METHOD FOR LIMITING THE LOSSES OF LIQUID HELIUM IN TRANSITIONS OF SUPERCONDUCTING MAGNETS TO THE NORMAL STATE

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A simple method for limiting the losses of liquid helium and the pressure rise in a cryostat in transitions of superconducting magnets to the normal state is suggested. It involves the application of a layer of porous fiber insulation to the magnet surface. We investigated the influence of such a layer on the amount of liquid helium evaporated and on the pressure rise in a cryostat in the transition of a superconducting laboratory-scale magnet to the normal state.

In transitions to the normal state (from now on "in transitions" for a simplicity) of superconducting magnets with a high current density ($\sim 10^8$ A/m^2), a considerable portion of the stored magnetic energy is liberated in the winding of the magnet due to the limited discharge voltage (usually, < 500 V). In immersible superconducting magnets, i.e., those located in liquid-helium cryostats, when the dimensions of the magnets are increased, this portion of energy can be much larger than the overall heat of evaporation of the entire liquid helium in the cryostat. When the removal of gas from the cryostat is limited and it is borne in mind that under normal conditions 1 liter of liquid helium gives 770 liters of gaseous helium, there is a danger that the pressure in the cryostat might exceed the level of operation of the protecting membranes (~2 atm). This leads to venting of the gas to the atmosphere and its irreversible loss. Moreover, the process of pressure rise in the cryostat becomes faster, because of the sudden boiling up of the liquid helium on the magnet surface, which is heated to high temperatures after its transition (~100 K). This happens because the liquid is captured by the gas flows and carried the upper, warm part of the cryostat, where it evaporates. We should note that the foregoing does not apply to superconducting magnets with circulation cooling (a cooling agent is pumped through the inner channels of the conductor) or with indirect cooling (a cooling agent is pumped through tubes being in thermal contact with the surface of the magnet). In these cases, the amount of cooling agent is small.

Of the few attempts to solve the problem of limiting the pressure rise in a cryostat in transitions of large immersible superconducting magnets we can mention work [1], in which it is suggested to enclose a magnet into a protecting cap with a regulated valve at the top. This reduces the quantity of liquid that can be evaporated in transitions and correspondingly decreases the pressure rise in the cryostat. Aside from the awkwardness of the construction, other drawbacks of this approach involve an increase in the dimensions of the cryostat. Care should be taken that after the displacement of liquid from under the cap by evaporated gas the cryostat not be overfilled with liquid.

Our approach to the problem consists in locating a layer of thermal insulation directly on the surface of the magnet. Physically, this represents the introduction of a large thermal resistance between the heated magnet and the liquid helium, which substantially reduces the temperature difference between the cooling agent and the heat-generating surface, thus preventing intense (as regards heat removal) film boiling.

In experiments we used a superconducting magnet with an inner diameter of 45 mm, an outer diameter of 150 mm, and a height of 150 mm that generated a magnetic field with an induction of 11.5 T. The magnet consisted of three sections: an inner section of niobium-tin and middle and outer sections of niobium-titanium conductors of different diameters. The magnet was located in a cryostat with an inner diameter of 210 mm and a height of 1140 mm; it hold 30 liters of liquid helium (see Fig. 1).

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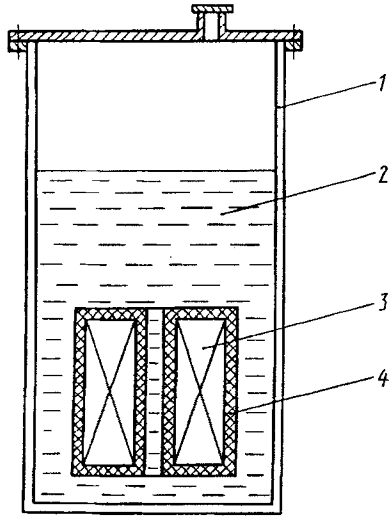

Fig. 1. Diagram of experimental setup: 1) cryostat; 2) cooling agent; 3) superconducting magnet; 4) heat-protecting shell.

To select an optimum thickness of the heat-protecting shell, it is necessary to take into account two opposite conditions. First, the shell should be thick enough that the heat flux to the cooling agent cannot exceed the critical heat flux corresponding to a change-over from the low-intensity heat removal of bubble boiling ($q < 10^4$ W/m^2) to a much more intense film boiling regime ($q > 2 \cdot 10^4$ W/m^2). Second, the shell should be thin enough not to greatly prolong the time of magnet cooling after transition (equality of the characteristic times of cooling of the shell and of the magnet itself).

In a model representation of the heat-protecting shell and winding of the magnet by a continuous layer, it is easy to obtain mathematical expressions for these conditions. The first condition leads to the following expression for the shell thickness:

$$d > \lambda_1 \frac{T_{cr}}{q_{cr1}}. \tag{1}$$

The second condition is transformed into the expression

$$d < (R_2 - R_1) \left(\frac{\lambda_1 c_2}{\lambda_2 c_1} \right)^{1/2}. \tag{2}$$

Using expressions (1) and (2) for a shell made of cotton wool, we obtain a thickness of from 5 to 50 mm. In conformity with these estimates, we made two 20-mm-thick cotton-wool and glass fibre heat-protecting shells for the magnet surface.

