THERMOPHYSICAL PROPERTIES OF EPOXY-IMPREGNATED SUPERCONDUCTIVE COILS OVER THE TEMPERATURE RANGE 4.2-350 K

L. E. Evseeva and S. A. Tanaeva

UDC 541.64:536.2

Results of an experimental study of temperature dependence of thermal conductivity and thermal diffusivity coefficients and specific heat of superconductive windings are analyzed.

Use of superconductive materials in the modern technology of high power electrophysical equipment requires careful study of heat transport processes in construction elements.

When steady state conditions in superconductive windings are disrupted upon a change in magnetic field, heat is liberated. For the duration of such transient processes the maximum allowable current in the superconductor is determined by the temperature distribution within the winding, especially in the insulating composition material therein, the thermal conductivity of which is finite. Despite the fact that the behavior of the composition material of windings under transient conditions is of great interest, the literature offers very little information on the thermophysical properties of windings as a whole, or the components from which they are made. The thermal conductivity and specific heat of superconductors and superconductive cables has been studied by a number of authors [1-4]. Significantly less data is available on thermophysical properties of windings [5, 6], with only the thermal conductivity having been determined or calculated.

The goal of the present study is to experimentally investigate the temperature dependence of thermophysical properties (thermal conductivity (λ), thermal diffusivity (a), and specific heat (c)) over the temperature range 4.2-350 K, and to establish empirical calculation formulas for determination of effective thermal conductivity of windings from the properties of their components in three mutually perpendicular directions, as well as specific heat.

The superconductive windings from which specimens were sectioned consisted of a niobium-titanium superconducting lead, wound in several layers each of which contained an approximately equal number of turns. Insulation between layers consisted of three layers of fiberglass. The entire winding was then impregnated with an epoxy binder. A cross section of the winding is shown in Fig. 1. The superconductive lead itself consisted of a bar with cross section 3.5×2 (mm^2), within which superconductive NbTi wires were placed within a copper matrix. Two different types of specimen were tested, with the one bar containing 19 superconductive wires, and the other 62 such wires. Since this material is significantly anisotropic, the thermophysical properties were measured in three mutually perpendicular directions: thermal flux directed along the winding bar, across the long side of the cross section, and across the short side of the cross section (Fig. 1). This was done by preparing three types of specimen in the form of plates with dimensions $50 \times 50 \times 10$ (mm^3).

The experimental study of thermophysical properties of the windings was carried out by the quasisteady state method, permitting determination of λ, a, c by a single experiment over a wide temperature interval (4.2-350 K) [7]. To determine specific heat in the superconductive transition region the adiabatic colorimeter method was also used. To measure temperature and temperature change over the specimen section thermocouples made of chromel and a Cu + 0.1% Fe + 0.02% Li alloy were used, with junctions calked into the specimen with copper foil and leads glued into a groove on the specimen surface by VT-200 glue. Since the specimen is a conductive material, the thermocouple junctions were placed in adjacent layers of the superconductive bus bar, separated from each other by three layers of fiberglass insulation. The maximum relative uncertainty in determining λ, a, c comprised 7-8%. However since the specimens in which the thermal flux was directed parallel to the bus bar were highly thermally

---

A. V. Lykov Heat and Mass Transport Institute, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 3. September, 1989. Original article submitted April 28, 1988.

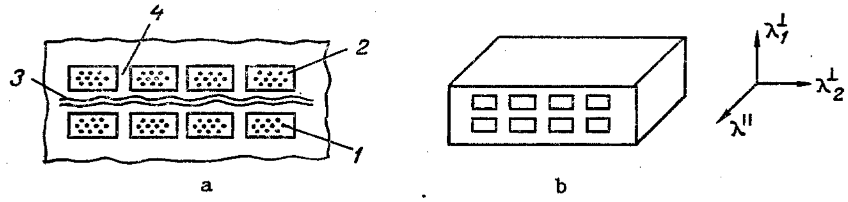

Fig. 1. Overall view of specimen (b) and its cross section (a): 1) superconductive lead; 2) stabilizing copper; 3) fiberglass; 4) epoxy compound.

conductive, and the given method is not designed for such high λ values, the uncertainty in measuring the effective thermal conductivity coefficient for them was significantly higher. Therefore, for the specimen in which the bus contained 19 NbTi conductors, only specific heat was measured, while for the specimen with three times as many superconductive wires a sensitive photoelectric apparatus (F116) was used only to determine the qualitative character of the temperature dependence of effective thermal conductivity.

