

ever, for relative estimates over a small interval of temperatures and pressures we can let $L_{11} = \text{const}$. For water, the required experimental data near the critical point are given in [4, 3]. We choose three values for the temperature: $T_1 = 365^\circ \text{C}$, $T_2 = 372^\circ \text{C}$, and $T_3 = 373^\circ \text{C}$ ($T_{\text{cr}} = 374.15^\circ \text{C}$). From (14) we obtain $\tau_3/\tau_2 = 2.8$, $\tau_3/\tau_1 = 27$, without allowing for differences in the volume of the vapor phase. From [3], we have $\tau_3 \approx 1.5 \text{ hr}$; therefore, $\tau_1 \approx 3 \text{ min}$. The last quantity is less than the time required to verify that the temperature is constant and to measure the pressure with a piston manometer.

In this type of experiment it is quite important that the substance be pure. Impurities not only change the slope of the condensation line but, near the critical point, they will also result in a slow drop in pressure to the equilibrium value with a different and probably much greater relaxation time than for the pure substance. This is due to very strong retardation in the diffusion impurity molecule near the critical point [5, 6].

At low pressures, where (1) is valid, we can find L_{11} and estimate the relaxation time (14). Allowing for the fact that $i = J_1/m$ and equating the flows in (1) and (7), we obtain

$$L_{11} = \alpha \left(\frac{mT}{2\pi k} \right)^{1/2} \rho^n. \quad (15)$$

For water at 100°C we have $\tau = 1.25 \cdot 10^{-2} \text{ sec}$ for $\alpha = 0.5$ and $V^n = 100 \text{ cm}^3$.

NOTATION

i is the molecular evaporation rate; p is the pressure; α is the condensation coefficient; m is the mass of a molecule; k is the Boltzmann constant; M is the

mass of the substance; V is the volume; v is the specific volume; ρ is the density; T is the temperature; U is the internal energy; μ is the chemical potential per unit mass; J_1 and J_2 are the mass and energy flows; $\tilde{U}^n = U^n + [(p^n/T^n - p^1/T^1)/(1/T^n - 1/T^1)] V^n$; H is the enthalpy; $h = H/M$; $l = h^n - h^1$ is the specific heat of the phase transition; $\Delta T = T - T_S$; $\Delta p = p - p_S$; $\gamma = -v(\partial p/\partial v)_T$ is the reciprocal of isothermic compressibility (the elasticity coefficient); t is the time; τ is the relaxation time. Quantities with one prime pertain to a liquid and those with double primes to a vapor. Quantities with the subscript s refer to the saturation line. Differentiation with respect to time is denoted by a dot.

REFERENCES

1. O. Knake and I. N. Stranskii, *Usp. fiz. n.*, 68, 261, 1959.
2. S. L. Rivkin, G. V. Troyanovskaya, and T. S. Akhundov, *Teplofizika vysokikh temperatur*, vol. 2, 219, 1964.
3. S. L. Rivkin, T. S. Akhundov, E. A. Kremenevskaya, and N. N. Asadullaeva, *Teploenergetika*, no. 4, 1966.
4. S. L. Rivkin and G. V. Troyanovskaya, *Teploenergetika*, no. 10, 1964.
5. I. R. Krichevskii, N. E. Khazanova, and L. R. Linshits, *IFZh*, no. 10, 1960.
6. M. Leontovich, *ZhETF*, 49, 1624, 1965.

8 June 1966

Kirov Ural Polytechnic Institute, Sverdlovsk

HEAT TRANSFER IN LIQUID HELIUM IN THE PULSED MODE

A. P. Smirnov

Inzhenerno-Fizicheskii Zhurnal, Vol. 13, No. 2, pp. 264-267, 1967

UDC 536.242

It is shown that for pulsed thermal loads on the boundary between a solid and liquid helium most of the heat transfer takes place to the liquid helium; consequently, such transfer mainly depends on the helium temperature. The phenomena accompanying this process are discussed.

When studying phenomena occurring in metals and semiconductors due to low-duration current pulses, we encounter a number of cases in which the Joule heat liberated determines the kinetics of the processes observed, particularly at liquid-helium temperatures. However, an analysis of thermal balance for the pulsed mode with large specific heat loads for precisely this temperature range was previously lacking in the litera-

ture. Given such a state for film superconductors on a dielectric backing, the solution to the problem essentially reduces to determining the effective heat transfer in the steady-state mode by using average values for the corresponding quantities. Calculations of such a type also lead to the conclusion that it is not necessary to allow for heat transfer directly from the film to the helium since the thermal conductivity of helium is much lower than that of the backings used [1].

