Experimental and Analytical Study of Two-Phase Flow in Microgravity

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ABSTRACT

Design of the two-phase flow systems which are anticipated to be utilized in future spacecraft thermal management systems requires a knowledge of two-phase flow and heat transfer parameters in reduced gravities. A program has been initiated by NASA to design a two-phase test loop and to perform a series of experiments to study the effect of gravity on the Critical Heat Flux (CHF) and onset of instability. The test loop is also instrumented to generate data for two-phase pressure drop. In addition to low gravity airplane trajectory testing, the experimental program consisted of a set of laboratory tests which were intended to generate data under the bounding conditions (+1g and -1g) in order to plan the test matrix. One set of airplane trajectory tests has been performed and several modifications to the test set-up have been identified. Preliminary test results have been used to demonstrate the applicability of the earth gravity models for prediction of the two-phase friction pressure drop.

INTRODUCTION

Two-phase systems are generally designed for operation under the nucleate boiling regime in order to utilize the high heat transfer characteristics of two-phase flow. Operation of these systems beyond the critical heat flux may lead to a sudden jump in the surface temperature due to reduction in the heat transfer coefficient (film boiling regime). This temperature is usually above the melting point of many materials; the maximum surface heat flux is also called the limit of stable burnout. In many practical situations, two-phase components fail at heat fluxes well below the limit of stable burnout. This is due to hydrodynamic instabilities which result in sudden reductions in flow and burnout at smaller heat fluxes. Knowledge of stable burnout limit and the onset of hydrodynamic instability is crucial for operation of any two-phase loop. At this stage, it is generally concluded that considerably more data, preferably under long duration steady-state conditions, is needed to complete and confirm the design approaches for application to reduced gravities.

Operation of the boiling systems under CHF is an important design limitation. Most industrial systems are designed based on empirical CHF correlations which are valid under narrow range of operating conditions. Unlike the early attempts in developing generalized CHF correlations based on the pool boiling mechanisms, it is now believed that critical heat flux depends on the flow pattern at CHF. In Ref. (1) the existing CHF models and correlations are divided into three categories based on the underlying assumption for the flow regime at CHF. Due to the effect of gravity on the flow pattern and void distribution, applicability of the existing CHF models at reduced gravities should be evaluated.

There are a number of static and dynamic instability mechanisms which should be considered for the design of two-phase systems operating in reduced gravities. Instabilities resulting from the interaction of the system components and the characteristic of two-phase flow are particularly important for systems operating under a forced convective mode of heat transfer.

Excursive or Ledinegg instability can be analyzed by static equations and it occurs under operating conditions which result in an increase in two-phase pressure drop with decreasing flow rate. For an imposed external pressure drop under such conditions, operation at more than one flow rate is possible. Small disturbances may lead to a shift from one flow rate to another (usually lower) in a non-recurring manner and burnout may occur. Using a force balance on a boiling channel, it can be shown that the system will be stable if the slope of the pressure drop-flow rate characteristic is less negative than the imposed external supply.

When several two-phase channels are used in parallel, the variations in the flow rate through one channel do not affect the overall pressure drop. This situation is similar to imposing a constant pressure drop across a single channel which is prone to excursive instability. In such cases, severe maldistribution of flow could occur which would lead to burnout.

The most common form of dynamic instability encountered in industrial systems at earth gravity is density wave oscillation. This mechanism is due to multiple feedback between the flow rate, vapor generation rate, and pressure drop within the boiling channel. This form of instability is usually analyzed with linear system methods and frequency domain stability methods. However, due to availability and the speed of present day computers, time domain analysis of the non-linear conservation equations is being used more frequently.

It is known that the pressure drop-flow characteristic and the void distribution, which are affected by the gravity level, strongly influence the stability limits. Although the stability criteria are system dependent, it is expected that for a given flow rate and power input to a boiling channel, the instability limits will be different under reduced gravities.

The main objective of this research activity was to design a test loop and perform a series of airplane trajectory experiments in order to generate data for the critical heat flux under reduced gravity conditions and to investigate the effect of gravity on hydrodynamic instabilities. The data will be used to evaluate the existing CHF models and, if necessary, develop applicable physically based models.

