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Measurement of liquid–solid contact in film boiling

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Abstract—An experimental study is conducted to measure liquid–solid (L–S) contacts in film boiling of water under atmospheric pressure. The test specimens selected for the present experiments are a silver sphere (30 mm in diameter) and two kinds of silver cylinders (20 mm in diameter and 60 mm long). 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. This impedance is related to the average fraction of the heat transfer area which is wetted by the liquid. Direct L–S contacts are intermittently observed on local portions of the heated surface in saturated film boiling, and the frequency of contact ranges between 1.0 and 3.1 Hz. In subcooled boiling, however, the contact frequency becomes extremely low with a little subcooling.

INTRODUCTION

MANY STUDIES have been carried out on film boiling heat transfer by assuming a continuous vapor film existing between the liquid and the heated surface. Even if direct liquid–solid contacts might occur due to a wavy motion of the vapor–liquid interface, it has been prevailing that the contribution of liquid–solid (L–S) contact to the film boiling heat transfer can be neglected since, under such a condition, not only the direct contact occurs on localized portions of the surface, and each during a short time, but the frequency of those contacts is very low.

Kikuchi *et al.* [1, 2] have recently proposed a theoretical model which explains the rapid cooldown of metals coated with a thin insulating layer. Here, they assumed the occurrence of local and intermittent L–S contacts in the film boiling regime for predicting the actual minimum film boiling temperature, $T_{\min}$, of the coated metal. The calculated results of $T_{\min}$ agreed well with the experimental data for saturated boiling of liquid nitrogen and water under atmospheric pressure.

An experimental study [3] was also conducted to investigate the effect of other factors on $T_{\min}$ in saturated and subcooled boiling of water under atmospheric conditions. In saturated boiling a thick vapor film covered all the heated surface and violent oscillations were observed on the interface of vapor and liquid. In subcooled boiling, however, the vapor film was very thin and the vapor–liquid interface was extremely calm.

In shallow immersion of the heated sphere into a subcooled water pool, the vapor collapsed coherently all over the sphere surface in a short time, less than 33 ms after the film boiling was maintained to a comparatively low temperature. In deep immersion, however, a local vapor collapse occurred on the edge of the support stem at a higher temperature, and then propagated to the other portions of the sphere. This incoherent collapse was observed on the edge of the cylinder. Similar collapses were reported by other investigators [4, 5].

This was attributed to the local and intermittent L–S contacts in film boiling. However, there are only several experiments [6–11] for directly measuring L–S contacts in film boiling since a sensor is exposed under high temperature conditions. This led the present authors to carry out an experimental study of intermittent L–S contact in film boiling.

A special method has been used for measuring L–S contact in boiling. This method is similar to that of Dhuga and Winterton [9]. They measured L–S contact in boiling by using the electrical impedance across a thin dielectric film (Al_2O_3), deposited on a heated metal surface, as an indicator of L–S contact in transition and nucleate boiling on the horizontal plane heated surface in methanol and water pools. Their experiment was limited to the wall temperature less than 350°C.

In the present experiment, however, a thin refractory paint coating has been used as an electrically insulating layer for measuring L–S contact in film boiling of water on the surface of a sphere, and two kinds of vertical cylinders, at high temperature greater than 350°C. This paper gives the experimental results of the frequency of L–S contact and contact area in film boiling, with particular emphasis on the limit condition of film boiling.

EXPERIMENTAL APPARATUS AND PROCEDURES

Figure 1 shows a schematic diagram of the experimental apparatus, which consists of a test specimen,

NOMENCLATURE

C	film capacitance [F]
f	frequency [Hz]
$\bar{f}$	average frequency [Hz]
j	unit of imaginary quantity
R	film resistance [Ω]
R_o	output resistance [Ω]
R_w	liquid resistance [Ω]
T	temperature of test specimen [K]
T_l	temperature of liquid [K]
T_{min}	minimum film boiling temperature [K]
T_{sat}	temperature of saturation [K]
ΔT_{sub}	subcooling of liquid, $T_{sat} - T_l$ [K]
X	fraction of area being wetted
Y	normalized output voltage
Z	electrical impedance [Ω].
Greek symbol	
ω	angular frequency [rad s^{-1}].

