Available online at www.sciencedirect.com
SCIENCE DIRECT®
International Journal of Heat and Mass Transfer 47 (2004) 5417–5426
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Marangoni effects on the boiling of 2-propanol/water mixtures in a confined space

Chen-li. Sun [a,*], Van P. Carey [b]

[a] Department of Mechanical Engineering, National Taiwan University of Science and Technology, 43 Sec., 4 Keelung Rd., Taipei 106, Taiwan
[b] Department of Mechanical Engineering, University of California, Berkeley, CA, USA

Received 5 March 2004; received in revised form 14 July 2004
Available online 16 September 2004

Abstract

In this study, boiling experiments were conducted with 2-propanol/water mixtures in a confined gap under various gravity levels to examine the Marangoni effects on near-bubble microscale transport. Full boiling curves were obtained and two boiling regimes determined—nucleate and pseudo film boiling. The transition condition and the critical heat flux were also identified. Relative to pool boiling, the gap geometry caused lower CHF values, and deteriorated heat transfer at high superheated temperatures. This influence was particularly significant when greater Marangoni forces were present under reduced gravity conditions. The results of this study demonstrate the complex interaction that these three factors—Marangoni force, gravity level, and gap size—have on heat transfer.

Keywords: Marangoni effects; Microgravity; Boiling; Confined space

1. Introduction

Pool boiling has long played a significant role in many technological applications due to its superior heat transfer performance. The complexities encountered in the boiling process have stimulated numerous investigators to conduct extensive research in this field. Straub [1] proposed the microwedge model as the primary heat transfer mechanism in nucleate boiling, which depicted that the majority of phase transition took place by evaporation of a very thin microlayer between the vapor bubble and the heated surface. In addition, he referred to the shear forces (caused by the bubble dynamics), thermocapillary convection and other methods that provided mass transport of latent energy as secondary transfer mechanisms. Hence, several researchers have studied the impacts of the secondary mechanisms on boiling, seeking alternative methods of heat transfer enhancement. For example, Kweon and Kim [2] have demonstrated that the presence of an electric field altered the bubble behavior and significantly enhanced the heat transfer in nucleate boiling due to the electrohydrodynamic (EHD) effects. On the other hand, the results by McGillis [3] indicated that concentration-induced Marangoni effects can greatly alter the characteristics of heat transfer in pool boiling, providing the potential to improve the performance of the system by using a binary mixture coolant.

* Corresponding author. Tel.: +886 2 2737 6452; fax: +886 2737 6460.
E-mail address: clsun@mail.ntust.edu.tw (C.-li. Sun).

0017-9310/$ - see front matter
doi:10.1016/j.ijheatmasstransfer.2004.07.014

Nomenclature

a system acceleration in vertical direction, m/s^2
Bo Bond number, $\sqrt{\frac{gL^2(\rho_l-\rho_v)}{\sigma}}$
c_m empirical constant in Eq. (5)
F mass diffusion factor as defined in Eq. (7)
F_D diffusion-induced suppression factor in Eq. (4)
g earth's gravitational acceleration, $9.8\,m/s^2$
L width of the gap (distance between heated surface and cold surface), m
Ma Marangoni number in Eq. (6), $\frac{\Delta\sigma}{\rho_l v_l^2}\left[\frac{\sigma}{g(\rho_l-\rho_v)}\right]^{\frac{1}{2}}Pr$
P pressure, kPa
Pr Prandtl number, $C_p\mu/k$
q'' heat flux, W/m^2
ΔT_{bp} temperature difference between the dew point and the bubble point, $T_d - T_{bp}$
ΔT_c subcooled temperature, $T_{bp} - T_c$
ΔT_h superheated temperature, $T_h - T_{bp}$
T_c cold plate surface temperature
T_h heated plate surface temperature
x liquid molar fraction of the more volatile component
y vapor molar fraction of the more volatile component

Greek symbols
α heat transfer coefficient, W/m^2
ρ density, kg/m^3
σ surface tension, N/m

Subscripts
b bulk
bp bubble point
CHF critical heat flux
d dew point
id ideal
l liquid
max maximum
min minimum
t thermocapillary
v vapor
x concentration-induced

The Marangoni effect of interest here is the liquid flow induced by the interfacial tension gradient that results from the depletion of the more volatile component of a binary mixture near the heated surface during the boiling process. For what are termed positive mixtures, the surface tension of the more volatile component is smaller than that of the less volatile component. The Marangoni forces tend to draw liquid toward the heated surface, resulting in a flow opposite to the thermocapillary convection for an upward facing heater. By conducting boiling experiments in microgravity, Ahmed [4] and Abe et al. [5] were able to study boiling phenomena that were not influenced by external body forces, and provided the opportunity to distinguish Marangoni forces from buoyancy effects in binary mixtures. Ahmed [4] found that Marangoni effects successfully sustained the pool boiling process for positive mixtures and achieved an equivalent critical heat flux (CHF) at microgravity, contrary to the deterioration of heat transfer for single component fluids observed by Oka et al. [6]. This suggested that the Marangoni effects became dominant under reduced gravity, and provided a means to improve heat transport performance in aerospace applications.

Nevertheless, the aforementioned research was limited to the pool boiling phenomena. The Marangoni effects on boiling in a confined space remained unknown, regardless of the fact that it is associated with a wide range of practical applications in many fields, including large-scale heat exchangers, micromixers (Evans et al. [7]) in bioengineering, bubble pumps (Lin et al. [8], Tsai and Lin [9]) in microelectromechanical systems (MEMS), and inkjet printheads (Finke [10]). One of the earliest studies on boiling in confined spaces was done by Ishibashi and Nishikawa [11]. They conducted extensive experiments of boiling in vertical annuli and found that the confined geometry repressed the microlayer underneath the vapor bubble, resulting in the enhancement of heat transfer at low superheat levels. Later, this augmentation effect on heat transfer was also confirmed for horizontal confined geometry by Katto et al. [12]. However, they found that the heat transfer deteriorated at higher superheat levels because of dryout patches on the heated surface caused by bubble coalescence in the gap geometry. To distinguish these two different characteristics, Yao and Chang [13] proposed a modified Bond number, which represents the ratio of the gap size to the departure diameter of the bubble, in order to identify two boiling regimes corresponding to these opposite heat transfer features.

