N95- 14555

325346

STUDY OF TWO-PHASE FLOW AND HEAT TRANSFER IN REDUCED GRAVITIES

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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 perform a series of experiments to generate the data for the Critical Heat Flux (CHF) and onset of instability under reduced gravities. In addition to low gravity airplane trajectory testing, the experimental program consists of a set of laboratory tests with vertical upflow and downflow configurations. Modularity is considered in the design of this experiment and the test loop is instrumented to provide data for two-phase pressure drop and flow regime behavior. Since the program is in the final stages of the design and construction task, this article is intended to discuss the phenomenon, design approach, and the description of the test loop.

INTRODUCTION

Design of two-phase systems for operation in reduced gravities requires a knowledge of two-phase flow and heat transfer in microgravity and high acceleration environments. In addition to the primary two-phase flow parameters, several criteria, including heat transfer boundaries and instability mechanisms, are expected to be strongly dependent on the acceleration levels. Unlike pool boiling, which has been studied extensively under high and low accelerations, very little work has been done on understanding and modeling two-phase flow. The recent and ongoing efforts have mainly concentrated on generating the data and developing models for two-phase pressure drop, flow regime transition, and two-phase heat transfer coefficients

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.

Background

There are a number of mechanisms which lead to hydrodynamic instability. Some of these mechanisms are not important for the systems designed for operation at earth gravity, but are believed to be significant for reduced gravity operation. 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. These include excursive, oscillatory, parallel channel, and density wave instabilities.

Excursive and Oscillatory Instabilities. Excursive or Ledinegg instability is the simplest form of hydrodynamic instability in forced convective systems. 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.

Pressure drop-flow rate characteristics of two-phase channels occasionally follow an "S" shaped behavior as shown in Figure 1. Operation in the negative slope part of this system may lead to excursive instability. If a dynamic feedback mechanism exists, it can also lead to an oscillatory behavior. An oscillation will occur if the slope of the pressure drop-flow rate characteristic is more negative than the imposed external supply system. In a constant head supply system (zero slope) as shown in Figure 1, operation at points 1 and 3 would be stable while operation at point 2 would be unstable (slope of the system characteristic is more negative than supply slope). Physically, if the flow rate at point 2 is slightly decreased along (A), the external system is supplying less pressure drop than is required to maintain the flow and the flow rate will be decreased until point 3 is reached.

