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Development of Optimal Bubble-Seeding Microheaters to Study Nucleate Boiling Heat Transfer in Microgravity

Ryan Martineau

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Ryan Martineau, Mechanical Engineering Department
JR Dennison, Mentor, Physics Department

Abstract

A current problem facing designers and engineers of new spaceflight systems is heat transfer. Nucleate boiling has proven to have high heat transfer rates (Incropera, 2007), but further study is required for optimal application of this heat transfer method in a microgravity environment. My proposal is to fund a research project to further the study of nucleate boiling in microgravity. The focus of study in the experiment will be on determining ideal surface geometries of heating elements based upon bubble departure dynamics, heat transfer rates, and characteristics of bubbles formed in the boiling process. An important element in the experiment will be the use of effectively two-dimensional surface heaters in contrast to thin wires used in other experiments. Work includes design and production of the surface heaters, test procedure development, data collection in microgravity from the heaters, and post-flight data analysis. This experiment will allow us to effectively study heat transfer from the surface heaters in microgravity, furthering the understanding and application of heat transfer by nucleate boiling.

Introduction

Spaceflight technology research continues, but enduring problems include designing effective heat transfer systems. On Earth, heat can be transferred convectively through working fluids and ultimately to the surrounding atmosphere. In space, no atmosphere is present, shifting the ultimate mode of heat transfer to radiation. On many probes and satellites, large radiators are deployed to increase the rate of heat transfer, while other systems are used to transfer heat to those radiators, which systems, due to the absence of a gravitational force, cannot rely on buoyant convection. A new type of heat transfer system could be developed using the high heat transfer rates of nucleate boiling. This intermediate system would still ultimately still lead to a radiator, but in the confined spaces on satellites and probes, this would be an efficient intermediate step, conducting heat away from sensitive components quickly and efficiently. This same process could be used on Earth where high heat transfer rates are necessary. Follow-Up Nucleate Boiling On-flight Experiment (FUNBOE) 2.0 will study what parameters in this configuration lead to the highest rates of heat transfer.

This experiment follows up the 2010 USU GAS team experiment in which three different surface geometries of heating elements were tested: a single thin wire, three wires twisted together, and four wires twisted together. The current experiment will compare the input parameters and heat transfer results of a proposed bubble-seeding microheater to those of a single fine wire and three wires twisted together. The parameters and heat transfer rates will also be compared with those from the previous experiment. Analyzing these results should reveal ideal parameters for heat transfer utilizing nucleate boiling, and enable further research into specific design specifications for heat transfer systems.

Objectives

1. Design a bubble-seeding surface heater suitable to boiling water in a microgravity experiment
2. Produce 20 surface heaters with which to obtain two data sets to analyze, and test with different parameters
3. Collect results and analyze to determine optimum parameter sets and any follow-up research needs

Background

In 2001, the USU GAS team ran an experiment to study boiling in space on the space shuttle – STS-108 (Koeln, 2009). It provided information on the dynamics of boiling in microgravity. Since then there have been a number of experiments and research conducted furthering the study of nucleate boiling (for example, Wang, 2003), and several have studied it in the context of a microgravity environment (Straub, 2005). However, the models of boiling dynamics in microgravity are incomplete or conflicting, so there is a need for more empirical data. For example, some experiments have resulted in low heat transfer and a quick heating element burnout (Fukada, 2004), while others have had success in testing different parameters and studying bubble dynamics and heat transfer rates (Liu, 2009).

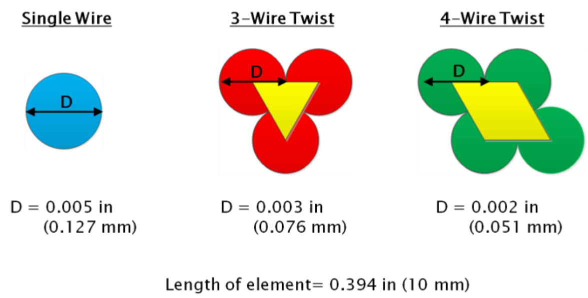

Figure 1 – Heating Element Wire Geometries from FUNBOE

Last year, to follow up on the 2001 experiment and expand the experiment to include varying power levels and surface geometries of heating elements, the USU GAS team conducted the FUNBOE experiment on NASA's "Weightless Wonder" aircraft. Two of the main findings were that bubble "jets" from the heating element surface lead to higher heat transfer rates, and that the likelihood of these jets forming was greater at higher power levels. The three types of heating element surface geometries observed in FUNBOE were a single thin wire, a three-wire twist, and a four-wire twist (see Figure 1). The single thin wire produced both bubbles that expanded before departing the wire and jets of bubbles quickly departing. The three wire twist required less excess heat to begin boiling, or in other words required less power to initiate boiling. The four-wire twist behaved more like a single wire in terms of heat transfer, but formed jets more frequently.

Nucleation is a process that occurs when a fluid undergoes a phase change. Bubbles tend to form on specific sites on a surface in contact with the fluid. Bubble-seeding is a process that enhances nucleation, using specific nucleation sites to hold a seed bubble that produces many more bubbles that leave the surface quickly, as a jet. A recent paper on a heat transfer experiment involving a bubble-seeding heater found that the boiling temperature of the heater was lower, meaning the heat transfer was improved, as the rate of bubble formation increased. A saturation point in the rate of bubble formation was observed, at several thousand Hertz, where the heat transfer rates stopped improving (Liu, 2009).

