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# TWO-PHASE FLOW IN PACKED COLUMNS AND GENERATION OF BUBBLY SUSPENSIONS FOR CHEMICAL PROCESSING IN SPACE

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## ABSTRACT

For long-duration space missions, the life support and In-Situ Resource Utilization (ISRU) systems necessary to lower the mass and volume of consumables carried from Earth will require more sophisticated chemical processing technologies involving gas-liquid two-phase flows. This paper discusses some preliminary two-phase flow work in packed columns and generation of bubbly suspensions, two types of flow systems that can exist in a number of chemical processing devices.

The experimental hardware for a co-current flow packed column operated in two ground-based low gravity facilities (two-second drop tower and KC-135 low-gravity aircraft) is described. The preliminary results of this experimental work are discussed. The flow regimes observed and the conditions under which these flow regimes occur are compared with the available co-current packed column experimental work performed in normal gravity.

For bubbly suspensions, the experimental hardware for generation of uniformly sized bubbles in Couette flow in microgravity conditions is described. Experimental work was performed on a number of bubbler designs, and the capillary bubble tube was found to produce the most consistent size bubbles. Low air flow rates and low Couette flow produce consistent 2-3 mm bubbles, the size of interest for the "Behavior of Rapidly Sheared Bubbly Suspension" flight experiment. Finally the mass transfer implications of these two-phase flows is qualitatively discussed.

## INTRODUCTION

As NASA pursues more long-duration manned missions, it will be necessary to develop or adapt a number of chemical processing technologies for operation in space. Some examples of these chemical processing requirements include life support systems such as waste water recovery, carbon dioxide removal from cabin atmospheres, bio-reactors to generate oxygen and food, and ISRU systems such as generation of methane and oxygen propellants and separation of buffer gases (argon, nitrogen) from the Mars atmosphere. A number of these chemical processing technologies involve two-phase flows operating under reduced gravity (on the Moon or Mars) and/or microgravity conditions (either in LEO or in-transit for a Moon or Mars mission). The two-phase flow aspects of these chemical processing technologies in normal gravity are either well-understood or extensive empirical databases exist to successfully design components that operate well under terrestrial conditions. However, under reduced and microgravity conditions, a number of fluid phenomena substantially effect the two-phase flow since the masking effects of buoyancy-driven forces are nearly eliminated. As the buoyancy forces become less dominant, other forces such as surface tension become more dominant and may dramatically effect mass and heat transfer, and indirectly impact the chemical reaction rates of these chemical processes [1].

### PRIOR RESEARCH IN TWO-PHASE FLOWS

The NASA Microgravity and Life Sciences program has funded a research program in fluid physics to address the issues of two-phase flow in reduced gravity conditions since the early 1980's. As an example, Jayawardena, Balakotaiah, and Witte [2] provided an excellent review of two-phase flow in tubes (pipes) under microgravity conditions. They discussed the observed bubble, slug, and annular flow regimes and presented flow pattern maps.

In order to aid in the design of chemical processing components to be operated in space, we are starting to look at the fluid phenomena in more complex systems such as bubbly suspension flows and two-phase flows in a packed media.

The emphasis of work at NASA Glenn in this area is two-fold. One is to obtain a more fundamental understanding of the fluid flow phenomena in a two-phase flow system in reduced and microgravity conditions. The second is to obtain empirical data and develop models of expected engineering systems, i.e. pursuing a similar research and development path as was done in the chemical processing industry to obtain the terrestrial (one-g) database. This paper will discuss experimental work performed in the areas of two-phase flows in packed beds and the generation of bubbly suspensions in reduced gravity.

## SIGNIFICANCE OF PACKED BED AND BUBBLY SUSPENSION FLOWS IN REDUCED GRAVITY

The simultaneous flow of gas and liquid through a fixed bed of particles occurs in many unit operations of interest to engineers. Examples of process equipment include separation (chromatographic and packed distillation) columns, gas-liquid reactors (trickle-bed reactors used in hydrodesulfurization, hydrogenation and hydrocracking of petroleum fractions), humidification, drying and gas absorption operations and extraction and leaching of minerals from ores. In addition to these normal gravity applications, gas-liquid flows through packed-beds are expected to occur in a variety of unit operations in microgravity. NASA recognizes that long duration manned space activities depend on the development of regenerative life support systems (RLSS) based on physicochemical and biological technologies [3]. The current emphasis is on biological technologies and their development is strongly emphasized by the Advanced Life Support (ALS) project of NASA [3]. Current NASA plans for the lunar base call for the development of equipment that can extract oxygen and hydrogen from lunar soil. The Mars exploration plans call for the development of equipment that can purify and recycle the astronauts' air and water [4,5]. The development of such equipment to carry out the unit operations (such as extraction, absorption, humidification, leaching, etc.) in these environments requires a fundamental understanding of the transport processes occurring in gas-liquid flows through packed-beds in reduced gravity.

Bubbly suspensions are important for mass and heat transport processes on Earth and in space. Understanding the behavior of bubbly suspensions in reduced gravity is crucial because of issues such as bubble segregation which could result in coalescence and impact heat and mass transport. For instance, bubble segregation is crucial to bio-reactors where oxygen bubbles are segregated by the flow field impacting the oxygen transport to cells. On the other hand, bubble segregation and coalescence is beneficial to phase separation processes.

Technology development for the generation of bubbly suspensions for space is also in direct support of a flight experiment titled "Behavior of Rapidly Sheared Bubbly Suspensions." The objective of this experiment is to study the behavior of bubbly suspensions under simple shear and nearly potential flow conditions.

## PACKED COLUMN

Gas and liquid two-phase flow in a vertical packed column occurs in many unit operations of interest to engineers and hence has been studied extensively for years. In normal gravity, the gas and liquid can flow either co-current or counter-current to each other. In addition, the flow can be either up (against gravity) or down. The most common configuration is a vertical column in which the liquid flows down while the gas flow is either counter-current; thus driven by buoyancy, or co-current with sufficient liquid flow to overcome buoyant forces. In the absence of gravity, only co-current flows can exist.

The different flow patterns that exist for non-foaming systems and the transitions between them when a gas and liquid flow co-currently in a vertical packed column has been summarized by Charpentier and Favier [6], Talmor [7], and Sato et al. [8]. In general, four flow regimes are distinguished. At low gas and liquid flow rates, the liquid flow is over the packing particles and gas occupies the void space. This regime is called the 'trickling flow' regime. As gas flow rates increase, liquid droplets can be dragged along with the gas flow. This flow regime is called 'blurring flow, mist flow or spray flow'. At higher liquid flow rates, the liquid tends to plug the gas channels between the particles. Subsequently the local pressure above the plug rises and the plug is blown away and travels downward through the column with a relatively high speed. This important flow regime is called 'pulsing flow'. At high liquid flow rates and low gas flow rates, a flow regime called 'bubble or dispersed bubble flow regime' is obtained.

