HEAT TRANSFER TO He I AND He II IN PULSED THERMAL LOADING

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Results are given on the effects of a pulsed thermal load on a copper specimen immersed in He I and He II. Estimates are made of the mean heat-transfer coefficient $\bar{\alpha}_p$ for He I, He II, and He I with $T_l < T_s$.

The applications of He I and He II are currently expanding, and it is therefore necessary to examine heat transfer in these media. In particular, there is heat transfer to He I and He II in pulse form in charged-particle accelerators using superconductivity [1-3]. He II has advantages for cooling superconducting systems relative to He I: The high thermal conductivity of He II makes it possible to provide reliable thermal contact between the elements, while the lower temperature enables one to increase the critical current in the superconductor, and the superfluid helium penetrates into the finest channels and increases the cooling performance.

Here we present results on the effects of a pulsed thermal load on a specimen immersed in He I and He II.

The rack of equipment included the following: a cryostat 0.25 m in diam. (Fig. 1), a stabilized current source for the temperature transducers, a digital voltmeter for recording the temperature and increments (jumps) in temperature, a pulse energy source, a fast pen recorder with a sensitivity of 20 mV/cm and with a chart speed of up to 250 mm/sec and responding in the range 0-100 Hz, and an oscilloscope and instruments for measuring the level of the liquid helium and the vapor pressure.

The specimen (Fig. 2) was a flat plate of size 0.1 × 0.1 m and thickness 0.005 m made of annealed copper grade M3. On one side of the plate, a nichrome heater with $R = 100\ \Omega$ was attached with Delta-Bond epoxide resin, which provides good insulation and relatively high thermal conductivity, while on the other side the Delta-Bond was used to attach three Allen-Bradley carbon resistors in special grooves, which were used as temperature transducers.

The thermal conductivities of copper and fiberglass plastic at $T = 4°K$ and $T = 2°K$ are such that the heat flux into the copper was almost 200 times that into the glass material. We therefore assume that the heat flux from the heater is directed only into the copper and passes to the liquid helium from the surface of the plate $F = 0.01\ m^2$.

In the cryostat (Fig. 1), the specimen is set horizontally with the heater downwards. The experiments were performed in liquid He I boiling at $T_l = T_s$ (T_l is the temperature of the liquid and T_s is the saturation temperature), and also in He II with $T_l = T_s$ (conversion of He I to He II was provided by pumping out the vapor), and also in liquid He I below its boiling point, $T_l < T_s$, which occurred after stopping the pumping and admitting gaseous helium at atmospheric pressure to the cryostat containing He II.

The digital voltmeter and fast pen recorder registered the temperature changes at the surface of the specimen due to the heat pulse. The relative error in measuring temperatures of 4.2°K was 0.5%, as against 1% at 2°K. Figure 3 shows the shape of the voltage pulse together with the corresponding values for the Joule heat produced in the pulse. The amount of energy stored in the capacitor was determined from $E = CU^2/2$ (J), where C is the capacitance of the pulsed source in F, and U is the voltage on the capacitor at the time of the pulse in V.

The pulse shape was kept constant in all experiments, and the energy loss in pulse transfer was about 0.1%. The material of the specimen (copper) could have affected the temperature change for pulses of duration $\tau \leq 10^{-3}$ sec.

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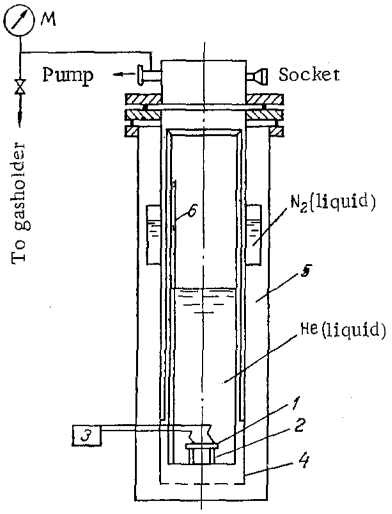

Fig. 1

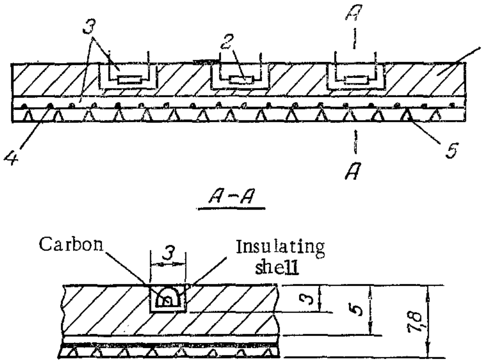

Fig. 2

Fig. 1. Cryostat with specimen: 1) specimen; 2) insulating substrate; 3) pulsed energy source with instruments for recording temperature change; 4) copper screen; 5) vacuum jacket; 6) superconducting helium-level indicator.