The experiments in this study were performed in order to closely examine the impact of a constrained space configuration on the Marangoni force effects during the boiling process of 2-propanol/water mixtures. In the experimental apparatus, a horizontal cold surface was added above the heated surface in parallel to form a confined gap ranging from 3.2 to 12.7 mm. The temperature gradient across the gap resulted in evaporation over the portion of the vapor–liquid interface near the heated surface, and condensation near the cold surface. This mass transport phenomenon inside the vapor bubble produced the heat pipe effect. Since the confining walls restricted the bubble motion, it also helped to eliminate other heat transfer mechanisms that are caused by the momentum transfer associated with bubble dynamics.

The system pressure in the test section was maintained at subatmospheric levels (5.54–9.42 kPa) throughout the experiments, with the bulk liquid temperature varying from slightly subcooled to near saturation. The subcooling $T_{bp} - T_c$ ranged from 10 to 30 K. 2-propanol/water mixtures were chosen as the test fluids due to the highly nonlinear dependency of their surface tensions on concentration in the low concentration range. The molar fractions of 2-propanol, x, used for this study were 0 (distilled water), 0.015, and 0.025. The surface tension gradient was at its maximum for $x = 0.015$, and was associated with the greatest Marangoni forces among the tested concentrations. Boiling experiments at the low and high gravity levels were conducted aboard NASA's modified KC-135A aircraft. By conducting the experiments under low gravity conditions, direct observation of the effects of the Marangoni forces on transport was possible without the presence of the obscuring buoyancy forces.

2. Experimental setup

The schematic of the experimental test system is depicted in Fig. 1(a). The apparatus was composed of the test section, the copper heater element, the condenser with the cooling circuits, the charging circuits and the vacuum system.

The test section was a 304.8 mm long, 76.2 mm × 76.2 mm square channel made of stainless steel (as shown in Fig. 1(b)), with the heater holding flange and condenser installed. The heated surface element consisted of a stainless steel holding flange and a copper element to accommodate the two electric cartridge heaters. Five T-type thermocouples with a 6.4 mm pitch were embedded along the subsurface portion of the copper element, which had a diameter of 12.7 mm. The nearest thermocouple was 2.2 mm from the top face of the cylinder, which made it possible to estimate the heated surface temperature with a total uncertainty of 3.3 K. The cartridge heaters were connected to a variable voltage controller that was capable of adjusting the power input during the boiling experiments. To reduce undesired heat loss, a fiberglass sheet was wrapped around the copper element to serve as thermal insulation. The copper element was silver soldered to the stainless steel holding flange with minimum joint area to virtually eliminate radial heat conduction. The total uncertainty of the heat flux calculated from the least-square fit of the five temperature measurements was determined to be 7.2% including the heat loss.

The copper condenser was bolted to the bottom wall of the test section to form the gap geometry. In addition, the use of the replacement plate created the flexibility of altering the size of the gap geometry. Initially, the presence of the condenser formed a default 12.7 mm gap without any replacement plate. To examine the influence of the gap geometry, a clamping suspension support was designed to attach an extra plate to the condenser. By attaching a 6.4 mm or 9.5 mm thick copper plate to the condenser, the gap between the heater surface and the condenser became either 6.4 mm or 3.2 mm, respectively. Inside the condenser, the coolant falling from the inlet impinged vertically on the center of the cavity and then discharged in the radial directions through guided fins. Cold water, which was used as the coolant in the condenser, was circulated from the reservoir tank to the condenser by a centrifugal pump. The temperature of the cold water was kept at 0 °C in the reservoir. The flow rate of the coolant was controlled by a variable voltage controller and the bypass valve. Two T-type thermocouples were attached to the inlet and outlet sections of the cooling circuits near the condenser. The cold plate temperature was then evaluated by taking the average of these two measurements. In addition, the bulk liquid temperature inside the test section was measured by a long thermocouple probe. The total uncertainties of the subcooled temperature and the bulk temperature were estimated to be 2.9 K and 1 K, respectively. Prior to each experiment, the test section was connected to the Vacu/Trol water-driven aspirator in order to produce the desired subatmospheric pressure in the system. The working fluid was boiled at low pressure for several minutes to reduce dissolved gas. The raw measurements of temperature, pressure and acceleration data were taken and recorded by a PC-based data acquisition system with a scanning frequency of 2.5 Hz. The test system, along with its support structure, was mounted on one NASA instrument rack, while the desktop computer, data acquisition system and two variable voltage controllers were mounted onto a similar rack.

The reduced and high gravity experiments were carried out aboard a KC-135A aircraft at the NASA Glenn Research Center. The specially modified Boeing KC-135A turbo jet performed a series of parabolic maneuvers that resulted in short periods of reduced gravitational acceleration during the in-flight falls, and high gravitational acceleration during the climbs. All the 1 g experiments were conducted in the Multiphase Transport Laboratory at the University of California, Berkeley.

