Enabling Nucleate Boiling Heat Transfer in Low Gravity Using Novel Surfaces Enhancements

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I. Executive Summary

Efficient thermal management for advanced life support, propulsion and science instrumentation systems on spacecrafts is among the technologies critical for the successful deployment of future space missions. Power needs of space platforms are expected to grow substantially in the near future to support exploration and colonization missions involving advanced science instruments and technology. This would require increasingly efficient methods of dealing with increased heat loads and higher rates of heat dissipation in outer space.

Thermal management on space platforms is generally performed using transport of a single phase cooling fluid from heat sources within the spacecraft to external radiators. Such systems have been used on Mercury, Gemini and Apollo NASA missions, the Russian MIR space station and Soyuz spacecraft, the U.S. Space Shuttle fleet and the International Space Station (ISS). The heat removal capability in a single phase circulating system relies on sensible heat capacity of the fluid which is limited by the system size and flow rate constraints in space environments.

The effectiveness of thermal management on space platforms can be greatly improved by making use of the latent heat capacity of the fluid. The associated reduction in pumping power and system size will be instrumental in enabling advanced space mission. Heat pipes utilize phase change to absorb latent heat which has been demonstrated to be effective on Earth. However, heat pipes have been found to have much less impact in space because of low gravity which deters buoyancy related dynamics of vapor bubbles on heated surfaces. In order to exploit the full potential of latent heat transfer in space environments, we must find a way to the remove vapor bubbles from the heated surface to make room for new bubbles to form and absorb latent heat.

The key challenge in improving the thermal capacity of two-phase thermal systems for space environments is to reduce the affinity of nucleated bubbles for the heated surface in order to minimize dryout. We propose to investigate means of reducing the force of wall adhesion on bubbles to enhance wall heat flux in low gravity situations. This can be achieved by either the manipulation of the contact angle using a surface of variable thermal conductivity and wettability, or by using micro-textured surfaces to decrease the rewetting timescale, achieved by the wicking action of micro-textures. We are proposing well-characterized numerical experiments using high fidelity Direct Numerical Simulation of two phase flow to investigate passive means of deterring surface adhesion of nucleated bubbles and facilitating rewetting for improving wall heat transfer under low gravity conditions. This affords a unique opportunity for a quantitative assessment of the improvement in heat transfer afforded by various surface enhancements. The proposed research will complement and advance NASA's efforts towards finding efficient means of dissipating heat from electronics, instruments and life support systems in space and low gravity environments.

II. Boiling heat transfer in low gravity

Understanding the effect of gravity on pool boiling has received much attention because of increased used of satellites for communication and growing interest in space missions [1]. Most of the early low gravity experiments used ground-based facilities like drop towers [2] and magnetic fields to compensate for earth gravity [3]. Aircraft [4, 5, 6] and sounding rockets [7, 8, 9] have also been used to produce low-g environments.

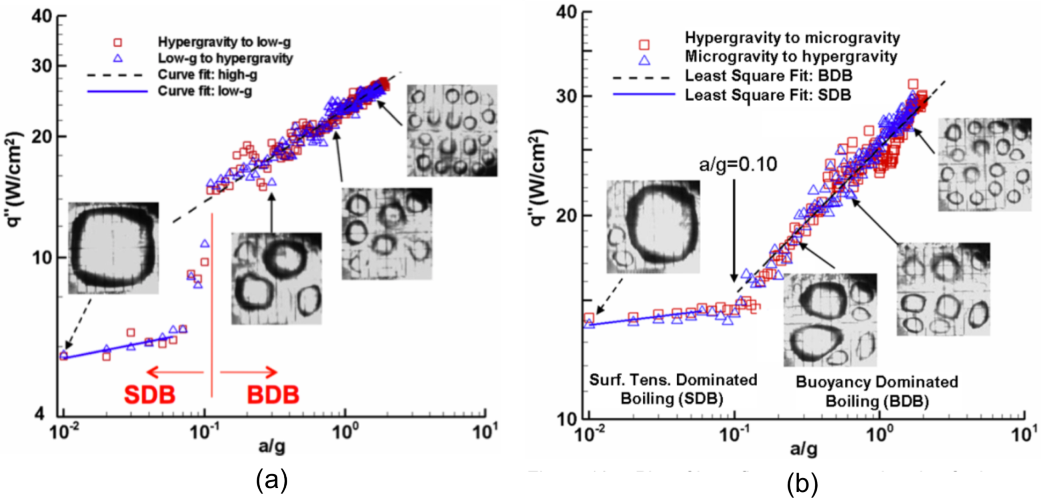

Figure 1: *Heat flux in boiling as a function of gravity. (a) Low subcooling, (b) high subcooling. Data from Raj et al. [10, 11, 12, 13]*

