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under Microgravity Conditions**

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Enhancements of Nucleate Boiling under Microgravity Conditions

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Abstract

This paper presents two means for enhancing nucleate boiling and critical heat flux under microgravity conditions: using micro-configured metal-graphite composites as the boiling surface and dilute aqueous solutions of long-chain alcohols as the working fluid. In the former, thermocapillary force induced by temperature difference between the graphite-fiber tips and the metal matrix plays an important role in bubble detachment. Thus boiling-heat transfer performance does not deteriorate in a reduced-gravity environment. In the latter cases, the surface tension-temperature gradient of the long-chain alcohol solutions turns positive as the temperature exceeds a certain value. Consequently, the Marangoni effect does not impede, but rather aids in bubble departure from the heating surface. This feature is most favorable in microgravity. As a result, the bubble size of departure is substantially reduced at higher frequencies.

Based on the existing experimental data, and a two-tier theoretical model, correlation formulas are derived for nucleate boiling on the copper-graphite and aluminum-graphite composite surfaces, in both the isolated and coalesced bubble regimes. In addition, performance equations for nucleate boiling and critical heat flux in dilute aqueous solutions of long-chain alcohols are obtained.

Introduction

Boiling heat transfer will be a key technology in space thermal management systems and other future space applications. A two-phase liquid-loop system, utilizing boiling heat transfer, is an attractive alternative to the single-phase liquid loop system used in the conventional Space Transportation System and Spacelab[1-3] due to its much higher heat transfer efficiency.

It is well known that surface tension effects, including temperature driven surface-tension gradients, are dominant when the buoyancy force is diminished in microgravity conditions. Unfortunately, most previous studies have shown that, rather than assisting in the detachment process, surface tension and its temperature driven gradients tend to keep the bubbles on the wall, and in that way impede bubble detachment. This, of course, is quite detrimental to boiling heat transfer.

The dependence of gravity and surface tension on the diameter of a bubble at departure is expressed through the Fritz relation [4]:

$$D = C \left[\frac{\sigma}{g(\rho_l - \rho_v)} \right]^{1/2} \quad (1)$$

where D is the departure diameter of the bubble, C is a constant which is a function of the properties of the liquid, σ is the surface tension, g is the gravitational

acceleration, ρ_l and ρ_v are the liquid density and the vapor density, respectively. According to this correlation, saturated nucleate boiling cannot occur when the gravity approaches zero. Indeed, Zell and Straub [5] observed that film boiling occurred immediately without the appearance of nucleate boiling when a moderate heat flux (30 kW/m^2) was imposed on a plate heater in a pool of saturated R113 during a ballistic rocket flight. Based on this observation, Zell and Straub concluded that saturated nucleate boiling on a flat plate could not be maintained under microgravity conditions. However, other experiments, including a later one by Zell et al. [6], reported that saturated nucleate boiling was established on a flat plate heater as well as on a thin wire.

Generally, the experimental results on boiling heat transfer under microgravity conditions are contradictory. In some experiments the boiling heat transfer coefficient was independent of gravity; in others it decreased or increased as gravity was reduced [7, 8]. The results of pool boiling experiments under reduced gravity ($\sim 10^{-2} \text{ g}$) conducted by Abe [9] and Oke et al. [10] show that the boiling behaviors of organic fluids, and water, under reduced gravity are considerably different. In the boiling of organic fluids most of the bubbles attached to the heater surface with a large contact area, and some bubbles coalesced with each other on the heater surface even at low heat fluxes. However, bubbles generated in water were spherical in shape, making only slight contact with the heater surface or being lifted from the surface. The heat transfer deterioration due to gravity reduction for the organic fluids was appreciable only at high heat fluxes. On the other hand, for water the deterioration occurred throughout the entire nucleate boiling regime. In spite of the complexity of

boiling in reduced gravity environments, three conclusions are generally agreed upon:

- 1) bubble departure becomes more difficult and the bubbles that detach from a heater surface readily coalesce with each other,
- 2) the transitions from the isolated bubble regime to the coalesced bubble regime and from the coalesced bubble regime to the vapor slug regime take place at relatively small heat fluxes, and
- 3) the critical heat flux (CHF) for all liquids in microgravity is considerably smaller than in normal gravity.

