

EXPERIMENTAL STUDY OF TWO-PHASE FLOWS UNDER REDUCED GRAVITY CONDITIONS

T. Roy^{1,2}, Y. Liu¹, Shao-Wen Chen¹, T. Hibiki¹, M. Ishii¹, and W. Duval³

¹Purdue University, West Lafayette, IN, USA

²Current Address: Norwegian University of Science and Technology, Trondheim, Norway

³NASA Glenn Research Center, Cleveland, OH, USA

tirthankar.roy@ntnu.no, liu130@purdue.edu, hibiki@purdue.edu, ishii@purdue.edu,
walter.m.duval@nasa.gov

Abstract

Study of gas-liquid two-phase flows under reduced gravity conditions is very important for space applications such as active thermal control systems. Two-fluid model along with Interfacial Area Transport Equation (IATE) is a useful tool available to dynamically predict the behavior of such two-phase flows under normal and reduced gravity conditions. As part of a big program experiments were carried out in a 304 mm inner diameter test facility on earth to generate a detailed experimental data base which is required for the evaluation of two-fluid model along with IATE under reduced gravity conditions. In the present case reduced gravity condition is simulated using two-liquids of similar densities. Such a large diameter test section was chosen to study the development of drops to their full. Twelve flow conditions were chosen around predicted bubbly flow to cap-bubbly flow transition region. Detailed local data was obtained at ten radial locations for each of three axial locations using double-sensor conductivity probes. Some of the results are presented here and discussed.

1. Introduction

One of the major applications of two-phase flow at microgravity conditions is the design and maintenance of active thermal control systems for future space stations and high-power communications satellites. There are several characteristics that make two-phase flows more desirable than single-phase flows for heat transfer purposes. First, the heat transfer coefficient in two-phase flow with phase change can be several orders of magnitude higher than that in single-phase flow. This results in a physically smaller system that can carry as much heat as a single-phase system with much larger size. Secondly, heat can be transferred to the fluid while maintaining a constant surface temperature. Another important application of two-phase flow is in the design of space nuclear power systems. Two-phase flow phenomena also occur in many life-support systems in space stations and space labs.

The prediction of two-phase flow behavior remains a challenge, despite a lot of research into the area. Over the years, the two-fluid model has been established as a practical model with sufficient details to describe two-phase flow problems. The two-fluid model uses six field equations to describe the flow and interfacial transfer terms to describe the interaction between the phases. It has been widely used to predict multi-dimensional and transient two-phase flow. It

has also proved to be very useful in cases where the flow changes significantly due to interactions within the dispersed phase. Several interfacial transfer terms arise on the right hand side of the mass, momentum and energy equations of the two-fluid model. These interaction terms can be expressed as a product of the interfacial area concentration and certain driving force for the transfer. Hence, the predictive capability of the two-fluid model can be said to rest on the accurate determination of the interfacial area concentration since the driving force for the transfer is usually known. In case of normal gravity two-phase flows, a novel approach that takes into account the dynamic changes of the structure of two-phase flow has been adopted by introducing the interfacial area transport equation (IATE). The interfacial area transport equation is formulated by mechanistically modeling the physical processes that govern the creation and destruction of interfacial area. The IATE dynamically models the changes in the flow structure and can, potentially, significantly improve the predictions. The IATE has been successfully developed for normal gravity conditions. It has been demonstrated that by using the IATE, the evolution of interfacial structures can be dynamically predicted for a flow field.

The ultimate objective of the present research is to develop IATE applicable to reduced gravity two-phase flows. To that purpose, a detailed ground-based experimental study has been carried out since 2004 [1, 2, 3, 4] to investigate two-phase flow structure under reduced-gravity conditions, and to establish a reliable database of local two-phase flow parameters. In the study, reduced-gravity condition was simulated using two immiscible liquids of similar densities. The detailed two-phase flow parameters were measured by global and local two-phase flow measurement techniques, including multi-sensor impedance void-meter, and local double- and four-sensor conductivity probes. In the previous phase of this research program extensive global and local two phase flow measurements were performed in a small diameter (25 mm inner diameter or ID) test section for a large number of flow conditions [1, 2, 3, 4]. “One-group” IATE was evaluated against the obtained data. The maximum error between the prediction and experimental data for the area-averaged interfacial area concentration in the ten test runs was found to be 22%. The current phase of the research program concentrated on experiments performed in a large-diameter (304 mm ID) test section.

