OBSERVATIONS OF GAS-LIQUID FLOWS THROUGH CONTRACTIONS IN MICROGRAVITY

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ABSTRACT:

Tests were conducted for an air-water flow through two sudden contractions aboard the NASA DC-9 low gravity aircraft. Flow rate, residual accelerations, void fraction, film thickness, and pressure drop data were recorded and flow visualization at 250 images per second were recorded. Some preliminary results based on the flow visualization data are presented for bubbly, slug and annular flow.

INTRODUCTION:

Studies of gas-liquid flows have been conducted by the nuclear and petroleum industries for many years. The influence of gravity on gas-liquid flows has been demonstrated many times by simply changing the orientation of the flow direction with respect to gravity. Changes in the flow regime, as well as the liquid film thickness and void fraction, have been documented for changing the angle between the gravity vector and the flow direction for as little as 0.25 [1].

Gas-liquid flows in reduced gravity have many space-based applications[2], and also have been studied for many years with the earliest studies by Evans[3]. More recent studies by Dukler, et. al.[4], Colin et. al.[5], Huckerby and Rezkallah[6], Kamp et al.[7], Bousman and Dukler[8], Bousman and McQuillen[9], Hill and Best[10], Colin and Fabre[11], Colin et al.[12], have focused on flow within straight cylindrical conduit. These studies have been conducted on aircraft flying low gravity trajectories and have revealed that the flow patterns, or flow regimes, are axi-symmetric because of the greater impact of surface tension forces in the slower flows and the lack of stratification caused by the reduced influence of buoyancy forces.

These studies have found that for gas-liquid flows in a reduced gravity environment, there are three flow regimes: Bubbly, slug, and annular. Bubbly flow consists of small gas bubbles suspended within a continous liquid phase. Slug flow consists of cylindrical-shaped bubbles with a spherical nose surrounded peripherally by a thin liquid film and separated by liquid slugs. The liquid slugs and thin liquid film may or may not contain smaller gas bubbles. The annular flow regime consists of a thin liquid film on the wall that surrounds a gas core. Waves of liquid are transported across the thin liquid film and may generate liquid droplets which are suspended within the gas core and eventually deposited back into the liquid film.

Similar flow regimes exist for vertical upflow and downflow in a normal gravity, and these flow regimes are also axi-symmetric. However, the presence of gravity induces density-driven shear forces that affects the behavior of the flow and the phenomena being observed. This is apparent when comparing the bubbly to slug flow transition for vertical flow in normal gravity with microgravity conditions because the lack of density driven shear permits bubble coalescence to occur much easier. It should also be noted that for the slug and annular flow regimes, the liquid film in normal gravity vertical upflow will reverse its direction, rising with passage of a liquid slug or roll wave and then slowing, stopping and falling between slugs or waves. For vertical downflow, the liquid film may slow, but never stops. For slug and annular flow in microgravity, the liquid film will slow and sometimes completely stop between slugs and roll waves depending on the frequency of the slugs and roll waves.

Most studies have focused on flow through straight conduit; however, there have been several normal gravity studies of flow through fittings that result in changes in the conduit geometry. Usually, these studies of flow through fittings have centered on determining the pressure drop through the fitting. Techniques to predict the pressure drop are usually compared against either a homogenous model or empirical models based on experimental data. To determine the pressure drop, the homogenous model uses the single phase correlations with an averaged gas and liquid density and a liquid viscosity. Tests were conducted aboard the NASA Lewis Research Center's DC-9 Microgravity Aircraft using the DC-9/KC-135 Two Phase Flow Rig to examine the behavior of gas-liquid flows through a sudden contraction.

EXPERIMENTAL HARDWARE AND TESTING:

An instrumented Plexiglas test section was installed in the DC-9/KC-135 rig described by McQuillen, et. al[13]. A Plexiglas test section, illustrated in Figure 1, consisting of four measurement locations was integrated into the rig. Two of these locations consisted of only pressure taps, while the other two locations consisted of pressure taps and conductivity probes. The conductivity probes were used as liquid film thickness probes and void fraction probes, similar to those described by Bousman (1995).