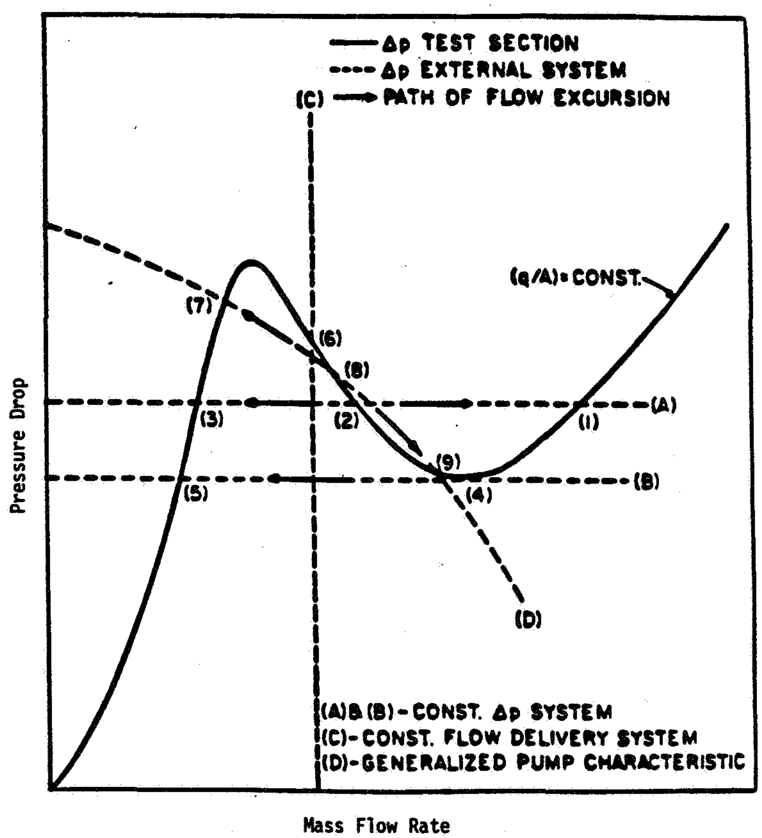

Figure 1. Graphical Interpretation of Excursive Instability

Parallel Channel Instabilities. 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.

Density Wave Instability. The most common form of 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 ΔP within the boiling channel. Small perturbations in the flow will result in pressure fluctuations in the single-phase portion of the channel. This in turn will result in void and therefore pressure fluctuations of the opposite sign in the two-phase region. With the right timing, the perturbations may acquire appropriate phases and become self-sustained.

For a given heat flux, the maximum and minimum of the pressure drop-flow rate characteristic depend on the particular system. A boiling channel with vertical upflow can operate into the negative slope region before becoming unstable. However, the same channel with downward flow will become unstable at the onset of subcooled void generation, which is very close to the minimum point. High accelerations ($g > g_o$) in the direction of the flow would be even more severe than downward flow since the bubbles will be swept upstream with higher velocities.

Generally, systems should be designed to avoid operation in the negative slope region completely. This is particularly important when several channels with multivalued characteristics operate in parallel. Due to the imposed constant pressure across the channels, severe flow maldistribution may result which could lead to unstable behavior and burnout. At earth gravity, this situation is usually avoided by orificing the flow at the entrance so that single-phase pressure drop is comparable to two-phase pressure drop. Orificing will shift the minimum to lower flow rates and lower negative slopes, therefore stabilizing the system. Two-phase systems for spacecraft applications may not be able to afford such large pressure drops (orifice or throttling valve) in the loop to stabilize the flow.

For a given flow rate, the negative slope region depends on the void distribution and the two-phase pressure drop. It is known that for the same conditions, two-phase pressure drops under reduced gravities are larger than at earth gravity. This would mean a steeper negative slope which could result in burnout at lower flow rates (or for a given flow rate burnout at a lower heat flux).

DESCRIPTION OF THE TEST LOOP

A test loop is designed for generating data for the critical heat flux (stable burnout) and the onset of two-phase flow instability under reduced gravity conditions. The schematic of the test loop is shown in Figure 2. The test system is packaged on two learjet racks and will be used to perform a series of normal gravity laboratory tests with vertical upflow and downflow configurations as well as airplane trajectory tests. For the laboratory tests, most of the components with the exception of the test section, will be mounted on the racks. This will avoid rotating and tilting the racks with flow direction.

The test apparatus 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, a flow visualization section, and a tube-in-tube condenser. A bypass leg across the test section path is provided for flow/pressure control as well as imposing a fixed pressure drop across the test section. The heated section, shown in Figure 3, consists of a 5/16 inch OD stainless steel tube with nickel-chromium heater wire wrapped over a 14 inch length of its mid-section. A high temperature bonding material is used to electrically insulate the heater wire from the test section and the outside environment. This material is magnesium oxide based and has a high thermal conductivity which results in excellent heat transfer and nearly uniform heating of the test section. Measured test section surface temperatures will be used to sense sudden rise in the wall temperature which indicate CHF or drop in flow rate due to instabilities. Ribbon type thermocouples are used to monitor the wall temperature in gaps between the wires and at the end of the heated section. One of these thermocouples is directly connected to a temperature controller and is used for safety purposes. Upon sensing a large temperature rise, the heater power is shut down, solenoid SV2 is closed, and SV3 is opened to flood the test section path.

The adiabatic section is two feet long and intended for two-phase pressure drop measurements over a region where the vapor phase content is known and does not change with distance. This section has the same diameter as the heated section and is thermally isolated from it with a Teflon flange. Differential pressures across two sections of the adiabatic tube will be measured and recorded. A purge system is provided which will run subcooled Freon through the sense lines prior to pressure measurements.