2. Literature Review

Many studies have been done to understand global flow patterns and their transitions for gas-liquid flows under reduced gravity conditions [5-14]. Most of the experiments were performed aboard drop towers or aboard aircrafts following parabolic trajectories with an air-water system. Some of these works propose flow regime transition criteria for adiabatic two-phase flows under reduced gravity conditions [6, 13]. Both drop tower and parabolic flight experiments are characterized by extremely small durations for which reduced gravity can be simulated and extreme limitations on the geometries of ducts being used in the experiments. In reduced gravity environments, especially for low-inertia two-phase flows, the flows will require an extremely large length of flow duct to reach fully developed conditions. This means that above mentioned experimental results have limited applicability in designing two-phase flow systems operating in reduced gravity environments. The two-fluid model along with IATE can prove extremely useful as it takes account of various mechanisms which drive the flow development. Given the initial

and boundary conditions this model can predict the subsequent two-phase flow behavior. This is very important in dealing with flows under substantial temporal and spatial development such as entrance flow, transients, and flow with strong phase distributions. However, it is essential to first evaluate the predictions of this model against experimental data obtained under reduced gravity environments.

Very few experimental programs have been carried out till date to generate detailed local data against which the two-fluid model along with the IATE can be evaluated. Towards this end Takamasa et al. [15] measured axial developments of one-dimensional void fraction, bubble number density, interfacial area concentration, and Sauter mean diameter of adiabatic nitrogen-water bubbly flows in a 9 mm-diameter pipe under microgravity environments. Marked bubble coalescence was observed due to trailing bubbles near the channel center coalescing with bubbles in the vicinity of the channel wall (velocity profile entrainment). Negligible bubble breakup was observed because of weak turbulence under tested flow conditions. Vasavada et al. [16] performed extensive experimental studies simulating reduced gravity environments in ground based facilities by using two immiscible liquids of similar densities in a 25 mm ID pipe. Important local two-phase parameters including dispersed phase fraction, interfacial area concentration, droplet number frequency and droplet velocity were acquired at two-axial locations using multi-sensor conductivity probes. From the acquired data it was shown that coalescence mechanism was enhanced by increasing the flow rate of either phase. Evidence of turbulence induced particle interaction mechanisms was also shown. The data presented highlighted the differences between flow structures of two-phase flows under normal and reduced gravity environments. Most important among the differences were a distinct reduction in the relative velocity between the phases and the large stable size of bubble/droplets in reduced gravity environments.

In the past many works have been done to develop drift-flux model as well as two-fluid model along with IATE which take gravity effects into consideration. Hibiki et al. [17] studied in detail the drift-flux model and proposed constitutive equations of the distribution parameter for bubbly flow which takes the gravity effect into account. The constitutive equations for slug, churn and annular flows, which are applicable to reduced gravity conditions, were recommended based on existing experimental and analytical studies. A comparison of the model with experimental data, over various flow regimes and a wide range of flow parameters taken at microgravity conditions, showed satisfactory agreement. Hibiki et al. [18] studied IATE taking into account the gravity effect. Comparison of the newly developed interfacial area transport equation with various experimental data taken at microgravity conditions showed satisfactory agreement. It was shown that the effect of gravity on interfacial area transport in a two-phase flow system is more pronounced for low liquid flow and low void fraction conditions, whereas the effect is negligible for high mixture volumetric flux conditions. Vasavada et al. [19] evaluated one dimensional one group IATE against data previously acquired by the author himself. Flow conditions lying in the bubbly and bubbly to slug transition flow regime were used for evaluation purposes. The comparisons showed that the modeled interaction mechanisms existing in the one dimensional one group IATE were physically sound. Moreover, they have shown to represent the physics existing in reduced-gravity two-phase flows for the flow conditions considered. The study

demonstrated the ability of the IATE to model the evolution of two-phase bubbly flows in reduced-gravity conditions.

3. Experimental Program

The details of the experimental program have been provided in [16]. Hence only an overview will be provided in the following paragraphs. The major differences between the current experimental facility and that of [16] is described in detail.

