CHARACTERIZATION OF ANNULAR TWO-PHASE GAS-LIQUID FLOWS IN MICROGRAVITY

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ABSTRACT

A series of two-phase gas-liquid flow experiments were developed to study annular flows in microgravity using the NASA Lewis Learjet. A test section was built to measure the liquid film thickness around the perimeter of the tube permitting the three dimensional nature of the gas-liquid interface to be observed. A second test section was used to measure the film thickness, pressure drop and wall shear stress in annular microgravity two-phase flows. Three liquids were studied to determine the effects of liquid viscosity and surface tension. The results of this study provide insight into the wave characteristics, pressure drop and droplet entrainment in microgravity annular flows.

INTRODUCTION

Two-phase gas-liquid flows are expected to occur in a wide variety of future space operations including: efficient, lightweight thermal transport systems on large spacecraft, storage and transfer of cryogenic propellants, two-phase power cycles and space nuclear power systems [1]. The lack of buoyancy between liquid and gas phases in the microgravity environment causes two-phase flows to behave differently than those on earth. Thus, in order to reliably design and operate gas-liquid flow systems in the microgravity environment, models which account for the behavior encountered in microgravity must be developed.

Microgravity gas-liquid flows distribute themselves into several distinct flow patterns depending on the flow rates of liquid and gas and fluid physical properties as described in Bousman and Dukler, 1993 [2]. Several studies have shown that the annular flow pattern, in which most of the liquid is in the form of a liquid film distributed around the inside perimeter of a pipe surrounding a core of gas and entrained droplets, encompasses most of the gas and liquid flow rate parameter space of interest in the previously mentioned applications [1,2,3]. Annular flow is the most prevalent flow pattern encountered in earth-based industrial applications as well.

Numerous studies of annular flow have shown that it is the rough, wavy gas-liquid interface which accounts for much of the greatly-enhanced momentum, heat and mass transfer effects observed [4]. Models based on flat or periodically wavy liquid films are completely inadequate. In order to develop realistic models of annular flow in the microgravity environment, the characteristics of the gas-liquid interface must be better understood. This work presents the initial results of an on-going experimental study of microgravity annular flows at the NASA Lewis Research Center.

EXPERIMENTAL APPARATUS

The facilities and experimental apparatus used in this study are described in more detail in Bousman and Dukler, 1994 [5]. Microgravity two-phase flow experiments are conducted on the NASA Lewis Learjet which can produce 20-25 second periods of microgravity (0 ± 0.02 g) by following a Keplerian trajectory [6]. A flow loop provides metered quantities of gas and liquid to an annular mixer. The two-phase mixture flows through a development section and into an instrumented test section.

Based on experience gained from previous flow pattern mapping studies, two test sections were constructed to provide the measurements needed to characterize annular flow. The first section consists of a 1.27 cm ID acrylic tube equipped with five parallel wire film thickness conductance probes. The first four probes are offset 60° angularly and

5 mm axially while the fifth probe is oriented the same as the first but located 5 cm downstream. The second test section is a 1.27 cm ID acrylic tube equipped with parallel wire probes to measure both film thickness and void fraction, two pressure transducers to measure the pressure drop in the system and a flush mounted hot-film wall shear stress probe. All signals were acquired at 1 kHz to provide sufficient resolution of the waves. In addition, high speed (400 frame/s) photography allowed for direct flow visualization. Three liquids were used in this study so that the effect of liquid physical properties could be determined: water (μ = 1 cP, σ = 70 dyne/cm), 50-50 wt% water-glycerin (μ = 6 cP, σ = 63 dyne/cm) and water-Zonyl FSP (a DuPont fluorosurfactant) (μ = 1 cP, σ = 20 dyne/cm).