Freon 114 is selected as the working fluid due to its low heat of vaporization which results in lower power requirements than other refrigerants. The test variables are power level, flow rate, and system pressure. The range of variation of these parameters are:

Flow Rate: 0.05 - 1.5 GPM

Power Level: 300 - 1000 Watts

Pressure: 35 - 60 psi

The measurements include fluid temperature and pressure, surface temperature of the test section, flow rate, and pressure drop across the adiabatic section. Turbine flow meters are used to measure the total flow rate and the flow rate in the test section leg. Flush mounted flow through thermocouples will be used to monitor the fluid temperature.

The condenser is a single pass tube-in-tube design which uses standard tube fittings for the end connections. It consists of a 40 inch long 1/2 inch diameter inner tube and 3/4 inch diameter outer tube. Pumped ice water is used as the heat rejection source.

The data acquisition and control system consists of a 486 PC, a high speed multifunction I/O board, and a 32 channel analog input multiplexer/amplifier. Labview for Windows is used for data acquisition and control. The software is used to control the experiment electrical loads, provide for calibration of the experiment inputs, and display/record the experiment inputs.

The user interface panel is mouse driven and consists of a set of indicators and controls. The manual controls include pump activation, heater enable button, pressure sense line purge control, test section flood button, data recording control, emergency stop, and software stop.

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.

Test Procedure

Two sets of tests are planned for the laboratory experiments which are aimed at investigating the effect of gravity on the onset of instability and the critical heat flux. Onset of unstable behavior will be studied by generating the pressure drop/flow characteristic of the system. These tests will be performed by measuring the pressure drop across a given length of the test section while the flow rate is reduced until unstable pressure fluctuations are observed or a sudden drop in flow rate is sensed. The pressure drop across the test section leg will be fixed by the bypass line. The critical heat flux tests will be carried out by gradually increasing the heat input to the test section until a surge in wall temperature is observed. At several heat input settings, the system will be brought to steady state to generate pressure drop data in the adiabatic section.

