Dynamics of Single and Multiple Bubbles and Associated Heat Transfer in Nucleate Boiling Under Low Gravity Conditions

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ABSTRACT: Experimental studies and numerical simulation of growth and lift-off processes of single bubbles formed on designed nucleation sites have been conducted under low-gravity conditions. Merging of multiple bubbles and lift-off processes during boiling of water in the parabola flights of KC-135 aircraft were also experimentally studied. The heating area of the flat heater surface was discretized and equipped with a number of small heating elements that were separately powered in the temperature-control mode. As such, the wall superheat remained nearly constant during the growth and departure of the bubbles, whereas the local heat flux varied during the boiling process. From numerical calculation it is found that peak of heat flux occurs locally at the contact line of bubble and heater surface. Dry conditions exist inside the bubble base area, which is characterized through a zero heat flux region in the numerical calculation and a lower heat flux period in the experimental results. During the merger of multiple bubbles, dry-out continues. In both the numerical calculations and experimental results, the bubble lift-off is associated with an apparent increase in heat flux. Wall heat flux variation with time and spatial distribution during the growth of a single bubble from numerical simulations are compared with experimental data.

KEYWORDS: dynamics; single bubble; multiple bubbles; heat transfer; nucleate boiling; low gravity

INTRODUCTION

Nucleate boiling is a liquid–vapor phase change process associated with bubble formation and is known to be a highly efficient mode of heat transfer. For space applications boiling is the heat transfer mode of choice since the size of the components can be significantly reduced for a given power rating. Applications of boiling heat transfer in space can be found in such areas as thermal management, fluid handling and control, and power systems. For space power systems based on the Rankine cycle (a representative power cycle), the key issues that need to be addressed are...
the magnitude of boiling heat transfer coefficient and the critical heat flux under low gravity conditions. The low gravity environment of the KC-135 aircraft provides a less expensive means to experimentally study the liquid–vapor phase change dynamics and the associated heat transfer characteristics and to validate numerical simulations for space applications.

Although, in the past decades, extensive experiments and modeling efforts have been made for boiling processes, a mechanistic model to describe the phenomena and predict the heat transfer coefficient without employing empirical constants has not been available for nucleate boiling on a horizontal surface. As such, the scaling of the effect of gravity on the dynamics and heat transfer during boiling has not been established. Consequently, one cannot extend the results from studies at Earth normal gravity to nucleate boiling under microgravity conditions.

Under microgravity conditions the early data of Keshock and Siegel\(^1,2\) on bubble growth and heat transfer show that the effect of reduced gravity is to reduce the buoyancy and inertia forces acting on a bubble. As a result, under reduced gravity, bubbles grow larger and stay longer on the heater surface. This in turn leads to merger of bubbles on the heater surface and existence of conditions similar to those for fully developed nucleate boiling. Thus, it was concluded that, under microgravity conditions, partial nucleate boiling region may be very short or non-existent.

Merte et al.\(^3\) and Lee and Merte\(^4\) reported results from pool boiling experiments conducted in the space shuttle for a surface of gold film sputtered on a quartz plate with an area 19×38 mm\(^2\). Subcooled boiling during long periods of microgravity was found to be unstable. The surface was found to dry out and rewet at higher surface heat flux. At 11.5°C subcooling, it was observed that after a period of growth of small bubbles and their coalescence, a larger bubble formed that stayed above the surface. The larger bubble acted as a reservoir sucking and removing the smaller bubbles from the surface. The average heat transfer coefficients during the dry-out and rewetting periods were found to be about the same. The nucleate boiling heat fluxes were higher than those obtained on a similar surface at Earth normal gravity, \(g_e\), conditions. It was concluded that subcooling exerts a negligible influence on the steady state microgravity heat transfer coefficient. The effect of Marangoni convection (thermocapillary flow) on the heat transfer was considered to be reduced at microgravity conditions.

Straub, Zell, and Vogel\(^5\) and Straub\(^6\) conducted a series of nucleate boiling experiments using thin platinum wires and a gold-coated flat plate as heaters under low gravity conditions in the flights of ballistic rockets and KC-135. In the experiments for the flat plate heater, with R12 as the test liquid, boiling curves similar to those at \(g_e\) were obtained when the liquid was saturated. With R113, rapid bubble growth and large bubbles (\(D \geq 2\,\text{cm}\)) were observed during the TEXUS ballistic rocket flight at a gravity level of \(10^{-4}\,g_e\). However, no bubbles were seen to lift off from the heater surface, and neither temperature nor heat flux reached a steady state. For subcooled R113 and R12, a reduction in heat transfer coefficient of up to 50% in comparison with that at \(g_e\) was obtained. It was observed that larger bubbles occupied the surface and at their edges many smaller bubbles formed, coalesced, and fed the larger ones.

