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(Review)

Review of Reduced Gravity Boiling Heat Transfer: US Research

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Abstract

A brief review of recent low gravity boiling research by investigators based in the United States is performed. Topics covered include bubble dynamics, nucleate pool boiling and CHF, transition boiling, boiling of mixtures, electric field effects, acoustic field effects, and flow boiling. Planned research activities and recommendations for future research are given.

1. Introduction

The relatively poor understanding of gravity effects on multiphase flow and phase-change heat transfer has been identified as one of the primary obstacles to reliable design of space based hardware and processes such as heat exchange, cryogenic fuel storage and transportation, propulsion, and electronic cooling[1,2]. Although much research in this area has been performed since the Space Station was proposed, the mechanisms by which heat is removed from surfaces under these environments are still unclear. This lack of understanding has led to use of lower power components in space-based systems since higher power systems requiring the use of two-phase flow has been considered to be risky. If gravity effects on two-phase flows can be quantified, the size and weight of these systems can be reduced, reducing the launch costs of components and space based systems.

Boiling is significantly affected by buoyancy. In low gravity environments, the magnitude of effects related to natural convection and buoyancy are small and physical mechanisms normally masked by natural convection in earth gravity such as Marangoni convection can substantially influence boiling and vapor bubble dynamics. Experiments to date have shown that commonly used correlations do not properly account for the effect of gravity on boiling processes. For example, the correlation by Rosenhow[3] for nucleate pool boiling

$$\frac{\dot{q}''}{(T_w - T_{sat})^3} C_{sf}^3 = \frac{\mu c_p^3}{h_{fg}^2 \mathrm{Pr}^{3s}} \sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}}$$

predicts that the heat flux goes to zero in the absence of gravity, but experiments to date have shown this to be erroneous. Another commonly used correlation for nucleate pool boiling is given by Cooper[4]

$$h_{nb} = 55(\dot{q}'')^{0.67} M^{-0.5} P_r^m (-\log_{10} P_r)^{-0.55}$$

where

$$m = 0.12 - 0.2 \log_{10} R_p$$

and P_r = reduced pressure, M = molecular weight, and R_p = rms surface roughness in microns. This correlation does not have any dependence on gravity, which again is inconsistent with experiments. Similarly, Stephan and Abdelsalam[5] used regression analysis to obtain correlations for various classes of fluids based on a large body of data, but the data were limited to fully developed nucleate boiling on horizontal surfaces under the influence of gravity. None of their final correlations contain gravity as a parameter.

CHF is also substantially affected by microgravity. In 1-g environments, Bo has been used as a correlating parameter for CHF. Zuber's[6] CHF model for an infinite horizontal surface assumes that vapor columns formed by the merger of bubbles become unstable due to a Helmholtz instability, blocking the supply of liquid to the surface. The jets are spaced λ_D (the Taylor wavelength) apart, where

$$\lambda_D = 2\pi\sqrt{3}\left[\frac{\sigma}{g(\rho_l - \rho_v)}\right]^{1/2} = 2\pi\sqrt{3}\,LBo^{-1/2} = \sqrt{3}\,\lambda_c$$

and is the wavelength that amplifies most rapidly. The critical wavelength, λ_c, is the wavelength below which a vapor layer underneath a liquid layer is stable. For heaters with Bo smaller than about 3 (heaters smaller than λ_D), the above model is not applicable, and surface tension dominates. Bubble coalescence is thought to be the mechanism for CHF under these conditions. Small Bo can result by decreasing the size of a heater in earth gravity, or by operating a large heater in a lower gravity environment. In the microgravity of space, even large heaters can have low Bo, and models based on Taylor and Helmholtz instabilities should not be applicable. Zuber's[6] correlation

$$\dot{q}''_{\max} = 0.131 \rho_v^{1/2} h_{fg} \sqrt[4]{g(\rho_l - \rho_v)\sigma}$$

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predicts a vanishing heat transfer as the acceleration approaches zero, as does the similar correlation of Lienhard and Dhir[7]. The macrolayer model of Haramura and Katto[8] is of similar form, and also predicts a vanishing heat transfer. Recent experimental data suggests that *Bo* is not the only quantity that determines whether buoyancy or instability controls the boiling process. For example, DiMarco and Grassi[9] studied boiling on a 0.2 mm diameter wire using R113 and FC–72 in low gravity. They observed that for a given R', defined as

$$R' = \sqrt{Bo} = \frac{R}{l_L}, \quad l_L = \sqrt{\frac{\sigma}{g(\rho_l - \rho_l)}},$$

earth gravity data showed a higher CHF relative to that on a flat plate than the microgravity data. Such findings suggest different non-dimensional groups containing acceleration and wire diameter are needed.