In successive experiments with the magnet without a shell and in heat-protecting shells we investigated the dependences of the pressure rise in the cryostat and of the amount of evaporated liquid on the time after transition (the duration of the transition itself was ~1 sec). The first dependence is presented in Fig. 2a. The glass fibre shell gave the best result. In this case, the pressure grew smoothly, its maximum was displaced to the region of large times and turned out to be much smaller than that for the case of a "naked" magnet. Figure 2b displays the dynamics of the change in the amount of the liquid evaporated from the cryostat. The level marked 11.5 liter on the ordinate axis corresponds to the stored magnetic energy expressed in terms of the amount of the liquid evaporated (the energy divided by the volumetric heat evaporation under normal conditions). The fact that the curves for the magnet in heat-protecting shells asymptotically approach this level but do not intersect it means the absence of dropwise entrainment of liquid by a gas in contrast to the magnet without a shell.

The use of the temperature dependence of the specific resistance of a copper matrix of superconducting wires [2] and measurements of electric resistances of the sections makes it possible to determine their mean

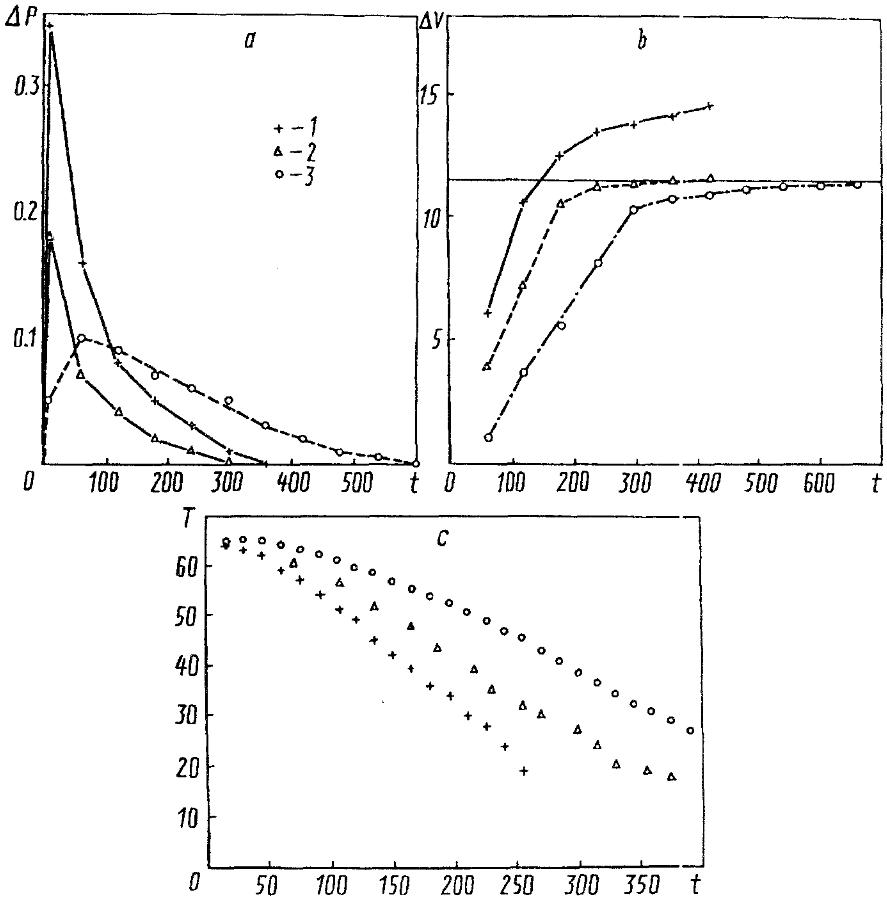

Fig. 2. Dependence of pressure rise in cryostat ΔP, 0.1 MPa (a) on the volume of liquid helium evaporated from the cryostat ΔV, 10^{-3} m^3 (b) and on the averaged temperature of the middle niobium-titanium section of the magnet T, K (C) on the time t, sec, after transition of superconducting magnet to the normal state: 1) magnet without a heat-protecting shell; 2) cotton-wool heat-protecting shell; 3) glass fibre heat-protecting shell.

temperatures immediately after transition and in the process of cooling virtually up to the return to the superconducting state. The effect of a heat-protecting shell and its material on the process of the cooling of a magnet after transition without addition of a cooling agent is displayed in Fig. 2c (the dynamics of cooling of the middle niobium-titanium section is shown as an example). It is seen that the presence of a heat-protecting shell on the surface of the magnet does not greatly prolong the time to the return to the superconducting state (by 3–4 min).

CONCLUSIONS

The results obtained indicate a positive effect of the layer of heat insulation on the surface of a superconducting magnet on thermal processes in a cryostat in transitions to the normal state.

First, the amount of evaporated liquid helium corresponds precisely to the magnetic energy stored in the magnet, indicating the absence of a dropwise entrainment of liquid by gas compared with the case without a heat-protecting shell. This makes it possible to save a large amount of liquid cooling agent in transitions of a superconducting magnet to the normal state (3 liters at the 11.5 level, constituting more than a quarter for the magnet used).

Second, pressure in the cryostat after transition of a superconducting magnet to the normal state increases more smoothly, and the maximum of this growth turns out to be substantially smaller (0.1 atm as against 0.35 for the case of the absence of a heat-protecting shell).

NOTATION

q, heat flux density (W/m^2); d, thickness of heat-protecting shell (m); λ_1, λ_2, thermal conductivity coefficients of heat-protecting shell and magnet averaged over the temperature range from the maximum heating of winding to the liquid helium temperature (W/(m·K); T_{cr}, critical temperature head corresponding to transition from the bubble to the film mode of boiling (K); q_{cr1}, density of the first critical heat flux, W/m^2; R_1, R_2, inner and outer radii of the magnet, m; c_1, c_2, specific volumetric heat capacities of heat-protecting shell and of magnet averaged over the temperature range from the maximum heating of the winding to the liquid helium temperature, J/(m^3·K).

REFERENCES

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