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Measurement of surface contact in transition boiling

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Abstract—A new method of measuring liquid–solid contact in boiling is described. The heat transfer surface is coated with a thin, electrically-insulating layer and the impedance between the metal substrate and the boiling liquid is measured. It is shown theoretically, and confirmed experimentally, that this impedance is related to the average fraction of the heat transfer area that is wetted by the liquid. The technique is applied, together with measurement of the boiling curve, to pool boiling of water and methanol.

INTRODUCTION

ALTHOUGH it is generally accepted now that the boiling liquid does contact the solid heat transfer surface during transition boiling, much of the early evidence was contradictory or inconclusive in nature. An early photographic study [1] deduced that there was no contact. Berenson [2] on the other hand, showed that surface properties such as roughness and contact angle influence the transition boiling heat transfer. It is difficult to account for this unless it is assumed that the liquid touches the surface. Other evidence for contact is given in refs. [3] and [4], and, specifically for the influence of surface condition on transition boiling heat transfer, in [5–8]. There is also qualitative evidence for contact in film boiling [9, 10].

In many recent studies it has been found convenient to correlate transition boiling results by assuming transition boiling to be a combination of both unstable nucleate boiling and unstable film boiling. As noted by Berenson [2], the variation of heat transfer with temperature is primarily a result of the change in the fraction of time each boiling regime exists at a given location on the heated surface.

Kalinin *et al.* [11] weighted the nucleate and film boiling heat transfer components and expressed the average transition boiling heat flux q_{tr} as:

$$q_{tr} = f q_{nb} + (1-f) q_{fb} \tag{1}$$

where

f fraction of area being wetted
q_{nb} nucleate boiling heat transfer in the transition regime
q_{fb} film boiling heat transfer in the transition regime.

They applied equation (1) to transition pool boiling results of various investigations [2, 4] with the values for q_{nb} and q_{fb} evaluated from correlations for nucleate and film boiling, respectively, extrapolated into the transition boiling region. The result of processing the experimental data in the form of the dependence of f on $\Delta\bar{T}$, a dimensionless wall temperature, could be expressed either as an exponential decrease or alternatively as $f = (1-\Delta\bar{T})^7$.

Several investigators [12–14] have used equation (1) as a basis for correlating their data, but unlike Kalinin *et al.*, took both q_{nb} and q_{fb} to be constant at their limiting values, i.e. $q_{nb} = q_{chf}$ and $q_{fb} = q_{mfb}$. Tong's expression [15] expresses the total transition heat flux, q_{tr}, as the sum of two components, i.e.

$$q_{tr} = q_{tb} + q_{fb} \tag{2}$$

where q_{tb} is the transition boiling component which decays with increasing T_w, the wall temperature. Tong relates the wetted area fraction, f, to q_{tb} by:

$$f = \frac{q_{tb}}{q_{nb}} \tag{3}$$

where q_{nb} can be approximated by q_{chf} in the transition boiling regime.

All the estimates of f mentioned so far are derived from heat transfer data, and necessitate assumptions about the nature of transition boiling.

Methods of estimating f *directly*

Conductive probes have been used to estimate the extent of surface contact more directly. Ragheb *et al.* [16] in their study of flow boiling of water at atmospheric pressure used a specially constructed zirconium probe to show that the measured onset of intermittent wetting is very close to the minimum heat flux point. Also, it was shown that the measured onset of continuous liquid contact coincides with the critical heat flux.

Their conductive probe was a 1-mm zirconium wire, the tip of which was coated with platinum to suit high temperature operation. The wire was insulated electrically from the copper test section by a zirconium oxide layer. The probe penetrated the inner wall of the copper cylinder with the tip made flush with the heat transfer surface. The electrical resistance between the platinum tip and the heated surface varies depending upon whether gaseous or liquid phase exist on the heated surface. With a dry wall, the resistance is very

NOMENCLATURE

A	film area [m^2]
A'	heat transfer area [m^2]
C	film capacitance [F]
d	film thickness [m]
f	fraction of wetted area
f'	frequency [Hz]
i	current signal
i_{nb}	current signal in non-boiling
k	dielectric constant of film
q_{chf}	critical heat flux [$W\ m^{-2}$]
q_{fb}	film boiling heat transfer in the transition regime [$W\ m^{-2}$]
q_{mfb}	minimum film boiling heat flux [$W\ m^{-2}$]
q_{nb}	nucleate boiling heat transfer in the transition regime [$W\ m^{-2}$]
q_{tb}	transition boiling component [$W\ m^{-2}$]
q_{tr}	transition boiling heat flux [$W\ m^{-2}$]
R	film resistance [Ω]
R_e	liquid resistance [Ω]
t	time [s]
$\Delta\bar{T}$	dimensionless temperature, $(T_w - T_{chf})/(T_{mfb} - T_{chf})$
T_{chf}	temperature corresponding to critical heat flux point [K]
T_{mfb}	temperature corresponding to minimum film boiling point [K]
T_w	wall temperature [K]
Z	electrical impedance [Ω].

Greek symbols

ε	permittivity of film [$F\ m^{-1}$]
ρ	film resistivity [Ωm]
ω	angular frequency [$rad\ s^{-1}$].

high. With a wet wall the slight conductivity of the water ensured a lower resistance.

The behaviour of the voltage drop measured between the probe and the adjacent copper wall during rewetting was as follows. There was a gradual rise of voltage drop with falling temperature during film boiling. This was thought to be the result of momentary dry collisions where no wetting of the wall takes place. This explanation is somewhat confusing in that a signal can only arise if the liquid wets the wall. Perhaps a more acceptable reasoning may have been to acknowledge momentary wetting of the wall in film boiling as evidenced from the voltage drop fluctuations and in view of the evidence for liquid–solid contact in film boiling [9, 10, 17].

In transition boiling, there was a sharp rise of voltage drop corresponding to increased wetting of the wall.