The following discussion describes the experimental design and preliminary results of a study to determine the effects of microgravity on flow patterns that exist for air-water systems (water and water-glycerin solutions). A wide range of gas and liquid flow rates and fluid properties are considered.

EXPERIMENTAL WORK TO DATE/SETUP

Two similar experimental apparatus were used to study two-phase flow through a packed column. The first set of experiments were conducted using the 2.2 second drop tower at NASA Glenn Research Center, the second set of experiments were conducted on the NASA KC-135 aircraft. Both experiments used the same packed column test section.

Packed Column Test Section

Figure 1 shows the test section for the packed column two-phase flow experiment which consisted of a rectangular column with a cross section of 2.5×5 cm and 60 cm long. The test section was made from a scratch resistant clear polycarbonate material with five flush mounted differential pressure transducers. The first pressure transducer was located approximately 4 cm from the inlet port and the subsequent pressure transducers were spaced at 13 cm intervals along the column. Absolute pressure transducers were located at the first and last positions. The inlet and outlet ports were 1.27 cm diameter tubes with a course mesh screen to hold the packing in place. The column was then packed with identically sized spherical glass beads.

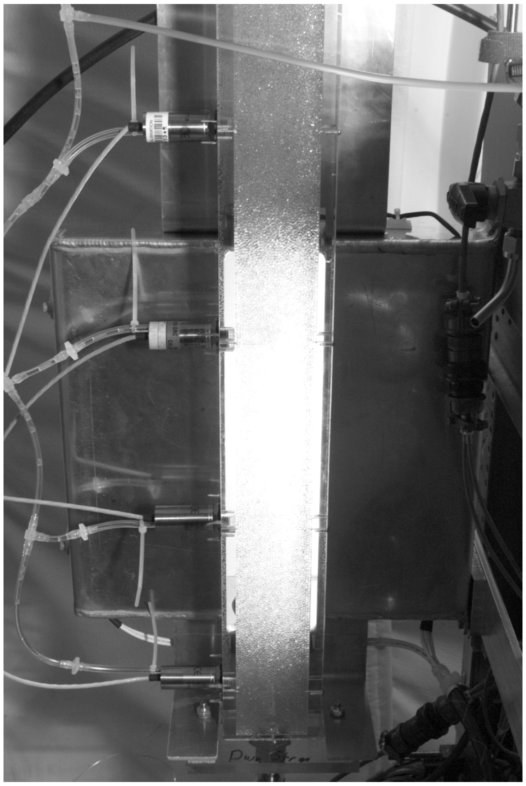

**Figure 1.—Packed column test section.**

2.2 Second Drop Tower Experimental Design

The Multiphase Flow Rig (MFR) was designed for use in a 2.2 second drop tower at NASA Glenn Research Center. It was designed to provide a wide range of air and water (or water/glycerin solutions) flow with state of the art high-speed digital imaging as well as data acquisition and control.

A high-speed digital video camera was used to visually confirm flow regimes at 500 frames per second. In addition to the imager, a data acquisition system with a 486 processor acquired and stored temperature, pressure and flow rate data.

A pressurized supply tank provides air pressure for both the air and water flow. Referring to the flow schematic in Fig. 2, the high-pressure air can be regulated between 20 and 3400 kPa just upstream of an electronically controlled solenoid valve. At the beginning of the drop, the solenoid valve opens and the regulated air passes through a filter and then an orifice. A pressure transducer records the pressure immediately upstream of the orifice. By maintaining choked flow conditions the mass flow rate of the air can be calculated. This section was designed for easy change-out of the orifice to increase the range of possible flow rates.

The liquid is also driven by regulated air. The maximum air pressure to the liquid supply tank is 340 kPa. Again, an electronically controlled solenoid valve opens to initiate flow at the beginning of the drop. A metering valve provides fine-tuning of the flow rate and a flow meter records the actual rate. The liquid supply tank is sized so that only 30 to 40 percent of the liquid volume will be used in a drop. This is to prevent air blowing through the liquid lines.

The two-phase mixture flows through the test section and then into a separator. The separator has a fine mesh screen that prevents the water from flowing through it, but allows the air to pass. The water accumulates in the separator and the air is vented overboard. Just prior to venting, the air passes through a back pressure regulator which was normally set between 35 to 70 kPa. The purpose of the regulator is to dampen out upstream pressure surges.

Aircraft Experimental Design

The Small Two-Phase Flow Experiment (STPFE) rig is made up of three main structures, two flight research instrument racks, and a ½” thick aluminum base plate which supports the two racks. The base plate also provides a mounting surface for the liquid supply and two-phase separator tanks. A simplified flow schematic is shown in Fig. 3.

The first flight research instrument rack, or flow metering rack, contains primarily the gas and liquid flow loops, thermocouple signal conditioning electronics, and the differential pressure transducer electronics. Mounted to this rack are the flow rate setting devices such as metering valves and pressure regulators, and flow rate

