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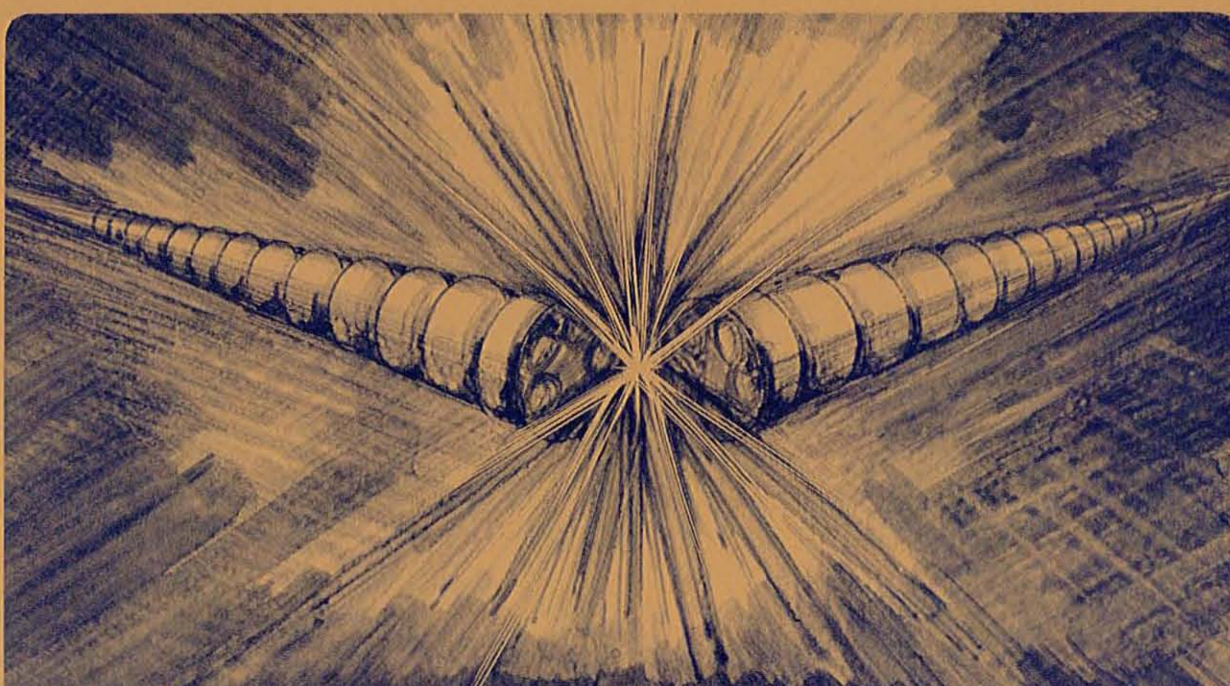

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INTRODUCTION

Recently the enhanced heat removal capability of unsaturated superfluid helium II has been exploited in fusion[1] and accelerator dipole[2] magnets. In superfluid the internal convection mechanism dominates the heat removal process and orientation with respect to gravity becomes of secondary importance. Heat transfer, however, can be influenced by the thermodynamic state of the liquid, especially with regard to possible phase transformations. The transformation from non-saturated He II must involve an He I state before the film boiling transition is experienced. Some steady state measurements of heat transfer to non-saturated He II have been previously reported.[3-10]

In typical magnet designs, cooling passages between turns result from gaps between the electrical insulation, and are typically on the order of a fraction of a millimeter. The purpose of the work reported here is to measure the attenuation of the heat transfer within such a restrictive geometry.

