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HEAT TRANSFER TO SUBCOOLED HE I

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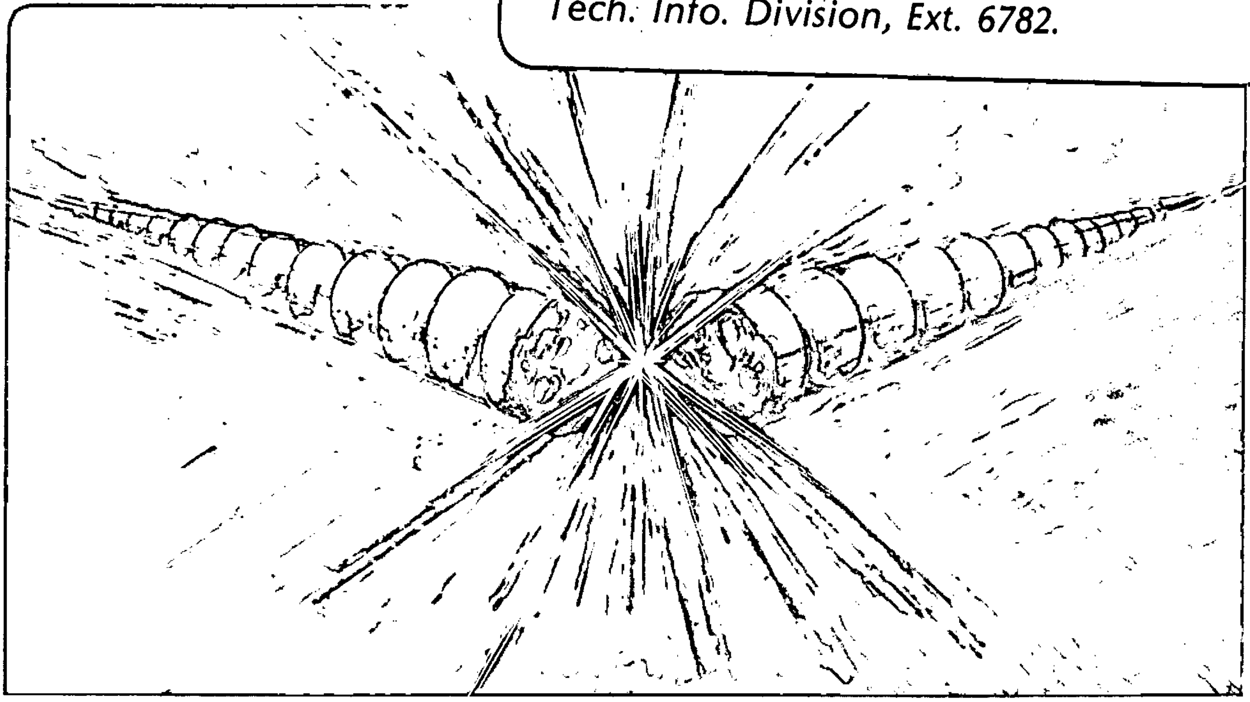

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INTRODUCTION

Designers of cryostable superconducting magnets, which operate in pool boiling He I, are aware of critical heat flux densities. The region of most general interest are the peak nucleate boiling and recovery heat fluxes at temperature that the conductor is no more than a few hundred millidegrees above the pool temperature. Systems which depend on nucleate boiling can face a convective region prior to the nucleate boiling transition. Thermal fluctuations can easily effect the pressure to an extent where the liquid becomes subcooled. Depending on the degree of subcooling the temperature difference at the transition to nucleate boiling, can exceed the temperature difference in all of the nucleate boiling region.

