The Behavior of Helium II in the Neighborhood of a Heat Radiating Surface

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Investigations have been made on the magnitudes of temperature discontinuities arising in the surface layer of He II in contact with a solid wall that is supplied with heat.

1 HELIUM II has practically infinite thermal conductivity and the thermal resistance within its volume is equal to zero. This means that the temperature is uniform at all interior points. However, in sufficiently small capillaries and slits a measurable temperature gradient appears, thanks to the thermo-mechanical effect. This gradient is associated with the flow of the normal component.

The basic features of the peculiar mechanism of heat transfer in He II find their explanation in researches based on Landau's theory of superfluidity[1]. However, up to now, there are several factors which lack a theoretical explanation. Among the unexplained phenomena is the presence of maximum thermal conductivity, observed by many authors in the temperature range 1.8-2.05° K[2]. In this connection, the temperature gradient along a capillary with constant thermal stress undergoes a minimum in the same temperature interval. Also unexplained is the presence of a significant thermal resistance, discovered by Kapitza[3], at the boundary between liquid He II and a solid surface which is emitting heat.

Recently, in a work by Khalatnikov[4], an explanation has been given of the fact of the presence of a thermal resistance near a heat radiating wall in contact with He II. In the work, which represents a significant step forward, it is shown that at a sufficient distance from the λ-point, heat is radiated in He II principally at the expense of the vibrations of the heated surface. For such a mechanism, Khalatnikov obtained the expression

$$\Delta T = w / aT^3, \tag{1}$$

where ΔT is the temperature difference between the heat radiating solid surface and the liquid He II in contact with it, w is the density of heat flow, T is the absolute temperature and a is some constant. It is evident from Eq. (1) that at constant thermal stress, the temperature difference ΔT decreases monotonically with increase of the temperature of the He II.

It is of interest to compare the results of this theory with experimental data available to us that we had obtained in 1948.

2. Experiments on the investigation of the behavior of He II near a heat emitting wall were set up in the following way: a constantan wire K and a copper wire Cu (diameter of each, 100 μ) were stretched parallel to one another on the glass frame R (Fig. 1). Each wire was held on the frame with the aid of a spring P. Both wires were coated with a layer of lacquer which provided electrical insulation. The constantan and copper were connected in series with a battery. Hence, the magnetic field on their surfaces was always the same. The constantan wire also servedas a heater. On the copper and constantan were wound the wires B_i and B_k of phosphor bronze, diameter 40 μ. These served as resistance thermometers. One of them was intended to measure the temperature near the heater, the other as a control thermometer which was balanced with the first by means of a potentiometric arrangement.

The leads of the bronze thermometers were connected in parallel, so that the measuring currents in them could be chosen so that the decrease in the voltage on the two thermometers was the same. The connection of the current and voltage leads of the thermometers to the potentiometer is clear from Fig. 1.

Because of the very nature of the arrangement of the thermometer relative to the constantan heater in our experiments, we measured not the actual

[1] L. D. Landau, J. Exper. Theoret. Phys. USSR 11, 592 (1941); 14, 112 (1944).

[2] W. H. Keesom, A. P. Keesom and B. F. Saris, Physica 5, 281 (1938); W. H. Keesom and B. F. Saris, Physica 7, 241 (1940); J. Allen, R. Peierls and M. Zaki Uddin, Nature 140, 62 (1937).

[3] P. L. Kapitza, J. Exper. Theoret. Phys. USSR 11, 1 (1941).

[4] I. M. Khalatnikov, J. Exper. Theoret. Phys. USSR 22, 687 (1952).

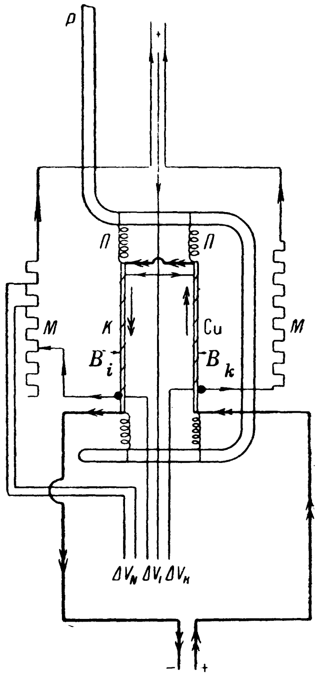

FIG. 1. Arrangement of the heater K, the copper conductor Cu and bronze thermometers B_i and B_k. The direction of the electric current through the current leads of the thermometers is shown by arrows. The directions of the electric current through the constantan heater and the copper wire are shown by the double arrows. R = glass frame, P = spring, M = plug in resistor box, ΔV_N = potential drop across standard resistance, ΔV_i, that on bronze thermometer B_i, ΔV_k, that on control bronze thermometer B_k; ΔV_N, ΔV_i, ΔV_k are connected to the potentiometer by appropriate leads.