Specific Heat. The temperature dependence of specific heat of superconductive materials is anomolous in form. At the critical temperature the specific heat suffers a discontinuity, corresponding to the transition from the superconductive to the normal state. Figure 2 shows the temperature dependence of specific heat of the superconductive windings in the temperature interval 4.2-350 K. In accordance with BCS theory the specific heat of the superconductor should undergo an abrupt change at the transition temperature T_c. But the character of the temperature dependence of the superconductive winding specimen specific heat permits the assumption that the transition to the superconductive state is "smeared", being accomplished over some temperature range of the order of 3-4 deg. This smearing is apparently related to the inhomogeneity of the winding specimen, since even in pure NbTi smearing of the superconductive transition (~2 K) has been observed [4]. It should be noted that at low temperature (up to 20 K) the specific heat of the thermoreactive materials with which the winding is impregnated is higher than the specific heat of metals, in particular, higher than that of copper. The specific heat of NbTi is also significantly higher than that of copper. Therefore, as is evident from Fig. 2, the specific heat of the specimen containing three times as many superconductors proves to be higher than that of the other specimens. The difference in specific heat values is observed up to T-20 K.

At low temperatures the specific heat of various resins can be described by an expression $c = C_1T + C_3T^3$ [8]. The specific heat of a metal in the normal state has the form

$$c_n = \gamma_n T + \beta_n T^3,$$

where $\gamma_n T$ is the contribution of the electron component and $\beta_n T^3$ is the phonon component. According to the Horter–Casimir model, the electron heat capacity in the superconductive state is $c_{es} = \alpha_s T^3$, while the specific heat of the superconductor is $c_s = (\alpha_s + \beta_s)T^3$. In the composition material the normal metal of the stabilizing matrix produces a contribution to the specific heat in the form of a linear term, so that in the superconductive state the specific heat of the superconductive bus $c_b = \gamma T + \beta T^3$. Then the specific heat of the entire region impregnated by the thermoreactive binder will have the form $c = AT + BT^3$. The coefficients A and B can be found by the normal method, with construction of the function $c/T = f(T^2)$. The following empirical expression was obtained for defining $c = f(T)$ in the range $4\ K < T < 7\ K$:

$$c = 0.014T + 2.1 \cdot 10^{-3}T^3$$

with a mean square deviation not exceeding 1%.

In the temperature range $12\ K < T < 30\ K$ the temperature dependence of specific heat can be approximated by a function of the form $c = A_1T^{2.55}$, where $A_1 = 2.056$ for specimens Nos. 2-4 and $A_1 = 2.535$ for specimen No. 1, while in the temperature range 30-80 K specific heat depends linearly on temperature: $c = A_2T + A_3$, where $A_2 = 3.6$, $A_3 = -73$.

It must also be noted that since the given material contains a polymer, the specific heat will depend on the heating rate, which also has an effect on the superconductive transition: the latter will be more diffuse the higher the heating rate.

