INVESTIGATION OF MECHANISMS ASSOCIATED WITH NUCLEATE BOILING UNDER MICROGRAVITY CONDITIONS

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ABSTRACT

The focus of the present work is to experimentally study and to analytically/numerically model the mechanisms of growth of bubbles attached to, and sliding along, a heated surface. To control the location of the active cavities, the number, the spacing, and the nucleation superheat, artificial cavities will be formed on silicon wafers. In order to study the effect of magnitude of components of gravitational acceleration acting parallel to, and normal to the surface, experiments will be conducted on surfaces inclined at different angles including a downward facing surface. Information on the temperature field around bubbles, bubble shape and size, and bubble induced liquid velocities will be obtained through the use of holography, video/high speed photography and hydrogen bubble techniques, respectively. Analytical/numerical models will be developed to describe the heat transfer including that through the micro-macro layer underneath and around a bubble. In the micro layer model capillary and disjoining pressures will be included. Evolution of the interface along with induced liquid motion will be modelled. Subsequent to the work at normal gravity, experiments will be conducted in the KC-135 or the Lear jet especially to learn about bubble growth/detachment under low gravity conditions. Finally, an experiment will be defined to be conducted under long duration of microgravity conditions in the space shuttle. The experiment in the space shuttle will provide microgravity data on bubble growth and detachment and will lead to a validation of the nucleate boiling heat transfer model developed from the preceding studies performed at normal and low gravity (KC-135 or Lear jet) conditions.

INTRODUCTION

Boiling is known to be a very efficient mode of heat transfer, and as such, it is employed in component cooling and in various energy conversion systems. For space applications boiling is the heat transfer mode of choice, since for a given power rating the size of the components can be significantly reduced. For any space mission the size, and in turn, the weight of the components plays an important role in the economics of the mission.

Applications of boiling heat transfer in space can be found in the areas of thermal management, fluid handling and control, and power systems. For space power systems based on the Rankine cycle (a representative power cycle), key issues that need to be addressed are the magnitude of nucleate boiling heat transfer coefficient and the critical heat flux under low-gravity conditions. Knowledge of nucleate boiling heat transfer coefficients is necessary to determine the overall resistance for transfer of heat from a source to a sink. The critical heat flux represents the upper limit of safe heat removal since for heat fluxes greater than critical heat flux, the surface will be covered with a vapor film which, in turn, will result in a rapid rise in the temperature or failure of the component.

Understanding and quantification of boiling heat fluxes at low-gravity conditions are also important for other space power systems such as thermionic reactors operating under transient conditions (see e.g., von Arx and Dhir[1]). Design of on-orbit storage and of supply systems for cryogenic propellants and life support fluids also requires quantitative data for boiling heat transfer. Additionally, an assessment of the cooling of electronic packages or power supply systems associated with various instrumentation and control systems requires a knowledge of boiling heat transfer coefficients.

Studies of boiling heat transfer for space applications impose unique constraints in terms of the number of experiments that can be conducted under microgravity conditions, the duration of the experiments and expense and difficulties involved in performing the experiments. Thus for space applications, it is even more important that a better understanding of the boiling mechanism be developed so that space experiments are needed only for confirmation of the predictions.

The objective of the present work is to delineate through experiments and analysis, the contributions of some of the key mechanisms to total heat transfer rate during nucleate boiling under microgravity conditions. This includes the contribution of micro/macro layer evaporation on single and merged bubbles attached to a heated wall, heat transfer during sliding of a bubble along a heater wall and heat transfer due to fluid motion resulting from bubble growth and Marangoni effect. The effect of fluid motion induced by a growing bubble on its detachment from the surface will also be considered.