From the mixer to the contraction, the test section diameter was 2.54 cm. Two different size test sections and contractions were fabricated and test: 1.27 and 1.90 cm. The contraction consisted of three Plexiglas blocks that were fabricated. The first block was the inlet piece which into which a 2.54 cm diameter hole was drilled for the flow. At one end of the block, a hole was drilled and tapped to accommodate a straight thread fitting. The inlet Plexiglas tubing was fed through the fitting into the block. The remaining two blocks were similar in construction except that the each of the blocks accommodated an o-ring for sealing against the block with the 2.54 cm diameter hole and that the hole diameters were either 1.27 or 1.90 cm.

The NAC HSV-500 high speed video system was used to record images of the contraction, both upstream and downstream at the contraction. The dual camera option for the video system was utilized, with the second camera focusing on the internals of the gas-liquid system.

Tests were conducted aboard the NASA DC-9 Reduced Gravity Aircraft. Air was used as the gas phase, and either water or a water-surfactant mixture was used as the liquid phase. Flow was initiated during the low gravity portion of the trajectory and the test duration was from 15 to 20 seconds.

RESULTS:

Currently, only the flow rate and video data have been reviewed. From the video data, observations were made about the behavior of the flow as it passed through the contraction.

As bubbly flow entered the contraction, there was no significant amount of coalescence among finely dispersed bubbles. Larger spherical bubbles would become Taylor bubbles as their diameters were confined by the contraction. If one considers the critical void fraction transition criteria first proposed by Dukler (1988) and assumes no slip,

$$\frac{U_{LS}}{U_{GS}} = \frac{1-\alpha}{\alpha}$$

or that proposed by Colin (1991) which was based on a drift-flux approach,

$$\frac{U_{LS}}{U_{GS}} = \frac{1-C_o\alpha}{C_o\alpha}$$

Where U_{LS} and U_{GS} are the superficial liquid and gas velocities, C_o is the slip ratio and a is the critical void fraction. Even though the superficial velocities are increasing as the flow progresses from the larger to the smaller diameter tubes, the ratio does not change. If there are large bubbles in the inlet, the transition occurs not because of coalescence in the contraction, but because of squeezing these large spherical bubbles, see Figure 2, that had probably coalesced from finer bubbles significantly upstream of the contraction.

For slug flow conditions, there were several interesting observations. First, at higher liquid flow rates, there was the generation of waves in the Taylor bubble as it passed through the contraction. For the 1.27 cm. diameter contraction, a significant amount of liquid bridging occurred. This liquid bridging, or snapoff as defined by Roof[4], is unstable and would collapse downstream. At lower liquid flow rates, the bridging would not occur. Apparently, this bridging may be a mechanism for the thin liquid films around the Taylor bubbles to reach some suitable thickness as the Taylor bubble moves through the contraction.

The axisymmetric shape of the Taylor bubble tails as they passed through the contraction would typically become non-axisymmetric as it would slosh from side to side. The wobbling was responsible for axial bubble coalescence if there was a bubble, either spherical or Taylor, that was very closely trailing the wobbling tail. This coalescence would only occur if the trailing bubble was separated by a very thin fluid layer from the leading bubble prior to entering the contraction. It is questionable about whether it is the wobbling tail itself that is responsible for the axial coalescence , or if it is that the trailing bubble is actually traveling faster through the contraction than the leading bubble.

Within the field of view of the camera, long liquid slugs would not totally breakdown into the roll waves as the slugs passed through the contraction. As the liquid slugs become thinner at higher gas flow rates, there was some penetration of the gas bubble into the liquid slug, however, the field of view was very limited. Zhao and Rezkallah[15] proposed a flow regime transition criteria based upon critical gas phase Weber Numbers which are defined as

$$We_{GS} = \frac{\rho_G U_{GS}^2 D}{\sigma}$$

Where r_G is the gas phase density and s is the surface tension. A critical Weber Number of 1 was used for the transition between either bubbly or slug flow regime and frothy slug-annular, and a critical Weber Number of 20 was used for the transition between frothy slug-annular and annular flow. By substituting mass flow rate for the superficial velocity, the Weber Number can be redefined as

$$We_{GS} = \frac{16 \dot{m}_{GS}^2}{\rho D^3 \sigma}$$

As can be seen, there is a significant diameter effect on the necessary flow rate to attain a critical Weber Number.