The purpose of this paper is to review recent (primarily after 1998) US based research on low gravity boiling heat transfer. Recent Japanese and European research is covered by other papers in this volume. Because of space limitations, only research performed in low gravity environments using vapor/liquid systems is included. The large body of data obtained in earth gravity using surfaces inclined to the gravity vector and/or gas/liquid systems are generally not included.

2. Early Research

Many of the early experimental studies regarding boiling heat transfer in microgravity environments were first performed under NASA sponsorship in drop towers during 1960's. The results of these early experiments were somewhat contradictory, with some experiments showing no effect of gravity on heat transfer and others showing a strong dependence. Much of the discrepancy can be attributed to the relatively short test times that were available since natural convection from before drop initiation could not be eliminated during the short drop time. Visual observations of the boiling process, however, revealed that a large increase in bubble size (up to a few millimeters) occurred under microgravity conditions, with small bubbles coalescing into larger bubbles a small distance from the heater. Siegel and Keshock[10], for example, found the bubble departure radius varied approximately as $a^{-1/3}$ for $0.1 < a/g < 1$, and according to $a^{-1/2}$ for lower gravities. The reader is referred to Siegel[11] and Clark[12] for a review of the early literature. A good review of the work through 2000 is provided by DiMarco and Grassi[13].

3. Bubble dynamics

The effect of low gravity on the dynamics of single bubbles using water was studied by Qui et al.[14]. A single artificial cavity that served as nucleation sites was micromachined into a silicon wafer that was heated from the backside by numerous strain gauge heating elements. The elements were grouped into different regions, with each region having its own thermocouple and feedback controller to keep it at a set temperature. The backside of the wafer was insulated with silicone rubber and mounted on a G–10 base. Measurements of the bubble shape vs. time were obtained from inception to departure under saturated and slightly subcooled conditions during the low gravity environment provided by the KC–135. The bubbles grew to a much larger size in low gravity compared to earth gravity (~2.5 mm in earth gravity up to 22 mm in low gravity). The bubble growth time also increased significantly. Because the bubbles grew so slowly, bubble departure could be predicted using a force balance between surface tension and buoyancy forces just prior to bubble departure when g_x and g_y were small compared to g_z. The departure diameter was found to scale with $g_z^{-0.5}$, consistent with the results of Siegel and Keshock[10] and the Fritz[15] correlation. Similar scaling was found from numerical simulations of the bubble growth by Son et al.[16]. The bubble growth time was found to scale with $g_z^{-1.05}$ from the experiments, which agreed well with the numerically obtained values of $g_z^{-0.93}$ between $0.01 < g_z/g_e < 1.8$. These results are for cases where the bubble size is much larger than the superheated liquid layer thickness for the majority of the bubble growth period. Subcooling had a negligible influence on the bubble departure diameter, but strongly influenced the bubble growth rate. Sliding bubbles occurred when $g_{xy} = \sqrt{g_x^2 + g_y^2}$ was similar to 0.01 g_e. The asymmetric forces on the bubble caused the bubble to distort, and the shear-lift force that developed resulted in a smaller departure diameter.

Local heat transfer measurements in low-g during single bubble dynamics and merger of two bubbles were studied by Qui et al.[17]. Five cavities micromachined into a silicon wafer provided nucleation sites (only two were active in this study). The power to the heating elements were monitored during the growth, merger, and departure process. The heating elements directly under the cavity for the single bubble study was observed to increase during bubble nucleation, decrease to a low value indicating dryout, then spike at bubble departure as liquid rewetted the surface just after liftoff. When two cavities were activated, the heat transfer under one of the cavities increased during bubble growth, decreased as dryout occurred, then increased at liftoff. Similar behavior was observed for the other cavity during growth and dryout, but the heat transfer remained low after merger, indicating continued dryout at that cavity.