Under microgravity conditions the early data of Keshock and Siegel[2] and Siegel and Keshock[3] on bubble growth and heat transfer show that the effect of reduced gravity is to reduce the buoyancy and inertia forces acting on a bubble. As a result, under reduced gravity bubbles grow larger and stay longer on the heater surface. This in turn leads to merger of bubbles on the heater surface and existence of conditions similar to fully developed nucleate boiling. Thus, under microgravity conditions partial nucleate boiling region may be very short or non-existent. Figure 1a compares photographs taken by Zell et al[4] for nucleate boiling on a wire under 1-g and μ-g conditions. It is interesting to note from Fig. 1b that data obtained under μ-g condition is described well by curves fared through the data obtained at 1-g. This is consistent with the conclusion of Siegel[5] that the effect of reduced gravity on nucleate boiling heat transfer coefficient under saturated and subcooled conditions is small.

Ervin et al[6] and Ervin and Merte[7] have studied transient nucleate boiling on a gold film sputtered on a quartz plate by using a 5-second drop tower (10^{-5} g_e) at NASA Lewis Research Center. In the experiments R-113 was used as the test liquid. From the Experiments it was found that time or temperature for initiation of nucleate boiling was greater for a pool at near saturation temperature than that for a subcooled pool. They also noted the occurrence of energetic boiling at relatively low heat fluxes. The energetic boiling in which vapor mass rapidly covered the heater was postulated to be associated with an instability at the wrinkled vapor-liquid interface. Hasan et al[8] have studied nucleate pool boiling of R-113 during the tank pressure control experiment (TPCE) under the low gravity environment of the space shuttle. They noted that at very low heat fluxes stable nucleate boiling could be sustained over a long period of time. The wall superheats accompanying the relatively low nucleate boiling heat fluxes were rather large. Recently Merte[9] has reported results of pool boiling experiments conducted in the space shuttle for the same surface that was used in the drop tower tests. Subcooled boiling during long periods of microgravity was found to be unstable. The surface was found to dryout and rewet. Average heat transfer coefficients during the dryout and rewetting periods were, however, found to be about the same. The nucleate boiling heat fluxes were higher than those obtained on a similar surface at earth normal gravity conditions.

Experimental studies of flow boiling under low gravity conditions are far fewer and limited than those for pool boiling. The earliest study of flow boiling under reduced gravity conditions is that of Cochran[10]. The experiments were conducted in drop towers with flow velocities varying from 4.2 to 11.5 cm/s. These short-duration (2.2 second) low gravity tests were focused on the boiling process near inception. In comparison to normal gravity tests, it was found that in microgravity, bubbles tended to stay on the heating surface, became large enough to coalesce with neighboring bubbles and acquired irregular shapes. The size of bubbles along the heating surface was found to correlate with thickness of the thermal layer. Very recently Saito et al[11] have studied flow boiling of water on a heater rod placed in a square channel. The experiments were conducted in Japanese low gravity experimental aircraft (MU-300) at 0.01 g_e for 20 seconds. In the experiments, subcooled nucleate boiling heat transfer data for water were taken at velocities varying from 3.7 - 22.9 cm/s and pressures in the range of 0.9 to 2.40 bars. Nucleate boiling heat transfer coefficients were found to increase slightly in the direction of flow and the magnitudes of the heat transfer coefficients were about the same as at normal gravity. Figure 1c shows their photographs of nucleate boiling at a flow velocity of 6 cm/sec under both normal and microgravity conditions. Existence of relatively large bubbles on the heated surface is evident. These bubbles slide along the heater surface over long distances.

Finally, it appears that recent studies of nucleate boiling under microgravity have shed light on this complex phenomena, however, the studies are non-conclusive. Questions remain on the stability of nucleate boiling, the equivalence of magnitudes of heat transfer coefficients at normal gravity and low gravity conditions and on the physics that underlies the phenomena. As such there is no mechanistic model that describes the observed physical behavior and the dependence of nucleate boiling heat flux on wall superheat.

