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EFFECTS OF GAP GEOMETRY AND GRAVITY ON BOILING AROUND A CONSTRAINED BUBBLE IN 2-PROPANOL/WATER MIXTURES

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ABSTRACT

In this study, boiling experiments were conducted with 2-propanol/water mixtures in confined gap geometry under various levels of gravity. The temperature field created within the parallel plate gap resulted in evaporation over the portion of the vapor-liquid interface of the bubble near the heated surface, and condensation near the cold surface. Full boiling curves were obtained and two boiling regimes – nucleate boiling and pseudo film boiling, the transition condition, and the critical heat flux (CHF), were identified. The observations indicate that the presence of the gap geometry pushed the nucleate boiling regime to a lower superheated temperature range and resulted in correspondingly lower heat flux. With further increases of wall superheat, the vapor generated by the boiling process was trapped in the gap and blanketed the heated surface. This caused premature occurrence of CHF conditions and deterioration of heat transfer in the pseudo film boiling regime. The influence of the confined space was particularly significant when greater Marangoni forces were present at reduced gravity conditions. The value of the CHF for x = 0.025, which corresponded to weaker Marangoni forces, was found to be greater than that of x = 0.015 with a 6.35 mm gap.

Keywords: Marangoni effects, microgravity, boiling, confined space

INTRODUCTION

Boiling in reduced gravity has significant applications in many aerospace engineering fields, including spacecraft thermal control designs that incorporate heat exchangers, heat pipes, microchannels, and cryogenic storage and transport systems. Many investigators have conducted intensive experimental research on pool boiling under various gravity levels, but none known to us has studied gravity effects on boiling in a confined space which is frequently encountered in a wide variety of heat transfer applications, such as heat exchangers, pressurized water reactors, and electronic component cooling.

For pool boiling in the nucleate boiling regime, Straub [1] pointed out that the Rohsenow equation, which predicts that the heat flux at a specified superheat level diminishes under reduced gravity, failed to predict the heat transfer for binary mixtures and pure organic fluids. On the contrary, an enhancement of 20 % was achieved even at low heat flux for some mixtures. This augmentation of heat transfer was also observed by Abe, *et al.* [2], Oka, *et al.* [3], and Lee, *et al.* [4].

For critical heat flux (CHF), Ahmed and Carey [5] found that by adding a proper amount of 2-propanol into water, the resulting Marangoni effect was able to sustain the boiling mechanism and assisted in maintaining the critical heat flux to within the same order of magnitude as the terrestrial condition under reduced gravity. Without the enhancement of concentration induced Marangoni effects, Shatto and Peterson [6] reported that the critical heat flux for distilled water decreased with decreasing gravity, and even fell below the $g^{1/8}$ trend predicted by Lienhard and Dhir [7] for a small cylinder.

Several experimental results for cryogenic fluids in film boiling were compared by Straub [8], who found that the film boiling could be maintained by surface tension forces in microgravity. The heat transfer coefficient was gradually decreased with decreasing gravity, but remained consistent for a/g < 0.01. Alternatively, Liu, *et al.* [9] proposed an analytical correlation for the film boiling of binary mixtures on a horizontal cylindrical heater. By taking the mass diffusion factor into account, the heat transfer coefficients were suggested to be proportional to $g^{1/4}$ by their model.

There are several studies that have focused on the influence of constrained space on boiling. The pioneering work by Ishibashi and Nishikawa [10] systematically examined the heat transfer of various saturated liquids while boiling in vertical annuli with the internal cylinder heated. Two different boiling characteristics were observed, and are thereafter referred to as the coalesced bubble regime and the isolated bubble regime. In the isolated bubble regime, many spherical bubbles were generated from the heated surface, then departed and rose upward. While in the coalesced bubble regime, large coalesced bubbles were fully generated in the confined space, then departed and rose regularly at a low frequency. This regime often occurred at low pressure or with a narrow gap. Similar boiling characteristics were also observed by Aoki*, et al.* [11], Yao and Chang [12] for vertical narrow annuli, and Bonjour and Lallemand [13] for narrow spaces between two vertical surfaces. However, boiling phenomena in the horizontal confined geometry were expected to be distinct from the phenomena in the vertical confined geometry, especially under earth gravity where the buoyancy effect operates in different directions. Katto*, et al.* [14] conducted boiling experiments of saturated water in a space bounded by two horizontal co-axial disks with a heated surface that faced upward. They found that a decrease in the gap size of the nucleate boiling regime augmented the heat transfer coefficient but diminished the CHF. Furthermore, Katto and Kosho [15] extended the work to boiling of R-113, ethyl alcohol and benzene in horizontally confined geometries and proposed a correlation for CHF within ±15 % agreement with the experimental data.