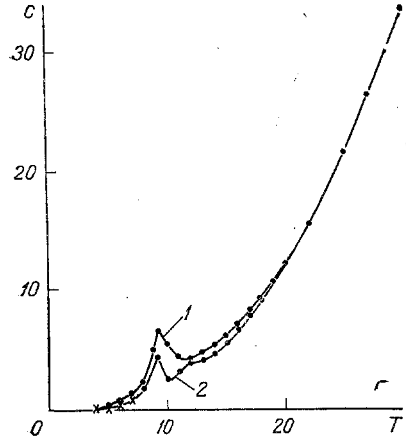

Fig. 2

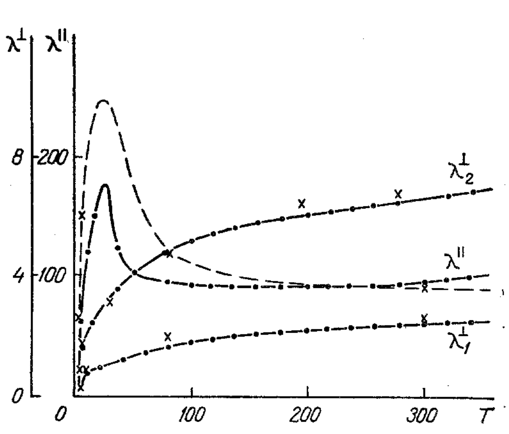

Fig. 3

Fig. 2. Temperature dependence of superconductive winding specific heat: 1) specimen No. 1 ($v_{NbTi_1} = 0.77$): 2) specimens Nos. 2-4 ($v_{NbTi} = 0.25$), c, $J \cdot kg^{-1} \cdot K^{-1}$: T, K.

Fig. 3. Temperature dependence of effective thermal conductivity coefficients of superconductive winding. $\lambda^{\perp}$, $\lambda^{\parallel}$, $W \cdot m^{-1} \cdot K^{-1}$.

Thermal Conductivity. While the specific heat of the given materials does not depend on the direction of the thermal flux, the effective thermal conductivity of the superconductive windings is significantly anisotropic, (according to some data [9], $\lambda^{\parallel}$ is some 300 times greater than $\lambda^{\perp}$). Figure 3 shows temperature dependences of the thermal conductivity coefficient in three mutually perpendicular directions. The thermal conductivity of the longitudinal specimen ($\lambda^{\parallel}$) has a maximum at T = 25 K, which is related to the similar change in the thermal conductivity of the copper, with a maximum occurring in the 20-30 K range. Absolute values of $\lambda^{\perp}$ in the one or the other direction are significantly lower than $\lambda^{\parallel}$. The form of the $\lambda^{\perp}$ temperature dependences is completely different from that of $\lambda^{\parallel}(T)$.

At T_c the $\lambda^{\perp}(T)$ curves show a slight "flare" in thermal conductivity, of the order of 0.08 W/(m·K) for $\lambda_1^{\perp}$ and 0.16 W/(m·K) for $\lambda_2^{\perp}$ which is the result of correlation of the contributions of the thermal conductivities of the composites entering into the composition of the superconductive winding.

Knowing the thermophysical properties of the winding components, we can calculate the effective thermal conductivity in the direction parallel to the thermal flux quite simply, if we neglect transposition of the superconductive lead. The thermal conductivity in the longitudinal direction is equal to

$$\lambda^{\parallel} = \lambda_b^{\parallel} v_b + \lambda_c v_c, \tag{1}$$

where $v_b = 0.913$ is the relative volume content of the superconductive bus, $v_c = 0.087$ is the relative volume content of the binder and fiberglass insulation: $\lambda_b^{\parallel}$ and λ_c are the thermal conductivity coefficients of the bus in the direction parallel to the flux and the binder with fiberglass.

In turn $\lambda_b^{\parallel}$ can be written in the form

$$\lambda_b^{\parallel} = \lambda_c v_c + \lambda_s (1 - v_c), \tag{2}$$

where λ_c and v_c are the thermal conductivity and relative volume content of the stabilizing copper, λ_s is the thermal conductivity of the superconductor.