Although the acceleration of gravity appears as a parameter in almost all the correlations used to predict boiling performance, the fundamental question concerning the effect of gravity on boiling has yet to be satisfactorily answered. Most correlations are based on experiments conducted on earth, in which several adjustable parameters are involved. Dhir [11] pointed out that the usefulness of the correlations diminished very rapidly as the parameters of interest started to fall outside the range of physical parameters for which the correlations are developed. The correlations involving several empirical constants tend to cloud the physics. Actually, due to its complex nature, a comprehensive understanding of the mechanisms of boiling has not been available. Also, the forces acting on the bubbles have not been properly taken into account. Buoyancy dominates in nucleate boiling on the earth and masks other forces, such as the Marangoni force induced by the surface tension gradient, the inertia force produced by the bubble growth, and others. These forces would play significant roles in bubble detachment and therefore in the nucleate boiling heat transfer when gravity is greatly reduced. Effects of some physical properties of the working fluid on the boiling behavior could also be unmasked in

microgravity. It is the effects of the fluid properties that could account for the difference in the gravity dependency of the boiling heat transfer performance between organic fluids and water that occurs in the reduced gravity [9, 10].

There are two fundamental approaches to enhancing boiling heat transfer: develop enhanced boiling surfaces and/or develop new working fluids.

A). Enhanced Boiling Surfaces: It is well known that surface geometry plays a key role in nucleate boiling heat transfer. Therefore, as a high-technology area of heat transfer, many enhanced boiling surfaces have been developed and studied. Only a few of these have become available commercially. Commercially enhanced boiling surfaces can be arranged into two basic categories: integral roughness surfaces (IRS) and porous boiling surfaces (PBS). Webb [12] and Thome [13, 14] gave general reviews of the enhancement of the boiling surfaces. Some of the surfaces can both enhance nucleate boiling heat transfer and increase the CHF, but some only enhance the nucleate boiling without any increase or even with much of a decrease in the CHF value [15]. Recently, O'Connor and You [16] investigated a painting technique to create a surface microstructure for enhanced boiling heat transfer. They reported an increase in boiling heat transfer three times greater than the unpainted surface, and a CHF increase of 109 percent. They pointed out that the CHF increase is due to surface microstructure and its influence on the boiling heat transfer characteristics. Wright and Gebhart [17, 18] investigated enhanced boiling performance on microconfigured surfaces and suggested a two-bubble model to explain the enhancement of the boiling heat transfer. A two-tier model was proposed by Zhang et al. [19] to explain the nucleate boiling process and performance enhancement on microconfigured surfaces.

The performance of pool boiling heat transfer on a composite surface was studied experimentally and numerically by Blagojevic et al. [20]. They found a plateau in the boiling curve in the CHF regime accompanied by a reduction in the peak heat flux. Yang and Zhang [21] 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 for searching for the proper construction of enhanced-boiling surfaces with a wider safety margin in the CHF regime.

Most of the current enhanced-boiling surfaces, either commercially available or under development, generally increase heat transfer performance in the nucleate boiling regime but do not have both a higher value of CHF and a uniform CHF operating region. The boiling performance on the enhanced surfaces is expected to deteriorate sharply with reduced gravity. The reason for this is that the complex construction of the surfaces makes the bubble detachment crucially dependent upon buoyancy. These enhanced surfaces usually also require higher primary and maintenance costs or have disadvantages of introducing additional pressure drops, and gradual loss of their enhancement effects on the nucleate boiling due to fouling. New enhanced-boiling surfaces, metal-graphite micro-configured composite surfaces, may provide the solution. The pool boiling experimental results show that the average boiling heat transfer coefficient of R113 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 [22]. Compared to other enhanced boiling surfaces, these types of composite surfaces