DESCRIPTION OF PROPOSED RESEARCH

It is evident from the review of the current literature carried out in the previous section, an important question that needs to be answered, but has not yet been answered, is how does microgravity affect nucleate boiling heat transfer under pool and low velocity forced flow conditions? As such the main objective of the present work is to develop a physical understanding of the key phenomena and to advance mechanistic models so that development of a model for nucleate boiling under microgravity conditions is facilitated. The work is both experimental and analytical/numerical in nature. Experiments are to be performed both at normal gravity as well as at low gravity conditions in the KC-135 or the Lear jet and in the space shuttle.

To be able to predict nucleate boiling heat transfer under microgravity conditions, a quantitative understanding of the following is needed.

1. Number density of active nucleation sites.

2. Heat transfer to a single bubble including that associated with micro/macro layer evaporation.

3. Bubble merger process and heat transfer to vapor stems supporting a large bubble (may be mushroom type) attached to heater wall.

4. Detachment process of small as well as large mushroom type of bubbles.

5. Flow field induced by bubbles during growth and detachment including that due to Marangoni effect.

6. Heat transfer and flow field for a bubble sliding along a heated wall.

Number density of active nucleation sites at a given superheat is a very important parameter. However, this is an extremely untractable parameter because of the random nature of the size and shape of the cavities on a commercial surface and their gas/vapor trapping ability. Although significant progress has been made in recent years (see Wang and Dhir[12]) in a priori prediction of number of sites that can become active at a given superheat, in the present work the number of cavities that nucleate and their spacing will be a control variable. This will be done by using the surface of a silicon wafer as the test surface. On the wafer surface, single and multiple artificial cavities of a specified geometry (cylindrical) and mouth diameter will be formed. Isolated bubbles will be studied on a single cavity formed on the surface, whereas bubble merger and bubble-bubble interactions will be studied by adjusting the spacing of the artificial cavities (2 or more). Figure 2a shows the typical cavity spacings that will be studied.

Thus the present work will focus only on items 2-6, identified above. Experiments in support of items 2, 3, 5, and 6 will be conducted at normal gravity. The Lear jet or KC-135 aircraft will be used to conduct experiments in support of items 4 and 5. Finally, an experiment combining all aspects of items 2-6 will be defined to be carried out in the space shuttle. In this experiment a "designed" surface, rather than a commercial surface, will be used. The designed surface will have a pre-specified distribution of artificial cavities that can nucleate at a given superheat.

Initially, the experiments at normal gravity will be performed on a downward facing surface. The downward facing surface is chosen so as to stabilize the bubbles and to create temperature field in the liquid solely determined by diffusion of heat from the wall. However, the experiments will subsequently be conducted, when the surface is inclined at different angles with the horizontal. This will provide different magnitudes of gravitational acceleration normal and parallel to the surface. Figure 2b shows the type of orientations that will be investigated. Holographic interferometry will be used to determine the temperature field in the liquid at the wall and around the bubble. Reflections from the liquid-vapor interface of the micro layer and plane surface will be used to create interference fringes. The fringe spacing will be used to determine the thickness of the micro layer at various radial locations

For merged bubbles, the holographic technique will provide information of the temperature field in the upper outer region of the bubbles only. Inner details will be missing. However, interference patterns still could be used to determine the microlayer thickness under each bubble. Knowing the total evaporation rate and heat transfer from the microlayer and along the outer portion of the bubbles, an assessment of the heat flux in the blocked region of the hologram will be made. This evaluation will be confirmed with that determined from single bubble studies. Video/high speed movies will provide information on the growth rate and shape of the bubbles. Liquid motion during bubble growth will be determined by using the hydrogen bubble technique. Any distortions and limitations on bubble size and shape by the heater and test section dimensions will be identified. A cross check on the calculated evaporation rate will be made by comparing the heat input rate obtained by using the information from the temperature field in the liquid, and thickness of the micro layer with that obtained from the observed bubble growth rate. To simulate low velocity flow boiling, a positive displacement pump will be used to create flow parallel to the heater surface. Experiments will be conducted with water and PF-5050 (C_5F_{12}). The test liquid PF-5050 is environmentally safe and has properties similar to R-113. The use of liquids with different wetting characteristics will allow us to determine the effect of wettability (contact angle) on microlayer thickness, and bubble growth and departure behavior.

