KINETICS OF THE DESTRUCTION OF SUPERFLUIDITY IN HELIUM

V. P. PESHKOV and V. K. TKACHENKO

Institute for Physics Problems, Academy of Sciences U.S.S.R.

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A study has been made of the kinetics of the destruction of superfluidity during heat transport along a helium-filled capillary 1.4 mm in diameter and 8 m long. For T = 1.34°K and superfluid component velocities exceeding the critical value by 1.04 — 1.6 times, turbulence fronts propagating at a constant velocity were observed, moving from the hot end to the cold at a rate of from 1 to 3.7 mm/sec, and from the cold end to the hot at from 0.1 to 2.5 mm/sec.

THE question of the nature of the destruction of superfluidity—of critical velocities—has remained up to now the least understood of all the properties of helium II. It has already been established by Kapitza[4] that critical velocities decrease as the dimensions of the passage increase, while Landau[2] has proposed a criterion for the destruction of superfluidity having the form $v_s > \epsilon/p$, where v_s is the superfluid component velocity, and ϵ is the energy and p the momentum of the excitation being created. The velocity must, however, according to this expression, be greater than the velocity of sound (~ 230 m/sec) for generation of a phonon, and greater than 70 m/sec for a roton, while the velocities observed for large capillaries are inversely proportional to their diameter and for d = 1.4 mm equal 0.11 cm/sec. The suggestion was first advanced by Onsager[3] that the cause of the destruction of superfluid motion lies in the generation of vortex structures. This viewpoint has since been confirmed and further developed.[4-7] The kinetics of the destruction of superfluidity have been investigated by Mendelssohn[8] who found a linear increase with time in the temperature difference between the ends of a long (1.5 m) capillary 1 mm in diameter with heat supplied to one end. He explained this as due to the movement of turbulence fronts, and observed velocities that were integral multiples of 4 cm/min. At the Institute for Physics Problems, V. Markov and Tkachenko have performed experiments to investigate the kinetics of the destruction of superfluidity, the results derived from which are presented in this paper.

The experiments were conducted in the apparatus represented in Fig. 1. A German-silver capillary 1 of 1.4 mm inside diameter and 800

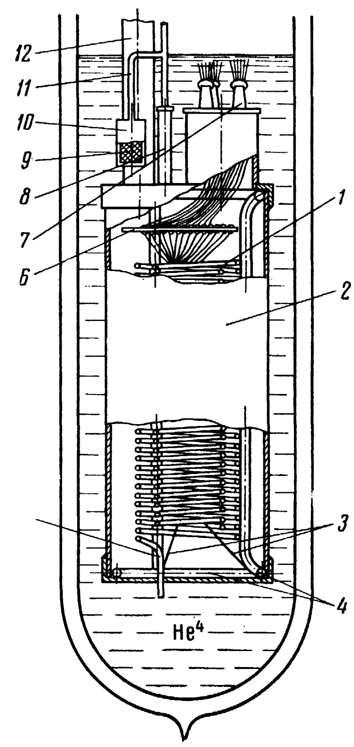

FIG. 1. Diagram of the apparatus (explanation in text).

cm long was located inside a vacuum jacket 2, 70 mm in diameter and 170 mm long. The capillary was attached by means of taut cotton threads to a framework 4 of glass rods. One end 5 of the capillary communicated with the helium bath. The other end was sealed off, and onto it was wound a heater (2580 Ω) of 50 μ diameter constantan. Twelve thermometers of 40 μ phosphor-bronze were also wound onto the capillary. One of these, R_1, was at a distance of 100 mm from the end of the capillary, another, R_{12}, 30 mm from the heater, and the remaining ten at approximately equal intervals between R_1 and R_{12}. The average resistance of the thermometers, at the temperatures of 1.3—1.4° K at which most of the runs were carried out, amounted to ~15—20 Ω. The thermometer leads were of 60 μ tinned constantan, soldered to a terminal strip 6. The leads were carried out of the vacuum jacket through a ferrochrome-glass seal 7. The vacuum jacket was evacuated at room temperature and then filled with 2 mm Hg of exchange gas (helium) through the tube 8. As the apparatus cooled to helium temperatures the exchange gas was gradually adsorbed by activated charcoal 9 placed in a bulb 10, via a tube 11 of 1.4 mm inside diameter and 100 mm long, and after a short while (~ 30 min) a hard vacuum was achieved within the jacket. By this time the capillary 1 had cooled to the temperature of the helium bath. The apparatus was supported from the Dewar cover by means of a tube 12.