EXPERIMENTAL APPARATUS

The schematic of the test loop is shown in Figure 1. It is a closed loop consisting of a magnetically coupled gear pump, a bladder type accumulator, a preheater section, a heated and an adiabatic test section, and a tube-in-tube condenser. The test system was packaged on two Learjet racks and used to perform a series of normal gravity laboratory tests, as well as one set of airplane trajectory tests aboard the NASA DC9 airplane, (2). The measurements included the fluid temperature and pressure, surface temperature of the test section, flow rate, and pressure drop across the adiabatic section. Turbine flow meters were used to measure the total flow rate and the flow rate in the test section leg. Flush mounted flow through thermocouples were used to monitor the fluid temperature.

The heated section consisted of a 5/16-inch OD stainless steel tube with nickel-chromium heater wire wrapped over a 14-inch length of its mid-section. Measured test section surface temperatures were used to sense sudden rise in the wall temperature which indicates CHF or drop in flow rate due to instabilities. Ribbon type thermocouples were used to monitor the wall temperature in gaps between the wires and at the end of the heated section. Upon sensing a large temperature rise, the heater power was shut down and the test section path was flooded. The adiabatic section is 22 inches long and is intended for two-phase pressure drop measurements over a region where the vapor phase content is known. Differential pressures across two sections of the adiabatic tube were measured and recorded. A purge system was used to flow subcooled liquid through the differential pressure transducer sense lines prior to recording.

Modularity of the test loop was one of the criteria in design and selection of the components. This loop can serve as a test bed for generating data for other two-phase flow parameters as well as evaluating the performance of loop components.

Freon 114 was used as the working fluid due to its low heat of vaporization and lower saturation pressure at ambient temperatures. The test variables were power level which ranged between 300 and 1000 watts, and flow rate which varied from 0.05 to 0.8 GPM. Due to phase-out of chlorofluorocarbons, a new working fluid is being evaluated which will be used in the future flights.

The earth gravity tests were intended for system checkout and to establish the test matrix and operational procedure of the reduced gravity tests. These tests were performed with vertical up (+1g) and vertical down (-1g) configurations in order to bound the reduced gravity conditions. The first set of airplane trajectory tests provided preliminary results on the two-phase pressure drop characteristics and indicated the need for modifications in design and operating procedures.

RESULTS AND DISCUSSION

As mentioned earlier, only one set of airplane tests has been completed so far. These tests indicated the need for several design and operational changes and it was decided to modify the loop to implement the changes and accommodate the replacement of the working fluid before the next series of flights. Several observations were made which are briefly discussed below.

1. Comparison of the tests with downflow and upflow configurations shows that CHF occurs at nearly the same power at low flow rates. As the flow rate is increased, CHF occurs at higher powers for upflow configuration. This could be due to the differences in void distribution for upflow and downflow. At low flow rates the exit quality is so high that there is probably no difference between the upflow and downflow conditions. Measured critical heat flux vs. the test section mass flux for the laboratory tests is shown in Figure 2.

2. Imposing a fixed pressure drop across the test section by opening a bypass valve resulted in a lower critical heat flux for vertical upflow. These tests were performed at fixed powers and by gradually lowering the flow rate. There were significant flow oscillations close to CHF which resulted in sudden surface temperature rise. However, the existence of a parallel channel seemed to make the downflow configuration more stable and the test section flow rate had to be substantially reduced to show any surface temperature rise.

3. The packaging of the loop and the procedure for the low gravity testing were developed based on the idea that the 2g acceleration at the start of the low gravity trajectory was directed towards the tail of the aircraft. Therefore, the test section was placed in a horizontal position with flow direction towards the front of the plane (opposite to the assumed gravity vector). This was intended to avoid flow stratification during the 2g portion of the flight which would result in temperature rise along the portion of the test section covered by vapor, and subsequent system shutdown. Actually, most of the gravity vector during the 2g acceleration was towards the floor of the plane which resulted in system shutdown prior to reduced gravity dive. However, a few CHF points at reduced gravities were obtained which will be compared to earth gravity conditions. The test loop is going to be modified and the next series of tests performed with a vertical up configuration to avoid this problem.

Although the preliminary tests provided only a few CHF data points at zero g, there is sufficient data for the two-phase pressure drop which can be used to evaluate the applicability of the earth gravity models. The two-phase friction multiplier is defined by the ratio of two-phase to single-phase liquid pressure drop at the total flow rate. The two-phase multiplier obtained from the measured pressure drop across the adiabatic section was compared to the predicted values by several models including Homogeneous Equilibrium Model (HEM), Friedel correlation (Ref. 3), Chisholm B (4), and Chisholm's fit to Lockhart Martinelli correlation (4). The comparisons given in Figures 3 and 4 show that most of the reduced gravity data can be satisfactorily predicted by HEM or the Friedel correlation. It should be noted that due to existence of stratified flow, the pressure drop at earth gravity with the horizontal test section would have been considerably smaller. Figure 5 shows that HEM and the Friedel correlation predict the vertical upflow data fairly well, except at high qualities where HEM seems to overpredict the two-phase friction multiplier. As shown in Figure 6, the two-phase pressure drop for vertical downflow configuration is underpredicted by HEM. Although the Friedel correlation has been developed from a large data base with vertical upflow configuration, and HEM is appropriate for homogeneous mixture of the phases (bubbly flow), they both seem to predict the reduced gravity pressure drop over a wide range of equilibrium qualities.

