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Effects of gravity on the boiling of binary fluid mixtures

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Abstract—Experiments have been conducted with water/2-propanol mixtures under reduced gravity, normal gravity and high gravity in order to investigate Marangoni effects and their interaction with the gravitational effect in the pool boiling of binary mixtures. The system pressure was subatmospheric (~ 8 kPa at 1 g_n) and the bulk liquid temperature varied from low subcooling to near saturation. The molar concentrations of 2-propanol tested were 0.015, 0.025 and 0.1. The reduced and high gravity experiments were conducted aboard a DC-9 aircraft at NASA Lewis Research Center. Boiling curves were obtained both for high gravity ($\sim 2\, g_n$) and reduced gravity ($\sim 0.01\, g_n$), and the duration of both the high gravity and reduced gravity period was approximately 20 s per parabola. For each concentration of 2-propanol, the critical heat flux (CHF) has been determined for normal and reduced gravity conditions. The present experimental data are compared with the available predictive correlations for binary mixture boiling heat transfer and critical heat flux conditions. Comparison of boiling curves obtained from the experiment under 2-g_n, 1-g_n and reduced gravity indicates that the boiling mechanism in these mixtures is nearly independent of gravity. The CHF values determined under reduced gravity conditions for each concentration did not change significantly from those measured under 1-g_n conditions. The results also indicate that the Marangoni mechanism is strong enough in these mixtures to sustain stable nucleate boiling under reduced gravity conditions. © 1998 Elsevier Science Ltd. All rights reserved.

INTRODUCTION

In many technological applications, vaporization of a working fluid is critically important. Recent efforts to improve component or system performance have lead some developers to consider the use of binary working fluids. In general, researchers have found that some binary mixtures offer potential for improved thermodynamic efficiency, or superior heat transfer performance. The advantages of using binary mixtures in heat pump systems have been explored by several investigators (Domanski [1], Cooper [2]). Previous studies of boiling in binary mixtures indicate that concentration gradients near the heated surface which arise during the boiling process may produce significant variation of the interfacial tension along the liquid–vapor interface of bubbles formed at the surface. The role of the surface tension gradient near the heated surface in the boiling process remains the subject of speculation, debate and experimental investigation.

Another perspective on the significance of Marangoni effects during binary mixture boiling can be obtained by considering two-phase thermal management systems for spacecraft. Systems of this type using pure working fluids have been extensively studied by Degroff *et al.* [3]. On earth, vaporization of a coolant provides an efficient means of removing rejected heat in power and thermal control systems. Due to the great density difference between the liquid and vapor phase, it is generally believed that the boiling process is strongly dependent on buoyancy forces. Therefore, when boiling occurs under microgravity conditions, buoyancy cannot be relied upon to move vapor away from a heated surface and move liquid towards the surface. If vapor accumulates, the heated surface may eventually be blanketed with a vapor film, slowing the vaporization process and greatly reducing heat transfer performance. Because wall dryout greatly reduces the heat transfer performance, it is desirable to design evaporators for thermal control systems so that dryout is avoided over the entire range of possible operating conditions.

Results of recent studies suggest that it may be possible to enhance the ability of the system to resist dryout and the onset of film boiling by using a binary coolant rather than a pure working fluid. McGillis and Carey [4] experimentally examined the pool boiling of mixtures of water and alcohol at low pressure on a small, 1.3 cm square heated surface. Boiling curves and the critical heat flux were determined for several different alcohol–water mixtures at a number of pressure and concentration combinations. Methanol/water, 2-propanol/water and ethylene glycol/water mixtures were tested. These experiments were done in a closed thermosiphon system so that concentrations in the liquid pool can be accurately maintained at a predetermined level throughout the test. At low con-

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NOMENCLATURE

A_0	empirical constant in Stephan–Körner correlation
B_0	scaling factor in Schlünder correlation
c_m	constant in McGillis–Carey correlation
CHF	critical heat flux
°C	degree centigrade
g	instantaneous acceleration
g_n	earth normal gravitational acceleration
P	total pressure
P_c	critical pressure
q''	heat flux
q''_m	critical or maximum heat flux
$q''_{m,MC}$	McGillis–Carey CHF
$q''_{m,sf}$	single-fluid CHF
t	time
T	temperature
T_{sat}	saturation temperature
x	liquid mole fraction
x_b	bulk liquid mole fraction of 2-propanol
x_p	liquid mole fraction of 2-propanol
y	vapor mole fraction
y_b	equilibrium vapor mole fraction.

Greek symbols

β_L	mass transfer coefficient
ΔT_{bp}	temperature difference between the dew point and bubble point
ΔT_{id}	ideal wall superheat for binary mixture
ρ_l	density of liquid mixture
σ	liquid surface tension.

Subscripts

b	bulk
c	critical
eg	ethylene glycol
id	ideal
n	normal or terrestrial
p	2-propanol
sat	saturated condition
s	saturation
1, 2	components of the mixture.

centrations of 2-propanol in water ($x_p < 0.2$), these investigators found that the critical heat flux (CHF) may be enhanced above that for either of the pure fluid components under comparable conditions. Interestingly, at low concentrations of ethylene glycol in water ($x_{eg} < 0.2$), the critical heat flux is observed to be lower than that of water. McGillis and Carey [4] found that the variation of the critical heat flux with concentration correlates strongly with the surface tension gradient. 2-propanol/water is a mixture wherein the more volatile component (2-propanol) has a lower surface tension than the surface tension of the less volatile component (water) and the surface tension gradients arising from the preferential evaporation of the more volatile component at the heated surface act to enhance the liquid motion towards the surface. We term such a mixture a *positive* mixture because of its enhancing effect on liquid delivery to the surface. A *negative* mixture is one where the more volatile component has a higher surface tension than the surface tension of less volatile component. Ethylene glycol/water is a negative mixture because the surface tension gradients act to decrease the liquid motion towards the heated surface.

The concentration difference established during vaporization of a non-azeotropic mixture results in a surface tension gradient along the liquid–vapor interface near the heater surface. At low concentrations, the variation of surface tension with concentration exhibits a strong negative slope for the 2-propanol/water mixture, whereas for a methanol and water mixture, the gradient is negative but less steep [4]. In both cases, however, the negative value of the surface tension gradient will produce stronger surface tension near the heated wall and weaker surface tension further away. This imbalance will tend to pull liquid from the bulk, where the surface tension is smaller, to the wall region where surface tension is larger. The higher temperature near the wall will tend to reduce the surface tension compared to the cooler bulk liquid condition. However, in the alcohol/water mixtures considered by McGillis and Carey [4], changes in the surface tension resulting from the temperature changes are negligible compared to those induced by concentration differences. Beginning with the well-known Zuber correlation for the critical heat flux for an upward-facing flat heated surface, these investigators replaced the restoring effect of buoyancy in the Zuber correlation with the combined effect of buoyancy and surface tension gradients. The final form of McGillis–Carey correlation for the critical heat flux of the binary mixtures can be written as follows:

$$q''_{m,MC} = q''_{m,sf}\left[1 + c_m\left(\frac{1}{\sigma}\right)\frac{\partial \sigma}{\partial x}(y_b - x_b)\right]^{1/4} \quad (1)$$

where $q''_{m,sf}$ is the CHF correlation for single component liquid with specific configuration and geometry of interest. $\sigma^{-1}(\partial\sigma/\partial x)(y_b - x_b)$ is the surface tension gradient parameter that characterizes Marangoni effects on the critical heat flux in binary mixtures. The slope of the mixture surface tension curve with respect to the liquid mole fraction of the more volatile component is $\partial\sigma/\partial x$. In the above expression, x_b is the concentration of the more volatile component in the bulk liquid and y_b is the concentration that would exist in the vapor phase in equilibrium with liquid at a concentration of x_b. McGillis and Carey [4] found that by adjusting the constant c_m in their correlation, they could match critical heat flux data for both their water/alcohol mixtures as well as the ethanol and water data of Reddy and Lienhard [5]. Agreement is quite good over the entire range of concentrations tested, and this model correlates these data better than other currently available schemes. Recently, Abe *et al.* [6] conducted pool boiling experiments with water–ethanol mixtures under microgravity conditions. These investigators found that the heat transfer was enhanced under microgravity and they attributed this enhancement to the Marangoni flow due to the surface tension gradient.