The aircraft data of Raj et al. [10, 11, 12, 13] shown in Fig. 1 reveals the existence of at least two prominant regimes; Buoyancy Dominated Boiling (BDB) and Surface tension Dominated Boiling (SDB). The slope in the BDB regime is a function of the wall superheat. The transition between the BDB and SDB regimes is a simple function of the Bond number, $Bo_{\text{trans}} = 4.41$, and the magnitude of the jump in heat transfer is given as, $1 - \exp(-C\ Ma)$, where Ma is the Marangoni number, ΔT_{sub} is the subcooling, and C is a constant. This model was validated using aircraft and ISS data over a wide range of subcoolings, heater sizes, dissolved gas concentration levels, and surface roughness under Lunar, Martian, and microgravity conditions [15].

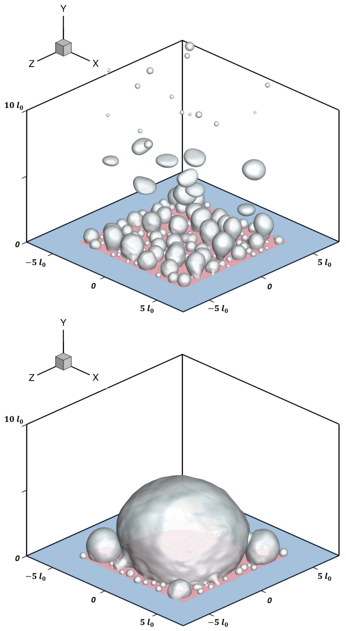

Figure 2: *Results from our numerical simulations [14] in earth gravity (left) and microgravity (right).*

We have carried out numerical simulation to understand and analyze experimental data. Our simulations have revealed that the overall heat transfer decreases with gravity because bubbles merge and grow to a larger size before they are removed by buoyancy, resulting in more dryout on the surface, as indicated in Fig. 2. The heat flux obtained from simulations is plotted in Figure 3 where the flux is scaled with the reference value in earth gravity. Our simulations show good agreement with the slope in BDB, the abrupt transition to SDB and the constant flux in the SDB regime.

Flow visualizations such as those in Fig. 2, suggest that the loss of flux in BDB is likely due to the increase in the force of wall adhesion relative to buoyancy. The shift between the two competing effects diminishes the ability of the bubbles to escape from the wall. As a results, more bubbles remain attached and grow in size at lower gravity, leading to more dry out and lower heat flux. At lower levels of gravity, smaller bubbles transfer momentum to the larger bubbles by merging. Such mergers can nudge larger bubbles to periodically detach. In view of such behaviors, it is likely that the force of adhesion, in opposition to buoyancy and convection, is governed by the contact angle. *It may therefore be possible to increase the force of adhesion at low gravity by allowing the contact line to adopt a more favorable orientation with respect to the wall.* Which could then lead to an increase of slope in BDB and also push the transition to the left, as shown by the hypothetical red lines in Fig. 3.

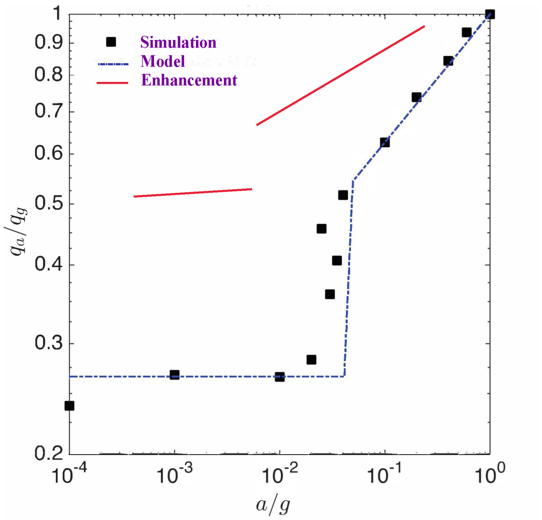

Figure 3: *Heat flux as a function of gravity obtained with our numerical simulations (symbols). The blue lines represent the model based on data in Fig. 1. Red lines indicate the hypothesized improvement in heat flux.*