Slug-annular and annular flow through the contraction resulted in significant roll wave generation in the contraction, particularly when slugs, or large liquid waves, entered the contraction. The roll wave generation in the contraction would continue until the time that there was either no or very little liquid motion in the annular film upstream of the contraction. Preliminary estimates of the liquid film motion, which were made by measuring entrained bubble velocities within the liquid film were less than 40 cm/s. Typical roll wave velocities range from 2 to 5 m/s.

While it is not uncommon to observe liquid film rupture and drainage in microgravity both in straight conduit and the contractions, occasionally a gas phase vena contracta was observed. In the first instance, this dryout actually occurred in a finely-dispersed bubbly flow. Gas bubbles would become entrained in the vena contracta increasing the size of the dryout. Periodically the dryout would "shed" a gas bubble and thus decrease the size. In the second case, as Taylor bubbles passed through the contraction, a gas pocket would be trapped within the vena contracta, see Figure 3. Large spherical bubbles or Taylor bubbles would dislodge the dryout.

FUTURE PLANS:

Analysis of the void fraction and liquid film thickness data both upstream and downstream of the contraction needs to be completed. It is hoped that by examining this data with respect to previously collected straight tube data for 1.27 and 1.90 cm tube diameters, that a model can be developed with regards to the flow development as it flows down the test section. In addition, the evolution of liquid slugs and roll waves as they pass through the contraction needs further analysis.

It appears that the transition from bubble to slug flow does not occur because of coalescence but by squeezing the bubbles. Additional tests in the bubbly flow regime, particularly near the transition to the slug flow regime will verify this.

Additional studies are planned for flow through sudden expansions. Some preliminary work was conducted in the NASA LeRC 2.2 second Drop Tower with slug flow entering an expansion of a 0.95 to 1.27 cm tube (3:4 Diameter Ratio) and a 0.95 to 2.54 cm tube (3:8 Diameter Ratio). Significantly different behaviors were observed. For the 0.95 to 1.27 cm. tube expansion, as slug flow entered the expansion, the cylindrical bubbles would shrink in the axial direction and expand radially. For the most part, the mechanism for transitioning from slug to bubbly flow was that cylindrical bubbles would shrink enough axially not to be considered a cylindrical bubble. Because of the relatively low flow rates, these cylindrical bubbles that became large spherical bubbles were not sheared into smaller bubbles. Figure 4 is an illustration of slug flow entering an expansion with this diameter ratio.

For the initial tests conducted with the 0.95 to 2.54 cm tube expansion, the two phase flow was initiated in normal gravity. The test section on this drop test rig was aligned horizontally. Most of the wall of the expanded area was dry. In normal gravity, as the two phase flow entered the expanded area, the liquid would project out into the area and fall onto the bottom of the test section and flow out. There were not much, if any, gas bubbles entrained in the liquid film flowing along the bottom of the test section. The flow regime in the expanded region during the normal gravity startup was stratified.

Upon the release of the test rig and the start of the free-fall or microgravity period, the flow resembled that depicted in Figure 5 and was of a two phase jet. The flow did not expanded radially to fill the available flow area as it had done for the 3:4 diameter ratio expansion. Similar to the small diameter expansion ratio, the cylindrical bubbles would shrink axially and expand radially as they entered the expanded region. However, the liquid for the most part did not wet the walls of the expansion. The gas in the large bubbles were separated from the gas in the expanded area by a thin liquid film.

For both the contractions and the expansions, tests in vertical upflow and downflow in normal gravity are planned.