Abarajith et al.[18] used the level set method to numerically simulate single bubbles growing in the low gravity environment of the KC–135. Both constant gravity level and the measured gravity level were used in the simulations. Good agreement was observed with the observed bubble shapes, especially when the measured gravity was taken into account. Small amounts of negative gravity were observed to flatten the bubble, increasing the wall heat transfer and the size of the bubble. It also increased the thermal boundary layer thickness. The bubble was observed to depart when it reached the lift-off diameter predicted by the Fritz correlation using the gravity at that instant.

4. Nucleate boiling and CHF

Transient measurements of nucleate boiling were performed by Ervin et al.[19] and Lee and Merte[20] using the 5.2 s drop tower at NASA. A relatively large (19.05 mm × 38.1 mm), flat heater made by depositing a 400 Angstrom gold film onto a quartz substrate was used. The thinness of the gold film allowed images of the boiling to be obtained through the bottom of the heater. Data was collected at three heat fluxes (4, 6, and 8 W/cm^2) and three subcoolings (0, 3, and 11°C). Explosive growth of a bubble with a ''roughened'' liquid-vapor hemispherical interface was sometimes observed during the experiments, typically at high wall superheats and low subcoolings. The growth rate could be higher than that predicted for inertially dominated growth with the bulk liquid superheated to the wall temperature due to the increased surface area. Quasi-homogeneous bubble growth could occur at temperatures well below the superheat limit.

Lee et al.[21] described the results of boiling on a flat plate heater obtained in the long duration microgravity provided by the Space Shuttle. Data was collected at three heat fluxes (2, 4, and 8 W/cm^2) and three subcoolings (0, 2.7, and 11°C) during three space experiments (STS–47 in 1992, STS–57 in 1993, and STS–60 in 1994) for a total of 27 data runs. Each data run lasted up to 120 s. The temperature of the heater was measured at a sampling rate of 10 Hz after a step change in power was imposed on the heater. The measurements were repeated after each flight to obtain 1 g data. True steady state boiling was obtained during 13 of the 27 runs; transient boiling was observed in the others. Steady state boiling always occurred at the two lower heat flux levels with 11°C subcooling. A large bubble formed during the initial nucleation, and could hover just over the heater or stay attached depending on how rapidly it grew initially. This bubble served as a vapor sink for the smaller bubbles generated on the surface in either case and allowed liquid to rewet the wall, resulting in higher than expected heat transfer. The size of this bubble remained roughly constant, indicating a balance between condensation at the bubble cap and vapor addition by coalescence with small bubbles at its base. The heat transfer coefficient for the lower wall heat flux was about 30% higher in microgravity than in earth gravity, and was speculated to be due to the increase in size of the bubbles on the surface. Transient dryout occurred at 8 W/cm^2 for all the subcoolings tested, and was usually associated with an increase in the dry area on the heater. Quasi-steady nucleate boiling sometimes occurred until the size of the large bubble increased until contact with the wall opposite the heater was made, inducing dryout on the heater. Based on the transient data obtained, CHF was estimated to occur between 4–6 W/cm^2, about 1/3 of the earth gravity values. For a given heat flux, lower wall temperatures were observed for higher subcooling.

Merte et al.[22] and Lee[23] describe results from two additional space flights (STS–72 and STS–76 in 1996). The heat fluxes on STS–72 were similar to those on the earlier three flights, but the subcooling was increased to a maximum of 22°C. The subcooling levels on STS–77 were similar to the earlier three flights, but the heat flux was decreased to a minimum of one-fourth that previously used. They found that the large vapor bubble above the heater tended to remain closer to the heater surface as the subcooling increased, and this was attributed to condensation at the bubble cap and the formation of Marangoni convection at higher subcoolings. Marangoni convection caused flow of liquid from the base of the bubble to the bubble cap causing the bubble to be impelled towards the surface. The bubble served as a sink for the small bubbles generated on the surface promoting heat transfer, but it also caused partial dryout on the heater, increasing the surface temperature. Large spikes in heat transfer were occasionally observed when dual large bubble formed on the heater, then coalesced to form a single large bubble that then became somewhat removed from the surface. Marangoni convection was also thought to cause the observed migration of small bubbles from their location of origin towards the large bubble for high subcooling (16.7–22°C) and a heat flux of 2 W/cm^2. Bubble velocities of 2 cm/s were common. The heat transfer coefficient when bubble migration was present was higher than that for 4 W/cm^2 at the same subcooling. A heat transfer enhancement of up to 40% was attributed to bubble migration. They also postulated that microlayer evaporation also contributed to significantly to wall heat transfer. Nucleate pool boiling curves that summarize the results of their space flight experiments are shown on **Fig. 1**. Higher subcooling generally results in smaller superheats. Higher heat fluxes occur in microgravity compared to earth gravity at lower superheats, but the CHF is about half that in earth gravity except for the high subcooling case in microgravity.