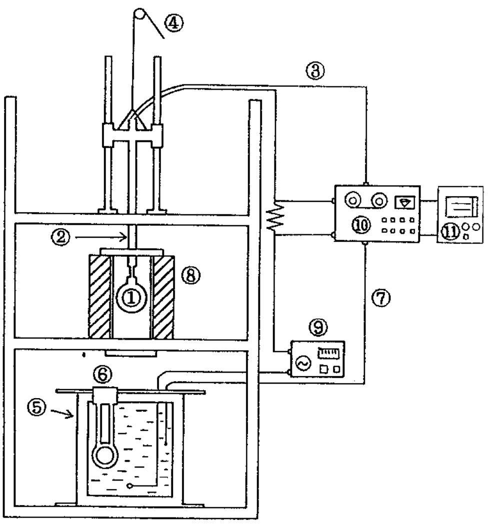


FIG. 1. Experimental apparatus: 1, test specimen; 2, support rod; 3, thermocouple lead for measurement of test specimen temperature; 4, support wire; 5, water vessel; 6, heater; 7, thermocouple lead for measurement of water temperature; 8, electric furnace; 9, function generator; 10, digital recorder; 11, monitor.

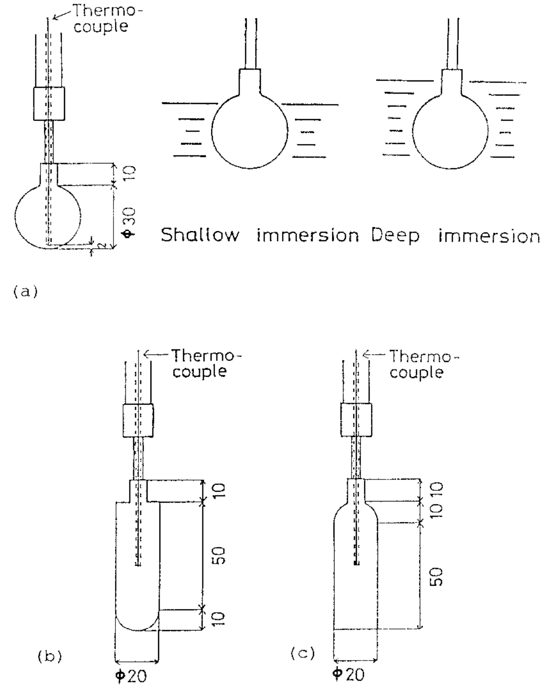


FIG. 2. Test specimens: (a) sphere; (b) cylinder I; (c) cylinder II.

an electric furnace, a water vessel, and instrumentations. The test specimens are a silver sphere of 30 mm in diameter and two vertical silver cylinders of 20 mm in diameter and 60 mm long, as shown in Fig. 2. Two methods of immersion are applied for investigating the effect of a support stem on L–S contact in film boiling on the sphere.

The heat transfer surface is coated with a thin (approximately 30 μm thick) refractory paint, which is used as an electrically insulating layer. By using the impedance across a thin insulating layer, L–S contact signals are measured. The boiling of a test liquid with slight electrical conductivity on an electrically insulating surface can be represented by an equivalent circuit in Fig. 3. The parallel combination of a resistor, R, and a capacitor, C, represents the combined effect of the vapor layer and the insulating layer. R_w is the liquid resistance.

If an alternating current is applied across the insulating layer during boiling, a current flows from the bulk liquid to the metal surface, with a value determined by the wetting taking place at the surface. Where liquid touches the solid surface, the system behaves, essentially, as a parallel-plate capacitor, with the liquid as one plate and the metal substrate as the

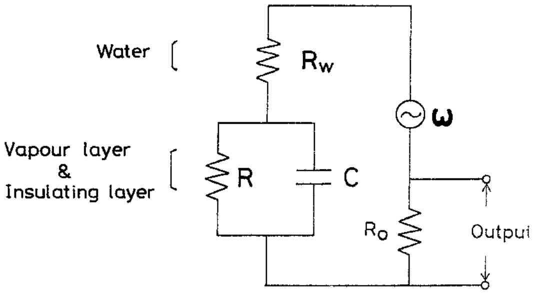


FIG. 3. Equivalent electrical circuit.