have unique attributes since they do not incur extra pressure drops, have no fouling, and offer low primary and maintenance costs. It has been also found that the CHF for Cu-Gr composites was extended to higher values compared to a pure copper surface. The metal-graphite micro-configured composite surfaces were found to have nonisothermal surfaces under boiling conditions [22, 23]. Based on the nonisothermal surface result, a reduced sensitivity of the CHF to superheat variation for the surfaces was predicted by Yang and Zhang [21]. Most recently, the authors have suggested a model to predict the CHF on metal-graphite composites [24]. However, the nucleate boiling mechanisms on the composite surfaces, especially in the CHF regime, have not been adequately studied.

B). New Working Fluids: Recently, many efforts have been made to try to enhance boiling heat transfer through Marangoni effects in fluid mixtures at normal gravity [25-27] as well as in microgravity [28, 29]. It was found that a small amount of surface-active additive considerably increases the nucleate boiling heat transfer coefficient of water at normal gravity [25, 26]. However, no test has yet been conducted under microgravity conditions. A serious problem with using a surfactant is its foaming in the vapor. McGillis and Carey [27] found that small additions of alcohol to water increased the CHF condition above that of the pure water and higher concentrations of the alcohol began decreasing the CHF condition to near that of the pure alcohol. On the other hand, for water-ethylene glycol mixtures, addition of the latter decreased the CHF condition relative to that of pure water. Abe et al. [28] tested water-ethanol mixtures of 11.3 wt% and 27.3 wt% of ethanol and found that heat transfer is enhanced by reductions in gravity over the major portion of the nucleate boiling regime, but the CHF decreases 20-

40% from the terrestrial level. Unfortunately, the boiling heat transfer performance of the mixtures at normal gravity is much worse than that of pure water, and, although enhanced under microgravity, it still cannot reach the level of pure water at normal gravity. Therefore, the water-ethanol mixtures are unacceptable for space applications. Ahmed and Carey [29] conducted an experiment with water-2-propanol mixtures under reduced gravity. They concluded that the Marangoni effect arising from the surface tension gradients due to concentration gradients is an active mechanism in the boiling of binary mixtures and that the boiling mechanism in these mixtures is nearly independent of gravity. Additionally, they found that in microgravity the larger the surface tension gradient with the concentration of 2-propanol in the mixture, the higher the CHF. The experimental results obtained by Abe et al. and by Ahmed and Carey clearly show that for so-called *positive* mixtures, in which the more volatile component has a lower value of surface tension, the Marangoni mechanism is strong enough in the mixtures to sustain stable nucleate boiling under microgravity conditions. The basic physical explanation of the Marangoni effect is as follows: The preferential evaporation of the more volatile component from the liquid-vapor interface occurs more intensively at positions closer to the heater surface. The variation in concentration along the bubble surface results in a surface tension gradient, and therefore, a Marangoni flow directed from the top of the bubble to the bottom of the bubble must be produced. The liquid adjacent to the bubble surface is dragged down towards the bottom of the bubble and thereby lifts it from the heater surface. However, for so-called *negative* mixtures, in which the more volatile component has a higher surface tension, such as water-ethylene glycol mixture, the surface tension

gradient induced by the variation in concentration is in the opposite direction to that for positive mixtures. Consequently, the Marangoni flow tends to keep the bubbles pressed to the heater surface and impedes bubble detachment. This is why the CHF of a water-ethylene glycol mixture decreased when comparing with that of pure water [28]. It is clear that only *positive* mixtures have the potential to be a boiling working fluid for space applications. However, the proper operating regimes of these binary mixtures are too narrow to use in practice, especially for space applications.

