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NONSTATIONARY HEAT TRANSFER IN A CHANNEL CONTAINING SATURATED He II: STEPPED HEAT LOADING

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Measurements have been made on the nonstationary temperature distribution in a channel containing saturated superfluid helium with local stepped heat input. A numerical method has been developed, which incorporates the variable thermophysical parameters for the helium.

Recently, superfluid helium has been used in superconducting devices [1, 2], and there has been extensive research on nonstationary heat transfer in it, mainly for superconductor stabilization. The most detailed studies have been made on nonstationary heat transfer in such helium at atmospheric pressure (unheated He II) in adiabatic channels having pulsed local heating under countercurrent conditions ($\rho v = 0$), which simulate the heat production in superconducting magnets [3-6]. Underheated He II has very good heat-transfer characteristics: it can accept heat pulses several times larger than the stationary critical flux without crisis or superfluidity loss [3, 4].

Much less use has been made of nonstationary heat transfer in saturated superfluid helium, since from the start preference has been given to using underheated He II.

We have examined nonstationary heat transfer in a channel containing saturated He II under countercurrent conditions ($\rho v = 0$) with local heat input to the middle of the channel as a stepped function.

It is considered that the transfer in such a case can be described by a one-dimensional nonstationary energy equation [3, 5]:

$$\rho c_p \frac{\partial T}{\partial \tau} = \frac{\partial q_T}{\partial x}. \tag{1}$$

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The local heat flux q_T related to internal convection is governed by the local temperature gradient, in accordance with the Görter-Mellink friction law [7], which can be put in modified form as

$$q_T = -k(T)\left(\frac{\partial T}{\partial x}\right)^{1/m}, \tag{2}$$

where $k(T) = \rho_s sT\left(\frac{\rho}{A(T)\rho_n}\right)^{1/m}$ characterizes the effective thermal conductivity of He II due to internal component convection. Then (1) and (2) give

$$\rho c_p \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left[k(T)\left(\frac{\partial T}{\partial x}\right)^{1/m}\right]. \tag{3}$$

When the heat is supplied as a stepped function at x = 0, the boundary conditions are

$$\begin{gathered} -k(T)\left(\frac{\partial T}{\partial x}\right)^{1/m}\Bigg|_{x=0} = q_0, \\ T(x,\,0) = T_b, \\ T(\infty,\,\tau) = T_b, \\ T(x,\,\tau) \leqslant T_\lambda. \end{gathered} \tag{4}$$

The problem for underheated He II has been solved on the assumption that the thermophysical properties of it and k(t) are constant correspondingly [3, 5]; k(T) and m in (3) are determined by fitting. However, the properties of He II vary considerably with temperature, so the fit is not always satisfactory, particularly near the λ point.

We devised a method of solving (3) by means of an explicit finite-difference scheme incorporating the temperature dependence of He II thermophysical parameters. A Fortran IV program was written for underheated and saturated He II, which gives the nonstationary longitudinal temperature distribution at any instant and correspondingly the time τ_{tr} to attain the λ transition temperature as a function of the heat flux for $q_0 > q_{cr}^{st}$.

We used a system (Fig. 1) consisting of a 12Kh18N10T stainless-steel coil 1, length L = 1.87 m, internal diameter $d = 3 \cdot 10^{-3}$ m, and a wall thickness $\delta = 0.5 \cdot 10^{-3}$ m. At the center of the coil, the copper tube 2 was soldered on having the same diameter and length $L_h = 2.5 \cdot 10^{-2}$ m, wall thickness $\delta_h = 0.4 \cdot 10^{-3}$ m, on which was wound the constantan heater 3. The heated element was coated on the outside with epoxide resin 4 reinforced with glass fiber. The coil was placed in the insulating vacuum jacket 5. The ends were connected to a bath containing saturated He II. Seven semiconductor resistance thermometers 7 type TPK were installed by means of special leads 6, which were crystals with face sizes of about $0.5 \cdot 10^{-3}$ m. Their response times were estimated as about 10^{-5} sec. Figure 1 shows the thermometer location. The thermometers were set at the center (T_4) and symmetrically on both sides of it at distances of 0.15 m (T_3 and T_6), 0.3 m (T_2 and T_7), and 0.6 m (T_1 and T_8). A similar thermometer was attached (soldered) to the outer surface of the copper tube. The measurement currents in the thermometers in the channel were chosen such that they also acted as liquid-vapor indicators (spontaneous temperature rise on entering the vapor).

The nonstationary heater input was produced by a generator providing a stepped voltage at the heater, leading edge shorter than 10 μsec. The power deposited and the nonstationary temperatures were recorded with a K121 beam oscillograph. The high-impedance sensors were matched to the galvanometers by differential amplifiers, which balanced out the dc components corresponding to the bath temperature and recorded only the temperature changes relative to the bath. Under steady conditions, the temperatures were monitored with an Shch301 combined digital instrument.