Fig. 2. Specimen with heater and temperature transducers: 1) copper plate ($\delta = 0.005$ m, 0.1×0.1 m); 2) Allen-Bradley resistor (three off); 3) Delta-Bond epoxide resin; 4) heater ($R = 100\ \Omega$); 5) fiberglass ($\delta = 0.001$ m, 0.1×0.1 m).

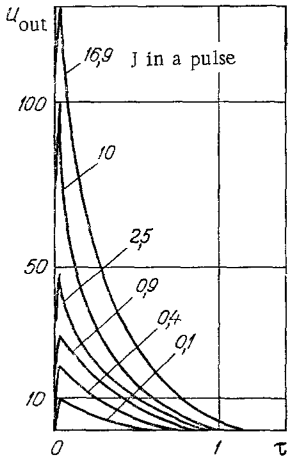

Fig. 3

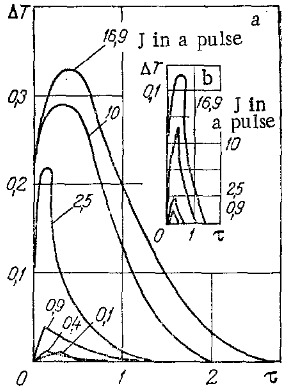

Fig. 4

Fig. 3. Form of the electrical pulse acting on the specimen in relation to time and amount of energy in a pulse; U_{out} is the voltage at the heater in V, while τ is time in sec.

Fig. 4. Temperature change at the surface of a specimen in relation to time and amount of thermal energy in a pulse: in He I with $T_s = 4.224$°K, $p = 1.01 \cdot 10^5$ Pa (a) and in He II with $T_s = 2.015$°K, $p = 0.03 \cdot 10^5$ Pa (b); T_s is saturation temperature and ΔT is in °K.

Figure 4a shows the observed change in surface temperature for the specimen in liquid He I at $T_l = T_s = 4.224$°K in relation to time and pulse energy. The data indicate that there is convective heat transfer in the He I at heat fluxes up to 100 W/m^2 (1.5 J in the pulse), while at higher fluxes up to 700 W/m^2 (16.9 J in the pulse) there is bubble boiling. These results agree with those of [4]. The mean heat-transfer coefficient for He I is given by Newton's formula as

$$\bar{\alpha}_p = \frac{Q_p}{\tau F \Delta T}, \quad (1)$$

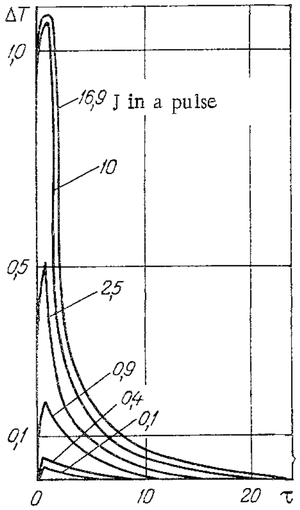

Fig. 5. Temperature change at the surface of a specimen in relation to time and amount of thermal energy in a pulse for nonboiling liquid He I; T_l = 2.18°K, p = $1.01 \cdot 10^5$ Pa.

where Q_p is the amount of energy in a pulse in J; τ, pulse length in sec; F, heat-transfer surface in m^2; and $\overline{\Delta T}$, mean value of the difference in temperature between the copper specimen and the helium in the bath in °K; the result is $\bar{\alpha}_p \simeq 3000$ [$W/m^2 \cdot K$].

The maximum temperature change in liquid He I is 0.3-0.33°K, while the length of the temperature pulse was twice that of the thermal pulse.

Figure 4b shows the observed surface temperature of the same specimen in liquid He II at $T_l = T_S$ = 2.015°K in relation to time and pulse energy. So far as we are aware, nothing has been published on heat transfer to He II with pulse heating. The heat-transfer coefficient for He II was estimated from (1) for the case of Fig. 4b as $\bar{\alpha}_p \simeq 27{,}000$ [$W/m^2 \cdot {}^\circ K$].