Metal-Graphite Composite Surfaces

Experimental studies were performed on nucleate pool boiling of pentane on copper-graphite (Cu-Gr) and aluminum-graphite (Al-Gr) composite surfaces with various fiber volume concentrations for heat fluxes up to 35 W/cm^2 . It is revealed that the onset of nucleate boiling (the isolated bubble regime) occurs at wall superheat of about 10°C for the Cu-Gr surface and 15°C for the Al-Gr surface, much lower than their respective pure metal surfaces. A significant enhancement in boiling heat transfer performance on the composite surfaces is achieved [30], as shown in Fig.1, due to the presence of micro-graphite fibers embedded in the matrix. Transition from an isolated bubble regime to a coalesced bubble regime in boiling occurs at a superheat of about 14°C on Cu-Gr surface and 19°C on Al-Gr surface.

According to a two-tier configuration and its mathematical model [19], and based on the existing experimental data, correlations for the boiling heat transfer performance in the isolated bubble regime and in the coalesced bubble regime are obtained as follows:

The boiling heat flux in the low heat flux boiling region (isolated bubble regime) is

mainly contributed by micro bubbles, with negligible heat conduction across the microlayer, and can be expressed as

$$q_l = \frac{\pi D_m^3}{6} \rho_v h_{fg} C_s (\Delta T_{sat})^m \quad (2)$$

where D_m is the maximum micro bubble diameter, ρ_v is the density of saturated vapor at the boiling point, h_{fg} is the latent heat of vaporization at the boiling point, ΔT_{sat} is the superheat, and C_s and m are constants determined by the experimental data. For the composite surfaces, D_m is related to the fiber diameter, d , and the area fraction of the fibers in the base material, α , by

$$D_m = \frac{d}{2} \sqrt{\frac{\pi}{\alpha}} \quad (3)$$

In the case of $\alpha = 0.5$ and $d = 8 \mu\text{m}$, the value of D_m is calculated at $10.03 \mu\text{m}$.

In the high heat flux boiling region (coalesced bubble regime), the boiling heat flux consists of two parts: latent heat transport by micro bubbles under the vapor stems and by evaporation on the interface along the macrolayer, which equals heat conduction across the macrolayer. The total heat flux is

$$q_h = q_{l,m} + k_l C_l (\Delta T_{sat} - \Delta T_t) \quad (4)$$

where, $q_{l,m}$ is the maximum value of the heat flux in the isolated bubble regime, k_l is heat conductivity of the working fluid, ΔT_t is superheat at the transition from the isolated bubble regime to the coalesced bubble regime, C_l is a constant which can be determined by experiments. The properties of pentane saturated vapor and liquid at the boiling point can be found in reference [31] and the relevant data are listed in Table 1.

Based on the experimental data shown in Fig. 1, the values of the constants C_s , m , and C_l , then can be estimated at 2.828×10^7 , 2.443 , and 2.389×10^3 , respectively for the Cu-Gr composite surface, and 2.544×10^5 , 3.805 , and 3.39×10^3 , respectively for the Al-Gr composite surface. The results calculated

Table 1. Properties of saturated pentane vapor and liquid at boiling point

Mol. weight	$t_b, ^\circ\text{C}$	$\rho_v, \text{kg/m}^3$	$k_l, \text{W/m K}$	$h_{fv}, \text{kJ/mol}$
72.146	36.06	0.003002	0.1086	25.79