EXPERIMENTS

The objective of the experiments is to provide in a very clean manner, the basic information that is needed to develop a mechanistic model for prediction of nucleate boiling heat flux as a function of wall superheat. With the presumption that dependence of cavity site density on wall superheat is known, (true for designed surface) the prediction of heat flux requires a knowledge of interfacial area per cavity, interfacial heat flux, and thickness of micro/macro layers. Size of bubbles at breakoff, bubble release frequency and the number of bubble release sites influence the time and area averaged heat transfer and also determine the vapor removal rate. Three types of experiments are proposed in the present work. These include experiments at normal gravity, in the KC-135 or the Lear jet and in the space shuttle.

Normal Gravity Experiments

The first set of experiments will be conducted on a downward facing rectangular surface. A silicon wafer attached to a copper block with a high thermal conductivity cement will serve as the test surface. A silicon wafer is used to eliminate cavities other than the prescribed artificial cavities. The copper block will be divided into three sections so that the central portion can have a heat flux different than that on the bounding or auxiliary surfaces and end effects are minimized. Figure 3 shows a schematic diagram of the apparatus. Heat input to the copper block will be controlled with several cartridge heaters embedded in the block. The heat flux on the central and the auxiliary surfaces will be determined from several 36 gage chromel-alumel thermocouples located discretely in the copper block. Silicon wafers with a thickness of 50 μm and a width and length of 1 and 3 cm respectively will be acquired commercially. Wafers will be visually inspected with an optical microscope to exclude surfaces having any pre-existing cavities. Artificial cavities in the shape of square cylinders will be formed on the surface with an etching process in the clean rooms of the School of Engineering and Applied Science at UCLA.

The test section will be mounted on one side of a liquid holding and viewing chamber. Four sides of the liquid chamber will have glass windows so that the boiling process can be viewed from two sides as well as from the bottom. On the sixth side of the viewing chamber, connection will be made to a positive displacement pump to create forced flow conditions on the heater surface. A provision will exist to orient the test surface at different angles to the gravitational acceleration vector.

The heat flux at the test surface will be determined from the output of the thermocouples embedded in the copper block. The temperature distribution in the liquid adjacent to the heated surface and the vapor liquid interface will be determined through holographic interferometry.

Interference fringe pattern obtained from laser beams reflected from the heater surface and from the liquid-vapor interface of the micro-layer will be used to determine the thickness of the micro-layer at various radial positions. Liquid velocity field created by the vapor bubble during its growth or by the liquid moving past the bubbles will be determined by using the hydrogen bubble technique. The hydrogen bubbles will be created on a copper electrode placed in the test liquid (water). The frequency of the pulse and the voltage difference will be varied until a well defined succession of bubble rows is observed. The size of the hydrogen bubbles is expected to be around 0.02 mm. For bubbles of this diameter, the rise velocity due to buoyancy will be less than 0.7 mm/s. Data for bubble growth and detachment process and bubble trajectory will be obtained from the video pictures.

Experiments will be conducted with saturated and subcooled water and PF-5050 (C_5F_{12}). Use of two fluids with different wetting characteristics will allow scaling of the effect of contact angle both at microscopic (through disjoining pressure) and macroscopic (experiments) levels.

Experiments in the KC-135 or the Lear Jet

Since at normal gravity, there is always a gravitational component parallel to and perpendicular to an inclined surface, the bubble shape and detachment, which are sensitive to magnitude of gravitational acceleration, must be studied under low gravity conditions. As such, it is proposed that during the later part of the third year and early part of the fourth year of the project, experiments be conducted in the KC-135 or the Lear jet. Although experiments will mainly focus on the bubble detachment process, the data for nucleate boiling heat transfer on designed surfaces will also be taken. The data will be very helpful in assessment of the overall heat transfer model, and in extrapolating it to microgravity conditions of the space shuttle. The experimental apparatus will be the same as used in the normal gravity experiments, except a few modifications will be made to accommodate the constraints of the aircraft facility. The holography facility will not be used in these experiments.

