

Enhancements of Nucleate Boiling and Critical Heat Flux Under Microgravity Conditions

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Two means are presented for enhancing nucleate boiling and critical heat flux under microgravity conditions: using microconfigured metal–graphite composites as the boiling surface and using dilute aqueous solutions of long-chain alcohols as the working fluid. In the former, thermocapillary force induced by the 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 case, 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 conditions. 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.

Nomenclature

A, b	= empirical constants
C	= constant, or concentration, mole/l
C_l	= constant
C_n	= constant
C_p	= specific heat (J/kg K)
C_s	= constant
D	= bubble diameter, m
d	= fiber diameter, m
f	= frequency of microbubbles, 1/s
g	= acceleration due to gravity, m/s ²
h	= heat transfer coefficient, W/m ² · K
h_{fg}	= latent heat of vaporization at boiling point, J/kg
Ja	= Jakob number
k	= thermal conductivity, W/m · K
m	= constant
N	= density of vapor stem, 1/cm ²
Nu	= Nusselt number
n	= constant
n_i	= number of graphite fiber tips in a vapor column
Pr	= Prandtl number
p	= empirical constant, or pressure, N/m ²
q	= heat flux, W/cm ²
Re	= Reynolds number
r	= bubble contact radius on wall surface, m
s	= empirical constant
T	= temperature, °C

T_{sat}	= liquid saturation temperature, °C
U_b	= superficial velocity, m/s
x	= concentration or temperature
α	= area fraction of fibers in base material
ΔT_i	= temperature difference between heating wall surface and interface along macrolayer, °C
ΔT_{sat}	= superheat, °C
ΔT_t	= superheat at transition from isolated to coalesced bubble regime, °C
ΔT_{wb}	= temperature difference between heating wall surface and bulk liquid
$\Delta \psi$	= available energy, N m
δ	= macrolayer thickness, m
ζ	= constant
η	= constant
θ	= contact angle, deg
κ	= liquid thermal diffusivity, m ² /s
λ_d	= Taylor wave node spacing, m
μ	= viscosity, N s/m ²
ξ	= constant
ρ	= density, kg/m ³
σ	= surface tension, N/m

Subscripts

b	= bubble
C	= critical
g	= due to gravity
h	= high heat flux region
i	= interface along macrolayer
j	= number, 1 for concentration, 2 for temperature
l	= low heat flux region or liquid
m	= maximum
sat	= saturation
v	= saturated vapor
w	= wall
Zuber	= given by Zuber model
$\Delta \sigma$	= due to surface-tension gradient
σ	= due to surface tension

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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, for example, those by Keshock and Siegel⁴ and Carey,⁵ have shown that, rather than assisting in the detachment process, surface tension tends to keep the bubbles on the wall and in that way to impede bubble detachment. The surface-tension gradient driven by temperature has been also considered as a force holding the bubbles attached to the wall surface.⁶ 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 relation⁷:

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

According to this correlation, saturated nucleate boiling cannot occur when the gravity approaches zero. Indeed, Zell and Straub⁸ observed that film boiling occurred immediately without the appearance of nucleate boiling when a moderate heat flux (30 kW/m²) 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.,⁹ reported that saturated nucleate boiling was established on a flat plate heater as well as on a thin wire.

Generally, the correlations based on experimental results of 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.^{10,11} As pointed out by Straub et al.,¹⁰ this is not surprising because the gravity is an independent parameter in pool boiling heat transfer, but very few experiments were conducted to prove its influence. The results of pool boiling experiments under reduced gravity ($\sim 10^{-2}$ g) conducted by Abe¹² and Oke et al.¹³ show that the boiling behaviors of organic fluids and of 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 due to the reduction of buoyancy, 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.

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 of 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. Dhir¹⁴ 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 were 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 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.^{12,13}

There are two fundamental approaches to enhancing boiling heat transfer: developing enhanced boiling surfaces and developing new working fluids. Discussion of enhanced boiling surfaces is followed by a discussion of developing new working fluids.