For specimen No. 1 the bus section and quantity of superconductor present are such that transposition of the superconductive wires can be neglected. Then $v_{NbTi} = 0.77$, $v_c = 0.23$ and knowing the thermophysical properties of the copper [10], NbTi [1], and binder [11], we can calculate $\lambda^{\parallel}$ of the winding. In Fig. 3 x is the calculated $\lambda^{\parallel}$ value. We see that the difference between $\lambda^{\parallel}_{exp}$ and $\lambda^{\parallel}_{calc}$ is large, but the qualitative character of $\lambda^{\parallel}(T)$ for the

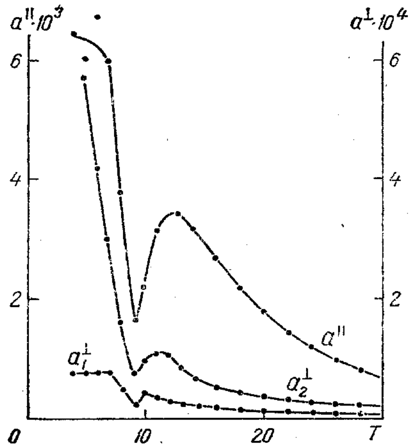

Fig. 4. Temperature dependences of superconductive winding thermal diffusivity coefficients. $a^{\perp}$, $a^{\parallel}$, $m^2 \cdot sec^{-1}$.

two cases agrees sufficiently well. The noncoincidence of the data may be caused by the high uncertainty of the method used to determine $\lambda^{\parallel}$, or by the fact that the thermal conductivity of the copper depends significantly on its purity and the technology of superconductive bus preparation, so that the λ_c values taken from [10] may not correspond to the true λ_c.

We will consider a model of the specimens in which the thermal flux is directed perpendicular to the superconductive bus. The transverse specimen can be represented as two parallel segments, one of which is the epoxy impregnating compound (in direction 2), or the epoxy compound with fiberglass (in direction 1), while the second consists of alternating layers of superconductive bus and epoxy compound with (1) or without (2) fiberglass (see Fig. 1). The thermal conductivity of the composite winding material in the transverse direction is determined by a combination of the effective thermal conductivities of the parallel segments, weighted for their respective areas:

$$\lambda^{\perp} = \lambda_1 \frac{S_1}{S_1 + S_2} + \lambda_2 \frac{S_2}{S_1 + S_2}, \tag{3}$$

where the subscript 1 refers to the epoxy compound, and 2 indicates the segment with the alternating layers.

$$\lambda_2 = \frac{(l_e + l_{fb} + l_b)\,\lambda_e \lambda_{fb} \lambda_b^{\perp}}{l_b \lambda_e \lambda_{fb} + l_e \lambda_{fb} \lambda_b^{\perp} + l_{fb} \lambda_e \lambda_b^{\perp}}, \tag{4}$$

where ℓ_e, ℓ_{fb}, ℓ_b are characteristic dimensions of the epoxy compound, fiberglass, and bus in the selected direction: λ_e, λ_{fb}, λ_b, are the corresponding thermal conductivity coefficients.

For a bus with square section and uniform distribution of superconductive wires [5] obtained the expression

$$\lambda_b^{\perp} = \lambda_c \left[\frac{\sqrt{1 + \frac{v_c}{v_s}} - 1}{\sqrt{1 + \frac{v_c}{v_s}}} + \frac{\lambda_s}{\left(\sqrt{1 + \frac{v_c}{v_s}} - 1\right)\lambda_s + \lambda_c} \right],$$

where λ_c and λ_s are the thermal conductivity coefficients of the copper and superconductor, v_c and v_s are their relative volume contents.

