NOTATION

x and r, axial and radial coordinates, m; u and v, axial and radial velocities, m/sec; q, thermal flux density, W/m^2; q_V, heat source power, W/m^3; t, temperature, °C; $\bar{t}_1$ and $\bar{t}_2$, mean-volume temperatures of liquid in tube and ring channel, °C; c, specific heat of liquid, J/kg•deg; ρ, liquid density, kg/m^3; λ, thermal-conductivity coefficient, W/m•deg; λ_t, turbulent thermal-conductivity coefficient, W/m•deg; λ_e, thermal conductivity of permeable wall, W/m•deg; Π, porosity; c_1, c_2, constants; $Nu = \alpha d/\lambda$, Nusselt number; $Re = ud/\nu$, Reynolds number; $Re_{fil} = v_1 d/\nu$, filtration parameter; $Pr = \nu/a$, Prandtl number. Indices: 1, inner surface of cable; 2, outer surface; 3, surface of impermeable shell.

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HELIUM TEMPERATURE FLUCTUATIONS IN VARIOUS PHASES

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UDC 536.248.2

Studies of helium temperature fluctuations in various phases are performed in liquid He I and He II and in gaseous He.

Boiling of liquid helium leads to the appearance of temperature fluctuations in the helium bath, which are transformed to noise in cryogenic measurement devices and limit the threshold sensitivity of the latter. Noise of this type appears most strongly in devices in which the temperature dependence of resistance in the region of the superconductive transition is employed, for example, in superconductive bolometers [1, 2] and cryotron amplifiers [3], and also in semiconductor bolometers [4] and photoresistors [5]. Fluctuations of this sort also appear in studies of noise in superconductors [6]. In the present study helium temperature fluctuations in various phases will be studied.

Experimental Technique. Measurements were performed by superconductive temperature sensors employing Pb—Sn films deposited on 0.3-mm-thick sapphire disks. Film thickness was 1000 Å, with sensitive element dimensions of 12 × 12 mm, $R_{\square}$(normal) = 1-2 Ω. After scribing the resistance at the operating point R = 4.5 Ω. The superconductive transition could be accomplished in the temperature range 1.8-4.5°K with a magnetic field perpendicular to the film. The field was generated by a superconductive solenoid. Maximum sensor sensitivity reached 2 V/°K ($T = 2.08$°K, $\Delta R/\Delta T = 20$ Ω/°K, $I = 100$ mA).

Measurements were performed in a cryostat without nitrogen cooling and a helium reservoir volume of 1.5 liter [7]. The sensors were installed parallel to the reservoir bottom at a distance of 30 mm from the bottom.

The measurement apparatus consisted of the temperature sensor connected to a circuit with load resistor, low noise amplifier, and spectrum analyzer for the range 1-400 Hz. Using a step-up transformer at the input to the circuit, threshold sensitivity at the lowest frequency reached $1.5 \cdot 10^{-8}$ °K•Hz$^{-1/2}$.

Experimental Results. Figure 1 presents spectra of helium temperature fluctuations in various phases: liquid He I and He II, and gaseous He. Most measurements were performed

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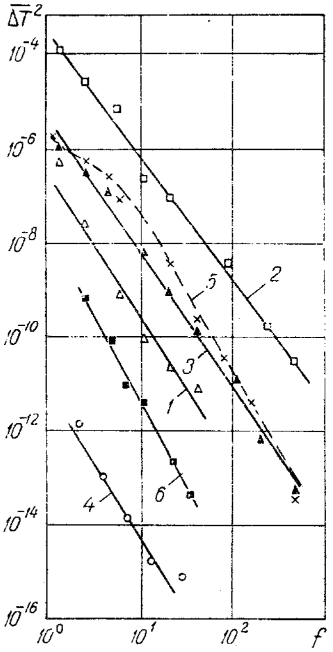

Fig. 1. Helium temperature fluctuation spectra: 1) liquid He I, T = 2.2°K, I = 2 mA, P = $1.2 \cdot 10^{-5}$ W•cm^{-2}; 2) liquid He I, T = 2.2°K, I = 80 mA, P = $2 \cdot 10^{-2}$ W•cm^{-2}; 3) liquid He I, T = 3.9°K, I = 80 mA, P = $2 \cdot 10^{-2}$ W•cm^{-2}; 4) liquid He II, T = 2.085°K, I = 80 mA, P = $2 \cdot 10^{-2}$ W•cm^{-2}; 5) gaseous He, T = 2.085°K, I = 10 mA, P = $3.0 \cdot 10^{-4}$ W•cm^{-2}; 6) liquid He I, T = 3.7°K, P = 10^{-7} W•cm^{-2} [8]. $\overline{\Delta T^2}$, °K²/Hz; f, Hz.

near the λ-point. Temperature fluctuations in gaseous helium were measured when the level of superfluid liquid helium in the cryostat was reduced to a point where the sensor was located in helium vapor. The observed spectra show a dependence $\overline{\Delta T^2} \sim 1/f^{\alpha}$, where $\alpha \simeq 3$ in the majority of regimes studied. It is interesting that fluctuations also occurred in the superfluid helium, with a spectrum the same as in He I.

