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MODELING OF COOLDOWN OF THE SPIRAL ELEMENTS OF CIRCULATION SYSTEMS FOR CRYOSTATS WITH A GASEOUS COOLANT. 2. SYSTEM OF DISK COILS

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The effect of the thermophysical properties of the structural materials and thermohydraulic parameters of the coolant on cooldown of a superconducting magnet with nonuniform distribution of the collant flow rate in the cooling channels is studied.

In the first part of this work we studied the effect of the thermophysical properties of the structural materials as well as the properties and state parameters of the coolant on the nature of the temperature fields and the cooling time of a single spiral disk coil of a superconducting magnet. However, the windings of such magnets consist of a set of adjacent disk coils, whose cooling channels are connected hydraulically in parallel. Heat transfer through the electrical insulation occurs between neighboring disk coils. Insignificant technological deviations during the preparation of the disk coils could cause the hydraulic characteristics of the cooling channels to differ from one another. This could cause the disk coils in the winding of the magnet to cool down at a different rate. The latter is undesirable from the viewpoint of both minimizing the cooldown time of the winding and the appearance of additional mechanical stresses in the structure. As shown in [1], the cooldown time of two thermally insulated but hydraulically coupled "long" channels ($\hat{S}t^* = \alpha \Pi L/(Gc_p)_g \geq 100$) increases severalfold, if there initially exists a small (~5%) nonuniformity in the flow-rate distribution in the channels, but the total flow rate is constant. This is explained by the fact that the relative fraction of the coolant flow in the colder channel increases with time, as a result of which its rate of cooling continues to increase, while the rate of cooling of the other channel decreases.

Interchannel heat transfer causes a redistribution of the contribution of the channels to the cooling of the system, as a result of which the channel with the higher coolant flow rate participates in the cooldown of the channel with the lower coolant flow rate. In addition, the temperature gradient between the channels decreases. A relation which permits evaluating the cooldown time of two "long" parallel, straight channels as a function of the degree of nonuniformity of the distribution of the coolant flow rate and the magnitude of the thermal resistance of the interchannel insulation is recommended in [2]. This relation can be put into the following dimensionless form:

$$t(\Theta = 0{,}5) = 1 + \frac{\ln 0{,}5}{K_{\perp}}(2g-1)(1-g), \tag{1}$$

where

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$$K_{\perp}=\frac{2}{R_{\perp}(Gc_p)_{\Sigma}}=\frac{2\lambda hL}{\delta(Gc_p)_{\Sigma}};\quad g=\frac{G_2}{G_1+G_2}=\frac{G_2}{G_{\Sigma}};$$
$$t=\frac{\tau}{\tau_b};\quad \tau_b=\frac{(Mc)_{\Sigma}}{(Gc_p)_{\Sigma}}.$$

Here the index 1 refers to the channel with the high coolant flow rate. Regions in which the effect of interchannel heat transfer on the cooldown time is strong are separated from regions in which this effect is weak. In the region with the strong effect ($K_{\perp} > 10 \ln 0.5 (2g - 1)(1 - g)$) the cooldown time of the system differs by less than 10% from τ_b. In the region with the weak effect ($K_{\perp} < \ln 0.5 (2g - 1)(1 - g)g/(0.91 - 2g)$) the cooldown time of the channel with the lower flow rate is determining.

The relation (1) is not suitable for spiral windings, since it does not take into account heat transfer between the loops of the spiral. The inequalities presented above, however, can be employed to evaluate the intensity of the thermal interaction between the neighboring disk coils of the winding of the superconducting magnet.

Under the cooldown conditions the total coolant flow rate and its distribution over the disk coils of the winding can change with time. For this reason, an accurate thermal calculation must be made simulteneously with the hydraulic calculation. An example of such calculations for a specific construction of the windings is described in [3]. The analysis involved in the generalization of the computational results to the family of coils of the spiral type, however, is difficult to carry out because of the large number of parameters determining the process. A more restricted problem, in which the conditions under which the temperature distribution over the disk coils of the winding and the rate at which the disk coils cool down are practically the same are sought, can be studied independently from the hydraulic problem, since under these conditions the ratio of the coolant flow rates along the cooling channels of the disk coils remains practically constant throughout the entire process [3].

We analyze below the effect of the thermophysical properties of the structural materials and the thermohydraulic parameters of the coolant on the simultaneity of the cooldown of the winding of a superconcuting magnet consisting of identical spiral disk coils cooled in parallel with a nonuniform distribution of the coolant flow rate in the channels.