RESULTS AND CONCLUSIONS

The general character of annular two phase flows in microgravity was studied using the five probe test section described above. A typical time trace of air-water annular flow in microgravity is shown in Figure 1. The measurement taken by the first four probes around the perimeter of the tube clearly shows that the waves are ring-like in nature. While the wave shape around the perimeter is irregular, the mean values of the film thicknesses measured by the probes are equal within the error of the measurement. Comparing the measurements of the first and fifth probe, which are both oriented along the bottom of the tube but separated axially by 5 cm, shows that the waves are continuously evolving in shape. Wave splitting and recombination events are frequently observed in these traces. The wave celerity measurements, computed by cross correlating the signals, show that the waves are moving in a narrow range of velocities.

The effect of the liquid physical properties is shown in Figure 2 where three film thickness time traces are presented at the same gas and liquid superficial velocities. Comparing the air-water and air-water/glycerin traces shows that increasing the liquid viscosity leads to a film which contains larger, rougher disturbance waves. The air-water/glycerin trace contains little smooth substrate film between disturbance waves. The effect of liquid surface tension is seen by comparing the air-water and air-water/Zonyl traces in Figure 2. These show that decreasing the surface tension produces an annular film which contains smoother, smaller disturbance waves with larger regions of smooth substrate film in between the disturbance waves. The frequency of disturbance waves in the water experiments is greater than that of either of the other two liquids. These observations are typical of runs in this study with superficial gas and liquid velocities in the range of 5-25 m/s and 0.07- 0.5 m/s respectively.

Since results from five probe test section showed the microgravity annular films to be axisymmetric in a mean sense, the remaining annular studies used the second test section which contained only one film thickness probe. The mean film thickness of air-water annular flows taken over the entire parameter space studied is shown in Figure 3 as a function of gas and liquid superficial velocities. As expected, the film thickness decreases with decreasing liquid superficial velocity but also decreases with increasing gas superficial velocity. The air-water/glycerin results showed the same trend but the mean values were 20-30% greater than those of the air-water experiments. The air-water/Zonyl experiments also showed a similar trend but mean film thickness values were 40-50% lower than the air-water values. Qualitatively, the experiments show that the wave amplitude decreases relative to the substrate thickness as the superficial gas velocity increases, leading to the reduction in mean film thickness shown. This can be quantified by computing the ratio of the standard deviation to mean film thickness as is shown for the air-water runs in Figure 4. The plot shows that this ratio is essentially independent of superficial liquid velocity but a strong function of the superficial gas velocity. It should be noted that the results are also nearly independent of liquid properties since results which are nearly identical to Figure 4 are obtained for both of the other liquids tested.

The mean pressure drops measured in the experiments are shown in Figure 5 for the air-water and air-water/glycerin experiments as well as the pressure drop for single phase gas flow computed from the Blasius correlation. The air-water/Zonyl runs are not shown because they are essentially identical to those measured for air-water. Figure 5 shows that there is a 5-15 fold increase of the gas flow pressure drop due to the presence of the liquid film. The small reduction in cross-sectional area in the pipe due to the presence of the liquid cannot account for this large change and clearly it is the waves which are responsible for the large increase in pressure drop. Figure 5 also shows that the pressure drop in the air-water/glycerin system is 15-25% greater than that in the air-water system. This is consistent with the higher amplitude disturbance waves on the air-water/glycerin liquid films as was shown in Figure 2.

A more detailed understanding of the annular flow pressure drop is possible if the total pressure drop is separated into its component parts as detailed by Fore, 1993 [7]. A force balance on the annular film yields

$$\frac{-\Delta P}{L} = \frac{4}{D}\tau_w + \frac{4}{D} g \rho_L \bar{h} + g\rho_{GC}\frac{(D-2\bar{h})^2}{D^2} + A_E \quad (1)$$

where τ_w is the mean wall shear stress and A_E is the body force due to droplet entrainment and deposition. The second and third terms in (1) are the hydrostatic heads of the liquid film and the gas core and are negligible in microgravity. The remaining terms are contributions to the total pressure drop due to wall friction and entrainment/deposition;

$$\frac{\Delta P_T}{L} = \frac{\Delta P_{WF}}{L} + \frac{\Delta P_E}{L} \quad (2)$$