Despite the aforementioned investigations, no previous literature was found that documents studies of the boiling of binary mixtures in a horizontal confined geometry under various gravity levels. In this study, experiments were conducted with 2-propanol/water mixtures under various gravity levels and gap sizes in order to investigate Marangoni effects on near-bubble microscale transport around a constrained bubble while boiling binary mixtures. The size of the confined gap was varied from 6.35 mm to 12.70 mm, while the system pressure in the test section was maintained in the subatmospheric range (5.54kPa to 9.42kPa) throughout the experiments. The bulk liquid temperature was varied from slightly subcooled to near saturation, and the cold plate temperature was purposely varied from 10 to 30 K subcooled in order to sustain the temperature gradient along the gap. The 2-propanol mole fractions used for the experiments were 0 (distilled water), 0.015, and 0.025. The surface tension gradient was maximal and produced the strongest Marangoni effect at molar fractions of 2-propanol $x = 0.015$.

NOMENCLATURE

a	system acceleration in vertical direction, m/s^2
Bo	Bond number, $\sqrt{\dfrac{gL^2(\rho_l - \rho_v)}{\sigma}}$
g	earth gravitational acceleration, 9.8 m/s^2
h_{lv}	latent heat of vaporization, J/kg
k	thermal conductivity, W/m·K
L	width of the gap (distance between heated surface and cold surface), m
P	pressure, kPa
q''	heat flux, W/m^2
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

Greek symbols

α	heat transfer coefficient, W/m^2
μ	dynamic viscosity, N·s/m^2
ρ	density, kg/m^3
σ	surface tension, N/m

Miscellaneous subscript symbols

bp	bubble point
CHF	critical heat flux
l	liquid
v	vapor
1g	earth gravity

EXPERIMENTAL SETUP

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

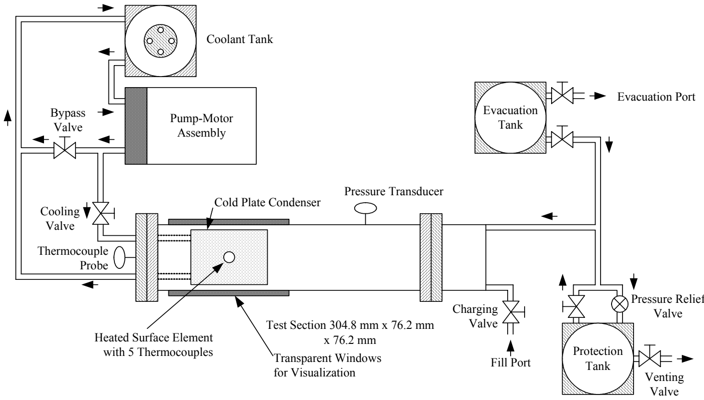

Fig. 1 Schematic diagram of the experimental system

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. 2 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 has a diameter of 12.7 mm. The nearest thermocouple was 2.2 mm away 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 heat conduction in radial direction. 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 thermal time constant of the copper element was estimated to be 0.5 s.