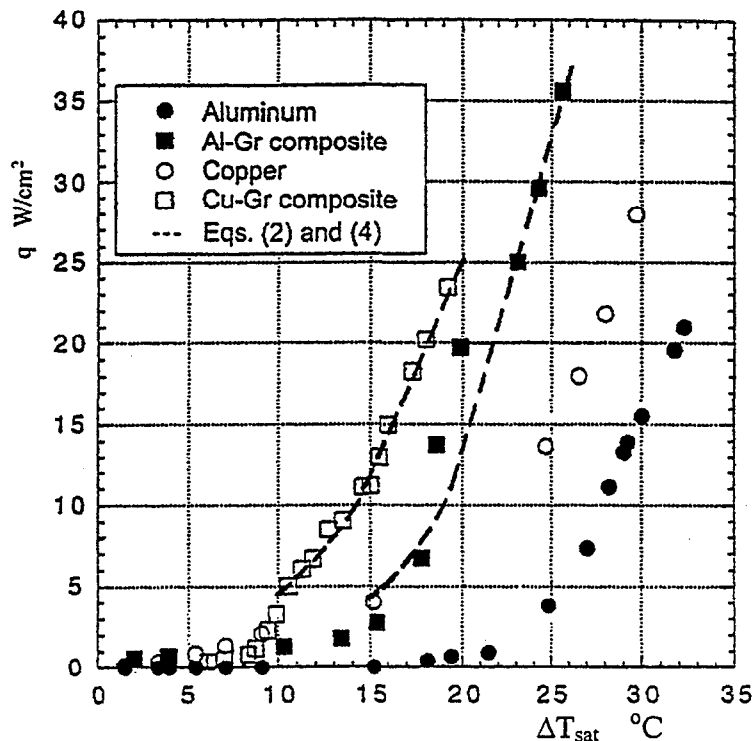


Fig. 1. Pool boiling performances of pentane on different surfaces

by Eqs. (2) and (4) are shown in Fig. 1 in dash lines. The two-tier configuration explains the constants C_s and m as the parameters related to the product of the active site density and the frequency of micro bubbles emitted from the composite surface; the constant C_l is the parameter related to macrolayer.

It is obvious that both q_l and q_h are independent from gravity, and therefore, the boiling performance on the metal-graphite composite surfaces would not deteriorate with reduced gravity. Undoubtedly, this kind of material is suitable to the space applications.

New Working Fluids

Water is an ideal working fluid for boiling heat transfer in both terrestrial and microgravity environments by virtue of its availability, cost and safety. However, its major shortcoming under microgravity is its significant deterioration in nucleate boiling performance and CHF with a decrease in gravity. This is due to lack of a driving force for vapor detachment from the heating surface. Furthermore, the Marangoni flow around bubbles induced by a negative surface tension-temperature gradient presses the bubbles onto the heating surface,

