ANALOG SIMULATION AS A MEANS OF CALCULATING THE COOLING OF LAMINATED MAGNETIC CIRCUITS

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A method of calculating the cooling of laminated magnetic circuits under vacuum conditions is proposed. The problem is reduced to finding the two-dimensional steady-state continuous temperature field for mixed boundary conditions. Numerical solutions are obtained for a heating core using the analog simulation technique and an EI-12 integrator.

This paper is concerned with the forced cooling of laminated magnetic circuits, transformers, electrical machines and MHD converters, and the calculation of the corresponding temperature fields under vacuum conditions.

A rather effective means of removing the joule heat from a magnetic circuit is to form channels in the clamping plates through which coolant can flow. If the pack is very thick there may be several such plates (Fig. 1). In this arrangement the insulated laminations are parallel to the plates. Although in this case the cooling rate is not as good as when the planes of the cooling elements are perpendicular to the laminations, the compression of the pack ensures close contact with the cooling plate and the absence of random gaps, which in a vacuum may lead to large temperature differences.

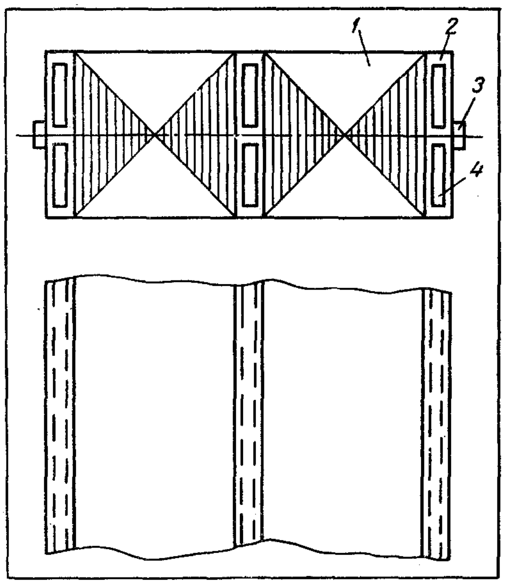

Fig. 1. Arrangement of cooling channels in magnetic circuit: 1) laminated magnetic circuit; 2) clamping plate with cooling channels; 3) clamping channel; 4) cooling channel.

The cooling channel may occupy only part of the total width of the pack (Fig. 1).

We investigated the cooling efficiency by determining the temperature distribution over the cross section of the core of a laminated magnetic circuit (Fig. 2).

The core shown in Fig. 2 is rectangular in cross section. The cooling sections fg and cb occupy part of the edges eh and da. The joule heat released per unit time in unit volume is equal to w.

It is assumed that: 1) the core is infinitely long; 2) the laminations and the insulation are ideally arranged so that the temperature and the heat flow vary continuously; 3) surface radiation is disregarded; 4) at the surfaces fg and cb there is Newtonian heat exchange with the coolant whose temperature remains constant in time; 5) the thermophysical constants are all independent of temperature; 6) the multilayered system is replaced by a continuous anisotropic material whose thermal conductivity is λ_1 in a direction perpendicular to the layers and λ_2 in a direction parallel to the layers; 7) heat is released uniformly throughout the system and not only in the sheets of metal.

With these assumptions, the steady-state problem is described by the following differential equation for the temperature T:

$$\lambda_1 \frac{\partial^2 T}{\partial x_2} + \lambda_2 \frac{\partial^2 T}{\partial y^2} + w = 0. \tag{1}$$

The conditions at the boundaries are as follows:

$$\left.\frac{\partial T}{\partial x}\right|_{cd} = 0; \quad \left.\frac{\partial T}{\partial y}\right|_{ed} = 0; \quad \left.\frac{\partial T}{\partial x}\right|_{ef} = 0;$$

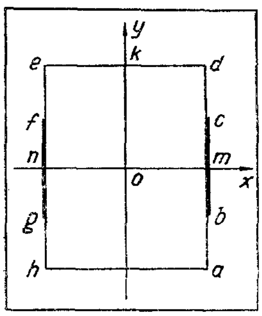

Fig. 2. Cross section of magnetic circuit.

