IAC-11-A2.2.10

SURFACE TENSION EFFECTS ON MICROGRAVITY BOILING

Eric D. Becnel
University of Alabama in Huntsville, United States of America, edb0001@uah.edu

Francis C Wessling
University of Alabama in Huntsville, United States of America, wesslif@uah.edu

Pool boiling in microgravity presents many challenges due to the lack of gravity driving the bubble departure. This paper presents an instrument to test the effects of varying materials, and therefore the surface tension, in its contribution to heat transfer. Previous research shows that in a microgravity environment, buoyancy is not a contributing factor in bubble departure. Surface tension drives this departure and affects the heat transfer. To better understand the effects of surface tension on boiling, a device has been designed to test multiple surface materials against a common fluid. The instrument allows for multiple samples to be tested using a common set of instrumentation.

The samples would be tested on orbit with critical measurements being fluid temperature, surface temperature, surface heat flux, fluid pressure and a supporting image of each test. The materials to be tested would be those commonly used for on orbit heat exchangers. Surface roughness comparisons of the same material can also be implemented. The fluid would be chosen based on that commonly used on orbit such as ammonia in the ISS. The instrument can be developed for a CubeSat platform with a total mass of 1kg and sized to be a 10cm cube. The test can be run quickly and packed in a very small instrument requiring a manageable amount of power and mass. The test for each material will be run individually and can be spaced an appropriate time apart for power and thermal management. The results of this test would improve the understanding of the physics of the boiling in microgravity. With this, the use of boiling fluids on orbit could be considered a suitable means of heat transfer.

I. EXPERIMENT PURPOSE

Heat transfer in low gravity can provide spacecraft and experiments with a thermally controlled environment using a fluid thermal management system. An example of such a system is International Space Station's Active Thermal Control System. It is used to get experimental, electrical and cabin heat from its respective source and radiate it to space using heat exchangers and an ammonia loop. This technology is critical when a controlled temperature range is required for experimental purposes or for sustaining life.

Due to the uncertain performance characteristics of microgravity boiling, the space industry has not taken advantage of the possible upper limits of spacecraft thermal control systems. Through on orbit experimentation, the properties of microgravity boiling can be better understood and perhaps open the door to a wide variety of heat transfer applications.

An apparatus (the Boiling Tube) has been designed to measure the cooling of a heated surface in a liquid. The Boiling Tube is an on-orbit instrument which tests the boiling characteristics of a variety of material surfaces. The experiment is designed to heat a given sample through a controlled temperature range and monitor key measurements to help define the characteristics of boiling in microgravity. Five samples will allow for a variety of surface conditions to be tested within a common experiment using a common set of instrumentation.

The Boiling Tube is designed to determine the heat transfer rates through what will be considered the free convection and nucleate boiling regimes in a gravity environment. For experimentation using water, this will require exceeding the saturation temperature of the fluid by thirty degrees Celsius at the surface of the heated sample. Measurements will be made on both the heating and cooling phases of each experiment.

II. MICROGRAVITY BOILING

There are three primary boiling regimes to consider in the microgravity environment. The first mode of boiling, referred to as the free convection regime is a function of gravity. It is dependent on heat conduction through the fluid and on gravity. This mode exists when the temperature of the heated surface exceeds the saturation temperature of the water by less than five degrees Kelvin on earth.

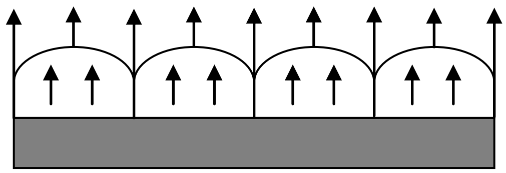

Fig. 1: Heat transfer within the Nucleate boiling regime without bubble departure incorporates conductive flow from the surface through the cell wall to the water along with from the top of the bubble to the water. Radiation through the vapor accounts for heat transfer from the surface to the fluid, through the bubble.