Kim et al.[24] used a microheater array consisting of ninety-six individual heaters each 0.27 × 0.27 mm in size to measure time and space resolved heat transfer during subcooled boiling of FC–72 using a parabolic aircraft to provide low gravity and high gravity environments. Their use of electronic feedback circuits

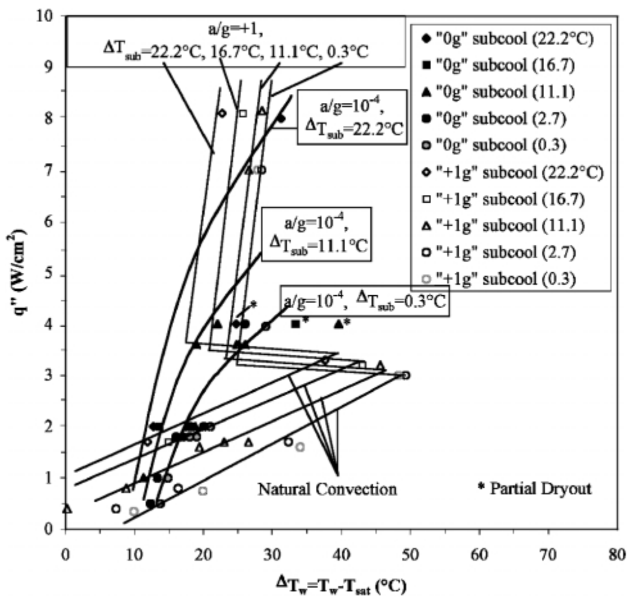

Fig. 1 Nucleate boiling curve from Lee[23].

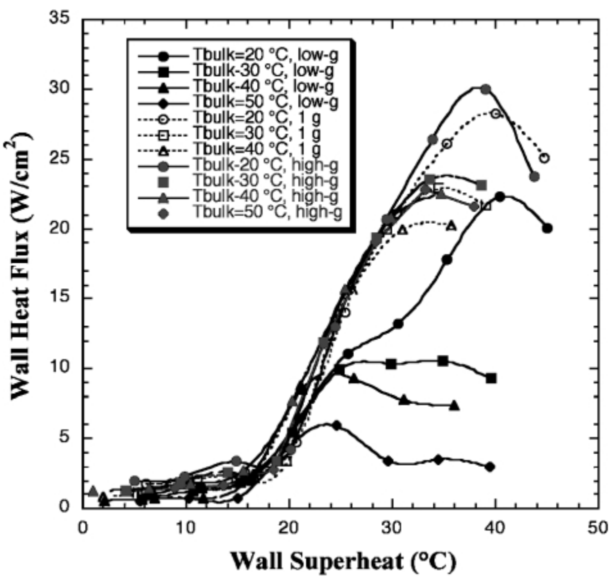

Fig. 2 Nucleate boiling curve from Kim et al.[24].

