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BOILING HEAT TRANSFER FROM A HORIZONTAL PLANE HEATER TO A POTASSIUM LAYER

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NOMENCLATURE

LL,	liquid level above heating surface [mm];
q,	heat flux [W m^{-2}];
SP,	system pressure [torr];
T_l,	liquid temperature [°C];
T_{sat},	saturation temperature [°C];
T_v,	vapor temperature [°C];
T_w,	heating surface temperature [°C];
y,	vertical distance normal to heating surface [mm];
α,	heat transfer coefficient [W m^{-2} K^{-1}].

INTRODUCTION

THE CHARACTERISTICS of pool boiling heat transfer are dependent on the motion of bubbles adjacent to a heating surface. Boiling heat transfer in a thin liquid layer, if the thickness of the layer is of the same order as the bubble departure radius, is dominantly controlled by the motion of large bubbles growing over the liquid free surface. This is because the bubble growth characteristics such as the growth rate, microlayer formation and dry patch formation are directly related to the boiling heat transfer.

According to the analysis by Dwyer and Hsu [1], the dry patch area formed beneath a bubble is negligibly small in nucleate pool boiling of liquid metals. However dry patch formation is observed in mercury thin layers [2], while the boiling heat transfer coefficient is larger in a thin layer of water than in a pool [3]. Large bubbles above the liquid free surface have been observed [2, 3].

This shorter communication presents the first report of our experimental studies on the boiling heat transfer from a horizontal plane heater to various liquid levels of potassium.

EXPERIMENTAL APPARATUS AND PROCEDURES

The test section is shown in Fig. 1. The vessel is made of type 316 stainless steel, with a rectangular cross section of 140 × 96 mm^2 and 210 mm high. In the center of the vessel, a heating surface of 1 mm thick type-625 Inconnel plate (1) is bonded to a 3 mm thick copper plate (2). An electrical insulation plate of boron nitride (3) separates the plate (2) and a nichrome heating element (4) which is heated by direct current. The effective heating area is 20 × 100 mm^2. Below the heating element alumina plates were used as thermal insulators.

Outside heat losses through the copper electrodes and the thermal insulator were measured using 0.5 mm O.D. sheathed chromel–alumel thermocouples inserted into the electrode and welded at both sides of the stainless plate (5), respectively. The heat loss through the electrodes was less than 15% of the total heat generation, and that through the insulation a few percent. By taking account of these heat losses, the heat flux at the heating surface could be calculated, assuming a uniform heat flux at the surface. To protect the heating element from oxidization, a helium gas atmosphere was used. The heating surface temperature was determined by making a simple

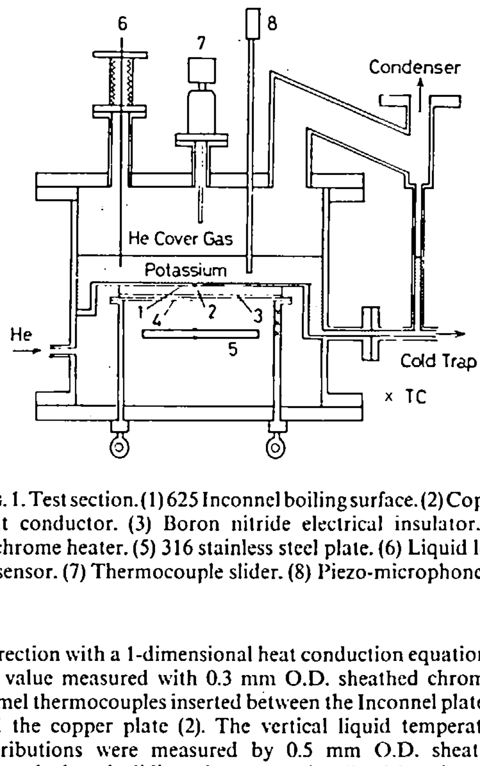

FIG. 1. Test section. (1) 625 Inconnel boiling surface. (2) Copper heat conductor. (3) Boron nitride electrical insulator. (4) Nichrome heater. (5) 316 stainless steel plate. (6) Liquid level sensor. (7) Thermocouple slider. (8) Piezo-microphone.