The second mode of boiling, the nucleate boiling regime, begins with bubble formation on the surface and lasts until bubbles coalesce to form a vapor film. In a gravity environment, this mode is initially driven by the insulating effects of vapor bubbles on the heated surface. When the vapor bubbles grow in size, buoyancy causes bubble departure and consequently fluid movement mixing the fluid near the surface.

In microgravity, the vapor bubbles form and create a similar insulating effect on the surface. As the bubbles collide, heat transfer is driven by the conduction through the vapor within each cell, conduction through the cell walls, and radiation from the heated surface to the fluid through the volume of the bubbles[1].

Finally, the third mode of boiling is the film boiling regime and represents the existence of a full layer of vapor across the heated surface. In a gravity environment, heat transfer in film boiling is driven by convection of the vapor within the film layer and radiation from the heated surface and the fluid. In microgravity, film boiling is isolated to conduction through the vapor layer and the radiative heat transfer[2].

III. EXPERIMENT OBJECTIVE

The driving factor for the nucleate boiling regime is significantly affected by the size of the forming bubbles. By changing the surface tension of the heated surface, the bubble dimensions change, creating more or less bubble cell walls. With more small sized bubbles, there is an increase in the total amount of cell wall for conduction, providing for increased cross-sectional area for conduction and provide higher heat transfer. On the other hand, with larger bubbles, the cell wall conduction is lower providing less heat transfer.

The experimental objective of the Boiling Tube is to identify the effects of surface tension on heat transfer in the nucleate boiling regime. Tests will be performed on each of five samples individually and each sample will have a different surface roughness or surface coating to vary the surface tension accordingly. The results of the test should quantitatively show the effect of surface tension on heat transfer rate from the surface to the water.

IV. MEASURMENTS

The surface temperature, the saturation temperature of the water, the water temperature and the heat flux from the surface to the water are the critical properties of interest. Additionally, photographs of the test will allow better understanding of the experiment results.

The saturation temperature of the water is found by measuring the water pressure and evaluating its properties accordingly. Saturation temperature is defined by the saturation pressure. Secured to one end of the chamber, a pressure sensor will be directly exposed to the fluid and provide an analog feedback for data acquisition.

Surface temperature of the heated sample will be determined using a thermistor in the body of the test surface. The power will be determined externally by measuring the voltage and current of the heating elements.

The water temperature will be measured using a thermistor exposed to the water within the chamber. By minimizing the sensor's mechanical support and mass, the response time of the thermistor will be minimized giving a more accurate measurement in the transient environment of the experiment.

A small camera will photograph the heated sample's surface. The camera will be mounted on one end of the test chamber in order to photograph all of the samples without needing movement or additional focusing. A transparent port will allow viewing for the camera and light transmission from illuminating LED's. The camera will take a series of images to monitor the bubble formation throughout the heating process. By aligning the samples in a circular array, a single camera can monitor the activity on all heated surfaces.

V. DESIGN CONSTRAINTS

The advantage of The Boiling Tube is its low cost deployment as a secondary payload. The instrument is designed to be a payload of a 1U CalPoly CubeSat. This requires minimal mass, size and power to operate.

Dimensionally, a CubeSat is 10x10x10cm. To reasonably fit within the satellite frame, panels, circuit boards, and other hardware, the instrument must consolidate its volume to a minimal size. Reasonable exterior dimensions of the instrument could be estimated as half or less of the internal volume of the CubeSat. This constrains the experiment to dimensions of roughly 8x8x4cm. The current instrument measures 3cm in diameter and is 5cm long, a relaxed fit within the CubeSat taking effectively 5% of the total satellite volume.

With a total satellite mass of one kilogram, the experiment needs to conserve mass in all aspects. The estimated total mass of The Boiling Tube is less than 100grams, 10% of the satellite mass, and a reasonable mass for this vehicle.