A calculation of $\lambda^{\perp}$ and $\lambda^{\parallel}$ was performed in [3] for a superconductive bus of rectangular cross section in which the multiwire conductor lies at an angle of 15°. With consideration of the fact that the wires were transposed in three mutually perpendicular directions and were not uniformly distributed over the bus section, but were located in the central portion, arranged not with cubic, but hexagonal packing, the calculation method of [3] was used to obtain the following expression for $\lambda^{\perp}$ of the bus:

$$\frac{1}{\lambda_{b}^{\perp}}=\frac{1}{\tilde{\lambda}^{\perp}+\tilde{\lambda}^{\parallel}}+\frac{1}{m}\left(\frac{1}{\tilde{\lambda}_{c}^{\perp}}\right) \tag{6}$$

where ($\tilde{\lambda}^{\perp}$ and $\tilde{\lambda}^{\parallel}$ are projections of $\lambda^{\perp}$ and $\lambda^{\parallel}$ in the direction of the thermal flux).

$$\frac{1}{\tilde{\lambda}^{\perp}}=\left(\frac{1}{\lambda_{s}^{\perp}}+\frac{m-1}{m}\frac{1}{\lambda_{c}^{\perp}}\right)\sqrt{\frac{1+\sin^{2}\varphi}{\cos\varphi}}, \tag{7}$$

$$\frac{1}{\tilde{\lambda}^{\parallel}}=(\lambda_{s}^{\parallel}+\lambda_{c}^{\parallel})\frac{\sin\varphi}{\sqrt{1+\cos^{2}\varphi}} \tag{8}$$

(m is the number of wires through which the thermal flux successively passes).

$$\lambda_{c}^{\perp}=\lambda_{c}\left[\frac{4}{\sqrt{3}}\operatorname{arctg}\left(\sqrt{3}\operatorname{tg}\frac{\pi}{2}\right)-\frac{\pi}{6}\right], \tag{9}$$

$$\lambda_{c}^{\parallel}=\left(1-\frac{\pi}{4}\right)\lambda_{c}, \tag{10}$$

$$\lambda_{s}^{\parallel}=\frac{\pi}{4}\lambda_{s}, \tag{11}$$

$$\lambda_{s}^{\perp}=\lambda_{s}, \tag{12}$$

$\varphi = 10°$ is the transposition angle.

Thus, knowing the thermal conductivity of the winding components and their relative volume content, Eq. (6) can be used to find $\lambda_{b}^{\perp}$, and then, substituting Eq. (4) in Eq. (3), the effective thermal conductivity of the winding in the transverse direction can be found. The values of $\lambda^{\perp}$ calculated in this manner are shown in Fig. 3 and denoted by the symbol (x). There is good agreement with $\lambda_{exp}^{\perp}$ at low temperatures.

Thermal Diffusivity. The thermal diffusivity coefficient plays an important role in determining stability criteria for superconductive magnets. For enthalpy stabilization it is necessary that the thermal diffusion coefficient, i.e., the thermal diffusivity, be greater than the magnetic, so that either the normal state region will be limited, or its temperature will be reduced and a superconductive state will develop therein. The rate of increase of the magnetic field in a superconductive magnet, proportional to the magnetic diffusion, is also limited to some degree by thermal diffusivity.

Figure 4 shows experimental temperature dependences of the thermal diffusivity coefficient of superconductive windings in three mutually perpendicular directions. We see that the thermal diffusivity coefficient, just like the specific heat, undergoes a discontinuity upon transition from the normal to the superconductive state. At T < 6 K a "plateau" occurs, apparently related to the low temperature "plateau" of metals [5]. On the curve of $a^{1}/_{2}(T)$ the "plateau" is absent because the values obtained at the given temperatures were simply too low. A high degree of anisotropy is also characteristic of the thermal diffusivity coeficient.

The studies performed indicate the need of experimental study of thermophysical properties of not only individual construction components, but, what is most important, of construction elements, especially those containing polymer composites.

LITERATURE CITED

1. K. Flachbart, A. Feher, S. Janos, et al., Phys. Status Solidi (B), 85, 545-551 (1978).
2. R. Khertsog and V. A. Malyuk, Measurement of Thermal Conductivity of Multiconductor Superconducting Cable in the Longitudinal Direction at Temperatures from 4 to 25 K in a Magnetic Field up to 7 T (Preprint OIYaI 9-12120) [in Russian], Dubna (1979).

