ENHANCED BOILING ON MICRO-CONFIGURED COMPOSITE SURFACES UNDER MICROGRAVITY CONDITIONS

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INTRODUCTION

As an efficient heat transfer mode, boiling has been considered in various aspects of space missions, such as in thermal management, in thermal power generation, in cooling devices and in other heat exchangers. It is self-evident that both economy and reliability are the crucial factors for any space mission. Nucleate boiling near the critical heat flux (CHF) can provide excellent economy along with high efficiency of heat transfer. However, nucleate boiling performance can deteriorate in a reduced gravity environment and nucleate boiling usually has a potentially dangerous characteristic in the CHF regime.

The performance of pool boiling heat transfer on a composite surface was studied experimentally and numerically by Blagojevic et al.[1]. They found a plateau in the boiling curve in the CHF regime accompanied by a reduction in the peak heat flux. Yang and Zhang [2] divided composite enhanced surfaces into two categories: discrete insert/matrix type composites and micro-configured insert into matrix types. They presented a hypothesis to explain the formation of the plateau of the boiling curve in the CHF region. This explanation may provide a guideline to search for the proper construction of enhanced boiling surfaces with a wider safety margin in the CHF regime.

New materials, such as micro-configured metal-graphite composites, could be an idea boiling surface for boiling enhancement. The pool boiling experimental results show that the average boiling heat transfer coefficient of Freon-113 in the nucleate boiling regime on the copper - graphite (Cu-Gr) composite surfaces, with up to 35°C wall superheat, is 3.0 to 4.6 times that for the pure copper heater surface [3]. Compared to other enhanced boiling surfaces these types of composite surfaces have unique attributes as they do not incur extra pressure drop, have no fouling and offer low primary and maintenance costs. The composite fabricated by SPARTA Inc. consists of a certain volume fraction of graphite fibers having diameters of 10 to15 μm embedded uniaxially within a copper matrix, as shown in Fig. 1. The metal-graphite micro-configured composite surfaces were found, through a numerical simulation, to have nonisothermal surfaces under boiling conditions [3, 4]. Based on the non-isothermal surface result, a reduced sensitivity of the CHF to superheat variation for the surfaces was predicted by Yang and Zhang [2].

Due to the nonisothermal conditions of the surfaces, the thermocapillary forces along the micro bubble base would benefit the bubble detachment and may play the main role in a microgravity environment. Because the bubble detachment manifests itself by a necking process, the thermocapillary forces formed by the temperature difference between the fiber tips and the copper matrix would neck the bubble and play a more important role in bubble detachment than buoyancy. Figure 2 shows the forces acting on a micro bubble on a composite surface. Therefore, it is reasonable to predict that the nucleate boiling performance of the surfaces, including that in the CHF regime, will not be reduced significantly when buoyancy vanishes under microgravity.