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 and porous boiling surfaces. Webb¹⁵ and Thome^{16,17} 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 a significant decrease, in the CHF value.¹⁸ Recently, O'Connor and You¹⁹ 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 for the unpainted surface and a CHF increase of 109%. They pointed out that the CHF increase is due to surface microstructure and its influence on the boiling heat transfer characteristics. Wright and Gebhart^{20,21} 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.²² 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.²³ They found a plateau in the boiling curve in the CHF regime accompanied by a reduction in the peak heat flux. Yang and Zhang²⁴ divided composite-enhanced surfaces into two categories: discrete insert/matrix-type composites and microconfigured 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.^{18,19,24} 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 on 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 microconfigured composite surfaces, may provide the solution for these problems. 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 3.0–4.6 times that on the pure copper heater surface.²⁵ Compared to other enhanced boiling surfaces, these types of composite surfaces have unique attributes because they do not incur extra pressure drops, have no fouling, and offer

low primary and maintenance costs. It has been found also that the CHF for Cu-Gr composites was extended to higher values compared to a pure cooper surface. The metal-graphite microconfigured composite surfaces were found to have nonisothermal surfaces under boiling conditions.^{25,26} Based on the nonisothermal surface result, a reduced sensitivity of the CHF to superheat variation for the surfaces was predicted by Yang and Zhang.²⁴ Most recently, the authors have suggested a model to predict the CHF on metal-graphite composites.²⁷ However, the nucleate boiling mechanisms on the composite surfaces, especially in the CHF regime, have not been adequately studied.

Recently, many efforts have been made to try to enhance boiling heat transfer through Marangoni effects in fluid mixtures at normal gravity,^{28–30} as well as in microgravity.^{31,32} It was found that a small amount of surface-active additive considerably increases the nucleate boiling heat transfer coefficient of water at normal gravity.^{28,29} 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 Carey³⁰ 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.³¹ tested water-ethanol mixtures of 11.3 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 Carey³² 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 is with the concentration of 2-propanol in the mixture, the higher the CHF is. The experimental results obtained by Abe et al.³¹ and by Ahmed and Carey³² 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 toward 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.³¹ 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

Nucleate Pool Boiling

Experimental studies were performed on nucleate pool boiling of pentane on Cu-Gr and aluminum-graphite (Al-Gr) composite

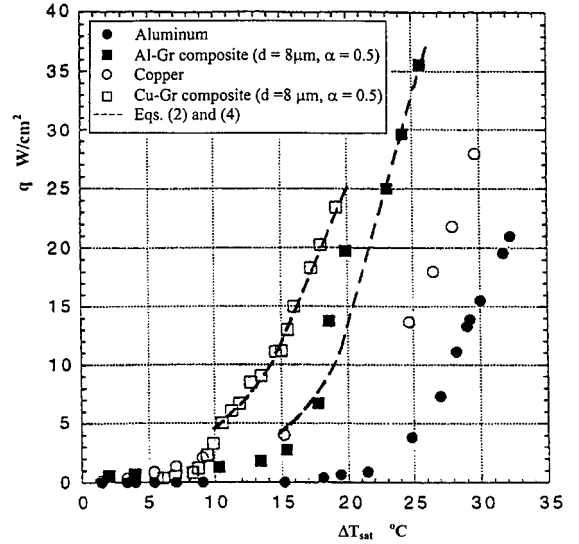


Fig. 1 Pool boiling performances of pentane on different surfaces.

surfaces with various fiber volume concentrations for heat fluxes up to 35 W/cm². It is revealed that a significant enhancement in boiling heat transfer performance on the composite surfaces is achieved,³³ as shown in Fig. 1, due to the presence of micrographite fibers embedded in the matrix. 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. 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,²² 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 microbubbles, with negligible heat conduction across the microlayer, and can be expressed as

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

where 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

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

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

In the high heat flux boiling region (coalesced bubble regime), the boiling heat flux consists of two parts: latent heat transport by microbubbles 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

$$q_h = (\pi D_m^3 / 6) \rho_v h_{fg} C_s (\Delta T_i)^m + k_l C_l (\Delta T_{sat} - \Delta T_i) \quad (4)$$