The pressure drop due to wall friction is computed from the wall shear stress measurements and Eq. (1). The rate of entrainment cannot be measured in the short microgravity periods available in ground-based microgravity facilities. The fraction of the total pressure drop attributed to wall friction is shown for air-water in Figure 6. As shown, the fraction approaches 100% for low flow rates suggesting that entrainment is nearly absent at low gas rates. As the gas rate increases, the fraction decreases achieving a minimum value of less than 40% and suggesting that the rate of entrainment is large at these gas velocities. The fraction is expected to trend back towards 100% at still higher gas velocities since the waves, and therefore entrainment of droplets from the crest of the waves, are significantly suppressed at velocities higher than 50 m/s at normal gravity. Limitations on the aircraft flow loop prevented this from being tested directly. The results indicate slightly less entrainment for the air-water/glycerin system but considerably more for the air-water/Zonyl with only 20% of the total pressure drop attributed to wall friction at the highest gas velocities. The increase in entrainment, coupled with a decrease in wave amplitude, may explain why the mean pressure drop is nearly the same as in the air-water experiments even though the waves are smaller for the air-water/Zonyl runs.

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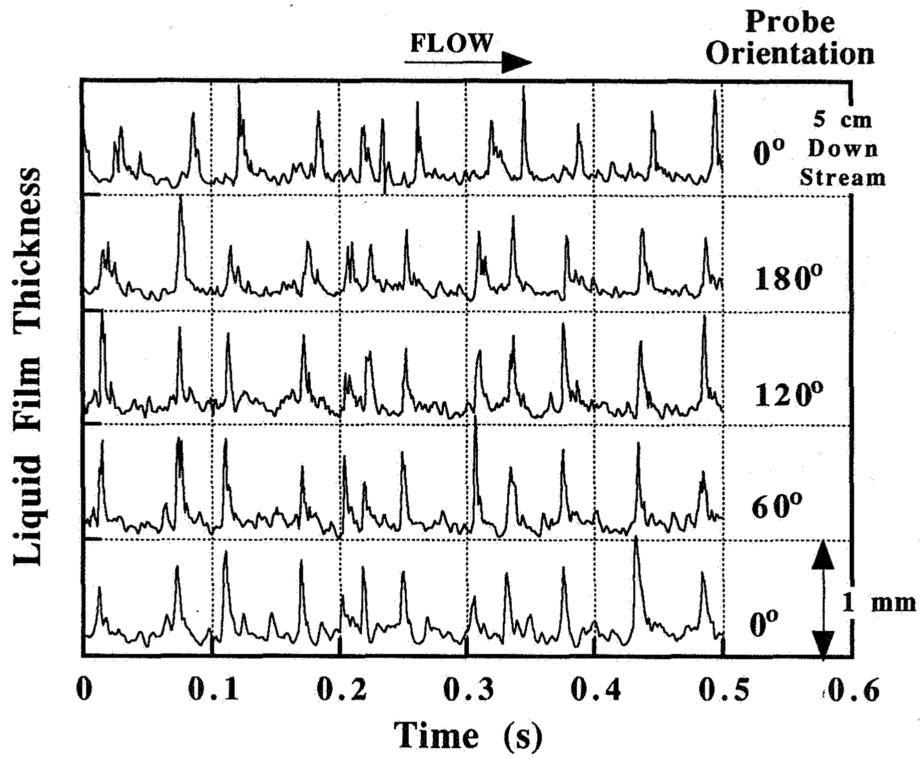