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EXPERIMENTAL APPARATUS

The heated surface is shown in Fig. 1. It consists of a copper cylinder with one end ($A = 1.27\ cm^2$) exposed to the bath. A heater winding is wrapped in a circumferential groove and a thermometer (Lake Shore Cryotronics "carbon glass") is located in a transversely drilled hole which is positioned between the heater and the exposed end. This assembly is potted in Stycast. Following machining, the exposed copper surface was allowed to oxidize with no subsequent surface treatment. An adiabatic surface machined from Nema G10 fiberglass to the same diameter as the heated surface was located parallel to and with its axis coincident with that of the heated surface. The spacing, δ, between the two surfaces, henceforth referred to as the gap, was adjustable. The assembly was located near the bottom of a vertical magnet test vessel of a height and volume of approximately 1.3 m and 100 liters (with magnet in place). The exposed surface faced downward for all but one test series (0.25 mm gap) in which case the exposed surface was oriented vertically. The magnet test facility, which has been previously described,[11] allows testing at liquid temperatures from about 4.5 K down to about 1.5 K at a pressure of approximately 1 atm. The bulk liquid temperature is measured with a thermometer (of the same type as on the heated surface) that is located approximately 50 cm from the heated surface. Thermometer read out and heater control are accomplished by an HP 9845B desk top computer, a programmable scanner (HP 3495A), and a programmable power supply (HP 6002A).

EXPERIMENTAL PROCEDURE

Once a selected bath temperature is reached, the refrigerant flow is reduced to a low level and manually modulated in response to bath temperature changes. At predetermined time intervals the computer commands the power supply to increase the current through the heater (steps of 1 to 4 mA are typical). After allowing 2 seconds for stability, the heater voltage and current are measured and converted into power. The scanner then switches approximately 1 μA into the heater and bath thermometers. The thermometer current and voltage is computed using calibration tables and a spline fit interpolation equation. Temperature accuracy is estimated to be better than ±5 mK. The temperature of the heated surface is extrapolated from the thermometer temperature, using the heater power and the temperature dependent thermal conductivity of copper. The Kapitza resistance is included in the measured surface conductance and its effect is not accounted for in arriving at the surface temperature.

Up to 100 data points were collected and stored in each run. During the run the data are displayed as a plot of heat flux vs surface temperature on the computer CRT and are available in a tabular print out.

The test pressure for all runs was approximately 1.2 atm.

TEST RESULTS AND DISCUSSION

Some results are shown in Figs. 2 and 3 in the form of heat flux density vs the temperature difference, $T_s - T_b$ (s = surface, b = bath). When the bath temperature approaches T_λ, ($T_\lambda - T_b < 50$ mK) the transitions between the various heat transfer regimes become very apparent (Fig. 2). As the bath temperature is lowered (Fig. 3) the transitions become less apparent but the overall characteristics remain.

With the unrestricted geometry (gap = ∞) there is a monotonic rise in ΔT with increasing heat flux (Fig. 2). When the liquid temperature at the heated surface reaches T_λ a transition to He I occurs followed by an almost simultaneous transition to film boiling. We refer to the heat flux density at the transition, q_{max}, as the limiting heat flux. Heat transfer to a confined geometry reveals some new details as are shown in Fig. 2 for the 0.25 mm vertical gap. Above a critical heat flux, on the order of 0.1 W/cm^2, mutual friction dominates the heat removal rate through the gap. This Gorter-Mellink region terminates at point A where the heat flux, q_λ, is sufficient to create a normal He I layer adjacent to the surface. The coexistence in the steady state of an He I layer in a He II bath prior to the inception of film boiling has previously been observed.[4] Increasing the heat flux up to point B is accompanied by an increase of the temperature of the subcooled He I layer up to the corresponding saturated value. At this temperature nucleate boiling commences and subsequent increases in the heat flux result in markedly enhanced heat transfer. When point C is reached the surface dries out and a transition to film boiling occurs. Except for a small hysteresis around the film boiling transition the original curve is traced with a decrease in power. A similar but less pronounced characteristic is seen for the horizontal channel (0.15 mm gap, Fig. 2).