The cooldown of the spiral disk coils interacting thermally with one another in pairs with a constant coolant flow rate along the cooling channels, under the condition that $St^* \geq 100$, is described by the dimensionless system of equations [by analogy with the system (4) from the first part of this work]

$$\frac{\partial\Theta_i}{\partial t}+A_i\frac{\partial\Theta_i}{\partial X_i}=Q_{1i}+Q_{2i},\quad i=1,\ \dots,\ I; \tag{2}$$

where $Q_{1i} = K_{\parallel}(\Theta_{i,j-1} - 2\Theta_{i,j} + \Theta_{i,j+1})$ is the magnitude of the heat inflow into the j-th loop of the i-th disk coil from the (j − 1)-st and (j + 1)-st loops of the same disk coil; $Q_{2i} = K_{\perp}(\Theta_{i-1,j} - 2\Theta_{i,j} + \Theta_{i+1,j})$ is the magnitude of the heat inflow into the same j-th loop of the same i-th disk coil from the neighboring (i − 1)-st and (i + 1)-st disk coils.

In the system of equations (2)

$$\Theta_i=\frac{T_i-T_{\text{fin}}}{T_{\text{ini}}-T_{\text{fin}}};\quad A_i=\frac{(Gc_p)_i}{(mc)_i}\,\frac{\sum_i (mc)_i}{\sum_i (Gc_p)_i};$$

$$K_{\parallel}=\frac{\sum_i (Mc)_i}{R_{\parallel}(mc)_i\sum_j (Gc_p)_i};\quad K_{\perp}=\frac{\sum_i (Mc)_i}{R_{\perp}(mc)_i\sum_i (Gc_p)_i};$$

$$t=\frac{\tau}{\tau_b};\quad \tau_b=\frac{\sum_i (Mc)_i}{\sum_i (Gc_p)_i};\quad X_i=\frac{x_iN}{L}.$$

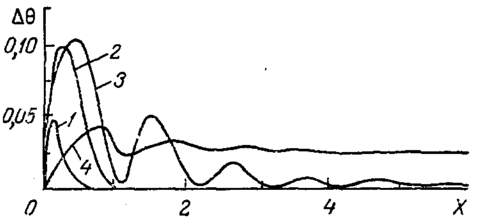

Fig. 1

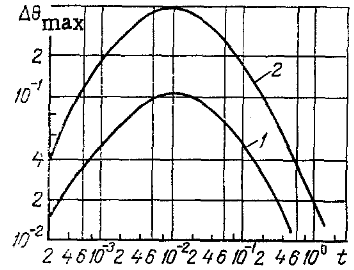

Fig. 2

Fig. 1. Profiles of the difference of the dimensionless temperatures along the cooling channels of neighboring disk coils ($K_\perp$ = 20, $K_\parallel^{(1)}$ = $K^{(2)}$ = 100, g = 0.417, N = 40): 1) t = 0.001; 2) 0.006; 3) 0.012; 4) 0.1.

Fig. 2. The change in the maximum dimensionless temperature difference between two neighboring disk coils as a function of time ($K_\perp$ = 20, $K_\parallel^{(1)} = K_\parallel^{(2)}$ = 100, N = 40): 1) g = 0.417; 2) 0.2.

The system (2) is supplemented by the obvious conditions $G_\Sigma = \sum_i G_i,\quad (Gc_p)_\Sigma = \sum_i (Gc_p)_i,$ $(mc)_\Sigma = \sum_i (mc)_i,\ (Mc)_\Sigma = \sum_i (Mc)_i$ and the corresponding initial and boundary conditions.

We shall examine the case of the cooldown of two identical spiral disk coils in thermal contact with one another by a gaseous coolant. Then $A_i = 2(Gc_p)_i/(Gc_p)_\Sigma,\ K_\parallel = 2L/((Gc_p)_\Sigma R_\parallel),$ $K_\perp = 2L/((Gc_p)_\Sigma R_\perp)$. Figures 1 and 2 show some results of the calculations using the system of equations (2). It is evident from Fig. 1 that the temperature difference near the inlet to the disk coil initially increases rapidly (curves 1 and 2). Later the distribution of the temperature difference acquires a periodic form along the channels with an amplitude which decreases in space and time. The spatial periodicity of the behavior of the curves is linked with the periodicity of the spiral structure. The nature of the change in the maximum temperature difference as a function of time $\Delta\Theta_{max}$ (see Fig. 2) is determined by the presence of competing processes, occurring during the cooldown of the disk coils. On the one hand, the existence of the nonuniformity of the coolant flow rate along the channels leads to the appearance and subsequent growth of the temperature head between the channels, while on the other the increase in the temperature difference and the surface area of active heat exchange between disk coils intensifies heat transfer, which encourages temperature equalization in the system. For this reason, rapid growth of the temperature head occurs only at the very beginning of the cooling process; later its rate of change slows down owing to intercoil heat transfer through the insulation. The last factor begins to dominate in time, which gives rise to a gradual reduction of the temperature difference between the disk coils. Thus the heat inflow through the insulation from the disk coil with the lower coolant flow rate to the disk coil with the higher coolant flow rate causes the hydraulically "best" disk coil to participate in the cooling of the "worst" coil.