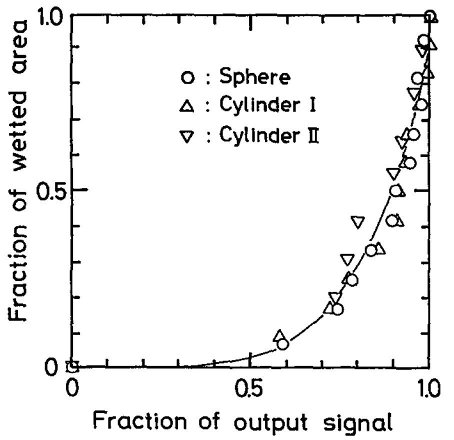


FIG. 4. Relation between output signal and wetted area.

other. The separation of the plates is just the thickness of the very thin insulating layer. Once film boiling starts, the separation becomes enormously greater and no current flows. If the alternation potential with an adequate frequency is applied, the imaginary impedance of this system becomes high, and the big change of output current of an L–S contact is measured. So the frequency and wetted area of an L–S contact are measured quantitatively.

The impedance of the assumed circuit of Fig. 3 is

$$Z(\omega) = R_w + 1/(1/R + j\omega C). \qquad (1)$$

The impedance depends on the area of the L–S contact. In the present experiment, the area was obtained by measuring the voltage on resistor R_o.

Figure 4 shows a relation between normalized output voltage, Y, and wetted area, X. It can be seen that the output signal is sensitive to L–S contact and the output voltage becomes higher with an increasing wetted area. A correlation is written as the following equation:

$$Y = 0.88X^5. \qquad (2)$$

RESULTS AND DISCUSSION

Figure 5(a) shows typical changes of temperature and L–S contact signal for a silver sphere immersed in saturated water. In this figure data are shown for both shallow immersion and deep immersion. The sphere temperature decreases with the elapse of time. Some spikes are observed in the L–S contact signal during film boiling. Violent oscillations are observed on the interface of vapor and liquid in photographs. These facts indicate the validity of the intermittent L–S contact model. The right scale of the vertical axis is the fraction of L–S contact area which is obtained with equation (2). Liquid–solid contacts occur on local portions of the heated surface and the fraction is less than 0.1% (corresponding to 2.8 mm^2) for shallow immersion. In deep immersion, however, the contact frequency is higher and the contact area fraction is approximately 1%. The contact frequency becomes higher and the contact area is enlarged as the condition approaches transition boiling.

Figure 5(b) shows the changes of temperature and L–S contact signal for 40 K of subcooling, ΔT_{sub}. In shallow immersion no L–S contact signals are observed in film boiling. This is attributed to the fact that the vapor–liquid interface is very calm. The vapor collapses coherently all over the sphere a short time after the film boiling is maintained to the extent of a comparatively low temperature. Due to the extremely low frequency of L–S contact, the data of minimum film boiling temperature, T_{min}^*, are scattered and some data are lower than the T_{min} for saturated boiling [3].

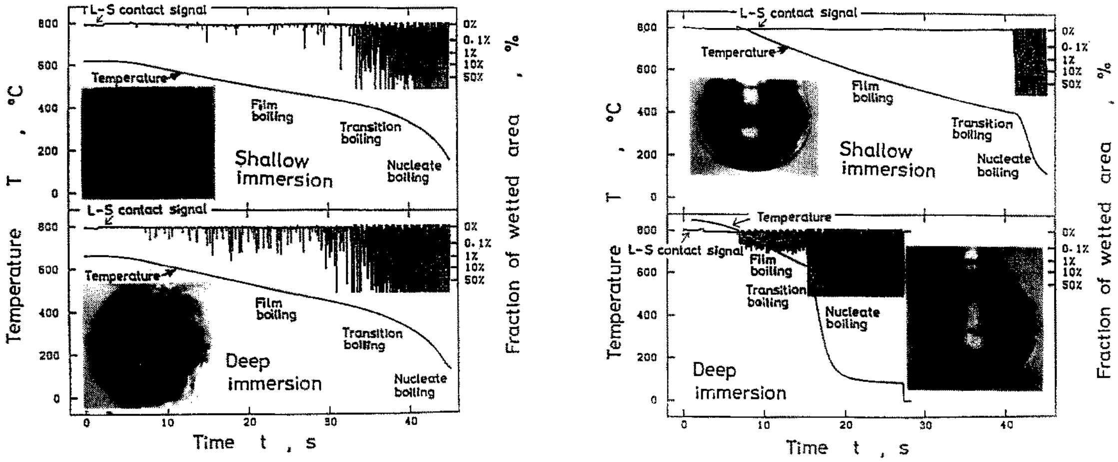
In deep immersion, however, a local vapor collapse occurs on the edge of the support rod at a higher temperature, and propagates to other portions of the sphere. This incoherent collapse is attributed to the local temperature drop at the rod edge, which may occur due to local and intermittent L–S contacts.