The important point here is that for certain binary fluid mixtures, there is substantial evidence that surface tension gradients resulting from concentration differences act to enhance the fluid motion towards the heated surface. For some mixtures [4] the effect on the critical heat flux is so great that this effect appears to be substantially stronger than the normal buoyancy effect at $1 g_n$. It is difficult, however, to fully assess the magnitude of the Marangoni effect under $1\text{-}g_n$ conditions because it is always combined with buoyancy. By conducting binary mixture nucleate boiling studies under reduced gravity conditions, the buoyancy effect would be removed, and the ability of Marangoni forces to induce liquid motion towards the surface would be directly observable. The reduced gravity environment can thus provide a unique capability to isolate the Marangoni mechanism and provide definitive information on its role in the boiling process. This information will allow a clearer understanding of its effect on $1\text{-}g$ boiling processes associated with the terrestrial applications and it will open a pathway to develop more accurate models of Marangoni effects on nucleate boiling in a variety of applications. In addition, reduced gravity binary boiling experiments may also pave the way for the use of binary coolants in spacecraft thermal control applications.

Binary mixture boiling experiments conducted at high gravity ($\sim 2\ g_n$) environments could also reveal important information about the strength of the coupling between the buoyancy effect and the Marangoni effect. The effects of gravity and the effects of the Marangoni mechanism on the boiling of binary mixtures might not be linear in nature and elevated gravity experiments could clearly define their interaction. Understanding this relationship is essential to characterize boiling in high gravity applications such as thermal control of rotating machinery by boiling of binary mixture coolant. Hence, the reduced gravity, normal gravity and high gravity experiments on the boiling of binary mixtures could not only reveal important information on the role of Marangoni mechanism on the boiling process but also on the interaction between the buoyancy effect and the Marangoni effect.

Siegel and Usiskin [7] conducted the first reduced gravity boiling experiments in a 0.7-s drop tower. Siegel [8] subsequently published a comprehensive summary of the early studies upto the mid-1960s. Internationally, a renewed interest in the microgravity boiling research has grown over the last years. One of the main reasons is to explore the scope of possible uses of pool boiling in thermal devices of space-bound systems and in materials processing in space. The other principal reason is to investigate the role of gravity in the boiling heat transfer and its parametric influence in pool boiling heat transfer correlations. In particular, the Marangoni effects which arise during boiling in some binary mixtures can be studied effectively in microgravity or reduced-gravity environment with little or no buoyancy effect. Recently, the effects of variable gravity on boiling heat transfer were summarized by Merte [9].

Ervin *et al.* [10] conducted pool boiling experiments using R113 for short duration in microgravity and in earth gravity with different orientations of the heater surface and subcoolings. Abe [11] summarized their first three reduced gravity pool boiling experiments on pure fluids conducted in parabolic flights and sounding rockets. The detailed results of the second phase of the program which consisted of reduced gravity experiments of three pure fluids—*n*-pentane, CFC-113 and water under subcooled conditions were reported by Oka *et al.* [12].

Straub and his co-workers [13, 14] have been investigating pool boiling of pure fluids under microgravity for the past 15 years. Recently, Straub [15] provided a brief summary of the results of German microgravity pool boiling experiments with a view to explain the role of surface tension for two-phase heat and mass transfer in the absence of gravity. Straub [15] argued that the real physical mechanism of the boiling process is not properly understood yet since the gravity-based correlation cannot be extrapolated to reduced or high gravity with reasonable accuracy. The most interesting aspect of the investigations of Straub and coworkers [13–15] is the recognition and importance of surface tension, thermocapillary convection and capillary pressure-driven flow in the pool boiling of pure fluids.

Based on 35 years of research on variable gravity, a general conclusion made by Merte [9] for saturated liquid and short duration test is that nucleate boiling will be enhanced if the buoyancy acts to hold the vapor bubbles near the heater surface, while at the same time permitting access of the liquid to the surface in order to prevent dryout. Abe *et al.* [6] provided a brief summary of the conclusions from the microgravity pool boiling experiments of pure fluids to stress the importance of using some binary mixtures in microgravity boiling to overcome the low heat transfer coefficients and low CHF of pure fluids under such conditions. Abe *et al.* [6] also reported the experimental results of microgravity pool boiling of ethanol/water mixture and showed that in the so-called 'positive' binary mixtures, heat transfer is enhanced due to the reduction of gravity and the reduction of CHF caused by reduced gravity is small compared to that of the pure fluids. These investigators ascribed the enhancement of heat transfer and small reduction of CHF of these binary mixtures to the Marangoni flow induced by an ethanol concentration gradient along the liquid–vapor interface due to the preferential evaporation of ethanol.

The important point to note about the boiling of ethanol/water mixtures studied by Abe *et al.* [6] is that the Marangoni effect, caused by a surface tension gradient due to a concentration gradient along the liquid vapor interface, plays a central role in the bubble detachment mechanism from the heater surface, the enhancement of heat transfer and the CHF condition under microgravity conditions. Therefore, it is reasonable to assume that Marangoni effect also influences the boiling mechanism in the binary mixtures significantly under terrestrial condition although it will be always combined with buoyancy effect. In principle, the heat transfer characteristics of a binary mixture could be altered if the surface tension gradient can be changed by properly selecting the components of the binary mixture and by tailoring the composition of the mixture. Moreover, since the heat transfer and the CHF can be enhanced by using a positive binary mixture, boiling a negative binary mixture can result in deterioration of heat transfer and the CHF.