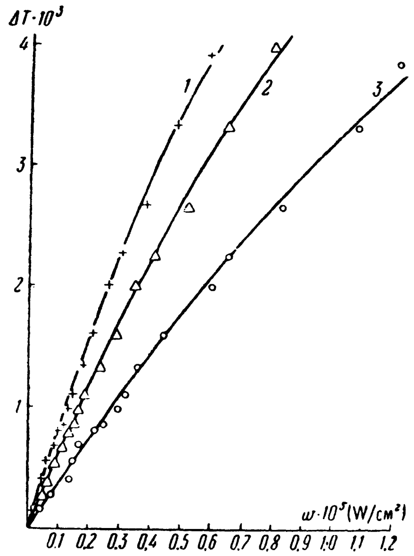

FIG. 2. Dependence on thermal flux of the drop in temperature near the heater. *1.* 1.60^0_5 K; *2.* 1.69°_6 K; *3.* 1.89°_1 K.

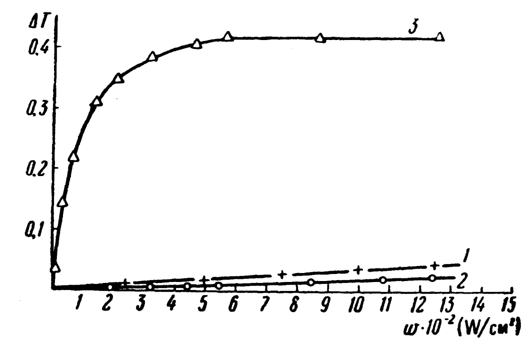

FIG. 3. Dependence on thermal flux at 8 atmospheres of the temperature drop near the heater. *1.* 1.63° K (He II); *2.* 2.045° K (He II); *3.* 2.175° K (He I).

rise in temperature of the heater above the temperature of the heating bath, but only the lower limit of the original temperature difference. It is therefore impossible to compare the results of Khalatnikov's theory directly with our experimental measurements. However, some general regularities, whose character does not depend on the particular form of the experiment, allow comparison.

3. The results of the measurement on the fall in temperature that takes place in the He II near the heated surface as a function of the thermal flux are shown in Fig. 2. It is evident from the graph that the dependence of ΔT on w--the heat flux--is by no means linear. It corresponds to the theoretical dependence only for relatively small flux.

Measurements carried out at a pressure of 8 atmospheres (Fig. 3) show that the thermal resistance under these conditions is changed by a factor of 10-20 relative to the thermal resistance observed at the saturated vapor pressure. It should also be noted that the dependence $\Delta T = f(w)$, obtained at $p = 8$ atm only begins to deviate from linearity at heatings that are at least 500 times larger than is observed in the case of saturated vapor pressure.

It can be seen from Fig. 3 that the character of the dependence $\Delta T = f(w)$ for He I is completely different from the character of the corresponding dependence obtained for He II*.

* Apparatus for the investigation of the properties of liquid helium under high pressures was put at our disposal by V. P. Peshkov and K. N. Zinov'ev, to whom we acknowledge our gratitude.

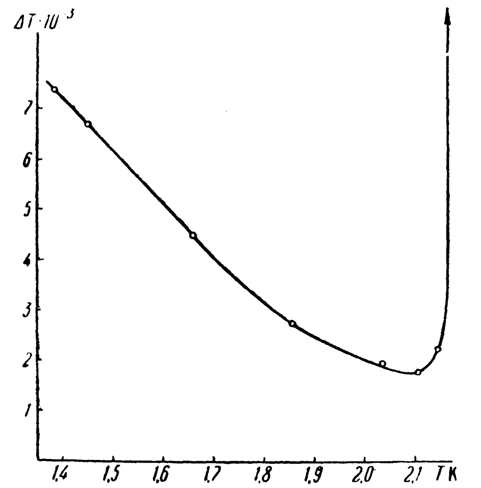

FIG. 4. Dependence on temperature of the thermal resistance for constant thermal flux at the heater.

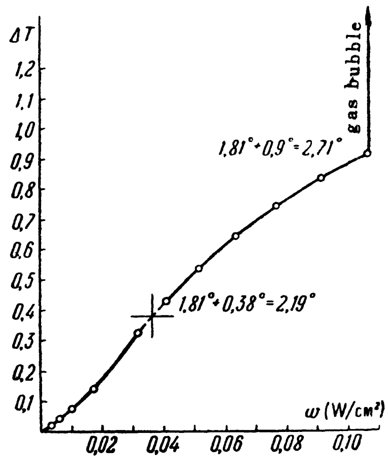

FIG. 5. Dependence of the thermal resistance on the thermal flux for the case of a capillary placed in a slit.

Investigation of the dependence $\Delta T = f(T)$ for constant heat flux w (in our case, $w = 0.836 \times 10^{-3}$ watt/cm^2) showed the presence of a minimum thermal resistance (maximum thermal conduction) at a temperature of 2.1° K. This minimum of the thermal resistance was not predicted by the theories which are limited to the treatment of the phenomenon only under the condition of being sufficiently far from the λ-point.