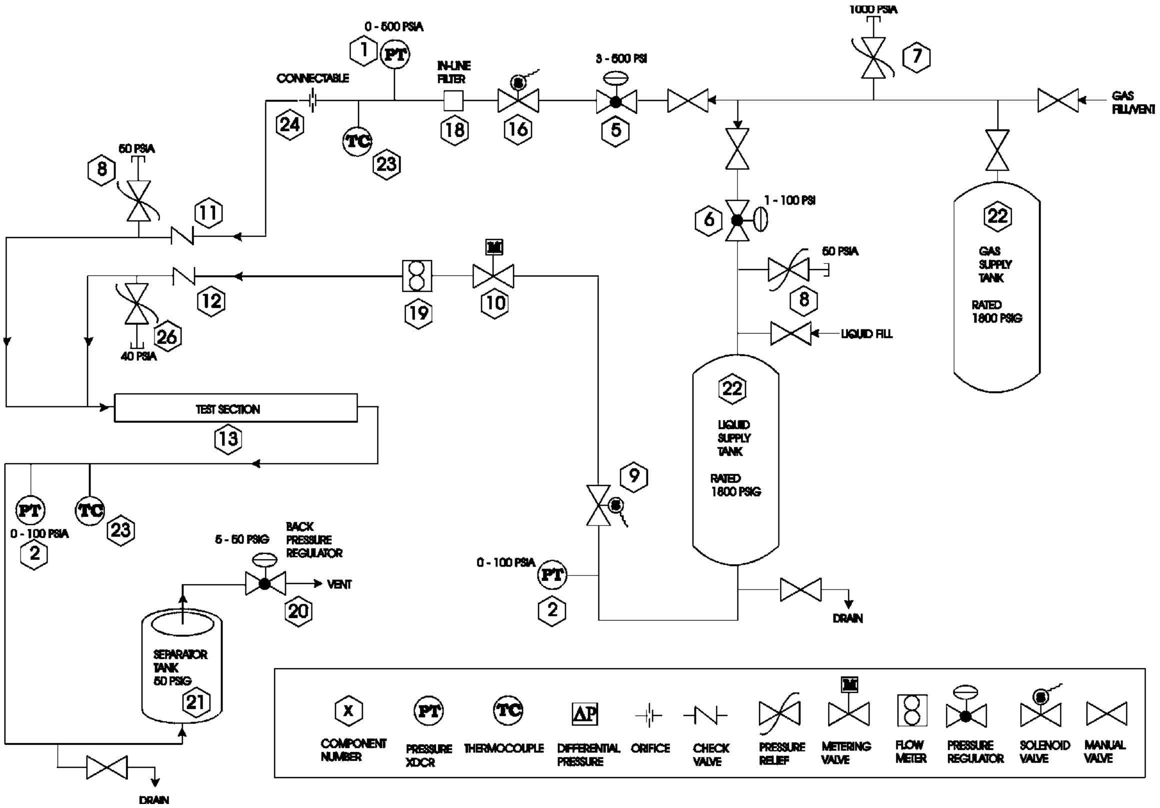

**Figure 2.—Flow schematic of the Multiphase Flow Rig (MFR) (1 psi = 6.89 kPa).**

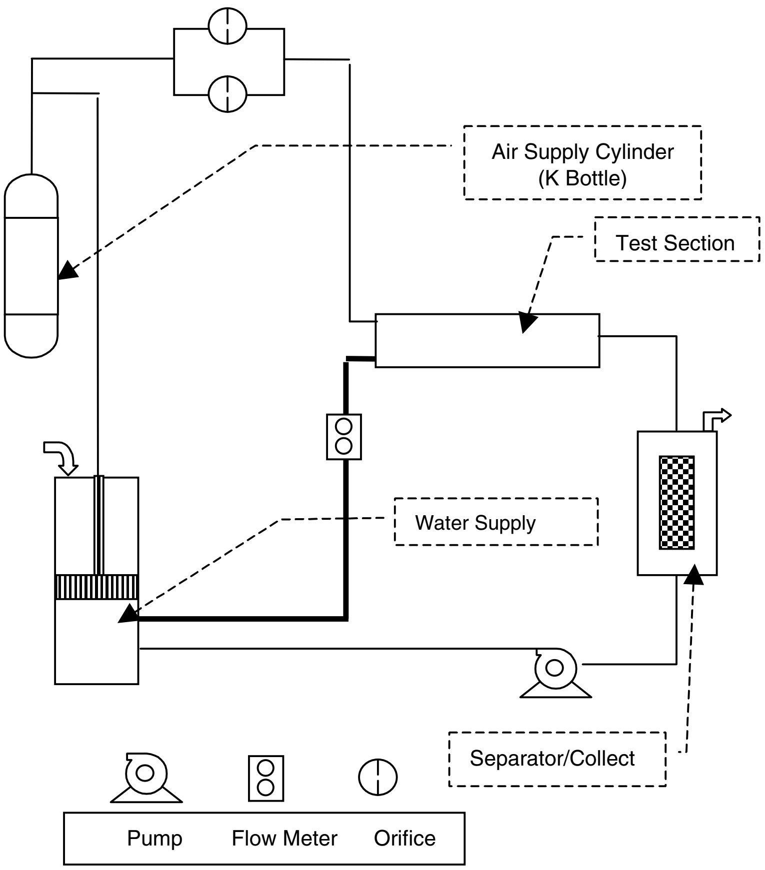

**Figure 3.—Flow schematic diagram of the KC-135 Small Two Phase Flow Experiment (STPFE).**

measuring devices, such as pressure transducers and flow meters. From this rack, flexible hoses carry the gas and liquid to the top of the vertically oriented test section. The two-phase mixture flows from top to bottom.

The second rack supports the test section. It also contains accelerometers, data acquisition and control electronics, as well as the operator interface panel and computer display that allow the operator to select program options and monitor the flow conditions.

Two tanks and a number of valves with interconnecting plumbing are mounted directly to the base plate that also serves to attach the two instrument racks to the aircraft floor. The liquid supply tank is an acrylic tank with aluminum end caps. Air pressure is used to drive a piston along a center shaft and drive the water through the metering system and into the test section. A two-phase separator/collector tank is also attached directly to the base plate. This tank receives the two-phase mixture from the test section and separates the liquid and gas phases. The air is then vented to the cabin via a back pressure regulator set between 35 to 70 kPa and the liquid is held in the tank until it can be pumped back to the supply tank between trajectories.

A high-speed SVHS video system was used to image the two-phase flow phenomena in the transparent test section at 500 frames per second.

A cylinder of compressed air mounted on a separate rack is used to provide the gas phase of the two-phase flow as well as the pressure to drive the liquid supply tank piston.

Test Matrix

The combined test matrices for both experiments were designed to provide a wide range of flow parameters, and include the major flow regimes. The flow map provided by Talmor [7] was used as a guide. Variations of several orders-of-magnitude in the important dimensionless numbers were obtained by varying the packing size, gas and liquid flow rates, and the liquid viscosity (by adding glycerin). The ranges of dimensionless numbers, flow rates, fluid properties and packing diameters used in these experiments were:

$0.18 < Re < 100$

$0.001 < We < 1.0$

$0.003 < G < 10$ g/(s cm$^2$)

$0.3 < L < 5$ g/(s cm$^2$)

$0.00095 < \rho_g < .0026$ g/cm$^3$

$1.0 < \rho_l < 1.2$ g/cm$^3$

$0.01 < \mu_l < 0.2$ g/(cm s)

$\mu_g = 1.8\times10^{-4}$ g/(cm s)

$\sigma_l = 72$ dynes/cm

$D_p = 0.2$ and 0.5 cm

where G and L are superficial mass velocities of the gas and liquid, $\rho_g$ and $\rho_l$ are the gas and liquid densities, $\mu_g$ and $\mu_l$ are the gas and liquid viscosities, $\sigma_l$ is the surface tension and $D_p$ is the packing diameter.