Theoretically based CHF models can be categorized based on the underlying mechanism which depends on the type of flow pattern at CHF. One class of models assumes annular flow regime when CHF occurs due to dryout of a liquid film at the wall. Another class of models assumes bubbly or dispersed flow pattern where a vapor film forms at the wall and prevents the liquid from contacting the surface. Models based on both of the above mechanisms should be considered for evaluating the reduced gravity data, as it becomes available. In the meantime, applicability of a correlation which is based on dimensional analysis and has been successfully applied to several fluids is evaluated here. The correlation developed by Katto and Ohno (5) is used to predict the data for vertical up and downflow configurations as shown in Figure 7. Two points which are believed to be CHF at zero g are also shown in this figure. These points were obtained due to reduction in the flow rate which was resulted from system pressure rise at reduced gravities. Generally, CHF is underpredicted by the Katto and Ohno correlation. The reduced gravity data points are close to CHF obtained under vertical upflow configuration, possibly indicating the same type of flow pattern. The model developed in Ref. (6) for annular flow CHF and the Weisman and Pei model for bubble coalescence at CHF will be used as basis for developing a CHF model applicable to reduced gravities.

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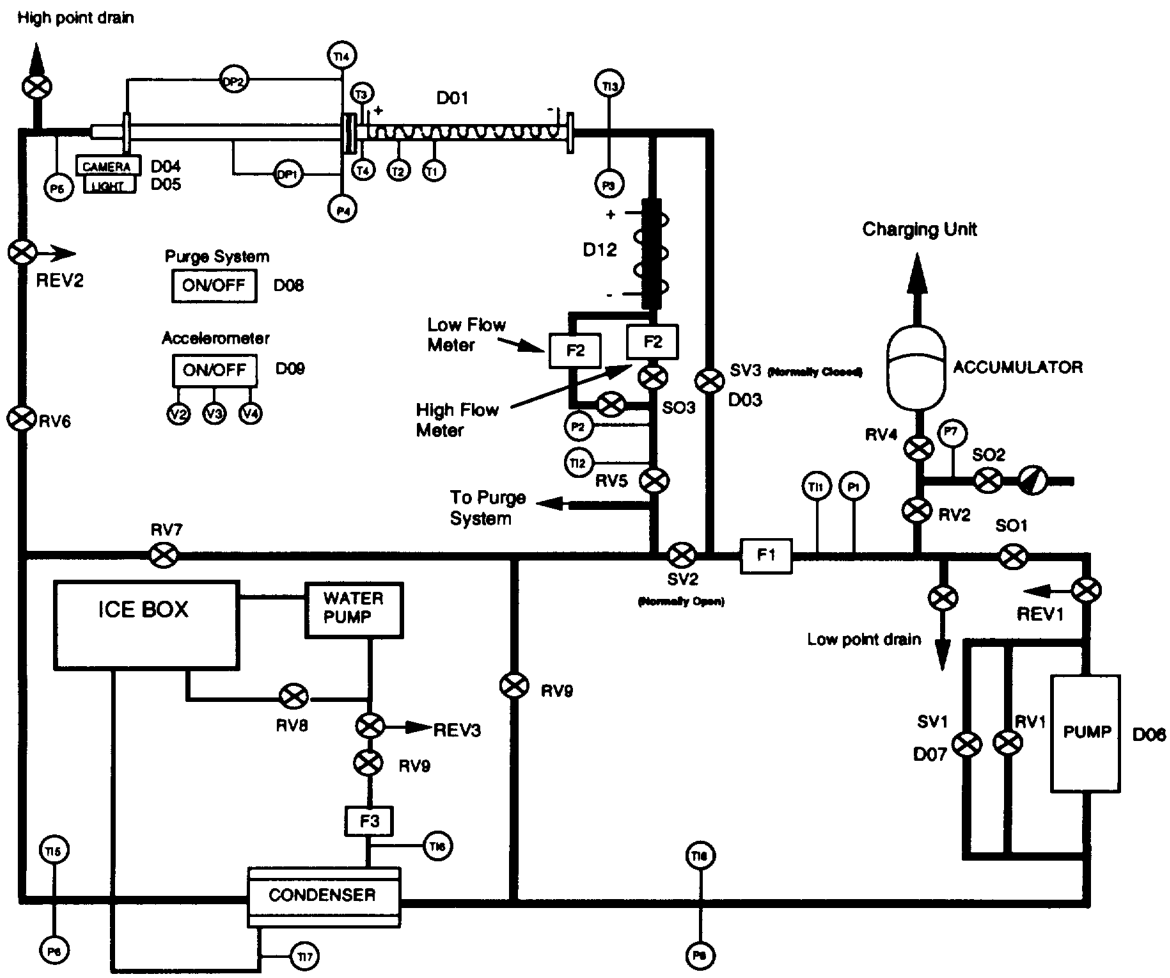