The first term of Eq. (4) is the maximum value of the heat flux in the isolated bubble regime. The temperature along the macrolayer interface in the coalesced bubble regime was reasonably approximated to the value of the heating surface temperature at the transition from the isolated bubble regime to the coalesced bubble regime, and so $\Delta T_i = T_w - T_i = \Delta T_{sat} - \Delta T_i$. The properties of saturated vapor and liquid of pentane at the boiling point can be found in Ref. 34. The relevant data are as follows: 72.146 mol wt, $t_b = 36.07^\circ\text{C}$, $\rho_v = 0.003002 \text{ kg/m}^3$, $k_l = 0.1086 \text{ W/m} \cdot \text{K}$, and $h_{fg} = 358.09 \text{ kJ/kg}$.

Based on the experimental data for the cases with $d = 8 \mu\text{m}$ and $\alpha = 0.5$, 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 by Eqs. (2) and (4) are also shown in Fig. 1 (dashed 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 microbubbles emitted from the composite surface; the constant C_l is the parameter related to the macrolayer.

CHF

The hydrodynamic model of CHF from the viewpoint of associated available energy proposed by McGills and Carey³⁰ may also be modified to incorporate the effects of the metal-graphite composite surfaces. The unique characteristics of the metal-graphite composite surfaces make it easier for the bubbles to detach from them than from pure-metal surfaces. Because of the poor wetting characteristics of graphite, each new microbubble has a continually extending base and, therefore, is provided with a larger surface-tension force that helps to keep it attached to the tip. As the new bubbles on the fiber tips grow and contact with the microbubbles residing on the metal matrix surface (between the fiber tips), the former attract and finally swallow the latter, pulling them away from the matrix surface, as shown in Figs. 2a and 2b. Hence, the bubbles sit on the tips instead of the matrix surface in the high heat flux regime, with a neck near the tip surface for its large contact angle, $\theta > 90^\circ$, as shown in Fig. 2c. The vapor columns formed at CHF have the same character, with a neck at the foot, as shown in Fig. 2d. The surface tension facilitates the vapor volume detachment through a necking process near the composite surface. Following McGillis and Carey,³⁰ the hydrodynamic model of Zuber³⁵ 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 (see Ref. 36). At any instant, the gravitational energy resulting from the body force to return the liquid to the heating surface per unit cell, that is, divided by the spacing of vapor columns, is given by

$$\Delta\psi_g = (\rho_l - \rho_v)\lambda_d \left[\pi \left(\lambda_d^2 / 16 \right) \right] g (\lambda_d / 2) \quad (5)$$

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 available energy of surface tension

$$\Delta\psi_\sigma = -\eta n_i \sigma \pi d \cos \theta (d/2) \quad (6)$$

should be added to the total available energy where the vapor sat in the vapor column. Substituting the $n_i = (\alpha/4)(\lambda_d/d)^2$ into the Eq.(6), we write $\Delta\psi_\sigma$ as

$$\Delta\psi_\sigma = -\eta \alpha \sigma \left(\pi \lambda_d^2 / 8 \right) \cos \theta \quad (7)$$

Additionally, as analyzed by Zhang and Chao,³⁷ the available energy associated with the Marangoni flow driven by surface-tension gradient

$$\Delta\psi_{\Delta\sigma} = \zeta \frac{\partial \sigma}{\partial T} \Delta T_{wb} \left(\pi \frac{\lambda_d}{2} \right) \lambda_d \quad (8)$$

should be also counted in the total available energy. Therefore, the total available energy is

$$\Delta\psi = \frac{\pi}{32} (\rho_l - \rho_v) \lambda_d^4 g + \zeta \frac{\pi}{2} \frac{\partial \sigma}{\partial T} \Delta T_{wb} \lambda_d^2 - \eta \alpha \sigma \pi \cos \theta \frac{\lambda_d^2}{8} \quad (9)$$