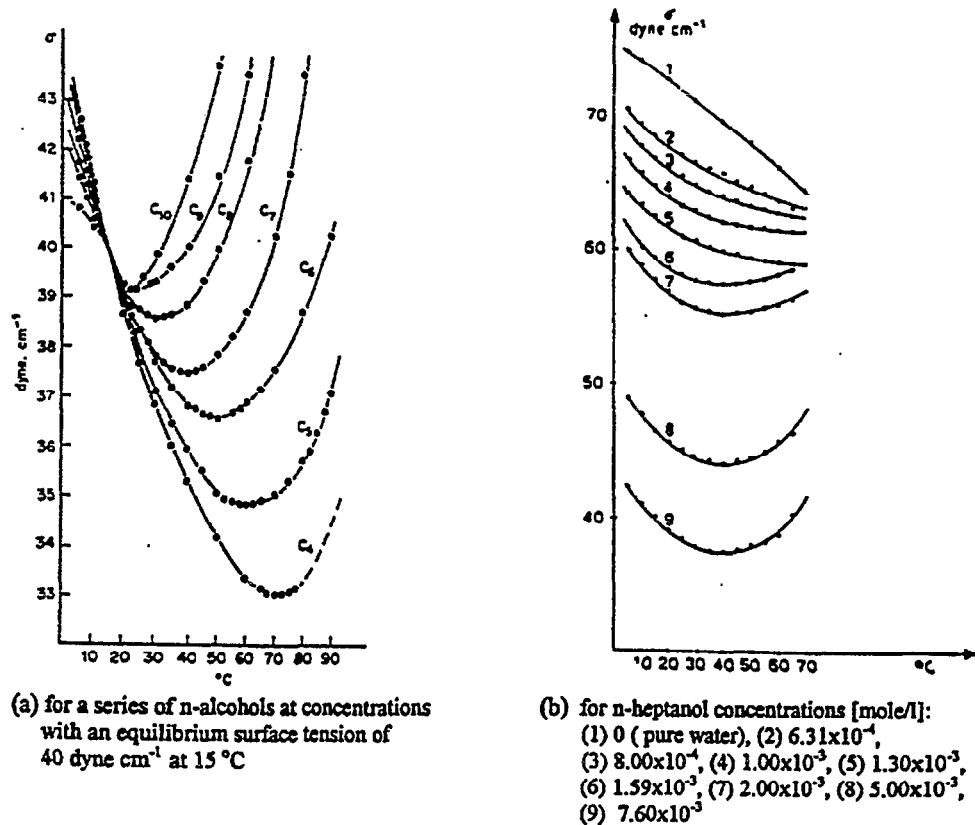


Fig. 2. Variation of the surface tension with temperature for aqueous solutions with long chain alcohols

resulting in an unfavorable situation for boiling performance.

In contrast, aqueous solutions of alcohols with a chain length longer than four carbon atoms have a positive surface tension-temperature gradient when the fluid temperature exceeds a certain value, as shown in Fig. 2 [32]. This surface tension force is assisted by the buoyant force in nucleate boiling on earth, while it becomes the principal driving force for bubble departure from the heating surface in microgravity environments. Consequently, bubble departure size is smaller in these aqueous solutions than in water, with a higher departure frequency.

Note that it requires addition of only a small quantity of the long-chain alcohols, on

the order of 10^{-3} mole per liter, to alter surface tension characteristics of water, without affecting other bulk properties [33]. Another important feature of these aqueous solutions is a very high value of the positive surface tension-temperature gradient when the fluid temperature is near its saturation point, thus inducing considerable driving force for bubble departure.

(i) Nucleate Pool Boiling

Experimental observations of nucleate pool boiling under microgravity conditions revealed that vapor bubbles generated in water tend to stay near the heating surface and to slide or oscillate on the surface being induced by coalescence. Thus, one may interpret the agitation of the thermal

boundary layer as serving as the principal mechanism of heat transfer. It is justifiable to apply Rohsenow's model for nucleate boiling under normal gravity to that in

$$\frac{1}{6} \rho_l g D^3 - \rho_l C_n^{2/n} \left[\frac{3}{2} C_n n^2 + n(n-1) \right] \left(\frac{D}{2} \right)^{2(2n-1)/n} + \frac{1}{2} \xi \frac{d\sigma}{dT} \Delta T_{wb} D - C_n^{2/n} n^2 r^2 \frac{\rho_l^2}{\rho_v} \left(\frac{D}{2} \right)^{2(n-1)/n} = 0 \quad (5)$$

where C_n , ξ , and n are constants which should be experimentally determined, ΔT_{wb} is the temperature difference between the wall and the bulk liquid, and r is the vapor bubble contact radius on the heating surface. As a first approximation, take $\xi=1$, $n=1/2$ and $C_n = 2bJa(\kappa/\pi)^{1/2}$, where b is an empirical constant which is about 0.86 for water under atmospheric conditions, κ is the liquid thermal diffusivity, Ja is the Jakob number, which equals $\rho_l C_{pl}(T_l - T_{sat})/\rho_v h_{fg}$, C_{pl} is the liquid specific heat, T_l is the temperature in the liquid surrounding the departure bubble, and T_{sat} is the liquid saturation temperature.

Rohsenow's model [35] proposes the relationship between the Nusselt number, Nu_b , the Reynolds, Re_b , and Prandtl number, Pr_l , as

$$Nu_b = \frac{hD}{k_l} = A Re_b^{(1-p)} Pr_l^{(1-s)} \quad (6)$$

where h is the heat transfer coefficient which is defined as

$$h = \frac{q}{\Delta T_{sat}(p_l)} \quad (7)$$

Here q is the heat flux while the superheat ΔT_{sat} is a function of the liquid pressure, p_l . The Reynolds number is defined as

$$Re_b = \frac{\rho_v U_b D}{\mu_l} \quad (8)$$

where μ_l is the liquid viscosity. The superficial velocity U_b is defined as

$$U_b = \frac{q}{\rho_v h_{fg}} \quad (9)$$

The quantities A , p , and s in Eq. (6) are empirical constants.

