Liquid-solid contact in steady-state transition pool boiling

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A recently developed technique of measuring liquid-solid contact has been applied to steady-state pool boiling of methanol. The boiling curve has also been measured. Contrary to the assumptions often made about transition boiling, the liquid-solid contact is not complete at the critical heat flux, and the heat flux during the liquid contact periods is not constant but falls with increasing temperature.

Keywords: transition pool boiling; liquid-solid contact; critical heat flux

Introduction

Previous studies of liquid-solid contact in pool boiling have covered all three regions of the boiling curve, though the main interest has concentrated on transition boiling. It is widely considered that the heat transfer rate in transition boiling is controlled by the extent of surface contact.

Some information is available for nucleate boiling, for surfaces close to or at the critical heat flux. In the Zuber[1] theory of the critical heat flux, the boiling crisis is attributed to a Helmholtz instability in the countercurrent flows of liquid toward the surface and vapor away from the surface. An assumption in the theory is that the fraction of the surface area occupied by vapor columns is $\pi/16$ or, in other words, that the fraction of wetted area f is about 0.80.

Photographic studies[1,3] close to the critical heat flux condition tend to confirm this. The results in Ref. 2 vary considerably according to the method used to approach burnout, but the vapor bubble coverage ranged from 0.10 to 0.38 of the surface area.

Quantitative studies of liquid-solid contact in transition boiling have mostly used either conductive probes or analysis of surface temperature fluctuations. Ragheb *et al.*[4-6] used an insulated wire inserted through the wall of the boiling heat transfer surface. To interpret the results, it was necessary to assume that the wetted area fraction f was zero at the minimum film boiling (mfb) point, that $f=1$ at the critical heat flux point, and that the probe signal varied linearly with f in between.

Another study with a conductive probe was concerned mainly with film boiling. Yao and Henry[7] have confirmed liquid-solid contacts in pool boiling of saturated ethanol and water on a horizontal, flat, gold-plated copper surface. The authors comment that in transition boiling the surface contact is virtually complete (in contradiction to the findings of most other studies).

A quite different technique of estimating the extent of surface contact is to study wall temperature fluctuations[8-11]. It is widely accepted that during transition boiling, the heated surface is alternately in contact with liquid and vapor. The alternating periods of high and low heat transfer (during the periods of liquid contact and vapor contact, respectively) lead to the wall temperature fluctuations that are characteristic of transition boiling. It is necessary to make assumptions about the nature of the processes occurring, and the actual temperature versus time graphs are different from the idealized behavior on which the analysis is based.

A more recent technique of measuring liquid-solid contact has been developed by Dhuga and Winterton[12,13]. If the metal heat transfer surface is covered with a very thin electrically insulating layer, thin enough not to affect the thermal properties of the surface, then in a measurement of electrical impedance between the metal substrate and the bulk liquid the current is forced to flow through the areas that are wetted. Provided that the impedance of the insulating layer is the dominant impedance in the system, the current will be proportional to the area of the layer that is available, i.e., to the wetted area. It is assumed that even a thin vapor layer gives effectively infinite impedance. Using anodized aluminum surfaces, we were able to confirm the dependence of current on surface area. Simultaneous measurement of the boiling curve and the degree of liquid-solid contact has been reported by Dhuga and Winterton[14]. These pool boiling experiments used a quenching technique. Both water and methanol were studied.

The purpose of this paper is to report what are believed to be the first results, using this more recent technique of surface contact measurement, for steady-state transition boiling. The transient, quenching technique has the advantage that experimental data for the entire boiling curve can be obtained quickly. On the other hand, the calculation of heat flux may involve a complicated inverse heat conduction routine, and the method of Ref. 14 requires accurate measurement of small temperature differences. Also, there is increasing evidence that the boiling curve is strongly affected by the speed of the transient[15-17]. In the transition region particularly, for given surface superheat, different heat flux values are obtained for transient heating, transient cooling, and steady state. To eliminate the complication of this additional, and difficult to control, parameter of the speed of the transient, is a strong case of steady-state measurements.

Correlation of heat flux and wetted area

It is assumed initially that in the transition region the heat flux can be considered as a combination of a component proportional to the fraction of wetted area f and a film boiling component; i.e.,

$$q_{tr} = fq_{lc} + (1-f)q_{vc} \tag{1}$$

where q_{lc} is the heat flux during the liquid contact and q_{vc} the heat flux during the vapor contact.