Over 250 data points were recorded. Some of the MFR test data was discarded because it was obvious fully developed flow was not achieved in the 2.2-second duration. Many of these conditions were repeated using the STPFE on the aircraft where periods of microgravity last from 20 to 22 seconds. By monitoring the average pressure drop at each of the five locations, statistical steady conditions were verified. A typical set of pressure traces is shown in Fig. 4 where steady flow occurs around 7 seconds into the parabolic trajectory.

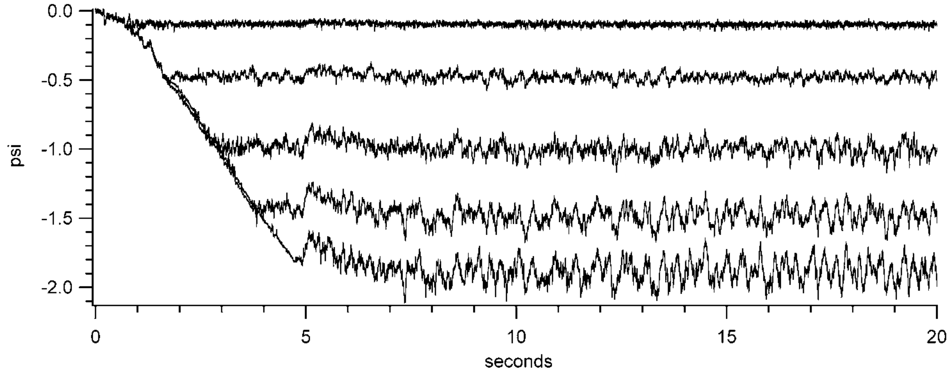

**Figure 4.—Typical set of pressure drop traces for packed bed (1 psi = 6.89 kPa).**

## PRELIMINARY RESULTS

### BASIS FOR TALMOR'S PLOT

One reference an engineer would consider when designing a packed column for low gravity operations would be the AIChE Journal publication by Talmor [7]. The paper is an excellent survey of multiple studies conducted in normal gravity for non-foaming systems including air-water/glycerin, $CO_2$-Hexane, Freon-Silicon Oil, and Natl. Gas/$CO_2$/Lube Oil. Talmor develops a non-dimensional map based on previous work by Oshinowo and Charles [9]. His objective is to create a generalized flow map in terms of useful coordinates that can be scaled over a very wide range (several orders of magnitude).

The basis for Talmor's map is that a driving-to-resistance force ratio can be developed for two-phase flow through a packed column similar to two-phase flow through an empty tube. The driving forces are inertia and gravity while the resistance forces are viscous and surface tension. By normalizing the inertia forces and using two-phase Froude, Weber and Reynolds numbers, Talmor derives the force ratio as:

$$\frac{1+(1/Fr)}{We+(1/Re)} = \frac{Inertia+Gravity}{Interface+Viscous} \quad \text{.............................} \quad (1)$$

Where Talmor defines:

$$Fr = \frac{[(L+G)\nu_{lg}]^2}{gD_h}$$

$$We = \frac{D_h(L+G)^2\nu_{lg}}{g_c\sigma_l}$$

$$Re = \frac{D_h(L+G)}{\mu_{lg}}$$

$$\nu_{lg} = \nu_l\frac{(L/G)}{1+(L/G)} + \nu_g\frac{1}{1+(L/G)}$$

$$\mu_{lg} = \mu_l\frac{(L/G)}{1+(L/G)} + \mu_g\frac{1}{1+(L/G)}$$

and

$$D_h = \frac{2\varepsilon D}{2+3(1-\varepsilon)(D/D_p)}$$

where $\varepsilon$ is the packing bed void fraction, $\nu_g$ and $\nu_l$ are the respective gas and liquid kinematic viscosities, and D is the bed diameter.

Talmor then presents a log-log plot with the above force ratio versus superficial volumetric gas-to-liquid ratio as coordinates. Talmor empirically fits a set of curves to indicate where the transitions between flow regimes should occur.

With this flow map in hand, the engineer seeking to design a packed column for use in low gravity could set the inverse of the gravity force (*1/Fr*) equal to zero. The plot could be used to size process equipment to operate within the desired flow regime.

### INITIAL OBSERVATIONS

#### Flow Regimes

Preliminary findings indicate that the assumption of neglecting the gravity driving force during low gravity operation does not hold in the viscous dominated region ($Re < 30$) of the Talmor plot. The observations are based on the fourth differential pressure transducer (approximately 43 cm downstream). Both high-speed imaging and pressure data factored into the determining the flow regime. Usually, the visual observation of the transition from bubbling flow to the lower frequency pulses was easy to determine. Higher frequency pulse flow required confirmation with the pressure data.

In microgravity conditions, with $1/(We + 1/Re) < 30$, pulse flow is observed well below Talmor's lower boundary line. In fact clear pulsing flow was observed for the region $1 < 1/(We + 1/Re) < 3$ with volumetric Gas-to-Liquid ratios as low as 3. Talmor observed the opposite trend in this region with the Beimesch and Kessler [10] data; who also used spherical packing in an air-water system. Talmor's plot shows bubbly flow with a volumetric gas-to-liquid ratio as high as 20 or 30. No bubbly flow was observed with a ratio above 10 in microgravity.

#### Overall Pressure Drop

Another observation was the average overall pressure drop across the test section increased in magnitude equivalent to the static liquid head on the vertical column when compared to identical normal or high gravity conditions for bubbly flow. However, gravity has much less of an influence for the overall pressure drop in pulse flow. Figure 5 shows a typical shift in overall pressure drop at 43 cm downstream of the inlet for bubbly flow. For this case, water-glycerin solution has a density of 1.104 g/cm$^3$. The static head is approximately 7.9 kPa (for 1.7 g's), while the observed pressure drop is about 8.2 kPa. In contrast, Fig. 6 shows a shift for pulse flow to only be about 3.7 kPa. The liquid density is 1.19 g/cm$^3$ for the pulse flow, which results in a static head of 8.5 kPa. As you continue to increase the gas-liquid ratio, the effects of gravity on the average overall pressure drop across the column continue to diminish.