In measuring the dependence of sensor noise voltage on bias current, it was established that for I < 5 mA, $\sqrt{\overline{\Delta U^2}} \sim I$, while for I > 5 mA, $\sqrt{\overline{\Delta U^2}} \sim I^2$. This result indicates that beginning with some value of power density dissipated in the sensor (in the given case P = $8 \cdot 10^{-5}$ W•cm^{-2}) additional temperature fluctuations occurred on the sensor surface. This is also obvious from Fig. 1, where spectrum 1 corresponds to P = $1.2 \cdot 10^{-5}$ W•cm^{-2}, and spectrum 4 to P = $2 \cdot 10^{-2}$ W•cm^{-2}. An analogous increase in fluctuations was observed when light from an incandescent lamp was directed on the sensor surface. In measuring the dependence of fluctuations on sensor resistance at constant current the function $\sqrt{\overline{\Delta T^2}} = f(P)$ was obtained, close to linear in the range of Joulean power $(3.5\text{-}14) \cdot 10^{-3}$ W•cm^{-2}. We note that in He II temperature fluctuations were independent of the Joulean power value up to P = $2 \cdot 10^{-2}$ W•cm^{-2}.

It is evident from Fig. 1 that upon transition of liquid helium into the superfluid state temperature fluctuations ($\sqrt{\overline{\Delta T^2}}$) decreased up to 200 times (spectra 1 and 6). The increase in temperature fluctuation in gaseous helium (spectrum 5) as compared to liquid He I (spectrum 1) was unexpected.

Analyzing the results obtained, we conclude that the temperature fluctuations in liquid He I are connected with bubble boiling of helium on the reservoir walls and on the sensor itself. At low bias currents the sensor records the boiling in the reservoir itself. This process corresponds to linear dependence of the sensor noise signal on current, as observed here and in [8]. At power dissipations >10^{-4} W•cm^{-2} temperature fluctuations increase due to helium boiling on the film itself. A similar boiling threshold was observed for vanadium foil in [6].

The cause of temperature fluctuations in liquid He II, in which bubble boiling does not occur, remains unclear. It is possible that they are caused by temperature fluctuations in

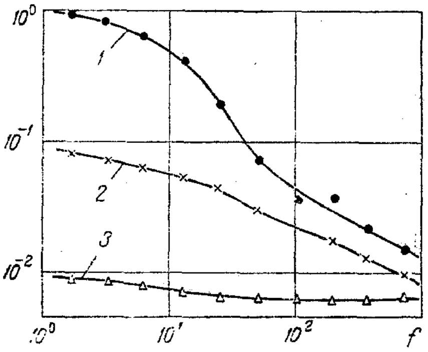

Fig. 2

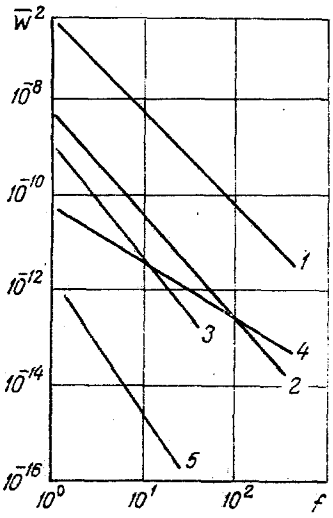

Fig. 3

Fig. 2. Sensor sensitivity (rel. units) versus frequency (f, Hz): 1) gaseous helium, T = 2.085°K, I = 10 mA; 2) liquid He I, T = 2.375°K, I = 10 mA; 3) liquid He II, T = 2.085°K, I = 10 mA.

Fig. 3. Power fluctuation spectra in helium: 1) liquid He I, T = 2.2°K, I = 80 mA; 2) liquid He I, T = 2.2°K, I = 10 mA; 3) liquid He I, T = 2.2°K, I = 2 mA; 4) gaseous He, T = 2.085°K, I = 10 mA; 5) liquid He II, T = 2.085°K, I = 80 mA; $\overline{W}^2$, W^2/Hz.

the gaseous He above the liquid He II surface, which, as the measurements have shown, are significant. It should be noted that temperature fluctuations in He II were not reported by [4, 6].

