Technical Notes

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Effects of Heater Orientation and Confinement on Liquid Nitrogen Pool Boiling

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Introduction

THIS study is concerned with the effects of the orientation and confinement of heated surfaces on critical heat flux (CHF) from the surfaces. This has implications for the design of high-performance, high-power electronic devices.[1–3] The effects of heater orientation are also important when the direction and magnitude of the gravitational field change. Small spacing, if a compact design is desirable, will restrict the motion of the nucleating vapor bubbles and lead to the premature onset of dryout and lower CHFs. The combined effects of orientation and confinement are expected to be complex. Several studies have concentrated either on effects of orientation of unconfined heaters or on confined heaters that are vertically oriented only.[4–9] However, the combined effects have been relatively unknown.

Liquid nitrogen (LN_2) has the desirable cryogenic temperature range for the cooling of electronic devices and has been used in several studies for such purposes.[1,2,10] Results from many pool boiling studies using room-temperature liquids may not be scaled to predict LN_2 boiling because its thermophysical properties under cryogenic conditions are very different. For example, surface tension, which is important for heat flux correlation, for water and LN_2 are 58.91×10^{-3} and 8.85×10^{-3} N/m at their boiling points, respectively. These properties include liquid-to-vapor density ratio and latent heat, which are important in pool boiling theory. The objectives of this study are, therefore, to quantify the effects of heater orientation and confinement on the heat transfer characteristics and CHF in LN_2 pool boiling.

Experimental Setup and Procedure

The detailed design of the experiment is described in Ref. 11. Both conduction and radiation heat transfer that may cause boiling away from the heater surface were prevented. The heater was contained in a chamber that was exposed to the room air through an opening on top of it, resulting in self-cooling. Therefore, the boiling took place under saturation conditions at 77.3 K.

The heater module is an acrylic block, serving as the base for the heater and an insulator. The heater was made of copper, and its construction is shown in Fig. 1a. The heater is rectangular in shape and has the dimensions $2.0 \times 1.0 \times 0.25$ cm. It was flush mounted to the heater module. A thermocouple (type E) was inserted through a hole 1 mm beneath the center of the heater surface; its bead was glued to the copper interior using OmegaBond epoxy. The copper heater was heated by a thin-film, nickel–chromium heating element. The film was coated on one side of a ceramic substrate using a chemical vapor deposition technique. The other side of the substrate was glued to the bottom of the copper block, also using OmegaBond epoxy. Both the ceramic substrate and the epoxy have high values of thermal conductivity. The downward-facing side of the thin-film heater was insulated using a silicon sealant. As a result, the heat transfer was directed from the thin resistor film to the copper surface that was exposed to LN_2 during the experiment, with negligible heat loss to all other sides of the heater. The uncertainty in determining heat flux was dependent on the heater surface area and the power measurements and was estimated to be about 0.50%. The thermocouple has a manufacturer-specified uncertainty of 1.5 K and was found to be repeatable within 1.0 K at the LN_2 temperature. The surface temperature T_w was calculated using $T_w = T + q''t/k$, where T is the measured temperature at the distance beneath the heater surface, t the distance between the thermocouple and the heater surface, k the thermal conductivity of copper, and q'' the heat input. The heater orientation is shown in Fig. 1b.

A computer-assisted system gathered the information for determining the heater surface temperature and energy dissipation rate

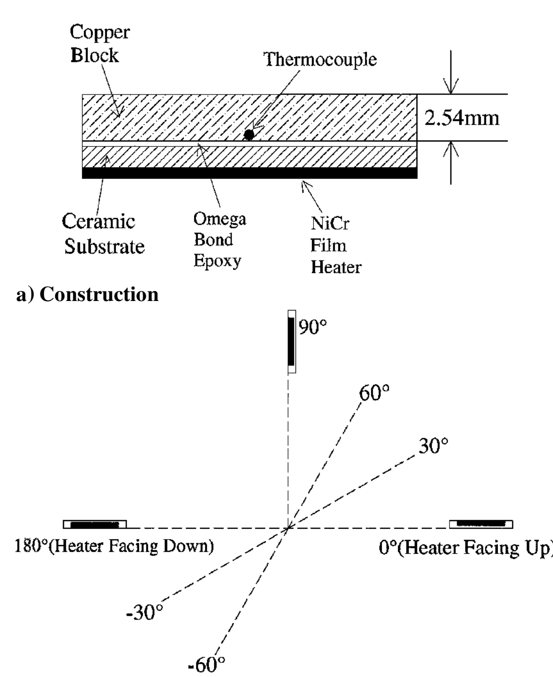

Fig. 1 Schematic of heater.