Figure 1 - Test Loop Schematic

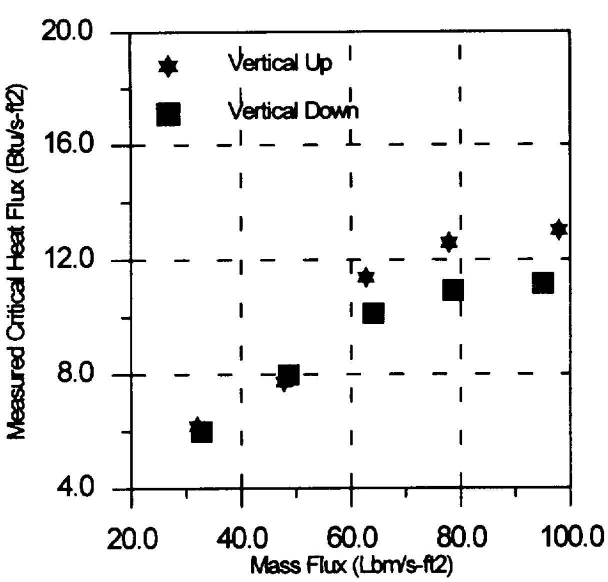

Figure 2. Experimental Critical Heat Flux vs. Mass Flux for Vertical Up and Down Flow Configurations.

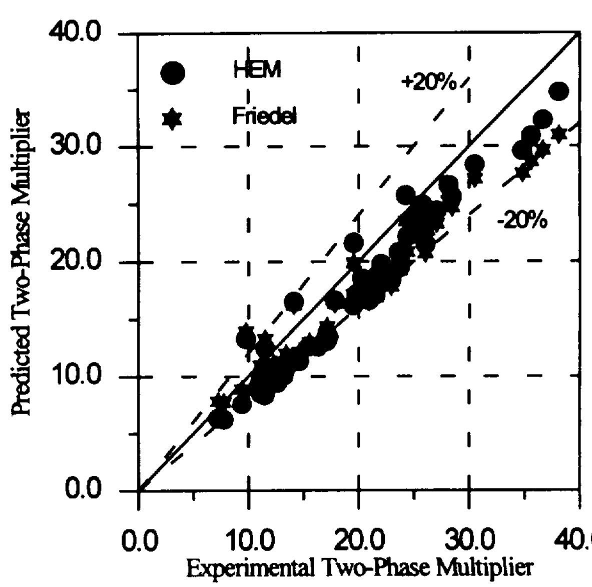

Figure 3. Comparison of the Predicted and Experimental Two-Phase Friction Multiplier Using HEm and Friedel for Reduced Gravity.

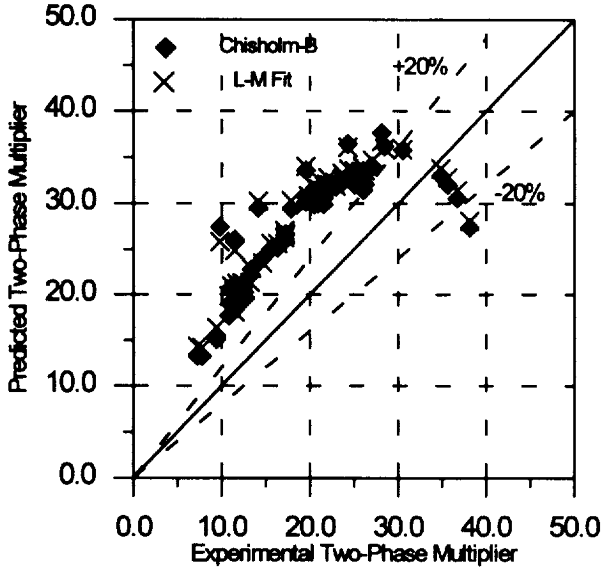

Figure 4. Comparison of the Predicted and Experimental Two-Phase Friction Multipliers Using Chisholm B and Fit to Lockhart-Martinelli for Reduced Gravity.