From above description it appears that results from studies conducted to date are inconclusive. Questions remain concerning the stability of nucleate boiling, the roles of liquid microlayer underneath the stationary and translating bubble, the reasons for equivalence of magnitudes of heat transfer coefficients at normal gravity and low
gravity conditions, and the overall physics that underlies these phenomena. As such, there is no mechanistic model that describes the observed physical behavior and the dependence of nucleate boiling heat flux on gravity and wall superheat during nucleate boiling. Detailed information on heat transfer characteristics associated with processes of bubble growth and lift-off at a well defined nucleation site is, therefore, needed. However, these characteristics for isolated nucleate boiling is least known.

Rogers and Mesler measured the transient surface temperature in nucleate boiling in the attempt to explore the behavior of the liquid microlayer underneath the bubbles in water at terrestrial gravity using an artificial cavity and thermocouple made on a nichrome strip plated with a thin nickel layer (heater surface). They found that the surface temperature at the nucleation site occasionally dropped 11–16°C in about 2 msec and the temperature recovered in 10–20 msec during single bubble boiling when the heating rate remained constant (5–10 W/cm²). It was concluded that bubble departure corresponds to temperature recovery and that the sudden temperature drop corresponds to initiation of bubble growth. However, they reported that no significant cooling is apparent as liquid returns to the surface during bubble departure. This fact is opposite to most hypotheses on nucleate boiling.

Recently, Kim and Benton conducted experiments of subcooled nucleate boiling of FC72 on array of miniature serpentine platinum heaters with feedback controls in terrestrial and low gravity conditions. The overall boiling phenomena are observed to be similar to those reported by Merte et al. Larger primary bubbles acted as a reservoir, sucking and removing the smaller bubbles from the surface. Large local heat flux fluctuations, for example, from 2 to 20 W/cm² for \( \Delta T_{\text{sub}} = 15^\circ C \) were recorded. A dry spot underneath the primary bubble was observed. The peak in heat flux occurred when the liquid rewetted the surface after the bubble slid over the measuring position. However, the heat flux over the total bubble life was not obtained.

In this paper, efforts to explore the local heat flux associated with bubble growth, merger, and lift-off on the designed nucleation sites are described both by means of numerical simulation and experiments under low gravity conditions.

DESCRIPTION OF NUMERICAL ANALYSIS

The numerical simulation model employed in this work is the same as that developed by Son, Dhir, and Ramanajapan to study bubble dynamics in a saturated liquid at Earth normal gravity. In the model a single bubble formed at a nucleation site is considered and the assumption of axisymmetry is invoked. For hydrodynamic and thermal analysis, the domain of interest is separated into micro- and macroregions, as shown in Figure 1. The microregion mainly encompasses the microlayer underneath the bubble. Heat from the solid surface is conducted through the microlayer and is used for evaporation at the interface. Forces acting on the liquid in the microlayer are those due to viscous drag, interfacial tension, long range molecular interactions, and vapor recoil. Neglecting inertia and convection terms in the momentum and energy equations, respectively, the radial thickness of the microlayer during the evolution of the bubble is calculated. For the macroregion, complete conservation equations for both vapor and liquid are used. The level set method is employed to obtain the shape of the evolving interface and the flow and temperature fields in the
vapor and the liquid. The shape of the interface obtained from the solutions for the micro- and macroregions was matched at the outer edge of the microlayer. Also, it was required that tangent to the interface at that location should yield the macroscopic contact angle. The magnitude of the Hamakar constant representing the long range forces was, in turn, related to the macroscopic contact angle. Thus, the effect of wettability of the surface was included in the model through the specification of the value of the Hamakar constant. For the objective of this paper, the calculation was carried out for the variation of surface heat flux during boiling of saturated water at $\Delta T_w = 8.5^\circ C$ and $g_e = 0.01 g_e$.

**EXPERIMENTS**

The experimental apparatus for the KC-135 flights is shown schematically in Figure 2. The system configuration is similar to that used by Merte et al. It consists of a test chamber ($D = 15 cm$, $H = 10 cm$), a bellows and a nitrogen ($N_2$) chamber. Three glass windows are installed on the walls of the test chamber for the visual observation. To control the system pressure transducers are installed in the test chamber and $N_2$ chamber. The test surface for studying nucleate boiling is installed at the bottom of the test chamber. In the vicinity of the heater surface a rake of six thermocouples is installed in the liquid pool to measure the temperature in the thermal boundary layer, another rake is placed in the upper portion of the chamber to measure the bulk liquid temperature.
FIGURE 2. Schematic of the experimental set-up.