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($q'' = I^2 R$, where I is the current and R is the resistance across the nickel–chromium heating element). The heat transfer rate was determined when the computer detected steady-state temperature signals after each increment (0.1 W/cm^2). CHF was deemed to have occurred when there was a rapid increase in ΔT ($=T_w - T_{sat}$) without a change in q''.

Results and Discussion

Effects of Heater Orientation in Open Pool Boiling

Heat flux curves of pool boiling as a function of heater superheat without confinement, that is, open pool boiling, are presented in Fig. 2. The results of Fig. 2 were found to be repeatable. The results for $\theta = 0$ deg are typical of pool boiling over an upward-facing heater. They agree well with the well-known ΔT^3 dependence for various fluids[12] except possibly at low ΔT and near CHF. The results for various orientations also agree with Rohsenow's correlation,[12] as can be seen in Fig. 2. The results for various orientations also appear to agree with the ΔT^3 correlation. A nearly third-power correlation was also found for liquid helium pool boiling for various heater orientations.[13] The value of ΔT for CHF (≈ 19 K) at $\theta = 0$ deg is similar to previously published results,[14] whereas the value of CHF (≈ 21 W/cm^2) at $\theta = 90$ deg agrees well with that found by Chui et al.[4]

The values of CHF for $\theta = 0$, 90, and 180 deg are 26.7 (at $\Delta T \approx 18$ K), 21.2 (at $\Delta T \approx 16$ K), and 9.4 W/cm^2 (at $\Delta T \approx 10$ K), respectively. It can be seen from Fig. 2 that, as the heater is turned from horizontally upward-facing ($\theta = 0$ deg) to horizontally downward-facing ($\theta = 180$ deg) positions, values of both CHF and corresponding values of ΔT for CHF decrease. The trend for CHF with heater orientation is similar to that found for liquid helium, also a cryogenic fluid, open pool boiling.[13] Such a decrease in CHF was attributed to the decreased opportunity for the vapor bubble to depart from the heater surface and the increased opportunity for bubbles to merge into a vapor film over the heater surface even at low q'' (Ref. 13). The formation of vapor film is expected to prevent the liquid from rewetting the surface, resulting in low CHF. It can also be seen from Fig. 2 that there appears to be no definite trend of h in the intermediate heat flux regime as θ is varied. In liquid helium pool boiling, the value of h was found to increase as the heater was rotated from upward-facing to downward-facing positions.[14] In the case of water, h was found to increase as the heater was rotated from upward-facing to downward-facing positions in the medium heat flux regime but was nearly independent of heater orientation at high heat flux, that is, more than about 30% of CHF.[15] In an earlier study, h in the medium heat flux regime was found to increase as much as 20% in water pool boiling as the heater was rotated from horizontal upward-facing to vertical positions.[16]

For effects of orientation on open pool boiling CHF, Brusstar and Merte[7] proposed a model based on the liquid replenishing rate related to the speed of the sliding motion of vapor bubbles over the heater surface due to buoyancy. In the absence of strong convection, their model suggested $q''_{c,\theta} = q_c|\sin\theta|^{1/2}$, where θ is the angle between the downward-facing heater surface and the horizontal plane and q_c is the CHF for upward-facing pool boiling. According to this model, a horizontal downward-facing heater produced no buoyancy component along the heater surface and should yield zero CHF, which was not observed in their R113 experiment nor in the present study. However, for inclined downward-facing heaters, the model prediction for $q''_{c,\theta}$ agreed well with experimental data, suggesting the importance of the sliding/escape motion of the vapor bubble.