The probe trace is somewhat puzzling. Although the authors state in [18] that the probe is never completely wet or dry at any given time in the transition region, no justification in support of the trace was given in [16]. In view of the very small probe that was used, it is not unreasonable to expect the probe tip to be alternately covered by vapour and liquid in transition boiling and thus give two switched resistance values, i.e. null or full-scale voltage fluctuations. It is probable that the response of the recording instrument did not allow the short time instantaneous wet/dry signal to be recorded but instead traced out an average value of the signal.

In a more recent study, Ragheb and Cheng [19] used the conductance probe described above for quantifying the extent of surface contact in transition boiling for water flowing in a tube at atmospheric pressure. They reported, based on a few simplifying assumptions, the measurement of fraction of wetted area as a function of surface temperature.

It was assumed that $f = 0$ at the minimum film boiling point and that $f = 1$ at the critical heat flux. Although not stated explicitly, their interpretation of the data also assumed that the average value of the probe signal varied linearly with f between these points. Their assumption of a linear fraction of contact between the liquid and surface was not substantiated. Thus, a calibration of the probe in terms of the fraction of wetted area is lacking.

The probe measurements were compared with the predictions of Kalinin *et al.* [11] and Tong [15]. The predicted area, using Tong's expression, was in closer agreement with the probe results.

Another study with a conductive probe was concerned mainly with film boiling. Yao and Henry [17] have confirmed liquid–solid contacts in pool film boiling of saturated ethanol and water on a horizontal, flat, gold-plated copper surface.

The area of contact in film boiling was estimated by a conductance probe tree, consisting of six probes on each of four arms, inserted in the boiling liquid. The probe was previously calibrated by measuring the voltage produced across a series 100 kΩ resistor by a given contact area of copper electrode in the base of a non-conducting lucite dish. Although primarily concerned with film boiling, the authors do comment that in transition boiling the surface contact is virtually complete.

The investigation of Yao and Henry, although pioneering in its field, has some shortcomings. The authors admit a factor of two in the uncertainty of the interpretation of contact area. Also the probe was inserted into the liquid to within 1.5 mm of the solid surface. It is possible that this arrangement could interfere with the normal boiling mechanism at the heated surface by inducing liquid–solid contacts. The probe signal could be influenced by changes in bulk resistance of the liquid. The ethanol and triple-distilled water that were used both had at least 100 kΩ resistance.

A quite different technique of estimating the extent of surface contact is to study wall temperature fluctuations. It is widely accepted that during transition boiling, the heated surface is alternately in contact with liquid and vapour. The alternating periods of high and low heat transfer (during the periods of liquid contact and vapour contact respectively) lead to the wall temperature fluctuations which are characteristic of transition boiling.

Nishikawa *et al.* [20] measured temperature fluctuations for saturated pool boiling of water on a 8-mm-diam. copper surface. Their analysis of surface temperature records explained transition boiling as a combination of nucleate and film boiling. The high frequency temperature fluctuations characteristic of nucleate boiling were observed during the temperature decreasing period which they interpreted as liquid–solid contact. No such fluctuations were observed during the temperature increasing period.

Also, they estimated the transition boiling heat flux from the fraction of time spent in nucleate and film boiling. For heat transfer due to liquid–solid contact, the nucleate boiling characteristic curve was extended into the transition boiling region. The contribution of film boiling heat flux was obtained experimentally throughout the required range using an artificially poorly-wettable heating surface. The agreement between the measured transition boiling heat flux and that estimated from temperature fluctuations was poor. A more recent application of this type of surface probe is described in [31].

Weisman *et al.* [21] recorded and analysed the wall temperature fluctuations characteristic of transition boiling in an effort to relate these oscillations to the periodic wetting of the heated surface. Their analysis, which was for flow boiling of water in a round-tube test section, adopted two different procedures, depending on superheat level, for estimating wetted area fractions. The analysis, however, proved inadequate in that it could not explain the temperature oscillation phenomenon. No matter what value of heat transfer coefficient was assumed for the time when the wall is wetted, the overall heat transfer rate was much below that actually observed.

More recently, Kao and Weisman [22] have assumed that the major cause of the observed temperature oscillations is the axial oscillation of a rewet front. This moving front model has been compared to data from the authors' experiments with a mercury-heated test section with good success.

In summary, though much effort has already been made towards the measurement of the degree of surface contact, there are still considerable experimental difficulties in measuring *f*. The very few results which are available in the open literature are far from complete in as much as the methods still involve fairly bold assumptions and may require a fairly involved analytical approach as is the case for the analysis of wall temperature fluctuations. Clearly, there is much scope for using new direct experimental techniques for the detailed investigation of the region immediately adjacent to the heated surface.

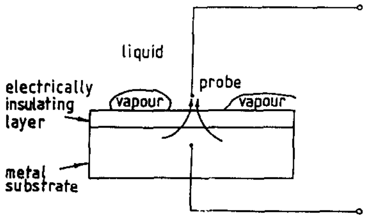

FIG. 1. Composite heat transfer surface (e.g. anodised aluminium surface). Current forced to flow through wetted area.

THE NEW METHOD OF MEASURING LIQUID–SOLID CONTACT

Consider a composite heat transfer surface consisting of a metal base covered with a thin, electrically-insulating layer, Fig. 1. The insulating layer is thin enough not to affect the thermal properties of the surface.

The boiling of a test liquid with slight electrical conductivity on, e.g. an anodised aluminium surface, can be represented by a network of resistances and capacitances, known as an equivalent circuit. The equivalent circuit proposed by Randles (Fig. 2) has been found to have a wide application to many electrochemical systems [23]. The parallel combination of the resistor *R* and capacitor *C* will represent the combined effect of the bulk oxide film and the electrochemical (liquid—Al_2O_3) interface. R_e is the liquid resistance. Other resistance and capacitance elements (e.g. those that can arise from electrochemical reactions at the probe–liquid interface) are assumed small and are neglected.