Even with a capillary of this length (800 cm) the temperature difference between the ends was only $\sim 3 \times 10^{-3}$ deg for a thermal current near the critical value. The magnitude of the measuring current in the thermometers (0.2 ma) was limited by the power dissipated through them, which must be small (1—2%) as compared with the power liberated in the heater. The change in the voltage across the thermometers as the thermal current was applied was therefore only 15 mv or less. Since the thermal processes in the capillary require a long time to develop (up to 1 hour), it was necessary to maintain the temperature of the helium bath constant to 10^{-5} deg. The temperature stabilizer described by Vetchinkin[9] was employed for this purpose.

Measurements of the variation with time of the thermometer temperatures with a thermal current flowing in the capillary were performed automatically (see measuring circuit in Fig. 2). The voltage across each of two fixed thermometers (R_7 and R_{11} in the circuit diagram) in the absence of a thermal current was compensated with the aid of storage batteries and potential dividers. As the thermal current was turned on the voltage drop across the thermometers increased as a result of the rise in temperature, and the signals emerging from the compensating circuits were amplified by F 116/1 photoamplifiers and applied to the input of an ÉPP 09-M1 multi-channel automatic potentiometer. The voltage across any desired third thermometer, connected via the switch S, was compensated by a PMS-48 potentiometer and was also recorded by the ÉPP 09-M1. The amplifier gains were so chosen as to give equal deflections on the automatic potentiometer for equal temperature changes in the thermometers.

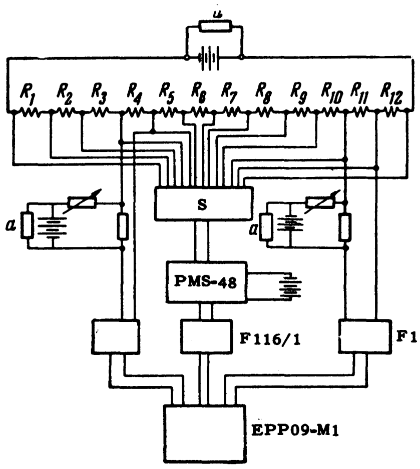

FIG. 2. Measuring circuit.

All four storage batteries in the circuit were maintained at the same temperature. A current of ~ 10 ma, adjusted with the aid of the resistances a to the same value as that in the potentiometer, flowed continuously in each of them. As a result, the possible variation with time in the emf's of the batteries was held to a minimum, and was identical for all four.

For a thermal current slightly exceeding the critical value, the way in which the thermal regime is established is found to depend strongly upon the previous history of the helium. When a supercritical heat transport regime had been set up in the capillary shortly (up to 10 min) prior to turning on the thermal current, the process usually occurred relatively rapidly, requiring no longer than 10 min. When, on the other hand, the helium had remained quiescent for some time—at least 20 min—then, as a rule, the establishment of the thermal regime occupied a prolonged interval—up to 1 hour. In this latter case, the process showed a number of characteristic features which made it possible to understand what was taking place.

In Fig. 3 is shown the variation with time of the thermometer readings for a typical slow proc-

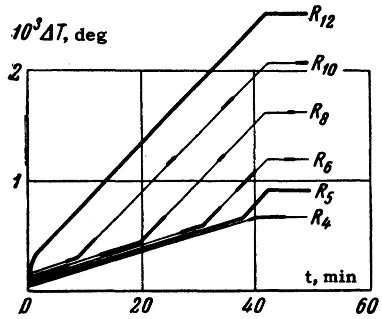

FIG. 3. Time dependence of thermometer temperatures for a thermal current in quiescent helium ($W = 4.4 \times 10^{-2}$ w/cm², $T = 1.34$°K).