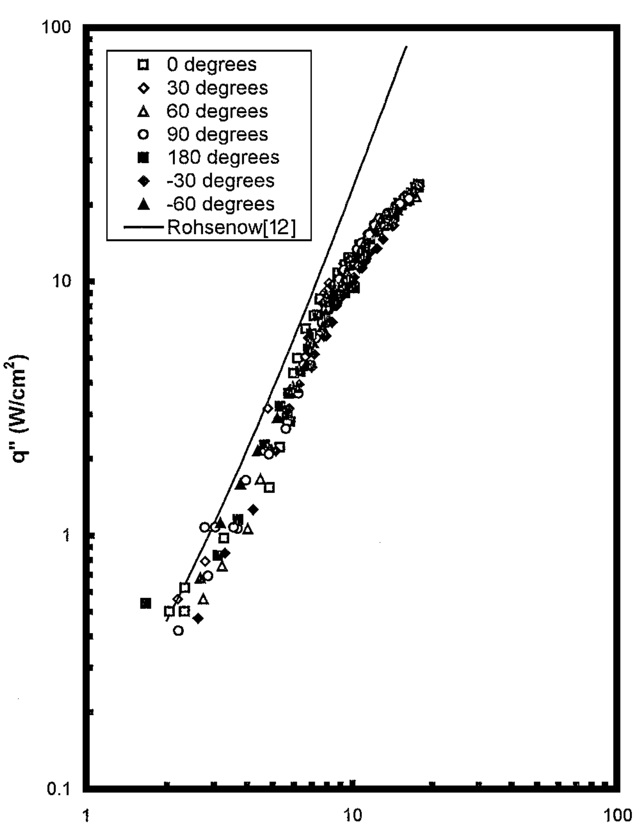

Fig. 2 Heat flux curve and critical heat flux of open pool boiling as a function of heater orientation; values of CHF for $\theta = 0$, 30, 60, 90, −30, −60, and 180 deg are 26.6, 23.6, 21.6, 21.2, 16.9, 19.1, and 9.4 W/cm^2, respectively.

Combined Effects of Confinement and Heater Orientation

Effects of confinement for $\theta = 0$, 90, and 180 deg were investigated for confinement spacing s equal to 3.0, 2.5, 1.5, and 0.75 cm. The spacing was the distance between the heater surface and a plate placed parallel to and in front of it. For illustration, only the results for $s = 2.5$ mm are presented in Fig. 3; results for other spacings are

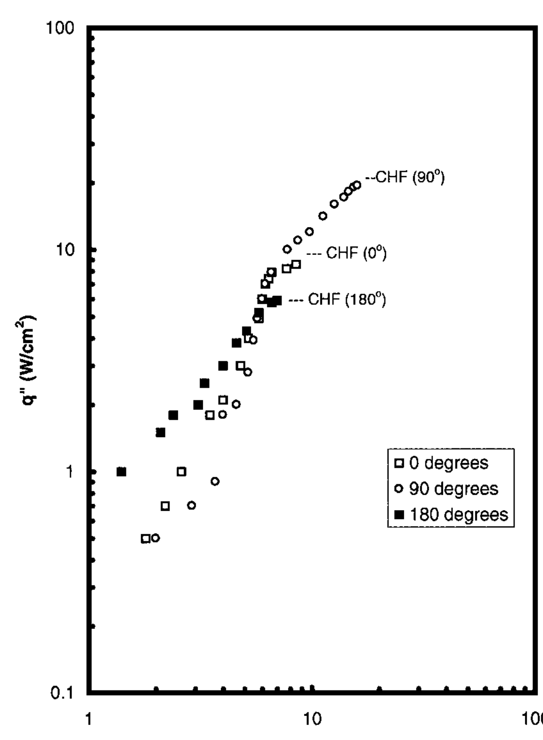

Fig. 3 Heat flux curve and critical heat flux with confined spacing $s = 2.5$ mm for $\theta = 0$, 90, and 180 deg.