The overall uncertainties for the molar fraction and system pressure were estimated to be 6.7% and 8.4%, respectively. The overall uncertainty of the built-in

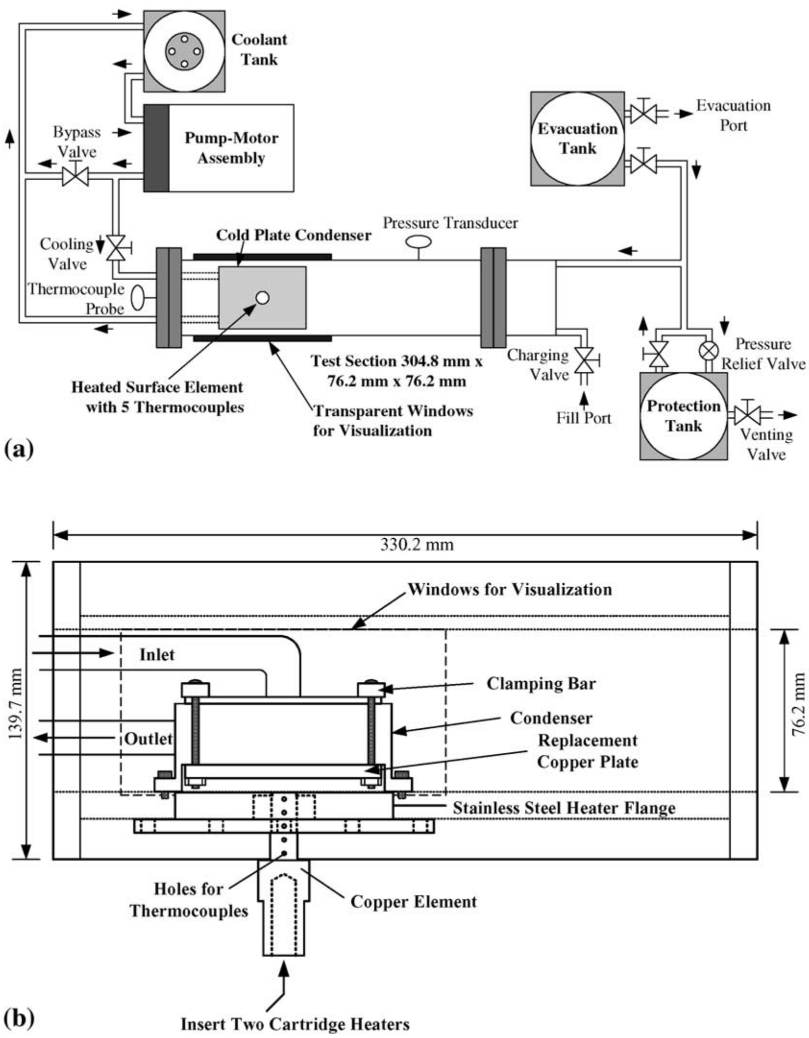

Fig. 1. (a) Schematic diagram of the experimental system, and (b) test section with the condenser and the heater element installed.

accelerometer in the KC-135A was roughly estimated to be 0.007 g. Physical properties of the 2-propanol/water mixtures were evaluated based on the methods and information provided by Poling et al. [14], McGillis [3], and Daubert and Danner [15]. And the overall uncertainty of the computed bubble point temperature was estimated to be 1%.

3. Results

Though it was found that the results with the gap constraint did not resemble the classical pool boiling curve, the observed boiling phenomena could still be classified into two different regimes similar to pool boiling. At low superheat levels, small bubbles grew from active nucleation sites on the heated surface, and were then released before growing to larger size and condensing in the subcooled bulk liquid. This is categorized as the nucleate boiling regime. Increasing the input heat flux caused the small bubbles to coalesce, and then to grow into a large, wavy vapor bubble. The resulting vapor bubble was trapped in the parallel-plate gap and began to blanket the heater surface, ultimately leading to the critical heat flux (CHF) condition. Beyond CHF, the heat flux decreased gradually with a rapid increase in the superheated temperature due to the low thermal conductivity of the vapor blanket that covered the heated surface. Under such conditions, nucleation only occurred at the perimeter of the bubble base, resulting dry patches on the heated surface. This was defined as the ‘‘pseudo film boiling’’ regime in this investigation.

The phase equilibrium diagram and surface tension vs. molar fraction for 2-propanol/water mixtures are

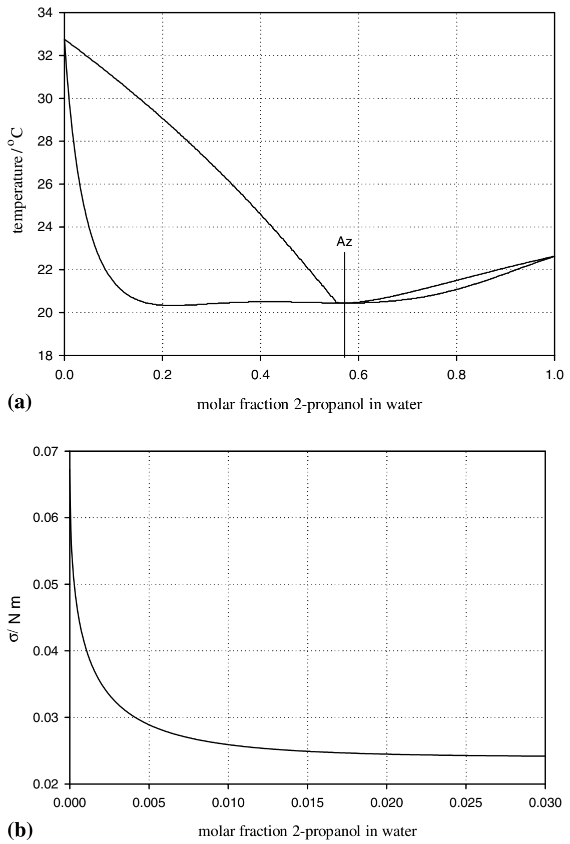

Fig. 2. (a) Phase equilibrium diagram, and (b) surface tension vs. concentration, for 2-propanol/water mixtures at bubble point temperature, $P = 5\,\text{kPa}$.