If an alternating potential is applied across the insulating film during boiling, a current is caused to

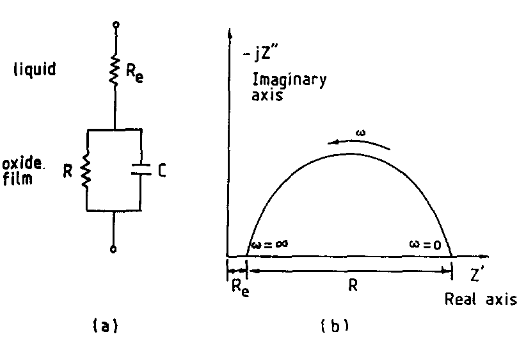

FIG. 2. A simple Randles-type equivalent circuit and impedance plot of an electrochemical cell. (a) Equivalent circuit; (b) impedance plotting in the complex plane (negative imaginary parts plotted above the real axis).

flow from the bulk liquid to the metal surface, with a value determined by the wetting taking place at the surface. Where liquid touches the surface, the system behaves essentially as a parallel plate capacitor with the liquid as one plate and the metal substrate as the other. The separation of the plates is just the thickness (d) of the very thin insulating layer. Once film boiling starts the separation becomes enormously greater.

The response of the circuit, in terms of a Nyquist plot, is also shown in Fig. 2. The capacitive reactance component is given on the imaginary axis (ordinate) and resistive component on the real (abscissa); ω is the angular frequency of the periodic voltage signal, frequency f' ($\omega = 2\pi f'$).

At high frequencies, typically greater than 10 kHz, the capacitor conducts easily, and effectively shorts out R; only the effect of solution resistance R_e remains. At low frequencies, i.e. as zero frequency or DC is approached, the capacitor ceases to conduct and the cell impedance becomes the sum of R_e and R.

The impedance of the assumed circuit of Fig. 2 is

$$Z(\omega) = R_e + \frac{1}{\frac{1}{R} + j\omega C}. \tag{4}$$

If the bulk liquid resistance, R_e, is made small by choosing a suitably conducting liquid such that the bulk oxide is the dominant resistance to current flow, then

$$Z(\omega) \approx \frac{1}{\frac{1}{R} + j\omega C} \tag{5}$$

$$\therefore |Z(\omega)| = \left[\frac{R^2}{1+\omega^2 R^2 C^2}\right]^{1/2}. \tag{6}$$

By substituting the expressions for resistance $R = \rho d/A$ and capacitance $C = k\varepsilon A/d$ of the oxide film, then

$$|Z(\omega)| = \frac{1}{A}\left[\frac{\rho^2 d^2}{1+\omega^2 k^2 \varepsilon^2 \rho^2}\right]^{1/2}.$$

That is

$$|Z(\omega)| = \frac{K}{A} \tag{7}$$

where

$$K = \left[\frac{\rho^2 d^2}{1+\omega^2 k^2 \varepsilon^2 \rho^2}\right]^{1/2}$$

= constant for constant film properties.

Hence, the measurement of electrical impedance (Z) (or its resistive or capacitive components) between the liquid and the metal substrate of the heat transfer surface will give the required information on the wetted area fraction.

Dielectric film formation

Thin, electrically-insulating films may be formed in a variety of ways, vacuum deposition techniques and anodisation being the principle methods. The vacuum methods of depositing thin films are thermal evaporation using either conventional heating or electron beams, sputtering, and chemical vapour deposition, CVD [24, 25]. Preliminary tests at Birmingham on the vacuum (thermal evaporation) method of depositing silicon monoxide (SiO) and bismuth oxide (Bi_2O_3) films on a copper surface have given coatings that have exhibited poor adhesion or poor insulation.

Anodisation

Anodising is an electrolytic oxidation process for producing protective films on metals such as aluminium. When aluminium is made the anode in a cell containing an electrolyte, a film of aluminium oxide (Al_2O_3) forms on the metal surface. Formation of the oxide depends on the migration of aluminium ions from the metal through the oxide to react at the oxide–electrolyte interface [26].

Two types of film can be produced on aluminium; a porous film characterised by substantial thickness (100 μm or so) and porous structure, or a barrier film of non-porous structure and small thickness (usually < 1 μm). The simplest criterion used to distinguish the two types of film is that barrier-type films are supposed insoluble in the forming electrolyte (e.g. ammonium tartrate), whereas the porous films are partially soluble (e.g. sulphuric acid as electrolyte).

The apparatus used was based on that described by Holland and Sutherland [27]. A circuit diagram of the anodising arrangement is given in Fig. 3. The power supply consists of a transformer, the output of which is connected to a bridge rectifier circuit capable of supplying 180 V and 2 A. For safety, the output is isolated from the mains supply. The output is smoothed by means of a 10 μF and a 47 μF capacitor across the output separated by an 82 Ω series resistance. The anodising voltage is controlled by a Variac in the input.

The electrochemical cell consists of the aluminium section to be anodised as the anode and aluminium foil as cathode immersed in an electrolyte. The electrolyte for producing an anodic barrier layer is a solution of 3% by weight ammonium tartrate in distilled water with sufficient tartaric acid solution added to obtain the desired pH of 5–5.5 [27].

Commercial grade aluminium samples of minimum

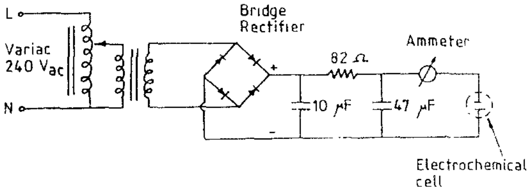

FIG. 3. A circuit for steady DC supply for anodising.

purity 99.0% were anodised. The area to be anodised was defined by masking with insulating tape. The procedure was to set the voltage to be applied across the cell to typically 140 V. The cell was then connected and the current voltage values were then recorded. The operation was continued for at least 4 h. The thickness of the barrier layer formed is estimated to be 0.1–0.2 μm. The value depends on the forming voltage, being 13–14 Å V^{-1} [27] (10^4 Å = 1 μm).