microgravity environments using the bubble departure diameter, D , predicted by Zhang and Chao [34]:

(ii) Critical Heat Flux

Following McGillis and Carey [27], the hydrodynamic model of Zuber [36] is employed to derive a correlation formula for the maximum pool boiling heat flux. The CHF is postulated to occur when the vapor column rising from a heating surface is distorted and blocks the liquid flowing down toward the surface, often referred to as Kelvin-Helmholtz instability [37]. At any instant, the gravitational energy resulting from the body force to return the liquid to the heating surface per unit cell (i.e., divided by the spacing of vapor columns) is given by

$$\Delta \psi_g = (\rho_l - \rho_v) \lambda_D \left(\pi \frac{\lambda_D^2}{16} \right) g \frac{\lambda_D}{2} \quad (10)$$

where λ_D is the spacing between two adjacent Taylor wave nodes defined as $2\pi[3\sigma/(\rho_l - \rho_v)g]^{1/2}$. The surface tension force exerting on the liquid-vapor interface induced by a surface tension-temperature gradient provides additional energy to return the liquid to the heating surface per unit cell of

$$\Delta \psi_\sigma = \zeta \frac{\partial \sigma}{\partial T} \Delta T_{wb} \left(\pi \frac{\lambda_D}{2} \right) \lambda_D \quad (11)$$

where ζ is a correction factor to be determined by experimental data. An addition of Eqs. (10) and (11) yields the total available energy as

$$\Delta \psi = \frac{\pi}{32} (\rho_l - \rho_v) \lambda_D^4 g + \zeta \frac{\pi}{2} \frac{\partial \sigma}{\partial T} \Delta T_{wb} \lambda_D^2 \quad (12)$$

Note that the second term in Eq. (12) was dropped in Zuber's original model. This is justified in pure liquids because of the low surface tension-temperature gradient.

However, this term becomes important in dilute aqueous solutions of long-chain alcohols because of high surface tension-temperature gradients. One obtains the CHF as

$$q_c = q_{C,Zuber} \left(1 + \frac{4}{3\pi^2} \zeta \frac{\partial \sigma}{\partial T} \Delta T_{wb} \right)^{1/4} \quad (13)$$

in which $q_{C,Zuber}$ denotes the Zuber's CHF expressed as

$$q_{C,Zuber} = \frac{\pi}{24} \rho_v h_{fg} \left(\frac{32\sigma\Delta\psi_g}{\pi\lambda_D^4 \rho_v^2} \right)^{1/4} \quad (14)$$

Equation (14) indicates that surface tension force acts to reduce the CHF in a boiling liquid with a negative surface tension-temperature gradient. By contrast, the CHF would be enhanced in liquids with a large positive surface tension-temperature gradient. Both Eqs. (5) and (14) are applicable under microgravity as well as normal gravity conditions. However, the correlation equations for nucleate pool boiling and CHF derived for pure liquids under normal gravity can not be applied in microgravity environments because of the lack of a driving force for bubble departure from the heating surface.

Conclusions

Two means of enhancing nucleate pool boiling and CHF under microgravity conditions have been investigated: Metal-graphite fiber-composite surfaces are suitable as the boiling surface without adverse effects from the reduced gravity. Dilute aqueous solutions of long-chain alcohols can enhance the performance by virtue of high, positive surface tension-temperature gradients useful as a driving force in microgravity environments. The study has achieved two objectives: Utilizing the existing experimental results and a two-tier model, correlation formulas have been derived for nucleate boiling on Cu-Gr and Al-Gr composite surfaces in both the

isolated and coalesced bubble regimes. In addition, correlation equations are obtained for predicting nucleate pool boiling and CHF in diluted aqueous solutions of long-chain alcohols.

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