Experiments in the Space Shuttle

To further quantify the effect of significantly reduced gravity ($0^{-5}g_e$) on the bubble detachment process in particular, and on the heat transfer in general, it is necessary that boiling experiments be carried out on the "designed" surface. These experiments will not only provide data on the scaling effect of gravity on various processes, including bubble growth and departure, but will also be valuable in validating the predictive model for nucleate boiling heat transfer under microgravity conditions. The experiments will be defined during the first two years of the project.

ANALYSIS

Along with the experimental work, attention will be focused on the modeling of the important thermal hydrodynamic processes. These include:

i. Shape of the vapor liquid interface, the thickness of the micro/macro layer and critical size of the bubble base.

ii. Heat Transfer across the micro/macro layers and evaporation at the interface.

iii. Bubble growth, breakoff and associated flow field including flow created by Marangoni effect.

iv. Flow field and heat transfer associated with a bubble sliding along a heated wall.

v. Generalization of results.

The shape and evolution of the vapor liquid interface of the micro-layer supporting a single bubble or a vapor stem, and heat transfer across the layer will be determined by solving two dimensional axi-symmetric transient momentum and energy equations for the liquid layer. The pressure gradient to overcome the drag experienced by the liquid in the microlayer will be provided by capillary force resulting from the change in the shape of the interface and from the disjoining pressure. The solution of governing equations for micro-layer will be coupled with the solution of transient two dimensional momentum equations for the liquid in the pool and the vapor pocket supported by the micro-layer. The governing equations will be solved in transformed variables using the finite difference method. Grids will be generated numerically. Significant experience exists in the group (e.g. see Son and Dhir[13]) in this area. Either constant temperature or constant heat flux conditions will be applied at the wall. Constant heat flux conditions will provide confirmation of a drop in temperature that may occur during a high rate of evaporation from the microlayers. Bubbles formed on inclined surfaces will not be symmetric. As a result, augmented two dimensional equations will have to be solved. Model predictions will be compared with the data.

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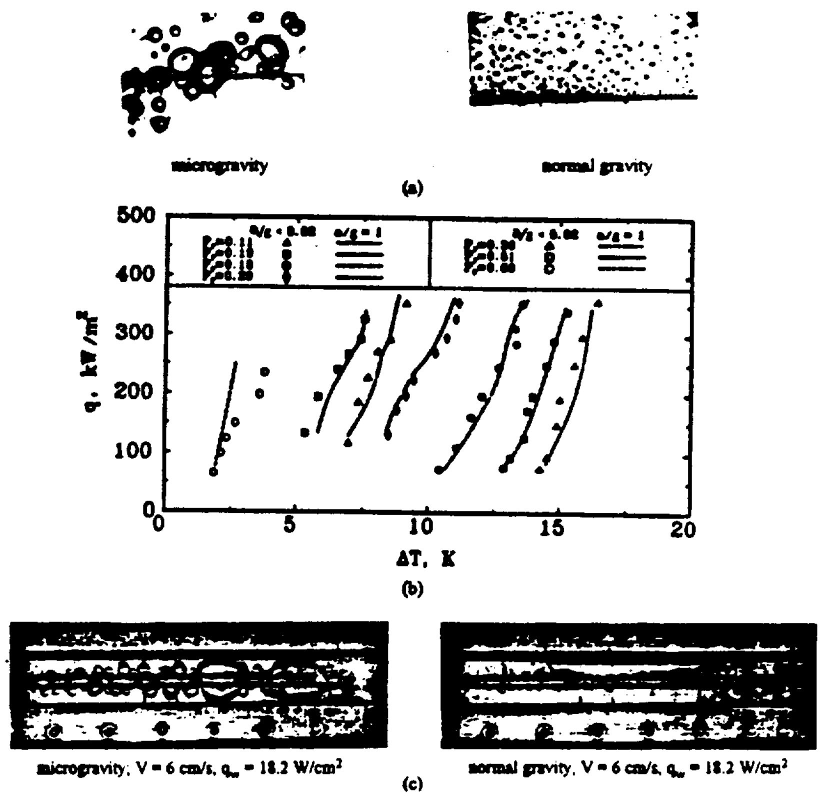