The final anodising current was usually in the range 1.0–2.0 A m^{-2}. Holland and Sutherland [27] suggest that impurities in commercial grade aluminium can prevent the formation of an impervious oxide so that high currents are passed for an indefinite period. Hass [28] anodised evaporated aluminium mirrors and found that after a few minutes the oxide formation was substantially complete and reports a final leakage current density of 1 mA dm^{-2} (=0.1 A m^{-2}). Smith [29] who anodised aluminium foil of 99.99% minimum purity using boric acid as electrolyte observed the final current density varied between 0.01–0.5 A m^{-2} depending on surface treatment and the applied voltage. Valid comparisons, however, are difficult to make because of the differing anodising conditions.

IMPEDANCE CHARACTERISTICS OF THE OXIDE FILM

A detailed investigation of the properties of the anodised layer was made using a Frequency Response Analyser (FRA, Schlumberger Solartron 1170), connected according to the circuit in Fig. 4. The probe used to make electrical contact with the bulk liquid was a 10-mm-long wire spiral, the lower end about 5 mm from the solid surface. It proved difficult to use the FRA while boiling was taking place. It was more convenient to record the voltage drop across the standard resistor (Fig. 4) continuously on a chart recorder.

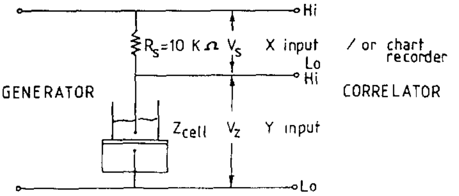

FIG. 4. A circuit for impedance measurement using a Frequency Response Analyser (FRA, Schlumberger, Solartron 1170).

The impedance characteristic of one anodic film is plotted in Fig. 5. Also provided for comparison are the impedance measurements for bulk liquid. The results (pure liquid, no boiling) confirm the Randles-type equivalent circuit to be an adequate representation of the system. In Fig. 5, the high frequency limit of the impedance which equals the electrolyte resistance, R_e, is less than 5 kΩ for water. The resistance, R, representative of the oxide film is given by the diameter of the semi-circular region extrapolated to the real axis (equals at least 100 kΩ for this film). The results for water and a second oxide film showed a similar trend with the impedance values for this oxide film being higher. The results with methanol as electrolyte indicated both a high capacitive impedance for this second film and a higher bulk electrolyte resistance.

As a result of these investigations, a frequency of 3 Hz was chosen for future work with the chart recorder. At around this frequency, the imaginary impedance of the oxide layer reaches a maximum.

In conclusion, heat transfer surfaces coated with thin, high impedance, insulating layers can be prepared by anodising. There is a certain amount of variation in the characteristics of films which are prepared in the same way. However, these differences will not interfere with the interpretation of the results. The new electrical method for liquid contact measurements requires only that the anodic film be the dominant resistance in the

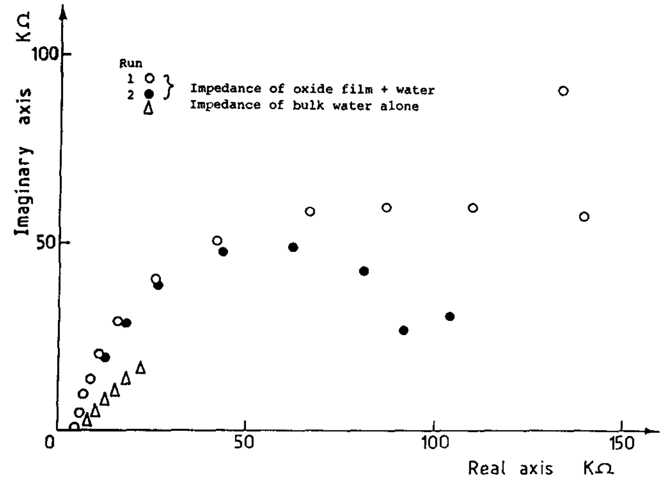

FIG. 5. Impedance characteristic of anodic film in water as electrolyte.

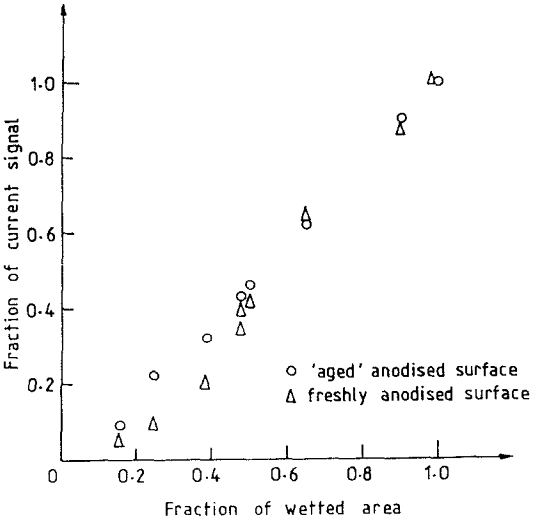

FIG. 6. A calibration curve of current signal with wetted area fraction for water on an anodised aluminium surface.

electrical path between the metal substrate and the measuring electrode immersed in the boiling liquid.

Confirmation of wetted area/impedance relation

Equation (7) states that the impedance of the oxide film is inversely proportional to the wetted area, or equivalently that the current through the film under a constant voltage is directly proportional to the wetted area. Tests of impedance vs area were made on two anodised surfaces, one on a freshly anodised surface and the other on an anodised surface aged by previous boiling.

The circuit used was similar to that shown in Fig. 4. The experimental measurements were made at room temperature, without boiling, for convenience. The voltage produced across a 10 kΩ resistor by a given surface contact area was measured on the chart recorder. These areas were represented by various diameter glass tubing carefully sealed onto the anodised surface using silicone rubber and soft white paraffin jelly. Water was the test liquid.