The present study investigated the Marangoni mechanism in the boiling of positive binary mixtures under reduced, normal and high gravity environments. Boiling of 2-propanol and water mixtures at three different concentrations has been investigated in a DC-9 aircraft which follows a parabolic trajectory and provides 20–25 s of reduced gravity and 20–25 s of high gravity in one parabolic maneuver. The reduced gravity level and high gravity level attained by the aircraft are about 0.01 g_n and 1.8–2.0 g_n, respectively. Four models of binary mixture heat transfer coefficients were tested in an attempt to correlate our experimental data. These are the correlations of Thome [16], Stephan and Körner [17], Schlünder [18] and Ünal [19]. Thome [16] developed a correlation for heat transfer coefficients of binary mixture boiling using only phase equilibrium data which is strictly valid for peak heat flux. Stephan and Körner [17] used an excess function formulation for determining the wall superheat in the boiling of binary mixture. These investigators, then evaluated the heat transfer coefficients using the expression for wall superheat. Based on the film theory of mass transfer, Schlünder [18] proposed a correlation by modeling the growth of a vapor bubble in a binary mixture. In this correlation, only the mass transfer was accounted in computing the local rise in the bubble point temperature. Ünal [19] suggested a correlation for the heat transfer coefficients of binary mixture boiling based on dimensional analysis. The form of the correlations are:

Thome [16]:

$$\frac{h}{h_{\mathrm{id}}} = \frac{1}{1+\Delta T_{\mathrm{bp}}/\Delta T_{\mathrm{id}}}. \tag{2}$$

Stephan and Körner [17]:

$$\frac{h}{h_{\mathrm{id}}} = \frac{1}{1+A_0(0.88+0.12P)|y-x|}. \tag{3}$$

Schlünder [18]:

$$\frac{h}{h_{\mathrm{id}}} = \frac{1}{1+\dfrac{(T_{\mathrm{s2}}-T_{\mathrm{s1}})|y-x|}{\Delta T_{\mathrm{id}}}\left[1-\exp\left(\dfrac{B_0 q''}{\beta_{\mathrm{l}}\rho_{\mathrm{l}}h_{\mathrm{fg}}}\right)\right]}. \tag{4}$$

Ünal [19]:

$$\frac{h}{h_{\mathrm{id}}} = \frac{1}{[1+(b_2+b_3)(1+b_4)][1+b_5]} \tag{5}$$

where

$$b_2 = (1-x)\ln\frac{1.01-x}{1.01-y} + x\ln\frac{x}{y} + |1-x|^{1.5}$$

$$b_3 = 0 \quad \text{for}\, x \geqslant 0.01$$

$$b_3 = (y/x)^{0.1}-1 \quad \text{for}\, x \leqslant 0.01$$

$$b_4 = 152(P/P_{\mathrm{c}})^{3.9}$$

$$b_5 = 0.92|y-x|^{0.001}(P/P_{\mathrm{c}})^{0.66}$$

and

$$x/y = 1 \quad \text{for}\, x = y = 0.$$

In equations (2) and (5), the ideal wall superheat, ΔT_{id}, is defined as the molar averaged value of the wall superheats of the pure components at the same heat flux as the mixture. Therefore, ΔT_{id} can be written as

$$\Delta T_{\mathrm{id}} = x\Delta T_1 + (1-x)\Delta T_2. \tag{6}$$

For the same heat flux for the mixture and the pure components, the ideal heat transfer coefficient, h_{id}, can be evaluated as

$$h_{\mathrm{id}} = \frac{q''}{\Delta T_{\mathrm{id}}} = \frac{1}{x/h_1 + (1-x)/h_2} \tag{7}$$

where h_1 and h_2 are the heat transfer coefficients for the pure components of the mixture.

In equation (2), ΔT_{bp} is the temperature difference between the dew point and bubble point curves at a fixed molar concentration of the mixture and this value is determined from the phase equilibrium data. The empirical constant A_0 in equation (3) depends on the particular mixture. Stephan and Körner [17] determined the value of A_0 for seventeen mixtures ranging from 0.42–3.56 and recommended the average value 1.53 for mixtures whose data are not available. The pressure P in equation (3) should be expressed in bar. In equation (4), T_s is the saturation temperature of the pure components at the same pressure as the mixture, B_0 is a scaling factor set equal to 1.0 and the mass transfer coefficient, β_L, was set to a constant value of 0.0002 m s^{-1}. In the above correlations, x and y are the liquid and vapor mole fraction of the more volatile component, respectively. Thus, $|y-x|$ can be considered as the mass transfer driving potential in the boiling of binary mixture. While the effect of mass transfer driving potential was embedded implicitly in the correlation of Thome [16], the other correlations contain the expression $|y-x|$ explicitly.

In order to evaluate the ideal heat transfer coefficients for binary mixture boiling, correlations for pure component heat transfer coefficients should be selected carefully. This is due to the fact that the accuracy of the predicted heat transfer coefficients for binary mixture boiling is strongly dependent on the satisfactory prediction of pure component heat transfer coefficients. Fujita and Tsutsui [20] recently investigated the heat transfer in nucleate pool boiling of five binary mixtures and the experimental data were compared with the available correlations. These investigators reported that the Stephan–Abdelsalam [21] correlation provided satisfactory prediction of the heat transfer coefficients for five pure single components with considerably different physical properties. Therefore, the Stephan–Abdelsalam correlation was chosen for single component heat transfer coefficients under normal gravity in the present investigation. It is noteworthy that the heat transfer coefficients of the binary mixture boiling, obtained from the correlations, do not show gravity dependence explicitly although it can be a factor if the pure component heat transfer coefficients depend on gravity. For a constant heat flux, the gravity dependence of the wall superheat can be written as [8]:

$$\Delta T/\Delta T_1 = (g/a)^n \tag{8}$$

where ΔT and ΔT_1 are the wall superheat at an acceleration of a and g (earth normal gravitational acceleration), respectively. The gravity dependence of the boiling heat transfer correlation is indicated by the exponent n. Since the value of n for dimensionless group correlations, like Stephan–Abdelsalam [21] correlation, is determined by regression analyses and best fit to the experimental data under normal gravity and do not have any physical meaning, the value of 'n' is chosen from physically-based Roshenow's correlation [22]. A computer program was written to evaluate the wall superheat for a given heat flux in order to generate boiling curves of 2-propanol/water mixtures from the correlations. The predicted curves are then compared to the boiling curves obtained from the experiments under reduced, normal and high gravity levels. The properties of binary mixtures are evaluated with the state of the art models and procedures and described in detail elsewhere [23–25].

EXPERIMENTAL SETUP AND PROCEDURE

Figure 1(a) shows the layout of the experimental hardware. The test section used in our experiments was a 30.48 cm long square (7.62 cm) channel made of stainless steel. The top plate and the two side plates were 0.64 cm thick and the bottom plate was 1.27 cm thick. The bottom plate had a rectangular cut-out to accommodate a replaceable heated surface element. The copper heater element and its stainless steel holder is shown in Fig. 1(b). The heated element was made of oxygen-free, high purity copper to ensure that the thermophysical properties of the element were defined to high accuracy. This element was machined to accommodate two cartridge heaters at the bottom end. The top half of the copper piece was fabricated to provide a long 1.2 cm diameter circular section. In this section, five holes were drilled to the center to hold thermocouple wires. The diameter and the depth of holes were 0.08 and 0.6 cm, respectively, and the bead diameter of the K-type thermocouples used in the experiment was about 0.06 cm. The thermocouples were inserted into the holes and were glued to the circular section of the heater outside the holes. A Metrabyte thermocouple board with integrated cold junction compensation and an IBM DACA board were used to scan the thermocouples and store the temperature in the computer. Along the perimeter of the top section, the copper heating element was silver soldered to the stainless steel holder. The contact area between the stainless steel and the copper was minimized to avoid heat loss. The heat loss was computed from a standard conduction model and it was less than 3% of the heat input. Electric cartridge heaters fitted into the bottom of the copper element provided the heat input which flows along the bar of circular cross section to the flush end exposed to the flow in the test section. The flush end of the copper heater element was a 1.2 cm diameter circular finger. Thermocouples installed along the copper bar allowed measurement of the temperature gradient in the bar, and hence the heat flux to the surface exposed to the flow. Lateral side walls of the test section had rectangular windows made of transparent polycarbonate for flow visualization. The system pump delivered fluid to the inlet header of the test section. A porous plate in the inlet header helped provide even flow distribution in the test section. Flow exiting the test section was piped to the system condenser. A Validyne pressure transducer installed in the test section was used to monitor the pressure in the system. The fluctuation of the measured pressure in the test section was generaly below 5%. However, there were step changes in the pressure during reduced gravity and high gravity due to static pressure head and an appropriate correction term was included due to this pressure change in order to represent the data at