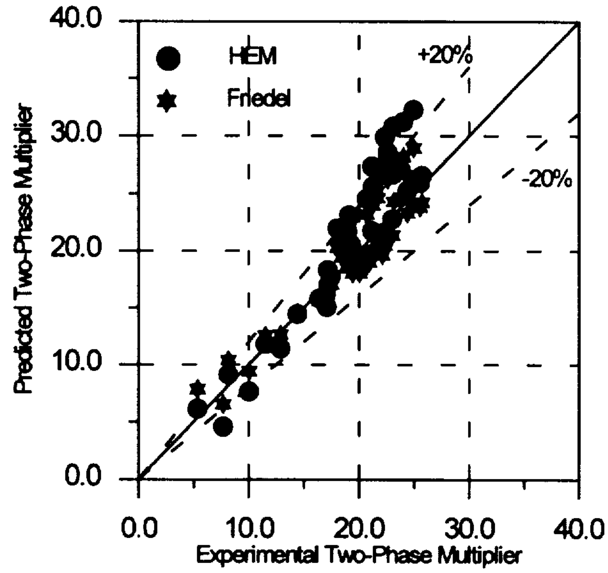

Figure 5. Comparison of the Predicted and Experimental Two-Phase Friction Multiplier Using HEM and Friedel for Vertical Upflow.

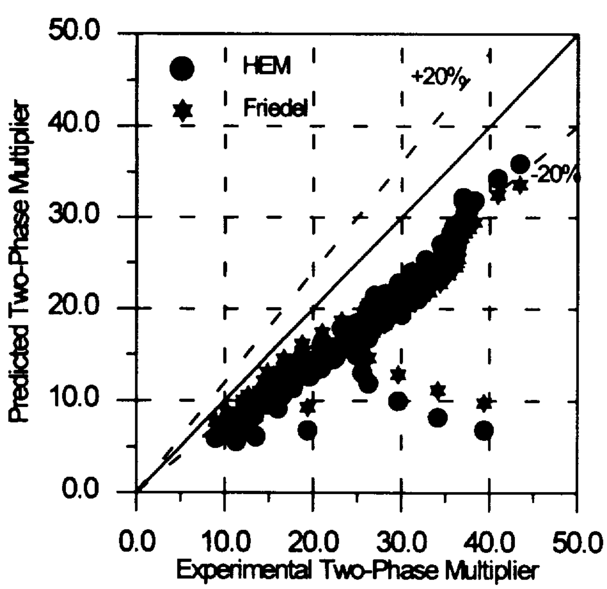

Figure 6. Comparison of the Predicted and Experimental Two-Phase Friction Multiplier Using HEM and Friedel for Vertical Downflow.

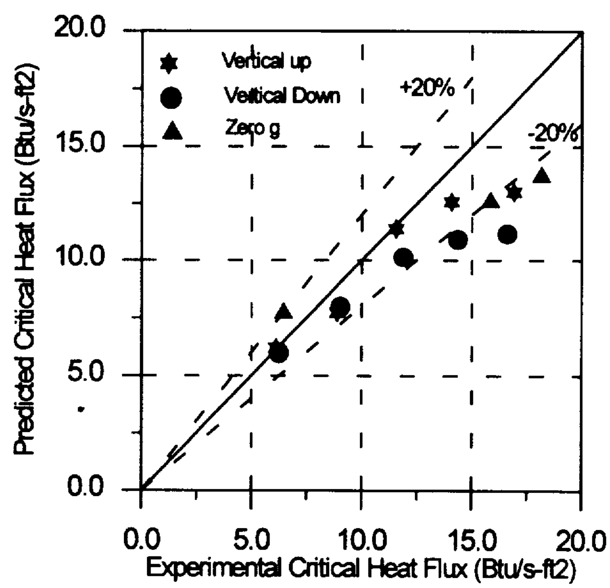

Figure 7. Comparison of predicted and Measured Critical Heat Flux Using Katto & Ohno Model for Vertical Up and Downflow.