The availability of a large volume (~ 100 liters) of subcooled He I at the LBL superconducting dipole test facility[1] provided the opportunity to study heat transfer. A copper block with an embedded heater was used to measure heat transfer. The temperature of the block was measured and the characteristic boiling curves recorded. The measurement accuracy of heater power and block temperature was sufficient to record the convection region prior to nucleate boiling. The effective size of the

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pool in the experimental apparatus could be restricted by introducing an adiabatic wall parallel to and a fixed distance from the heated surface. Free convection heat transfer, limiting heat flux to subcooled He I, and geometry effects are reported.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus and procedure are almost identical to those previously reported in Ref. 2 for tests performed in He II. The heated surface, shown in Fig. 1, consists of a copper cylinder ($A = 1.27\ cm^2$) with one end exposed to the bath. A thermometer (Lake Shore Cryotronics "carbon glass") is located in a hole positioned between the heater and the exposed end. The assembly is potted in "Stycast". A NEMA G10 fiberglass disk of the same diameter was placed in front of and parallel to the exposed end. The spacing, d, between the two surfaces, henceforth referred to as the gap, was adjustable. The exposed surface which had no surface treatment, was either vertical or facing downwards during the tests.

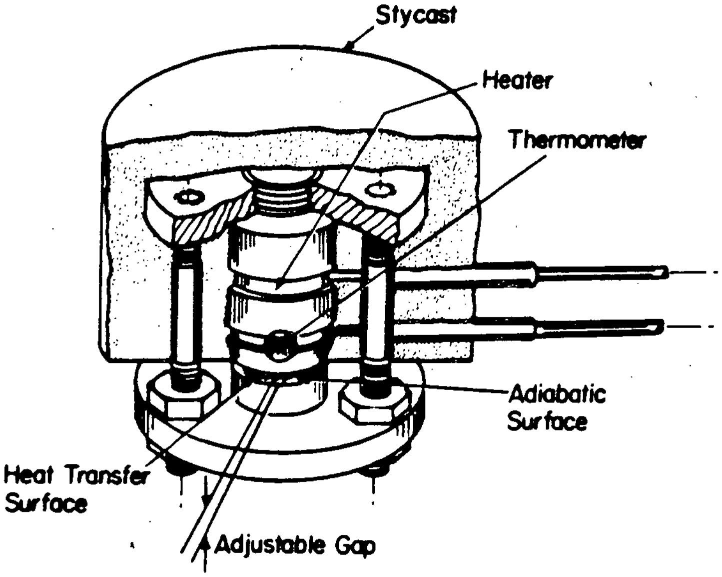

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Fig. 1 Experimental Assembly

The assembly was placed at the bottom of a magnet test vessel of height and volume of approximately 1.3 m and 100 liters (with magnet in place). The magnet test facility allows testing at temperatures from 4.5 K to about 1.5 K at a pressure of approximately 1 atm. The liquid is cooled at the vessel top. With free convection as the mixing force, stratification was minimal and the maximum temperature difference was about 100 mK within the entire vessel. 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. With the existing stratification the bath temperature at the heater vicinity was known to better than 50 mK. Thermometer read out and heater control are accomplished by an HP 9845 desktop computer, a programmable scanner (HP 3495A), and a programmable power supply (HP 6002A). During cooldown, 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. During warmup, bath temperature regulation was unnecessary primarily due to the large total thermal mass to heat input ratio. At predetermined time intervals the computer commands the power supply to increase the current through the heater (typical steps are 1 to 4 mA). After allowing 4 seconds for stability, the heater voltage and current are measured and converted into power. The scanner then switches approximately 1 μA into the bath and heater thermometers. The thermometer current and voltage are measured, the resistance computed and the temperature determined using calibration tables and a spline fit interpolation. Temperature accuracy is estimated to be ±10 mK in the range reported. The temperature of the heated surface is extrapolated from the measured temperature, using the heater power and the temperature dependent thermal conductivity of copper. Up to 100 data points were collected and stored in each run.

The test pressure for all runs was approximately 1.2 atm.

TEST RESULTS AND DISCUSSION

Typical boiling curves between a heated vertical surface and subcooled He I are shown in Fig. 2. Heat is removed in region A by natural convection until the surface temperature exceeds that of the pressure corresponding to the saturated value (point a), and nucleation begins. Region B with its enhanced heat transfer suffers a crisis at point b where the transition to film boiling occurs. When the liquid bath is further subcooled the magnitude of the heat flux density at points a and b is increased.