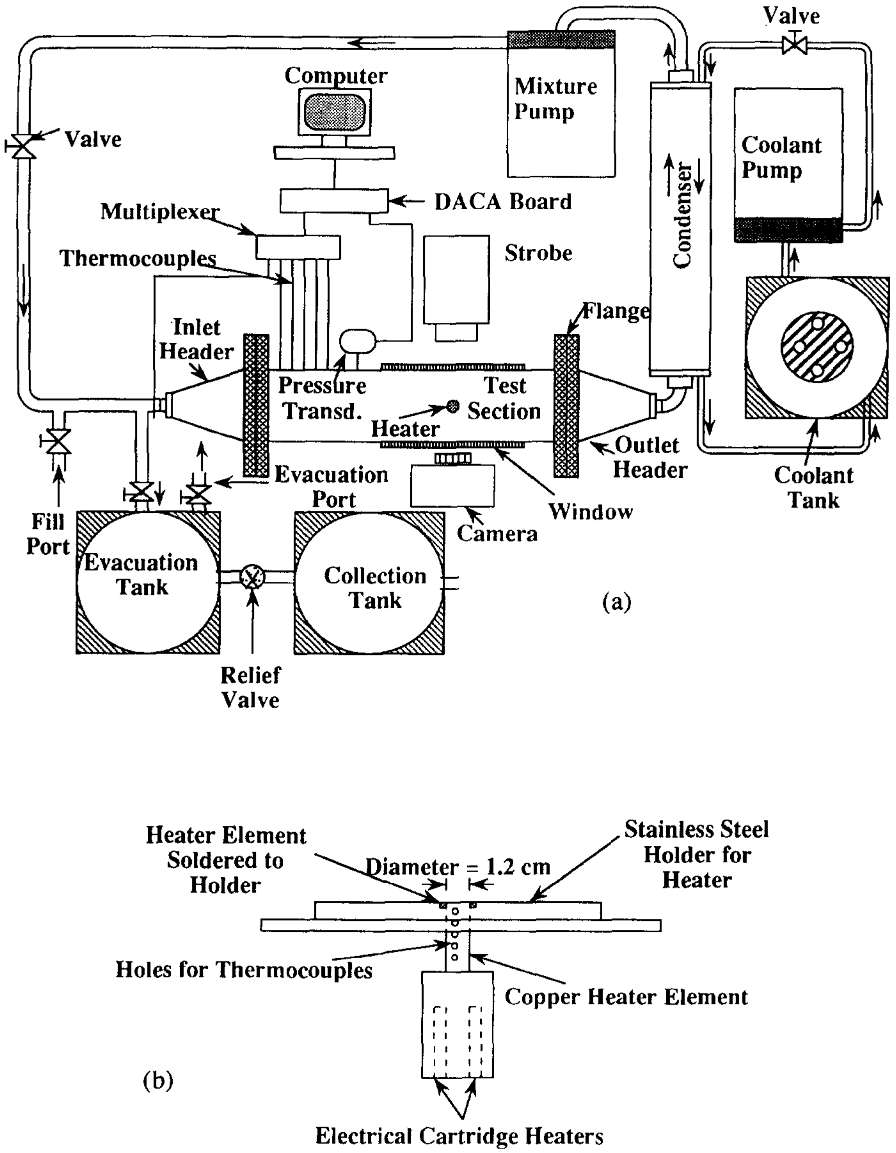

Fig. 1. (a) Layout of the experimental system, (b) copper heater element and its holder.

constant pressure. Experimental uncertainties in the pressure and differential temperature measurements were ±0.2 kPa (4%) and 0.2°C, respectively. The heat flux to the exposed heater surface could be determined within ±5% including the heat loss. The uncertainty in the value of mole fraction is 0.2%. The overall uncertainty in the computation of the bubble point temperature is estimated to be about 1°C.

The experimental setup consisted of two flow circuits; one for the binary mixture and the other for the coolant flow in the condenser. The components of the binary mixture circuit were the test section, a pump and the tubes in the condenser. The heater element at the bottom of the test section heated up the binary mixture. The purpose of the pump was to maintain a constant flow in the test section and the condenser. The intention of this design was to provide a weak bulk convective motion that would not affect the nucleate boiling process on the heated surface, but would carry vapor bubbles that leave the surface during the boiling process to the condenser. The objective was to sustain a steady nucleate boiling process while maintaining constant pressure and bulk concentration in the test section. The coolant circuit considered of a coolant pump, a coolant tank and the shell of the condenser. A support structure for the test system was built by using 13/16″ aluminum Unistrut bar. The test system along with its support structure was mounted in one of two Learjet racks provided by NASA. The computer, data acquisition system and all the electrical components were mounted on another Learjet rack. The thermocouple and pressure data were monitored using a PC-based data acquisition system.

The binary mixture circuit was evacuated by a vacuum pump. Distilled water and laboratory grade 2-propanol were used to prepare the mixture. The flow of binary mixture from the charging tank filled up the system when the fill port was opened. To degas the mixture, pressure was lowered much below the working pressure of the system which caused the noncondensable gases to leave the mixture. The collected noncondensable gases in the evacuation tank were purged from the experimental system by the vacuum pump. The pressure of the system could be lowered by bleeding vapor from the evacuation tank or could be increased by filling the system with more liquid mixture. When pressure became steady, the pumps were turned on. Electrical power was supplied to the cartridge heater and the heat flux to the binary mixture was controlled by a variac. The heat flux was obtained from a least-square fit of the five thermocouples embedded along the heater element and the surface temperature was computed by extrapolation. The experiment was continued until the system reached the critical heat flux. During 1-g_n experiments, the system pressure and temperature were stabilized for the upward facing heater surface and the experiment is conducted for this orientation. At the end of the experiment, there was a cool down period when the system pressure and the temperature was re-stabilized. At that point, the rack was oriented to conduct experiments for the downward-facing configuration. The test surface of the heater did not change appreciably for 4–5 complete experimental runs. For most cases, the surface of the heater was cleaned with emery paper and alcohol after each experiment. During the flight experiment, pressure was maintained constant in each flight experiment. At the beginning of every other parabola, the heat flux was set and the temperature profile in the heater element was monitored and recorded. When the flight experienced a transition from 2 g_n to reduced gravity, the gravitational part of the heat flux was expected to approach zero while the heat flux due to Marangoni effects became the dominant mechanism to sustain nucleate boiling. Therefore, the system experienced a transient heat transfer mode and restabilized at a new heat flux value which was monitored from the thermocouple readings. The normal gravity experiments for the boiling of binary mixture were performed in the Multiphase Transport Laboratory at the University of California at Berkeley and the reduced and elevated gravity experiments were performed in the DC-9 reduced gravity aircraft at NASA Lewis Research Center.