correction with a 1-dimensional heat conduction equation to the value measured with 0.3 mm O.D. sheathed chromel-alumel thermocouples inserted between the Inconnel plate (1) and the copper plate (2). The vertical liquid temperature distributions were measured by 0.5 mm O.D. sheathed chromel–alumel sliding thermocouples (7). The electrical resistance-type liquid level sensor (6) was used to determine the potassium liquid level. A wave guide rod, immersed in potassium, has its outside end connected to a piezo-microphone (8). This was used to detect the boiling sound. The RMS value of the intensity was recorded on a multi-pen recorder.

Potassium, purified by the cold trap method, was added until a desired liquid level in the boiling vessel was reached, and then boiled under an atmosphere of helium gas.

The range of variables covered was: system pressures, 30–50 torr; liquid levels above the heating surface, 6–30 mm. The maximum heat flux was 6 × 10^5 W m^{-2}.

EXPERIMENTAL RESULTS AND DISCUSSION

The effect of the liquid level on natural convection heat transfer is observed when the thickness of the liquid layer is decreased to the same order as that of the boundary layer.

Figure 2 shows the vertical liquid temperature distributions in natural convection for liquid levels of 6 and 28 mm. Each distribution is measured under the condition of boiling experiments where the vapor temperature T_v is kept almost at the saturation temperature T_{sat} corresponding to the system

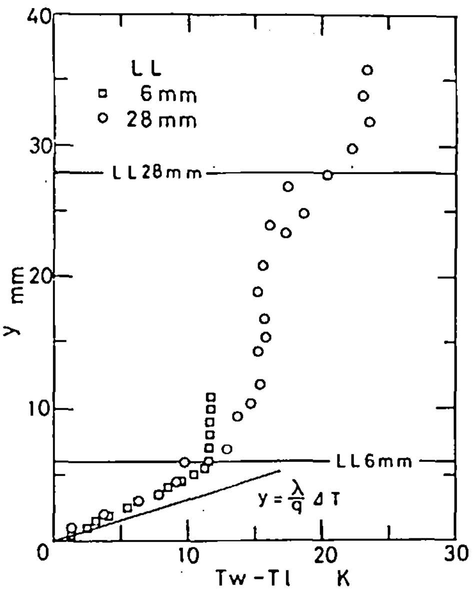

FIG. 2. Vertical temperature distribution in natural convection for 6 and 28 mm liquid levels, 50 torr system pressure and 1.0×10^5 W m^{-2} heat flux.

pressure. Thus the liquid temperature is superheated. The straight line in Fig. 2 shows the temperature distribution calculated by heat conduction. In the case of higher liquid levels, it can be seen that the ordinary distribution consists of the boundary region near the heating surface and the bulk region. In the case of lower liquid levels, however, the bulk region is not apparently observed, and the heat conduction through the liquid layer is dominant owing to the high thermal conductivity of potassium. This result indicates that as the liquid level decreases, the temperature difference between the heating surface and the vapor at the fixed heat flux decreases also. Since the vapor temperature is always near the saturation temperature T_{sat}, a higher heat flux is needed to provide the thinner liquid with sufficient superheating to cause the inception of boiling. This is shown in Fig. 3 where the solid circles indicate the heat flux at which boiling occurs, while the open circles indicate that boiling does not occur.

Figure 4 shows an example of recorder chart traces of heating surface temperature T_w, liquid temperature T_l, vapor temperature T_v and the RMS value of the boiling sound intensity. In the present experiment, boiling is entirely intermittent. The vapor temperature is always near the saturation temperature. Before the inception of boiling, the surface and liquid temperatures are superheated above the saturation temperature. When boiling occurs, the surface and liquid temperatures drop and the boiling sounds are detected. Since the boiling is intermittent, the temperature difference $T_w - T_l$ fluctuates between periods of natural convection and boiling. For boiling in thick liquid layers, $T_w - T_l$ is suitable for indicating natural convection heat transfer as well as boiling heat transfer on the diagram of boiling curves since the bulk liquid temperature in natural convection can be defined as mentioned above and the liquid temperature during boiling is almost equal to the saturation temperature as shown in Fig. 4.

