Heat Transfer from a Single Nucleation Site
During Saturated Pool Boiling of FC-72 Using an Array of 100 Micron Heaters

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ABSTRACT
Boiling heat transfer has been used in the thermal control of compact devices since the discovery of high heat transfer coefficients associated with boiling phenomena. The objective of the current work is to investigate and determine boiling heat transfer mechanisms in single and multiple bubble modes with a constant surface temperature boundary condition. The heat transfer data contained in this paper is unique because it is acquired at many locations simultaneously using a microscale heater array instead of at a single point underneath the bubbles, which yields a more detailed picture of the heat transfer process. 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 data indicated that the area influenced by the bubble departure 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.

INTRODUCTION
Despite many decades of study, there are still many conflicting models regarding the mechanisms by which heat is transferred during boiling. Many of the early models were based on bubble agitation/micro convection being the primary mechanism. These models did not include phase change, but relied on an analogy with forced convection, i.e., the role of the bubble is to change the length and velocity scales used to correlate data.

The vapor-liquid exchange model proposed by Forster and Grief [1] assumes that bubbles act as micropumps that remove a quantity of hot liquid from the wall equal to a hemisphere at the maximum bubble radius, replacing it with cold liquid from the bulk. The heat transfer from a single site is the energy required to heat this volume of liquid from the bulk temperature to the average of the wall and bulk temperatures.

Building on the work of Han and Griffith [2], Mikic and Rohsenow [3] developed a model of bubble heat transfer that assumes the bubble scavenges away the superheated layer surrounding the bubble over some area of influence as it departs, allowing colder liquid from the bulk to contact the surface. The superheated layer is then renewed during the waiting time (time after bubble departure and before nucleation of a new bubble) by transient conduction into a semi-infinite liquid. Transient conduction into this bulk liquid after bubble departure was the assumed mode of heat transfer.

Cooper and Lloyd [4] and van Stralen et al. [5] proposed a model based on the evaporation of a thin microlayer that forms between a hemispherically growing bubble and the wall during inertially controlled growth. Heat transfer through this microlayer was proposed to be the primary mechanism for bubble growth.

The proliferation of models and continuing controversy surrounding single bubble heat transfer is a direct result of the lack of reliable data regarding local heat transfer information in the vicinity of the bubble. The vast majority of experimental work performed to date regarding boiling has utilized single heaters that were large compared to individual bubbles, making it difficult to look at details of the boiling process. These experiments usually used a single heating element operated at constant power, making it difficult to obtain information about local temperature variations underneath bubbles. Other experiments have utilized surfaces held at constant temperature averaged over the entire heater, but the local heat flux and temperature were not measurable and could vary significantly across the heater.

Yaddanapudi and Kim [6] and Kim et al. [7] used a 96-element microheater array with individual heaters nominally 270 μm on a side to obtain wall heat transfer information under single bubbles at two wall
superheats. In both cases they found that bubble heat transfer mechanisms were different from the widely accepted view that microlayer evaporation is the dominant heat transfer mechanism in saturated pool boiling. The results also indicated that transient conduction and/or microconvection was the primary heat transfer mechanism, consistent with the model of Mikic and Rohsenow [3]. However, the area of influence of the departing bubble was much smaller than the model suggested, and the temperature of the liquid coming into contact with the wall after bubble departure was much higher than the bulk temperature. Because the departing bubble was about 380 µm in diameter, the spatial resolution used in this study was insufficient to determine the area of influence of the bubble. In this paper, we examine the results obtained using a 96 element heater array similar to the one used earlier, but with individual heaters nominally 100 µm x 100 µm. Wall heat transfer due to single bubbles separated by a distinct waiting time as well as multiple bubble nucleating one after another from a single site are examined.

**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 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 0.00125 °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 [8].

**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 directly calculated from this voltage and the heater resistance. The heater temperature was controlled by a digital potentiometer placed in a leg of the Wheatstone bridge.

Sixteen of these circuits were constructed on a single card. Six of these cards plugged into a motherboard that routed the signals from the host computer to the individual feedback circuits. The reader is referred to Bae et al. [9] 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 that given chamber temperature. Each heater in the array could be varied over a 20 °C range in 4 °C increments. The uncertainty in heater temperature is 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 Fig. 3 was provided by NASA and used in the experiments. The bellows and the surrounding housing allowed the test section pressure to be controlled. A stirrer was used to break up any stratification within the test chamber, while a series of Kapton heaters attached to the outside of the chamber were used to control the bulk liquid temperature.