shown in Fig. 2(a) and (b). During the boiling process, the concentration gradient created a surface tension difference along the bubble interface, a phenomenon referred to as the concentration-induced Marangoni effect. For positive mixtures like 2-propanol/water mixtures, where the more volatile liquid has lower surface tension, the surface tension gradient tends to draw liquids toward the heated surface and separates bubbles. On the other hand, the thermocapillary effect creates opposite influences for 2-propanol/water mixtures. Cold region results in lower surface tension on the interface that pulls liquids toward the cold plate. The comparison of the concentration-induced Marangoni effect and the thermocapillary effect was evaluated by the corresponding differences of the surface tensions $\Delta\sigma_t/\Delta\sigma_x$:

$$\frac{\Delta\sigma_t}{\Delta\sigma_x} = \frac{(\partial\sigma/\partial T)_x(T_{\max} - T_{\min})}{(\partial\sigma/\partial x)_T(x_{\max} - x_{\min})} \tag{1}$$

where $T_{\max}$ and $T_{\min}$ were the maximum and minimum temperature on the liquid–vapor interface, and $x_{\max}$ and $x_{\min}$ were the maximum and minimum liquid concentration of 2-propanol on the interface. The value of $\Delta\sigma_t/\Delta\sigma_x$ was estimated to be in the order of 10^{-4} at our test conditions due to the steep surface tension gradient for $x < 0.01$. This indicated the thermocapillary effects were proportionally small. Apparently, the addition of a small amount of 2-propanol into the water inhibited coalescence of small embryos into larger bubbles, reduced dry-out on the heated surface, and delayed the CHF condition.

The boiling curves for $x = 0$ and $x = 0.015$ at terrestrial gravity are shown in Fig. 3(a). By facilitating nucleate boiling with minimal coalescence, the 2-propanal/water mixtures were able to deliver high heat flux at small superheat levels. On the other hand, the strong surface tension of the distilled water ($x = 0$) resulted in the retention of a stable bubble in the gap. This led directly to partial dryout (pseudo film boiling), and resulted in poor heat transfer. The maximum heat flux for distilled water was only about $2 \times 10^5\,\text{W/m}^2$, while the CHF for the $x = 0.015$ mixture exceeded $10^6\,\text{W/m}^2$. In the pseudo film boiling regime, the addition of 2-propanol was observed to cause waves on the vapor–liquid interface. This disturbance might evoke a mixing effect near the interface which augments the heat transfer. For $\Delta T_h < 50\,\text{K}$, the heat transfer coefficient for $x = 0.015$ was 4–6 times of that of $x = 0$. However, this augmentation quickly diminished with an increase in superheat levels beyond 50 K. The heat transfer coefficient for $x = 0.015$ decreased to 6000–7000 $\text{W/m}^2\,\text{K}$ when ΔT_h exceeded 100 K. This suggests that although the Marangoni effect proved to enhance heat transfer below $\Delta T_h = 50\,\text{K}$, the effect was less important at higher superheated temperatures under normal gravity.

Similar phenomena were observed under reduced gravity conditions, as shown in Fig. 3(b). Bubbles were stabilized to stay in the gap and fluctuated slowly for $x = 0$, 0.015, and 0.025 in the pseudo film boiling regime. For distilled water, the top portion of the bubble did not reach the cold plate and demonstrated less instability. The boiling curves in the nucleate boiling regime for $x = 0.015$ and 0.025 showed a trend that resembled the pool boiling (no gap) results of Ahmed [4] under corresponding conditions. Nevertheless, the CHF condition for $x = 0.015$ with a 6.4 mm gap was reached at a lower superheated temperature ($\Delta T_h = 22\,\text{K}$) compared to $\Delta T_h = 33\,\text{K}$ for $x = 0.025$. The value of the CHF for $x = 0.015$ was also found to be about 65.2% lower than the CHF for $x = 0.025$. However, Ahmed [4] found that the CHF for $x = 0.015$ was enhanced by 25% more than the CHF for $x = 0.025$ for pool boiling at microgravity. This revealed that the CHF characteristics with the gap geometry differed from the pool boiling results. Moreover, the heat transfer for $x = 0.025$ was found to be always greater than that for $x = 0.015$ in the pseudo film boiling regime under reduced gravity. This showed that with the presence of the gap geometry, the weaker

Marangoni effects ($x = 0.025$) actually corresponded to the better heat transfer performance at higher superheat levels under reduced gravity. For $\Delta T_h > 40\,K$, the heat transfer rate for $x = 0.015$ was even poorer than distilled water.

Under high gravity ($a/g = 1.466$–1.891), the buoyancy was so strong that it overpowered the Marangoni effect on heat transfer. Bubbles were highly unstable for all three tested concentration and remained in the nucleate boiling regime for $x = 0$ and 0.015. According to Fig. 3(c), distilled water reached the same level of heat flux at smallest superheat. This resulted in greater heat transfer coefficient for distilled water than that of any other tested concentration of the 2-propanol/watrer mixtures. Since the Marangoni forces acted in the opposite direction to the buoyancy, the heat transfer performance was the poorest for $x = 0.015$, which corresponded to the greatest surface gradient. There was no CHF reached for $x = 0$ and 0.015, they remained in the nucleate boiling regime throughout the tests. The only CHF observed under high gravity was $1.5 \times 10^6\ W/m^2$ for $x = 0.025$. In the pseudo film boiling regime, the heat transfer coefficient for $x = 0.025$ diminished from $31{,}400\,W/m^2\,K$ at $\Delta T_h = 47\,K$ to $12{,}900\,W/m^2\,K$ at $\Delta T_h = 96\,K$.

