TEMPERATURE STABILIZATION CONDITIONS FOR A CRYOGENIC CABLE

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Conditions for temperature stabilization of a cryogenic cable are analyzed as a function of redistribution of coolant flow over axial and peripheral channels.

To satisfy the needs of high power consumers, in the near future it will be necessary to construct several open wire or coaxial transmission lines to handle maximum power. From the economic viewpoint such lines may prove inferior to cryogenic electric transmission lines [1].

At the present time studies are being performed to develop reliable cryogenic transmission lines [2]. Since the operating regime of such cables is characterized by an almost constant temperature value along the length of the cryogenic line, determination of temperature stabilization conditions is of primary importance.

The present study will analyze the temperature stabilization conditions in a one-phase cable, constructed in the form of a permeable tube located within a hermetic shield. A diagram of a 3-m section of such a cable is shown in Fig. 1.

The current lead is placed over a rigid bar which serves as a support and maintains the required geometry. A braided cable is used for the current lead. Several layers of glass cloth are wound around the current lead, and the outer current lead is also braided and is fitted over the glass cloth wrapping. The external diameter of the cable is 20 mm, with internal diameter 14 mm. Current is introduced at the cable ends by a coaxial current lead formed of rolled copper screening. The inner tube is connected to the inner current lead and the outer tube to the outer current lead. The cable is located in a hermetic chamber 40 mm in diameter. To compensate for cable heat intake, the hermetic chamber is clad in a cryogenic sleeve, which it is separated from by a vacuum space. The cryogenic liquid which maintains the cable temperature is supplied through an internal axial channel in the support bar, and due to the permeability of the braided conductor and the insulation, partially filters out into the peripheral space, producing a liquid flow which cools the cable in an outward direction. The velocities of the central and peripheral flows can be regulated. In the operating mode the temperature differential over length and radius of the cable must not exceed a value of several degrees. The temperature along the length and radius of the cable can change due to heat liberation in the current leads and heat intake from the outer shell. Our task consists of determining the conditions which permit maintaining a given temperature in the cable by varying the ratio of axial central flow to peripheral flow, i.e., the value of filtration as a function of heat liberation and heat intake, which in turn are determined by the cable construction.

The process of heat exchange in the construction studied here is characterized by a change in heat-transfer coefficient over cable length due to inconstancy of axial velocities in the central and peripheral channels.

The following assumptions were made in solving the problem of temperature distribution in the cable.

1. The flow and heat exchange over the entire length are considered developed, and the heat-transfer coefficients are specified by the corresponding axial velocities in the channels and the filtration rate.

2. Filtration rate is constant over cable length.

3. Axial temperature gradients are constant over the cross section of the corresponding channel $(\partial/\partial r)(\partial t/\partial x) = 0$.

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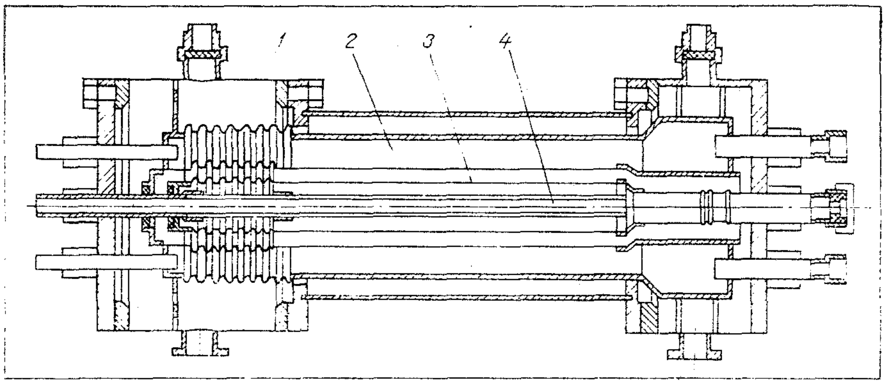

Fig. 1. Diagram of experimental apparatus: 1) vacuum shell; 2) nitrogen bath; 3) intermediate shield; 4) experimental specimen.

The assumptions made permit division of the general problem into two independent problems of heat transfer in a circular porous tube and a ring-shaped gap with permeable inner wall and boundary conditions of the second kind [3, 4]. As the basic equation, we take the energy equation without the term considering heat transfer by thermal conductivity in the axial direction:

$$c\rho\left(v\frac{\partial t}{\partial r}+u\frac{\partial t}{\partial x}\right)=\frac{\lambda}{r}\frac{\partial}{\partial r}\left[\left(1+\frac{\lambda_t}{\lambda}\right)r\frac{\partial t}{\partial r}\right], \tag{1}$$

where λ_T is the turbulent analog of the thermal-conductivity coefficient, with boundary conditions

$$\partial t(0)/\partial r = 0,\quad t(r_1) = t_1 \text{ for the tube,} \tag{2}$$

$$\partial t(r_3)/\partial r = q_3/(\lambda+\lambda_t),\quad t(r_2)=t_2 \text{ for the ring.} \tag{3}$$