FIGURE 3. Silicon wafer instrumented with strain gage heaters and thermocouples: (A) overview, (B) cavity positions.
Distilled, filtered, and degassed water was used as the test liquid. Two video cameras operating at 250 frames/second were installed from two directions at an angle of 90° to record the boiling processes. The liquid temperature and pressure in the chamber were controlled according to the set points established by the operator on board. A three-component accelerometer is installed on the frame on which the equipment is mounted.

A polished silicon wafer, 101.6 mm in diameter and 400 µm in thickness, was used as the test surface for the nucleate boiling experiments. From the manufacturer's specification the roughness of the bare polished wafer is less than 5 Å. Five cylindrical cavities with diameters 10 µm (No. 1), 7 µm (Nos. 2 and 4), and 4 µm (Nos. 3 and 5) were etched to a depth of about 100 µm in the wafer center via the deep reactive ion etching technique (DRIE), see Figure 3B.

At the back of the Silicon wafer strain gages were bonded as heating elements. In the central area, miniature elements of size 2×2 mm² were used and grouped so as to cover small areas of the test surface (Fig. 3A). In each group, a thermocouple was directly attached to the wafer. The heater surface temperatures in different regions were then separately controlled through a multichannel feedback control system. The surface superheat could be maintained constant during an experimental run and can be automatically changed to the desired set-point. The local heating rate in the individual small area was recorded during the experiments. In the outer area larger elements with an effective heating area of 6.5×6.5 mm² per element were used. The power lead wires and the thermocouple wires were led out from the hole in the base made from phenolic garolite grade 10 (G-10). The wafer was cast with RTV, silicon rubber, on the G-10 base. The base in turn is mounted in the test chamber.

During the flight experiments, the cavity was activated by energizing the heating elements underneath the cavity before the plane took off. The wall superheat at the cavity area was gradually increased until the inception occurred. After activation, the wall superheat was set at the desired value. The detailed procedure can be found in Qiu et al. 10

The low gravity condition, \( g_z = \pm 0.04 \, g_e \) during the parabolic flights of KC-135 lasted about 20 seconds. Uncertainty in the gravity level measurement is mainly from the synchronization uncertainty between the accelerometer recording and the high speed video recording. The gravity level \( g_z \) itself varied within \( \pm 0.04 \, g_e \) due to flight conditions. An examination using a laser pulse with signal recorded in the data files and pulse light displayed in the view of the video recording shows a mismatch in time of less than 0.5 sec, which corresponds to the maximum uncertainty of \( \pm 0.002 \, g_e \) in the level of gravity, \( g_z \), normal to the test surface. The uncertainty in the pressure measurement is \( \pm 0.0034 \, \text{MPa} \). This value yields an uncertainty in evaluating the saturation temperature of \( \pm 0.1 ^\circ C \). The temperature measurements of the heater surface and the liquid have an accuracy of 0.1°C. The uncertainty in the evaluation of bubble size is \( \pm 0.05 \, \text{mm} \).

RESULTS OF NUMERICAL SIMULATION

Figure 4 shows the bubble contours during a typical bubble growth and lift-off cycle. During most time of the bubble life (0–1.39 sec in 1.77 sec) the bubble base is
either expanding outward or remaining constant at the maximum diameter. Thereaf-
	er, the bubble base begins to shrink rapidly, which indicates that the bubble starts to

lift from the surface. The corresponding heat flux distributions are shown in Figure 5 for selected

times. A local peak in heat flux is seen to exist at each time before bubble lift-off.

**FIGURE 4.** Bubble growth pattern at $\Delta T_w = 8.5^\circ$C and $g_z = 0.01g_c$. 
FIGURE 5. Local heat flux from numerical simulation for $\Delta T_w = 8.5^\circ C$ and $g_z = 0.01g_e$.

FIGURE 6. Velocity field at $t = 3.4\text{ sec}$, $T_w - T_s = 8\text{ K}$, $\Delta T_{\text{sub}} = 0\text{ K}$, $g_z = 0.02g_e$.11
The peak first moves outward, reaches a position of maximum radius, and then moves back toward the cavity \((r = 0)\). The location of the peak approximately corresponds to the position of the contact line between the bubble and the surface. The farthest position of the peak from the center of the cavity occurs when the bubble base diameter acquires its maximum value. The high heat flux at the contact line region is caused by the high rate of evaporation of liquid into the bubble. However, during the lift-off phase of the bubble, as the bubble base shrinks, inflow of cold liquid leads to enhanced heat transfer in the region surrounding the peak. An example of the flow field calculated by Singh and Dhir\(^{11}\) is given in FIGURE 6. In the area away from the location of peak heat flux, the heat flux decreases with the radius as the thermal boundary layer thickens.