The results of the tests of impedance vs area are shown in Fig. 6. The average value of the current signal, as measured on the chart recorder, is proportional to the wetted area fraction. A further run with a clean aluminium surface (free of Al_2O_3) gave a constant signal regardless of wetted area.

POOL BOILING RIG

A schematic view of the apparatus is shown in Fig. 7.

A pool of liquid is maintained in a glass tube (100-mm high, 28-mm I.D.) clamped securely onto the aluminium test section using a preformed PTFE seal. The upper side of the tube is connected to a glass expansion chamber open to the atmosphere.

The aluminium test section comprises a rectangular block as the base with a cylindrical top section (28- or 32-mm diam., 30-mm long) which is detachable for ease of surface preparation. The bottom section is drilled to fit four Watlow cartridge heaters, each rated at 250 W. The test section is lagged with 20–30 mm of glass fibre wool.

The design of the block is such that:

1. The heat would be constrained to flow in an approximately one-dimensional way to give an accurate indication of the temperature gradient and heat flux.
2. The large thermal capacity of the lower part of the block would ensure a reasonable time spent in traversing the transition boiling region.

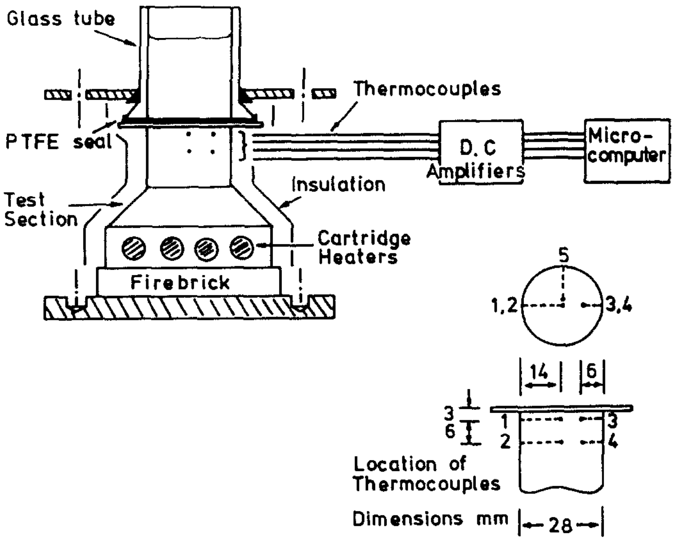

FIG. 7. A schematic diagram of the experimental apparatus for transient tests.

Four thermocouples (1.5-mm diam., stainless-steel sheathed, mineral insulated, chromel–alumel) are provided at two axial locations. At each axial location one thermocouple is placed in the centre of the aluminium cylinder, the other either 6 or 8 mm from the edge. A fifth thermocouple, 3 mm below the surface, as shown in Fig. 7, is used for the chart recorder trace. To improve the thermal contact between the thermocouples and the aluminium test section, a small amount of soft solder for aluminium (Fry's Metals. No. 703, a tin/zinc mixture) is placed at the bottom of the thermocouple holes. This solder is solid at temperatures below 199°C, fully liquid above 310°C. The thermocouples themselves are not of the electrically grounded type because the AC signal used for the surface impedance measurement would then be picked up. The time constant of the thermocouples in water, as quoted by the manufacturers, is <0.3 s.

Each of the four thermocouples used for the boiling curve measurements is connected to a DC amplifier and then into a data acquisition system consisting of an A to D converter and a BBC model B microcomputer. Sets of all four temperatures are read 25 times s^{-1}. Since there is no need for such a large number of temperature readings, and they show some scatter, they are then averaged in groups of 10 for transition boiling and groups of 80 for most of nucleate and film boiling. Effectively then temperatures are read every 0.4 s in transition boiling. The maximum rate of change of temperature recorded in the boiling experiments is around 20°C s^{-1}.

Experimental technique

A series of transient boiling tests was conducted at atmospheric pressure. The anodised surface was first cleaned with acetone followed by water or methanol as appropriate. Water or methanol was used as the test liquid. Prior to each transient data-taking run, boiling was maintained for at least 10 min to degas the test liquid.

At the start of a test, full heater power in excess of the critical heat flux was applied until film boiling was seen to be established. The heaters were switched off. The various temperatures and the current signal were recorded during cooling.

The q vs ΔT boiling curve was obtained from the temperature vs time data by solving the one-dimensional heat conduction equation. The radial temperature variation was small, at most 2°C for methanol and 7°C for water. At the critical heat flux the radial temperature gradient was around 16% of the axial gradient. To allow for these small radial variations, the temperature used in the one-dimensional calculation is the average of the two thermocouple readings at a given axial location, i.e.

$$T_A = (T_1+T_3)/2 \quad \text{and} \quad T_B = (T_2+T_4)/2.$$

A heat balance for a region of depth 6 mm below the boiling surface, containing the surface thermocouples, gives the heat flux q as

$$q = k'\frac{(T_B-T_A)}{\Delta x} - \frac{mc}{A'}\frac{[T_A - T_A(\text{old})]}{\Delta t}$$

where m is the mass of the 6-mm region, c the specific heat, A' the boiling heat transfer area and k' the thermal conductivity.

Strictly speaking, this equation is only correct for true differentials. Effectively the 6-mm-deep region below the surface has been treated as one region, with a uniform temperature T_A, in a lumped parameter analysis. Reference [32] suggests that a lumped parameter approach may be reasonable for high conductivity material of these dimensions. Also the estimate of T_A is improved by having two thermocouples.

In order to interpret the current signal i measuring the impedance across the boiling surface, the signal obtained in non-boiling is taken as a datum. In other words, the wetted area fraction f is i/i_{nb}, where i_{nb} is the signal obtained in non-boiling.