In interpreting the spectra obtained here it is necessary to consider the frequency dependence of sensor sensitivity. Figure 2 shows the measured frequency characteristics of the sensor in a helium environment in various phases. Cyclical heating of the sensor was accomplished by a modulated radiation flux from an incandescent lamp. In liquid He II in the range 1.6-800 Hz sensitivity was independent of frequency. Upon transition of liquid helium to the normal state sensitivity increased abruptly by a factor of 10 at the lowest frequency. In gaseous He the sensitivity increased even more and the frequency dependence became more complex. The observed frequency properties of the sensors indicate a significant change in the mechanism of heat transfer from the sensitive film upon change in the phase state of the surrounding helium.

The sensor heat-transfer coefficient G ($W \cdot {}^\circ K^{-1}$) was determined experimentally with a heater film deposited on the opposite side of the substrate. Experimental results were as follows: G (HE II) = 3.3 $W \cdot {}^\circ K^{-1}$, G (He I) = 0.3 $W \cdot {}^\circ K^{-1}$, G (gaseous He) = 0.03 $W \cdot {}^\circ K^{-1}$. It follows from these measurements that the Kapitsa thermal resistance at the film—He II boundary at T = 2.085°K is equal to 0.44 ${}^\circ K \cdot cm^2 W^{-1}$. For comparison, we note that in [9] for an Sn—He II boundary R_T = 0.6${}^\circ K \cdot cm^2 W^{-1}$ at T = 2.08°K was obtained.

If one considers the sensor as a device measuring thermal flux power in the helium, it is convenient to transform the temperature fluctuations into power fluctuations:

$$\Delta\overline{W}^2(f) = \Delta\overline{T}^2(f)\,G^2(f). \qquad (1)$$

Figure 3 shows the results of such a transformation, which was performed with consideration of the measured heat-transfer coefficient and frequency characteristic. These graphs offer a picture of the intensity and frequency distribution of thermal power fluctuations which occur in helium in various phases. It is evident, for example, that the power fluctuation spectrum in gaseous helium has a smoother dependence on frequency than the temperature fluctuation spectrum. Here the dependence is close to 1/f. Such a change in the spectrum is explained by the frequency characteristic of the sensor. The lowest power fluctuations were observed in superfluid He; for example, for f = 10 Hz they comprise $\sqrt{\Delta\overline{W}^2} = 7 \cdot 10^{-8}$ W•Hz$^{-1/2}$. For He I at $P = 2 \cdot 10^{-2}$ W•cm^{-2}, where helium boils on the sensor itself, fluctuations increase to $\sqrt{\Delta\overline{W}^2} = 8 \cdot 10^{-5}$ W•Hz$^{-1/2}$.

NOTATION

$R_\square$, resistance of square; R, resistance of temperature sensor; $\Delta R/\Delta T$, slope; I, bias current; P, power dissipation density; f, frequency; T, temperature; $\Delta\overline{T}^2$, mean square of temperature fluctuations; $\sqrt{\Delta\overline{T}^2}$, effective value of temperature fluctuations; $\sqrt{\Delta\overline{U}^2}$, effective value of noise voltage; $\Delta\overline{W}^2$, mean square power fluctuation; $\sqrt{\Delta\overline{W}^2}$, effective value of power fluctuation; G, heat transfer coefficient; R_T, thermal resistance.

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DYNAMIC DISLODGEMENT OF A VISCOPLASTIC LIQUID FILM

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UDC 532.135

A solution is obtained for the problem of shaking a viscoplastic film of limiting thickness off a flat or cylindrical surface moving in accordance with an exponential law.

A film of viscoplastic liquid on a vertical surface is characterized by the limiting static value of the thickness at which the film still will not flow under the influence of gravity. One method of dislodging such a film is to vibrate the wall. It is used, for example, in vibratory filters to remove the residue.

The limiting thickness of the film R_h is determined from the balance of friction and gravity forces. For a vertical cylindrical body

$$R_h = R\left(1 \pm \frac{2\tau_0}{\rho g R}\right)^{\frac{1}{2}}, \tag{1}$$

where R is the cylinder radius; τ_0 is the yield limit; ρ is density; g is the acceleration of gravity; the plus sign is taken for a film on the outside and the minus sign for a film on the inside surface of the cylinder.

Let us first consider the case $(\tau_0/\rho g R) \ll 1$. Then the cylindrical surface may be regarded as plane. We assume that the wall, coated with a film of limiting thickness, is moving in the direction of the gravity force at a constant velocity U_0 and at the initial instant of time $(t' = 0)$ begins to decelerate, its velocity varying in accordance with the law

$$U = U_0 f(t'),$$

where $f(0) = 1$. As a result, two flow zones develop in the film: In the wall region, where the stresses exceed τ_0, we have viscoplastic flow; elsewhere the stresses are less than τ_0

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