Figure 6(a) shows a typical change of temperature and L–S contact signal for the shallow immersion of a silver cylinder in saturated water. In this figure the data for two kinds of cylinders are shown. In each case L–S contacts are observed in film boiling. However, the contact frequency is lower, and the contact area is smaller, compared to the sphere. This implies that L–S contacts more frequently occur on the upper surface of the sphere.

Figure 6(b) shows the change of temperature and L–S contact signal for the shallow immersion of a silver cylinder in subcooled water of $\Delta T_{sub} = 20$ K. For cylinder I there are no signals of L–S contact during film boiling. For cylinder II, however, frequent L–S contacts are observed in the later period of film boiling, namely in the lower temperature region. Liquid–solid contacts occur at the bottom edge of cylinder II, and the vapor collapse propagates to the other portions of the cylinder.

Figure 7 shows a distribution of L–S contact frequency for some temperature ranges. A silver sphere was immersed into saturated water. The horizontal axis is L–S contact frequency and the vertical axis is the number of data. The frequency becomes higher with lower temperature. The left portion of the figure is for shallow immersion and the right portion is for deep immersion. The higher frequency is for deep immersion than for shallow immersion at each temperature. Curves in this figure show normal distributions. Some data are extremely different from the normal distribution since the data are not too many.

The average value, $\bar{f}$, of L–S contact frequency is correlated with liquid subcooling, ΔT_{sub}, in Fig. 8. The parameter is the temperature, T, of the test specimen. The figure contains both data for shallow and deep immersion. At each case, $\bar{f}$ decreases rapidly with higher ΔT_{sub}. There are no L–S contacts at $\Delta T =$ 20 K. There is a tendency of lower $\bar{f}$ with higher T. At each temperature, higher frequency is observed for deep immersion. For cylindrical geometries there



(a)

(b)

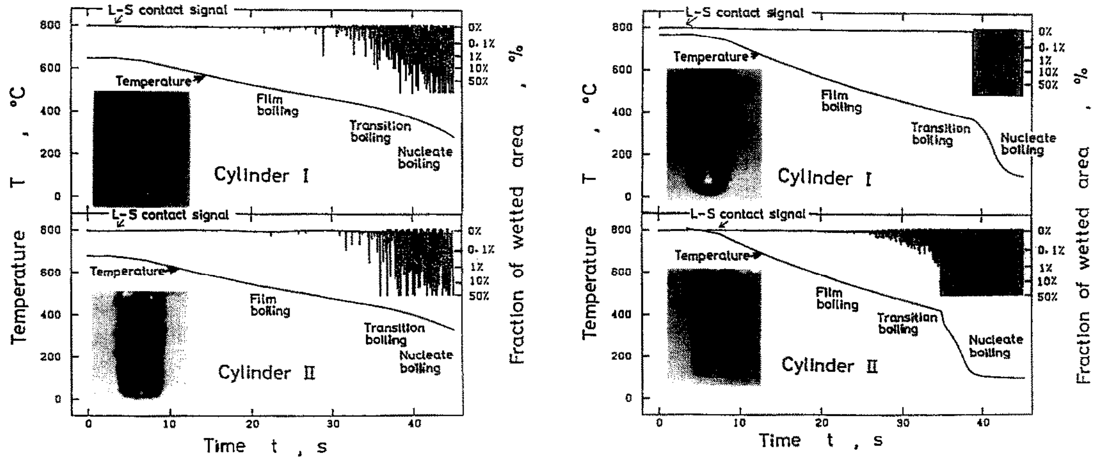
FIG. 5. Changes of temperature and L–S contact signal for sphere: (a) $\Delta T_{sub} = 0$ K; (b) $\Delta T_{sub} = 40$ K.

are not enough data for the calculation of the average value and, thus, further data are needed.