RESULTS AND DISCUSSIONS

For a particular experimental run, P was the fluid pressure on the heater element including the hydrostatic pressure of the fluid column. In general, the pressure fluctuation was within the range of the estimated uncertainty in the measurement. However, the bubble-point temperature of the mixture was computed at the actual pressure for each data point and subtracted from the wall temperature of the heater in order to determine the wall superheat. The procedure to compute the bubble point temperature of binary mixtures are described in detail by Ahmed [26]. Figure 2 shows the boiling curve for 2-propanol/water binary mixture at earth-normal gravity for two different orientations of the heater surface; upward facing and downward facing. The molar concentration of 2-propanol in the mixture is 0.015. Also shown in the plot is the critical heat flux for water at the same pressure computed from McGillis–Carey correlation [4]. It is evident from the plot that the critical heat flux of 2-propanol/water ($x_p = 0.015$) is greater than that of pure water under the same condition by a factor of three at same system pressure and orientation. Another interesting point to note is that the critical heat flux of 2-propanol/water ($x_p = 0.015$) at downward facing heater configuration is substantially more than that of pure water at upward facing configuration. The heat transfer is enhanced as the heater surface is oriented from horizontal up to horizontal down configuration apparently because the heated layer of fluid stays close to the heater surface and close proximity of the bubble to the heater surface increases the microlayer area and/or decreases its thickness, as was observed by Merte [9]. But this improvement in heat transfer, in pure fluids, is usualy offset by lower CHF under this condition because a large single bubble blocks the supply of liquid to the heater surface. The higher CHF of the binary mixture for the downward heater compared to the CHF of pure water on an upward facing heater suggests that Marangoni forces due to concentration gradients along the liquid–vapor interface act to draw liquid towards the heater surface.

The transient wall superheat and g-level during an experimental cycle in a DC-9 reduced gravity flight are shown in Fig. 3. Although the DC-9 aircraft is used for reduced gravity environment for 20–25 s, there is an elevated gravity (1.8–2.0 g_n) period during each parabolic maneuver which also lasts 10–25 s. During this change in gravity level, the hydrostatic pressure of the system changes by 2 kPa/1 g_n resulting in a shift in the saturation temperature of the binary mixture by about 4–5°C/1 g_n. The wall superheat changes during this change in gravity level but reaches a steady state value within 1°C during both the elevated gravity period and the reduced gravity period. Since the heater was insulated along the circumference, the conduction can be assumed to be one-dimensional. The thermal time constant (which can be estimated as L^2/α) for the 4 cm long copper heater is 14 s. Since the duration of both the reduced and the high gravity period was more than this time constant, the heat flux obtained from the thermocouples were essentialy steady state values for the system. Moreover, the temperature profiles along the heater

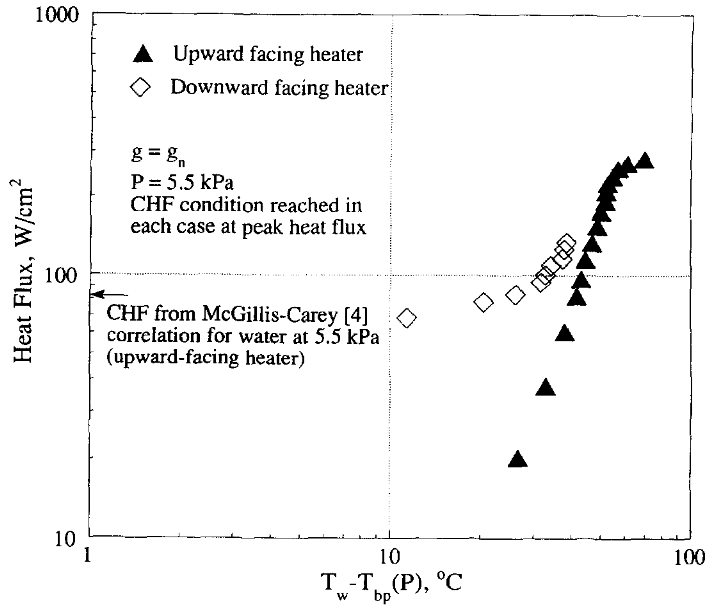

Fig. 2. Boiling curves of water/2-propanol mixture ($x_p = 0.015$) for upward and downward facing heater surface under normal gravity.

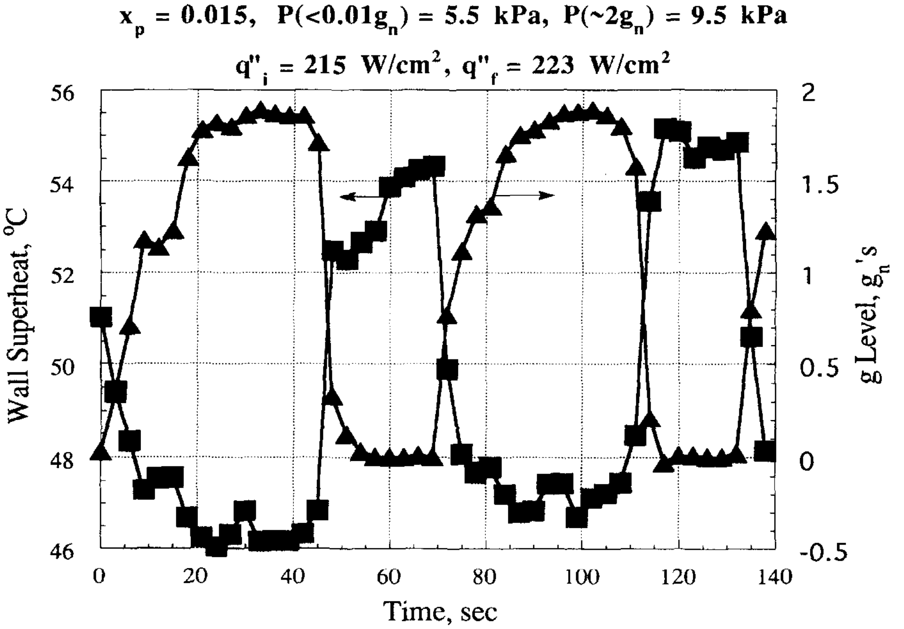

Fig. 3. Variation of g-level and wall superheat during an experimental cycle aboard DC-9 reduced gravity aircraft for $x_p = 0.015$.

obtained from five thermocouples were studied in detail [26] and found to ensure the steady state condition of the system.