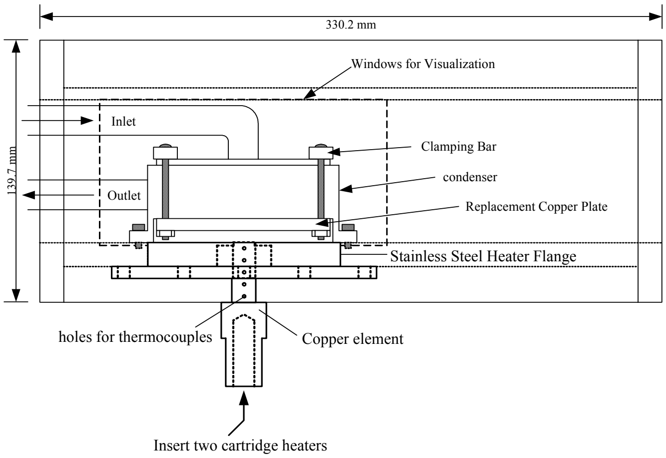

Fig. 2 Test section with the condenser and the heater element installed

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 6.3 mm or 9.5 mm thick copper plate, the gap between the condenser and the heater surface 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 the guided vanes. 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 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 the PC-based data acquisition system with a scanning frequency of 2.5 Hz. The test system, along with its support structure, was mounted on a NASA instrument rack, while the desktop computer, data acquisition system and two variable voltage controllers were all mounted onto another one.

The reduced and high gravity experiments were carried out aboard a KC-135A aircraft at 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 fall in-flights, and high gravitational acceleration during the climb pull-ups. The input heat flux was adjusted in every other parabola to ensure the steady state of the system. All the 1g experiments were conducted in the Multiphase Transport Laboratory, University of California at 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 accelerometer in KC-135A was roughly estimated to be 0.007g. The values of the physical properties of 2-propanol/water mixtures were evaluated based on the methods and information provided by Poling*, et al.* [16], McGillis [17], and Daubert and Danner [18]. And the overall uncertainty of the computed bubble point temperature was estimated to be 1 %.

RESULTS

Though it was found that the results with the gap constraint did not resemble the pool boiling curve, the observed boiling phenomena could still be classified into two different regimes similar to the pool boiling. At low superheat levels, small bubbles were grown from active nucleation sites on the heated surface, and were then released before growing to larger size and condensed in the subcooled bulk liquid. This is categorized as the nucleate boiling regime. Further increases of the input heat flux caused the small bubbles to coalesce, and then to grow into a large, wavy vapor bubble. The resulting large vapor bubble was trapped in the parallel-plate gap and started 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 and dry patches were observed on the heated surface. This was defined as the “pseudo film boiling” in this investigation.

The boiling curve for distilled water (x = 0) inside the gap is shown in Fig. 3. It was found that nucleation was rarely observed for ΔT_h < 20K under low gravity. As the superheat levels increased, the gap geometry sustained a large fluctuating bubble and transitioned directly into the pseudo film boiling mode. The same phenomenon was also observed under terrestrial conditions. The heated surface was mostly dried out when nucleate boiling only occurred at the perimeter of the bubble base, with the top portion of the bubble attached to the cold plate. Buoyancy tended to bring more vapor to the top wall and made the bubble reassemble to the frustum of a circular cone. It increased the contact area of the bubble with the cold plate and therefore enhanced the condensation effect. A tiny liquid droplet was even observed to occasionally hang from the center of the cold plate due to condensation. Without buoyancy, the vapor-liquid interface became wavy and less stable. The nature of this instability created some mixing effects and resulted in better heat transfer. In addition, the bubble tended to remain in a cylindrical shape while the heated surface was partially dried out.

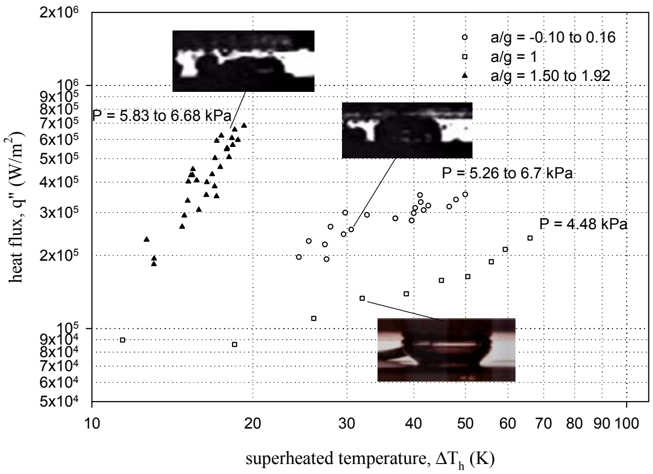

Fig.3 Boiling curve of distilled water under various gravity levels, *x* = 0, gap = 6.4 mm (solid symbols represent nucleate boiling regime, while open symbols represent pseudo film boiling regime)