The second term of the right-hand side of Eq. (9) is unfavorable to the CHF when normal pure liquids are used as the working fluid: They have negative surface-tension gradients with temperature. Usually, this can be ignored in pure liquids because of the small value of the surface-tension gradient on the liquid-vapor interface. However, when dilute aqueous solutions of long-chain alcohols, which have an unusual Marangoni effect, are used as the working fluid, this term becomes a considerably larger positive value and, therefore, enhances the CHF. According to Zuber's model, the CHF is given by

$$q_{C,Zuber} = \frac{\pi}{24} \rho_v h_{fg} \left(\frac{32\sigma \Delta\psi_g}{\pi \lambda_d^4 \rho_v^2} \right)^{\frac{1}{4}} \quad (10)$$

where $\Delta\psi_g$ is the available gravitational energy that equals the first term of the right side of Eq. (9). Replacement of $\Delta\psi_g$ by $\Delta\psi$ in Eq. (10) yields

$$q_C = q_{C,Zuber} \left(1 + \frac{4}{3\pi^2 \sigma} \zeta \frac{\partial \sigma}{\partial T} \Delta T_{wb} - \frac{\eta \alpha \cos \theta}{3\pi^2} \right)^{\frac{1}{4}} \quad (11)$$

Based on the experimental results, all boiling curves will congregate at the critical point of a particular graphite-fiber concentration

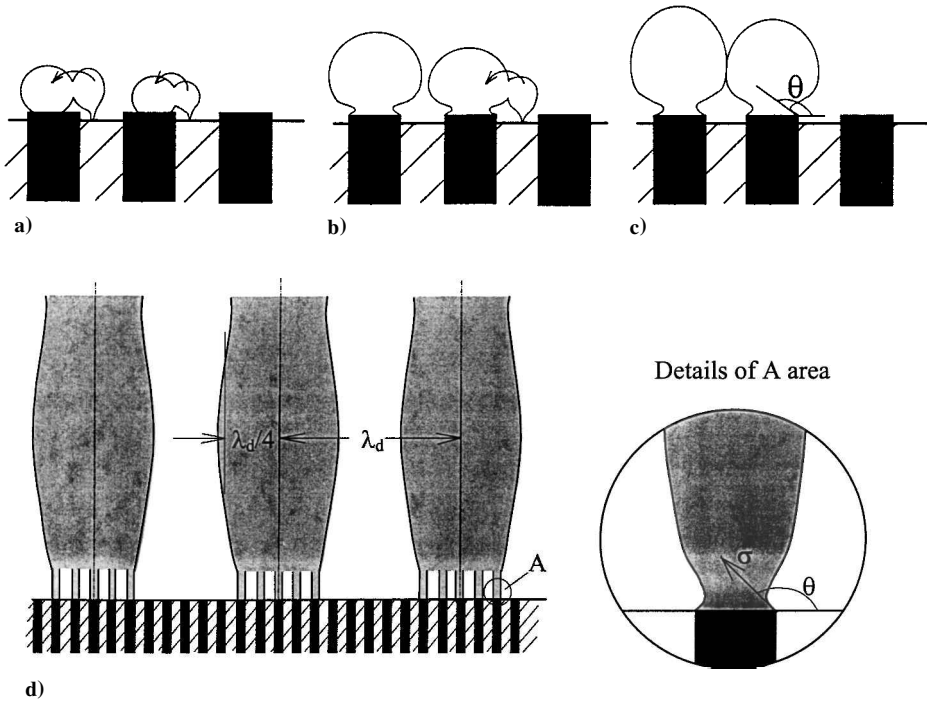


Fig. 2 Vapor columns in CHF.

$\alpha_c = \frac{1}{4}$ as mentioned earlier, and, therefore, for the metal-graphite composite surface the CHF is given by

$$q_c = q_{c,Zuber} \left(1 + \frac{4}{3\pi^2\sigma} \zeta \frac{\partial \sigma}{\partial T} \Delta T_{wb} - \frac{\eta \cos \theta}{12\pi^2} \right)^{\frac{1}{4}} \quad (12)$$

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 will not deteriorate with reduced gravity. Undoubtedly, this kind of material is suitable to 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. Its major shortcoming under microgravity is its significant deterioration in nucleate boiling performance and CHF with a decrease in gravity.³⁸ 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, 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. 3 (Ref. 39). This surface-tension force is assisted by the buoyant force in nucleate boiling on Earth, where as it would become the principal driving force for bubble departure from the heating surface in microgravity environments. Consequently, bubble departure size would be 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/l, to alter surface tension characteristics of water without affecting other bulk properties.⁴⁰ 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.

