THEORETICAL–EXPERIMENTAL STUDY OF THE COOLING

OF SPIRAL CHANNELS

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A method of calculating temperature fields and time of cooling of spiral channels is developed and verified empirically.

The principal design used for toroidal-field superconducting magnets [1, 2] is a disk coil spirally wound from a hollow superconducting material. Before the coil is wound, the conductor is coated with a layer of electrical insulating material made of glass strip to insulate the current-carrying turns of the spiral from each other. The magnet is cooled to its working temperature and cryostated with a coolant which is circulated through cooling channels in the conductor. This operation must be carried out in such a way as to not create dangerous thermal stresses in the coil and not make cooling time too long or cooling costs too high.

The studies [3, 4] described a theoretical method which makes it possible to determine the temperature fields during cooling and the cooling time for a single disk coil. Estimates show that the temperature of the material in the cross section of the conductor is almost uniform. This makes it possible to describe the cooling process in a spiral disk coil by system of equations (1), with the appropriate initial and boundary conditions:

$$(\rho c_v f)_g \frac{\partial T_g}{\partial t} + (c_p G)_g \frac{\partial T_g}{\partial x} = \alpha \Pi (T_w - T_g),$$

$$(\rho c F)_w \frac{\partial T_w}{\partial t} = \alpha \Pi (T_g - T_w) + q_{\text{ovr}} + q_{\text{it}}, \tag{1}$$

$$\Delta P = \zeta \frac{l}{d_{\text{h}}} \frac{G_g^2}{2\rho_g f_g^2},$$

where

$$q_{\text{ovr}} = \frac{T_{wi-1} - T_{wi}}{R_{i,i-1}} + \frac{T_{wi+1} - T_{wi}}{R_{i,i+1}}$$

is a quantity determining the heat received by the i-th turn from the adjacent turns $(i-1)$ and $(i+1)$.

The coordinate x is directed along the cooling channel. Heat transfer between the channel wall and coolant is accounted for by heat-transfer coefficient α, while heat transfer between adjacent turns of the spiral is accounted for by the heat-transfer resistance per unit length of the conductor $R = \delta/h\lambda_{\text{in}}$.

In the case where the heat transfer from the channel wall to the coolant is fairly substantial ($(\alpha\Pi l/Gc_p)_g \geq 100$ [5]), the temperatures of the wall and coolant are nearly the same and system (1) can be replaced by the simpler system

$$((\rho c_v f)_g + (\rho c F)_w) \frac{\partial T}{\partial t} + (G c_p)_g \frac{\partial T}{\partial x} = q_{\text{ovr}} + q_{\text{it}}, \tag{2}$$

$$\Delta P = \zeta \frac{l}{d_{\text{h}}} \frac{G_g^2}{2\rho_g f_g^2},$$

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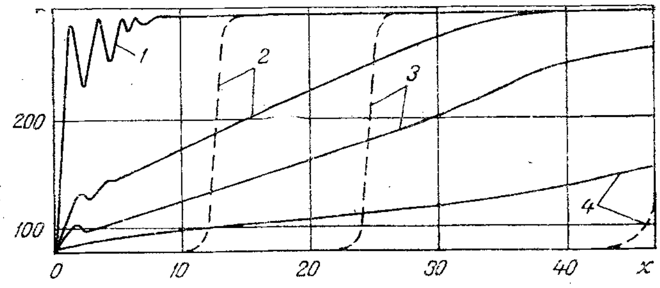

Fig. 1. Temperature fields in a conductor during the cooling of spiral and straight channels: 1) 1 min; 2) 10; 3) 20; 4) 40 (the solid line is the spiral, while the dashed line is the straight channel). T, °K; x, m.

where

$$q_{\text{ovi}} = \frac{T_{i-1} - T_i}{R_{i,i-1}} + \frac{T_{i+1} - T_i}{R_{i,i+1}}.$$