Under high gravity (*a/g* = 1.50 to 1.92), the nucleate boiling mode was the only one observed for distilled water. The bubbles fluctuated, merged, and released in a very rapid fashion at this gravity level. Embryos were formed and coalesced but collapsed before growing to larger sizes. The chaotic nature of this process produced a strong mixing effect that enhanced the heat transfer efficiency and made high heat transfer rates with low superheat levels possible.

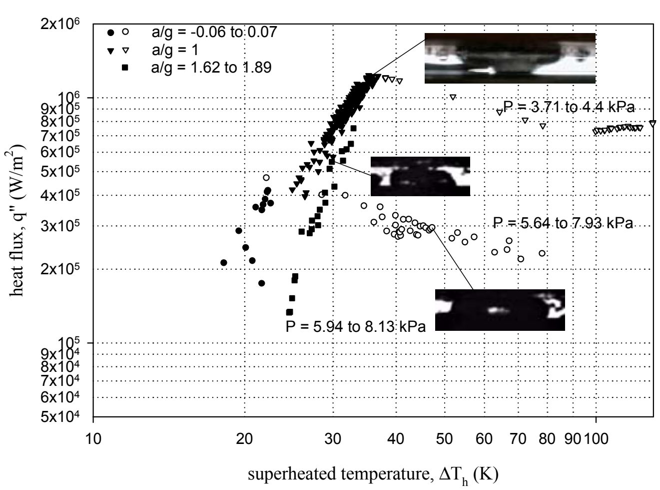

Fig.4 Boiling curve of 2-propanol/water mixtures under various gravity levels, *x* = 0.015, gap = 6.4 mm (solid symbols represent nucleate boiling regime, while open symbols represent pseudo film boiling regime)

The nature of 2-propanol/water mixtures is that they produce different surface tensions along the bubble interface during the boiling, 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 push bubbles away from each other. This will make it harder for the small bubbles to coalesce to a larger size. The boiling curves for x = 0.015 with a 6.4 mm gap under various gravity levels is shown in Fig. 4. In the nucleate boiling regime under reduced gravity for x = 0.015 with a 6.4 mm gap, the same level of heat flux was reached at lower superheated temperature compared to that under terrestrial and high gravity. Similar increases, albeit of a smaller magnitude, were also observed for the same concentration (x = 0.015) with a 12.7 mm gap, as represented in Fig. 5.

However, CHF under reduced gravity was greatly diminished to less than 50 % of that under terrestrial conditions, and was also reached at a superheated temperature 10 K lower than that under terrestrial conditions for x = 0.015 with a 6.4 mm gap. Due to the space constraint, the vapor formed a large bubble that blanketed the heated surface under reduced gravity and caused the CHF to decrease accordingly. With a wider gap to provide more space for the bubble growth and mobility, CHF at low gravity for x = 0.015 with a 12.7 mm gap was found to improve by more than 40 % of that for the same concentration with a 6.4 mm gap.

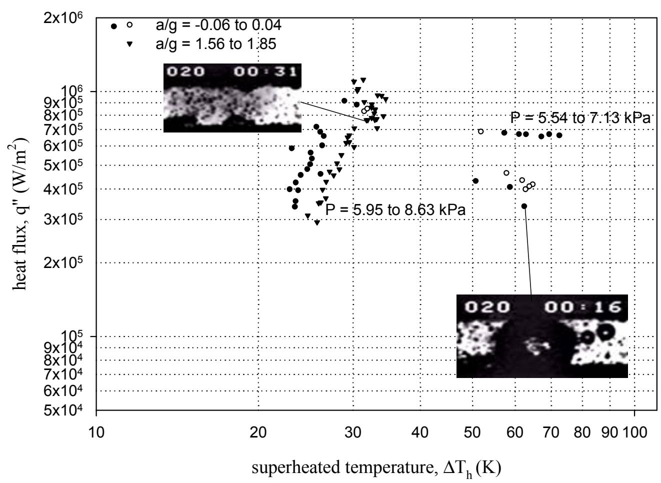

Fig.5 Boiling curve of 2-propanol/water mixtures under various gravity levels, *x* = 0.015, gap = 12.7 mm (solid symbols represent nucleate boiling regime, while open symbols represent pseudo film boiling regime)