The boiling curves at reduced gravity for three different concentrations are plotted in Fig. 4. The molar concentrations of the 2-propanol/water binary mixtures are 0.015, 0.025, 0.1 and the surface tension gradients of these mixtures decrease with concentration. The log–log plots show that the boiling curves roughly follow the general 1/3 power law ($\Delta T_{sat} \sim (q'')^{1/3}$). Since the system pressure was slightly higher for 0.1 concentration than the other concentrations tested during the flight test, the boiling curve for this concentration was replotted by adding

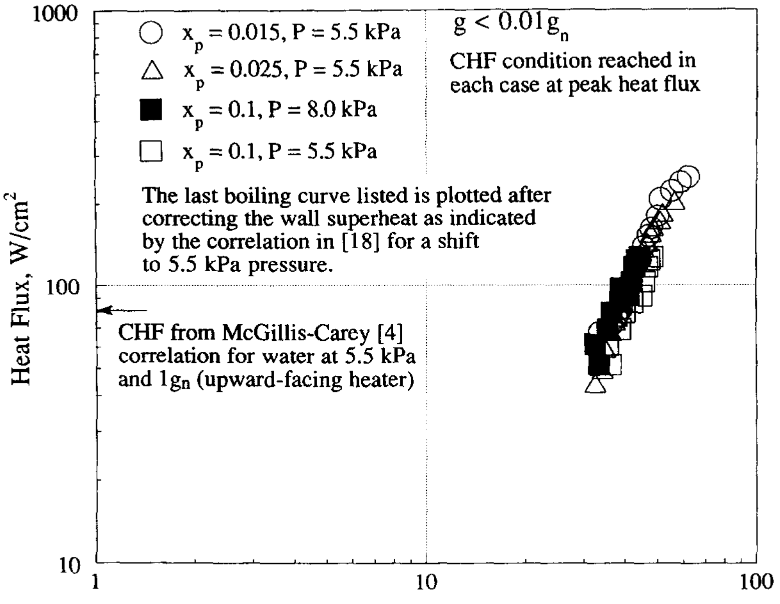

Fig. 4. Reduced gravity boiling curves for water/2-propanol mixtures at different concentrations.

a correction term in the wall superheat value due to the small variation in the pressure determined from the correlation of Schlünder [18]. Other than the CHF condition, the heat transfer characteristics of the 2-propanol/water binary mixtures are not apparently affected by the concentration of the mixtures. The variation of the surface tension gradient of a water/2-propanol mixture with the concentration of 2-propanol, computed from state-of-the art models [23], is shown in Fig. 5. It is clear from the plot that the surface tension gradient is very high when the concentration of 2-propanol is below 0.02 and the gradient gradualy diminishes as the concentration reaches about 0.2. The boiling curves (Fig. 4) imply that the higher the surface tension gradient the higher the critical heat flux. It is evident that the critical heat flux correlates strongly with the surface tension gradient and hence the Marangoni effect. At the heater surface, alcohol evaporates preferentially which has a lower surface tension. Therefore, the surface tension of the liquid close to the solid–liquid–vapor interface is higher than the bulk surface tension around liquid–vapor interface. This surface tension gradient apparently causes more liquid to flow towards the heater surface and delays the onset of dry-out.

Figure 6 shows the boiling curves for the same concentrations of 2-propanol/water mixtures at high gravity level obtained from the DC-9 flight experiments. The gravity level during this part of the experiments were between 1.8–2.0 g_n. However, the hydrostatic pressure on the heater surface changed by 2 kPa/1 g_n due to higher gravity level and the critical heat flux condition was not attained at this gravity level. The boiling curves are similar and the heat transfer characteristics seem not to change significantly with the concentration of the mixture.

At different gravity levels, the boiling curves for the 0.015 molar concentration of 2-propanol/water binary mixture are shown in Fig. 7. The nominal system pressure was 5.5 kPa for both reduced gravity and normal gravity experiments but the pressure was 9.5 kPa for high gravity experiment. To investigate the role of gravity on the boiling heat transfer characteristics of binary mixtures at constant pressure, the boiling curve for high gravity was replotted using a correction term for the change in pressure as described earlier. The curves show that the boiling heat transfer was virtually the same under reduced gravity and terrestrial conditions. However, the critical heat flux of the mixture under reduced gravity decreased by about 10% for 0.015 mole fraction mixture compared to the terrestrial level. Similar reduced gravity boiling characteristics of ethanol/water binary mixtures were reported by Abe *et al.* [6]. Figure 8 shows the boiling curves at different gravity levels for the 0.025 molar concentration of 2-propanol in water. The nominal system pressure was the same as the previous case. The trend of the curve is consistent.

Figure 9 shows the comparison of the boiling curves obtained from four correlations and the experimental curve for normal gravity for a 2-propanol concentration of 0.015. The agreement between the experimental curve and the predicted curves from the correlation of Thome [16] and Schlünder [18] are good for normal gravity. However, the reduced gravity boiling curves from these correlations do not agree as

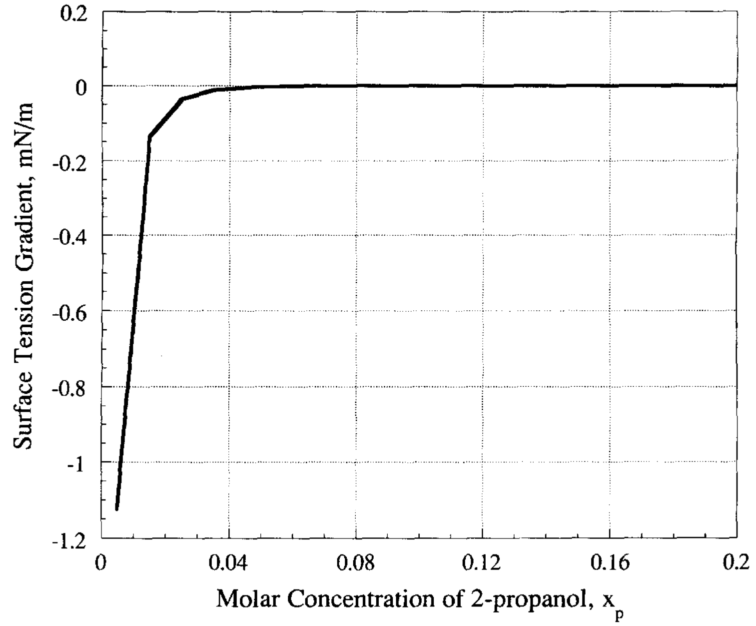

Fig. 5. Variation of surface tension gradient with the concentration of 2-propanol in the mixture [23].

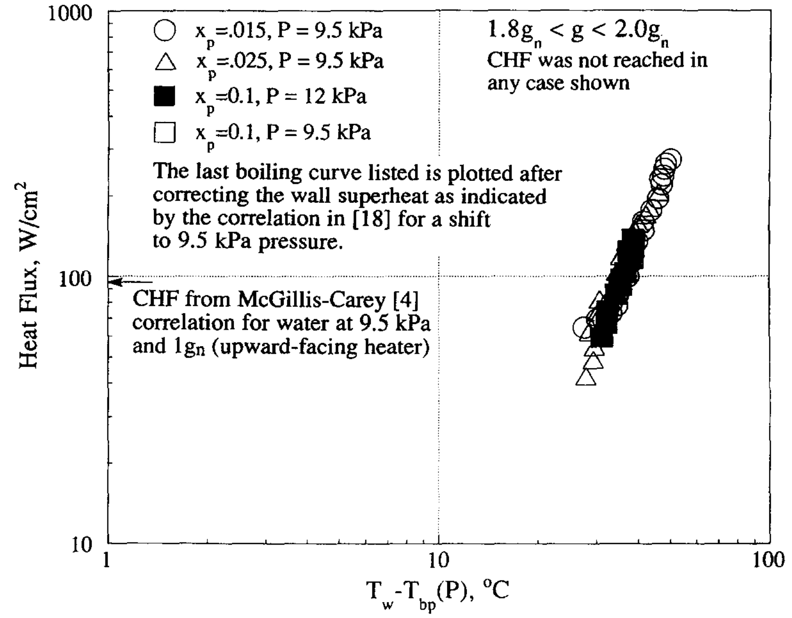

Fig. 6. High gravity boiling curves or water/2-propanol mixtures at different concentrations.

shown in Fig. 10. Figure 11 shows that these two correlations predicts the boiling curves at high gravity with reasonable accuracy. The predicted CHF values from McGillis–Carey correlation are compared with the experimental value for normal and reduced gravity in Fig. 12. The variation of the CHF value with the gravity from the same correlation and the limited experimental data are plotted in Fig. 13. Although the agreement is good for normal gravity, the reduced gravity CHF is underestimated by the correlation.