To eliminate the axial temperature gradient, equations were employed reflecting the law of energy conservation for the tube

$$2q_1 = 2v_1\rho c(t_1-\bar{t}_1)+r_1\rho c\bar{u}_1\frac{d\bar{t}_1}{dx} \tag{4}$$

and ring

$$2r_2q_2+2r_3q_3=2r_2v_2\rho c(t_2-\bar{t}_2)+\rho c(r_3^2-r_2^2)\bar{u}_2\frac{d\bar{t}_2}{dx}. \tag{5}$$

It follows from the assumption of constant axial temperature gradients that local values of the axial temperature gradient are equal to corresponding values of the axial gradient of mean volume temperature. Then

$$\frac{\partial t_1}{\partial x}=\frac{d\bar{t}_1}{dx}=\frac{2q_1}{r_1\rho c\bar{u}_1}\left(1-\frac{\mathrm{Re}_{\mathrm{fil}}\mathrm{Pr}}{\mathrm{Nu}_1}\right), \tag{6}$$

$$\frac{\partial t_2}{dx}=\frac{d\bar{t}_2}{dx}=\frac{2r_2q_2}{(r_3^2-r_2^2)\rho c\bar{u}_2}\left(1+\frac{\mathrm{Re}_{\mathrm{fil}}\mathrm{Pr}}{\mathrm{Nu}_2}+\frac{r_3q_3}{r_2q_2}\right). \tag{7}$$

By substituting these equations in Eq. (1) we obtain ordinary differential equations, integration of which with appropriate boundary conditions gives the radial temperature distribution. Temperature distribution over the length can be determined from Eqs. (6), (7) if thermal flux values q_1 and q_2 and the power produced by internal heat liberation in the current lead are known. To find q_1 and q_2 we turn again to the third assumption. By definition

$$\mathrm{Nu}=\frac{qd}{\lambda(t_\omega-\bar{t})}. \tag{8}$$

Differentiation of this expression with respect to x gives

$$q'=\mathrm{Nu}'\frac{\lambda}{d}(t_\omega-\bar{t})+\mathrm{Nu}\frac{\lambda}{d}(t'_\omega-\bar{t}').$$

Since the axial temperature gradient is constant,

$$t'_\omega=\bar{t}' \text{ and } q'=\frac{q}{\mathrm{Nu}}\mathrm{Nu}'.$$

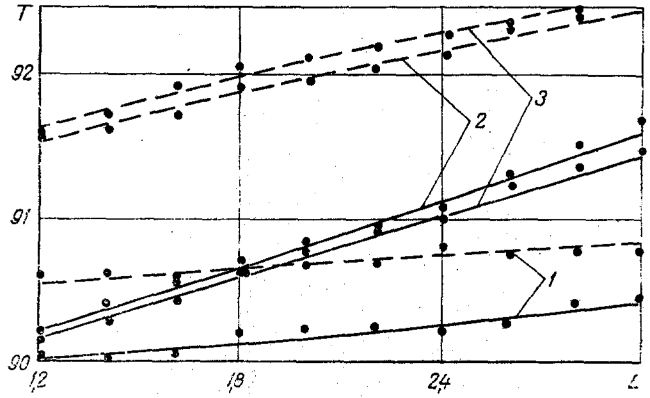

Fig. 2. Temperature distributions over inner (dashed lines) and outer (solid lines) current conductors and comparison with experimental data (points): 1) q_1 = 62 W/m², Re_{fil} = 29; 2) q_1 = 186 W/m², Re_{fil} = 29; 3) q_1 = 186 W/m², Re_{fil} = 18. T, °K; L, m.

Hence

$$q_1 = c_1 \mathrm{Nu}_1 \text{ and } q_2 = c_2 \mathrm{Nu}_2.$$

To determine the constants c_1 and c_2, we integrate the energy equation for the current-carrying cable

$$\rho c \Pi \frac{r_1}{r} \frac{\partial t}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \lambda_e \frac{\partial t}{\partial r} \right) + q_v \tag{9}$$

with boundary conditions at $r = r_1$, $t_1 = t_1(x)$, $\partial t/\partial r = q_1/\lambda_e$.

The temperature change over thickness of the current lead equals

$$t_2 - t_1 = \int_{r_1}^{r_2} \frac{\exp(S)}{r \lambda_e} \left[r_1 c_1 \mathrm{Nu}_1 - \int_{r_1}^{r_2} \frac{q_v r dr}{\exp(S)} \right] dr, \tag{10}$$

where

$$S = \int_{r_1}^{r_2} \frac{r_1 v_1 \rho c \Pi}{\lambda_e r} dr$$

Using the law of energy conservation for the current lead

$$(r_2^2 - r_1^2) q_v = 2 r_1 c_1 \mathrm{Nu}_1 + 2 r_2 c_2 \mathrm{Nu}_2 + 2 r_1 v_1 \rho c (t_2 - t_1). \tag{11}$$