ess of establishing the thermal regime ($T = 1.34°K$ and $W = 1.19 W_{cr}$). The readings of the hottest thermometer, R_{12}, and an intermediate one, R_5, were recorded continuously. The thermometers were numbered in order from the cold to the warm end of the capillary. The third input of the recorder was switched from one intermediate thermometer to another, as indicated by the heavy line segments in Fig. 3. The linearity of the rise in temperature with time over well-defined intervals, and the occurrence of quite sharp changes in the heating rate, are immediately evident. It can easily be seen that the breaks in the temperature vs time curves take place at the various thermometers in a definite sequence: R_{10}, R_8, R_6, R_5. This testifies to the fact that a turbulence front increasing the thermal resistance of the helium propagates at a constant velocity from the hot end of the capillary. The velocity of advance of the turbulence front, v_H, can be computed from the known times corresponding to the breaks in the curves for the various thermometers, and the positions of the thermometers along the capillary. In the case cited, $v_H = 2.2 \pm 0.1$ mm/sec. A similar pattern, it was found, is followed at the cold end: a turbulence front also advances from this end, with a propagation velocity $v_C = 1 \pm 0.03$ mm/sec.

The velocity of the fronts is shown as a function of thermal current density ($T = 1.34°K$) in Fig. 4. We found the critical thermal flux to be $3.7 \times 10^{-2} \pm 0.1 \times 10^{-2}$ w/cm², from measurements of the temperature gradient in the capillary. The corresponding velocities are $v_n = 1.85$ cm/sec and $v_s = 0.114$ cm/sec. It can easily be seen that for this current density the velocities v_H and v_C fall nearly to zero. We note that even for a thermal flux of 6×10^{-2} w/cm² —somewhat more than 1.5 times the critical value—turbulence is not generated within the capillary. The turbulence originates only at the ends of the capillary, from which it propagates at a well-defined velocity but does not completely fill the capillary. The temperature difference which develops almost at once between thermometers when the current is turned on, evident in the initial portions of the curves in Fig. 3, is associated with Poiseuille flow of the normal component of the helium. For still higher thermal currents the generation of turbulence within the capillary becomes possible, but is of a random character.

Turbulence within the capillary can develop even for only slightly supercritical fluxes if insufficient time has been allowed for the helium to become quiet. In Fig. 5 a run is recorded in which, in addition to the fronts advancing from the ends of the capillary, there was a source of turbulence within the capillary, in the vicinity of thermometer no. 8, from which turbulence fronts also moved outward. Figure 6 illustrates the pattern of propagation of the fronts. At each point in time t the portion of the capillary corresponding to the region showing steep temperature gradients in Fig. 6 was enveloped in turbulence. The break in the curve R_{11} at the point a corresponds to the passage through R_{11} of the front advancing from the hot end; the break b corresponds to the meeting between this front and the front advancing from R_8. At the point c the front proceeding from the center towards the cold end has passed through R_5, and at d it has encountered the front moving from the cold end, with which the process of es-

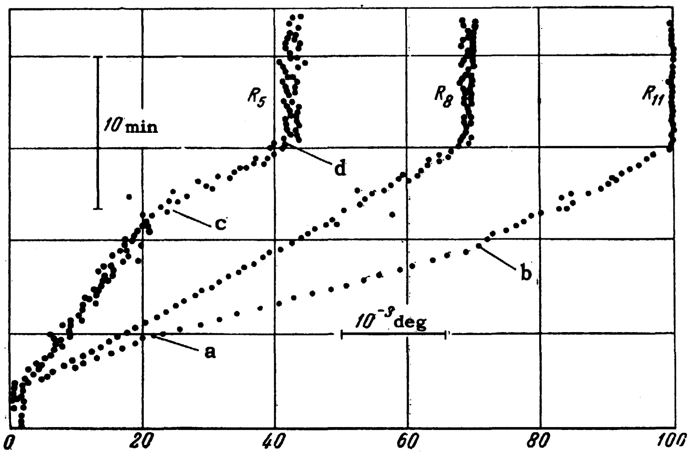

FIG. 5. Diagram of temperature readings as recorded by an EPP09-M1 for fronts propagating from ends and center of capillary.