4. Discussions

Pool boiling correlations of binary mixtures based on different postulates of the mass transfer resistance were compared with our experimental results to access their usefulness for boiling in a gap geometry. For heat transfer in nucleate pool boiling, Stephan and Korner [16] used $|y_b - x_b|$as the key factor and proposed:

$$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + A \mid y_b - x_b \mid} \tag{2}$$

where $\alpha_{id} = q''/\Delta T_{h,id}$ is the ideal heat transfer coefficient of the binary mixtures, $\Delta T_{h,id}$ is the molar fraction

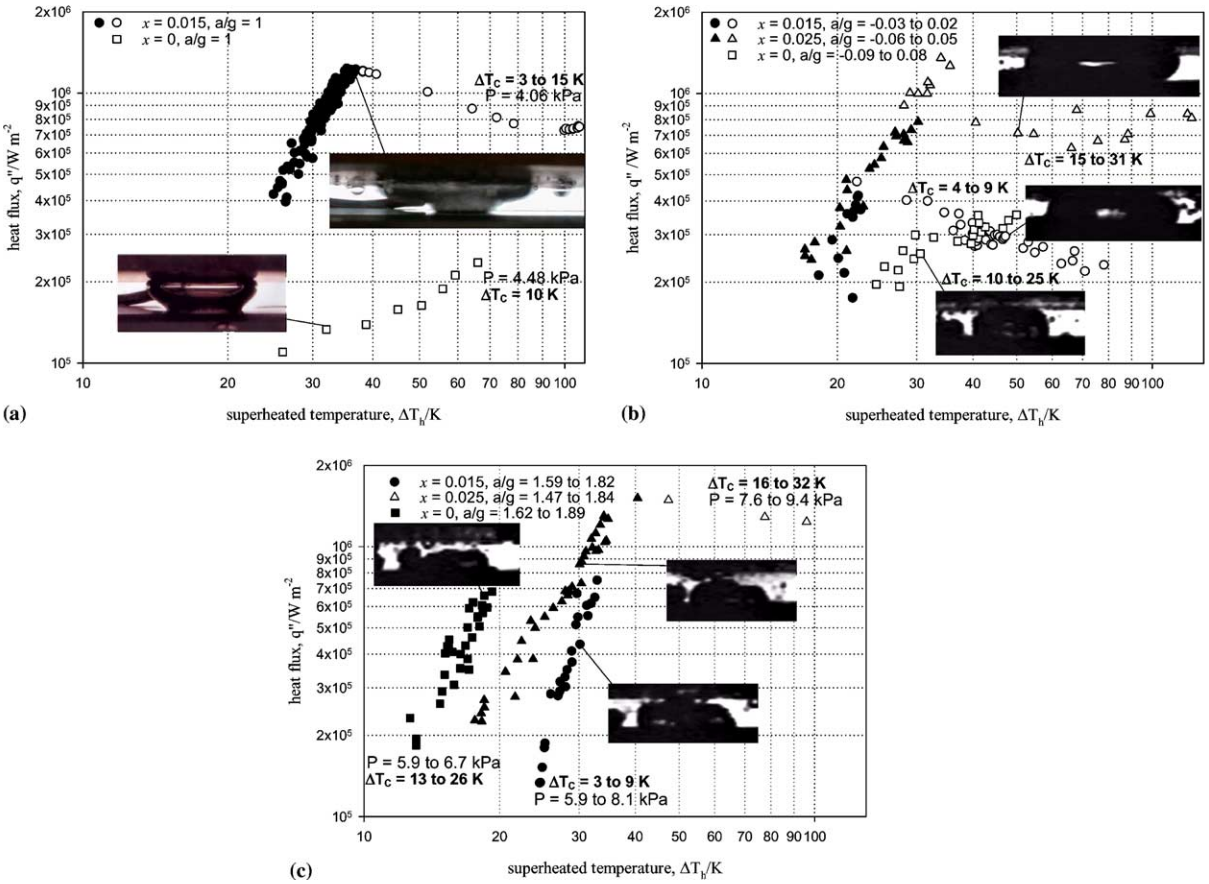

Fig. 3. Comparison of boiling curves for 2-propanol/water mixtures and distilled water ($x = 0$), $L = 6.4\,mm$, (a) under normal gravity, (b) under reduced gravity, and (c) under high gravity. Solid symbols represent nucleate boiling regime, while open symbols represent pseudo film boiling regime.

weighted average of the pure fluid superheats, and A is a parameter that depends on the fluid type and pressure. Fujita et al. [17] suggested an empirical correlation for nucleate pool boiling that employed the boiling range, ΔT_{bp}, for the mass diffusion effect:

$$\frac{\alpha}{\alpha_{\mathrm{id}}}=\frac{1}{1+\left[1-\exp\left(-2.8\frac{\Delta T_{\mathrm{h,id}}}{T_{\mathrm{bp},2}-T_{\mathrm{bp},1}}\right)\right]\left(\frac{\Delta T_{\mathrm{bp}}}{\Delta T_{\mathrm{h,id}}}\right)} \quad (3)$$

Instead of the empirical approach, Kandlikar [18] presented a theoretical analysis to model the mixing effect on nucleate pool boiling heat transfer of binary mixtures. He introduced a pseudo-single component heat transfer coefficient, α_{psc} by applying the averaged mixture properties to the Stephan and Abdelsalam [19] correlation. The mass diffusion resistance at the bubble interface was taken into account by the diffusion-induced suppression factor F_{D}. Hence, the heat transfer coefficient could be expressed as:

$$\alpha=\alpha_{\mathrm{psc}}F_{\mathrm{D}} \quad (4)$$

The comparison of these three correlations and the experimental results is depicted in Fig. 4. It was found that the above correlations underestimated the experimental values by over 30%.