RESULTS OF SIMULTANEOUS WETTED AREA AND HEAT TRANSFER MEASUREMENTS

The transient boiling curves obtained during the cooling of the block with methanol are presented in Fig. 8. They show good reproducibility in the nucleate and film boiling regions, but some effect of surface ageing in transition boiling. The current trace for wetted area corresponding to run 1 in Fig. 8 is shown in Fig. 9. The corresponding wetted area fraction results are shown in Fig. 10.

In the film boiling heat transfer regime, the current signal is negligible. The signal starts to deviate from that of the film boiling region over the temperature range corresponding to the minimum film boiling point.

As the surface cools, the amplitude of the current signal in transition boiling becomes gradually larger. This corresponds to the increased wetting on the wall. It is interesting to note that about half of the increase in wetted area occurs in a very narrow temperature range (about 55–40°C wall superheat). This is the region just below the critical heat flux, where the measurement of steady-state transition boiling data is difficult [30].

The onset of the fairly constant high amplitude signal of nucleate boiling corresponds to the separately measured critical heat flux, though, as might be expected, the wetted area continues to increase slightly as temperature falls further in nucleate boiling. A separate measurement of the bulk liquid impedance during boiling showed that under all conditions it was small compared with the impedance across the boiling surface.

The estimated fraction of wetted area f vs wall superheat results shown in Fig. 10 display a pronounced curve, unlike the straight line trend reported previously by Ragheb and Cheng [19] and Kalinin *et al.* [11].

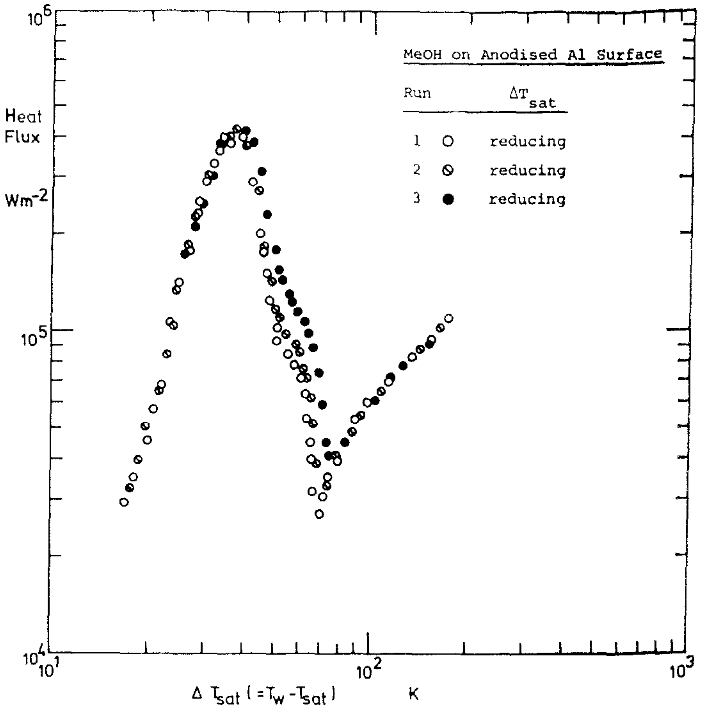

FIG. 8. Transient pool boiling data for methanol at atmospheric pressure.

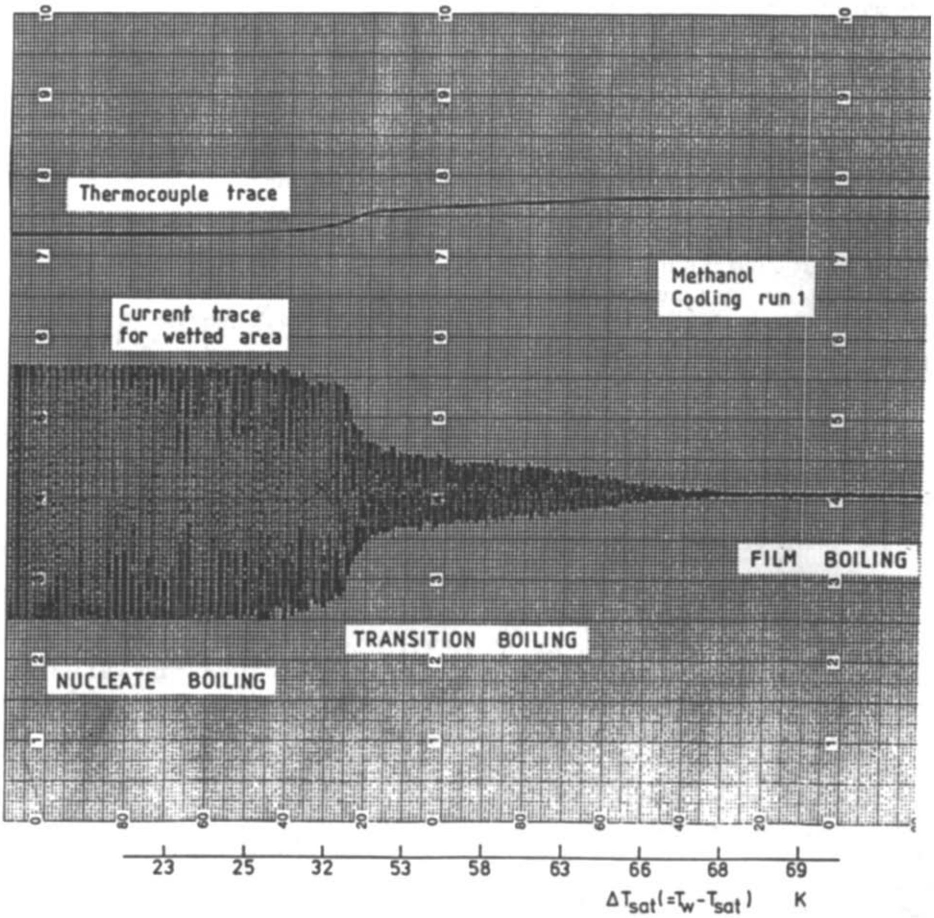

FIG. 9. A current and temperature trace for a transient cooling run of methanol pool boiling on an anodised aluminium surface.

