicates that the bubbles were produced under similar process. Also, when the measured values from each plate were compared to the diameter of bubbles from plate 1, the ratios agree substantially with those found for the predicted diameters, and this suggests that the holes in the plate act as nozzles which influence the final bubble size. Evidently, the bubbles produced due to the gas pocket formation are larger than those shown in Table 2 and therefore adversely affect the efficiency of the system.

The formation of the gas pocket created surges and back pressure in the system and could lead to failure if it is not prevented. About six inches of gas was observed below the upper plate with 1/8-inch holes but no gas pocket was observed when 1/2-inch holes were on the plate for the same operating condition. It was also found that the smaller the  $A_h/A$  ratio, the earlier the onset of surges and gas build-up. These results indicate that a smooth and efficient operation of the cell can be enhanced by high  $A_h/A$  ratios.

### Reverse Flow in the Column

An important requirement is that there be no reverse flow through the upper plate, and towards the circulating tank. To study this possibility cupric sulfate solution was introduced into the upper column below the overflow port, and the downward migration of the blue color was followed. In experiments with plate 1, the blue color descended through the plate when only the make-up water or only the gas passed through the column; this downward flow of the color was attributed to the mixing current that was created by either fluid.

When the flow rates of the gas and the make-up water were set at 2 liters per minute and 0.25 gpm, respectively, the color did not descend below the upper plate, but the downward migration of the color resumed when the flow rates were 4.5 liters per minute of gas and 0.25 gpm of make-up water. These conditions are shown in Figure 4 as points A and B, where A represents 2.0 liters per minute and 0.25 gpm and B represents 4.5 liters per minute and 0.25 gpm for gas and water flow rates. Since the region above the curve (Figure 4) is associated with surges and irregular bubbles, then the observed movement of the color towards the plate, at point B, could be attributed to the anisokinetic flow of bubbles due to surging. On the other hand, at point A which is in the region of smooth, fine and spherical bubbles, no reverse flow was observed. This indicates that a reversal of flow can be prevented if one operates the system below the curve of the flow regime of the given plate.

Further tests on the reverse flow conditions were carried out by measuring the electrical resistance between the upper and lower plates. The flow rates were set as in the previous section but the concentration of the salt ( $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ) was increased. At the flow rates of point A, the resistance measurements taken between the plates did not change significantly after the addition of the salt, confirming no reversal of flow for these conditions. However, significant drop in the resistance was observed when the system was operated under condition B, thus confirming the salt migration below the upper plate due to a reversal of the flow.

## CONCLUSIONS

1. In the experimental bubble column flotation unit, smooth and stable bubble regime is diminished by reducing the circulatory water flow rate.
2. A stable flow of bubbles in the cell is enhanced by large  $Q_L/Q_g$  and  $A_h/A$  ratios.
3. The flow regime is different for each plate and the stable region decreases with the hole diameters on the plate.
4. Whenever a gas pocket developed in the experimental unit, the produced bubbles were large and irregular and their diameters show some dependence on the size of the holes on the upper plate.
5. Reversal of flow of the fluids in the cell can be prevented if the unit is operated within the stable regime.



## RECOMMENDATIONS

1. More studies should be carried out to establish any dependence of the stable regime on the size of the holes on the plate, given the distinct regime exhibited by each plate, and the observed linear relationship between the gas and the make-up water momentum flux.
2. The effect of the plate thickness on the stability and characteristics of the bubbles should also be investigated.
3. The flow into the circulating tank with various inlet orientation should be studied to establish the effect of inlet size and distribution on the performance of the cell.
4. More nozzle sizes should be investigated to have a better understanding of the nozzle effect on the flow dynamics.
5. The length of the lower column should be varied to see how it might affect the final bubble characteristics.
6. The experimental system should be modified (or redesigned) to permit more flow of the circulating water and gas-flow rates. With such a system, greater momentum fluxes (e.g., as in Figures 4 and 5) through the constriction plate holes could be achieved so that the dynamics of the two-phase flow at greater flow rates could be determined.