3.1 Experimental Facility

The experiments were performed in a 304 mm inner diameter (ID) test section using nearly equi-density liquids to simulate a reduced-gravity condition. The fluids used were water as the continuous phase and an organic fluid, Therminol 59® (hereafter referred to as Therminol only), as the dispersed phase. The justification for the experimental approach, method of selection of the working fluids and the physical properties of the working fluids are provided in [16]. The basic idea being that in low inertia flows the similarity of two-phase flow structure in two different geometries can be insured by preservation of the ratios of important internal length scales to the external ones. The physical properties are repeated here, in Table 1, for the convenience of the readers.

Table 1 Properties of Therminol and water

Liquid	Density (kg/m ³)	Dynamic Viscosity ($\times 10^{-3}$ kg/m·s)	Interfacial Tension ($\times 10^{-3}$ N/m)
Therminol 59 (Alkyl Substituted Aromatic)	971.2	7.0	42.5
Water	998.0	1.0	-

For the current experimental study, a test section consisting of a 304 mm ID round pipe, was used. Since the maximum stable drop diameter is very large for the current experimental study (about 50 cm), a large diameter test section enabled the observation of the complete growth of drops. In the case of small diameter test sections, drops elongated in lengthwise direction after its size became comparable to channel diameter. Such drops were considered as slug drops previously. A schematic diagram showing the general layout of the test facility is shown in Figure 1. The test section was constructed from Pyrex® glass pipes. The height of this test section was approximately 4.5 m giving a L/D_h of about 17. The exit of the injector section was considered as the origin for measurement in the direction of flow. As shown in the schematic, water and Therminol were pumped into the test section using centrifugal pumps from their respective tanks.