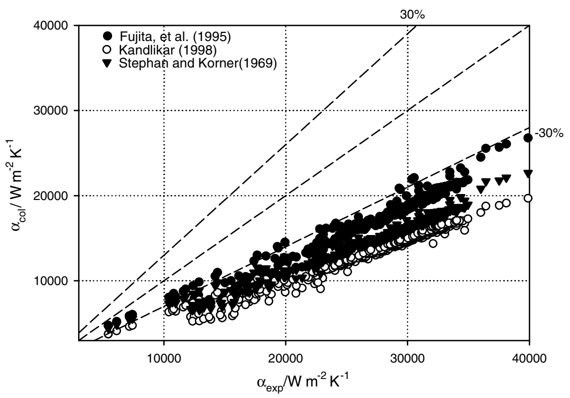

Fig. 4. Comparison of correlations and experimental data for heat transfer coefficients of 2-propanol/water mixtures in nucleate boiling, $L = 6.4\,\mathrm{mm}$, $a/g = 1$, -0.06 to 0.05, and 1.62–1.89, $\Delta T_{\mathrm{c}} = 3$–$32\,\mathrm{K}$.

To evaluate the CHF of binary mixtures in pool boiling, McGillis [3] used the surface tension difference corresponding to different molar fractions at the liquid–vapor interface to calculate the Marangoni forces and suggested:

$$q''_{\mathrm{CHF,MC}}=q''_{\mathrm{CHF,Zuber}}\left[1+c_m\left(\frac{1}{\sigma}\right)\frac{\partial\sigma}{\partial x}(y_{\mathrm{b}}-x_{\mathrm{b}})\right]^{\frac{1}{4}} \quad (5)$$

Fujita et al. [20] also incorporated the Marangoni effect into their empirical correlation and proposed:

$$q''_{\mathrm{CHF,Fujita}}=q''_{\mathrm{CHF,Zuber}}\left(1+4.18\times10^{-4}\frac{|Ma|^{1.68}}{Ma}\right) \quad (6)$$

where Ma is the Marangoni number defined as $Ma=\frac{\Delta\sigma}{\rho_1 v_1^2}\left[\frac{\sigma}{g(\rho_1-\rho_{\mathrm{v}})}\right]^{\frac{1}{2}}Pr$ in their investigation. The value of $q''_{\mathrm{CHF,Zuber}}$ in Eqs. (5) and (6) was evaluated by using molar-weighted properties in the Lienhard and Dhir [21] correlation. The CHF values calculated by the correlations, Eqs. (5) and (6), and those found empirically are listed in Table 1. The correlations underpredicted the experiment by 14.0–81.8%. In addition, the molar fraction dependence derived from Eqs. (5) and (6) did not match the experimental results with the gap geometry. At first glance, Eq. (5) predicted that the CHF would increase with the magnitude of the Marangoni parameter, $(\frac{1}{\sigma})\frac{\partial\sigma}{\partial x}(y_{\mathrm{b}}-x_{\mathrm{b}})$, for positive mixtures. However, the CHF corresponding to stronger Marangoni forces was found to be lower than that corresponding to weaker Marangoni forces with the gap geometry.

For the pseudo film boiling regime, the theoretical correlation of film boiling by Liu et al. [22] for a horizontal cylinder was used for comparison:

$$\alpha=\alpha_{\mathrm{id}}(1+F)^n \quad (7)$$

where α_{id} is the ideal heat transfer coefficient of a binary mixture evaluated by the Berenson [23] correlation, n is 0.25 as suggested by Liu et al., and F is the mass diffusion factor. According to Fig. 5, the experimental heat transfer coefficients for $x = 0.015$ with a 6.4mm gap had a very steep decline with the increase of superheats, while Eq. (7) predicted a moderate variation. Though Sakurai et al. [24] suggested that the rapid deterioration with increasing superheats might be relevant to the subcooled temperature imposed in the system, the data for

Table 1
CHF conditions comparisons

a/g	x_{b}	ΔT_{c} (K)	$q''_{\mathrm{CHF,exp}}$ (W m^{-2})	$q''_{\mathrm{CHF,MC}}$ (W m^{-2})	% difference	$q''_{\mathrm{CHF,Fujita}}$ (W m^{-2})	% difference
1	0.015	5	1.234×10^{6}	7.407×10^{5}	−40.0%	6.046×10^{5}	−51.0%
0.01	0.015	7	4.717×10^{5}	4.058×10^{5}	−14.0%	3.297×10^{5}	−30.1%
0.00	0.025	25	1.355×10^{6}	2.722×10^{5}	−79.9%	2.463×10^{5}	−81.8%
1.76	0.025	25	1.514×10^{6}	8.102×10^{5}	−46.5%	7.336×10^{5}	−51.5%

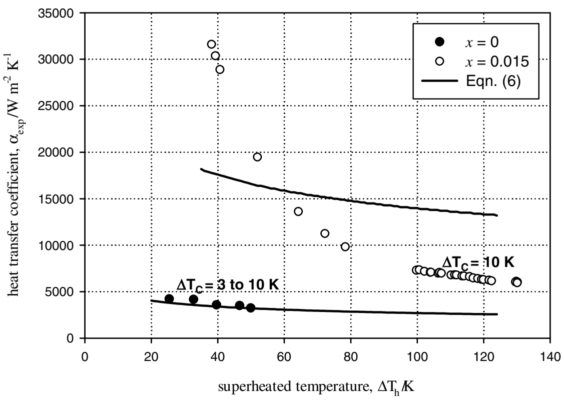

Fig. 5. Heat transfer coefficients for 2-propanol/water mixtures in pseudo film boiling regime, $L = 6.4$ mm, $a/g = 1$.

distilled water does not exhibit the same trend as for $x = 0.015$.