Figure 1: Comparison of normal and microgravity results: (a) pool boiling bubble size[4], (b) pool boiling heat transfer coefficient[4], (c) flow boiling bubble size[11].

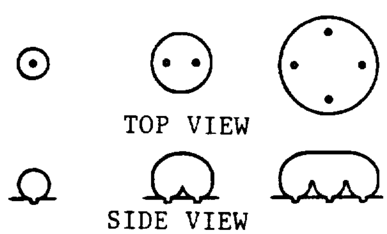

Figure 2a: Number and orientation of active cavity sites.

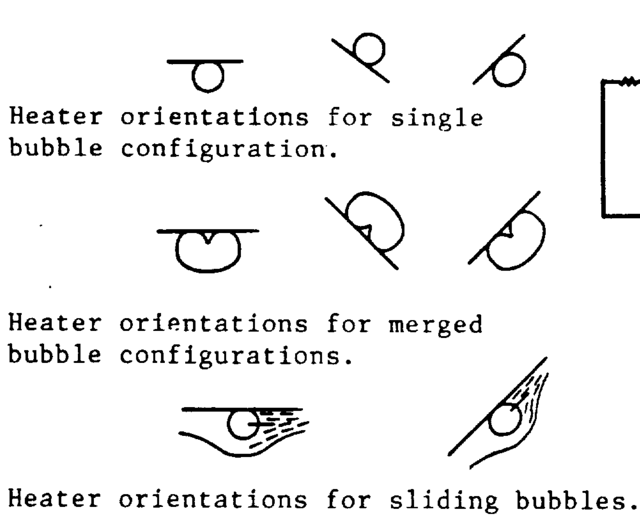

Figure 2b: Heater orientations to be studied for flow and heat transfer during bubble growth and during sliding motion of a bubble.

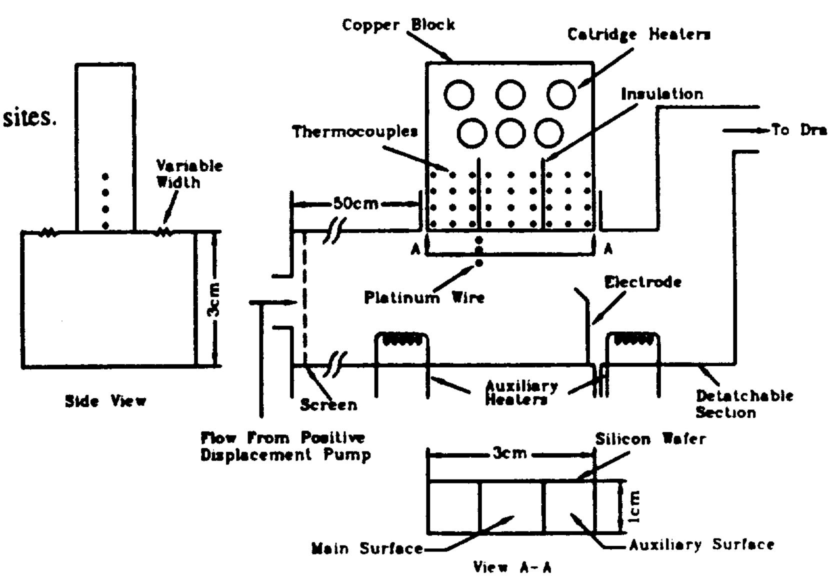

Figure 3: Schematic diagram of the Experimental Apparatus