The Ohio State University Research

The following report from Ohio State University for the period September-December, 1995 contains the following brief chapters:

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INTRINSIC FLOW BEHAVIOR IN A SLURRY BUBBLE COLUMN AT HIGH PRESSURE AND HIGH TEMPERATURE CONDITIONS

(Quarterly Report)

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WORK PERFORMED

1. *Measurement of interfacial surface tension between liquid and gas*

An area of high pressure and high temperature operation of slurry bubble column systems which is not fully understood is the effect of the physical property (densities, viscosity, surface tension, etc.) of the gas and liquid phases on the transport phenomena as the pressure and temperature increase. It may be possible to characterize the transport phenomena of slurry bubble column systems operated at high pressure and high temperature based on the physical properties of the phases rather than the operating pressure and temperature.

Slowinski *et al.* (1957) and Massoudi and King (1974) studied the pressure effects on the interfacial surface tension between the gas and liquid. Their results showed that the interfacial surface tension decreases approximately linearly with increasing gas pressure. The extent of reduction in the interfacial surface tension with pressure varies with the type of gas. The change in surface tension with pressure and temperature also depends on the liquid molecular structure and its molecular weight. The surface tension of a liquid in equilibrium with its own vapor decreases with increasing temperature in a low pressure system. Under high pressure conditions, the surface tension tends to increase with increasing temperature for some liquid mixtures (Reid *et al.*, 1977). Due to the important role surface tension plays in the dynamic behavior of the bubble motion, it is necessary to determine how the surface tension of various gas and liquid mixtures changes with pressure and temperature.

A capillary probe developed last quarter was used to measure the interfacial surface tension between Paratherm NF heat transfer fluid and nitrogen. The detailed design of the system was described in the first quarterly report. The schematic diagram of the system is shown in Fig. 1. Some modifications were done on the supporting rod after preliminary tests. A separate experiment was conducted to calibrate the capillary probe.

Interfacial surface tension varies with the absorption of nitrogen into Paratherm NF heat transfer fluid. The interfacial surface tension was measured when the liquid is saturated with the pressurizing nitrogen and liquid vapor. The measurements were carried out for pressures ranging from atmospheric pressure to 3000 psig, and temperatures of 27 and 56.5 °C. The experimental data are shown in Fig. 2. As can be seen from Fig. 2, the surface tension decreases linearly with an increase in pressure at both temperatures. The changes of the interfacial surface tension between Paratherm NF heat transfer fluid and N_2 with the pressure show the same trend as that of water - N_2 system (Slowinski *et al.*, 1957).

2. ***Bubble effects on the transient flow pattern in bubble columns***

The experiment on transient flow structure in a two-dimensional bubble column under ambient conditions was carried out in this quarter. The experiments focused on the identification of the transient flow structure, and the relationship between the flow regimes (time-averaged macroscopic behavior) and the transient flow structure.

Two-dimensional systems were employed to yield important qualitative information in gas-liquid systems. Figure 3 shows the schematic diagram of the experimental system. Two 2-D columns made of transparent Plexiglass sheets have been used as the test columns. Column A is 48.3 cm in width, 1.27 cm in depth and 160 cm in height and consists of two movable partitions between the Plexiglass sheets which allow the width of the bed to be varied. The viewing section of Column B is 60.96 cm in width, 228.6 cm in height, and 0.64 cm in depth. Below the viewing section is the gas distributor which consists of 0.016 cm I.D. tube injectors, flush mounted on the column wall, 10 cm above the liquid inlet. The gas through each injector is individually regulated by a solenoid valve and a needle valve which are connected to the plenum compartment outside the column. The distance between two adjacent bubble injectors is 5.08 cm and the distance from the end injector to the sidewall is 3.81 cm. When the width of Column A is changed, there is no liquid and gas flow through the region outside the partitions.

Tap water was used as the liquid phase. The liquid phase was operated under batch conditions for all studies. Neutrally buoyant Pliolite particles of 200-500 μm were used as the liquid tracer. To ensure that the seeding particles follow the flow closely and have virtually no effects on the flow structure, the concentration of the seeding particles was maintained around 0.1% and the Stokes number of the seeding particles was much smaller than 1. Air was used as the gas phase. The gas pressure was maintained within 4 to 10 psig upstream of the gas plenum. The superficial gas velocity ranges from 0.1 to 6.1 cm/s. Acetate particles (d_p = 1.5 mm, ρ_s = 1250 kg/m^3) were used as the solids phase in the study of slurry bubble column systems.