Convection Crises

An exploded view of the transition from convection to nucleate boiling at various degrees of subcooling is shown in Fig. 3. In the subcooled case, the amount of superheating depends only on the pressure. Figure 4 shows the measured temperature limit (point a, Fig. 2) for various degrees of subcooling and is compared with the calculated homogeneous nucleation limit and experimental data (from Flint) taken at saturation.[3] The

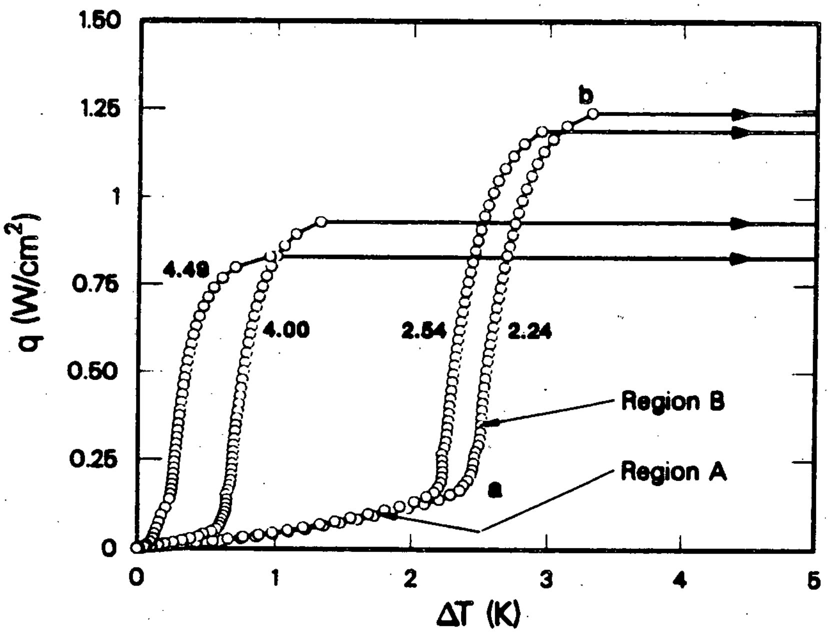

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Fig. 2 Boiling curves in subcooled He I (1.2 atm)

heat flux density q_o associated with the transition to nucleate boiling is plotted in Fig. 5. These values are almost 50 percent less than those measured for saturated conditions and vary by about 20 percent due to surface inclination.

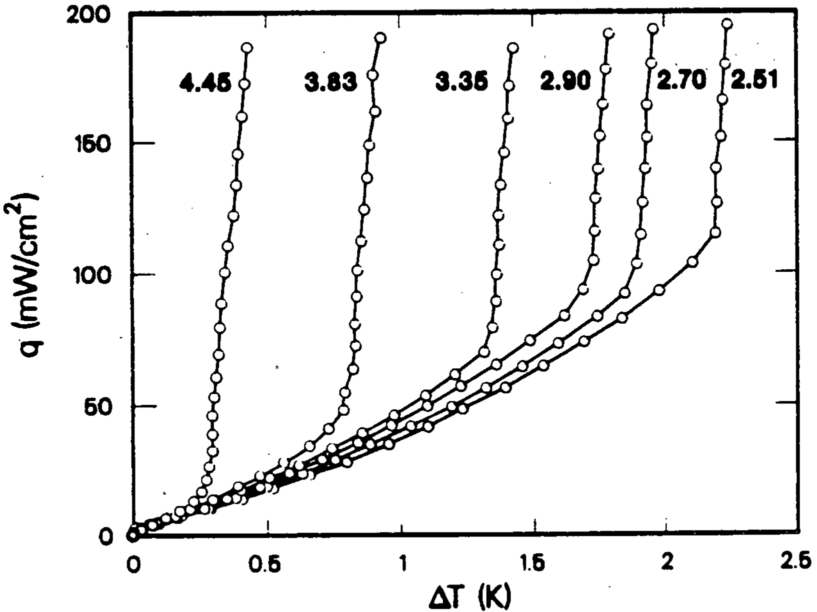

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Fig. 3 The transition from convection to nucleate boiling in subcooled He I (1.2 atm)