CONCLUSION

An experimental study has been conducted to investigate L–S contacts in film boiling with measurement of impedance between the metal (coated with a thin electrically insulating layer) and liquid. The following facts are concluded.

(1) In saturated boiling, L–S contacts of several times per second can be measured. In subcooled boiling, however, contact frequency becomes lower and



(a)

(b)

FIG. 6. Changes of temperature and L–S contact signal for cylinder in shallow immersion: (a) $\Delta T_{sub} = 0$ K; (b) $\Delta T_{sub} = 20$ K.

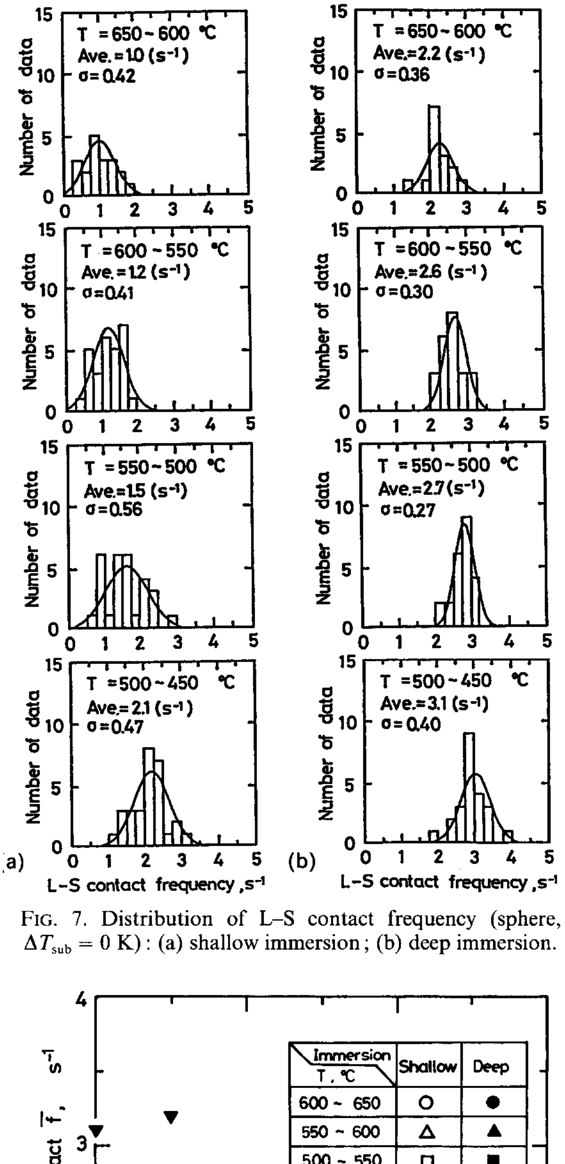


FIG. 7. Distribution of L–S contact frequency (sphere, $\Delta T_{sub} = 0$ K): (a) shallow immersion; (b) deep immersion.

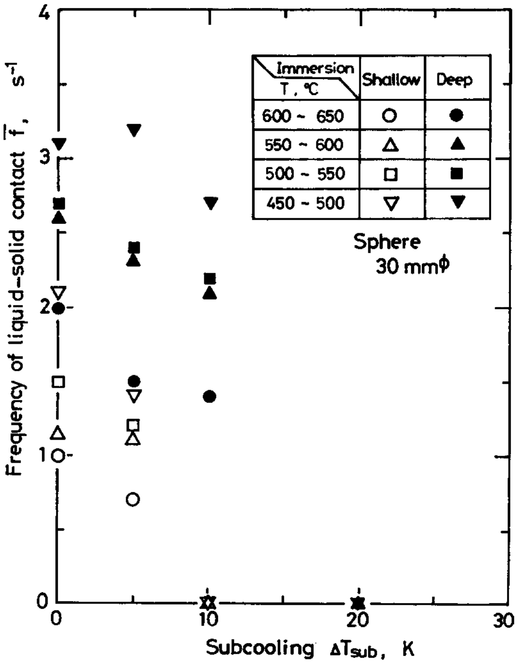


FIG. 8. Effect of subcooling on average value of L–S contact frequency.

for $\Delta T_{sub} > 20$ K there are rare contacts. This fact implies large scatterings in minimum film boiling temperature, and in heat flux in subcooled boiling, as indicated in the previous report [3].