Fig. 1 A Photo of Magnified Cu-Gr Composite Surface

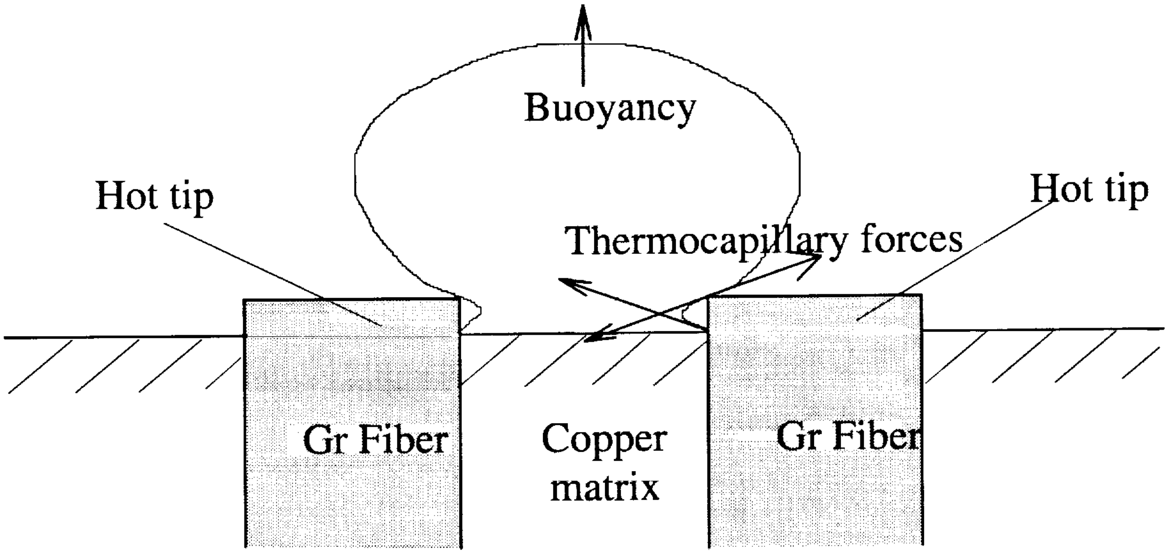


Fig. 2 Micro bubble detachment on a composite surface

EXPERIMENTAL SETUP

A schematic of the experimental setup is shown in Fig. 3.