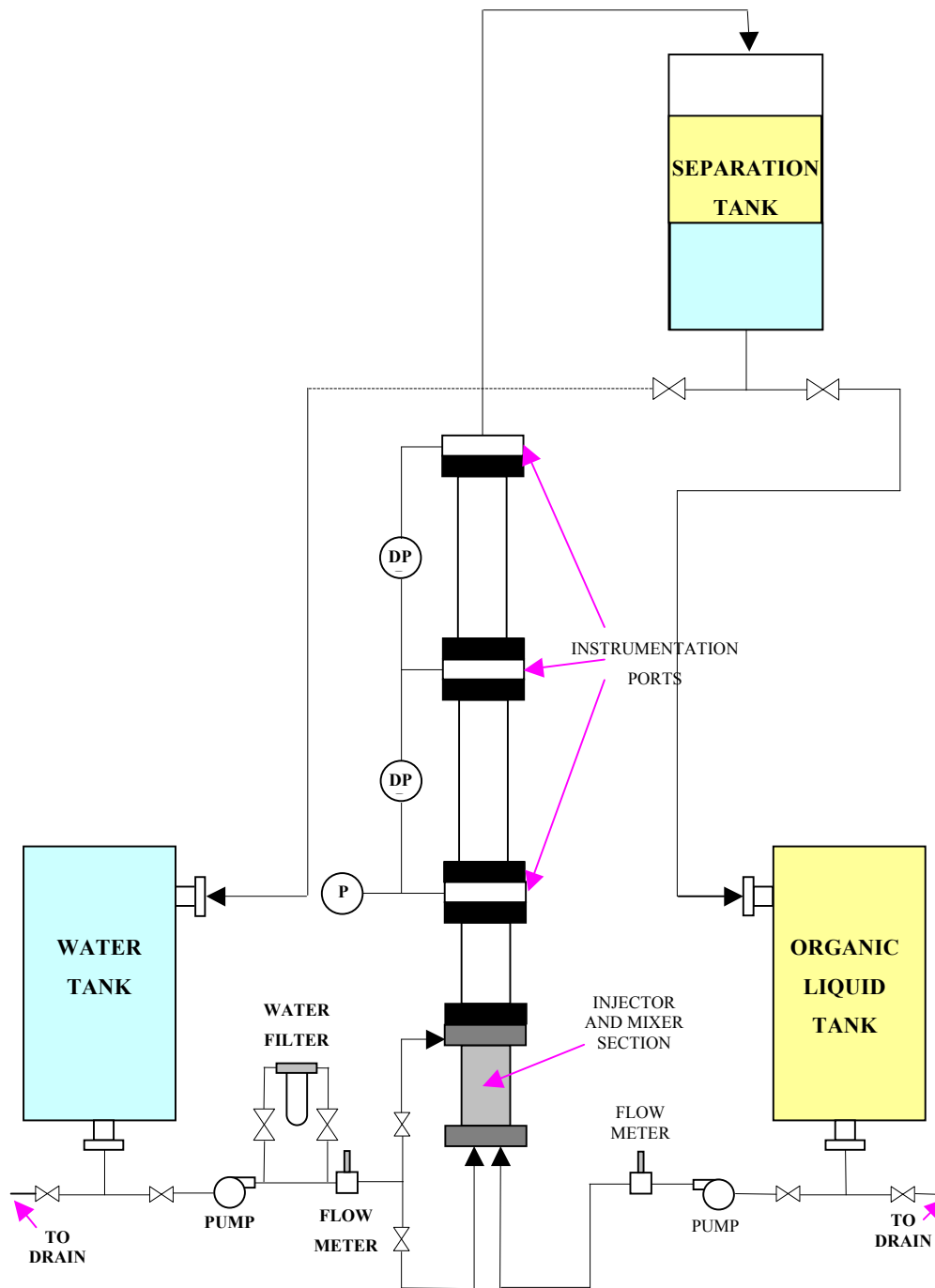


Figure 1 Schematic of experimental facility

Therminol was metered using a pair of rotameters (accuracy about 2 % of the full scale). The flow rates of water through the outer and inner annuli were measured using magnetic flowmeters. The fluids entered the test section through the injector. The mixture then flowed through the 304 mm ID test section. Upon exiting the test section, the mixture was injected into a separator tank. The mixture was then allowed to separate under effect of gravity in the separator tank. This arrangement required the experiments to be run as batch processes. Taking into account the limitations imposed by the capacities of the liquid storage tanks and the pumps, for most of the experiments performed during this phase of the research the run times varied from 3-5 minutes. Two runs were performed for each flow condition to ensure statistically significant values of local two-phase flow parameters being recorded. The injector consisted of 19 custom-made spargers (uniformly distributed across the flow area) through which the dispersed phase was discharged into the continuous phase. Each sparger consisted of a 9.5 mm OD tube into whose wall small holes were drilled. Each sparger was surrounded by a 25 mm ID S.S. tube. Water entered the injector section from two locations. A S.S. flange containing eight holes of 25 mm diameter on the injector's sides was used to inject the 'primary' flow of water into the test section. Water also flowed through the annulus formed between each 'sparger' and the 25 mm OD tubes surrounding them. This 'secondary' flow helped to shear off the drops from the 'sparger' holes. The injector also contained a flow straightener to ensure uniformity of the 'primary' flow of water across the flow cross section. This flow straightener consisted of two S.S. meshes with a mesh size of 2 mm which were cut to fit the inner diameter of the pipe enclosing the injector section and were mounted on supports welded to the inside of this pipe. Delrin balls about 25 mm in diameter were sandwiched between these meshes.

3.2 Double Sensor Probe Methodology

The instrumentation port for present test section had an integrated design consisting of two inserts for local multi-sensor conductivity probes and a multi-sensor impedance voidmeter. The impedance voidmeter was not used during this phase of experiments. The height of each instrumentation port was approximately 68 mm. The instrumentation port for the 304 mm ID test section is shown pictorially in Figure 2.

The conductivity probe has been one of the most widely used local measurement instruments in two-phase flows. The principle of the probe is based on the intrinsic difference in the electrical conductivity between the dispersed phase and the continuous phase. The characteristic rise/fall of the impedance (converted to voltage signals through an electrical circuit) between the sensors and the common ground can be obtained as the drops pass through the exposed tips of the probe sensors. The time-averaged dispersed phase fraction can be obtained by dividing the sum of time occupied by the dispersed phase by the total measurement time. The double-sensor probe is made of two thin electrodes. The tip of each electrode is exposed to the two-phase mixture and measures the impedance between the probe tip and the common ground. The time delay, Δt , of the two impedance signals (corresponding to responses of the two electrodes) can be utilized to determine the time taken by the droplet surface to travel from the upstream probe sensor to the downstream sensor. Since the separation of the two electrode tips is known, defined as Δs , a measurable droplet axial velocity, $\Delta s/\Delta t$, is obtained. For the measurement of the local time-averaged interfacial area concentration, formula has been suggested after considering the effects

of the droplet lateral motion and the probe spacing [20]. Much more on the design of multi-sensor conductivity probes, the associated circuit board and associated signal processing schemes can be found elsewhere [21].