As the bath temperature is lowered from T_λ, the nucleate boiling transition (point B) becomes increasingly less obvious, until it completely disappears (Fig. 3), however, the transition points (A,C) corresponding to q_λ and q_{max} can always be seen with a restricted geometry. The equivalence between q_λ and q_{max} for the unrestricted case is typical.

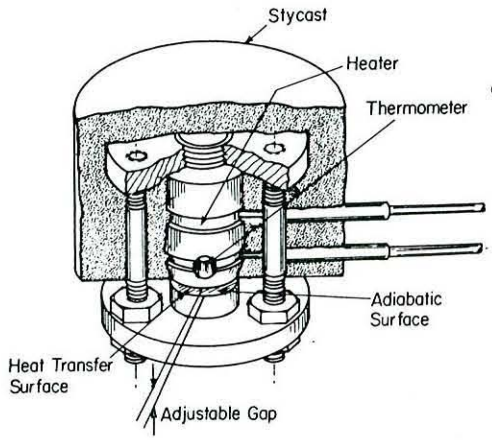

Fig. 1. Experimental assembly.

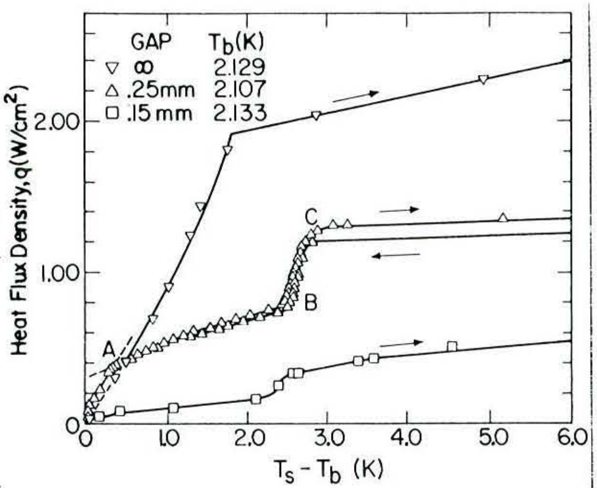

Fig. 2. Characteristic results near T_λ.

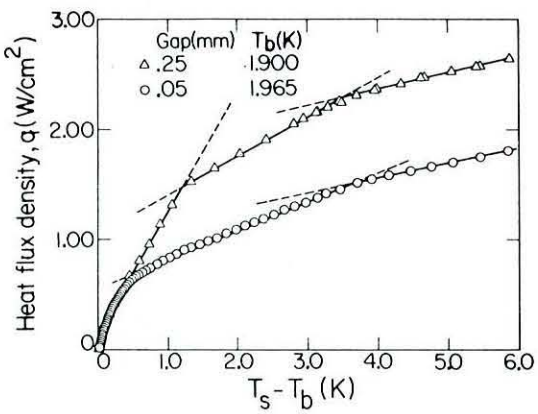

Fig. 3. Characteristic results near 1.9 K.

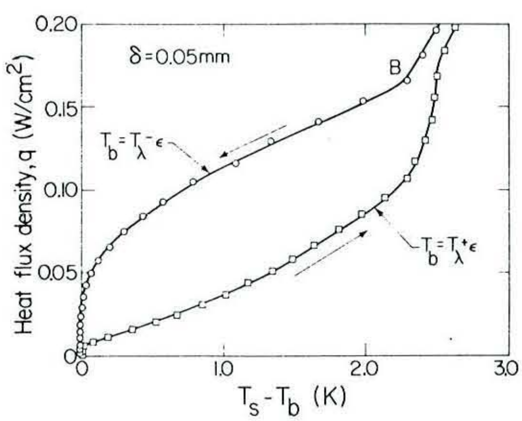

Fig. 4. Heat transfer at the lambda point.

One case where the bath temperature dropped thru the lambda point during the course of the run is shown in Fig. 4. On the increasing portion of the heat flux cycle the bath temperature was on the He I side of T_λ. With decreasing heat flux the He II/He I interface propagated[12] toward and reached the heated surface at point B. The difference in the heat transfer characteristics on either side of the lambda point are apparent.