Measurements were made under stationary and nonstationary conditions at 1.7-2.0 K in the bath with the liquid 50-150 mm above the element. Before each experiment, the temperature sensors were calibrated from a standard thermometer installed in the He II. In the nonstationary experiments, the sensors were calibrated together with the amplitude and oscilloscope channels from the beam deflection. Temperatures in the range 1.6-4.5 K were measured to ±0.01 K under stationary conditions, or ±0.02 K under nonstationary ones.

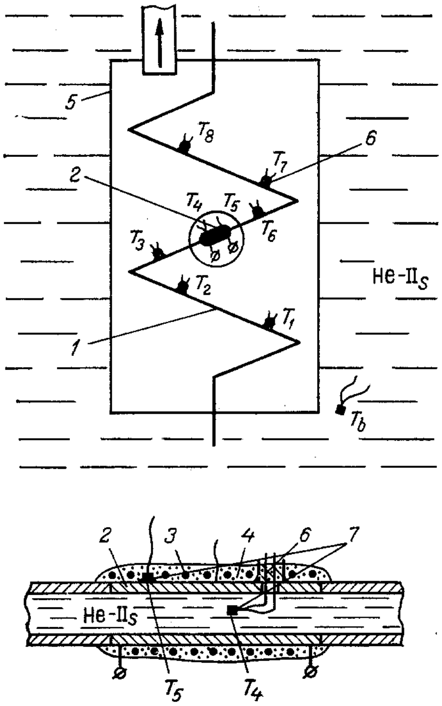

Fig. 1. The working element.

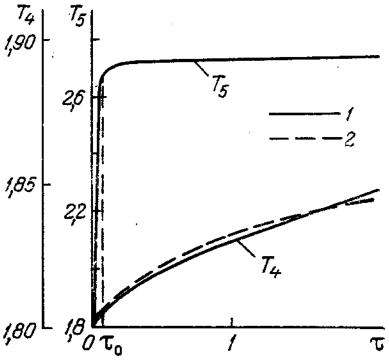

Fig. 2. Time course of heater wall temperature at the center T_4 for $q_0 < q_{cr}^{st}$: $T_b = 1.8$ K, H = 80 mm, $q_0 = 2.1\cdot10^4$ W/m^2: 1) experiment; 2) calculation from (3); T in K and τ in sec.

The stationary experiments were of calibration type. Up to the crisis, where a vapor film is formed on the heated surface, the transfer occurs in Kapitsa thermoresistance mode. The local conductivities under those conditions were h_k = 600-900 W/m^2•K in accordance with the temperature, which is somewhat below the values of [8] for copper specimens having mechanically worked and annealed surfaces. The low h_K may be due to oxide films on the inner surface. The He II was superheated near the heater before the crisis by 0.06-0.12 K, which agrees satisfactorily withthe [8, 9] data.

The stationary longitudinal temperature distribution at subcritical loading is described satisfactorily by (2) with m = 3.1.

On stepped loading less than the stationary critical flux (Fig. 2), the heater temperature became approximately constant within $\tau_0 \approx 3$ msec (τ_0 characterizes the lag). The nonstationary temperature change in the He II was calculated from (3) and agreed well with experiment with the m = 3.1 determined from the stationary transfer.

The channel temperature settling time was fairly long, namely about 23 sec from loading at q = $2.1\cdot10^4$ W/m^2; throughout it, the Kapitsa mode applied.

When the heat load exceeded the stationary critical value (Fig. 3), T_5 rose rapidly for $\tau_0 \approx 2$ msec but then varied only slightly up to τ_{tr}. During τ_{tr}, the heat was transmitted by the Kapitsa mechanism. The central temperature T_4 rose monotonically. At τ_{tr}, the heater

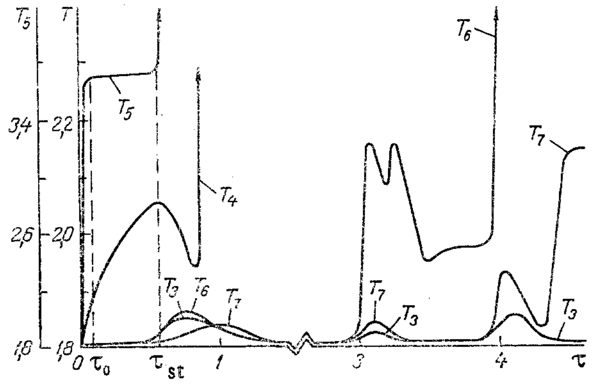

Fig. 3

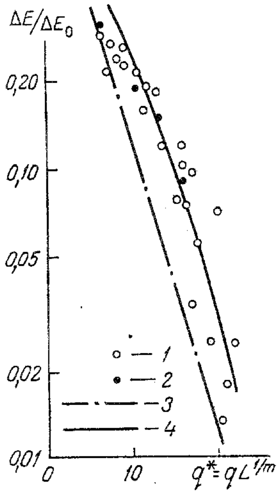

Fig. 4

Fig. 3. Time course of heater wall temperature T_5 and He II temperature at the center T_4 for $q > q_{cr}^{st}$; $T_b = 1.8$ K, H = 80 mm, $q_0 = 7.9 \cdot 10^4$ W/m².