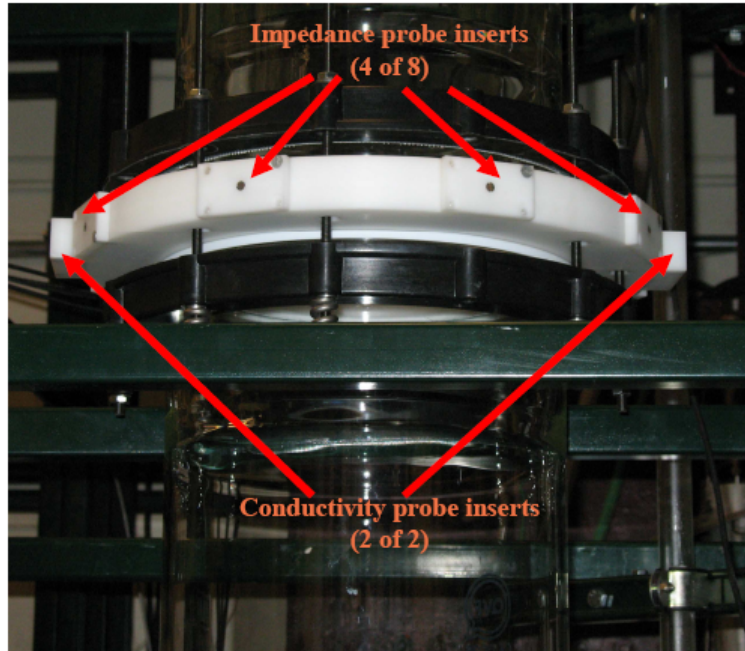


Figure 2 Instrumentation port for the 304 mm ID test facility

The present experiments were found to be extremely time consuming. To reduce the numbers of times experiments have to be repeated slightly modified design of double-sensor conductivity probes were used. Ten double-sensor conductivity probes were screwed on to a 1/4" OD stainless steel tube as shown in Figure 3. This allowed the measurement of local two-phase flow parameters at ten radial locations simultaneously, thereby, greatly reducing the effort needed to obtain detailed local two-phase flow parameters. Three such assemblies were used to measure local two-phase flow parameters at three axial locations ($L/D_h=1.7, 5.0, 8.3$) simultaneously. The total flow area was divided into ten equal segments and the ten double-sensor conductivity probes were then placed at the center of each circle/annulus thus created. A frequency of 5000 Hz was used to acquire data from the double-sensor conductivity probes to minimize the error associated with interface velocity measurements.

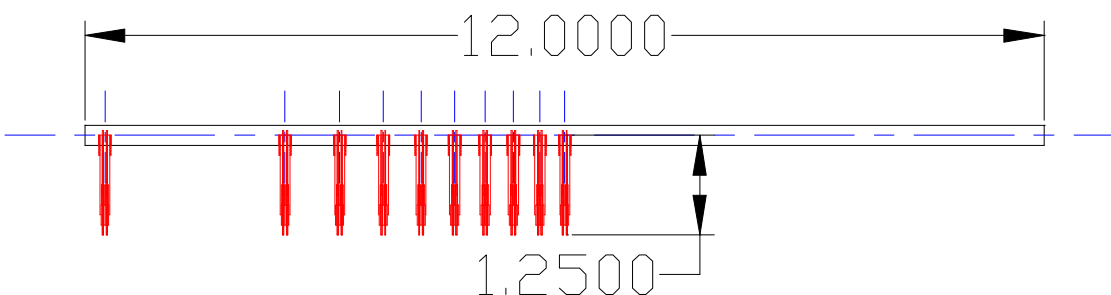


Figure 3 Modified design of double-sensor conductivity probes (dimensions in mm).