III. Research Objectives

In the proposed work we will investigate the opportunity for improving the heat flux associated with boiling for a range of gravity conditions. We propose to find means of dynamically altering the contact angle to reduce the force of wall adhesion or using textured surfaces to decrease the rewetting time scale. Both measures can be expected to improve wall heat flux. Our hypotheses driven research effort has the following salient features.

Hypothesis 1: With decreasing gravity, the force of wall adhesion is increasingly governed by the contact angle.

The adhesion of bubbles to the heated wall under low gravity conditions will be governed mainly by the contact angle between the bubble and the wall. The heat flux is insensitive to gravity in the SDB regime. This could be because low gravity does not allow buoyancy to overcome the force of wall adhesion that pulls the bubble downwards as indicated in Fig. 4(a). The numerical solution will be used to calculate the relative effect of these forces, which can be then compared with the forcing produced by bubble mergers and natural convection at different gravity levels. *Data available with NASA will be used for validation by relating visual observations of the bubble departure rate to the average contact angle under Earth normal gravity conditions.*

Hypothesis 2: The force of adhesion under low gravity can be increased by using spatially varying thermal conductivity.

As nucleating bubbles grow in size or translate on the wall, the associated motion of the contact

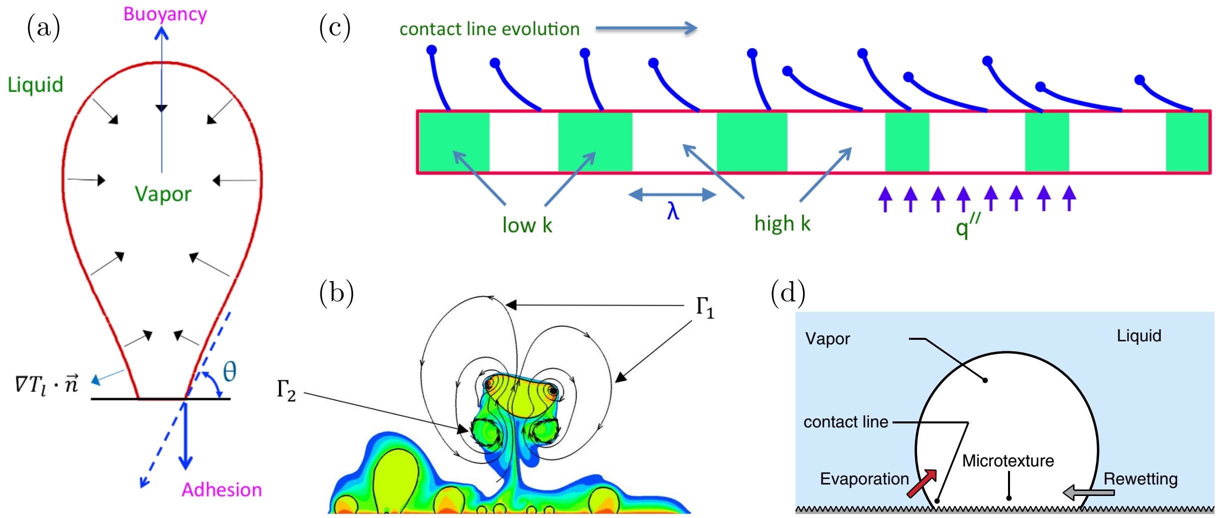

Figure 4: *(a) The forces of buoyancy and adhesion compete to detach the bubble from the wall. (b) Influence of variable thermal conductivity heater on the contact angle (c) Temperature gradients and flow circulation patterns around the nucleating and departing bubbles. (d) Microtextured surfaces can enhance heat flux.*