Figure 1 Circumferential Distribution of an Annular Film in Microgravity

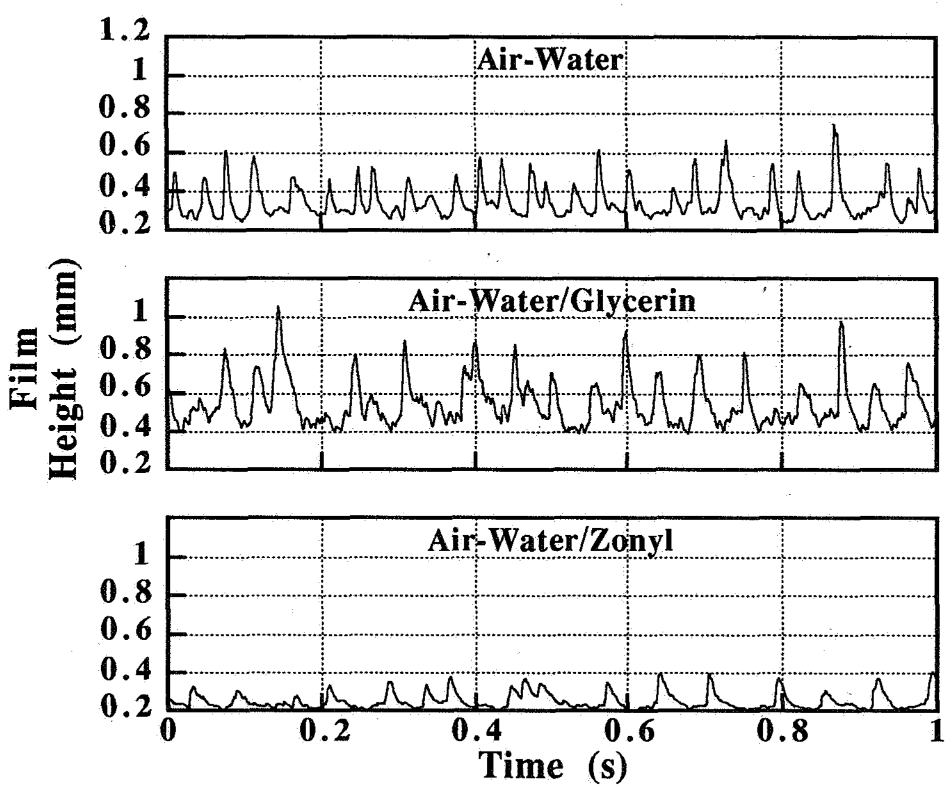

Figure 2 Film Thickness Time Traces of Annular Flow at Ugs = 25 m/s, Uls = 0.1 m/s for Air-Water, Air-Water/Glycerin and Air-Water/Zonyl