to keep each of the heaters in the array at a constant temperature enabled them to obtain heat transfer in the nucleate boiling, CHF, and transition boiling regimes. The heater design also allowed images of the boiling process to be obtained through the heated surface. Data was obtained at superheats as high as 45°C and subcoolings between 7–34°C. The formation of a primary bubble surrounded by many smaller ''satellite'' bubbles was observed, similar to the observations of Merte[22], despite the large difference in heater size. Their observations indicated that low gravity boiling heat transfer is dominated by the formation of a large primary bubble on the surface by the coalescence of smaller bubbles. Dryout occurred under the primary bubble, causing CHF in low gravity to be significantly lower than in earth gravity. The primary bubble also limited the size of the smaller satellite bubbles, causing significant bubble activity and higher heat transfer rates. Boiling curves showing the effect of subcooling and gravity are shown on **Fig. 2**. Subcooling is observed to have a strong effect on the size of the primary bubble and on CHF. CHF increases with higher subcooling and gravity level. The effect of g-jitter must be considered for the low gravity curves. Higher wall superheat is generally associated with larger primary bubbles, which are more sensitive to g-jitter. When the primary bubble moves on the surface or departs due to g-jitter, liquid rewets the surface and results in higher wall heat transfer than would occur in a true microgravity environment. The data at low subcooling and high wall superheats (especially those beyond CHF) may be artificially high as a result. By sampling the heat transfer from each individual heater in the array only when small bubbles were present on that heater (satellite bubbles in low gravity, the bubbles that form everywhere on the heater during nucleate boiling or when liquid contacted the surface during transition boiling in earth and high gravity) it was possible to measure the ''nucleate boiling heat flux''. It was shown that the nucleate boiling heat flux collapsed onto a single curve, indicating that the small scale boiling was independent of subcooling and gravity level. This suggests that if one is able to predict the extent of the dry area in microgravity (or lunar and martian gravity), then one can predict the microgravity boiling curve from earth gravity boiling data. It also suggests that CHF in low gravity simply results from the competition between increasing heat transfer from the satellite bubbles and the increase in the dry area under the primary bubble.

Shatto and Peterson[25] studied CHF using a cylindrical cartridge heater (9.4 mm dia. × 44.5 mm long) immersed in water on the KC–135. The pressure was reduced to approximately 1/4 atm ($T_{sat} \sim 64$°C) for safety reasons, and the bulk liquid was subcooled by less than 2.0°C. For the cylinder used in this study, $R' < 0.4$, indicating that it was a small cylinder. CHF was taken to occur when the vapor on the heater abruptly changed from individual bubble departure to a thick, pulsating vapor film. At high heat flux (>20 W/cm^2), vapor columns were ejected from the surface at regular intervals. CHF increased with gravity during the nominally ''zero-g'' parabola, from about 10 W/cm^2 at $g_z/g_e \sim 0.0005$ to 25 W/cm^2 at $g_z/g_e \sim 0.044$, and was lower than the CHF correlation of Lienhard and Dhir[7] by an average of 40%. They argued that the difference between the data and the correlation are caused by thermocapillary effects. Thermocapillary convection has been observed by numerous researchers[22,24,26] to form around bubbles and result in a jet of liquid leaving the bubble cap. This liquid exerts a reaction force on the bubble, counteracting bubble departure mechanisms. Following the work of McGillis and Carey[27], they derived an empirical correlation with two adjustable constants. Although they obtained good agreement between the correlation and their data by appropriate choice of constants, the correlation did not agree with the CHF data of Usiskin and Siegel[28] on wires for $0.05 < g_z/g_e < 0.3$. It is somewhat puzzling that the authors invoke a thermocapillary convection based mechanism to explain their results. Thermocapillary effects have been observed in experiments that used refrigerants or similar fluids. It is much more difficult to observe with water, and the effects die out asymptotically as steady state heat transfer is reached even when they do occur[26,29]. Oka et al.[30] also did not observe thermocapillary convection in their study of boiling in microgravity using water.

5. Transition Boiling

Xu and Kawaji[31] were perhaps the first to study transition boiling in microgravity. The surface-averaged heat flux and liquid-solid contact frequency were measured with a fast response, 25.4 mm diameter heat flux gauge built onto a stainless steel plate during a quench with PF–5060. The low gravity environment was obtained using a DC–9 aircraft. They observed that the frequency of liquid re-wetting in low gravity was significantly lower than that in earth gravity. Vapor film collapse and spreading of the liquid film were thought to be the dominant modes of liquid-solid contact. In earth gravity, both modes were equally significant, but vapor film collapse became less significant in low gravity resulting in lower contact frequencies. The heat flux was observed to fluctuate by several hundred kW/m^2 during the quench.

