Heat Transfer from a Single Nucleation Site During Pool Boiling of FC-72: Effect of Subcooling

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INTRODUCTION

The mechanisms by which bubbles transfer energy from a wall is actively being investigated experimentally and numerically, partly due to the large heat transfer that can be attained during boiling and partly because its intellectual appeal. Many mechanisms for bubble heat transfer have been suggested (see Carey–1992 for a short review) but the microconvection model of Mikic and Rosenhow (1969) and the microlayer model of Cooper and Lloyd (1969) seem to be most widely cited. The large number of experimental studies to date have been supplemented recently by numerical simulations made possible by advances in computer hardware and interface tracking codes. Examples of recent numerical simulations include Welch (1998), Son et al. (1999), and Yoon, et al. (2001).

The objective of this work is to determine the mechanisms by which heat transfer occurs for bubbles nucleating from a single site under low and high subcooling levels, and builds on previous work. Yaddanapudi and Kim (2001) presented local heat transfer data underneath single bubbles nucleating periodically from a single site for saturated FC-72 at 1 atm ($T_{sat}=56.7$ °C) and wall temperature 79.2 °C. They used a heater array with individual heaters 270 μm in size. The bubble departure diameter was about 370 μm,

ABSTRACT

Heat transfer measurements under bubbles nucleating from a single site have been obtained using a microheater array with 100 μm resolution with low and high subcooled bulk liquid. Images of the growing bubbles were captured from below and from the side using two high-speed digital video cameras, allowing bubble behavior to be correlated with the heat transfer measurements. The individual bubble departure diameter and energy transfer were larger with low subcooling but the departure frequency increased at high subcooling, resulting in higher overall heat transfer. The bubble growth for both subcoolings was primarily due to energy transfer from the superheated liquid layer–relatively little was due to wall heat transfer during the bubble growth process. Transient conduction and/or microconvection appeared to be the dominant heat transfer mechanism by which bubbles transfer energy. A single bubble that oscillated on the surface was also observed in subcooled boiling. Wall heat transfer was inversely related to the bubble size, again indicating the transition conduction and/or microconvection was the mechanism for heat transfer.

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only slightly larger than a single heater. Their results indicated that bubble heat transfer mechanisms were different from the widely accepted view of microlayer evaporation being the dominant heat transfer mechanism in saturated pool boiling. Bubble growth occurred primarily due to energy gained from the superheated liquid layer. Bubble departure resulted in removal of part of the superheated layer, allowing energy to be transferred from the wall through transient conduction and/or microconvection.

Demiray and Kim (2002) presented local heat transfer data underneath bubbles nucleating from a single site for single and vertically merging bubbles under conditions similar to Yaddanapuditi and Kim (2001), but using an array with heaters 100 μm in size. The surface temperature of the heater array and the bulk fluid temperature during the experiment were 76 °C and 52 °C, respectively. Bubbles that nucleated at this site alternated between two modes: single bubble mode and multiple bubble mode. In the single bubble mode, discrete bubbles departed from the heater array with a waiting time between the departure of one bubble and nucleation of the following bubble. In the multiple bubble mode, bubble nucleation was observed immediately after the previous bubble departed. The departing bubble pulled the growing bubble off the surface prematurely and the bubbles merged vertically forming small vapor columns. The data indicated that the area influenced by a single bubble departing the surface was approximately half the departure diameter. Microlayer evaporation was observed to contribute a significant, but not dominant, fraction of the wall heat transfer in the single bubble mode. Microlayer evaporation was insignificant in the multiple bubble mode, and heat transfer occurred mainly through transient conduction/microconvection during liquid rewetting as the bubble departs the surface.

EXPERIMENTAL APPARATUS

Heater array

An array of 96 platinum resistance heater elements deposited on a quartz wafer provided local surface heat flux and temperature measurements. A photograph of the heater array is shown in Figure 1. Each element in the array was approximately square in shape, nominally 0.01 mm² in area, and consisted of 2 μm wide Pt lines spaced 2 μm apart. Each heater had a nominal resistance of 8 kΩ with a temperature coefficient of resistance of 0.0019 °C⁻¹. The lines that supply power to the heaters are routed between the heaters and the PGA board. The details of the construction of a similar heater array are given in Rule and Kim [1999].