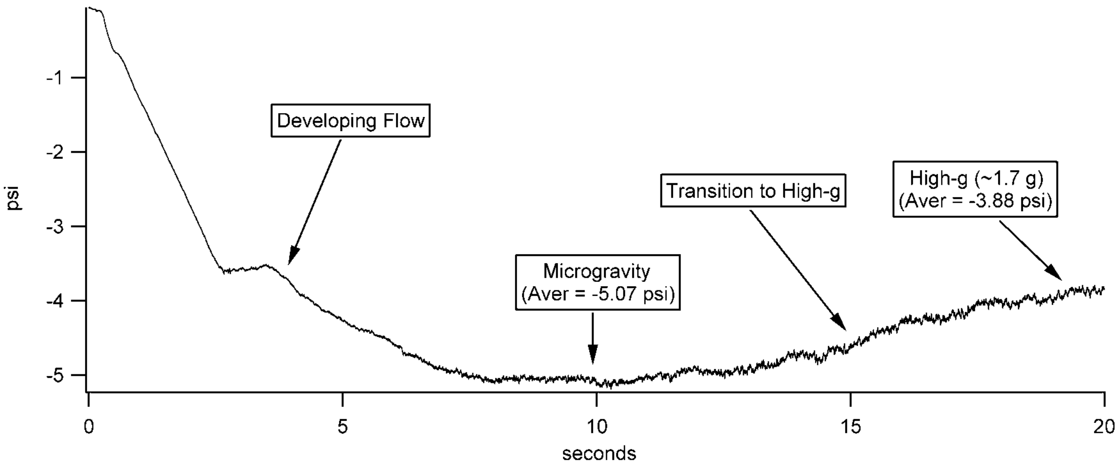

Figure 5.—Shift in average pressure drop across column for bubbly flow (1 psi = 6.89 kPa).

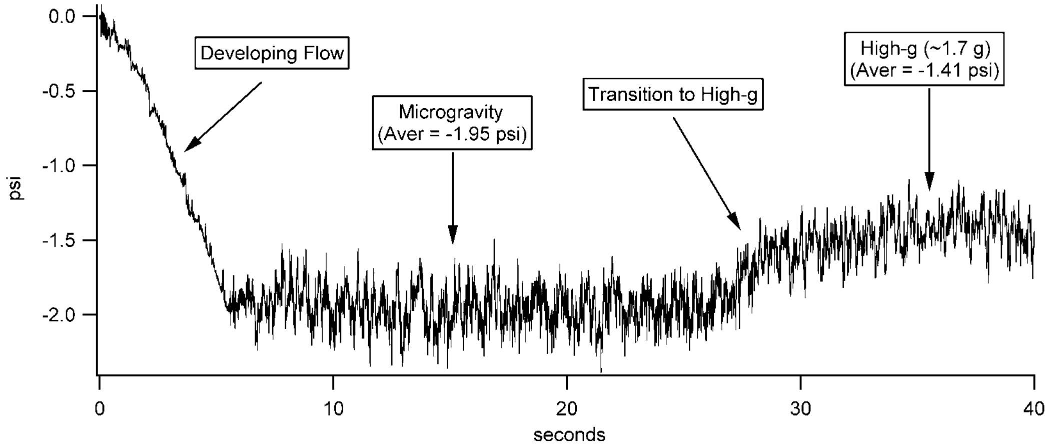

Figure 6.—Shift in average pressure drop across column for pulsed flow (1 psi = 6.89 kPa).

## BUBBLY SUSPENSIONS

Considering the motivation given in the introduction to develop a method to generate a uniform mono-disperse bubbly suspension in low gravity, two approaches for creating the bubbly suspension under low gravity conditions were explored. The first was to create bubbles from a chemical reaction of an effervescent material with water. The chemical reaction results in $CO_2$ bubbles formed in the continuous phase (water). The second was to directly inject air into water and detach the bubbles by inducing a relative motion between the bubble and the surrounding body of water [11]. These two approaches are described in detail below.

### BUBBLY SUSPENSION USING EFFERVESCENT MATERIAL

Experiments to create a bubbly suspension using an effervescent material were conducted on the DC-9 aircraft low gravity platform. The bubbler consisted of a circular tablet of Alka-Seltzer®™ fully coated/masked except in small areas of different shapes where the chemical reaction with water can take place. The tablet was spun in still water and the diameter of the generated $CO_2$ bubbles was measured. Such measurement of the bubble diameter showed poly-dispersity in the bubble distribution. Furthermore, the unknown kinetics of the chemical reaction and the solid residues that could result from such a reaction were of concern, as well as the sensitivity of the $CO_2$ solubility in water to pressure and temperature variations. This approach was therefore abandoned.

### BUBBLY SUSPENSION BY DIRECT AIR INJECTION IN STILL WATER

Two approaches were taken in developing this method of suspension generation. The first considered a spinning bubbler in a body of water whereas the second considered a stationary bubbler in a moving body of water. The relative motion was necessary for bubble detachment (via drag force) as pointed out by Kim *et al.* [11].

### Spinning Bubbler designs and Suspension Assessment

The approach of injecting air into the water using a nozzle resulted in different bubbler designs that were tested in low gravity. Cylindrical, T-shaped, sintered metal filter and capillary bubblers, depicted in Fig. 7 were tested. Air was injected into these bubblers from an air bottle. The bubblers were spun at different angular velocities and bubble generation was studied under different conditions involving air flow rate and spin speed. Figure 8 shows a gallery of the bubblers operating in still water.

The most promising design was the capillary bubbler that consisted of a rotating body connected to a capillary through which air was injected into the liquid. The rotation was needed for establishing detachment in low gravity. This bubbler design was developed further for better control on the spin rate and gas flow rate. Figure 9 shows a summary of the bubble diameter as a function of local liquid relative velocity and the air flow rates. The trend of the data shows that as we increase the s0pin velocity of the bubbler, the bubble diameter decreases due to the higher drag force acting on it.

### Stationary Bubbler design in a Couette cell and Suspension Assessment

The aforementioned flight experiment calls for shearing a suspension in a couette cell under microgravity conditions. For this purpose, a couette system and a flow loop were built and used as a test bed for testing bubbler concepts and the diagnostics for bubble collision frequency and void fraction measurements in the couette gap.

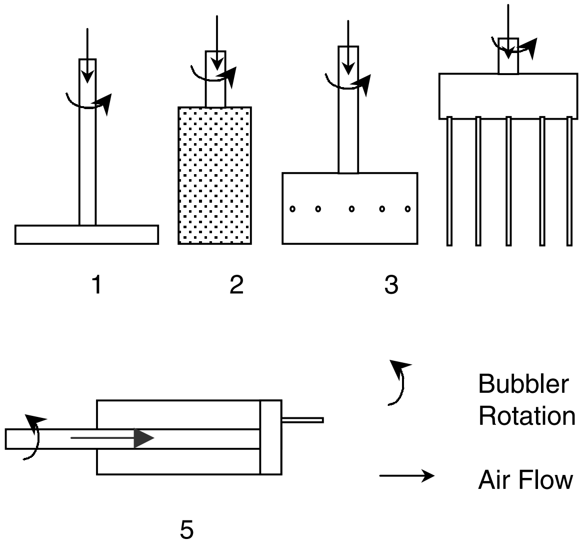

Figure 7.—Various bubble design used in early experiments of suspension generation. 1) T-shape, 2) Sintererd metal, 3) Cylindrical, 4) Capillary, and 5) Improved capillary bubblers.