In several articles [2, 3], only non-steady-state processes in a backing are considered, and heat transfer to helium is allowed for by means of parameters characteristic of the steady-state mode at low thermal loads.

Data have recently been obtained indicating that heat transfer to liquid helium increases considerably for large specific heat loads ($\sim 1 \text{ W/cm}^2$), even in the steady-state mode, and becomes comparable with heat transfer to the backing [4]. As will be shown below, allowance for the effect of helium makes a considerable contribution to the thermal balance of the pulsed system.

§I. Consider the thermal balance for a specimen in the form of a film on a dielectric backing and bathed in liquid helium. If the passage of a current pulse through the film liberates a quantity of heat qt and heats the film to some temperature T , the temperature in the surrounding space will rise simultaneously; here the dimension a of the heated region gradually increases. This increase during time t is given by $a_1 \sim (\chi_1 t)^{1/2}$ in a backing with thermal diffusivity χ_1 and by $a_2 \sim (\chi_2 t)^{1/2}$ in helium. Since $\chi_1 \gg \chi_2$, then $a_1 > a_2$ i. e., the volume of helium heated by the thermal pulse is less than the volume of the backing heated within the same time. However, the specific heat of helium is very high in comparison with that of the backings used [5]; therefore, the amount of heat given off to the helium during the time t is also considerable. If during the time the pulse acts the region a is much smaller than the film width d ($a \ll d$), we can use the solution to the one-dimensional problem of heat propagation from a source with the power q at the boundary $a = 0$ into a medium with thermal conductivity κ (without allowing for the specific heat of the specimen and the thermal resistance at the boundaries) [6]:

$$\begin{aligned} \kappa T(a, t) = \\ = \int_0^t \sqrt{\frac{\kappa}{\pi(t-\tau)}} q(\tau) \exp\left(-\frac{a^2}{4\chi(t-\tau)}\right) d\tau. \quad (1) \end{aligned}$$

At the boundary (of the film), the temperature (for $q = \text{const}$) is given by

$$\begin{aligned} T(0, t) = \\ = \frac{1}{\kappa} \int_0^t \sqrt{\frac{\kappa}{\pi(t-\tau)}} q d\tau = \frac{2q}{V \pi \kappa c_p \rho} \sqrt{t}. \quad (2) \end{aligned}$$

If at the time $t = t_0$, the film temperature $T(0, t) = T_0(0, t_0)$; this means that the part q_1 of heat is absorbed by the backing and the part q_2 is given off to the liquid helium, and

$$\frac{q_2}{q_1} = \sqrt{\frac{\kappa_2 c_{p2} \rho_2}{\kappa_1 c_{p1} \rho_1}}. \quad (3)$$

If we compare the heat transfer to liquid helium with the heat transfer from the specimen to the glass backing for temperatures of $4.2\text{--}2.19^\circ \text{K}$, we will always have $q_2 > q_1$, i. e., heat transfer mainly occurs to the helium. Thus, for a temperature of 3.5°K the heat transfer to liquid helium is five times greater than the heat transfer to the glass backing. Allowance for thermal resistance at the film-backing and film-helium boundaries naturally leads to a certain change in relation (3); however, at present, it is difficult to perform an exact quantitative calculation since there

are no data on the coefficient of heat transfer to helium in the pulsed mode and on this coefficient's dependence on the specific thermal power. Nevertheless, on the basis of the data of [4], we can expect that (3) will apply for films deposited on a glass backing and for specific thermal loads $q > 1 \text{ W/cm}^2$ (when the thermal resistance of the film-helium and film-backing boundaries are comparable); however, the film will be much hotter [6].

In making a precise calculation of thermal balance we should allow for the specific heat of the film, the heat of evaporation of helium, and the high helium density near the film [7]. If this is done, we see that, in the pulsed mode, specimens immersed in liquid helium are cooled much more intensely but that heat transfer depends on temperature.

The maximum decrease in heat transfer to helium and, consequently, the greatest degree of overheating of the specimens should be expected in the 2.5°K temperature range.