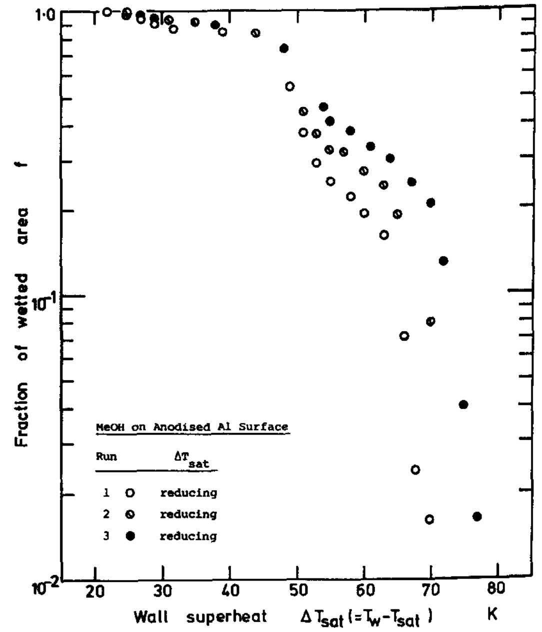

FIG. 10. Measured fraction of wetted area during transition pool boiling of methanol at atmospheric pressure.

The experimental results obtained for water are illustrated by Figs. 11–13. Figure 11 shows the heat transfer measurements for saturated water obtained during three transient cooling runs.

A curious feature of the current trace obtained with water (Fig. 12), not exhibited by methanol, is that there is a dramatic and as yet unexplained shift of about 1 V in the DC signal level near the region of critical heat flux. However, it was observed from a separate test of immersing two electrodes in water that a DC voltage was generated and this voltage increased with temperature. Since the procedure for relating the current trace to the wetted area fraction requires only the ratio of the amplitudes of the AC current signal, the drift in the DC signal level can be ignored. This appears to be a strong argument for using alternating current rather than the direct current used in other studies [16, 17].

The estimated fraction of wetted area from current traces for runs one to three is presented in Fig. 13. The figure also shows for comparison the predicted fraction of wetted area using Tong's expression [equation (3)] based on the separately measured transition boiling curves. Although both the measured and predicted results display the trend of decreasing f with wall superheat, generally the agreement is poor. A constant value for the minimum heat flux, q_{mfb}, was used instead of the strictly correct application which requires film boiling data to be extrapolated into the transition region.

It is interesting to note that the f data predicted by Tong's expression does not necessarily give a straight line (Fig. 13) but is very much dependent on the shape of the measured transition boiling curve. A straight line would result, as in the case of Ragheb and Cheng [19],

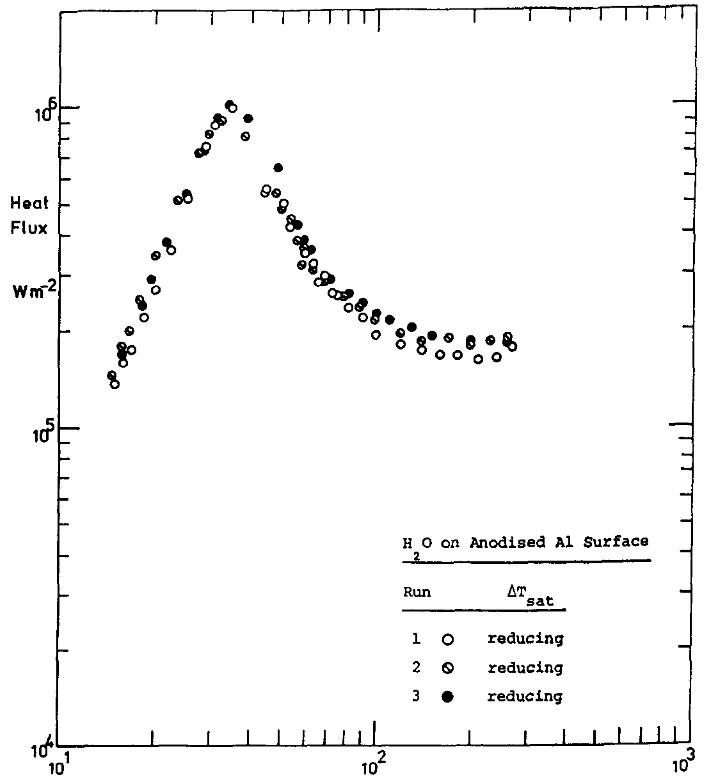

FIG. 11. Transient pool boiling data for water at atmospheric pressure.