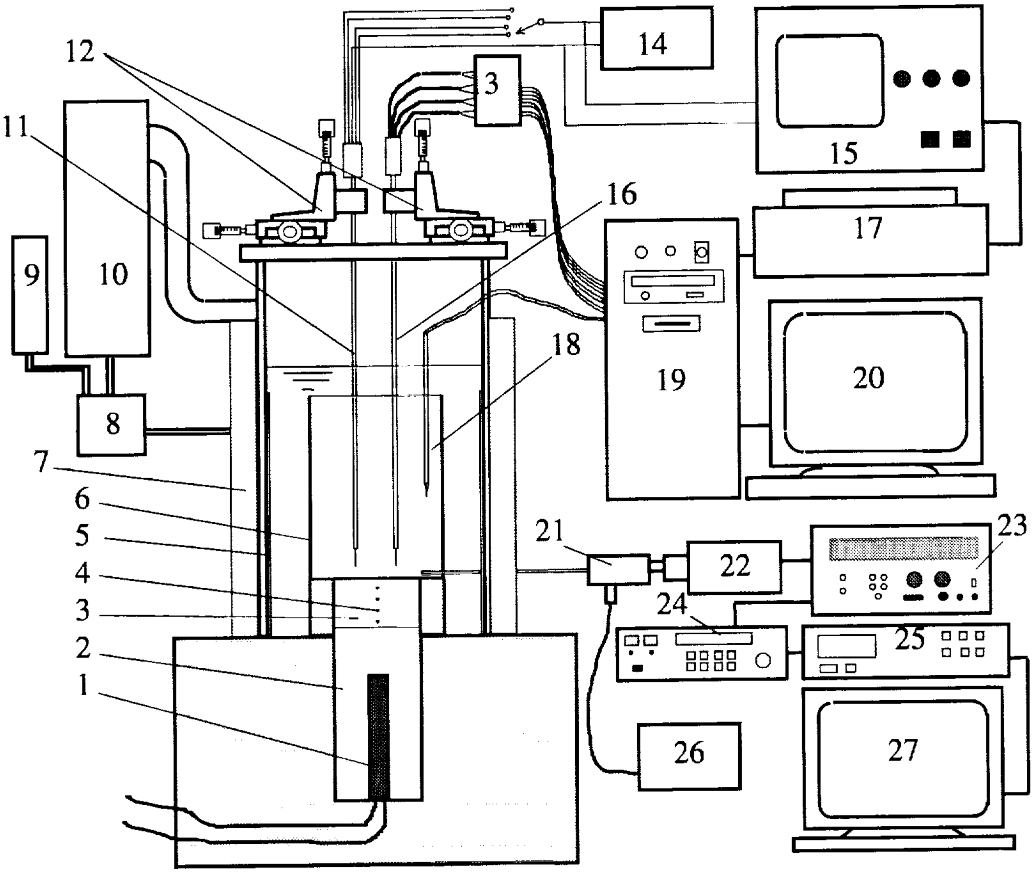


Fig. 3 Schematic of the Experimental Setup

It will be slightly modified to meet the constraints for the experiments in the space shuttle. A micro-configured composite test sample *3*, serving as the boiling surface and insulated on its side wall, is glued to the heat conducting copper block *2* by using high temperature epoxy with high thermal conductivity. As the main heater, a cartridge heater *1*, whose power is supplied and varied by an adjustable voltage controller, is inserted into the copper block surrounded by an insulator. Four thermocouples *4* are embedded on the centerline of the test sample to measure the temperatures along the heat transfer path, and the temperature of the boiling surface can be determined by extrapolation. A strip heater *5* is placed on the wall of the boiling vessel as the auxiliary heater to maintain the working liquid at a saturated temperature. To prevent the heating effect of the strip heater on the boiling surface, the glass sleeve *6* is placed on the extension plate of the boiling surface. Insulating material *7* is used to protect the heat loss from the boiling vessel. A condensation system used to recover the evaporating working fluid, consists of the condensate preheater *8*, condenser 9, and main condenser *10*. The micro electrical resistance probe set *11* and the micro-thermocouple set *16* are held, respectively, by three-dimensional micrometer stages *12* which can sense movements to 0.1 μm in the vertical direction and 1 μm in the two horizontal directions. The temperature data measured by the micro-thermocouple set are recorded by the computer data acquisition system consisting of the terminator connector *13*, the computer data acquisition *19* and the monitor *20*. The Oscillator *14* and the oscilloscope *15* constitute the frequency measurement system to detect and count the micro bubbles emitted from the boiling surface. A printer *17* is shared by the temperature and the frequency measurement systems. A thermocouple *18* is used to monitor the working fluid temperature. The high magnification borescope probe *21* is inserted into the boiling vessel and immersed in the working liquid to capture the motion of embryonic bubbles which are illuminated by light source *26* through a glass fiber light guide cable. A high speed motion recorder system consists of a high speed video camera *22* and the motion analyzer *23* which provides immediate, slow-motion playback through the regular video recorder *24* and the monitor *27*. Any interesting details can be printed out instantly by the color video printer *25*. Before using the high speed recorder system a regular video camera can be utilized to replace *22* and *23* in preliminary tests the system.

MATHEMATICAL MODEL

An analytical model will be developed to help provide fundamental understanding of the coupled heat transfer and bubble formation mechanisms. According to the two-tier model for nucleate boiling on micro-configured composite surfaces, the micro bubbles coalesce at their maximum cross section, as shown in Fig. 4, and their diameter, D, is related to the fiber diameter, d, and the volume fraction of the fiber, α, by

$$D = (d/2) \sqrt{(\pi/\alpha)} \tag{1}$$

The plane of coalescence of the micro bubbles is regarded as the maximum thickness of the liquid film entrapped between the micro bubbles, δ_m which can be determined as

$$\delta_m = (d/2) \sqrt{[(\pi/4\alpha) - (\sqrt{(\pi/2\alpha)} - 1)^2]} \tag{2}$$

The volume of liquid trapped between the micro bubbles, then, is

$$V_l = (3\pi/4)\, D^2 \delta_m + (\pi/3)\, \delta_m^3 \tag{3}$$

Idealizing the liquid volume as a column of constant cross-section, the microlayer thickness can be derived as

$$\delta = [(3/4)\, D^2 \delta_m + (1/3)\, \delta_m^3] / [(3/4)\, D^2 + \delta_m^2] \tag{4}$$

Assuming the bubbles that have coalesced to form a vapor mass (mushroom) are of same diameter, D_m, the liquid volume being entrapped between the bubbles is

$$V_{l,m} = D_m^3 [\cos\theta /2 - (\pi/8)(\cos\theta - \cos^3\theta /3)] \quad (5)$$

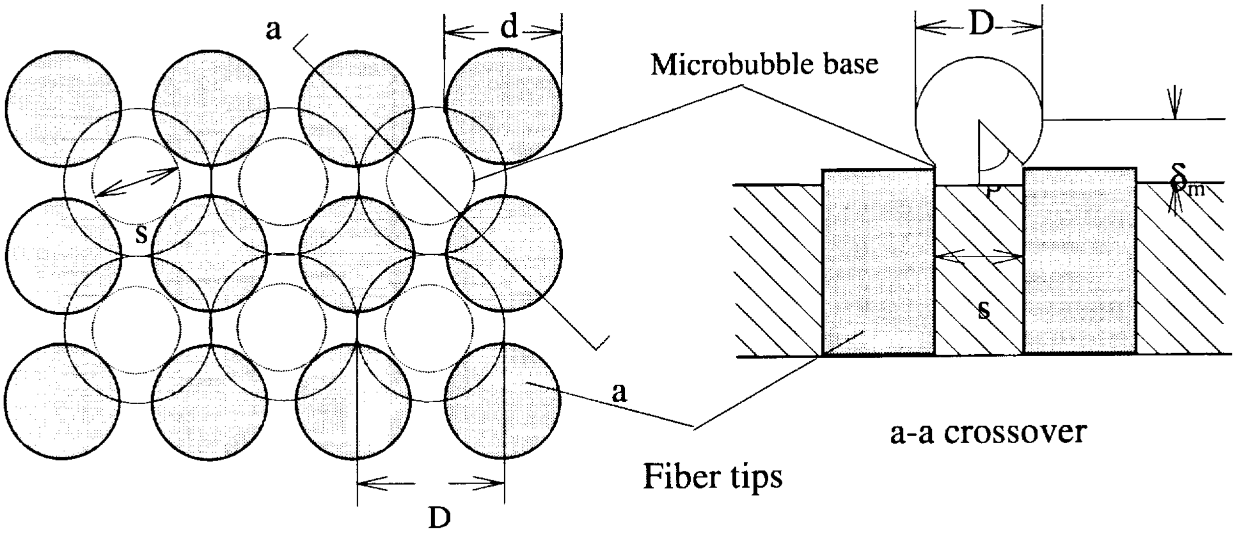
The macrolayer thickness can be shown to be