A high resolution (800 X 490 pixel) CCD camera equipped with variable electronic shutter ranging from 1/60 to 1/8000 s was used to record the image of the flow field. A Particle Image Velocimetry (PIV) system developed by Chen and Fan (1992) was applied to measure local flow structures in the 2-D bubble columns. The PIV system is a non-intrusive technique which provides quantitative results on a flow plane including instantaneous velocity distributions of different phases, velocity fluctuations, gas and solid holdups, bubble sizes and their distributions, and other statistical flow information.

Based on the macroscopic bubble flow behavior in bubble columns, three different flow regimes are commonly identified, i.e. dispersed bubble, churn-turbulent and slugging (Muroyama and Fan, 1985). A gross circulating flow of liquid is observed for these systems under both the dispersed bubble and churn-turbulent (coalesced bubble) regimes (e.g., De Nevers, 1968; Freedman and Davidson, 1969; Hills, 1974). In general, the gross circulation comprises an upward flow in the central region and a downward flow along the wall with the inversion point (zero axial liquid velocity) located at about 0.5 to 0.7 radius of the column (Walter and Blanch, 1983). This non-uniform velocity distribution is significant in characterizing the column hydrodynamics, phase mixing characteristics, heat transfer and mass transfer. Based on the bubble dynamics and local liquid flow patterns, Tzeng *et al.* (1993) found that when the gross flow circulation occurs in the system, there are four distinct flow regions, namely central plume region, fast bubble flow region, vortical flow region, and descending flow region, as shown in Figure 4.

The macroscopic flow behavior and flow regimes are directly linked to the transient flow structure. Figure 5 shows a sample of the transient bubbling behavior in the dispersed bubble regime and coalesced bubble regime. A homogeneous flow regime, a regime containing four regions of flow, and a regime of containing three regions of flow are seen as the gas velocity is increased in a 2-D bubble column. The dispersed bubble flow regime exists up to a gas velocity of 1 cm/s. This regime is characterized by a relatively uniform gas holdup profile, uniform bubble size and a rather flat liquid velocity profile. The bubbles in this regime are observed to rise rectilinearly in the form of bubble streams. No coalescence or clustering of the bubbles in the individual bubble streams or with adjacent bubble streams occurs. The liquid phase is carried upward in the region of the bubble streams by the wake motion and the liquid drift effects associated with the bubble motion. The liquid falls downward between adjacent bubble streams with continuous downward streams adjacent to the sidewalls. This descending motion of the liquid coupled with the rising motion of the adjacent bubble stream generates small vortices in the liquid streams between the rising bubble streams and the region adjacent to the sidewalls. The vortices located adjacent to the sidewalls are observed to increase in size as the gas velocity increases in the dispersed bubble regime due to the migration of bubbles away from the sidewalls. In this regime, the induced liquid flow is dominated by the drift effects of the rising bubble streams.

The 4-region flow condition exists for gas velocities between 1 and 3 cm/s. This condition is characterized by a gross circulation of the liquid phase, wherein the liquid rises in the middle portion of the column and descends adjacent to the sidewalls. The four flow regions (Figure 5) and the resulting flow phenomena were reported by Tzeng et al. (1993). In columns of width less than 20 cm the central plume region becomes indistinguishable from the fast bubble flow region yielding a 3-region flow.

The 3-region flow condition occurs at gas velocities greater than 1 cm/s for small columns (< 20 cm width) and at 3 cm/s for larger columns (> 20 cm). In the 3-region flow condition the two fast bubble flow regions merge together to form one central fast bubble region in the center of the column. The gas flow in this regime is dominated by bubble coalescence and break-up. The liquid flow is dominated by the wake effects from the large bubbles rising in the central part of the column. The vortical flow region and descending flow regions are still observable. It is noted that in a column of very small width, this flow commonly leads to the slugging condition.

3. *High pressure and temperature slurry column shakedown*

A test run of the high pressure and temperature bubble column was completed this quarter. It has been verified that the system can be operated at pressures up to 3000 psig. The liquid velocity can be varied from 0 to 10 cm/s at room temperature. Very high gas velocities can be achieved depending on the gas cylinder's capacity and the duration of each test. It was found that gas-liquid separation does work well. In this system, a single stage pressure regulator is used to release the pressure from system pressure (up to 3000 psig) to the atmospheric pressure. The liquid is atomized into fine droplets when it passes through the regulator. It is difficult to separate these fine droplets in the exhaust reservoir. We are still searching for solutions to this problem.