In the region with smaller radius than that of the location of peak in heat flux, the heat flux is very small. A dry region underneath the bubble is assumed to exist in the model. The transition from the maximum in heat flux to the dry region with almost zero heat is seen to occur in a very short distance.

A particular location on the heater surface experiences two peaks in heat flux. One occurs during the bubble base expansion and the other occurs during the lift-off period. This can be seen in FIGURE 7, which shows the heat flux histories at few selected positions. In the present case, the most outward position of the heat flux peak occurs at radius \(r = 4.3\) mm. Near the center of the calculation domain where the cavity is located, the longest period of low heat flux exists.

**FIGURE 7.** Heat flux during a bubble growth/lift-off cycle as a function of time in selected radii.

EXPERIMENTAL RESULTS

Since the details on single and multiple bubble dynamics at low gravity are reported elsewhere,\(^{10}\) only the relevant bubble behavior is described here.
FIGURE 8. Growth rate and heat flux of a single bubble at $\Delta T_w = 5.0^\circ C$, $\Delta T_{\text{sub}} = 1.6^\circ C$: (A) bubble equivalent diameter, (B) heat flux from the elements underneath the cavity, (C) gravity level.
Single Bubble Growth and Lift-off

FIGURE 8A shows the bubble equivalent diameter and bubble base diameter during growth and lift-off process for a single bubble on cavity 1. The maximum bubble base diameter is about 7 mm, whereas the bubble lift-off diameter is 16.2 mm. About the same value of bubble lift-off diameter is obtained when scaling is carried out for the gravity level of \( g_z = 0.025 g_e \). The corresponding heat flux from the elements underneath cavity 1 is shown in Figure 8B. The heat flux value is obtained from the recorded total heat flow to the two heating elements directly under the cavity divided by the area of the elements. It is seen that the heat flux decreases to a nearly constant value during bubble growth. Formation of a dry spot underneath the bubble is believed to be the cause of this behavior. A non-zero value of the power input is a result of heat loss into the backing material and radially outward conduction along the wafer, because the temperature in the surrounding area is set at slightly lower value than the cavity area. The heat flux attains a nearly constant value when the bubble base radius attains its maximum value and remains at that value until just before lift-off of the bubble. A peak in heat flux occurs just after lift-off. The top part of the peak in heat flux is not seen here because this value exceeded the maximum power input to the heater, which was limited to prevent the heating elements from burn-out. It should be noted that, because of thermal inertia of the heater, there is always a delay in the change in power input and in turn in the recorded peak in heat flux. The peaks are believed to be associated with transient conduction into the cooler liquid that flows inward as the bubble lifts off from the heater surface. The segmented heat flux distribution as a function of radius is plotted in Figure 9. This shows that the high heat flux mainly appears in the region \( r \leq 4 \) mm, which corresponds to the maximum base area. There is a shift with time between the occurrence of highest heat fluxes in the regions 0–2 mm and 2–4 mm in radius. This fact reflects the radial outward and inward movement of the local heat flux peak within the region corresponding to maximum bubble base area.

FIGURE 9. Distributions of heat flux at \( \Delta T_w = 5.0°C, \Delta T_{sub} = 1.6°C \).
FIGURE 10. Pictures during growth and lift-off of three single bubbles at $\Delta T_w = 6.2^\circ C$ and $\Delta T_{sub} = 0.8^\circ C$. 

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Similar behavior was seen in all cases related to growth and lift-off of single bubbles. Figure 10 shows the pictures of three single bubbles during growth and lift-off processes. The dynamic behavior of each of these bubbles was found to be similar to that of a single bubble described above and also previously described by Qiu, et al. The bubbles lifted off when buoyancy exceeded the surface tension force. Because of the phase difference in the growth of the bubbles and time variations in the level of gravity normal to the heater surface, the lift-off diameters are different, as is shown in Figures 11 and 12. The corresponding heat flux under cavity 1 is

![Graphs showing bubble growth and lift-off](image)

**FIGURE 11.** Histories of single bubble number 1 at \(\Delta T_w = 6.2^\circ C, \Delta T_{sub} = 0.8^\circ C\): (A) bubble equivalent diameter, (B) gravity level, (C) heat flux from the heating elements under cavity 1.
plotted in Figure 11C. It can be seen that, during the growth of the bubble, the heat flux decreases and just after lift-off a peak in heat flux occurs. Similar peaks also occur during the lift-off of bubbles 2 and 3, as shown in Figure 12B. The higher level of sustained heat flux after the occurrence of the peaks is believed to be due to increased natural convection heat transfer as gravity increases after the plane leaves the parabola.