Experimental and Calculated Values of the Temperature Drop in the Magnetic Circuit

$\frac{l_{max}-l}{l_{max}}$	ΔT exp.	ΔT calc.	$\frac{l_{max}-l}{l_{max}}$	ΔT exp.	ΔT calc.
0	1.53	0	0.55	140	140.7
0.11	37.9	38	0.66	154	155.8
0.22	69.8	70	0.77	165	166.5
0.33	97.6	98	0.88	172	172.9
0.44	121	121	0.99	174	173

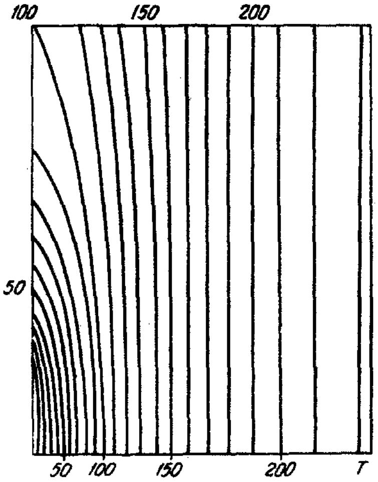

Fig. 3. Temperature field in magnetic circuit.

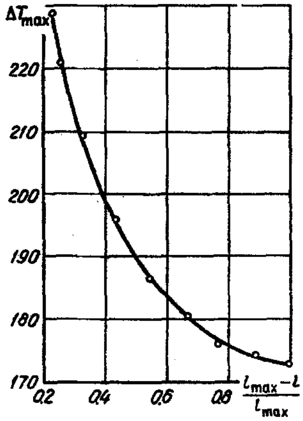

Fig. 4. Maximum temperature drop in magnetic circuit as a function of the length of the cooling section.

$$\left.\frac{\partial T}{\partial x}\right|_{gh} = 0; \quad \left.\frac{\partial T}{\partial y}\right|_{ha} = 0; \quad \left.\frac{\partial T}{\partial x}\right|_{ab} = 0;$$

$$-\lambda_1 \left.\frac{\partial T}{\partial x}\right|_{bc} = \alpha (T_{bc} - \theta);$$

$$\lambda_1 \left.\frac{\partial T}{\partial x}\right|_{fg} = \alpha (T_{fg} - \theta).$$

For simplicity it has been assumed that $\theta = 0$.

Since for these boundary conditions the Poisson equation (1) is difficult to solve by approximate analytic methods, we used analog simulation.

Mathematically, the problem of a temperature field with heat sources corresponds to the problem of an electrical field with current sources.

By way of illustration, we present the results of a calculation, on an EI-12 integrator, of the temperature field of a core of rectangular cross section made of permendur laminations insulated from each other with a special high-temperature composition. The coolant was dowtherm.

The cross section measured $13.5 \cdot 10^{-2} \times 13.5 \cdot 10^{-2}$ m, $\lambda_1 = 1.52$ W/m·deg, $\lambda_2 = 15.8$ W/m·deg; $\alpha = 4760$ W/m^2·deg; $w = 1.155 \cdot 10^5$ W/m^3.

The dimensions of the cooling boundary were varied.

The temperature field for a quarter of the cross section is shown in Fig. 3 for a cooling boundary equal to half the length of the corresponding side.

In Fig. 4 the maximum temperature of the core is shown as a function of the dimensions of the cooling boundary.

The results obtained analytically and on the integrator were compared for the simple case when heat exchange takes place over the entire surface of the opposite faces and the isotherms are straight lines. In this case, the temperature drop reckoned from the axis of the core is written as

$$\Delta t = -\frac{w}{2\lambda_1} l^2,$$

where l is the distance from the core axis to the point at which the temperature is determined.

The good agreement between the results is evident from the table.

NOTATION

λ_1 is the thermal conductivity in a direction perpendicular to the layers; λ_2 is the thermal conductivity in a direction parallel to the layers; w is the joule heat released in the core per unit time in unit volume; T is the temperature; x and y are Cartesian coordinates; α is the heat transfer coefficient; θ is the coolant temperature; l is the distance from core axis; Δt is the temperature drop over length l.

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