The maximum change in surface temperature in liquid He II was about 0.1°K, while the length of the temperature pulse was no greater than that of the thermal one.

Landau's theory of superfluidity [5] implies that there is a flow of normal component in liquid He II from the heated side, which transports the heat, while there is an equal but opposite flow of the superfluid component. No macroscopic real flow is observed in the helium. Kapitsa has shown that this mechanism is responsible for the phenomenally high thermal conductivity of liquid He II, which is thousands of times the conductivity of copper. Transfer of heat from a solid to He II [6, 7] leads to the Kapitsa resistance, which is seen as a temperature difference ΔT at the boundary between the solid and the He II. This discontinuity is ascribed to a hypothetical thermally conducting layer characterized by $\alpha_0 = Q/F\Delta T$, which is essentially the heat-transfer coefficient from the solid wall to He II and is usually called the Kapitsa conductance.

At the present time, no theory exists for pulse heat transfer in liquid He II, and it is therefore impossible to perform any theoretical estimate of α_0 in pulse mode. There is no doubt that the very high value of α characteristic of pulse heating should stimulate theoretical investigation.

Figure 5 shows the observed surface temperature change for the same specimen in liquid He I at $T_l < T_S$, T_l = 2.18°K (boiling in a nonboiling liquid) in relation to time and thermal pulse size. The length of the temperature pulse is almost 20 times that of the thermal pulse, while the maximum temperature change is more than 1.0°K. This behavior of the temperature pulse is due to details of the heat transfer in helium when the temperature of the liquid is less than the saturation temperature (there is no vapor production in the bulk but surface boiling occurs).

According to (1), the mean heat-transfer coefficient for the case of Fig. 5 is $\bar{\alpha}_p \simeq 300$ [$W/m^2 \cdot {}^\circ K$].

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NUCLEATE BOILING

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The study deals with the effect of the surface conditions on the nucleate boiling curve. A relation is proposed which describes the complete nucleate boiling curve.

Nucleate boiling is of extraordinary practical significance, more than other modes of heat dissipation, inasmuch as it facilitates dumping of large thermal fluxes at relatively low temperature heads. At the same time, this is one of the most intricate heat transfer processes and no complete theory of it has yet been developed which takes into account all the factors influencing the intensity of heat transfer.

One basic difficulty in constructing a theory of nucleate boiling is the unavailability of sufficient information about the effect of conditions at the heat emitting surface on nucleate boiling, which has been shown already [1, 2] to largely determine the intensity of heat transfer. On the one hand, the nucleate boiling curve is conservative with respect to such parameters as the gravitation constant, the velocity of the main mass flux of liquid, and particularly the liquid underheating (which substantially affects the pattern of nucleate boiling), parameters seemingly important from the standpoint of the heat dissipation mechanism on the basis of which various models of the process have been constructed. On the other hand, the position and the slope of the nucleate boiling curve are largely determined by the roughness of the heating surface. Indeed, a change in the surface roughness can change the intensity of heat dissipation by a factor of 5-10. Since the mode of nucleate boiling depends so much on the surface roughness, it should be interesting to find out how the boiling curve will change as the roughness dimension and the number of active vapor formation centers decrease toward zero, i.e., as the ideal case of a surface without vapor formation centers and a liquid without dissolved gas is being approached.

It is well known that an increase of the roughness of the heating surface causes the boiling curve to shift toward lower underheat temperatures. Beginning with a class 6-7 surface finish, however, further increase of the roughness hardly affects the position of the nucleate boiling curve. Surfaces with such a treatment are called "technical-grade surfaces." Most theoretical relations pertaining to heat emission during nucleate boiling are generalizations of data obtained with such surfaces. As the roughness decreases, vapor formation at the surface becomes more difficult and in most experiments [1] the slope of the boiling curve has been found to increase.

It is nowadays universally assumed that, under real conditions, surface irregularities filled with gas constitute the vapor formation centers. The dimension of critical vapor formating nucleus is in this case equal to the radius of the opening of a surface cavity [3, 4] which constitutes such a vapor formation center, namely

$$R_{\mathrm{cr}} = 2\sigma T''/(r\rho''\Delta T). \tag{1}$$

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