Henry and Kim[32] obtained post-CHF boiling data for FC–72 using the same microheater array used by Kim et al.[24] on the KC–135. At low subcooling, the heat transfer after CHF monotonically decreased with superheat due to vapor covering an increasingly larger fraction of the heated area. At higher subcoolings, however, they observed a decrease in heat flux with superheat immediately after CHF, followed by a sharp increase due to the formation of a strong Marangoni convection around the primary bubble. In fact, the heat flux levels reached in the post-CHF region were higher than at CHF. Visual observations indicated that Marangoni convection caused colder fluid to come into contact with the primary bubble cap and decreased the bubble size, resulting in higher wall heat transfer.

6. Boiling of Mixtures

Concentration gradients can arise at the heated surface during boiling of mixtures due to preferential evaporation of the more volatile component. This can lead to Marangoni convection and pumping of liquid to the wall, delaying the onset of CHF. Ahmed and Carey[33] studied the effects of gravity on the boiling of a non-azeotropic binary mixture of water and 2-propanol with low subcooling using the KC–135. Boiling curves were obtained at various gravity levels (0.01 g, 1 g, and 1.8 g) and mixture concentrations (2-proponal concentrations of 0.015, 0.025, and 0.1). For a given gravity level, the nucleate boiling heat transfer was similar for all mixtures. CHF varied significantly, however, with the highest CHF observed for a 2-proponal concentration of 0.015. CHF was found to correlate directly with the surface tension gradient at the base of the bubble. All mixtures showed much higher CHF values than for pure water. Although visual observations were not given, the high CHF was attributed to the development of strong Marangoni convection around the bubble which helped maintain a liquid layer on the surface. Similar results were obtained by Abe et al.[34]. For a given concentration, similar nucleate boiling curves were observed in low gravity and earth gravity, and a slight enhancement was observed for high gravity. CHF values for low gravity were only 10% smaller than those for earth gravity at a concentration of 0.015. Correlations commonly used to predict boiling of mixtures[35–38] and CHF[27] predicted the earth and high gravity data well, but significantly underpredicted the low gravity data.

Sun and Carey[39] studied gravity effects on boiling of 2-propanol/water mixtures within the gap formed by a copper heating element 12.7 mm in diameter and a cold plate. The spacing varied between 6.4–12.7 mm, and the cold plate temperature was subcooled by 10–30 K to provide a temperature gradient within the gap. Low gravity and high gravity data was obtained in the KC–135. In low gravity, nucleation was rarely found for superheats less than 20 K for pure water and a 6.4 mm gap. When boiling did occur, a large bubble formed between the gap and transition to a ''pseudo film boiling'' regime was observed where nucleation only occurred at the perimeter of the bubble base and dry patches formed on the heater. Similar behavior was observed when the molar concentration of 2-propanol was increased to 0.015. CHF in was observed to vary according to $g^{0.17}$.

7. Electric Field Effects

Electric fields have been shown to mitigate the effects of reduced gravity on boiling heat transfer by providing a body force on the bubbles. Snyder et al.[40] studied the effects of electric fields during saturated and subcooled (15°C) boiling of FC–72 on a 0.25 mm diameter platinum wire. The wire served as both temperature sensor and heating element. The wire was placed between two 2.54×2.54 cm electrodes oriented 13 degrees to each other to provide a non-uniform electric field. Two electrode spacings were used such that dielectrophoretic forces (DEP) equal to 1 g and 2 g could be produced at a voltage of 23 KV. By varying the orientation of the test rig with respect to gravity, the DEP could assist or oppose gravity. Microgravity data was determined in a 2.1 s drop tower. They defined an effective gravity ratio $g'_{b,e}$ as the ratio between the sum of gravity and DEP forces to that of gravity alone. In the nucleate boiling regime, they found the bubble behavior close to the wire and heat transfer for $g'_{b=1,e=0}=1$ and $g'_{b=1,e=-2}=-1$ to be very similar. They also found similar behavior for $g'_{b=1,e=0}=1$ and $g'_{b=1,e=-2}=-1$, indicating that the boiling behavior can be determined using an earth gravity or variable gravity heat transfer correlation if the effective gravity is known. CHF followed a $g^{0.25}$ dependence for $1<g'_{b,e}<3$, but significantly higher CHF values were observed as $g'_{b,e}$ became small.