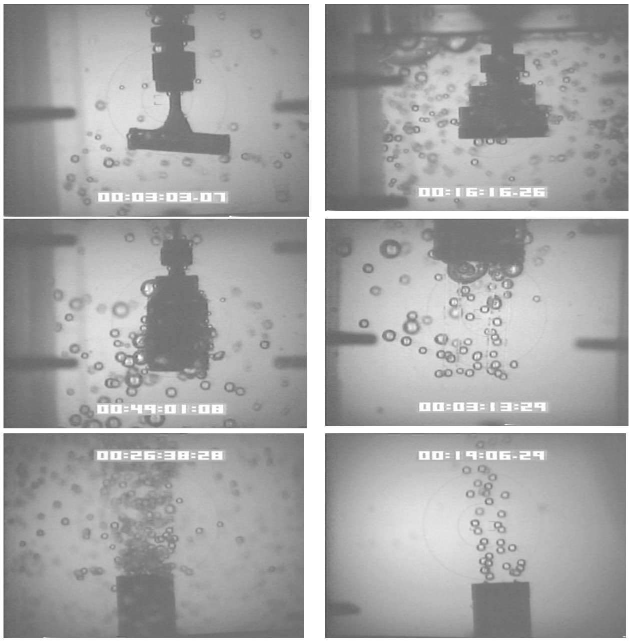

Figure 8.—Gallery of bubblers tested during the early phase of suspension generation studies.

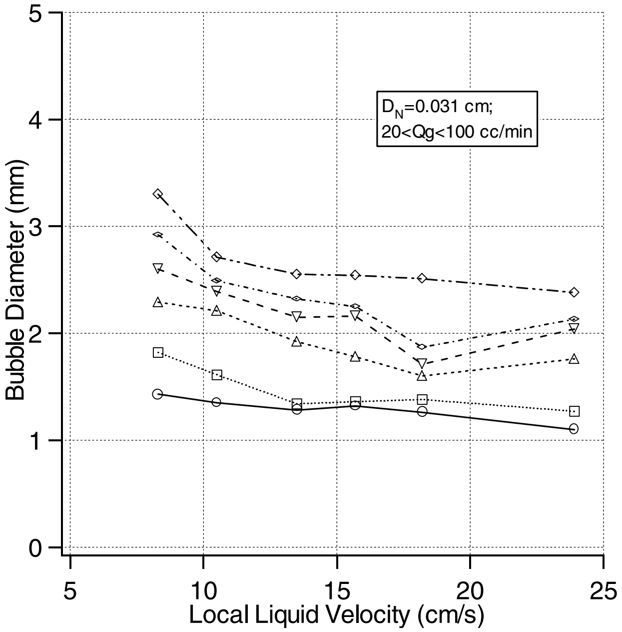

Figure 9.—Summary of the bubble diameter as a function of local liquid relative velocity and the air flow rates for the spinning bubbler design.

## Hardware Description

### Couette and Flow Loop

The flow loop is depicted in Fig. 10. The experiment rack included a couette assembly, which consisted of a couette, a drive motor, a bubbler, and a hot wire probe anemometer. Magnesium sulfate ($MgSO_4$) salt was added to the water in the couette to create a 0.05 molar solution to reduce bubble coalescence. The couette was designed to hold approximately 3 liters of water between the inner and outer cylinders. The outer cylinder is optically clear (acrylic), and capable of spinning from 0–100 rpm driven by a motor with a DC speed controller. The inner cylinder, also acrylic, was stationary. The acrylic top and stainless steel bottom of the couette rotated with the outer cylinder. The couette seal material was made of a fluoropolymer. A tachometer, pressure transducer, and a type K thermocouple were added to the couette assembly.

### Bubble Injection

Bubbles were produced in the couette through a capillary tube attached to the couette inner cylinder. Three different capillary sizes were tested, one size per flight (0.031, 0.041, and 0.051 cm diameters).

A piston-type 2.54 cm ID pump was used to remove water from the couette while pumping air in through the bubbler. A mass flow meter (0–50 sccm) was added to the air line. Operating in the reverse direction, the same pump was used to simultaneously remove air while replacing the water in the couette.

### Separation, Fluid Re-circulation and Diagnostics

A re-circulation system was used during the high-g period to remove any remaining air from the top of the couette. This was accomplished by pumping water into the bottom of the couette from an accumulation tank using a 12VDC marine pump. A hot wire probe anemometer was used to test the dynamics of bubble-probe collision. The probe was mounted just downstream of the bubbler, attached to the inner cylinder with the probe head positioned in the flow field. An S-VHS high speed (1000 frames/s) camera and four standard 30 frames/second video cameras were used to view the experiment. Three of the standard speed video cameras were identical, industrial black and white cameras. The purpose for the high speed camera was to measure bubble diameter and assess suspension monodispersity.