This equation has been used many times (e.g., Refs. 18–22), though with q_{lc} identified as a nucleate boiling term and q_{vc} as a film boiling term. Kalinin[18] considered that both should be extrapolated from outside the transition boiling region. In nucleate boiling this does not seem to work very well because to continue the very rapid increase of heat flux with temperature characteristic of nucleate boiling into the transition region is liable to lead to very high predicted heat fluxes.

In Refs. 19–21 both terms are considered constant, with q_{lc} equal to the critical heat flux q_{crit} and q_{vc} equal to the mfb heat flux q_{mfb}. Equation 1 shows that this approach is equivalent to saying $f=1$ at the critical heat flux and $f=0$ at the mfb point.

The measurements to be described later and those of Ref. 14 are not consistent with this; in particular, they show f significantly less than 1 at the critical heat flux. For the mfb point (and the adjacent film boiling region) the measurements give f very close to zero, though there is a very small signal corresponding to $f=0.01$ or less. For simplicity it is assumed that $f=0$ at the mfb point.

Retaining Equation 1 and the assumption that q_{lc} and q_{vc} are constant (but rejecting obviously the assumption $f=1$ at the critical heat flux) and applying the equation to the mfb point give $q_{vc}=q_{mfb}$. Any other experimental value of f is enough to determine q_{lc}, but the obvious point to choose is the critical heat flux. Consequently Equation 1 becomes

$$q_{tr}=fq_{lc}+(1-f)q_{mfb} \tag{2}$$

with

$$q_{lc}=\frac{q_{crit}-(1-f_{crit})q_{mfb}}{f_{crit}} \tag{3}$$

This is the simplest possible equation, assuming a linear dependence of heat flux on f and given that $f<1$ at the critical heat flux.

Apparatus

The pool boiling test section is shown in Figure 1. For steady-state tests that include the transition boiling region it is necessary to have a short distance between the cartridge heaters and the boiling surface and low thermal capacity heaters[23]. Temperature control was maintained with a Eurotherm controller (model 820, of the logic output type with a 0.1-s cycle time). The controlling thermocouple, type K, was of the bare junction type with 0.19-mm wires soldered to the bottom of a 1.6-mm-diameter hole located 3 mm below the center of the boiling surface. Heat flux was calculated from the electricity consumption measured by a standard meter, with correction for heat losses measured in a separate test as a function of temperature. Care was needed in measuring the heat losses, since in the worst case (at the mfb point) the losses were comparable with the heat transferred to the boiling liquid. Repeat measurements at fixed surface temperature within a given run gave corrected heat flux values within 2%. Uncertainty on the heat losses contributes a further error of up to 2%.

The measurement of liquid-solid contact followed the technique described in Ref. 12. This involved anodizing the aluminum surface. Prior to anodizing, the surface was polished with emery paper 320, degreased with acetone, and then washed with deionized water. Electrical contact with the bulk liquid was through a flat spiral electrode held parallel to the boiling surface and about 5 mm away.

A number of minor improvements on the basic technique of Ref. 12 were made. Instead of dipping the test section upside down into a pool of electrolyte for anodizing, which may have had the disadvantage of allowing gas bubbles to become trapped against the surface, the test section was anodized right way up. A pool of electrolyte, larger than the final boiling heat transfer surface, was held on the surface by a glass tube and a silicone rubber seal. Certainly, in favorable cases, higher electrical impedances were obtained for the aluminum oxide layer. An unfortunate feature of the technique is that surfaces prepared under nominally identical conditions show different impedance characteristics, including, in a proportion of cases, surfaces where the impedance is so low that the surface has to be rejected even before any detailed checks are carried out.

Another improvement was that the detailed investigation of the impedance characteristics of the aluminum oxide layer