Feedback control circuit

Each heater in the array was kept at constant temperature by individual feedback circuits similar to those used in hotwire anemometry—see Figure 2 for a schematic of the circuit. Any imbalance in the Wheatstone bridge was sensed by an amplifier, which provided enough power to the heater to bring the bridge back into balance. The output of the circuit was the voltage across the heater. The heat dissipated by a given heater could be calculated directly from this voltage and the heater resistance. The heater temperature was controlled by varying the wiper position of the digital
potentiometer. The reader is referred to Bae et al. [1999] for additional details regarding the electronics of the circuits.

**Heater calibration**

The heater array was calibrated in an oven held within 0.1 °C of the set temperature. Calibration consisted of finding the digital potentiometer wiper position that caused the feedback loop to just begin regulating for a given chamber temperature. Each heater in the array could be varied over a 120 °C range in 0.4 °C increments. The uncertainty in heater temperature was less than 1 °C.

**Data acquisition system**

The two data acquisition cards (PCI-DAS6402/16), each capable of scanning 64 analog input channels at a maximum speed of 200 kHz, were installed inside a Dell OptiPlex GX110 computer. Each card sampled the outputs of 48 heaters. The system was used to obtain time-resolved data at 3704 Hz from each heater for a period of four seconds. Both data acquisition cards were triggered by the same rising edge of a TTL signal from the computer.

**Boiling rig**

The boiling rig shown in Figure 3 was used in the experiments. FC-72 filled the boiling chamber. The bellows and the surrounding housing allowed the test section pressure to be changed when needed. A stirrer was used to break up any stratification within the test chamber, while a series of thin film heaters attached to the outside of the chamber were used to control the bulk liquid temperature. The stirrer was turned off before the start of data acquisition to allow the bulk fluid motion to die out.

**High speed video**

The semi-transparent nature of the heater array enabled images to be taken from below with a high-speed digital video camera (Vision Research Phantom IV) set to acquire 256x256 resolution images at 3704 fps. A group of high performance white LEDs was mounted over the heater array within the chamber in order to provide a bright, diffuse background for bottom-view pictures of the bubble. A second high-speed digital video camera (Vision Research Phantom IV) was used to record side-view images at the same speed and resolution. A halogen lamp next to a glass window in the boiling chamber provided light for side view images. Due to the heat produced by the lamp, the lamp was turned on only during the data acquisition time. Recording of both cameras was initiated using the same signal used to trigger the data acquisition system, enabling heat transfer measurements and video records to be made simultaneously.

**Data reduction**

Because each heater had its own feedback control circuit, we were able to measure the instantaneous power required to maintain each heater at a constant temperature. Some of the power supplied to the heaters, however, is conducted from the heater elements to the surrounding substrate and can eventually be lost by natural convection to the bulk liquid. In this study, we are interested in the heat transfer induced only by the bubble action. The heat transfer excursions around a slowly varying baseline were assumed to be a consequence of bubble formation and departure. The baseline of the heat transfer curve exhibited a low frequency oscillation, which is likely due to a natural convection flow over the heater driven by the temperature difference between the bulk liquid and the heater array. To obtain the effect of the bubble only, a sixth degree polynomial was fitted to selected points on the baseline and subtracted from the time-resolved heat transfer for each heater in the array. The resulting heat transfer curve could exhibit both positive and negative values. Negative values of heat transfer result if liquid dryout during bubble growth above a heater occurred, resulting in a lower heat transfer than would have occurred in the case of natural convection in the absence of a bubble.

An example of the data reduction is shown on Figure 4, in which the total heat transferred from the array is obtained by summing the heat transferred from each
heater together and plotted on the upper curve. Excursions in heat transfer above a slowly varying baseline are observed. These excursions correspond to a single or multiple bubble growth sequence from a single nucleation site on the surface. The baseline obtained by a curve fit is overlaid on this curve. The lower curve was obtained by subtracting the baseline from the total heat transfer curve and is the net change in heat transfer due to the presence of the bubble on the surface.

RESULTS
All data were obtained with the wall temperature fixed at \( T_{\text{wall}} \approx 76 \) °C and \( P=1 \) atm (\( T_{\text{sat}} \approx 57 \) °C). Two subcooling levels were investigated. The data taken with \( T_{\text{bulk}} = 52 \) °C will be referred to as low subcooling, while the data taken with \( T_{\text{bulk}} = 41 \) °C will be referred to as high subcooling.