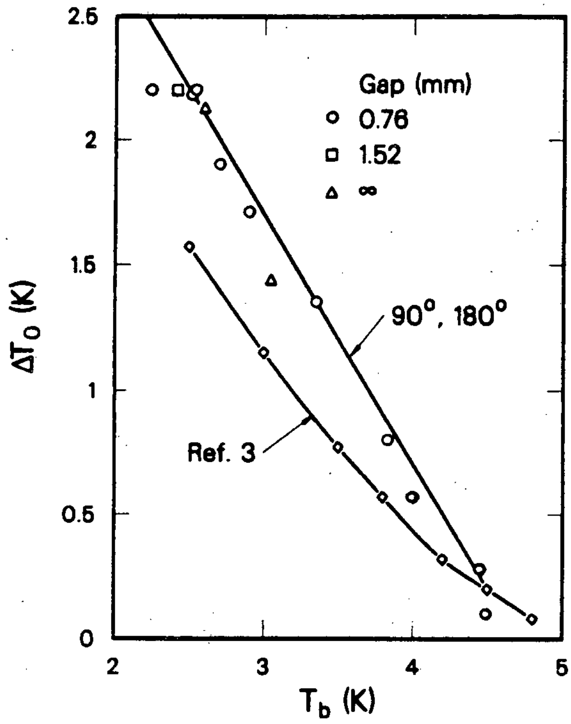

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Fig. 4

Temperature limit at the transition to nucleate boiling (91° ≡ vertical; 181° ≡ facing down)

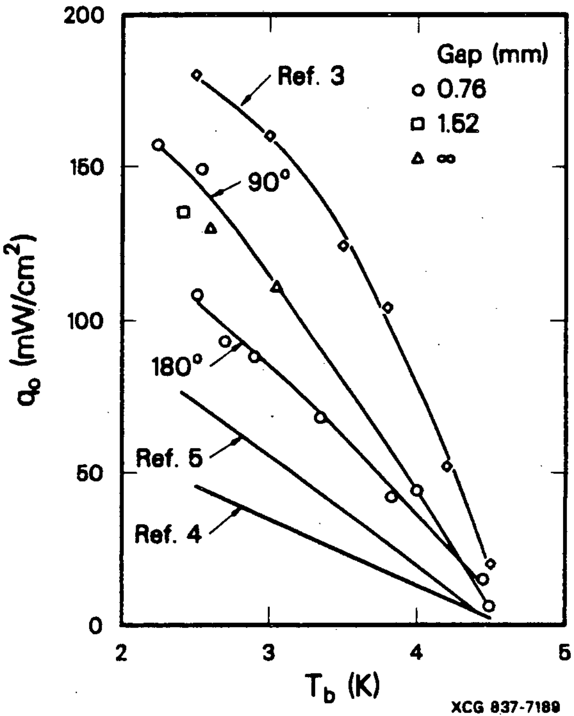

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Fig. 5

Heat flux density at the nucleate boiling transition; 1.2 atm (Ref. 3, at saturation)

Boiling Crises

The heat flux density at the film boiling transition is plotted in Fig. 6 as a function of the subcooled bath temperature. When the heated surface is in a vertical orientation heat transfer seems unaffected by gap sizes greater than 0.76 mm. Altering the orientation so that heat is emitted downwards reduces the film boiling transition significantly.