Calculations with systems (1) and (2) showed that the character of the cooling is significantly affected by heat transfer between the turns of the spiral. Figure 1 compared the conductor temperature distribution in the direction of coolant flow for a spiral disk coil and a straight conductor. The length and cross-sectional dimensions of the channels and the coolant flow rates were the same in both cases. It is apparent that an extensive temperature front is formed in a spiral with an insulation of finite resistance, instead of the moving temperature front typical of "long" channels [5-7]. Due to heat transfer through the inter-turn insulation, the temperature of the wall in the outlet cross section of the spiral channel decreases more rapidly than in the case of a "long" straight channel. As a result, the time of cooling of the spiral is greater. Also, during cooling of spirals there may be a wavelike temperature distribution along the conductor. The wavelength here is equal to the length of a turn of the spiral. The amplitude of the temperature wave decreases with time and with increasing distance from the channel inlet. This phenomenon is connected with additional transfer of heat through the inter-turn insulation to the region where the coolant enters the spiral.

The cooling of a conductor was studied experimentally on a model of a toroidal-field superconducting disk coil. A sectional view of the experimental spiral element, made of copper tubing and having 25 turns, is shown in Fig. 2. The length of the channel is 50.4 m; the inside and outside diameters of the spiral are 0.39 and 0.87 m. The insulating material between the turns was a compound based on epoxy resin with a filter. The total cooled mass of the element was 10.8 kg.

Tests of the element were conducted on a large helium test stand [4]. During the tests we measured the helium temperature at the channel inlet, the helium pressure at the inlet and outlet, and the temperature distribution along the copper tube.

In two series of experiments the cooling was done from room temperatures to nitrogen temperatures at a constant coolant flow rate. In the first series, the temperature of the helium at the inlet was changed suddenly. This was done by quickly opening the inlet control valve. During the second series, we ensured a linear decrease in helium temperature at the inlet over time through appropriate regulation of the power supplied to the electric heater located between the valve and the test element. The same cooling regime was repeated several times in each series of tests.

Figure 3 shows theoretical and experimental distributions of temperatures along the cooling channel for different moments of time. The thermophysical properties of the materials in the test element were a function of the test temperature. The heat-transfer resistance between the turns of the spiral was calculated from the thermal conductivity of the compound and was refined by comparing variants of calculating the cooling process against the empirical data with a stepped change in coolant temperature at the inlet. A preliminary analysis showed that the effective thickness of the inter-turn insulation of the disk coil model, made of a circular tube, was equal to the minimum gap between the adjacent channels (see Fig. 2). The

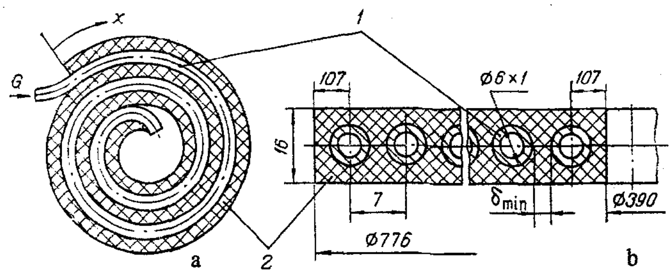

Fig. 2. General view and sectional view of test element: a) general view; b) sectional view of test element; 1) spiral channel; 2) insulating layer.