Total heat flux
Heat transfer excursions from the baseline due to nucleating bubbles for both subcoolings are shown on Figure 5. The low subcooling case consisted of single bubble events separated by relatively long waiting times with the exception of L10 (a double bubble event) and L13 (a triple bubble event). The reader is referred to Demiray and Kim (2002) for a discussion of the heat transfer behavior for L10 and L13. The high subcooling case consisted of thirteen single bubble events (H1–H13) followed by a single bubble that oscillated on the surface (H14). A few trends are immediately evident. Bubble departure occurred much more frequently for high subcooling than low subcooling, consistent with the observations of other researchers (e.g., Forster and Grief-1959). The waiting time between bubbles for high subcooling was very short, and varied between 0 ms and 10 ms. The waiting time for low subcooling was much longer—between 0 ms and over 200 ms. Although the peak heat transfer for high subcooling was roughly two thirds that for low subcooling, the time averaged heat transfer for high subcooling was 3.5 mW vs. 0.98 mW for low subcooling due to the higher departure frequency.

The heat transfer associated with single bubble events for both subcoolings are shown superimposed on each other on Figure 6 where time for each bubble was shifted so that \( t=0 \) corresponds to nucleation of the bubble on the surface. The low subcooling case shows an evolution from a double peaked heat transfer profile (bubbles L1–L4) similar to what was observed by Yaddanapu and Kim (2001) and Demiray and Kim (2002) to a profile with a single peak (bubbles L5–L9). Demiray and Kim (2002) attributed the first peak at \( \approx 1.2 \) ms for bubble L1 to evaporation of a thin microlayer trapped between the growing bubble and the heated wall as the bubble grows nearly hemispherically in a superheated liquid layer. The reason for the evolution from this profile to that observed for bubbles L5–L9 is unclear, but may be due to

![Figure 4: Example of bubble heat transfer calculation.](image)

![Figure 5: Comparison of bubble heat transfer with low and high subcooling. Note the difference in time scales.](image)
fluctuations in the temperature of the superheated liquid layer. Evidence for this is seen in the unreduced heat transfer data shown on Figure 4. The magnitude of the excursion above the baseline heat transfer (recall that the baseline heat transfer is a measure of the substrate conduction plus natural convection) in this plot does not appear to correlate with the waiting time between bubbles, but does seem to be inversely correlated to the magnitude of the baseline heat transfer. Because the substrate conduction is nominally constant, an increase in the baseline heat transfer is indicative of a decrease in the local liquid temperature due to natural convection. The highly subcooled heat flux profiles have a shape similar to those for bubbles L5–L9, but with smaller magnitude. This seems to indicate that the rapid rise in heat transfer upon bubble nucleation (and therefore significant microlayer evaporation) resulting in a double peaked profile (bubbles L1–L4) occurs only when the bulk liquid is significantly superheated.

Space and time resolved heat transfer

Images showing the evolution of the bubbles Bubble L1 and H5 are shown on Figure 7. Each heater in the array has been colored according to the heat transfer. The heat transfer behavior for each of these bubbles is discussed below.

Bubble L1 was discussed in Demiray and Kim (2002), so only a brief summary is given here. Nucleation occurred between 0 ms–0.27 ms. Based on the bottom view images, the bubble grew to nearly full size by 1.89 ms after nucleation. The bubble shape seemed to be approximately hemispherical. A large increase in the heat transfer under almost the entire bubble was observed during this time, consistent with evaporation from a microlayer between the bubble and the wall. Starting from 2.16 ms, the development of a low heat transfer region at the center of the bubble is observed, indicating progressive dryout of the microlayer. The dry spot size, as evidenced by the inner circle, reaches a maximum around 3.51 ms. The bubble began to depart the surface at this time, and the dry spot shrinks as the bubble necks down. Higher heat transfer is observed on the center heaters as they were rewetted by the bulk liquid. Bubble departure occurred at 5.13 ms, and is associated with a spike in heat transfer at the center heaters that decays with time.
The images for bubble H5 (subcooled case) is shown on Figure 7b. It is immediately apparent from these images that the maximum diameter of the bubble is much smaller than for the low subcooling case. The heat transfer behavior is similar to that observed for bubble L5. An apparently hemispherical bubble grows shortly after nucleation and high heat transfer is observed, indicating the formation of a microlayer. The heat transfer at the center of the bubble begins to decrease starting about 0.81 ms, and reaches a minimum at 2.16 ms indicating dryout of the microlayer. The heat transfer at the center of the heater begins to increase as the dark inner ring shrinks, indicating rewetting of the heater before bubble departure at 2.7 ms.