CRITICAL HEAT FLUX

The critical heat flux values are plotted in Fig. 5 as a function of T_b. For the unrestricted geometry, q_{max} $(= q_\lambda)$ increases from about 0.4 W/cm^2 near the lambda point $(T_\lambda - T_b \leqslant 5$ mK), to 10.5 W/cm^2 at T_b = 1.837 K. In the He I region at $T_b - T_\lambda \approx 6$ mK we have found the transition to film boiling of this subcooled liquid to occur at about 0.4 W/cm^2. Lyon[13] has found that the film boiling transition of saturated He I at 1 atm for a downward facing surface occurs at 0.2 W/cm^2. Therefore, although speculative we expect that in the region of $T_\lambda - T_b \leqslant 5$ mK, for a downward surface, the curves for q_λ and q_{max} should diverge. Also shown for comparison are two sets of measurements by Kobayashi[6,7] for upward facing Nichrome[6] and Nichrome and copper[7] surfaces and measurements by van Sciver[8] from a cylindrical copper surface. The present data falls very close to the center of the data by Kobayashi and significantly above the data by van Sciver. Kobayashi comments on the difficulty of maintaining steady temperatures in his 5 liter test vessel at the higher heat rates.[6] Our 100 liter liquid volume very much attenuates this problem. The temperature drift during a run was typically on the order of 5 mK or less and never exceeded about 20 mK.

Both q_λ and q_{max} are shown for the restricted geometries. The dominant role of mutual friction in these geometries is clearly evident. The limiting heat flux is significantly reduced relative to the unrestricted case and the formation of an He I layer typically occurs at $q_\lambda/q_{max} \approx 0.5$. As a result of the presence of the He I layer, heat transfer is influenced by channel orientation when the heat flux is increased above q_λ.

SURFACE CONDUCTANCE

The surface conductance $(\equiv q/\Delta T)$ for the unrestricted case is plotted vs $T_s - T_b$ for various T_b (Fig. 6). No significant dependence on bath temperature is found. In the range of $T_s - T_b$ of 1 to 4.5 K, the conductance is seen to vary from about 1 to 2.3 W/cm^2. The conductance h_{max}, at the limiting heat flux (upper line Fig. 7) falls from about 2.6 at T_b = 1.8 K to about .7 as T_λ is approached.

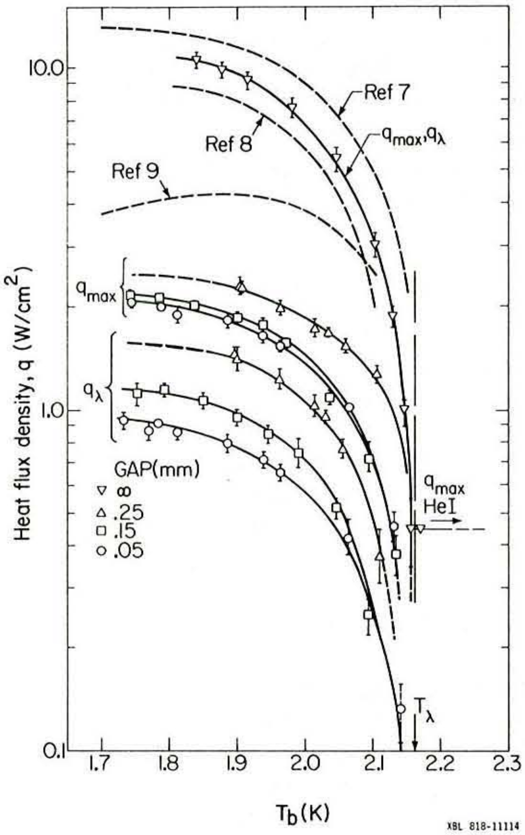

Fig. 5. Critical heat flux.