According to the above comparisons in different boiling regimes, the gap geometry was shown to alter the characteristics of the heat transfer for 2-propanol/water mixtures. Under the earth's gravity, the vapor bubble was restricted by the confining gap, and pulled upward by buoyancy to form a mushroom shape. However, the vapor formed more symmetrically under reduced gravity. This resulted in a thinner liquid film underneath the vapor bubble, and a shorter conduction path between the heated surface and the bubble interface that augmented the heat transfer. Under high gravity, the gap effect was minimized because the departing bubbles' diameter was so small that they departed from the heated surface before reaching the cold plate. This implies that the evaporation process did not interfere with the confined geometry under high gravity, yielding a lower heat transfer rate in the nucleate boiling regime. This characteristic is similar to the results from pool boiling.

Conversely, the gap geometry played a different role in determining the CHF and pseudo film boiling heat transfer rates. Although the CHF was reported to be nearly independent of gravity for 2-propanol/water mixtures for free pool boiling, this was not the case with the presence of the confined gap. In the confined geometry, the value of the CHF under reduced gravity was found to be much less than that under terrestrial conditions. It is believed that, under terrestrial gravity, buoyancy helped to rip vapor bubbles off the heated surface, and continuous nucleation occurred at the stem portion of the bubble mushroom. This mechanism not only resulted in a higher CHF, but it also helped to maintain higher heat transfer coefficients in the pseudo film boiling regime under earth's gravity.

Yao and Chang [13] demonstrated that the Bond number was an important parameter in indicating this geometry effect. The Bond number is defined to be the ratio of the gap size, L, to the departure diameter of the isolated bubble, which was assumed to be the capillary length scale:

$$Bo = \frac{L}{\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}} \tag{8}$$

According to Bonjour and Lallemand [25], the squeezing effect becomes more important for low Bond numbers ($Bo \leqslant 1$) since the gap is narrower than the bubble diameter. On the other hand, for high Bond numbers, boiling can be almost considered unconfined. However, it was found that the experimental results did not asymptotically rejoin the pool boiling curve for 2-propanol/water mixtures, even for $Bo = 4$. In Eq. (8) the departure diameter of the bubble was estimated by the capillary length scale, which may not reflect reality. Straub [26] reported that the departure diameter was independent of the gravity levels. This suggested the need for a new model to evaluate the departure diameter for the calculation of the Bond number, particularly for binary mixtures whose interfacial phenomena are highly different from those of pure liquids. In Fig. 6, a regime map is presented for 2-propanol/water mixtures at $x = 0.015$ by using the Bond numbers evaluated by Eq. (8) and the superheat levels. However, this regime definition is not applicable to other concentrations. A more sophisticated correlation for the departure diameter of the bubble might help to identify a more universal regime map for this geometric configuration.

Ultimately, the influence of the gap geometry on boiling was found to be most significant under reduced gravity and almost negligible under high gravity. However, this effect is completely opposite for different boiling regimes, since the gap assisted the heat transfer in the nucleate boiling regime but hindered it for the pseudo film boiling regimes. The effect of the confined gap geometry was also found to reduce the CHF values.

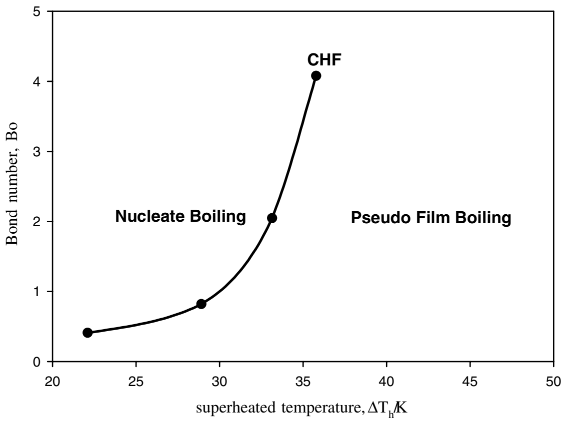

Fig. 6. Regime map for 2-propanol/water mixtures with the gap geometry, $x = 0.015$, based on experimental data in this study.

5. Concluding remarks

In this study, small bubbles were generated and condensed quickly in the nucleate boiling regime. The agitation in the system resulted in great heat transfer performance. In the nucleate boiling regime, the values predicted by the pool boiling correlations were over 30% lower than the experimental results. As the superheat level increased, the bubbles coalesced into a large vapor slug that was constrained by the gap geometry and started to blanket the heated surface. The maximum heat flux, (i.e. the critical heat flux, CHF), was then reached. Under reduced gravity, the CHF for $x = 0.025$, which corresponded to weaker Marangoni forces, was almost triple in magnitude of that for $x = 0.015$. Thus, CHF exhibits different concentration dependencies with and without gap geometry. The correlations were found to underestimate the experimental CHF by 14.0–81.8%. The pseudo film boiling regime was obtained by further increasing the superheat level, creating a slow, fluctuated bubble where boiling only occurred at its base perimeter because the heated surface was dried out. Due to the rapid descent with increasing superheat, the heat transfer is only improved at low superheat levels ($\Delta T_h < 40\,\mathrm{K}$) for $x = 0.015$ when compared to the distilled water results.

The boiling heat transfer is greatly improved by adding a small amount of 2-propanol into the water under earth and reduced gravity environments. With the gap geometry, a 0.025 molar fraction of 2-propanol seemed to be a better choice for heat transfer improvement near and beyond CHF.

Acknowledgments

This study was supported by the NASA Office of Life and Microgravity Sciences and Applications under grant No. NAG3-2105. The authors also wish to acknowledge and thank Mr. Brian Motil of the NASA Glenn Research Center for his assistance during the KC-135A flight tests.