The experimental curve $\Delta T = f(T)$ which we obtained in the temperature interval from 1.6 to 2.1° K is satisfactorily fitted (Fig. 4) by the function

$$\Delta T = \mathrm{const}/T^4. \tag{2}$$

In this case the experimental points lie on the curve of Eq. (2) with an accuracy to within ±2%. For temperatures below 1.6° K, the experimental curve (in agreement with theory) is better fitted by the equation

$$\Delta T = \mathrm{const}/T^3. \tag{1'}$$

Since the value of the coefficient a in Eq. (1) was computed by Khalatnikov only for platinum, comparison of the computed values from experiment and theory is not possible.

4. Consideration of the curve of Fig. 4 shows that, close to the λ-point (temperature of the helium bath at 2.17° K), the resistance of the phosphor bronze increases sharply. This corresponds to a temperature which appreciably exceeds the λ-point. This indicates that, at a bath temperature of 2.17° K, a heat flux of 8.36×10^{-4} watt/cm^2 is quite sufficient to produce superheating by 0.016 °, which results in the transition through the λ-point, and in the production of a stable gas bubble.

The problem then arises as to the superheating which can be achieved in a layer of the He II which is adjacent to the heater.

Investigation of this phenomenon was carried out by means of a glass capillary, on whose surface a thin layer of platinum was applied by cathode sputtering. The film had a resistance of 780 ohms and served as a heater. The external diameter of the capillary was 0.317 mm, the diameter of the internal opening, 0.140 mm. In other experiments, a constantan wire, which had been coated on the outside of a capillary of approximately the same dimensions, served as a heater. To eliminate the effect of the magnetic field of the current in the constantan heater on the reading of the bronze thermometer, the constantan was wound in bifilar fashion with a copper wire of the same diameter.

The platinum capillary of the capillary with constantan heater was clamped between two plane parallel plates. A resistance thermometer was stretched across the capillary. Thus assembled, the apparatus was submerged in the He II. At the time of the experiment, the power W at the heater, and the corresponding rise in resistance ΔR were measured.

As in the much earlier experiments of Strelkov[5], visual observation was carried on through a slit made of plane parallel glasses, which enabled us to fix precisely the moment of the origin of the gas bubble, and also to determine the maximum

[5] P. G. Strelkov, J. Exper. Theoret. Phys. USSR **10**, 1225 (1940).

possible heating of the liquid helium near the capillary.

5. The heat flux through 1 cm^2 of transverse cross section of the slit is plotted along the abscissa in Fig. 5:

$$w = W / dl, \tag{3}$$

where d and l are the diameter and length of the capillary.

It is evident from the curve at 1.81° K that the gas bubble arises at temperatures which greatly exceed the λ-temperature. Thus, the superheatings which are obtained in He II in contact with a sufficiently powerful heater, can reach enormous size, of the order of 1° and beyond. Moreover, in irradiation by a heater of large heat flux, the heater, as can be seen from the curve of Fig. 5, is surrounded (even at rather low temperatures) by a thin layer of He I, rather than by He II.

The character of the dependence $\Delta T = f(w)$ for small values of w in the case of a capillary clamped between two parallel surfaces is completely determined by the law of heat transmission through a slit[6], in which grad T is taken with the heat flow, with viscosity, temperature and other quantities determined by the state of He II.

The heat flux for which the gas bubble arises varies considerably in dependence on the depth of the submerged apparatus beneath the surface of the liquid helium.

It should be noted that, at a temperature of 1.8° K, with heating to 2.186° K of a thin layer of He II which surrounds the capillary, we communicate to the normal and superfluid components relative velocities of the order of 20-30 cm/sec. Of course, these velocities are known to lie in the critical region.

Along with the experiments just described, we have set up experiments for the purpose of establishing the presence of a temperature discontinuity on the boundary of the He II and a solid wall emanating cold. However, such discontinuities have not been obtained.

CONCLUSIONS

1. The behavior of He II near a heat radiating solid surface has been investigated. It is shown that under these conditions a significant thermal resistance arises in a thin layer of He II.

2. The dependence of the temperature drop on the heat flux has been found. For a heater freely in contact with He II, this dependence is linear only for small heat fluxes.

3. The thermal resistance near a heat radiating surface is significantly decreased at elevated pressures.

4. It is established that superheating reaching 1° is possible in the neighborhood of a heat emitting surface in He II. For large heat fluxes, such superheatings are possible even at the temperature of a helium bath lying much lower than the λ-point. These lead to the formation of a thin layer of He I around the heater. Meanwhile, even at a very slight distance from the surface of the heater it has not been possible to find any sort of temperature gradient in the He II.

[6] E. L. Andronikashvili, J. Exper. Theoret. Phys. USSR **19**, 535 (1949).

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