Nucleate Pool Boiling

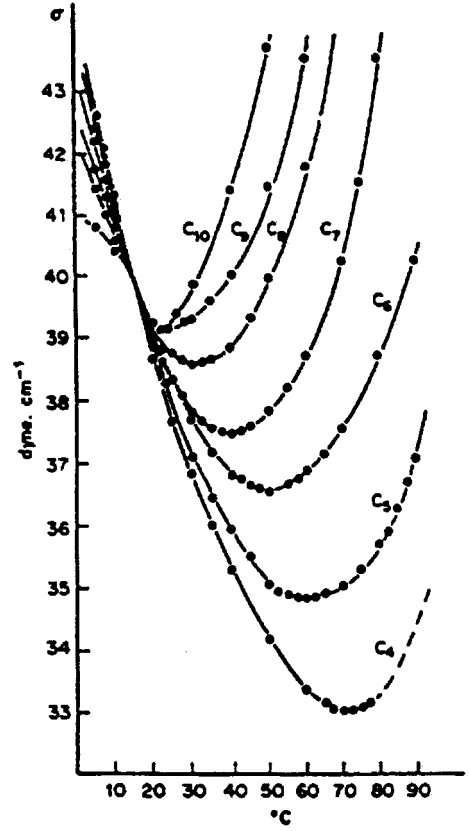
Experimental observations of nucleate pool boiling under microgravity conditions revealed that the boiling behavior of water is characterized by vertical motions of coalescing bubbles.^{13,41} This could greatly increase the turbulence induced near the surface and aid in promoting a high heat transfer coefficient.⁴¹ Therefore, it is justifiable to apply Rohsenow's model for nucleate boiling under normal gravity to that in microgravity environments using the bubble departure diameter predicted by Zhang and Chao³⁷ with consideration of the Marangoni force produced by the liquid concentration gradient along the interface of the bubble:

$$\begin{aligned} \frac{1}{6} \rho_l g D^3 - \rho_l C_n^{2/n} \left[\frac{3}{2} C_n n^2 + n(n-1) \right] \left(\frac{D}{2} \right)^{2(2n-1)/n} \\ + \frac{D}{2} \sum_{j=1,2} \left(\xi_j \frac{d\sigma}{dx_j} \Delta x_{j,wb} \right) - C_n^{2/n} n^2 r^2 \frac{\rho_l^2}{\rho_v} \left(\frac{D}{2} \right)^{2(n-1)/n} = 0 \end{aligned} \quad (13)$$

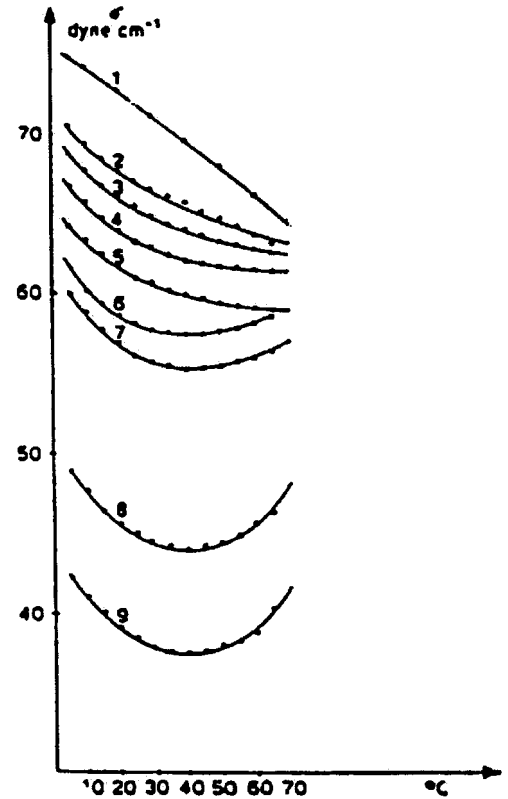
As a first approximation, take $\xi_j = 1$, $n = \frac{1}{2}$, and $C_n = 2bJa(\kappa/\pi)^{\frac{1}{2}}$, where b is an empirical constant, which is about 0.86 for water under atmospheric conditions, κ is the liquid thermal diffusivity, and Jakob number $Ja = \rho_l C_{pl}(T_l - T_{sat})/\rho_v h_{fg}$.