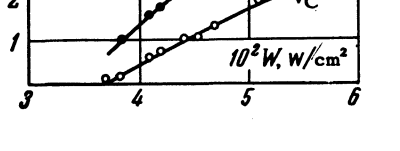

FIG. 4. Dependence of front velocity upon thermal current density (T = 1.34°K).

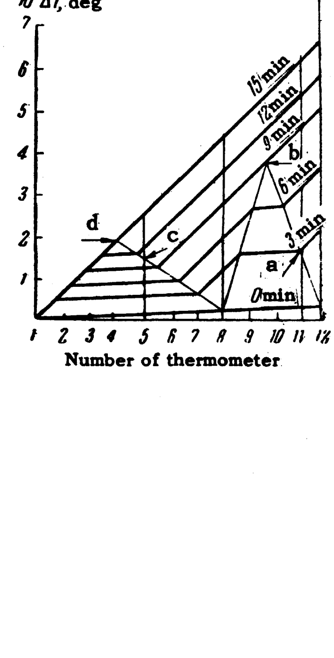

FIG. 6. Temperature distribution, relative to bath temperature, along the capillary. The spacing of the thermometers along the capillary is indicated on the x axis.

tablishing the thermal regime has come to an end. In other runs, central fronts arose at other points; for example, near R_6 or R_9.

The process of establishment of the thermal regime in quiescent helium in the case of a large thermal flux is represented in Fig. 7. The abundance of internal fronts makes it impossible to understand the process in detail.

The dependence of the temperature gradient upon the magnitude of the thermal flux is shown in Fig. 8. It is evident that the experimental data in the supercritical region are well represented by the formula

$$\mathrm{grad}\, T = (A\rho_n/\rho_s^3 S^4 T^3)(W^3 - W_0^3),$$

where $W_0 = 2.25 \times 10^{-2} \pm 7\%$ w/cm², and A = 32 ± 5% cm-sec/g. The value of the constant A agrees with the data of Vinen.[4]

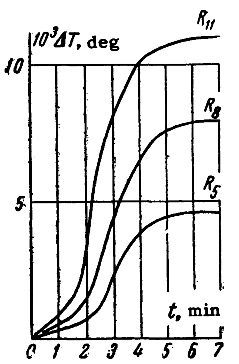

FIG. 7. Process of establishing regime for a large thermal flux (W = 7.05 w/cm², T = 1.34°K).

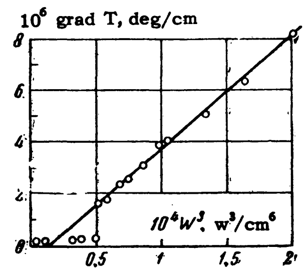

FIG. 8. Dependence of final temperature gradient in capillary upon thermal flux.

The experiments described above permit the following hypotheses to be advanced regarding the pattern of the destruction of superfluidity in broad capillaries. It has been established that even well beyond the critical condition (by 1.5 times) the development of sources of turbulence within the capillary is strongly opposed; if, however, such a source does appear, then turbulence fronts propagate from it in both directions. Since the force of interaction between the normal and superfluid components is proportional to $(v_s - v_n)^3$, the profile of v_s in the regime established will, as has already been pointed out[10,7] be closely parabolic, in order that the difference $v_n - v_s$ remain constant across the capillary. Hence at low temperatures, for which $v_n \gg v_s$, v_s will be in the same direction as v_n at the center of the capillary, and in the opposite direction near its periphery.

Thus the propagation of turbulence fronts may be represented in terms of the formation at some point of vortex rings, which, interacting with one another near the center of the capillary, slip past each other and move in the direction of the thermal current. Vortex rings having circulations of the same sign situated near the wall move in the opposite direction, also playing, as it were, a game of leap-frog. Vortices of large radius must accelerate their motion as they approach the wall, but in so doing they rapidly lose energy, decreasing their length—i.e., radius—and slowing their movement. This last circumstance leads to the situation that for conditions only slightly beyond criticality the velocity of turbulence front advancing from the cold to the hot end is much lower than the velocity of the front moving in the opposite direction. It is clear that this pattern is strongly distorted by the thermal motion, converting regular into chaotic turbulence; the general tendency, however, remains.

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