**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 enough light for side view images. 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 considered and 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 total time-resolved heat trace for each heater in the array. The resulting heat transfer curve could exhibit both positive and negative values. Negative values of heat transfer could 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 Fig. 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, and each was assigned a number as indicated in Fig. 4. 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

Data were obtained under slightly subcooled pool boiling conditions using FC-72 at 1 atm ($T_{sat}$=56.7 °C). The surface temperature of the heater array and the bulk fluid temperature during the experiment were 76 °C and 52 °C, respectively. It was observed that the bubbles nucleated persistently from a single site on the array.

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. Events 10, 12, and 13 on Figure 4 were multiple bubble modes, with the remainder being single bubble modes. Events 10, 12, and 13 were composed to two, three, and three nucleation events, respectively.

**Single bubble Mode**

Time resolved images of a single bubble event 1 taken from below are shown on Fig. 5. Each heater in the array has been colored according to the heat transfer. Side view images are shown on Fig. 6. 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 are 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.

**Evaluation of superheated liquid model**

A plot of the time varying physical bubble diameter was obtained by fitting a circular template to the bubbles shown on Fig. 5. The wall heat transfer data shown in Fig. 4. 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:

$$d_{eq}(t) = \sqrt[3]{\frac{6}{\pi \cdot h_{fg} \cdot \int h(t)A_h \, dt}}$$

Assuming the time $t = 0$ to be the start of nucleation for a single bubble, the equivalent diameter is plotted along with the physical diameter on Fig. 7. The slight decrease in measured physical diameter after about 0.8 ms is due to the distortion of the bubble geometry during the growth time. It is seen that $d_{eq}$ is significantly lower than the measured bubble diameter during the bubble growth time, implying that the heat transferred from the wall cannot account for the bubble growth alone. This indicates that the bubble must have gained the great majority of its energy from the superheated liquid layer surrounding the bubble. This conclusion is consistent with the results of the study performed by Kim et al. [7].

American Institute of Aeronautics and Astronautics
**Evaluation of transient conduction model**

Mikic and Rohsenow [3] assumed that the bubble scavenged away the superheated layer over an area twice the bubble departure diameter (area ratio AR=4.0). They also assumed that the temperature of the liquid coming into contact with the wall was the bulk liquid temperature. As observed in the colorized bottom-view images (Fig. 5), the area of influence after bubble departure is contained within approximately half of the bubble departure diameter (Area Ratio AR=0.25). Plots of the transient conduction curve assuming various wall-to-liquid temperature differences (DT) and AR are compared to the actual heat transfer variation in Fig. 8. Assuming the rewetting liquid is at the bulk liquid temperature, the transient conduction curve is best fit to the measured heat trace when AR=0.1 as seen in Fig. 8. However, the rewetting liquid temperature is unknown. From the present data, one can clearly state that DT should be smaller since the heaters within the area of influence would be subjected to rewetting of colder liquid from the bulk during shrinkage of base diameter until departure. This allows the liquid surrounding the bubble base to be preheated gradually in advance.

In a study conducted by Kim et al. [7], it was predicted that AR=0.4, which is consistent with the present data and images. We can conclude from the higher spatial resolution underneath the bubble and better time-resolved data that the temperature of the rewetting liquid is higher than that of the bulk. However, it still needs to be studied numerically to make a quantitative conclusion.

**Multiple bubble mode**

Multiple bubble mode is defined as an event that consists of at least two bubbles that nucleate and depart without any waiting time in between. In this paper, we will examine only the data that were recorded during multiple bubble event 13. Side view images of this process are shown on Fig. 9. The multiple bubble mode starts with the first bubble nucleating between 0 - 0.27 ms. This bubble departs from the surface at 5.4 ms. A second bubble is observed to immediately nucleate in the wake of the first bubble. After a growth period, the second bubble is pulled off the surface prematurely by the influence of the first bubble rising in the liquid. The initial spherical bubble shape is distorted under the influence of the first-departed bubble and the vertical merging with it. Departure of the second bubble occurs at 10.26 ms and is immediately followed by the nucleation of a third bubble. This bubble grows on the surface and departure occurs at 17.82 ms - no immediate nucleation is observed after the third bubble departs.