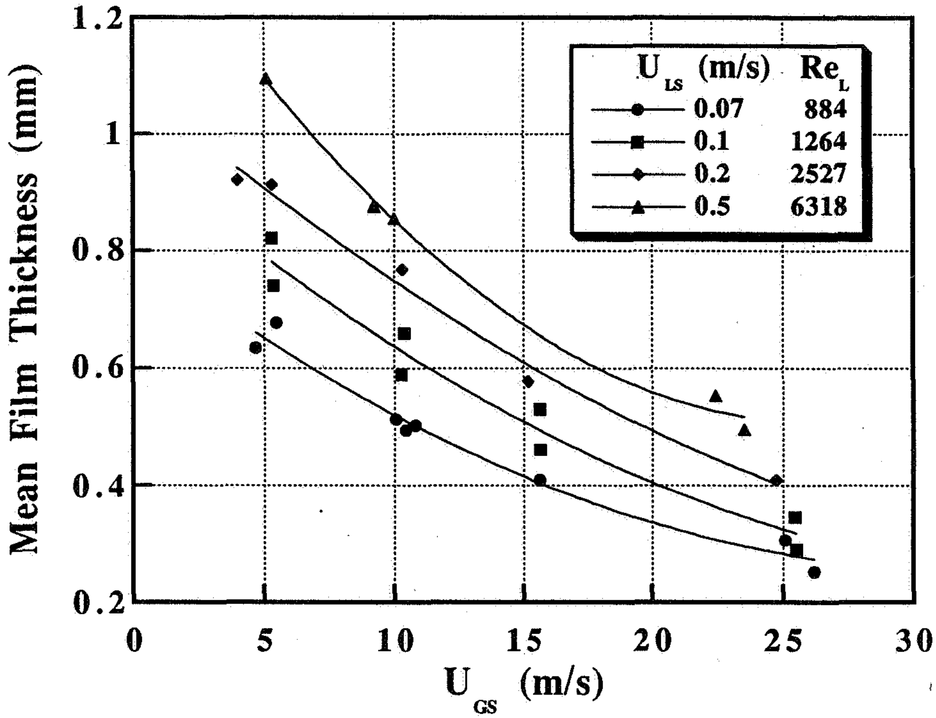

Figure 3 Mean Film Thickness in Microgravity Air-Water Annular Flow

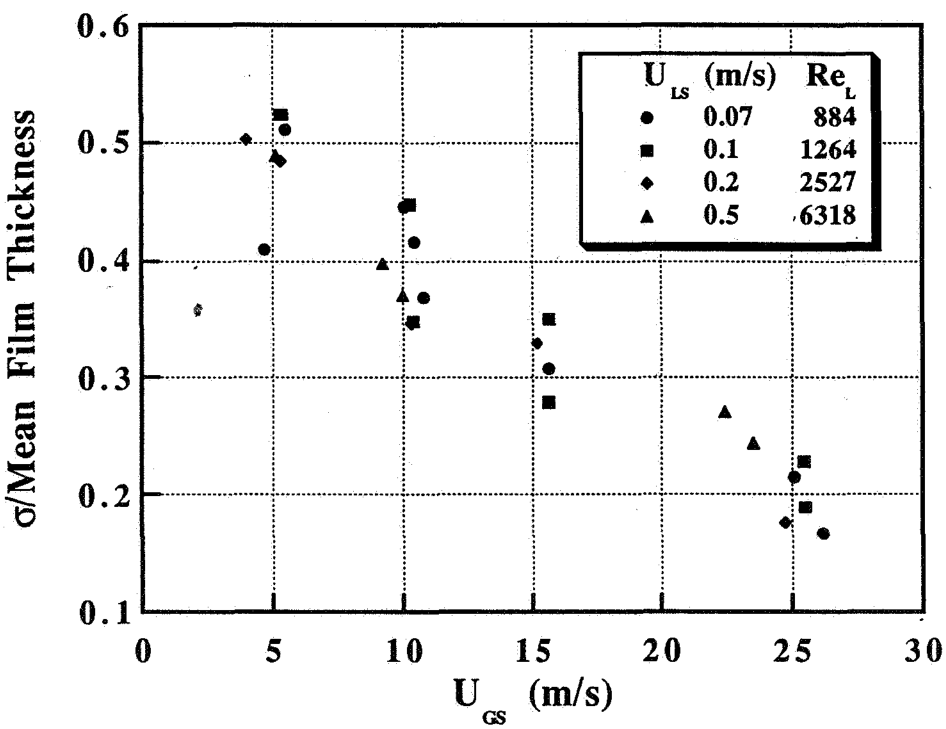

Figure 4 Ratio of Standard Deviation to Mean Film Thickness for Microgravity Air-Water Annular Flow