Differentiating with respect to x, and considering Eqs. (6), (7),

$$c_1 \left[2 r_1 \mathrm{Nu}_1' - \frac{4 v_1 (\mathrm{Nu}_1 - \mathrm{Re}_{fil} \mathrm{Pr})}{\bar{u}_1} \right] + c_2 2 r_2 \left[\mathrm{Nu}_2' + \frac{\mathrm{Nu}_2 + \mathrm{Re}_{fil} \mathrm{Pr}}{(r_3^2 - r_2^2) \bar{u}_2} \right] = \frac{4 r_1 v_1 r_3 q_3}{(r_3^2 - r_2^2) \bar{u}_2}. \tag{12}$$

Equations (10)-(12) form a closed system for determining c_1 and c_2, after which evaluation of the temperature distribution over the cable length is possible. In a stationary operating mode in a superconductive cable, the temperature of the outer surface of the current-carrying cable is of primary importance and must not exceed some completely specified temperature.

Using the calculations described, the effects of various factors on the temperature field were analyzed. For comparison with experiment, all calculations were made for a 1.8-m-long cable segment, and values of the heat-transfer coefficients on the surfaces of the current-carrying lead were determined from experimental data.

Figure 2 presents experimental and calculated temperature distributions of the inner and outer current leads over the cable length for various coolant flow rates at the input to the cable.

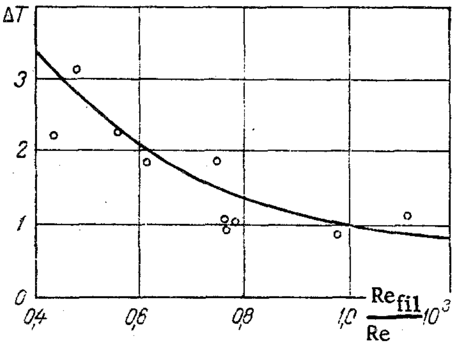

Fig. 3

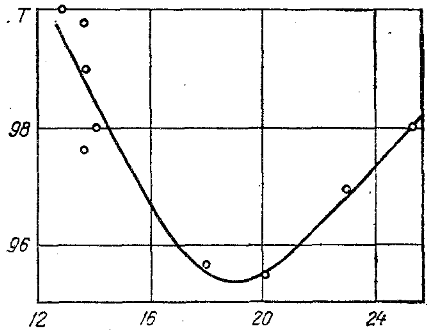

Fig. 4

Fig. 3. Temperature difference across cable thickness versus ratio of coolant fluxes, ΔT, °K.

Fig. 4. Temperature T of conductor versus filtration rate Re_{fil}.

It should be noted that the calculated values of temperature difference between inner current lead wall and liquid are about the same as the temperature differences across the cable. It is obvious that the temperature of both surfaces increases monotonically, but due to the increase in axial velocity in the outer ring channel the axial temperature gradient decreases with length, while in the inner channel this gradient increases due to inconstant mass loss. As a result, the temperature difference across the thickness of the porous current lead $t_2 - t_1$ changes with cable length, but always remains positive.

Of prime importance is the varying character of the temperature fields with change in the ratio between power produced by heat liberation and the amount of heat intake. It was established that in the case of dominant heat liberation in the current leads there develops a significant temperature difference across the cable thickness, and an increase in power leads to a uniform increase in both the temperature difference and the axial temperature gradients in both channels. If, however, heat intake from the outside predominates, then $t_2 - t_1$ is significantly less, while the value of c_2 is always negative; i.e., the thermal flux on the outer surface of the current lead is directed into the cable.

Radial flow through the current lead plays a special role in this case. Increase in filtration rate leads, first, to a reduction in the temperature difference across the wall thickness, as is evident from Fig. 3. Second, it leads to a decrease in the axial temperature gradient in the ring channel due to the constant increase in flow velocity. However the axial gradient in the tube then rises. Up to a certain time the first two effects dominate and the temperature of the external surface of the current lead decreases with increase in filtration. But there exists a critical flow velocity, above which the temperature growth in the outer channel begins to dominate, and further increase in filtration rate leads to increase in temperature of the conductor (Fig. 4). The optimum filtration rate can be determined from the relationship

$$Re_{fil} = 0.315 \frac{r_1}{L} Re. \tag{13}$$

Comparison of experimental and calculated data shows good agreement of not only temperature values, but also of the character of the temperature distribution on both the inner and outer surfaces of the experimental specimen, on the basis of which we may conclude the validity of the assumptions used in this method of calculating the cooling regime of a cryogenic cable.

Thus, for temperature stabilization in a permeable cryogenic cable at a specified level it is desirable to create conditions such that Re_{fil} be optimum, i.e., be determined from Eq. (13), and the ratio of flow velocities in the central axial and outer ring channels should be found from the relationship

$$\frac{Re_{fil}}{Re} = (0.8 - 1.2) \cdot 10^{-2}.$$

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 = αd/λ, Nusselt number; Re = ud/ν, Reynolds number; $Re_{fil} = v_1 d/\nu$, filtration parameter; Pr = ν/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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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, $R_{\sqsubset}$ (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, ΔR/ΔT = 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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