line depends on local flow dynamics that are governed by the interaction of inertial, capillary and thermal effects in the vicinity of the contact line. The resulting changes in the contact angle effect the force of wall-adhesion relative to that of buoyancy. The dynamic contact angle is a function of contact line speed, which depends on the rate of evaporation close to the wall, which in turn is a function of wall temperature as indicated in Fig. 4(b). *The dynamic contact angle can therefore be influenced by manipulating wall temperatures using spatially varying patterns of thermal conductivity.* Numerical simulations will be used to determine the relationship between the contact line speed and the wall thermal temperature for various patterns of thermal conductively as indicated in Fig. 4(c).

Hypothesis 3: Micro textured surfaces can increase wall heat flux at low gravity and also influence the contact angle.

Micro-textures on heated surfaces, as indicated in Fig. 4(d), are known to increase the heat flux substantially at both critical heat flux (CHF) and lower temperatures. This happen due to the improved wettability and enhanced evaporation at some optimal density of the texture. However, the enhancement is documented only for Earth gravity conditions. It is not known whether it would have the same effect at low gravity. Even though the Bond number will be relatively small, it is not clear how the contact line dynamics at low gravity will effect the process. *Our investigation will attempt to find the relationship between various forms of surface enhancements and gravity levels.*

IV. Heat flux enhancement in pool boiling

The wettability of the surface is an important parameter that impacts the force of wall adhesion during bubble motion. It has been observed that bubbles with smaller contact angle grew faster and moved more quickly on the heater surface [16]. The greater mobility of the bubbles indicates a weaker force of wall adhesion compared to the case for water with a higher static contact angle.

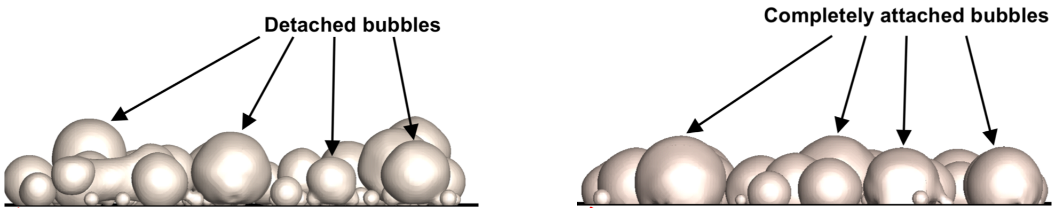

Figure 5: *Nucleating bubble profiles obtained from our numerical simulation. (left) Using a smaller static contact angle and (right) a larger static contact angle.*

The effect of the dynamic contact angle on the affinity of the bubble for the wall will be examined in detail, as noted in Hypothesis 1. Our preliminary results suggest that a smaller contact angle leads to a weaker force of wall adhesion while a large static contact angle helps keep the bubbles attached to the wall. This is shown in Fig. 5 where a small static angle leads to loosely attached bubbles while in the case of a dynamic contact angle the bubbles are more firmly attached, resulting in a comparatively lower heat flux at the wall.

Surface textures also have the ability to substantially enhance wall heat flux. While the essential mechanisms for this are not yet completely clear, various hypothesis have been advanced to provide a fundamental description. A few recent studies on parametric [18, 19] have proposed a monotonic increase in critical heat flux (CHF) as a function of surface texture density by using a static force balance at the contact line [20]. Other studies have suggested that surface wetting plays a more prominent role in heat flux enhancement compared to roughness. However, liquid imbibition (or wicking) into the microstructures has been shown to be strongly related to CHF [21, 22]. A more recent study notes that the CHF on a textured with micropillers depends non-monotonically on texture density [17]. The authors argue that surface texture essentially effects the rewetting time scale, making it easier to rewet at higher wall superheats. The enhancement in rewetting is claimed to be related to the capillary imbibition or a wicking effect of the surface texture or micropillers in their case. All existing studies of the effect of surface texture are carried out under normal gravity and at CHF conditions. However, the essential mechanism of capillary induced rewetting is likely to be carried over to the low gravity regime as well, which will be the focus in the testing of Hypothesis 3.