**Measured and equivalent diameter**

The wall heat transfer data shown in Figure 6 can be used to compute an equivalent bubble diameter ($d_{eq}$) by assuming that all the heat transferred from all of the heaters goes into latent heat:

$$\int \frac{\sqrt{\mathcal{H}_m^2(t)}}{6} h^e dt = \int q(t) A_b \, dt$$

where time $t = 0$ is assumed to be the start of nucleation for a single bubble. A plot of the time varying physical bubble diameter was obtained by fitting a circular template to the outer dark ring of the bubbles shown on Figure 7, and is assumed to be a measure of the bubble volume. If the bubble were actually a hemisphere (approximately true for the bubble just after nucleation) instead of sphere (bubble shape close to departure), then the bubble diameter as measured above would be about $2^{1/3} = 1.26$ larger than the diameter of a spherical bubble of the same volume. The equivalent diameter is plotted along with the physical diameter on Figure 8 for representative single bubbles at low and high subcoolings. The slight decrease in measured physical diameter after about 0.8 ms for bubbles L5 and L6 to about 91% of the maximum bubble diameter is most likely due to a transition from a hemispherical to a spherical shape as the bubble grows on the heater. A similar decrease in measured physical diameter at departure to about 84% of the maximum diameter is also observed for bubbles H5 and H6, and may be due to transition between a hemispherical to spherical shape as well as condensation at the top of the bubble. It is seen that $d_{eq}$ is significantly smaller than the physical bubble diameter during the bubble growth time, indicating that the heat transferred from the wall cannot account for the bubble growth alone. This implies that the bubble must have gained the majority of its energy from the superheated liquid layer surrounding the bubble. This conclusion is consistent with the results of the study performed by Yaddanapuddi and Kim (2001) and Demiray and Kim (2002).

The bubbles in the high subcooling case are significantly smaller than those in low subcooling, and suggests that the thinner superheated liquid layer in the high subcooling case is not able to sustain growth of as large a bubble. The lower temperatures and thinner superheated layer in the highly subcooled case also cause the bubble to grow more slowly, limiting the amount of liquid trapped in the microlayer. Increased condensation at the top of the bubble also acts to limit the bubble size.

**Bubble heat flux**

The heat fluxes under two bubbles for the high and low subcooling cases obtained by dividing the time resolved heat transfer by the time resolved bubble projected area are shown on Figure 9. The heat fluxes for the high subcooling case are lower than those for the low subcooling case until about 1 ms, after which it increases substantially above it. It is interesting to note from the space resolved measurements (Figure 7) that the contact line diameter begins to decrease starting from about 1 ms. The higher heat flux for the highly subcooled case after this time in Figure 9 may be indicative of colder liquid rewetting the surface, resulting in higher transient conduction.
oscillating in phase with the projected diameter, but the magnitude of the fluctuation is larger.

The heat transfer is seen to vary inversely with the projected bubble diameter and the inner contact line diameter (i.e., the heat transfer decreases as the bubble grows, and increases as it shrinks), indicating that the wall heat transfer does not govern the bubble behavior. Since higher heat transfer occurs when liquid rewets the wall, transient conduction/microconvection appears to be the main mode of heat transfer for the oscillating bubble as well.

**CONCLUSIONS**

A microheater array was used to obtain time and space resolved wall heat transfer data under bubbles nucleating from a single nucleation site under low and high subcooling conditions. The bubbles gained the majority of their energy from the superheated liquid layer and not from the wall, indicating that microlayer heat transfer was not significant. Transient conduction/microconvection was the dominant mechanism for bubble heat transfer.

**REFERENCES**


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**Oscillating bubbles, highly subcooled case**

A single bubble in the highly subcooled case was observed to grow and shrink numerous times on the surface (bubble H14) before eventually departing. The projected outer diameter of the bubble along with the apparent diameter of the inner contact line obtained by fitting a circular template to the bottom view images is plotted on Figure 10 along with the wall heat transfer. The size of the projected bubble diameter oscillated in size while growing steadily larger. The oscillatory bubble motion is probably caused by the bubble growing within the superheated layer then shrinking as condensation occurs over the bubble cap as it grows beyond the superheated layer into the colder bulk liquid. The increase in bubble size with time indicates growth of the superheated layer thickness due to pumping action of the oscillating bubble. The inner contact line diameter