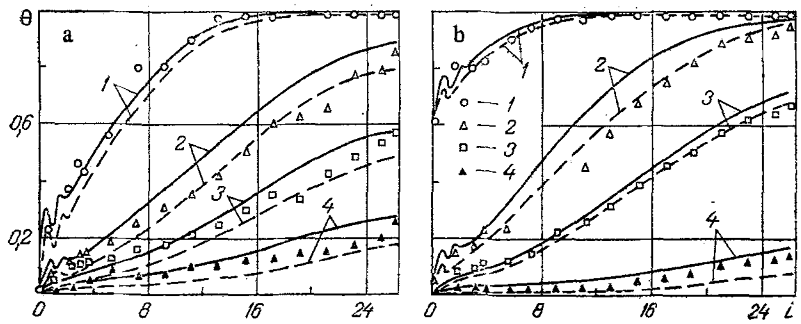

Fig. 3. Comparison of experimental and theoretical data on the cooling of the spiral test element: a) with a stepped change in coolant temperature at the channel inlet, flow rate $0.55 \cdot 10^{-3}$ kg/sec (1 — 300 sec; 2 — 1200 sec; 3 — 1800 sec; 4 — 2400 sec); b) with a linear change in coolant temperature at the channel inlet, time of temperature reduction 14 min, flow rate $0.63 \cdot 10^{-3}$ kg/sec (1 — 300 sec; 2 — 1200 sec; 3 — 1800 sec; 4 — 3600 sec; the solid line denotes results calculated with system (1), and the dashed line denotes data obtained with system (2)).

level of the heat inflow from outside was determined experimentally from the final steady state and was on the order of 40 W.

It can be seen from the figures that the results of calculations by methods (1) and (2) agree well with the test data for the initial stage of cooling and agree satisfactorily (mean deviation of theoretical data from experimental data 5-12%) during the intermediate stage. During the final stage of the cooling process, the results obtained by method (2) differ by 20% from the test data, while the results obtained by method (1) agree well with the test data. The discrepancy between the results calculated by the two theoretical methods (1) and (2) is due to an increase in the degree of effect of heat transfer to the coolant on cooling. Thus, simpler method (2) can be used to calculate cooling at the initial and intermediate stages, while it is preferable to use system (1) for the final stage.

Analysis of the test data showed that cooling is regular given a sufficiently long time. In particular, with a stepped change in coolant temperature at the inlet (Fig. 3a), the distribution of the flow temperature obeys the following exponential law beginning at a certain moment of time $\tau > \tau^*$

$$T(x, \tau) = T(x, \tau^*) \exp[k(\tau - \tau^*)].$$

The above theoretical—experimental study of the cooling of spiral channels also made it possible to develop a simplified model of a disk coil in order to determine the cooling time of the spiral. The model is in the form of a single channel of a length equal to the length of the entire spiral channel referred to the total number of turns, which is equivalent to the length of the middle turn of the disk coil (l_{mi}). The principal parameters of the model channel are determined by the relations $G_{mod} = G$, $m_{mod} = M/l_{mi}$, $S_{mod} = \Pi l$, $\zeta_{mod} = \zeta$.

The above method makes it possible, with an accuracy sufficient for practical purposes, to make use of well-known results of studies on determining the cooling time of single channels with allowance for the second cooling period [5].

NOTATION

G, coolant flow rate, kg/sec; d_h, hydraulic diameter, m; ΔP, pressure drop between the inlet and outlet of the cooling channel, N/m^2; Π, perimeter wetted by the flow, m; F, f, cross-sectional areas of conductor and cooling channel, respectively, m^2; h, thickness of disk coil, m; M, m, total and unit cooled masses, kg; k, coefficient, 1/sec; S, internal heat-transfer surface of cooling channel, m^2; T, temperature, °K; t, time, sec; x, longitudinal coordinate along the cooling-channel axis, m; l, length of the conductor, m; R, heat-transfer resistance of the inter-turn insulation per unit length of the channel, K·m/W; c, specific heat, J/(kg·K); q, heat inflow per unit length of channel, W/m; α, heat-transfer coefficient, W/(m^2·K); ρ, density, kg/m^3; λ, thermal conductivity, W/(m·K); δ, thickness of the inter-turn insulation, m; ζ, coefficient of hydraulic resistance; $\theta = (T - T_{fin})/(T_{ini} - T_{fin})$, dimensionless temperature. Indices: w, wall; g, gas; v, at constant volume; p, at constant pressure; in, insulation; ini, fin, initial and final states; mi, middle turn; mod, model; i, number of turn; min, minimum value; ovr, overflow; it, internal.

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