For x = 0.015 with a 6.4 mm gap in the pseudo film boiling regime, the bubble tended to be squashed toward the cold plate under terrestrial gravity. The Marangoni effect induced a liquid flow against the direction of buoyancy, and initiated instability in the vapor-liquid interface. Under reduced gravity, the bubble grew to a flat barrel shape and tended to be more stable with no observed buoyancy. This was contrary to the results for distilled water (x = 0), for which the bubble was more stable with the presence of gravity.

Although boiling within the 6.4 mm gap was stable, increasing the gap size destroyed this steadiness. An unstable, rounder bubble was observed in the pseudo film boiling regime for the same concentration with a 12.7 mm gap. There were two trends observed beyond the CHF point from the boiling curve for this particular condition. For the same superheat level, two different corresponding heat fluxes were found to occur. In the lower heat flux region, a round bubble was observed to occur with dry patches on the heated surface. Alternatively, while in the high heat flux region, tiny embryos were observed that were more similar to the nucleate boiling mode. Since the quantity of the generated vapor was insufficient to support the bubble that filled the gap, the top portion of the bubble barely touched the cold plate, and the gap therefore failed to firmly sustain the bubble. As a result, fluids occasionally flushed the bubble away from the heated surface and made it start from nucleate boiling again.

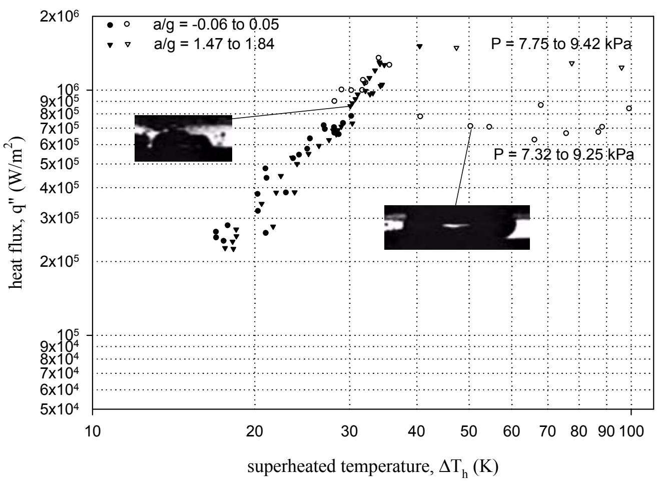

Fig.6 Boiling curve of 2-propanol/water mixtures under various gravity levels, x = 0.025, gap = 6.4 mm (solid symbols represent nucleate boiling regime, while open symbols represent pseudo film boiling regime)

For x = 0.025, which corresponded to a weaker Marangoni influence, the boiling curves taken under reduced and high gravity were almost indistinguishable in the nucleate boiling regime before the CHF point, as indicated in Fig. 6. The only CHF found under high gravity was for x = 0.025 with a 6.4 mm gap, with a CHF value comparable to that under reduced gravity and a corresponding superheat difference of less than 5K.

For x = 0.025 with a 6.4 mm gap, pseudo film boiling was reached under both reduced and high gravity. While the bubbles started to become more stable near and beyond CHF (ΔT_h > 30 K) at low gravity, it was not until ΔT_h > 50 K that they stabilized at high gravity levels. Furthermore, the heat transfer under high gravity in this regime was 40 % greater than that under reduced gravity.