The nature of a CubeSat, along with most satellites, is a tight limit on power. By constraining the mass and volume of the instrument, the necessary power is inherently restricted. Reasonable CubeSat batteries can have a capacity of approximately 2000 to 4000 milli-amp hour lithium polymer batteries, with a cell voltage of 4.2 volts. Under the expected loads, to be described later, the full experiment should consume less than 15mAh of battery capacity. This accounts for less than 1% of capacity of the battery. Photovoltaic solar cells will recharge the batteries.

Accompanying the stated restrictions, the CalPoly CubeSat specification 2.1.4 requires that "No pressure vessels over 1.2 standard atmosphere shall be permitted." This argument limits the working fluid selection to a fluid which is in the liquid state at 1.2 atmospheres or below. Water meets these requirements. Additionally, specification 2.1.4.1 requires that "Pressure vessels shall have a factor of safety no less than 4", imposing a minimum structural design for the vessel.

VI. DETAILED DESIGN

The five samples to be heated will be cylinder shaped and heated from their insides. This will isolate the boiling to the exterior surface of the sample. Each sample will have a heating resistor, a suspending polyamide string, a thermistor, and epoxy to hold it together. The wires of both the resistor and the thermistor will need to be minimal size to reduce the thermal loss due to conduction through the wires themselves. The samples need to achieve 30 degrees or more above the saturation temperature to complete the testing of the nucleate boiling regime.

The samples will be suspended by the polyamide strings pulled tight between the base plate and the upper support ring within the experiment. The wires for both the resistor and the thermistor will be extended to the base plate where they will be soldered to the pass through wires.

The resistor will be mounted concentrically with the sample material to provide an even temperature across the boiling surface. The lead wires will be extended away from the sample then down to the base plate. The lead wires will be soldered to the pre-epoxied wire pass-throughs.

The thermistor within the sample will provide the sample temperature measurements during the ramp up and down of its temperature. The lead wires will also be soldered to the electrical pass throughs.

Individually, each experiment will require measurements for the water temperature, water pressure, and the surface temperature. Additionally, each test will be supported by images showing bubble formation at key points of the test. By aligning the samples in a circular array, a single camera can monitor the activity on all heated surfaces.

The instrument will be mechanically secured to the base plate. This will allow for a detailed inspection of the instrument before and after its casing gets installed. The upper bulkhead will contain only the pressure sensor and the necessary fixturing locations for all thread compression rods.

The circuit will have the ability to power each of the five heating channels. It will need to gather their respective voltage and current loads to determine the power input to the sample. The thermistor will need to be measured to get the sample temperature. The camera module and LEDs will also be circuit board mounted and will align with the ring of heated samples.

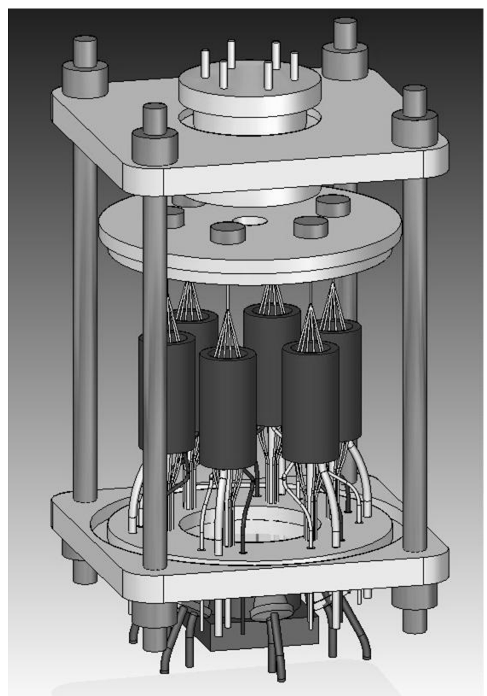

Fig. 2: The heat samples within the chamber, are located within the field of view of the camera, (located near the figure bottom). The pressure sensor, located at the top of the chamber, will measure the water pressure. The samples to be tested will be mounted in a radial pattern around the camera's field of view.