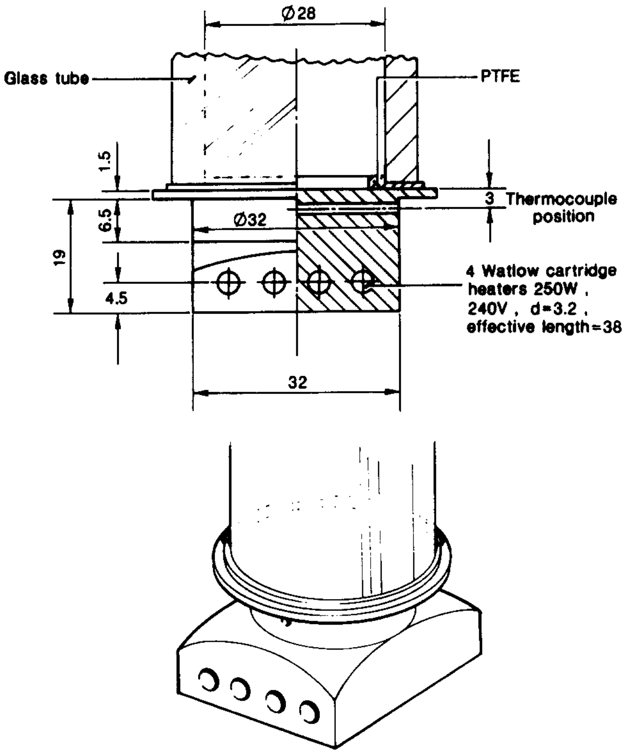

Figure 1 Apparatus used for the boiling measurements. Front view and section (above) and general appearance (below). Dimensions in millimeters

Notation

f	Fraction of area wetted by liquid
q	Heat flux
T	Temperature
θ	Dimensionless temperature given by Equation 4a

Subscripts

crit	Critical heat flux
vc	Contribution from vapor contact
mfb	Minimum film boiling
lc	Contribution from liquid contact
tr	Transition boiling
W	Wall

(using a frequency response analyzer) was performed at saturation temperature rather than room temperature.

To meausre surface contact during boiling, we applied a 2-V, 3-Hz signal across the boiling surface and a 5-kΩ resistor in series. The voltage developed across the resistor was displayed on a chart recorder. Before the equipment was assembled, it had been feared that the ac signal would interfere with the temperature signal from the bare junction thermocouple (a fast response thermocouple is essential for good temperature control). No ac pickup was found, presumably because virtually none of the 2 V supplied appears across the highly conductive aluminum block. The block and the temperature controller were grounded through a common point.

Results

To help in understanding the measurements of the real and imaginary parts of the electrical impedance, Figure 2 shows both the idealized equivalent electrical circuit and the ideal characteristics. It is assumed that the aluminum oxide layer has resistance and capacitance in parallel, and these are then in series with the bulk resistance of the liquid (methanol). At very high frequencies the capacitor shorts out the oxide layer resistance, and a real impedance equal to that of the bulk liquid R_e is measured. At very low frequencies the capacitor does not conduct at all, so again a real impedance is measured, equal to $R+R_e$. At intermediate frequencies there is a significant imaginary component.

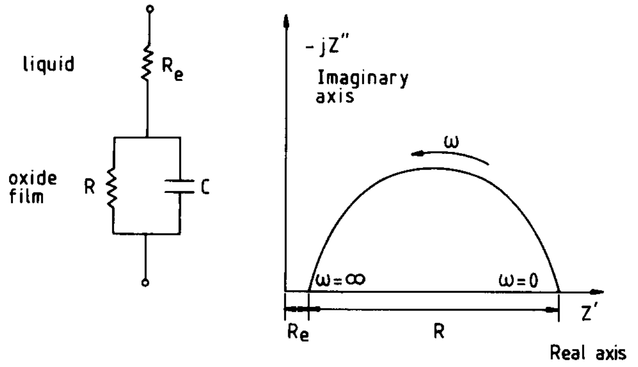

Figure 2 The equivalent circuit for the bulk liquid and the anodized layer plus the expected variation of impedance with frequency

Figure 3 shows the measured impedance at different frequencies for the surface used in the boiling measurements. Although there are some changes with time and with temperature during the boiling runs, they are surprisingly small. Also, at 3 Hz, which had previously been chosen for other reasons, the characteristics are particularly stable. This is easier to see in Table 1. Figure 3 also shows measurements made during boiling at 17 K superheat, after the third boiling run. These results are less accurate since the FRA proved more difficult to use with some fluctuations in the readings. The values on the graph are averages of two or three readings.

The results for the surface contact as a function of temperature are shown in Figure 4, the boiling curves in Figure 5. A number of features are of interest. For run 1, particularly in nucleate boiling, the surfaces did not seem to have settled down. Runs 2 and 3 show more reproducible behavior. For each run, measurements started at the lowest temperature. In all cases in transition boiling there is a correspondence between Figures 4 and 5; i.e., better contact is reflected in better heat transfer.