In addition, some interesting heat transfer characteristics were observed in the transition period between low and high gravity during the KC-135A experiments. It was found that the transition between gravity levels might cause switching from one regime to another in a very short period of time. A rapid jump from pseudo film boiling back to nucleate boiling changed the corresponding superheat by more than 10 K for a 6.4 mm gap (x = 0, 0.015, 0.025), and 20 K for a 12.7 mm gap (x = 0.015) under gravity transition. Since the thermal time constant of the heater was very short (0.5 s) and the input heat flux was fixed, the rapid temperature drop was primarily caused by the disappearance of the vapor blanket at high gravity levels. If the initial superheated temperature was high enough at the beginning of the gravity transition, the vapor blanket tended to form on the heater surface and caused a switch to pseudo film boiling at reduced gravity. The data points in the pseudo film boiling were carefully taken near the end of the reduced gravity period to insure steady state was reached.

DISCUSSIONS

Since there was no correlation available for boiling of binary mixtures in a confined gap, conventional correlations for pool boiling were used to compare with our experimental results. In nucleate boiling, the dependency of heat transfer on gravity has been represented in the form of the power law by Straub [19]:

$$\frac{\alpha}{\alpha_{1g}} = \left(\frac{a}{g}\right)^n \tag{1}$$

In the Rohsenow [20] correlation, the exponent is equal to 0.5 in Eq. (1). This implies that the heat transfer coefficient is strongly reduced with decreasing gravity. However, Ahmed [21] found that the heat transfer coefficients were nearly independent of gravity regardless of the concentration of the 2-propanol/water mixtures. In addition, Straub [1] concluded that gravity and natural convection do not play a dominant role in pool boiling heat transfer. Nevertheless, gravity seems to play an important role for x = 0.015 with a gap constraint. With the gap geometry, the heat transfer coefficient under reduced gravity was enhanced to more than 20 % of that at earth gravity. This suggests that the gap geometry may alter the nature of the gravity dependency.

Regarding to CHF, the Zuber correlation, which derived from the hydrodynamic theory of film instability, indicates that it has a $g^{1/4}$ dependency:

$$q''_{CHF,Zuber} = 0.131 \rho_v h_{lv} \left[\frac{\sigma(\rho_l - \rho_v) g}{\rho_v{}^2}\right]^{\frac{1}{4}} \tag{2}$$

However, this relationship was found to underestimate most of the experimental data under microgravity. For binary mixtures, Ahmed and Carey [5] reported that the CHF was nearly independent of gravity since the concentration induced Marangoni effect was equally important and successfully sustained boiling without buoyancy. This was, however, found to contradict the results obtained with the gap geometry configuration, which indicated that the CHF for low gravity was diminished to 40 % of that at earth gravity for x = 0.015 with a 6.4 mm gap.

According to the above comparisons, it was found that the gap geometry altered 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 maintained a mushroom shape due to the effects of buoyancy. However, the vapor grew isotropically in lateral directions under reduced gravity. This growth combined with the compressive influence of the gap geometry, caused the liquid film under the vapor to become thinner, resulting in an increase of heat transfer. Under high gravity, the gap effect was minimized because the departing bubbles' diameter was so small that they did not even reach the cold plate before departure from the heated surface. 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, which is similar to the pool boiling circumstance.

For laminar film boiling on a horizontal flat plate, the Berenson [22] correlation suggests that the heat transfer coefficient was proportional to $g^{3/8}$:

$$\alpha = 0.425\left\{\left[\frac{k_v^{\,3} g \rho_v (\rho_l - \rho_v) h_{lv}}{\mu_v \Delta T_h}\right]\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{\frac{1}{2}}\right\}^{\frac{1}{4}} \quad (3)$$

Moreover, the experimental results of film boiling under reduced gravity was summarized by Straub [8]. He found that the gravity dependency of the heat transfer coefficients fell within $g^{0.16}$ to $g^{0.33}$ for $a/g > 0.01$. However, our results from the pseudo film boiling regime did not really follow these trends. The heat transfer coefficient under reduced gravity was diminished to less than 30 % of that under terrestrial conditions for x = 0.015 with a 6.4 mm gap, whereas it was almost doubled for x = 0 with the same gap size. For both x = 0 and 0.015 with a 6.4 mm gap at low gravity, the heat transfer coefficient was found to be quite consistent, regardless of the small deviation in gravity.