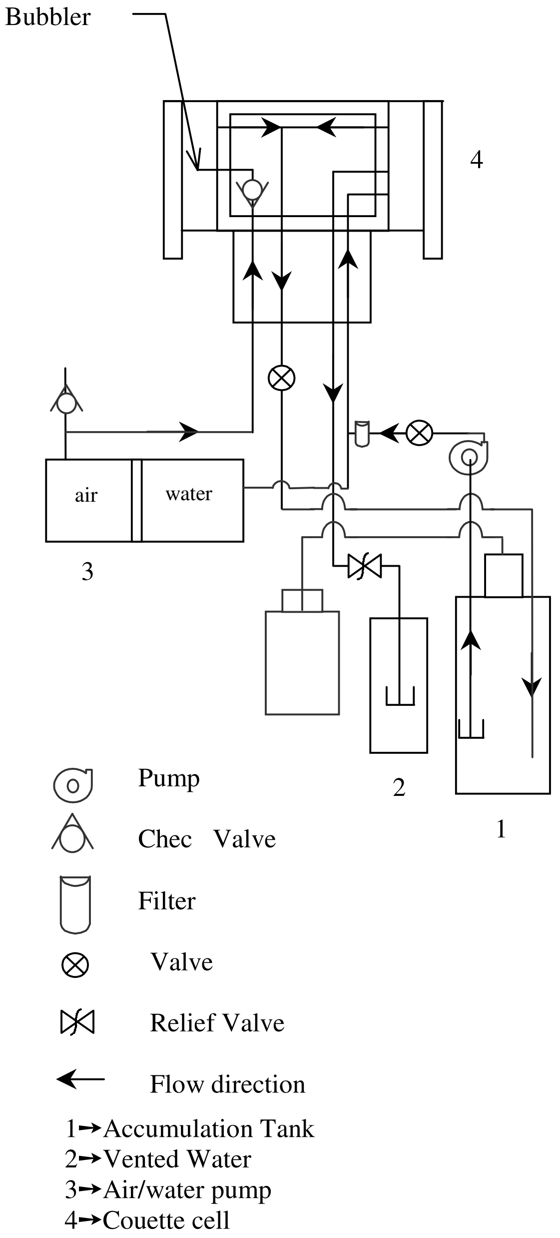

**Figure 10.—Simplified flow diagram of the bubbly suspension generation experiment.**

Bubble Distribution Assessment

Figure 11 shows a top view of the couette cell as bubbles were being produced from the bubbler that is inserted into the flow. The air flow rate $Q_g$ is on the order of ~20 cc/min, inner orifice diameter $D_N$ of 0.051 cm and the liquid velocity evaluated at 0.25 cm from the inner wall and estimated by equation 2 to be on the order of 3 cm/s.

Figures 12 through 14 show that bubble diameter plotted as a function of the calculated liquid velocity for bubbles generated from the three nozzle diameters of 0.031, 0.041 and 0.051 cm. Liquid velocity was calculated using [12],

$$u(r) = \frac{1}{r_2^2 - r_1^2}\left[\alpha r - \frac{\beta}{r}\right]; r_1 \le r \le r_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where $r_1$ and $r_2$ are the inner and outer radii of the Couette cell, r is the radial position into the Couette gap, $\alpha$ and $\beta$ are given by:

$$\alpha = \omega_2 r_2^2 - \omega_1 r_1^2$$

$$\beta = r_1^2 r_2^2 (\omega_2 - \omega_1)$$

where $\omega_1$ and $\omega_2$ are the angular velocities of the inner and outer shells respectively. Since the outer shell is only spinning, $\omega_1$ is zero.

We see from the figures that in order to produce bubbles in the range between 2 and 3 mm, we need to operate at lower liquid velocities (2 to 8 cm/s) and gas flow rates (9 to 16 $\text{cm}^3$/min). The higher uncertainties (error bars) on the bubble diameter in Fig. 14 are probably caused by the bubble sampling method used for bubble diameter measurements over the entire low gravity period.

The data shown in Fig. 12 through 14 exhibit a trend that is seen by several investigators (Bhunia et al.[13] and Nahra et al. [14]). The nozzle diameter as shown in these figures plays an important role in determining the bubble diameter at detachment. The uncertainties in some of the data points can be attributed to the fluctuation in the gas flow, which in turn can be attributed to the bubble formation process. It is however worth noting that the bubble diameter measured from this experiment shows that the bubble size is uniform and that the generated bubbles are fairly mono-disperse.

MASS TRANSFER IMPLICATIONS

As mentioned earlier in this paper, the focus of our research is on the two-phase fluid mechanics in packed columns and the generation of bubbly suspensions. However, for the chemical processes mentioned earlier, effective mass transfer is the design goal. Therefore, it would be useful to qualitatively comment on the mass transfer implications of these flow systems.

Mass transfer in a co-current flow bubbly suspension could be lower in microgravity than in normal gravity counter-current conditions for two reasons. In co-current flow, a large concentration driving force exists at the initial point of gas-liquid contact; as the gas and liquid flow in the same direction through the column or other flow system, this concentration driving force decreases. Counter-current flow, not achievable in microgravity conditions, allows the gas bubbles to contact “fresher” liquid as they pass “up” the column maintaining a large concentration driving force over the length of the column and thereby enhancing the overall mass transfer. This mass transfer phenomenon is analogous to heat transfer in co-current versus counter-current heat exchangers.

The second reason is for which convection mass transfer could be significantly reduced is due to the reduced relative liquid to gas velocities in co-current flow. Higher convection mass transfer is expected in opposing gas and liquid flows in counter-current conditions. Improvement of mass transfer in these conditions could be accomplished with reduced bubble size, increasing the area to gas volume ratio. This makes generation of small and uniform bubbly suspensions and limiting of bubble coalescence important for high rates of mass transfer.

Volumetric gas-to-liquid ratios near unity could provide optimum mass transfer. Assuming that the two phases are well-mixed (i.e. small gas bubbles well-dispersed in the liquid), the gas-liquid mass transfer area is maximized when gas and liquid volumes are nearly equal.

The bubbly flow regime may provide an optimum design point for mass transfer in packed columns operating in microgravity. This regime most closely resembles the “loading” flow regime that is the design goal for terrestrial counter-current packed column designs. Because the flow appears be a steady-state flow and seems to vary linearly with small changes in fluid or liquid flow rates, it may turn out to be a safe operating regime for designing

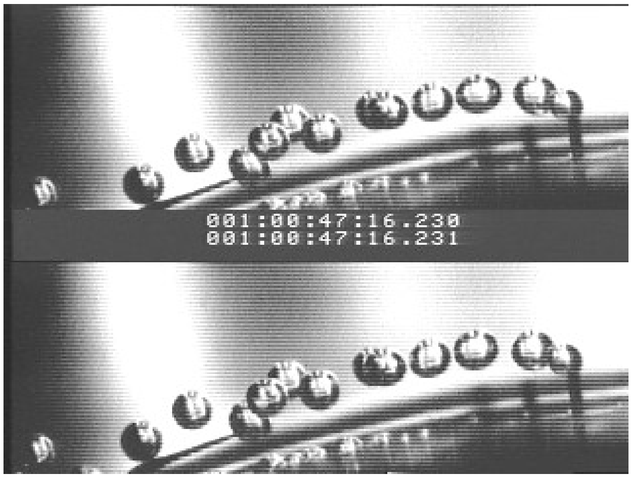

**Figure 11.—Bubble formation and detachment from a nozzle in a cross shear flow. *Qg* = 20 cc/min, $D_N$ = .051 cm, and $U_L$ = 3 cm/s.**