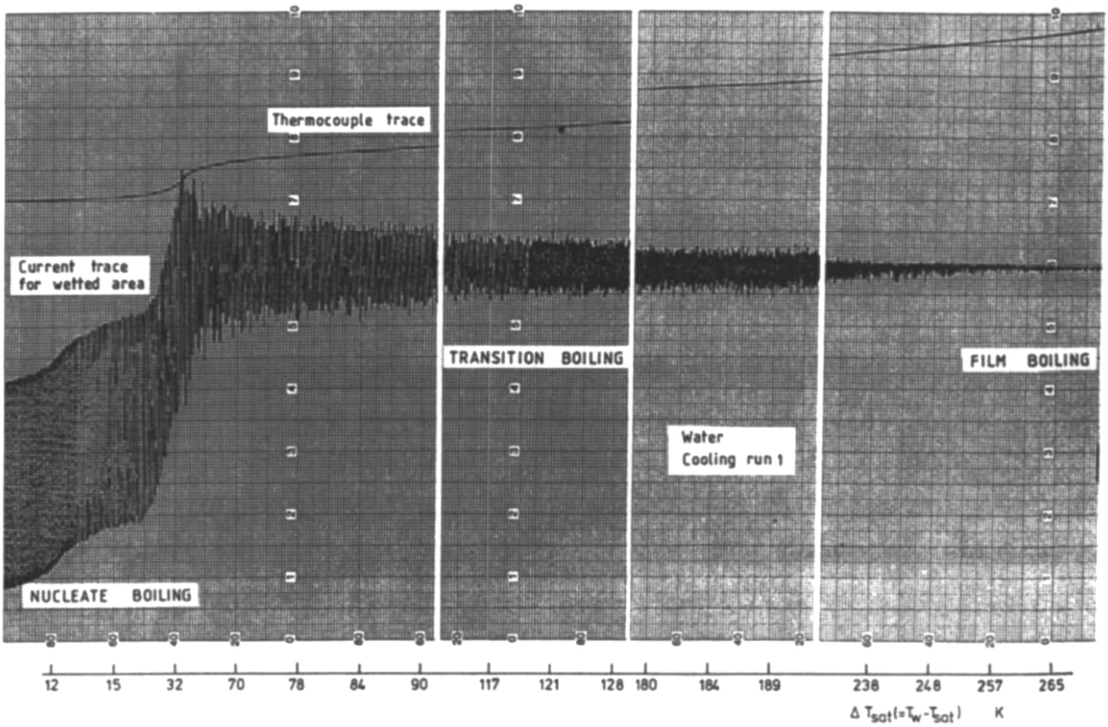

FIG. 12. A current and temperature trace for a transient cooling run of water pool boiling on an anodised aluminium surface.

from the exponential decay of the transition boiling component (q_{tb}) in terms of T_w.

A comparison of the results with Kalinin *et al.*'s equation [11] was not made. The fractions of wetted area predicted by Kalinin *et al.*'s equation were shown by Ragheb and Cheng to lie below those predicted by Tong. A necessary result of Kalinin *et al.*'s approach where the nucleate boiling curve is extrapolated into the transition boiling region is that the *f* values are very small, and would give worse agreement than Tong's approach.

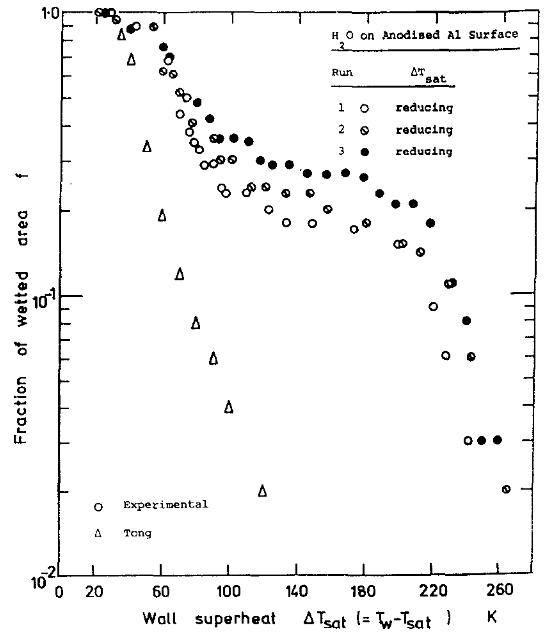

FIG. 13. Comparison of measured and predicted fraction of wetted area.

CONCLUSIONS

By depositing a thin dielectric layer onto the heat transfer surface, and measuring the impedance across the layer during boiling, it is possible to calculate the extent of liquid–solid contact. The theory suggests that the current across the layer is directly proportional to the wetted area and this is confirmed experimentally.

Simultaneous measurement of the boiling curve shows that the wetted area fraction falls very rapidly as the temperature rises above the critical heat flux point, reaching a value of at most a few percent by the minimum film boiling point.

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MESURE DU CONTACT SUPERFICIEL DANS L'EBULLITION DE TRANSITION

Résumé—On décrit une nouvelle méthode de mesure du contact liquide–solide dans l'ébullition. La surface est recouverte d'une fine couche isolante électrique et on mesure l'impédance entre le substrat métallique et le liquide bouillant. On montre théoriquement, ce qui est confirmé expérimentalement, que cette impédance est reliée à la fraction moyenne de l'aire de transfert thermique qui est mouillée par le liquide. La technique est appliquée, avec la détermination de la couche d'ébullition, à l'ébullition en réservoir d'eau et de méthanol.

MESSUNGEN DES OBERFLÄCHENKONTAKTES BEIM ÜBERGANGSSIEDEN

Zusammenfassung—Es wird eine neue Methode zur Messung des Flüssigkeit–Wand-Kontaktes beim Sieden beschrieben. Die Wärmeübertragungsfläche ist mit einer dünnen, elektrisch nichtleitenden Schicht bedampft. Die Impedanz zwischen dem Metallsubstrat und der siedenden Flüssigkeit wird gemessen. Es wird theoretisch gezeigt und experimentell bestätigt, daß die Impedanz mit dem mittleren Anteil der mit Flüssigkeit benetzten Wärmeübertragungsfläche in Beziehung steht. Die Technik wird beim Behältersieden von Wasser und Methanol und bei Messungen der Siedekurve angewendet.

ИЗМЕРЕНИЕ ПОВЕРХНОСТНОГО КОНТАКТА ПРИ ПЕРЕХОДНОМ РЕЖИМЕ КИПЕНИЯ

Аннотация—Описывается новый метод измерения контакта между жидкостью и твердым телом при кипении. Поверхность теплообмена покрыта тонким слоем диэлектрика. Измеряется полное сопротивление между металлической подложкой и кипящей жидкостью. Теоретически и экспериментально показано, что величина этого импеданса зависит от средней величины поверхности теплообмена, смачиваемой жидкостью. Экспериментальные исследования проводились в большом обьеме кипящей воды и метанола, для которых также измерялись кривые кипения.