Conversely, the gap geometry played a different role on CHF and pseudo film boiling. 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 the buoyancy helped to clear out vapor bubbles near 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 [12] demonstrated that the Bond number was an important parameter to indicate the geometry effect. The Bond number is defined to be the ratio of the gap size to the departure diameter of the isolated bubble, which was assumed to be the capillary length scale:

$$Bo = \frac{L}{\sqrt{\dfrac{\sigma}{g(\rho_l - \rho_v)}}} \quad (4)$$

According to Bonjour and Lallemand [13], the squeezing effect becomes more important for low Bond numbers ($Bo \leq 1$) 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. (4) the departure diameter of the bubble was estimated by the capillary length scale, which may not reflect reality. Straub [8] 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 the pure liquids. In Fig. 7, a regime map is presented for 2-propanol/water mixtures at x = 0.015 by using the Bond numbers evaluated by Eq. (4) 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 to depict this geometric effect.

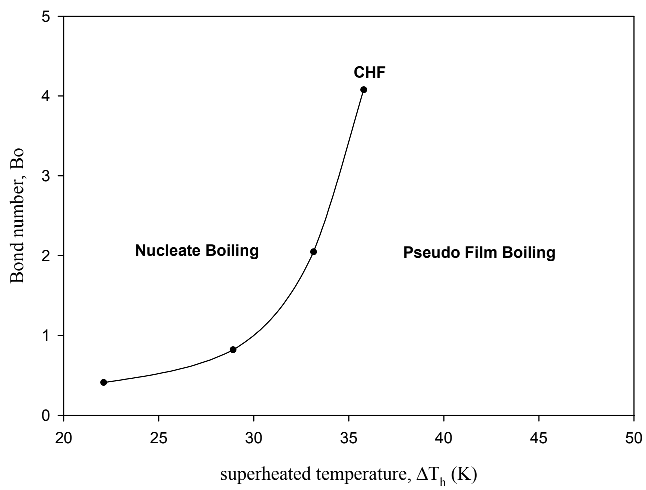

Fig. 7 Regime map for 2-propanol/water mixtures with the gap geometry, *x* = 0.015, based on experimental data in this study

Consequently, 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 hinderred it for the pseudo film boiling regimes. The effect of the confined gap geometry was also found to reduce the CHF values.

CONCLUDING REMARK

In the presence of the gap geometry, the gravity dependency of heat transfer in nucleate boiling regime was contrarily predicted by Rohsenow [20] correlation. For x = 0.015 with a 6.4 mm gap, α/α_{1g} was 1.242 at low gravity which indicated a heat transfer enhancement, while Rohsenow correlation revealed a deficit value of 0.032. On the other hand, α/α_{1g} was 0.946 at high gravity, which was 27.5 % lower than the value predicted by Rohsenow correlation.

Gravity was found to have a significant impact on the CHF condition when the gap geometry was in place. The maximum value of CHF was found for x = 0.025 with a 6.4 mm gap within our test matrices under reduced gravity. The gravity dependency of the CHF for x = 0.015 with a 6.4 mm gap was best approximated by $g^{0.17}$, which fell between the $g^{1/4}$ and $g^{1/8}$

regression lines suggested by Shatto and Peterson [6] for pool boiling.

For film boiling, the Berenson [22] correlation predicted α/α_{1g} = 0.23 for a/g = 0.02, which matched the pseudo film boiling results to within 12 % for x = 0.015 with a 6.4 mm gap. However, it failed to indicate the heat transfer enhancement (α/α_{1g} = 2.07) for x = 0.

The gravity remained a minor factor in the heat transfer mechanism within the nucleate and pseudo film boiling regimes in this study. With the aid of concentration induced Marangoni effects, the boiling was not only maintained but also enhanced with the absence of gravity. However, a tradeoff occurs with a poorer heat transfer under microgravity during pseudo film boiling regimes.

According to the observations of this study, the influence of the gap geometry becomes more significant in conjunction with the following conditions:

1. The reduction of the gap size
2. The decrease of the gravity level
3. Stronger Marangoni effects

As the result, the influences of the gap size, the gravity levels and the Marangoni effects on boiling heat transfer are not independent, but mutually interact with one other. Hence, the gap size can be optimally selected for a specific condition (boiling regime, concentration, gravity, pressure and so forth) in order to reach the best heat transfer performance in the system.

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