A test run of the system with addition of solids particles was also completed. It has been verified that the system can be operated in a wide range of liquid velocity for completely particle suspension. Liquid-particle separation is achieved in the disengagement section.

WORK TO BE PERFORMED NEXT QUARTER

1. Experiments on transient flow structure in 2-D bubble column will be emphasized on the column scale effects.
2. Measurements of interfacial surface tension will be continued next quarter in a system with CO_2. Measurements of liquid viscosity under high pressure and temperature will be started.

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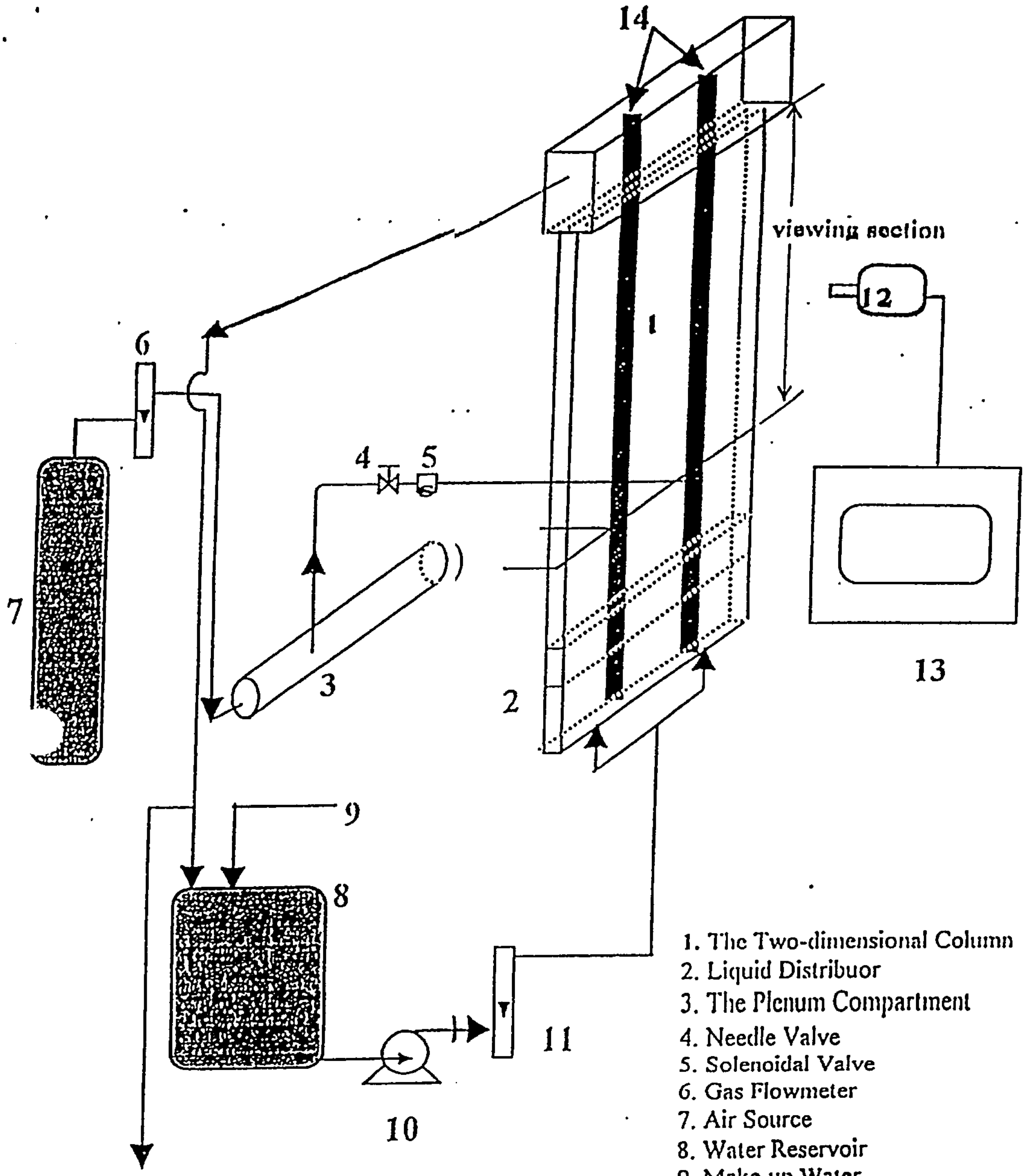