References

[1] J. Straub, The micro wedge model: a physical description of nucleate boiling without external forces, in: L. Ratke, H. Walter, B. Feuerbacher (Eds.), Proceedings of the 9th European Symposium on Gravity-Dependent Phenomena in Physical Sciences Materials and Fluids Under Low Gravity, Springer-Verlag, Berlin, Germany, 1995, pp. 351–359.

[2] Y.C. Kweon, M.H. Kim, Experimental study on nucleate boiling enhancement and bubble dynamic behavior in saturated pool boiling using a nonuniform DC electric field, Int. J. Multiphase Flow 26 (8) (2000) 1351–1368.

[3] W.R. McGillis, Boiling from localized heat sources in pure and binary fluid systems, Ph.D. thesis, University of California, Berkeley, CA, 1993.

[4] S. Ahmed, Marangoni effects in the boiling of binary fluid mixtures, Ph.D. thesis, University of California, Berkeley, CA, 1996.

[5] Y. Abe, T. Oka, Y.H. Mori, A. Nagashima, Pool boiling of a non-azeotropic binary mixture under microgravity, Int. J. Heat Mass Transfer 37 (16) (1994) 2405–2413.

[6] T. Oka, Y. Abe, Y.H. Mori, A. Nagashima, Pool boiling heater of *n*-pentane, CFC-113, and water under reduced gravity: parabolic flight experiments with a transparent, J. Heat Transfer 117 (2) (1995) 408–417.

[7] J. Evans, D. Liepmann, A.P. Pisano, Planar laminar mixer [MEMS fluid processing system], in: The Tenth Annual International Workshop on Micro Electro Mechanical Systems. An Investigation of Micro Structures, Sensors, Actuators, Machines and Robots (Cat. No. 97CH36021). Proceedings IEEE The Tenth Annual International Workshop on Micro Electro Mechanical Systems. An Investigation of Micro Structures, Sensors, Actuators, Machines and Robots, IEEE, Nagoya, Japan, 1997, pp. 96–101.

[8] L. Lin, A.P. Pisano, A.P. Lee, Microbubble powered actuator, in: 1991 International Conference on Solid-State Sensors and Actuators, IEEE, San Francisco, CA, USA, 1991, pp. 1041–1044.

[9] J.-H. Tsai, L. Lin, Transient thermal bubble formation on polysilicon micro-resisters, Transactions of the ASME, J. Heat Transfer 124 (2) (2002) 375–382.

[10] D.L. Finke, MEMS devices in ink-jet printers, in: Sensors Expo, Helmers Publishing & Expocon Management, Boston, MA, USA, 1997, pp. 251–253.

[11] E. Ishibashi, K. Nishikawa, Saturated boiling heat transfer in narrow spaces, Int. J. Heat Mass Transfer 12 (8) (1969) 863–893.

[12] Y. Katto, S. Yokoya, K. Teraoka, Nucleate and transition boiling in a narrow space between two horizontal, parallel disk-surfaces, Bull. Jpn. Soc. Mech. Eng. 20 (143) (1977) 638–643.

[13] S. Yao, Y. Chang, Pool boiling heat transfer in a confined space, Int. J. Heat Mass Transfer 26 (6) (1983) 841–848.

[14] B.E. Poling, J.M. Prausnitz, J.P. O'Connell, The Properties of Gases and Liquids, McGraw-Hill, New York, 2001.

[15] T.E. Daubert, R.P. Danner, Data Compilation Tables of Properties of Pure Compounds, American Institute of Chemical Engineers, New York, 1985.

[16] K. Stephan, M. Korner, Calculation of heat transfer of evaporating binary liquid mixtures, Chemie Ingenieur Technik 41 (7) (1969) 409–417.

[17] Y. Fujita, Q. Bai, M. Tsutsui, Nucleate boiling of binary mixtures and heat transfer correlation, Memoirs of the Faculty of Engineering, Kyushu University, vol. 55(3), 1995, pp. 303–331.

[18] S.G. Kandlikar, Boiling heat transfer with binary mixtures. I. A theoretical model for pool boiling, Transactions of the ASME, J. Heat Transfer 120 (2) (1998) 380–387.

[19] K. Stephan, M. Abdelsalam, Heat-transfer correlations for natural convection boiling, Int. J. Heat Mass Transfer 23 (1) (1980) 73–87.

[20] Y. Fujita, Q. Bai, M. Tsutsui, Critical heat flux of binary mixtures in pool boiling, in: Proceedings of the 1995

ASME/JSME Thermal Engineering Joint Conference-Maui, Hawaii, 1995, pp. 193–200.
[21] J.H. Lienhard, V.K. Dhir, Hydrodynamic prediction of peak pool-boiling heat fluxes from finite bodies, J. Heat Transfer 95 (2) (1973) 152–158.
[22] M.H. Liu, Y.M. Yang, J.R. Maa, Prediction of film boiling heat transfer coefficients for binary mixtures, Heat Mass Transfer 32 (4) (1997) 261–269.
[23] P.J. Berenson, Film-boiling heat transfer from a horizontal surface, J. Heat Transfer 83 (3) (1961) 351–358.
[24] A. Sakurai, M. Shiotsu, K. Hata, Effect of system pressure on film-boiling heat transfer, minimum heat flux, and minimum temperature, Nucl. Sci. Eng. 88 (3) (1984) 321–330.
[25] J. Bonjour, M. Lallemand, Flow patterns during boiling in a narrow space between two vertical surfaces, Int. J. Multiphase Flow 24 (6) (1998) 947–960.
[26] J. Straub, Boiling heat transfer and bubble dynamics in microgravity, in: J.P. Hartnett, T.F. Irvine Jr. (Eds.), Advances in Heat Transfer, vol. 35, Academic Press, San Diego, CA, 2001, pp. 58–168.