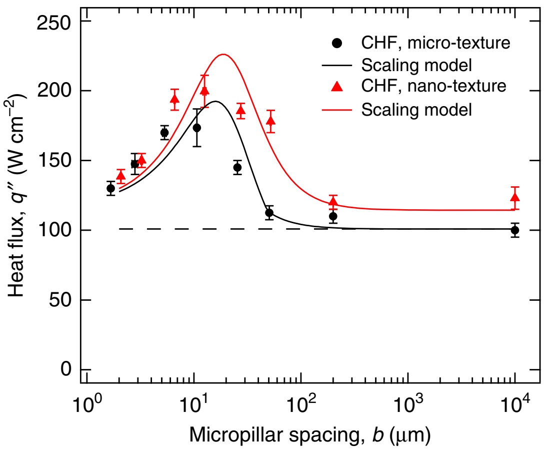

Figure 6: *CHF goes though a maximum on textured surfaces for an optimal texture density [17]*

V. Research plan and implementation

We will use high fidelity direct numerical simulation to characterize the thermal and fluid dynamic behavior of the nucleate boiling process. Our numerical simulations of nucleate boiling can resolve the complex interaction of liquid and vapor phases involving phase transition and contact line dynamics, including (i) interface transport, (ii) phase discontinuity, (iii) singular interfacial forces,

(iv) contact line dynamics and (v) fluid-solid interaction. Our computational methods and solvers have been described in detail in [23, 24, 25, 26, 27, 28, 29]. With the help of such tools we are able to simulate the transport of mass, momentum and energy in two-phase flow with high precision.

Our parallel Navier-Stokes solver for multiphase flow is high accuracy, fully 3-D and employs Cartesian grid, octree based, mass conservative adaptive mesh refinement, to maximize the use of computational nodes and features an optimized algebraic multigrid linear solver. Such features provide for an extremely efficient tool for interrogating the fundamental physics of boiling heat transfer across the entire spectrum of gravity conditions relevant for this study. Various aspects of the solver have been validated using MABE and NPBX databases available with NASA based on computations on the NASA advanced supercomputing infrastructure (NAS).

In order to test Hypothesis 1 stated in section II, we will first carry out simulations on a plain surface to obtain reference data. We will document data for bubble sizes and contact angles using simulations to establish a base line case correlating the bubble size with the contact angle for a range of gravity conditions. We will then vary the static contact angles to investigate the dependence of bubble size and departure rate on the contact angle for various gravity levels. This procedure would serve to illustrate the affect of the contact angle on the force of wall adhesion as a first step.

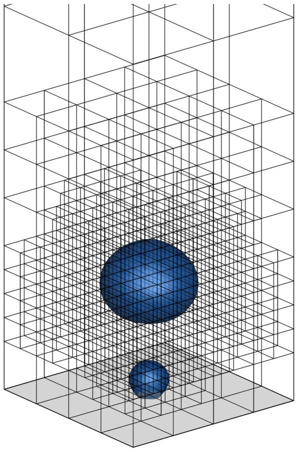

Figure 7: *Adaptive mesh refinement around the bubbles used in our simulation of nucleate boiling.*

In order to test Hypothesis 2, noted in section II, we will use variable thermal conductivity, as indicated in Fig. 4(c). Various patterns will be considered, ranging from striated bands to checkered patterns with different wavelengths, λ. Fig. 4(c) illustrates the idea that high conductively regions will be cooler than low conductively regions which will lead to a smaller and larger contact angles, respectively, for the contact angle as the contact line moves across the heater. This implies that if the wavelength is set to high, then the contact angle will progressively become smaller for a moving contact line, as indicated in the figure. However, such behavior will depend on the contact line speed and the dynamic contact angle as well as the time scale of thermal adjustment to the changes in wetted surface area and the local Prandtl number. Simulation data for plain surface will help us quantify the thermal response under various gravity conditions, which would help design conductively patterns in a more systematic manner.

Hypothesis 3 will be tested by setting up micropillered surface textures of various texture densities. The capillary wicking action of the textures will be studied under various conditions and its effect on the heat flux and bubble departure will be documented. Particular focus will be on characterizing rewetting time scales for low gravity conditions. It will also be interesting to observe the behavior of the contact angle in response motion over textured surfaces.

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