3. U. Esher, Inzh. Fiz. Zh., 44, No. 3, 451-457 (1983).
4. B. Ya. Sukharevskii, A. V. Alapina, and Yu. A. Dushechkin, Zh. Éksp. Teor. Fiz., 54, No. 6, 1675-1679 (1968).
5. G. Brekhna, Superconductive Magnetic Systems [in Russian], Moscow (1976).
6. J. G. Hust, Cryogen., 5, No. 1, 8-11 (1975).
7. L. L. Vasil'ev, S. A. Tanaeva, and G. I. Bobrova, Porous Materials in Cryogenic Technology [in Russian], Minsk (1979).
8. R. Berman, Thermal Conductivity of Solids [in Russian], Moscow (1979).
9. T. E. Laskaris, Teploperedachiya, 100, No. 4, 157-163 (1978).
10. A. A. Novitskii and I. G. Kozhevnikov, Thermophysical Properties of Materials at Low Temperatures. A Handbook [in Russian], Moscow (1982).
11. L. S. Domorod, Energy and Mass Transport Processes in Porous Media with Phase Transitions [in Russian], Minsk (1982), pp. 128-134.

INSULATION PERFORMANCE FOR INDUSTRIAL VESSELS CONTAINING LIQUID N_2 AND H_2

G. G. Zhun', V. F. Getmanets, P. N. Yurchenko, R. S. Mikhal'chenko, V. I. Shalaev, and A. E. Kuts

UDC 536.21:536.48

A screenless method of using the cold in the vapor is found to be highly effective.

The performance in thermal shielding for cryogenic vessels in substantially dependent on how far use is made of the cold in the coolant vapor. We have found that maximum use can be made of this for small nitrogen vessels by a screenless method, i.e., by providing good contact between the layers of screening-vacuum insulation and the neck of the vessel throughout its length [1]. Particular interest therefore attaches to evaluating the performance of this simple method on nitrogen-free vessels containing liquid hydrogen, where the reduction in heat leak can attain a factor of 5-8. At present, there are commercial hydrogen vessels fitted with nitrogen guard jackets, which makes them heavy and complicates their use.

We have measured the heat transfer and performance in using the cold from nitrogen vapor or parahydrogen in a commercial Kh-34B vessel in various styles (Table 1). The heat transfer to the coolant vapor was evaluated by means of a standard polystyrene plug or a glass plug with vacuum-porous insulation. In the latter case, the vapor was passed through the central channel or through a gap between the plug and the neck. The neck was made of fiberglass plastic and was 210 mm long, diameter 60 mm, and wall thickness 1.2 mm. Outside, the neck was covered with 6-8 layers of EVTI-7 glass cloth. In the standard vessel, the insulation package had good thermal contact with this layer, while to eliminate it, we also made a vessel in which the insulation and the neck were separated by a gap of 2 mm. The insulation pack had an average thickness of 70 mm and consisted on PET-DA screens and new particularly effective inserts made of USNT-10 synthetic fibers containing carbon adsorbents.

Table 1 shows that the heat leaks to the hydrogen are less by a factor of three than to nitrogen. In these experiments, the polystyrene plug was cemented on all sides with a film of PET-DA. In the absence of that film, the hydrogen vapor diffused into the plug, which increased the heat leak appreciably. During the experiments lasting 1.5 months, there was no deterioration in the leakage due to hydrogen diffusing through the wall of the fiberglass neck.

We evaluated the insulation characteristics and the cold use by our method of calculating the thermal shielding [1, 2], which involves solving nonlinear two-dimensional conjugate thermal conduction equations for the plug and insulation pack, the one-dimensional case for thermal conduction in the neck with allowance for the heat transfer with the coolant vapors, and the radiative and conductive heat exchange between the outer wall of the neck and the insulation pack.

Low-Temperature Technical Physics Institute, Ukrainian Academy of Sciences, Kharkov.
Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 3, pp. 478-480, September, 1989. Original article submitted April 13, 1988.