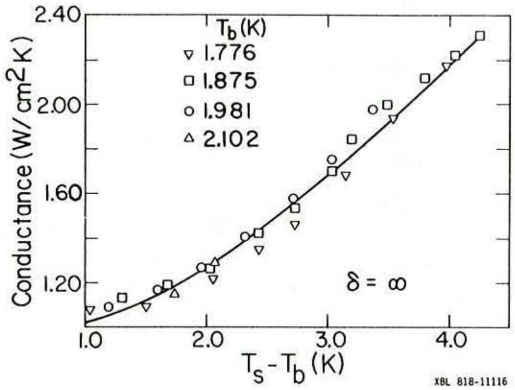

Fig. 6. Conductance as function of temperature difference.

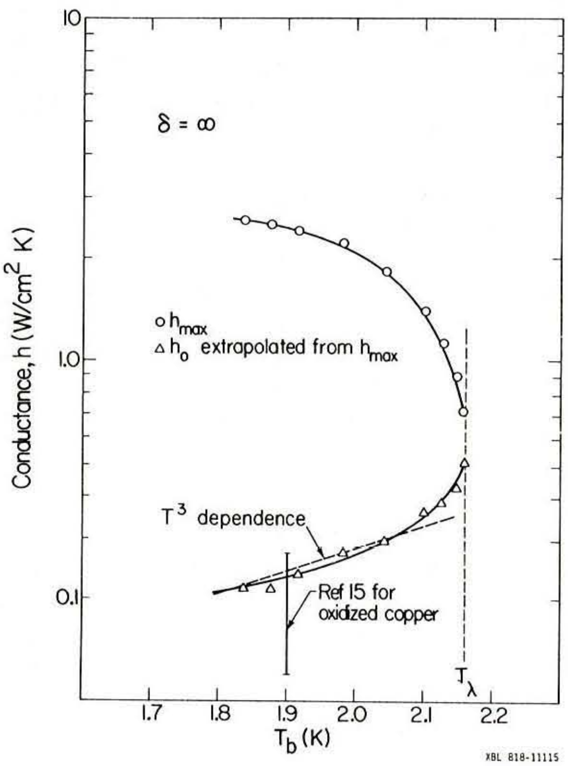

Fig. 7. Conductance at the limiting heat flux and Kapitza conductance.

The Kapitza conductance, which is defined as

$$h_0 = \left(\frac{q}{\Delta T}\right)_{\Delta T \to 0} ,$$

was computed from the above values of q_{max} using the expanded form of the T^3 dependence as originally suggested by Frederking[14]:

$$\frac{h_{max}}{h_0} = 1 + \frac{3}{2}\left(\frac{\Delta T_{max}}{T}\right) + \left(\frac{\Delta T_{max}}{T}\right)^2 + \frac{1}{4}\left(\frac{\Delta T_{max}}{T}\right)^3.$$

The computed h_0 values show the anticipated T^3 dependence at low temperatures, and near the lambda point, h_0 approaches the conductance at the limiting heat flux. For comparison, the range in h_0 for oxidized copper in saturated He II as reported by Snyder[15] is shown.

CONCLUSIONS

Appreciable heat flux densities are possible in pressurized (1 atm) He II. For an unrestricted geometry the transition to film boiling reaches over 10 W/cm^2 at 1.8 K. This transition is a simultaneous transition to He I and vapor. For downward facing surface at $T_\lambda - T_b < 5$ mk a steady state existence of a He I layer at the heated surface prior to a film boiling is possible. In a restricted geometry in which mutual friction dominates, a transition to a He I film on the heated surface occurs prior to the film boiling. When an He I layer is formed normal convection in He I and nucleate boiling can play important roles. Heat flux densities of the order of 1 W/cm^2 are achievable in narrow passages as small as 0.05 mm with an aspect ratio typical of that found in magnet design.

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