Table 1 Total impedance (kΩ) at 3 Hz (surface at 64°C)

Before first boiling run	129
After first boiling run	129
After third boiling run	130

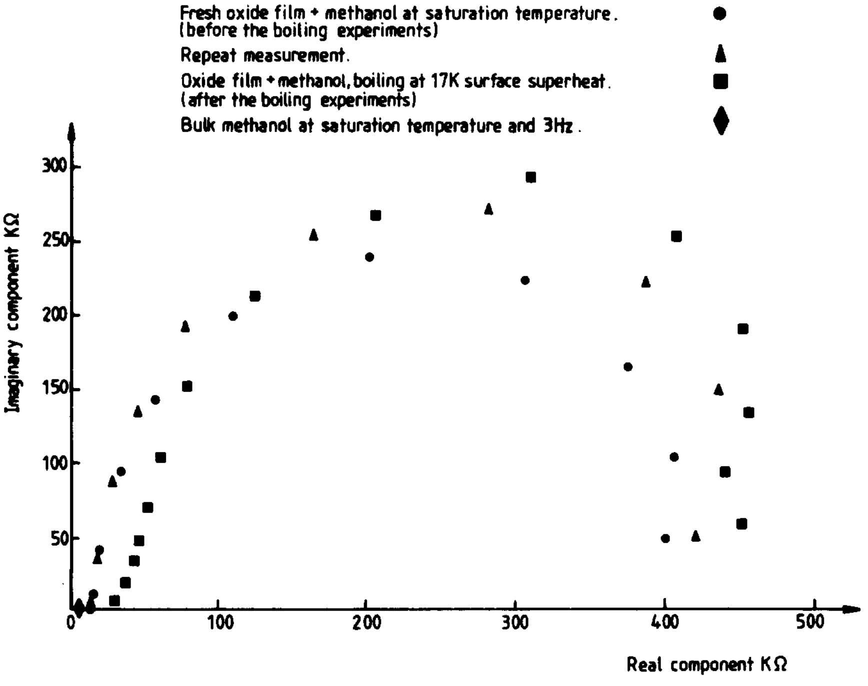

Figure 3 Measured impedance variation for the anodized surface used in the boiling tests

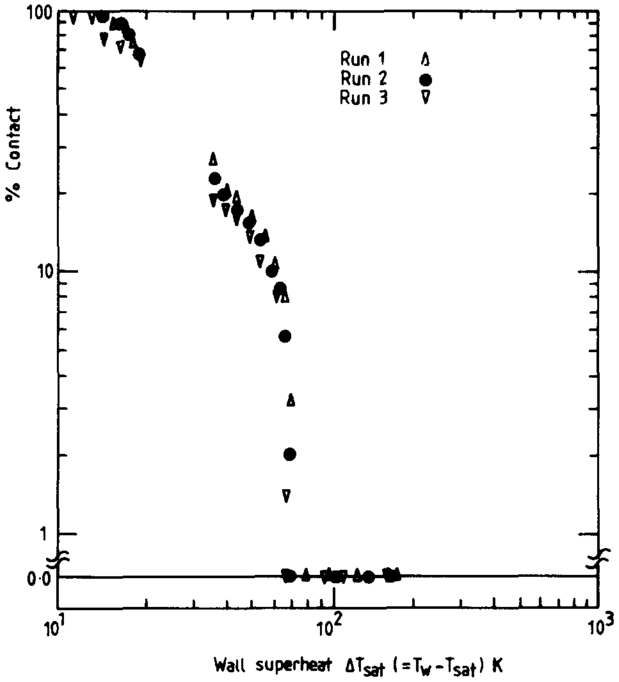

Figure 4 Measured fraction of wetted area

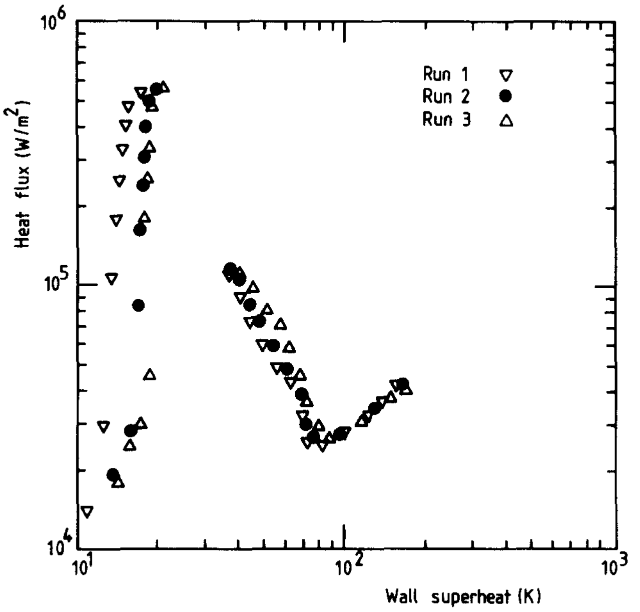

Figure 5 The boiling curves for methanol at atmospheric pressure corresponding to the fractions of wetted area shown in Figure 4

There is a well-defined mfb point on both graphs, and contact is zero in film boiling (to the accuracy of the measurement, certainly <1%).