The important characteristics of the boiling of pure fluids under reduced gravity reported by Oka *et al.* [12], Straub *et al.* [13, 14] and Merte [8] are that heat transfer generally deteriorated in microgravity and critical heat flux decreased severely. However, these detrimental characteristics of reduced gravity boiling

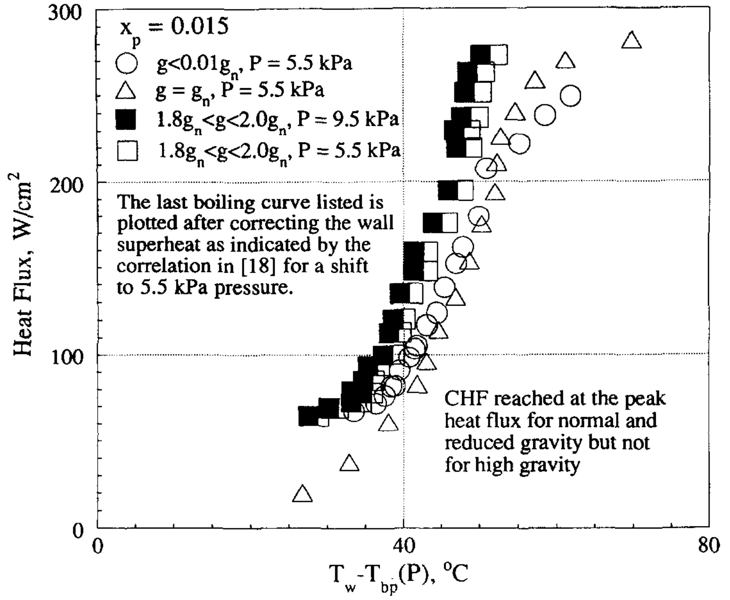

Fig. 7. Effect of gravity on the boiling of water/2-propanol mixture for $x_p = 0.015$.

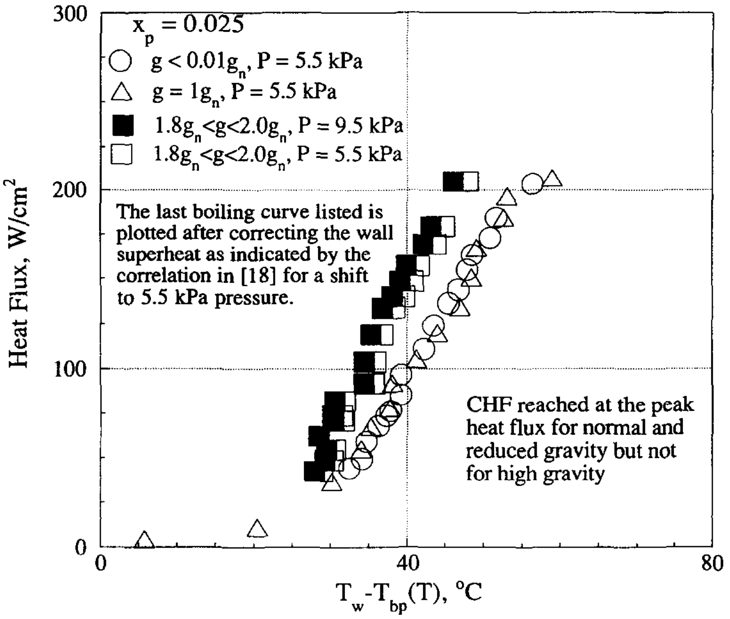

Fig. 8. Effect of gravity on the boiling of water/2-propanol mixture for $x_p = 0.025$.

of pure fluids were not observed in the boiling of binary mixtures in the present investigation. Boiling heat transfer and the critical heat flux condition in the boiling some binary mixtures were found to be independent of gravity level.

CONCLUDING REMARKS

The data obtained in this investigation imply that the Marangoni effect arising from the surface tension gradients due to concentration gradients is an active mechanism in the boiling of binary mixtures such as 2-propanol/water. At a molar concentration of 0.015 of 2-propanol in water, where the surface tension gradient is highest among the concentrations tested, the critical heat flux is a factor of three greater than that of pure water for similar conditions under normal gravity. The present data for the reduced gravity boiling of binary mixtures indicates that the higher the surface tension gradient of the mixture, the higher the critical heat flux which is the fundamental basis for McGillis–Carey [14] correlation. Since the buoyancy

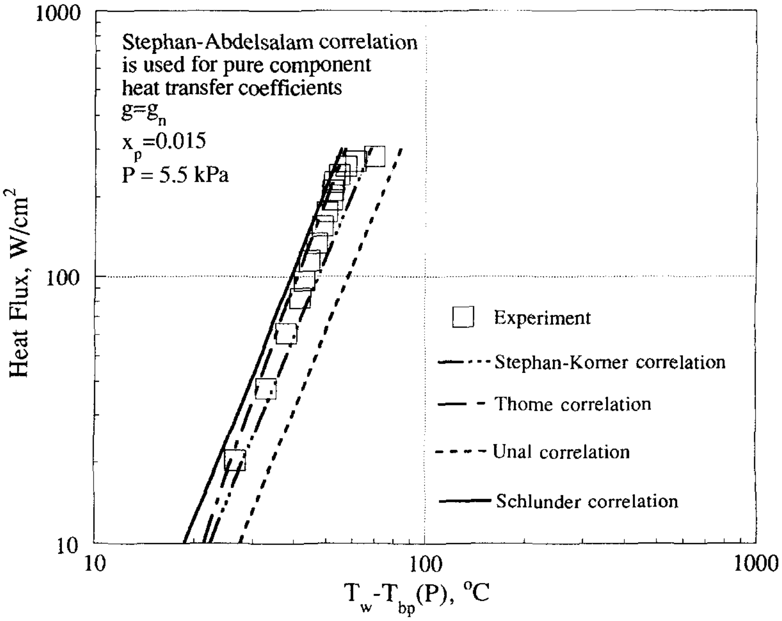

Fig. 9. Comparison of the normal gravity boiling curves for $x_p = 0.015$ obtained from the experiment and the predictive models.