The continuous decrease of heat flux for bubble 1 during the growth period is a result of the reduced heat transfer in the dry area underneath the bubble as bubble base expands. The non-zero value of heat flux during bubble growth is again due to the radially outward conduction into the silicon wafer and the heat loss into the backing materials. Because the heaters placed under cavities for bubbles 2 and 3 are not symmetric, the conductive heat transfer to the surrounding area more strongly affects the profile of input power to these heaters. Consequently, during the later stages of growth of the bubbles, a small increase in heat flux is observed. This is somewhat contradictory to the observation made for cavity 1 placed in the center of the wafer.
Growth, Merger, and Lift-off of Multiple Bubbles

The heat flux during merger and lift-off processes of multiple bubbles was also measured. In Figure 13 the results of two bubbles merger are plotted. The bubble equivalent diameter is plotted in Figure 13A and the heat flux underneath cavities 1 and 4 is plotted in Figure 13B. It can be seen that the heat flux under cavity 1 decreases and then rapidly increases after the bubble lift-off. The heat flux profile for cavity 4 shows similar behavior, but in a less pronounced way. There is no apparent change in heat flux at the time of merger. This fact indicates that dry areas underneath the merging bubbles continue to persist, even during the merger process. The peak in heat flux after the lift-off for cavity 4 is not as pronounced as that for cavity 1. This may again be the result of asymmetric location of cavity 4 with respect to the center of the wafer. Figure 14 shows the area-averaged heat flux in various rings of

![Figure 13](image-url)

**Figure 13.** Bubble diameters and heat fluxes during two bubble merger and lift-off: (A) bubble equivalent diameter, (B) heat fluxes from elements under the cavities.
the heaters placed on the back side of the wafer. A reduction in heat transfer in the inner region is seen during the bubble growth. However, heat flux in the outer most region continues to be high.

**COMPARISON OF NUMERICAL SIMULATION AND EXPERIMENTAL RESULTS**

Because the gravity level during the KC-135 flight experiments varied within a range $\pm 0.04\,g_e$ and the test parameters were also somewhat different from that used in the numerical computations, the bubble growth periods differ between the simulations and the experiments. To compare the results, time is normalized using bubble growth period $t_g$ as the characteristic time. Also, the measured heat flux is actually an averaged value over an area supporting a group of heating elements. Thus, the heat flux from the numerical prediction is also averaged over the corresponding radial ring. **FIGURE 15** shows heat flux averaged over radial rings as a function of normalized time from the results of numerical simulations as given in **FIGURE 7**.

In **FIGURE 16** a comparison of the heat flux in the central circular area underneath the cavity is made for the case for which results are plotted in **FIGURE 11**. Qualitative agreement in the variation of the heat flux as a function of time can be seen. The difference in heat flux level between the prediction and the data may seem large, but in reality, when integrated over the area where the heaters are mounted, it is not much beyond the uncertainty in measurements. For three selected times the heat fluxes as a function of radius are also compared in **FIGURE 17**. The top part of figure is for the period of initial bubble growth and the last is for the time at which bubble lifts off. The middle part of the figure is for the time just before lift-off. As shown in the figure, the trends in prediction and the data are again consistent.
FIGURE 15. Heat flux averaged over radial segments and normalized with time as predicted from numerical simulation for $\Delta T_w = 8.5^\circ C$ and $g_z = 0.01 g_c$: (A) as a function of time, (B) as function of radius.
CONCLUDING REMARKS

1. Bubble shape and local surface heat flux during growth and lift-off of a single bubble are numerically computed using level set method for the low gravity condition.

2. By making artificial cavities in the polished Silicon wafer, well defined nucleation sites have been activated. Miniature heating elements and thermocouples are used for individual control. This approach has allowed experimental study of dynamics and local heat transfer of single and multiple vapor bubbles during nucleate boiling in low gravity conditions of KC-135.

3. From numerical simulations a peak in local heat flux is predicted to occur at the bubble-surface contact line.

4. A dry region exists in the bubble base area. In numerical simulations this is characterized by a zero heat flux but with a low heat flux in the experimental results.

5. In both the numerical predictions and experimental results the bubble lift-off is associated with an apparent increase in local heat flux.

6. Numerical predictions and experimental data give a consistent trend with respect to time variation of heat flux associated with single bubble growth and lift-off.

7. During the merger of multiple bubbles, a dry region underneath the bubbles continues to exist.

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FIGURE 17. Comparison of heat flux for all segments with data described in Figure 11.