Measurements could not be made close to the critical heat flux in transition boiling because temperature control could not be achieved. If a temperature in this range was set on the temperature controller, the actual temperature oscillated by ±10 K. The measurements shown in Figure 5 displayed temperature oscillations of at most ±3 K (much less for the nucleate and film boiling regions).

Figure 6 shows a comparison between the heat flux measurements for run 2 and the prediction of Equations 2 and 3 (solid line). Considering that the equations are already fitted at the two ends of the transition region, the agreement is very poor. Note there were no surface contact measurements in the region where the temperature could not be controlled, so the prediction here is an extrapolation.

Discussion

The measured fraction of wetted-area values at the critical heat flux, at around 65%, are on the low side compared with the estimates in the introduction. They are also slightly lower than those reported in Ref. 14 using a quenching technique.

Equations 2 and 3 overestimate the transition boiling heat flux. In the middle part of the transition region the error is about a factor of 2. A similar conclusion was found in Ref. 14. In other words, as the surface temperature increases beyond the critical heat flux point, heat flux falls much faster than surface contact.

Since Equation 1 with q_{lc} constant fails to fit the experimental data, it is of interest to discover just how q_{lc} does vary with temperature. Equation 1 can be used in reverse to calculate q_{lc} from the measured q_{tr} and f values. It is still necessary to make some assumption about q_{vc}. It turns out that assuming q_{vc} constant (at the mfb value) gives a simpler and smoother variation of q_{lc} (but the change in the q_{lc} values if q_{vc} is extrapolated from the film boiling region is quite small). It is clear that q_{lc} falls with increasing temperature to a roughly constant value of a little over 2×10^5 W m^{-2} as the film boiling region is approached. It seems reasonable to attempt to correlate q_{lc} in the transition region with the excess temperature beyond the critical heat flux point. A dimensionless measure of this is

$$\theta=\frac{T_w-T_{crit}}{T_{mfb}-T_{crit}} \tag{4a}$$

The experimental values of q_{lc} are correlated well by

$$q_{lc}=2\times10^5+(6.03\times10^5)(1-\theta)^3 \tag{4b}$$

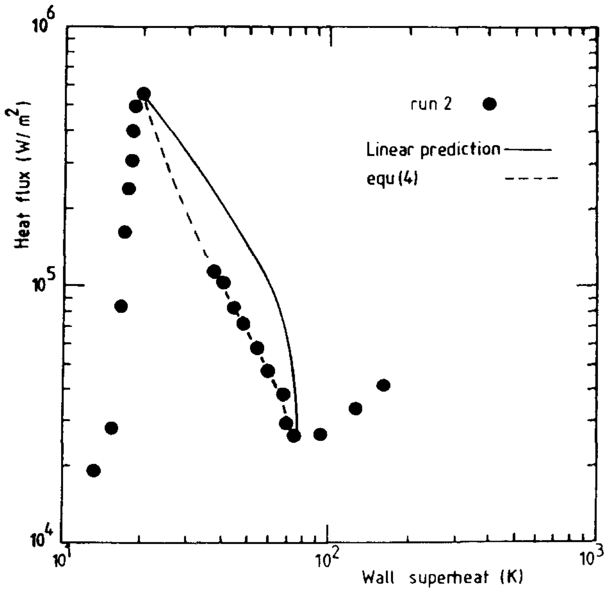

Figure 6 The boiling curve for run 2 together with predictions based on the fraction of wetted area from Figure 4

Using this expression in Equation 1, with $q_{vc} = q_{mfb}$ and the measured f values, generates the dashed line in Figure 6. The experimental heat flux values are given to within 6%.

Conclusions

The measured extent of liquid-solid contact at the critical heat flux is consistent with estimates but slightly lower than earlier ones in the literature and significantly below the 100% sometimes assumed.

In transition boiling the heat flux during the liquid contact periods (q_{lc}) is not constant but falls with increasing temperature, reaching a roughly constant value of a little over 2×10^5 W m^{-2} as the film boiling region is approached.

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