Snyder and Chung[41] studied the effects of electrode geometry during boiling of FC–72 on a flat plate heater (2.54 cm × 2.54 cm) constructed by sputtering a thin gold film onto a Pyrex substrate. Flat plate, pin, and diverging-plate electrodes were used to provide the DEP. The DEP distribution was observed to have a very strong influence on the bubble behavior. Strong bubble motion was observed directly underneath the pin electrode where the DEP force was strongest, but the bubble motion quickly decayed as the radial distance from the electrode increased. The flat plate electrode produced strong bubble motion at the edges where the electric field gradient was strong, but a substantial amount of stationary vapor bubbles were observed directly under the electrode where the DEP force was uniform. The diverging-plate electrode produced the highest heat transfer, and pushed the bubbles across the heater surface. The magnitude of the bubble motion increased with increasing voltage for all electrode geometries. Significant enhancement in wall heat transfer was observed when the DEP forces were present.

A numerical and experimental study was carried out by Snyder et al.[42,43] to clarify the effect of electrode geometry on boiling. Numerical simulations were carried out for infinite and finite diverging-plate electrodes. The numerical results indicated that the finite electrode was found to produce very large DEP forces at the edges which caused a large acceleration on the bubble, but this force decreased rapidly. The infinite-plate electrode produced a smaller but more continuous driving force and resulted in the furthest bubble transport. The bubble detachment diameters were found to scale with $(g'_{b,e})^{0.5}$. Potentially more effective electrode geometries were proposed.

Additional work on the effectiveness of electric fields for bubble removal was performed by Iacona et al.[44], and Herman et al.[45] using air bubble injected into PF5052 (Tsat = 50°C at 1 atm) through a 1.5 mm diameter hole in a 15 mm diameter copper plate. A KC–135 was used to provide the low gravity environment. Flat plate electrodes that provided electric fields up to 15.5 kV/cm were used. The electric field caused the bubbles to elongate and the departure diameter to decrease in low gravity, but the departure diameter was larger than in earth gravity, indicating that the electric field could not replace gravity. The bubble shape agreed fairly well with numerical simulations. Chang, et al.[46] used a similar rig, but with a 5 mm diameter spherical electrode to study bubble detachment under a non-uniform electric field (electric potential differences up to 25 kV) and variable gravity (earth, Martian, lunar, and low gravity) using a KC–135. Bubble departure diameter was found to vary with gravity according to g_z^{-m} where $0.24<m<0.31$ when no electric field was present. The bubble detachment volume, frequency, and shape were not found to vary significantly with electric field, indicating that gravity has a much more pronounced effect on bubble behavior, contrary to the observations of other researchers. Experiments with higher electric fields are currently underway.

8. Acoustic Field Effects

Acoustic fields can also be used to provide a body force in place of gravity to remove bubbles from a heater wall. Hao, et al.[47] theoretically studied removal of growing vapor bubbles from a flat wall using acoustic pressure (Bjerknes) forces in the absence of gravity. Because potential flow was assumed, the wall could be accounted for by inclusion of an ''image'' bubble. The motion of the bubble was influenced by the imposed sound field and by the attractive force of the image bubble. With the wave fronts parallel to the wall, it was found that the imposed sound field was not able to overcome the attractive force imposed by the image bubble, making bubble removal difficult. They suggested using a sound front parallel to the surface to move bubbles along the wall where they could be removed or condensed.

Sitter et al.[48,49] studied the effect of acoustic fields during boiling on a 0.25 mm diameter platinum wire in FC–72 using a 2.1 s drop tower to provide the microgravity environment. The wire was placed in a chamber with a high-intensity acoustic sounding wave (2.6 atm) at 10.18 kHz. The heat transfer for a given wall superheat was always higher with the acoustic field than without, and the highest heat transfer occurred with the heater placed at the antinode for both terrestrial and microgravity boiling. When the wire was placed at the antinode in microgravity, the vapor bubbles were driven off the wire and accumulated were the pressure node was located. Cavitation caused large bubbles to break up into smaller bubbles, which then moved about the chamber due to acoustic streaming. These small bubbles eventually coalesced at the pressure node. Acoustic streaming was observed to bring colder ambient fluid to the wire, enhancing heat transfer.