$$\Delta = (D_m \cos\theta / 2) [1 - \pi (1 - \cos^2\theta / 3) / 4] / (1 - \pi \sin^2\theta / 4) \quad (6)$$

where, θ is the contact angle. According to the two tier model the primary contributors of the boiling heat transfer in the low heat flux boiling region are micro bubbles. Therefore, the boiling heat flux, q_l, can be expressed as

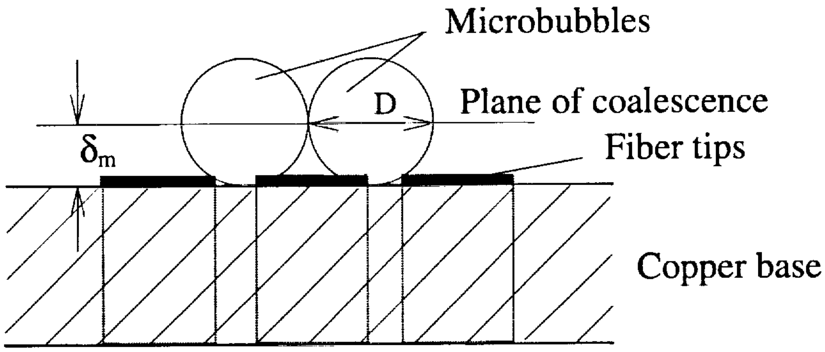
$$q_l = f\, n\, \rho_v\, h_{fg}\, \pi D^3 / 6 \quad (7)$$

where f is the frequency of the micro bubbles emitted from the surface, n, the active



(a) top view of multiple microbubbles and fiber tips

(b) side view of a single micro-bubble on the composite surface



(c) side view of cross section

Fig. 4 Mechanism of Microlayer Formation on a Composite Surface

site density, ρ_v, the density of vapor and, h_{fg}, the latent heat of vaporization. In the high heat flux boiling region, the boiling heat flux consists of two parts: latent heat transport by the micro bubbles under the vapor stems and evaporation on the interface along the macrolayer which equals the heat conduction across the macrolayer (refer to Fig. 4). The total heat flux, q_h, is

$$q_h = f\, n\, \rho_v\, h_{fg}\, \pi\, D^3 / 6 + N\, V_{l.m}\, k_l\, \Delta t_w / \Delta^2 \qquad (8)$$

where N is density of the vapor stem, k_l, thermal conductivity of the working fluid, Δt_w, wall superheat. The CHF, q_{cr}, can be evaluated as the macrolayer evaporates to dryness before the mushroom departs, and can be expressed as

$$q_{cr} = (n\, V_l + N\, V_{l.m})\, \rho_l\, h_{fg} / \tau_d \qquad (9)$$

where τ_d is the vapor mushroom hovering time.

To predict the heat fluxes the parameters f, n, D, N, D_m and τ_d have to be determined. All of the parameters can be directly measured through the experiments except for n and N. The relationships between n, N and q_l, q_h will be determined through the experimental data processing. Solving a two dimensional conduction equation coupled with the evaporation boundary condition for the macrolayer to refine the second term in Eq. 8, allows further improvement of the model. The effects of microgravity on the heat fluxes should be reflected in changes of the frequency f and the diameter D_m. Definite mathematical expressions of these quantities will be developed based on the results of the ground-based low gravity experiments. The puzzle as to why a smooth and continuous transition of the boiling mechanism occurs across the isolated and coalesced bubble regimes will hopefully be resolved from the evaluation of Eqs. 7 and 8.

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