4. Results and Discussion

Local two-phase flow data were obtained for 12 flow conditions which are tabulated in Table 2 and are plotted in Figure 4. Four different continuous phase (water) superficial velocities were chosen for each of three different dispersed phase (Therminol) superficial velocities. The solid line on the plot in Figure 4 represents the transition boundary from bubbly to slug as predicted by the Mishima and Ishii [22]. The flow conditions were chosen around this transition boundary where significant flow structure and interfacial area development are expected. This was to generate a more meaningful local two-phase flow parameter database against which the evaluation of the IATE can be performed. The experimental results shall be briefly discussed below. Detailed analysis shall form the part of a future publication. Figure 5 and Figure 6 compare the dispersed phase fraction and the interfacial area concentration profiles at the instrumentation port closest to the exit of the test section for 3 different test conditions-Runs 1, 4 and 9. It can be seen that increase in the continuous phase flow rate keeping the dispersed phase flow rate the same decreases the local dispersed phase fractions (Figure 5 (a) vs. (b)). An increasing the dispersed phase flow rate keeping the continuous phase flow rate the same increases the local dispersed phase fractions (Figure 5 (a) vs. (c)). Similar trends were observed with all the other data. The Group 1 dispersed phase fraction and interfacial area concentration profiles are more or less flat whereas Group 2 profiles show a distinct core peaking. Although not shown here the axial velocities of either group of drops are very close to one another owing to the small difference in densities between the phases. As can be observed from the figures Group-2 drops exist in almost all flow conditions. Apparently this is not to be expected according to the Mishima-Ishii model. However, it is to be kept in mind that Mishima-Ishii model is applicable to fully developed two-phase flows. And in low inertia two-phase flows under reduced gravity environments as is simulated by current experiments, it is not easy to attain fully developed two-phase flows. That implies that inlet conditions would tend to affect the subsequent flow structure. In the current experiments the size of the droplets at the inlet were found to be relatively big which corroborates well with the measurements. Lots of inter- and intra-group droplet interaction mechanisms could be seen at play, especially at high flow rates of either phase. Due to low inertia of the flows turbulent disintegration and random collision mechanisms of interfacial area creation/destruction can be expected to be less dominant. On the other hand, other mechanisms such as wake entrainment, shearing-off and surface instability can be expected to be dominant. However conclusive remarks about these mechanisms can only be

made only after IATE has been evaluated against the obtained data which shall be the subject matter of future publications.

Table 2 Test matrix

Run #	Area Averaged Superficial Velocity of Continuous Phase (Water) [cm/s]	Area Averaged Superficial Velocity of Dispersed Phase (Therminol) [cm/s]
1	0.000	0.893
2	0.893	0.893
3	1.790	0.893
4	2.680	0.893
5	0.000	1.790
6	0.893	1.790
7	1.790	1.790
8	2.680	1.790
9	0.000	2.680
10	0.893	2.680
11	1.790	2.680
12	2.680	2.680