The boiling curve for the thick liquid level of 30 mm is shown in Fig. 5. The liquid temperature is measured at a point 20 mm above the heating surface. The open circles in this figure represent the temperature difference during natural convection and the solid circles represent that during nucleate boiling. At fixed heat flux, the temperature difference varies because the boiling is intermittent. The straight line represents

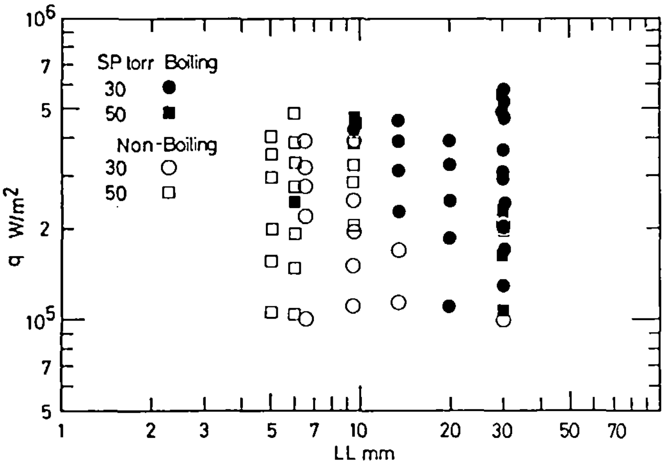

FIG. 3. Heat flux vs liquid level plot, showing boiling region.

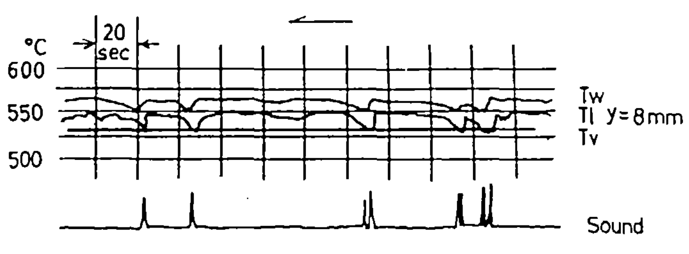

FIG. 4. Recorder traces of temperatures and boiling sound for 30 mm liquid level, 50 torr system pressure (T_{sat} = 528°C) and 1.6×10^5 W m^{-2} heat flux.

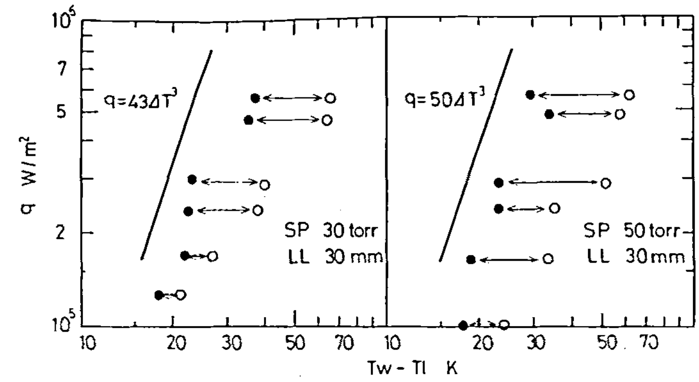

FIG. 5. Boiling curves for 30 mm liquid level and 30 and 50 torr system pressures.

empirical formula reported by Subbotin *et al.* [4] for continuous boiling heat transfer from a horizontal plane heater to potassium. Though the boiling heat transfer coefficient in the present experiment is a little smaller than that reported by Subbotin *et al.*, the heat flux shows a tendency to be proportional to about the third power of the temperature difference.

In order to investigate the effect of liquid level on boiling heat transfer, the heat transfer coefficient α can be defined as $q/(T_w - T_v)$, because the liquid temperature drops to the saturation temperature during boiling and T_v remains at the saturation temperature. The experimental results indicate no apparent effects of liquid level more than 6 mm on $\alpha/q^{2/3}$ for the system pressures of 30 and 50 torr. Further studies should be conducted to widen the range of such variables as the heat flux, system pressure and liquid level.

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