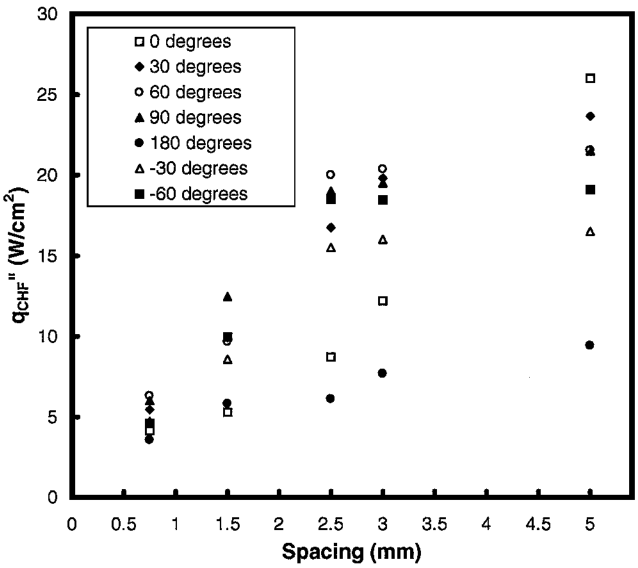

Fig. 4 Critical heat fluxes with confinements at various orientations; pool boiling ($s = \infty$) data are plotted at $s = 5.0$ mm.

similar. The difference in ΔT at CHF for $\theta = 0$ and 180 deg is about 2 K, compared to 4.3 K for $s = 3.0$ mm and 8 K for open boiling (the latter can be found in Fig. 2). For all spacings, the ΔT at CHF was found to decrease with a decrease in s.

With confinement, the values of CHF and the corresponding ΔT with $\theta = 90$ deg are larger than those either with $\theta = 0$ deg or with $\theta = 180$ deg. For $s = 2.5$ mm (Fig. 3), ΔT for $\theta = 90$ deg is approximately 17 K, compared to about 8.5 and 6.5 K for $\theta = 0$ and 180 deg, respectively. Although not reported here, similar results were found for other values of s during the course of this investigation.

In Fig. 4, the effect of confinement on CHF is shown for various values of θ. The data for open pool boiling are plotted at $s = 5$ mm, as indicated in Fig. 4. It is seen that the value of CHF for each of $\theta = -30$, ± 60, 90, and 180 deg does not appear to change as s is increased beyond 2.5 mm. The critical value of the spacing for these orientations appears to be approximately 2.5 mm (Fig. 4). The critical value of s for $\theta = 0$ and 30 deg must be larger than 3.0 mm because the values of CHF appear to continue to increase beyond $s = 2.5$ mm. In a recent study, it was reported that, for $\theta = 90$ deg in FC-72 boiling, the values of CHF were the same for $s =$ and > 2.3 mm (Ref. 5). Because the characteristic bubble is related to the fluid surface tension (8.85×10^{-3} and 12.0×10^{-3} N/m, respectively, for LN_2 and FC-72) at their respective boiling temperatures, the critical spacing for the two liquids is expected to be similar. It is believed that spacing below the critical value would impede the movement of the bubble to depart to allow liquid replenishing the heater surface, resulting in lower values of CHF. For visualization of bubble movement at various orientations using fluids other than LN_2, see Ref. 9. Note that a mechanistic model was proposed for the upward-facing orientations.

From Fig. 4, it is also seen that the upward-facing heaters yield higher values of CHF than the downward-facing heaters for larger values of s. As s is decreased, the CHF is maximum when the heater is at a vertical or nearly vertical position ($\theta = 90$ and ± 60 deg), depending on the spacing, because these orientations provide the most efficient bubble escape.

Conclusion

1) The heat flux for LN_2 open pool boiling was found to depend on surface superheat in a manner similar to that of other fluids, that is, $q'' \propto \Delta T^n$ with $n \approx 3$. The slope of the heat flux curve, that is, the heat transfer coefficient h, appears to be independent of the heater orientation, as opposed to the finding for water that it increases as the heater is rotated from upward-facing to downward-facing positions.

2) In LN_2 pool boiling, upward-facing heaters were found to give higher values of CHF than downward-facing heaters. This is probably because the buoyancy force acts to remove vapor bubbles from the heater surface and enables the liquid to replenish the surface. When the heater is confined with a plate parallel to and in front of it, the most favorable orientations for the bubble to rapidly escape and for the liquid to replenish the heater surface are the nearly vertical orientations.

3) There appears to be a spacing above which the value of CHF was found to be similar to those of unconfined heaters. Below the spacing, CHF decreases with decreasing spacing and occurs at lower surface superheat. The value of this spacing depends on the heater orientation.

Acknowledgments

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