9. Flow Boiling

Bubbles can be swept off a heated surface during flow boiling, thereby providing high heat transfer and CHF levels. At high flow velocities, the heat transfer becomes independent of gravity, but the velocities above which this occurs is not yet known. Terrestrial experiments performed with the test section oriented in various directions relative to the gravity vector have indicated that bubble departure size decreases as the flow velocity is increased due to an additional lift force on the bubble. Very little work to date has been performed on flow boiling in low gravity due to the large power requirements and the long transients required for steady state to be reached. Results from ground-based research should become available soon.

Ma and Chung[50,51] studied flow boiling of FC-72 over a 2.54 cm × 2.54 cm flat plate heater using a 2.1 s drop tower. The liquid velocity across the heater varied from 0 to 30 cm/s. Increasing velocity resulted in increased wall heat transfer with a corresponding decrease in the average bubble size in microgravity. For a heat flux of 5.1 W/cm^2, the average surface superheat in microgravity was almost the same as in earth gravity when the flow velocity reached 20 cm/s. Similarly, the bubble generation frequency and bubble shape became similar to those in earth gravity at high flow rates. A flow boiling regime map was proposed.

CHF in flow boiling using a 0.25 mm diameter wire in cross-flow with FC-72 subcooled by 26°C was studied by Ma and Chung[52] using a 2.1 s drop tower. Feedback control was used to set the wire temperature and the power required to do this was measured, enabling measurements to be made into the transition and film boiling regimes. The maximum flow Reynolds number was 188 (30 cm/s). CHF for earth gravity was always larger than for microgravity, but the difference decreased with increasing velocity. For example, the ratio between earth gravity and microgravity CHF was 1.9 for Re = 49, but it decreased to 1.16 for Re = 188. Visualization of the flow also indicated increasing similarity between earth gravity and microgravity bubble behavior with increasing velocity.

10. Future Work

Two US pool boiling experiments are expected to be conducted on the ISS within the next few years. The Nucleate Pool Boiling Experiment (NPBX) from UCLA will study the dynamics of single and multiple bubbles growing on a silicon wafer with micro-machined cavities. The Microheater Array Boiling Experiment (MABE, http: //microgravity.grc.nasa.gov/6712/BXF_web/MABE/microheater1.htm) will use two microheater arrays (2.7 mm × 2.7 mm and 7.0 mm × 7.0 mm) to obtain boiling curves under various combinations of heater size, bulk subcooling, and bulk pressure. Both NPBX and MABE will be conducted within the Boiling Experiment Facility (BXF, http: //microgravity.grc.nasa.gov/6712/BXF _ web/boilig1.htm) that will be flown on the Microgravity Science Glovebox (MSG). A multi-user two-phase facility for the ISS, currently referred to as the Two Phase Flow Facility (TøFFy), is being contemplated for the Fluids Integrated Rack (FIR). TøFFy would have multiple test sections whereby different heat exchangers could be used to study flow boiling and condensation phenomena, flow maldistribution, system stability, etc. Measurements of pressure drop, void fraction, heat flux, temperatures are planned along with high-speed imaging and other diagnostics.

11. Conclusions and Recommendations

Experiments to date have shown that boiling can be used to provide substantial heat transfer in microgravity, and future pool boiling experiments should provide information on the basic mechanisms by which heat is transferred. Electric and acoustic fields along with boiling of mixtures have shown potential for increasing wall heat transfer during pool boiling. Small amounts of dissolved gases can significantly affect subcooled pool boiling heat transfer through the formation of Marangoni convection around the primary bubble, resulting in a smaller primary bubble and higher wall heat transfer. Models for Marangoni convection need to be developed and verified against quantitative data. The effects of other parameters on pool boiling remain largely unknown. Enhanced surfaces offer the possibility of greatly increasing wall heat transfer, but no work is currently available. Surface energy gradients on a heated surface might be utilized to remove bubbles without using flow boiling. Even basic information on the effect of surface geometry on reduced gravity boiling heat transfer is not understood. Continued development of numerical techniques is needed so that two-phase flows systems can be efficiently designed.

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