Rohsenow's model (see Ref. 5) proposes the relationship between the Nusselt number Nu_b , the Reynolds number Re_b , and the Prandtl number Pr_l as

$$Nu_b = hD/k_l = AR e_b^{(1-p)} Pr_l^{(1-s)} \quad (14)$$



a) For a series of n -alcohols at concentrations with an equilibrium surface tension of 40 dyne cm^{-1} at 15°C



b) For n -heptanol concentrations [mole/l]: 1) 0 (pure water), 2) 6.31×10^{-4} , 3) 8.00×10^{-4} , 4) 1.00×10^{-3} , 5) 1.30×10^{-3} , 6) 1.59×10^{-3} , 7) 2.00×10^{-3} , 8) 5.00×10^{-3} , 9) 7.60×10^{-3}

Fig. 3 Variation of the surface tension with temperature for aqueous solutions with long-chain alcohols.

where h is the heat transfer coefficient, which is defined as

$$h = q / \Delta T_{\text{sat}}(p_l) \quad (15)$$

where ΔT_{sat} is a function of the liquid pressure p_l . The Reynolds number is defined as

$$Re_b = \rho_v U_b D / \mu_l \quad (16)$$

The superficial velocity U_b is defined as

$$U_b = q / \rho_v h_{fg} \quad (17)$$

CHF

As already mentioned, 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. There are two kinds of energy acting to return the liquid to the heating surface per unit cell: One is the gravitational energy resulting from the body force, and the other is the surface-tension energy exerting on the liquid-vapor interface induced by surface-tension-concentration gradient and surface-tension-temperature gradient. The latter is

$$\Delta\psi_{\Delta\sigma} = \sum_{j=1,2} \zeta_j \frac{\partial\sigma}{\partial x_j} \Delta x_{j,wb} \left(\pi \frac{\lambda_d}{2} \right) \lambda_d \quad (18)$$

where x_1 stands for C and x_2 stands for T . Hence, the total available energy is

$$\Delta\psi = \frac{\pi}{32} (\rho_l - \rho_v) \lambda_d^4 g + \sum_{j=1,2} \zeta_j \frac{\pi}{2} \frac{\partial\sigma}{\partial x_j} \Delta x_{j,wb} \lambda_d^2 \quad (19)$$

Note that only the first term in Eq. (19) appears in Zuber's original model. This is justified in pure liquids because of no concentration gradient and the low surface-tension-temperature gradient. However, both surface-tension-concentration gradient and surface-tension-temperature gradient become important in dilute aqueous solutions of long-chain alcohols. One obtains the CHF as

$$q_C = q_{C,\text{Zuber}} \left[1 + \frac{4}{3\pi^2\sigma} \left(\zeta_1 \frac{\partial\sigma}{\partial C} \Delta C_{wb} + \zeta_2 \frac{\partial\sigma}{\partial T} \Delta T_{wb} \right) \right]^{\frac{1}{4}} \quad (20)$$

Equation (20) indicates that surface-tension force induced by temperature gradient 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. (13) and (20) would be 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 would be 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 both surface-tension-concentration gradient and high, positive surface-tension-temperature gradient useful as driving forces in microgravity environments. The study has achieved two objectives: When the existing experimental results and a two-tier model are used, correlation formulas have been derived for nucleate boiling on Cu-Gr and Al-Gr composite surfaces in nucleate boiling, including both the isolated and coalesced bubble regimes. In addition, a correlation equation is obtained for predicting CHF. Correlation equations are also obtained for predicting nucleate pool boiling and CHF in diluted aqueous solutions of long-chain alcohols.

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