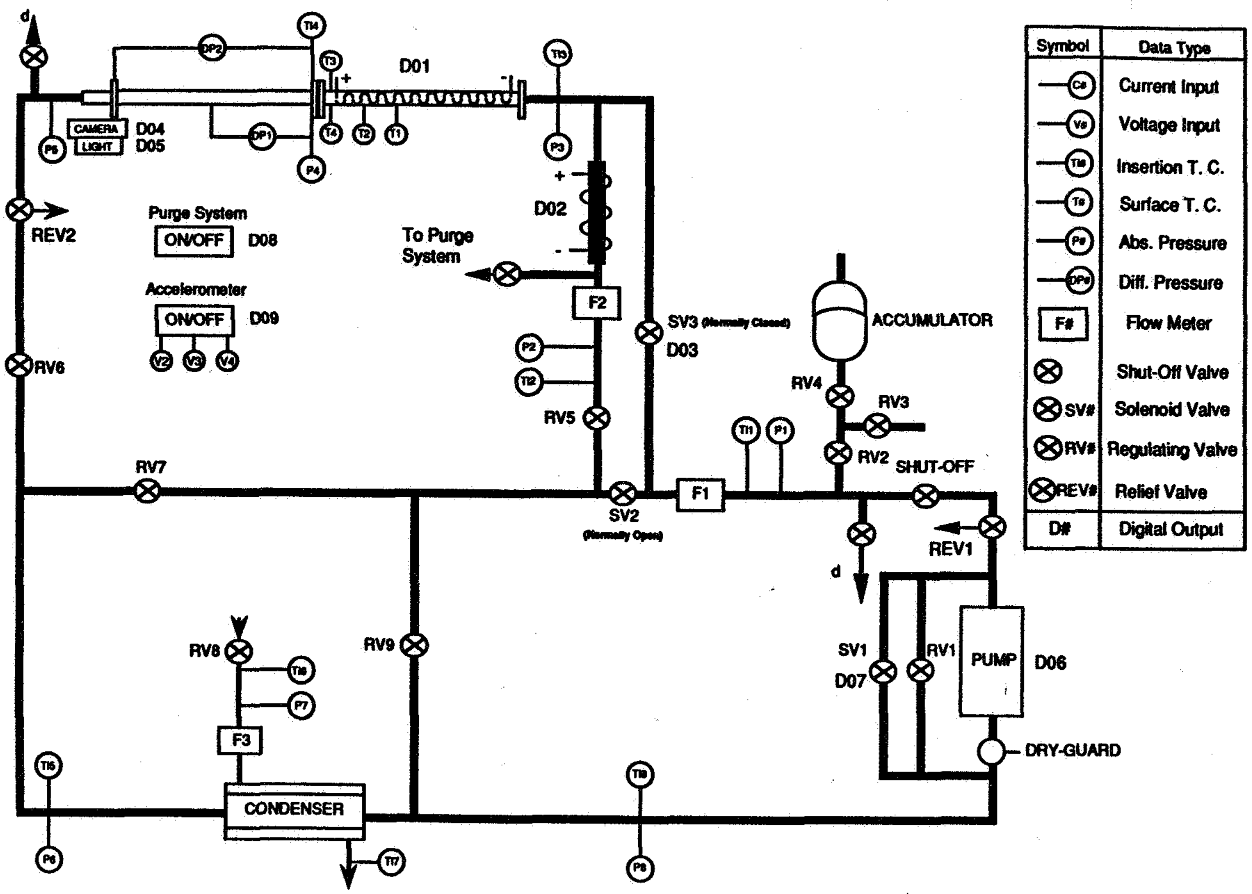

Figure 2. Flow Schematic of the Test Loop

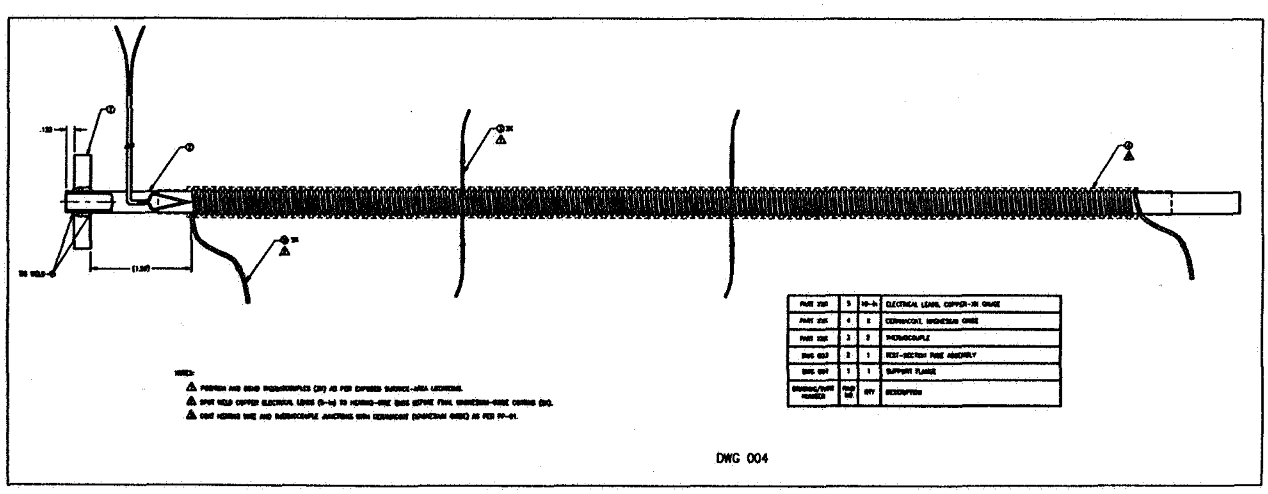

Figure 3 - Heated Test Section