1. The Two-dimensional Column
2. Liquid Distribuor
3. The Plenum Compartment
4. Needle Valve
5. Solenoidal Valve
6. Gas Flowmeter
7. Air Source
8. Water Reservoir
9. Make-up Water
10. Liquid Pump
11. Liquid Flowmeter
12. Camera System
13. Image Analyzer
14. Partitions

Figure 3. Schematic diliagram of the two-dimensional bubble column

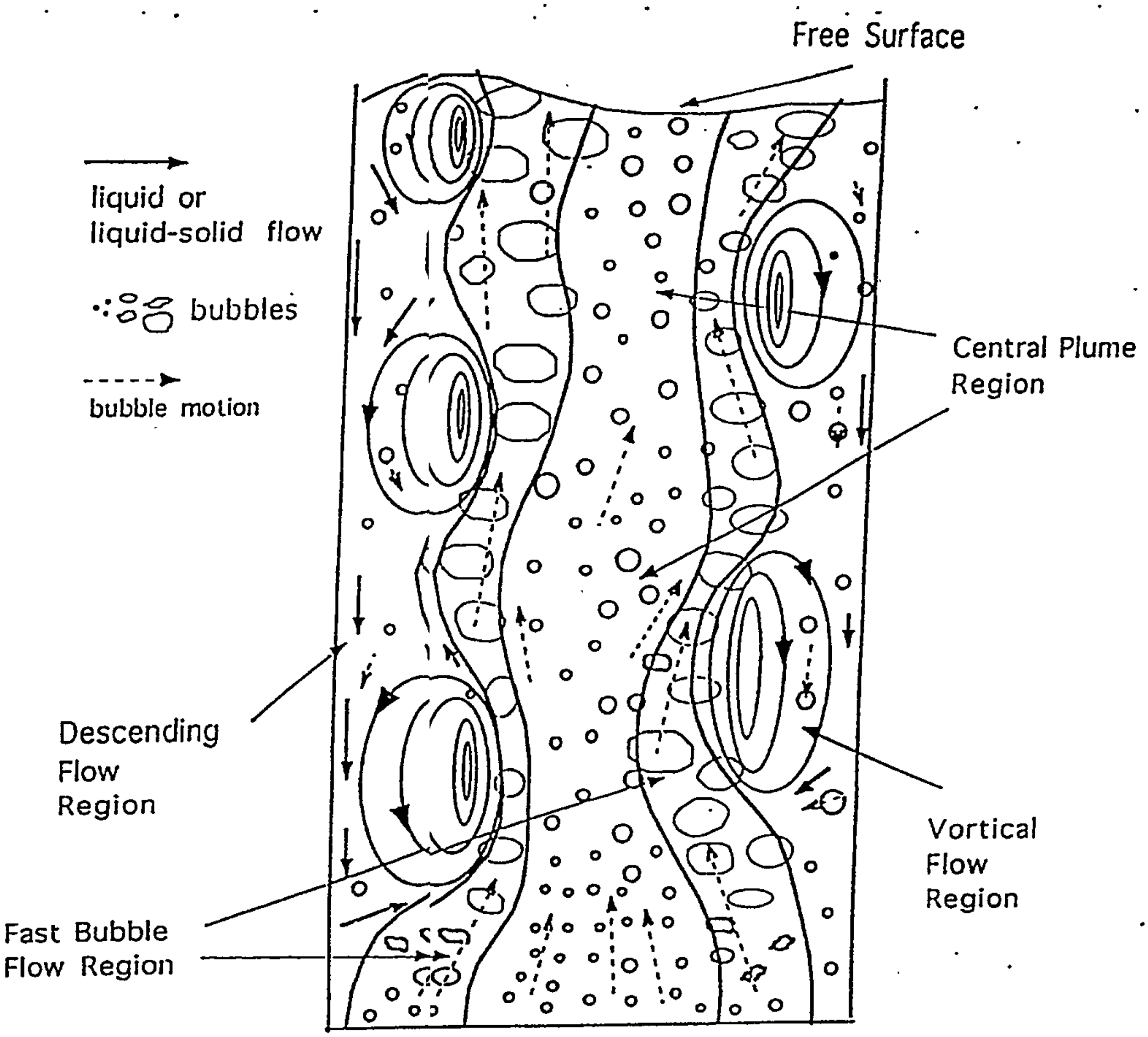
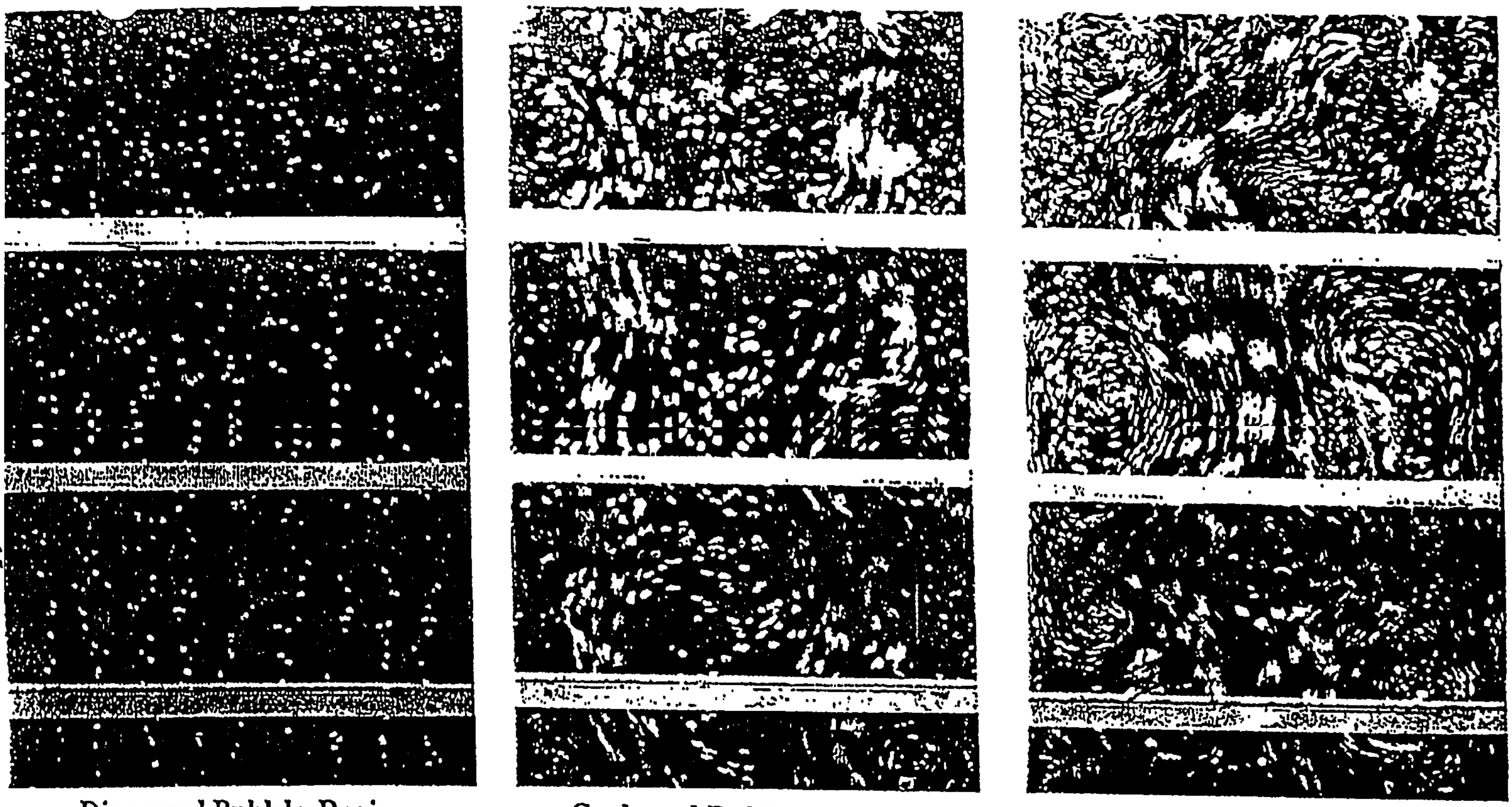


Figure 4. Classification of regicions accounting for the macroscopic flow structures in 2-D bubble columns.


Dispersed Bubble Regime

Coalesced Bubble Regime
(4-region flow)

Coalesced Bubble Regime
(3-region flow)

Figure 5. Flow regimes in a two-dimensional bubble column