Thermal conductivity in a sample simulating the winding structure of Bi-2223/Ag epoxy impregnated coils

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Abstract. We measured the effective thermal conductivity in samples simulating the structure of Bi-2223/Ag impregnated coils at liquid nitrogen temperature. We also studied the effect of the sample orientation with respect to the coolant surface: samples with the cooled surface in the horizontal and vertical positions were measured. The effect of heat drains located between the layers of the tape on the effective thermal conductivity was studied. Its increase is important for coils conductively cooled by refrigerators. Our experimental results are compared with those obtained by other authors using model calculations.

1. Introduction
Thermal conductivity is an important parameter of HTS superconducting windings cooled by conduction as well as for those cooled by liquid nitrogen. As known, the HTS tapes (Bi-2223, YBCO) carrying transport current or exposed to AC external field can produce heat. The resistive transition starts in areas with the largest field component perpendicular to the tape plane. In these tape sections the heat dissipation is the largest. The maximal stable current which can be carried by the winding is controlled by thermal processes in the winding.

Another source of heat are AC losses in the winding operating in AC regime. It is very important to evacuate the heat to the coolant at the minimal heating of the winding. The heat flux is driven by the temperature gradients depending on the thermal material properties and local orientation of flux. We studied the thermal conductivity in models simulating windings and tried to increase the thermal conductivity by heat drains.

Our study was mainly experimental. In this work we studied thermal conductivity of winding structures simulating impregnated Bi-2223/Ag windings, we also prepared a sample with heat drains, which were used many years ago in NbTi coils, operating with large $dI/dt$.

Thermal conductivity of particular elements of the winding was experimentally studied in broad temperature interval from helium to room temperatures [1]-[7]. The temperature distribution within the cross-section of a model winding structure was calculated in [8].

Nevertheless, thermal conductivity of a real winding is less clear. It is important to compare the results obtained by theoretical models based on numerical simulations [9] with experiment.
2. The model of a winding structure

The coil winding is an isotropic structure with respect to the orientation of the heat flux. In the radial direction the tapes are stacked and the gaps are filled by epoxy resin. The integral thermal conductivity can be calculated by a similar way as that used for electric circuits. The thermal conductivity of silver is dominant. The resulting thermal conductivity is given by the parallel connection of silver, superconducting filaments and epoxy resin. In the axial direction of the coil winding the configuration is more complex and the numerical calculations of the effective thermal conductivity is necessary. Another way is to build this configuration in form of an experimental model and to test the effective thermal conductivity behavior of the whole complex with an appropriate temperature gradient at some selected temperature level. In our study we have chosen this way. The scheme of the structure is in Figure 1. We used the model winding with matrix of 6 x 10 pieces. The heater is located at one side of the columnar structure. The structure is covered by thermally insulating material, except the side opposite to the heater. The complex is immersed in LN$_2$ at 77 K. The differential thermocouples were used to monitor temperature field in the sample. TC-1 measures the temperature difference in the axial direction, between points 1 and 2, $\Delta T_1$ (see Figure 1). The thermocouple TC-2 monitors the temperature difference between point 2 and the coolant, $\Delta T_2$.

![Figure 1](image-url)  
*Figure 1* The scheme of a model winding structure with thermally insulating envelope

3. The model of winding structure with drains

The conductively cooled coils are often surrounded by a cover from high thermal conductivity material to improve the cooling of the winding. Less attention is paid to improve the effective thermal conductivity of the coil structure itself, especially in the axial direction. We used a simple method to improve effective thermal conductivity of a model structure using insulated copper wires build in parallel with stacked columns (see Figure 2). The geometry and realization of the sample was practically the same as that used in the standard winding structure without drains. In both cases the volume fraction of epoxy was around 3 %.
4. Results and discussion

The maximum temperature increase at one side of the heated model structure was 10 K. In the calculation of the effective thermal conductivity we use the outer sample dimensions and suppose it is macroscopically homogeneous. The radial heat removal through the thermal insulation was neglected and the heat flux density is calculated as power dissipated in the heater divided by surface $A$ of the backside. The temperature drop $\Delta T_j$ over the distance 30.6 mm parallel to the column axis represents the gradient.

The effective thermal conductivity is calculated according as

$$\lambda_{\text{eff}} = \frac{l}{A \Delta T} \int q \, da,$$

(1)
where $\Delta T$ is the temperature difference between the ends of the measured body portion, $\lambda_{\text{eff}}$ is the effective thermal conductivity, $l = 30.6$ mm is the length of the measured portion, and $A$ is the cross-sectional area of the body. We got $\lambda_{\text{eff}} = 15$ W m$^{-1}$ K$^{-1}$. The surprise was that the simple model calculation involving thermal conductivities of constituents (Ag, Bi-2223, epoxy) revealed approximately the same result: $\lambda = 11.945$ W m$^{-1}$ K$^{-1}$.

The incorporation of parallel drains in the model structure dramatically improved the effective thermal conductivity in the direction parallel to coil axis. Effective thermal conductivity increased 5 to 10 times. We found that the effective thermal conductivity of the winding structure is strongly influenced by the relative presence of epoxy in the structure volume. This may explain lower effective thermal conductivities for standard structure configuration (without drains) obtained in numerical calculations in [9] (3-4 W m$^{-1}$ K$^{-1}$ for 10 % epoxy at 77 K). A change of the sample orientation with respect to the surface (samples with the cooled surface in the horizontal and vertical positions) has a very little effect.

5. Conclusion

The measurement of effective thermal conductivity of models of Bi-2223/Ag epoxy impregnated coil structure in its axial direction showed that the thermal conductivity is two orders of magnitude lower than the silver matrix conductivity. It is still three times higher than that obtained by numerical models used in [5]. This is probably a consequence of a smaller portion of epoxy in the structure volume in our experiment that was anticipated in calculations in [9].

Implementation of parallel copper drains in the model structure significantly increased the effective thermal conductivity in the axial coil direction which is of importance especially for conductively cooled Bi-2223 coils.

6. Acknowledgements

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