We shall call the equalization time, which we shall denote by t_e, the time at which the maximum of the dimensionless temperature difference between the disk coils $\Delta\Theta_{max}$ assumes a value of the order of 0.01-0.02 (in this case it may be assumed that the temperatures of the neighboring spiral channels are actually equal along their entire length). Figure 3 shows the curves of $\Delta\Theta_{max}$ as a function of time for different degrees of nonuniformity of the coolant flow rate along the channel and different values of the thermal interaction parameter between the disk coils $K_\perp$. It is evident from the figures that the equalization time is significantly affected by both the intensity of the interdisk heat transfer and the degree of nonuniformity of the flow rate distribution. For values of g close to 0.5 (Fig. 3a) relatively weak interdisk heat transfer gives rise to rapid equalization of the temperature in neighboring disk coils. As the nonuniformity of the flow rate distribution increases (for example, Figs. 3b and c) the magnitude of the parameter $K_\perp$, for which the equalization time of the temperature of the disk coils remains the same, increases. It is also evident from the figures that even for very significant nonuniformities of the flow rate along the channels (Figs. 3c and d) heat transfer between disk coils, owing to the low values of the paramter $K_\perp$ ($K_\perp$ = 20), equalizes the temperatures in neighboring disk coils to a degree of nonuniformity of 2-3% in a time t ≃ 1. Nonetheless, at the initial stage of cooldown under these conditions $\Delta\Theta_{max}$ is

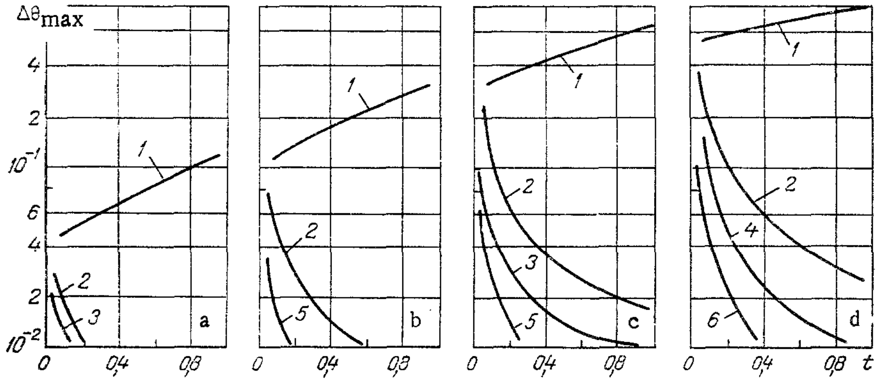

Fig. 3. Effect of nonuniformity of the coolant flow rate g along the channel and the thermal interaction parameter $K_\perp$ on the change in the maximum of the dimensionless temperature difference between two neighboring disk coils as a function of time ($K_\parallel^{(1)} = K_\parallel^{(2)} = 100$, N = 40): a) g = 0.47; b) 0.417; c) 0.33; d) 0.2; 1) $K_\perp$ = 0; 2) 20; 3) 40; 4) 60; 5) 80; 6) 100.

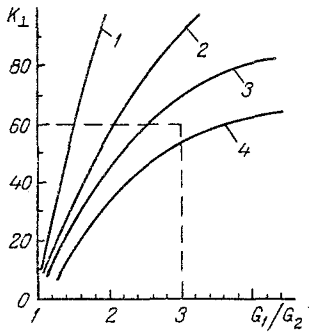

Fig. 4. Diagram of the effect of the nonuniformity of the flow rate distribution of the coolant g and the thermal interaction parameter $K_\perp$ on the temperature equalization time for cooldown of the spiral disk coils: 1) t_e = 0.2; 2) 0.3; 3) 0.5; 4) 1.

often significant ($\Delta\Theta_{max}$ = 0.2–0.5) and does not fall below the level $\Delta\Theta_{max}$ = 0.1 over a time of the order of t ≈ 0.1–0.2.