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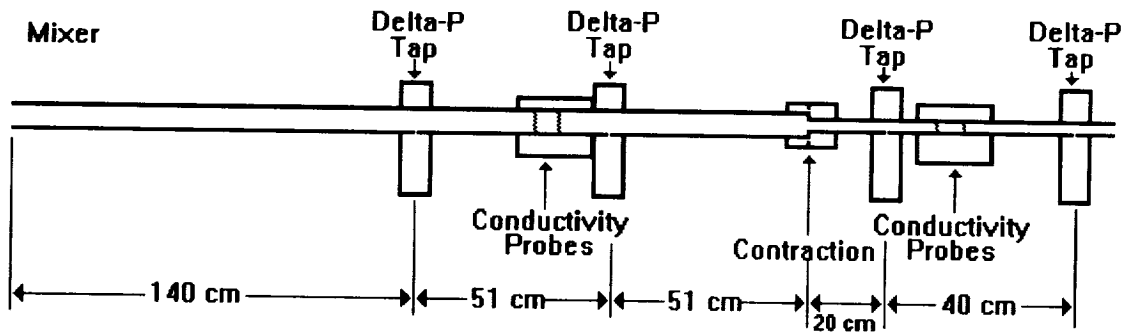```

Figurre 2:  Bubble to Slug Flow

Figure 1: Schematic of test section

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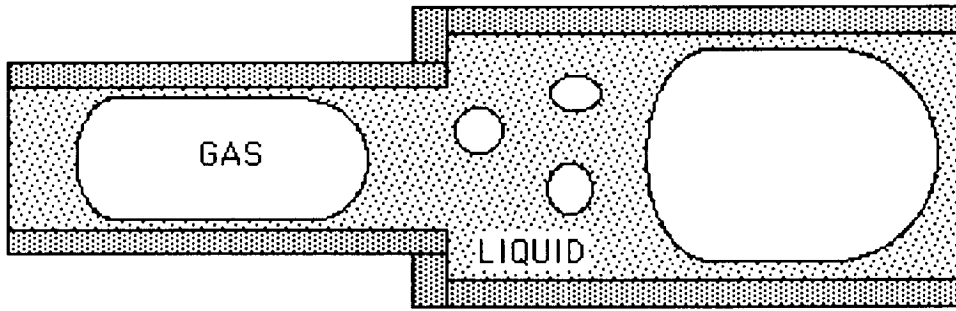Figure 3: Wall Dryout Downstream at Contraction After Taylor Bubble Passage

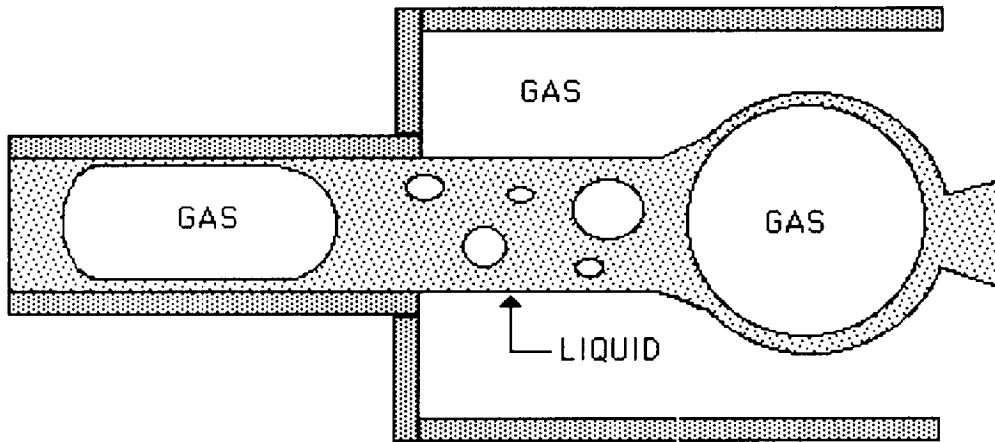**Figure 4: Microgravity Slug Flow through a 3:4 Diameter Ratio Expansion**



**Figure 5: Microgravity Slug Flow through a 3:8 Diameter Ratio Expansion**

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