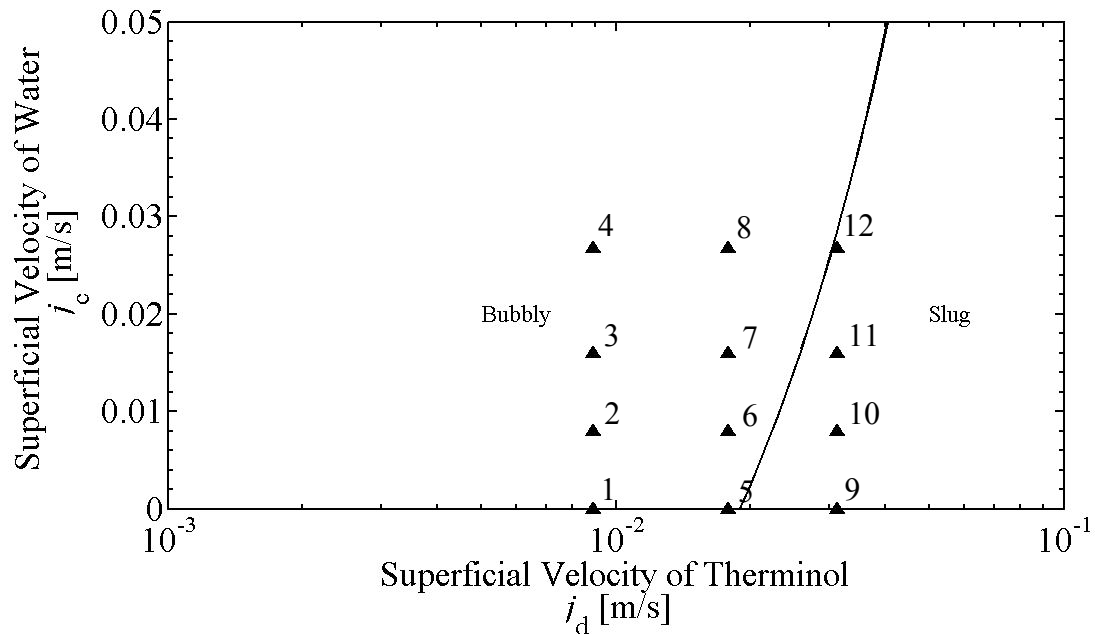
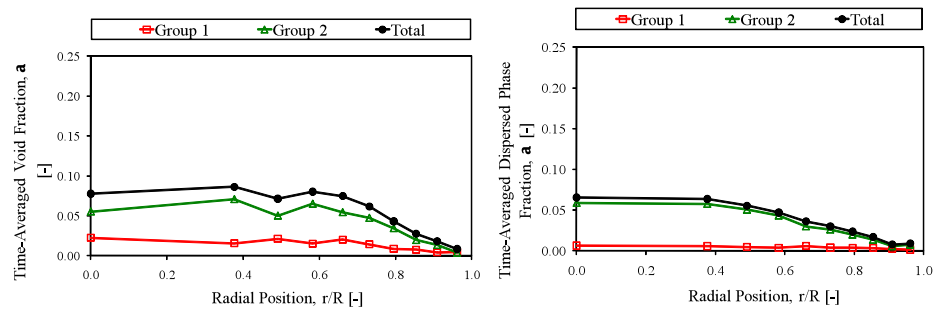
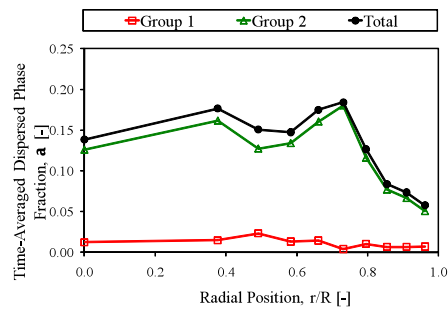


Figure 4 Test matrix and Mishima-Ishii flow regime transition boundaries.



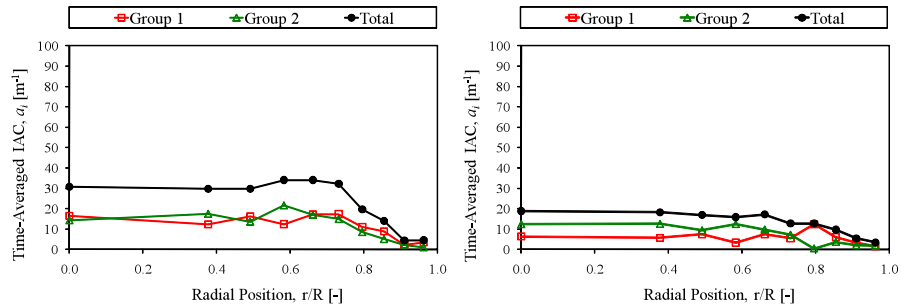
(a) Run 1

(b) Run 4



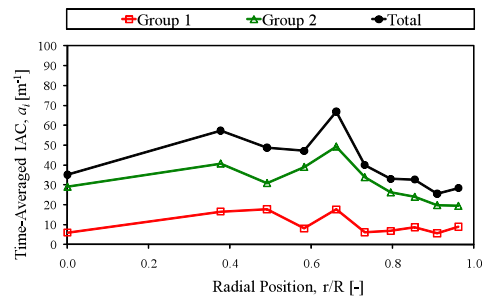
(c) Run 9

Figure 5 Dispersed phase fraction profiles



(a) Run 1

(b) Run 4



(c) Run 9

Figure 6 Interfacial area concentration profiles

5. Conclusions

Experiments were performed in a 304 mm ID pipe using two liquids of similar densities to simulate low inertia gas-liquid flows in reduced gravity environments. Detailed data on local two-phase flow parameters were obtained using double-sensor conductivity probes. Initial processing of the data has been performed and some of the results have been presented here. Future work includes comparison of the obtained data against IATE predictions and evaluation of various models in the IATE.

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