The curves shown in Fig. 4 correspond to different values of the equalization time of the temperature to $\Delta\theta_{max} \approx 0.01$ in neighboring disk coils (t_e = 0.2, 0.3, 0.5, and 1). With the help of the figure the temperature equalization time t_e can be evaluated for known values of the nonuniformity of the flow-rate distribution and the parameter $K_\perp$. For example, let $G_1/G_2 = 3$ and $K_\perp = 60$. Then it follows from Fig. 4 that the temperatures of neighboring disk coils will become practically identical within a time $0.5 < t_e < 1$, since the point of intersection of the normals, reconstructed from the corresponding locations of the coordinate axes, lies between the lines t_e = 1 and t_e = 0.5.

The results presented here and in the first part of this work make it possible to analyze the cooldown process for disk coils whose cooling channels are connected hydraulically in parallel. In the case when the values of g and $K_\perp$ are such that the points corresponding to them in the plane of Fig. 4 lie above the curve t_e = 0.2, the disk coils cool down simultaneously, while the temperatures of the disk coils are practically equal throughout the entire process. If the points of intersection of the normals lie above the curve t_e = 1 but below the curve t_e = 0.2, the disk coils also cool down simultaneously, but for a definite period of time there is a temperature gradient between the disk coils, whose magnitude and change with time can be evaluated employing Fig. 3. In all cases, when the points corresponding to definite values of the parameters g and $K_\perp$ lie above the curve t_e = 1, the cooldown time can be estimated by employing the relations presented in Part 1 of this work, using in this case the total flow rate for the coolant flow rate and the total mass for the mass of the object. If the parameters g and $K_\perp$ are such that the points on the diagram corresponding to them lie below the curve t_e = 1, the disk coils cool down with a significant temperature gradient between them. To estimate the cooldown time of the system in this case the coolant flow rate in the "worst" (in the hydraulic sense) disk coil must be used, in addition to the results of [1, 2].

Simple estimates carried out for disk coils of a superconducting magnet system of the T-15 setup show that 5% deviation of the hydraulic diameter of the cooling channels from the nominal value leads to nonuniformities of the coolant flow rate along the channel of the order of 40%. Estimate of the value of the parameter of heat transfer between disk coils for T-15 gives $K_{\perp} = 80$. It is evident from Fig. 4 that the point corresponding to these values lies above the curve $t_e = 0.2$, so that the disk coils of the superconducting winding cool down at practically the same rate.

NOTATION

c, specific heat capacity, J/(kg•K); G, mass flow rate of the coolant, kg/sec; g, magnitude of the nonuniformity of the distribution of the coolant flow rate in a system of two channels; H and h, width and thickness of the conductor, m; I, number of disk coils in the winding; i, number of the disk coil; $K_{\perp}$, $K_{\parallel}$, dimensionless thermal interaction parameter between neighboring disk coils and between neighboring loops of the spiral; L, length of the cooling channel, m; M, mass, kg; m, mass per unit length of the channel, kg/m; N, number of loops in the spiral; Q, dimensionless thermal load per unit length; $R_{\parallel} = \delta/(\lambda H)$, $R_{\perp} = \delta/(\lambda h)$, thermal resistance of a unit length of the insulation layer between neighboring loops of the disk coil and between disk coils, K•m/W; T, temperature, °K; t, dimensionless time; X and x, dimensionless and dimensional (m) spatial coordinates; δ, thickness of the interloop insulation, m; λ, coefficient of thermal conductivity of the insulation, W/(m•K); $\Theta = (T_w - T_{fin})/(T_{ini} - T_{fin})$, dimensionless excess temperature of the wall; $\Delta\Theta$, dimensionless temperature difference; τ, time, sec; $\tau_b = (Mc)_{\Sigma}/(Gc_p)_{\Sigma}$, heat-balance cooldown time, sec; $St^* = \alpha\Pi L/(Gc_p)_g$, modified Stanton parameter. The indices are: p, constant pressure; w, wall; ini, fin, initial and final states; Σ, total value; e, equalization time of the temperature; max, maximum value; and g, gas.

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INTERNAL STRUCTURE OF COMPOSITE MATERIALS BY USING COMPUTER TOMOGRAPHY

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Results are presented of tomographic investigations of the internal structure parameters of composite materials characterized by an elementary cell density distribution over the specimen volume.

To solve many characteristic heat and mass transfer problems in shells of composite materials, a preliminary investigation of properties of their internal structure is necessary. The quantity of inhomogeneities and defects, their size, orientation, and mutual location in space will predetermine elapsing processes to a great extent. The predominance of any transfer mechanism and the very physics of the phenomenon depend on the internal structure of composites.

Utilization of x ray computer tomography affords great possibilities in investigations. Without disturbing the integrity of the shell specimen it permits reconstruction of the pattern of its spatial sections, measurement of the geometric dimensions and the relative arrangement of internal structure elements, and a quantitative estimation of the density distribution of the material and the porosity in any section of the specimen.

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