§II. Since overheating of the specimens is accompanied by heating of the helium layer near the specimen, "thermal waves" appear [6] and sound is generated [9]; this occurs because of the high expansion coefficient of helium under the action of thermal shock [8]. For the high specific thermal loads associated with the new heat-transfer mechanisms and accompanied by mass transport [4], we can expect intense bathing of the specimen surface by cold layers of helium even during the time the thermal pulse acts. With the existence of a shock wave and boiling of the helium this can lead to a decline in the helium temperature near the film. At the end of the pulse, the temperature of the helium layer, and of the specimen as well, can even be lower than the bath temperature.

The relaxation processes in this case, as for overheating, are determined by the properties of the helium since $q_2 > q_1$ and $\chi_2 \ll \chi_1$. Evidently, it is just the type of relaxation processes in helium that affect the measurement of critical currents when we study the breakdown of superconductivity in film specimens by current pulses of different shape and duration [9–11]. The most pronounced effect of heat transfer to helium will be observed in the helium λ -transition region. Upon a further drop in temperature, heat transfer to helium is considerably reduced owing to the Kapitza temperature discontinuity [6]. We can expect that the process considered of heat transfer to liquid helium will also affect the nature of thermal instability when measuring critical currents by the attenuation in a coil [12].

§III. Experiments on tin films in liquid helium confirm that this method of analyzing heat transfer to a fluid in the pulse mode is justified*. The change in specimen temperature is nonmonotonic, depending on the pulse thermal power.

When heat transfer takes place primarily from the specimen to the helium, the helium boils; this can be

*A detailed treatment of the experimental results will be published in a separate article.

seen with a microscope. For the range studied of pulse powers, the heat liberation (up to 15 W/cm^2) observed when the helium boils fixes the configuration of the temperature field at the end of the pulse. The helium boils on the entire surface of the specimen even when the total amount of heat liberated in the pulse is 30 erg/cm^2 . This fact can be used in studying the kinetics of processes accompanied by the liberation of heat over almost any time range (current pulses of nanosecond duration were used in the experiments), if the object to be studied is bathed with the liquid. This method can be recommended for revealing inhomogeneities of current distribution in metals and semiconductors, for studying the intermediate state during the breakdown of superconductivity by a current, for tracing the kinetics of heat liberation during metal and alloy deformation, etc.

With this method, high resolution in determining temperature and heat liberation distributions is achieved since the size of the bubbles of boiling liquid is a few microns.

NOTATION

T is the temperature; t is the time; q is the specific power; a is the dimension of the heated area; d is the film width; χ is the thermal diffusivity of the medium; κ is the thermal conductivity of the medium; c_p is the specific heat of the medium; ρ is the density of the medium. The subscript 1 denotes the backing parameters and the subscript 2 liquid helium.

REFERENCES

1. E. C. Crittenden, I. W. Cooper, and F. W. Schmidlin, *Proc. IRE*, **48**, 1233, 1960.
2. R. F. Broom and E. H. Rhoderic, *Brit. Journ. Appl. Phys.*, **11**, 292, 1960.
3. S. Ya. Berkovich, P. P. Golovistikov, and R. A. Chentsov, *IFZh*, **6**, 99, 1963.
4. A. P. Dorey, *Cryogenics*, **5**, 146, 1965.
5. G. K. White, *Experimental Technology in Low-Temperature Physics* [Russian translation], Fizmatgiz, Moscow, 1961.
6. L. D. Landau and E. M. Lifshits, *Mechanics of Continuous Media* [in Russian], GITTL, Moscow, 1964.
7. Kuang Voi-Yen, *ZhETF*, **42**, 921, 1962.
8. A. A. Grinberg, A. A. Kastal'skii, and S. M. Ryvkin *ZhTF*, **35**, 376, 1965.
9. A. P. Smirnov, V. N. Totubalin, and I. S. Parshina, *ZhETF*, **49**, 117, 1965.
10. A. M. Kolchin, Yu. G. Mikhailov, N. M. Reinov, A. V. Rummyantseva, A. P. Smirnov, and V. N. Totubalin, *ZhETF*, **40**, 1543, 1961.
11. E. M. Hartlin, R. M. Wertheimer, and G. M. Graham, *Canad. Journ. of Phys.*, **42**, 1282, 1964.
12. S. Ya. Berkovich, *Radiotekhnika i Elektronika*, **8**, 257, 1963.

10 November 1966

Ioffe Physicotechnical
Institute, Leningrad