Fig. 4. Reduced critical pulse energy as a function of input power: 1) with underheated He II [3, 4]; 2) with saturated He II; 3) Seyfert's calculations [3]; 4) calculation from (3).

temperature T_5 rose sharply, while T_4 fell briefly, after which it also rose sharply. The rise in T_5 at τ_{tr} and the simultaneous fall in T_4 indicate a boiling crisis and vapor film formation. This vapor formation was accompanied by heat transfer deterioration and the absorption of latent heat of evaporation in the channel, as is evident from the brief fall in T_4, after which the vapor extends to the entire cross section under the heater: T_4 responds to the vapor with a sharp rise.

Subsequently, vapor was always present at the center under the heater, as T_4 indicated, and the pattern corresponded to stationary heat input. The vapor zone periodically propagated up the channel and displaced the liquid, as was recorded by T_6 and T_7. Then the liquid filled the channel again and the process repeated. The liquid-vapor column oscillated. Small-amplitude temperature oscillations were recorded by T_3 in the lower part (T_1 and T_2 were not operating in this experiment). Very likely, the vapor from the heater zone partially penetrated into the lower part but condensed rapidly. The condensation heat propagates down the channel by thermal conduction in the He II and is recorded as a pulse by T_3. This periodic vapor production with saturated He II has been detected by experiment [9]. It is evident [10, 11] that metastable superheating occurs in saturated He II under certain conditions, with subsequent boiling, and vapor formation, with the vapor condensing rapidly. The procsss is periodic.

It is particularly notable that stepped loading produced superheating ΔT_{cr} preceding the crisis much exceeding the values under stationary conditions, with the values ranging up to the λ transition point T_λ. It has been suggested [9] that the superheating under stationary conditions is due to pressure rise consequent on the on the heat transfer along the channel by internal convection (friction of the normal component at the wall). Good agreement is obtained with experiment [9] on incorporating this factor into the model for the stationary critical flux. Under nonstationary conditions, the pressure rise may be more substantial because of the dynamic component arising from acceleration and interaction, which is probably responsible for the more substantial superheating. There may also be metastable superheating under nonstationary conditions. Further measurements are required on the pressure in the channel to elucidate the superheating mechanism.

For $q > q_{cr}^{st}$, the crisis sets in after τ_{tr} following the step; τ_{tr} was several seconds, but it decreased as the power increased. Our results and other data [3, 4] for underheated He II are plotted in Fig. 4 in the [3] coordinates, where $\Delta E = q_0 \tau^{st}$ is the critical pulse energy, i.e., the energy supplied before the crisis, while $\Delta E_0 = \rho[i(T_\lambda) - i(T_b)]L$ is the energy needed to be supplied to the entire mass of He II in the channel to heat it to the λ transition point. Our data for saturated He II agree well with those for the underheated form. The following interpretation is given: a pulse $q_1^* = q_1 L_1^1/m$ input to a channel having a length L_1 does not produce a crisis if the energy is less than ΔE_1.

Figure 4 also shows Seyfert's numerical calculations [3] and calculations from (3) for saturated He II based on the temperature dependence of the thermophysical parameters, which itself is based on m = 3.1 in (3) derived from stationary transfer. The variable-property calculations agree better with experiment than do Seyfert's.

We conclude that saturated He II responds to pulse loading as does underheated He II, but complete elucidation of the superheating mechanism under nonstationary conditions is at present lacking, so the conclusion can be extended only to the conditions used.

NOTATION

ρ, density; v, velocity; c, specific heat; T, temperature; τ, time; q, heat flux density referred to the cross section; x, longitudinal coordinate (along the axis); s, specific entropy; A(T), Görter–Mellink constant; m, exponent; k(T), temperature-dependent parameter; L, length; d, diameter; δ, thickness; h_K, Kapitsa conductivity coefficient; i, specific enthalpy; ΔE, energy referred to cross section; H, liquid level height. Subscripts: s, superfluid He II component; n, normal He II component; p, at constant pressure; b, parameters in He II bulk; λ, parameters at λ point; h, heater; cr, critical; st, stationary.

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INVESTIGATION OF THE HEAT TRANSFER OF CRYOGENIC FLUIDS IN A CENTRIFUGAL FORCE FIELD

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Results of an experimental investigation of heat transfer during the boiling of cryogenic fluids (nitrogen, hydrogen, helium) in a large volume in a broad range of overloads and fluid levels above the heat eliminating surface are considered.

Different cryogenic fluids are utilized as coolants in many branches of the national economy. Knowledge of their heat transfer characteristics (heat elimination coefficients, boiling crises) permits maximal intensification of the working processes, elevation of the efficiency of installations and aggregates.

An analysis of results of an experimental investigation of the heat transfer of cryogenic fluids in a centrifugal force field (similarly to those elucidated in [1]) under the combined influence of pressure, overloads, and underheating on the heat-transfer intensity is represented in this paper.

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