The ratio of the film boiling onset in subcooled liquids to peak nucleate boiling under saturated condition is expressed as

$$F_r = 1 + a\left(\frac{\rho_v}{\rho_\ell}\right)^{3/4}\theta \qquad (1)$$

where

$$F_r = \frac{q_{pnb\ sub.}}{q_{pnb\ sat.}}$$

$$\theta = \frac{C_p\left(T_{sat} - T_{bath}\right)}{L}\ , \text{ and}$$

L is the latent heat of vaporization at T_{sat}.

For He I at $T_{sat} = 4.4$ K; $C_p = 6.01$ J/gr/K, $L = 19.15$ J/gr

$$\left(\frac{\rho_v}{\rho_\ell}\right)^{3/4} = 3.78$$

The value for F_r as a function of θ is plotted in Fig. 7. Fitted with a value of $a = 0.198$, the data fall well within the experimental accuracy of the data taken by Verkin (Ref. 4).

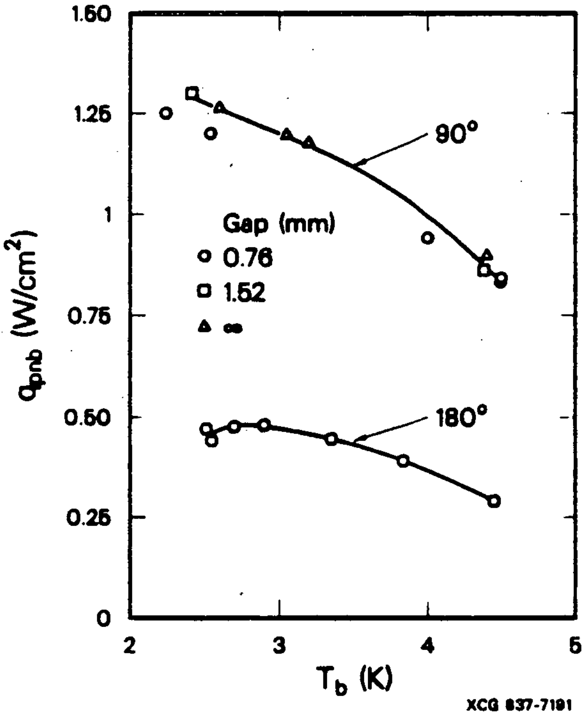

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Fig. 6

Peak nucleate boiling heat flux in subcooled He I, at 1.2 atm

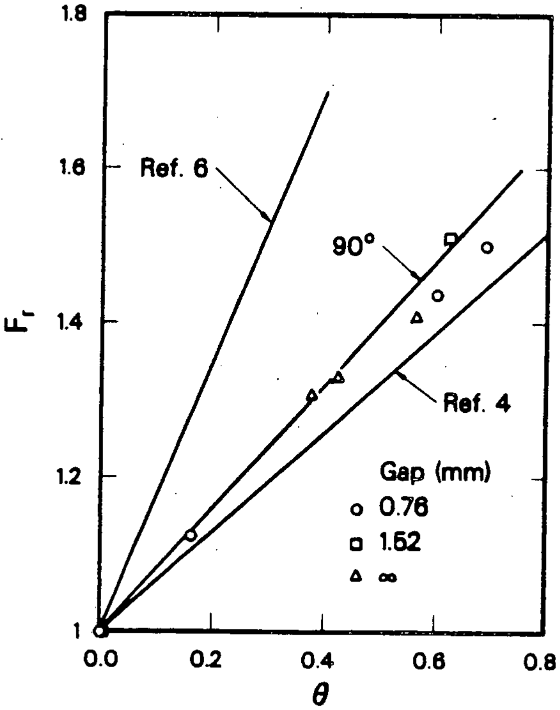

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Fig. 7

Peak nulceate boiling ratio as a function of the dimensionless degree of subcooling

CONCLUSIONS

The expected increase in the peak nucleate boiling heat flux correlates with equation 1. At 1.2 atm this increase seems to have a maximum which is 50% higher than the peak nucleate boiling at saturation. The heat flux density at the transition from convection to nucleate boiling has been measured at different degrees of subcooling. The values are lower than the ones measured for saturated He I.

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