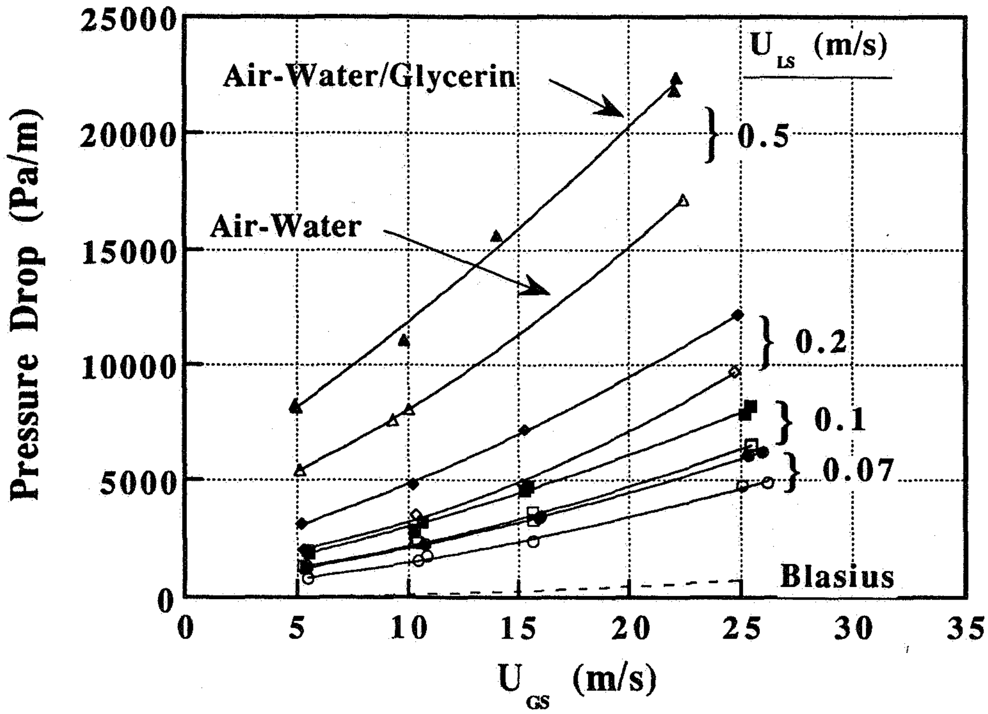

Figure 5 Pressure Drop for Annular Flow in Microgravity, 1.27 cm ID Tube

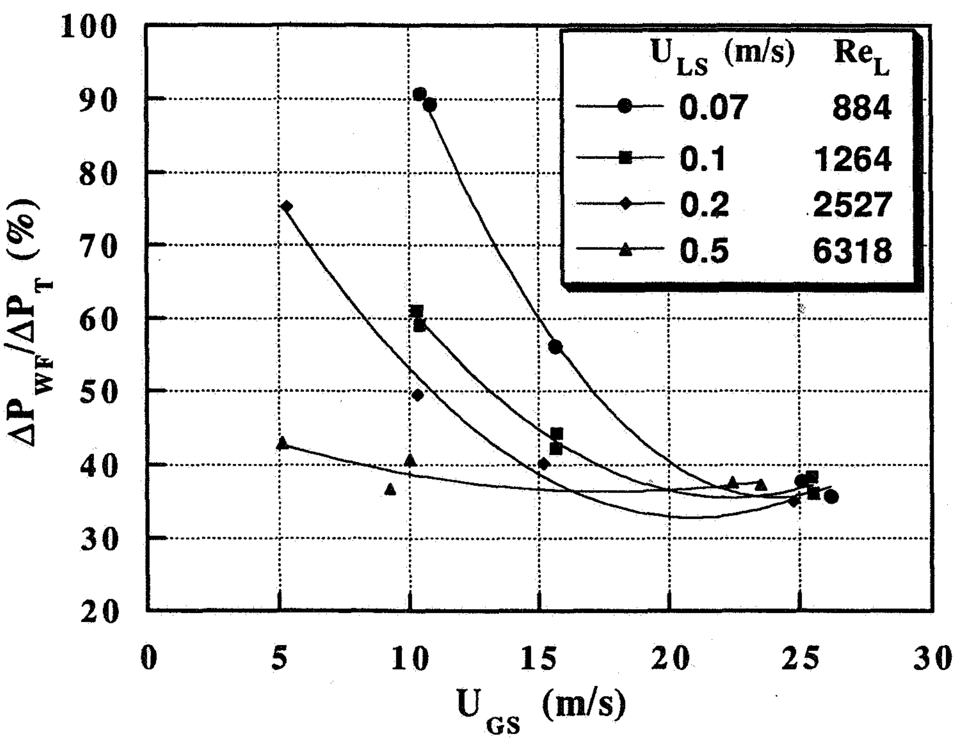

Figure 6 Fraction of Total Pressure Drop Due to Wall Friction, Air-Water, 1.27 cm ID Tube