(2) In deep immersion, L–S contacts are frequently observed on the top rod support. This local contact causes the incoherent collapse in subcooled boiling.

(3) In saturated boiling, the contact frequency is lower for a cylinder than for a sphere. In subcooled boiling, however, L–S contacts at the bottom edge causes the incoherent vapor collapse.

These experimental results imply the validity of the intermittent L–S contact model, which was already proposed in the earlier paper [1, 2].

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MESURE DU CONTACT LIQUIDE–SOLIDE DANS L'EBULLITION EN FILM

Résumé—On étudie expérimentalement les contacts liquide–solide (L–S) pendant l'ébullition en film de l'eau à la pression atmosphérique. Les échantillons sélectionnés sont une sphère d'argent (30 mm de diamètre) et deux cylindres d'argent (20 mm de diamètre et 60 mm de long). La surface est recouverte d'une couche mince, électriquement isolante et l'impédance entre le substrat métallique et le liquide en ébullition est mesurée. Cette impédance est reliée à la fraction d'aire de transfert thermique mouillée par le liquide. On observe des contacts directs L–S intermittents pendant l'ébullition saturée en film et la fréquence du contact est entre 1,0 et 3,1 Hz. Néanmoins pendant l'ébullition sous-refroidie, la fréquence devient extrêmement faible avec un léger sous-refroidissement.

MESSUNG DES FLÜSSIG/FEST-KONTAKTES BEIM FILMSIEDEN

Zusammenfassung—In einer experimentellen Arbeit wird der Kontakt zwischen Flüssigkeit und fester Oberfläche (L–S) beim Filmsieden von Wasser unter Atmosphärendruck untersucht. Folgende geometrische Anordnungen werden betrachtet: Eine Silberkugel (Durchmesser 30 mm) und zwei Arten von Silberzylindern (Durchmesser 20 mm und Länge 60 mm). Die wärmeübertragende Oberfläche ist mit einer dünnen, elektrisch isolierenden Schicht überzogen. Die Impedanz zwischen dem metallischen Substrat und der siedenden Flüssigkeit wird gemessen. Diese Impedanz wird dem mittleren Anteil der wärmeübertragenden Oberfläche, der von Flüssigkeit benetzt ist, zugeordnet. Beim gesättigten Filmsieden wird an Teilen der beheizten Oberfläche intermittierend ein direkter L–S Kontakt beobachtet. Die Frequenz solcher Kontakte bewegt sich im Bereich zwischen 1,0 und 3,1 Hz. Beim unterkühlten Sieden wird die Kontaktfrequenz jedoch bereits bei geringer Unterkühlung extrem gering.

ИССЛЕДОВАНИЕ КОНТАКТА ЖИДКОСТИ С ТВЕРДЫМ ТЕЛОМ ПРИ ПЛЕНОЧНОМ КИПЕНИИ

Аннотация—Экспериментально определяются границы раздела жидкость – твердое тело в процессе пленочного кипения воды при атмосферном давлении. В качестве экспериментальных образцов использовались серебряная сфера (диаметром 30 мм) и два вида серебряных цилиндров (диаметром 20 мм и длиной 60 мм). Поверхность теплопереноса была покрыта тонким электроизоляционным слоем. Измерялся имперяся импеданс между металлической подложкой и кипящей жидкостью, зависящий от средней доли площади, смачиваемой жидкостью, на которой имеет место теплоперенос. При насыщенном пленочном кипении на отдельных участках нагретой поверхности наблюдались прерывистые контакты жидкости с твердым телом, частота которых варьировалась в интервале 1,0–3,1 Гц. Однако в условиях кипения при незначительном недогреве частота контактов весьма существенно снижалась.