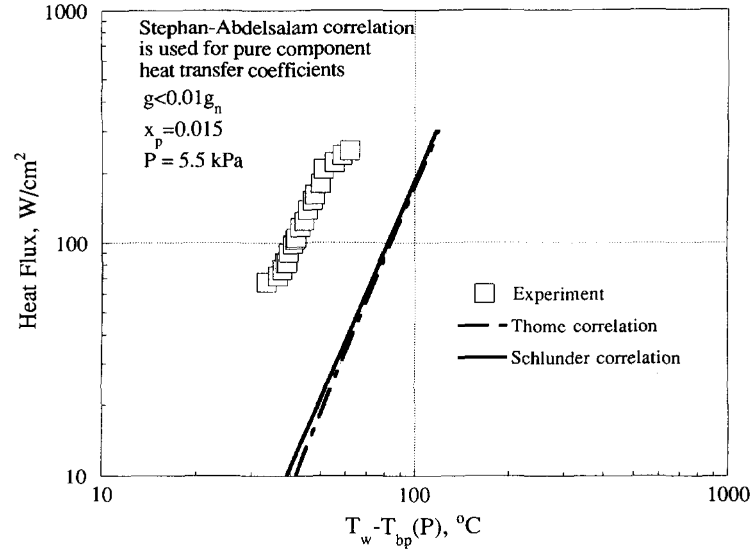

Fig. 10. Comparison of the reduced gravity boiling curves for $x_p = 0.015$ obtained from the experiment and the predictive models.

effects on the boiling are virtually negligible under reduced gravity, the present investigation proves decisively that robust pool boiling of binary mixtures can be sustained under reduced gravity if the surface tension-driven flow or Marangoni flow is strong enough to maintain a liquid layer on the heater surface. The effect of gravity on the boiling curves of binary mixtures found in this investigation are consistent with the trends in data reported by Abe *et al.* [6]. Comparing the present data for boiling curves with the available correlations of binary mixture boiling, the correlations of Thome [16] and Schlünder [18] are found to work well for normal and high gravity. On the contrary, these correlations cannot predict the boiling heat transfer characteristics of binary mixtures under reduced gravity. The agreement between the predicted and the experimental boiling curves for elevated gravity, which is only twice the normal gravity,

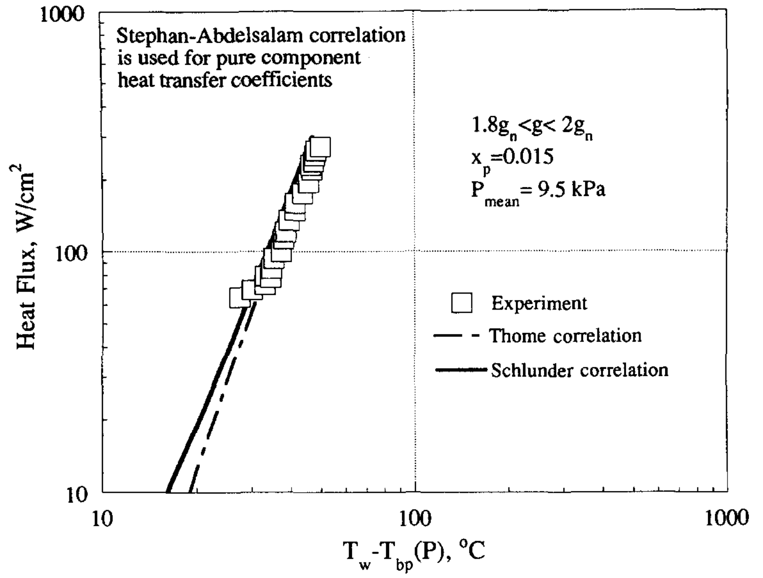

Fig. 11. Comparison of the high gravity boiling curves for $x_p = 0.015$ obtained from the experiment and the predictive models.

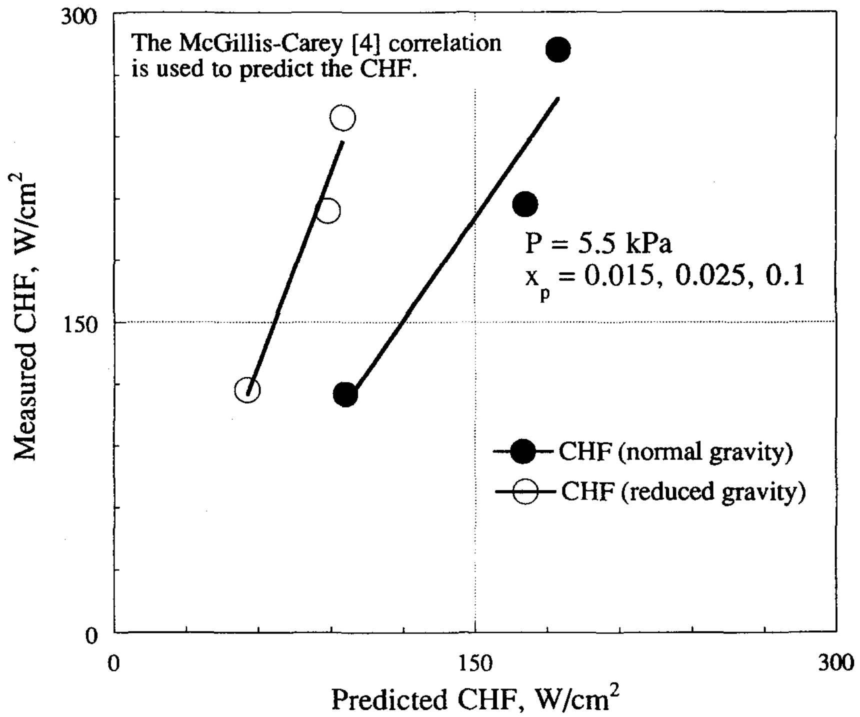

Fig. 12. Comparison of the CHF value obtained from the experiment and the McGillis–Carey correlation for reduced gravity and normal gravity.

provides the confidence in using the predictive correlations for the boiling of binary mixtures when the gravity change is relatively small. However, the vast difference in the predicted and the experimental boiling curves for reduced gravity, which is one hundredth of the normal gravity, clearly indicates that these correlations are not valid when the gravity changes by orders of magnitude. The predicted CHF value obtained from McGillis–Carey correlation [4] agrees well with the experiment for normal gravity but under-

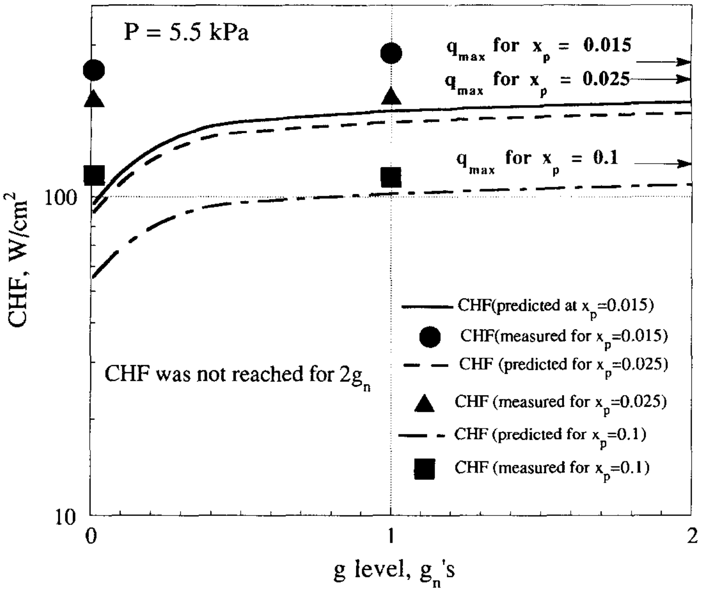

Fig. 13. Effect of gravity on the CHF condition obtained from McGillis–Carey correlation and from limited experimental data.

estimates the CHF for boiling under reduced gravity.

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