VII. ANTICIPATED PREFORMANCE

Initial approximations for the performance help determine the necessary parameters for input power, sensor selection, and chamber design. The heated sample surface needs to exceed the saturation temperature by 30 degrees Kelvin. By keeping the pressure at 1 atmosphere, the saturation temperature is 373.15 Kelvin, Therefore the surface needs to be heated to at least 413.15 Kelvin. Keeping the chamber at a constant pressure will keep the target temperature constant. To do this, a thin, flexible walled air volume is contained in the fluid to account for fluid expansion. Also, performing the experiment in a short time frame will reduce the power introduced to the system, the increase in bulk fluid temperature and the corresponding volumetric expansion.

To minimize required energy to heat the sample and achieve the targeted temperature, the power introduced to the sample should be much greater than the heat dissipated to the water. The maximum heat dissipation, found at the critical heat flux, is strongly dependent to the local acceleration at the surface of the boiling. Local acceleration at the surface can be created by aerodynamic drag, attitude control, or any other cause of acceleration. The performance, seen on Figure 3, shows the dependence on the critical heat flux on the local acceleration. To complete the design of this instrument, further predictions need to be made with respect to the local acceleration of the fluid.

VIII. DESIGN RESULTS

The next stage in development is system level fabrication and testing. The analysis results are favorable to continue development of the Boiling Tube for delivery as a CubeSat experiment. Experiment validation will first be held in a 1 gravity environment, a predictable, accessible and well understood environment. Upon validation, the CubeSat launch will provide a very low cost experiment platform to implement the long term, orbital experiment. The results of this research will expand the understanding of microgravity heat transfer in the boiling regimes.

IX. DESIGN RESULTS

The author would like to recognize the University of Alabama in Huntsville, the Department of Mechanical and Aerospace Engineering, and the Office of the Vice President for Research for making this project possible.

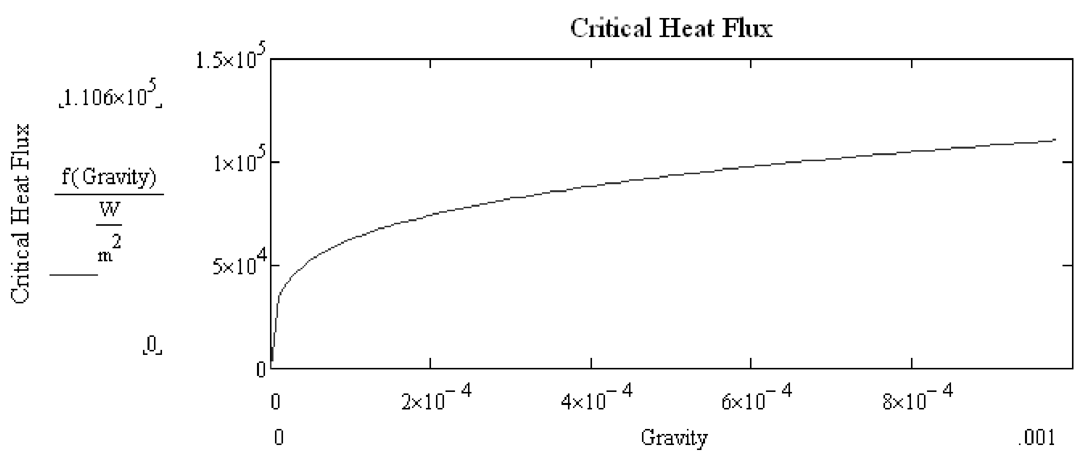

Fig. 3: Critical heat flux as a function of local acceleration.

[1] Straub, Johannes, "Boiling Heat Transfer and Bubble Dynamics in Microgravity" Advances in Heat Transfer, Volume 35. Ed. Hartnett, Irvine, Cho, and Greene. Academic Press (2001).

[2] Incorpera, Frank P., Davis P. Dewitt, Theodore L. Bergman, and Adrienne S. Lavine. "Fundamentals of heat and Mass Transfer" John Wiley & Sons, Inc. (2007).