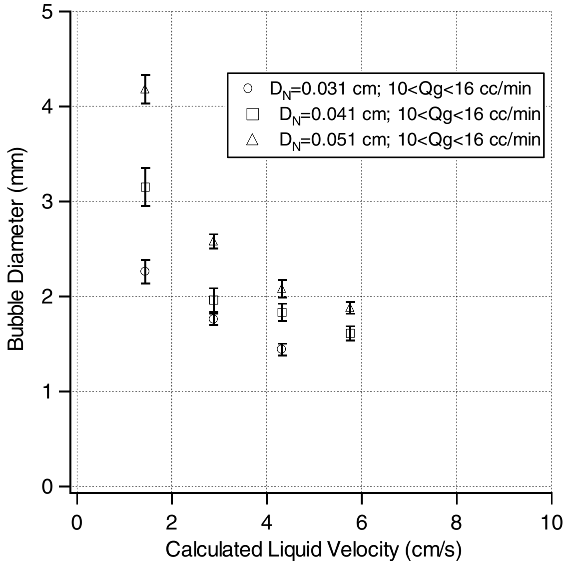

**Figure 12.—Bubble diameter as a function of the calculated liquid velocity for a bubbler tip location of *d* = 0.25 cm and 10<*Qg*<16 cc/min.**

robust packed column equipment. Also, the low liquid and gas flow rates needed for bubbly flow assure relatively long residence times in the packed column necessary for low mass transfer rate systems. If the common problem of "channeling" (one phase flow rate much greater than the other at points in the column) can be addressed by making good design choices, (e.g. packing type), then bubbly flow may be the ideal regime for microgravity packed column operation. Obviously, more experimental work is needed to verify these points.

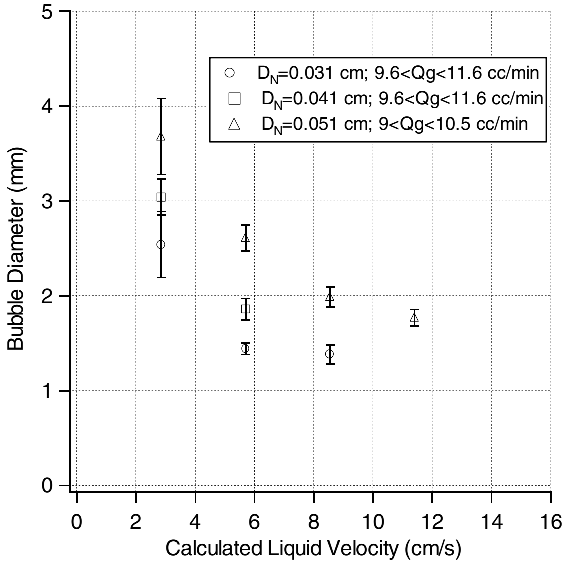

**Figure 13.—Bubble diameter as a function of the calculated liquid velocity for a bubbler tip location of *d* = 0.5 cm and 9<*Qg*<12 cc/min.**

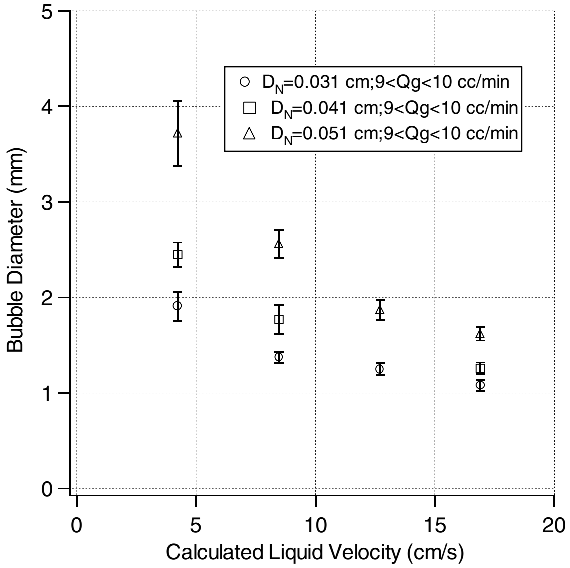

**Figure 14.—Bubble diameter as a function of the calculated liquid velocity for a bubbler tip location of *d* = 0.75 cm and 9<*Qg*<10 cc/min.**

## CONCLUDING REMARKS

### PACKED COLUMN

Direct application of some of the standard flow maps for two-phase flow in a packed column might not be possible in microgravity. Two important design criteria, flow regime and overall pressure drop may be difficult to predict without further testing. In certain conditions at moderately low Reynolds numbers, the same gas-to-liquid ratio that results in bubbly flow in normal gravity may be an order of magnitude too high for a packed column on a spacecraft. Furthermore, columns properly sized for overall pressure drop in terrestrial applications may experience too much of an increase in pressure drop for use in space. Future work to develop flow regime and pressure drop models for the operation of packed beds in microgravity is underway.

## BUBBLE SUSPENSION

We presented in this paper the results of the effort aimed toward the generation and establishment of a bubbly suspension in low gravity. These results included the characterization of suspensions generated by various bubbler designs, which included the spinning and stationary bubblers. Data scattering was explained in terms of the air flow rate fluctuations. We also concluded that the air flow rates and liquid velocities should be small in order to produce bubbles within 2 and 3 mm in diameter. This is shown in Fig. 12 through 14. Future work encompasses continuing the data analyses of later experiments of suspension generation performed on board of the KC-135. These data analyses include the determination of the bubble diameter under different conditions of couette spin and gas flow rate, the experimental determination of the gas flow rate from bubble volume and time to detachment measurements, and the operation of the suspension diagnostics. These include the hot wire anemometer and impedance probes, which are intended to measure the bubble concentration and bubble speed respectively.

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

| | |
|---|---|
| ALS | Advanced Life Support |
| ISRU | In-Situ Resource Utilization |
| MFR | Multiphase Flow Rig |
| RLSS | Regenerative Life Support Systems |
| STPFE | Small Two-Phase Flow Experiment |

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For long-duration space missions, the life support and In-Situ Resource Utilization (ISRU) systems necessary to lower the mass and volume of consumables carried from Earth will require more sophisticated chemical processing technologies involving gas-liquid two-phase flows. This paper discusses some preliminary two-phase flow work in packed columns and generation of bubbly suspensions, two types of flow systems that can exist in a number of chemical processing devices. The experimental hardware for a co-current flow packed column operated in two ground-based low gravity facilities (two-second drop tower and KC-135 low-gravity aircraft) is described. The preliminary results of this experimental work are discussed. The flow regimes observed and the conditions under which these flow regimes occur are compared with the available co-current packed column experimental work performed in normal gravity. For bubbly suspensions, the experimental hardware for generation of uniformly sized bubbles in Couette flow in microgravity conditions is described. Experimental work was performed on a number of bubbler designs, and the capillary bubble tube was found to produce the most consistent size bubbles. Low air flow rates and low Couette flow produce consistent 2-3 mm bubbles, the size of interest for the “Behavior of Rapidly Sheared Bubbly Suspension” flight experiment. Finally the mass transfer implications of these two-phase flows is qualitatively discussed.

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