The heat transfer distribution at the wall superimposed on the high-speed images are shown on Fig. 10. The heat transfer distribution for the first bubble is seen to be very similar to that observed for the single bubble event. A large heat transfer is observed just after bubble nucleation due to microlayer evaporation. The dry spot at the center of the bubble grows as the microlayer dries out, then shrinks as the bubble departs at 5.4 ms. The large heat transfer at the center of the array at bubble departure suggests that the entire heater surface is wetted with liquid, i.e., the departing bubble does not leave a vapor layer covering the heaters. The heat transfer after departure of the first bubble decays with time even as the second bubble grows (5.40 ms to 7.83 ms), and may be associated with growth of another dry spot on the surface. Bubble growth during this time may be due to evaporation at the three-phase contact line, or from the superheated liquid layer. Microlayer evaporation is not observed, indicating that much of the energy contained within the superheated liquid layer was depleted during the growth of the first bubble. The side view images (Fig. 9) indicate that merging of the second bubble with the first bubble occurs between 7.83 ms and 10.26 ms. The heat transfer distribution during this time indicates high heat transfer along the circumference of the bubble as it is pulled off the surface, which is consistent with rewetting of the surface with liquid. The majority of heat transfer during growth and departure of the second bubble seems to occur during the rewetting process before bubble departure by transient conduction and/or microconvection. Heat transfer distributions for the third bubble as it grows and departs the surface are very similar to those for the second bubble, but the third bubble is not prematurely pulled off the surface by merger with the previous bubbles.

Time-varying physical and equivalent diameters are plotted along with the total heat transfer for event 13 on Fig. 11. The first nucleation is followed by rapid bubble growth. The corresponding rapid increase in heat transfer is likely due to microlayer evaporation. As in the single nucleation event, however, the equivalent diameter indicates that the wall heat transfer cannot account for the large bubble size. The nucleation of the second bubble is not accompanied by an increase in heat transfer, and the bubble growth rate is seen to be much slower than for the first bubble. The equivalent diameter again indicates that the bubble gains energy from the superheated liquid layer during bubble growth. The heat transfer continues to decrease after nucleation until the second bubble begins to merge with the first bubble at 7.83 ms. The heat transfer increases during this merging process and peaks when the second bubble departs the surface. Nucleation of the third bubble is accompanied by a decrease in heat transfer as well. The heat transfer rises again as the bubble begins to pull off the surface at 15 ms. The peak in heat transfer again corresponds to bubble departure. Similar observations were made for events 10 and 12.
CONCLUSIONS

Space and time resolved heat transfer variations due to bubble activity on a 96 element heater array consisting of 100 mm heaters were visualized by using a high speed digital video camera to obtain images of bubble growth and departure, then colorizing each heater in the array according the instantaneous heat transfer. The current study indicates that the area of influence of the bubble is much smaller than the projected bubble area at departure, which validates the predicted area ratio in the study conducted by Kim et al. [7]. The examination of a calculated equivalent diameter with the measured physical diameter during the single bubble mode supports the idea that the bubble gains energy from the wall as well as from a superheated layer that develops during the waiting time. Microlayer evaporation was observed to contribute a significant, but not dominant, fraction of the wall heat transfer in this mode. Examination of wall heat transfer during multiple bubble modes indicated that microlayer evaporation is insignificant after the first bubble, and that heat transfer occurs mainly through transient conduction and/or microconvection during liquid rewetting as the bubble departs the surface.

ACKNOWLEDGEMENTS

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NOMENCLATURE

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<td>$A$</td>
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<td>$d$</td>
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<tr>
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<td>Wall-to-liquid temperature difference</td>
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Greek

$\rho$ Density

Subscripts

$eq$ Equivalent

$h$ Heater

$sat$ Saturation

$v$ Vapor

Superscripts

$\cdot$ Per unit time

$\"$ Per unit area

REFERENCES

Figure 1: Photograph of heater array with a single bubble nucleating on the surface.

Figure 2: A schematic diagram of the feedback control circuit.
Figure 3: Schematic of experimental apparatus.

Figure 4: Total heat transfer vs. time.
Figure 5: Colorized bottom-view images. The non-functional heaters are noted in gray.

Figure 6: Side-view images of bubble growth. The numbers printed below the images indicate the time in milliseconds.
Figure 7: Physical and equivalent bubble diameter vs. time.

Figure 8: Wall heat transfer compared with transient conduction model.
Figure 9: Side-view images of multiple bubble event 13.
The numbers printed below the images indicate the time in milliseconds. The time interval between succeeding frames is 0.27 ms. The black-underlined images in the timeline show bubble nucleation and the last red-underlined image indicates the final bubble departure.
Figure 10: Colorized bottom-view images of multiple bubble event 13. Non-functional heaters are noted in gray. The black-underlined images in the timeline show bubble nucleation and the red-underlined image indicates the final bubble departure.
Figure 11: Physical and equivalent diameters of multiple bubble event 13 along with total heat transfer trace.