Experiment

FUNBOE 2.0 will use the data and existing equipment from the previous FUNBOE flight and the results from the 2009 Chinese experiment to develop a set of testing parameters. FUNBOE 2.0, like FUNBOE, will be tested on board NASA's "Weightless Wonder," and the flight will include 30 periods of microgravity on two subsequent days in June 2011, each weightless period lasting approximately 30 seconds. Each wire or surface heater will be placed in an individual boiling chamber. A set of chambers will be loaded into an apparatus currently in design for the test flight. Several chambers, a separate set during each period of weightlessness, will be tested at a time, allowing the cells to reach a static fluid temperature in preparation for their next testing period. Computer systems will process the data on-flight. Data acquired from each boiling chamber will include the voltage across each heating element, current through the element, heater temperature, temperature of experimental fluid at discrete distances away from the heating element, and high definition (1080p) video from orthogonal angles to allow visual analysis of the bubble-seeding effect and bubble departure dynamics. Ten different power levels will be tested using BK Precision power supplies and a square wave signal from an existing Data Acquisition System. This square wave will be amplified through a voltage-follower op amp circuit to regulate voltage and current to the microheater array. The experiment will be repeated on two consecutive days to test reproducibility.

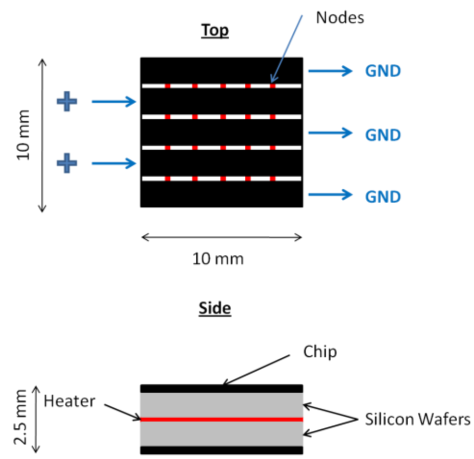

Figure 2 – Proposed Surface Heater Design

The experiment will include, for comparison and expanded study: a single thin wire, a three wire twist (see Figure 1), and a two-dimensional surface heater. The length of the wires and the estimated size of one side of the surface heater are both 1 cm. The wires will be platinum, and the surface heater will consist of a nichrome element sandwiched between two silicon wafers designed to seed bubbles with gold microheaters at the marked nodes (see Figure 2). At each node in the figure will be a microheater element. These will add slight amounts of heat to the surface, and the heat they add will be configured to produce seed bubbles. The chips will increase the heat transfer from the main heating element. Square wave electrical pulses will go through each node at several hundred hertz, about five volts, and less than ten amperes. Ground testing during development will be part of an iterative process to determine the optimal inputs for the on-flight experiment.

The surface heaters will be made in the microfabrication facilities in the USU Center for Surface Analysis and Applications (CSAA) in the USU Physics Department. Standard photolithography and thermal vapor deposition techniques used in microcircuit fabrication will be used to develop microheaters with different heater sizes and geometries and varying node geometries. Ground testing in normal gravity will be conducted to determine proper heater dimensions and refine the surface design to optimize the bubble-seeding function of the microheaters that will be used in the experiment. Two planned node configurations will be produced and ground-tested: a single longer central node, and six rows of 5 smaller nodes. Professor TC Shen will provide instructions and supervision for the use of the CSAA facilities.

The analysis of the experiment after testing will compare results of the data collected and attempt to narrow down a set of ideal parameters that optimize heat transfer rates, including voltage and current levels, power pulse frequency, and surface geometry. The video footage will be used, along with the other inputs and the fluid temperature to study the dynamics involved in departing bubbles and jets, and how it correlates to the rates of heat transfer. The practicality of the type of proposed heater system will be assessed.

My part in FUNBOE 2.0, funded through this proposal, will include development, testing, and production of the surface heaters. This will be the focus of experimental analysis. Development will include an iterative process to test dimensions and input capabilities, testing the nucleate boiling properties of the heater to determine the proper flight design. I will also take part in the design and construction of the on-board apparatus. I will carry out post-flight data analysis and prepare presentations based on the results.

Dissemination of Research

In May 2011 at the Rocky Mountain NASA Space Grant Consortium Symposium, I will present a poster on the experiment focusing on the microheater design and results from ground tests. I also plan to present at the April 2012 Student Showcase, Utah Posters on the Hill in Salt Lake City, and to the USU AIAA branch. The Get Away Special team conducts outreach to local schools, reaching over 3,000 students in the last two years, and a presentation will be adapted including the results of this experiment, aimed at elementary and secondary school-age student audiences. Pending the impact of flight test results, the data and conclusions will be presented at Small Satellite conferences and other conferences where the results will be meaningful, and papers will be submitted to scientific journals, such as the International Journal of Heat and Mass Transfer.

Timeline

Date	Experiment Phase
February 2011	Construct experimental apparatus and begin surface heater design
March 2011	Finalize surface heater design and begin fabrication and refinement
April – May 2011	Complete development and testing
June 2011	Fly experiment in Houston with NASA
July – August 2011	Perform data analysis on experiment
September 2011	Final report to URCO

Budget

The budget will cover materials and production costs of heating elements and a power supply to send precise voltages and currents to the heating elements during the test flights.

Item	Cost	Sponsor
Materials and facilities for Surface Heater fabrication	$500	USU Center for Surface Analysis and Applications (CSAA)
Platinum Wire	$120	URCO
BK Precision 1696 Computer-Controlled Power Supply	$350	URCO
Voltage-follower op amp and circuit materials	$30	URCO

The amount requested from the Undergraduate Research & Creative Opportunities fund is $500. The remaining $500 will be sponsored by the Physics Department.

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