LITERATURE CITED

1. H. A. Barnes, P. Townsend, and K. Walters, Rheol. Acta, 10, No. 4, 517-527 (1971).
2. D. W. Sundstrom and A. Kaufman, Int. Eng. Chem. Process. Des. Sev., 16, No. 3, 320-325 (1977).
3. N. Phan-Thien and J. Dudeh, J. Non-Newtonian Fluid Mech., 11, No. 1/2, 147-161 (1982).
4. A. N. Kekalov, V. I. Popov, and E. M. Khabakhpasheva, Abstracts for the Third All-Union Conference on the Mechanics of Anomalous Systems [in Russian], Baku (1982), pp. 27-28.
5. A. A. Pozdeev and N. V. Shakirov, Advances in Polymer Rheology: Proceedings of the Eleventh All-Union Rheology Symposium [in Russian], Vol. 1, Moscow (1982), pp. 232-233.
6. N. Phan-Thien, Rheology, Vol. 2, Fluids, G. Astarita (ed.), New York (1980), pp. 71-77.
7. M. F. Edwards, D. A. Nellist, and W. L. Wilkinson, Chem. Eng. Sci., 27, No. 3, 545-553 (1972).
8. J. M. Davis, S. Bhumiratant, and R. B. Bird, J. Non-Newtonian Fluid Mech., No. 3, 237-259 (1977/78).
9. O. Manero and K. Walters, Rheol. Acta, 19, No. 3, 274-284 (1980).
10. N. Phan-Thien, J. Rheol., 35, No. 3, 293-314 (1981).
11. O. Manero, B. Mena, and R. Valenzuela, Rheol. Acta, 17, No. 6, 693-697 (1978).
12. B. Mena, O. Manero, and D. M. Binding, J. Non-Newtonian Fluid Mech., No. 5, 427-448 (1979).
13. Z. P. Shul'man and B. M. Khusid, Nonstationary Convective Transport Processes in Memory Media [in Russian], Minsk (1983).
14. G. V. Vinogradov and A. Ya. Malkin, Polymer Rheology [in Russian], Moscow (1977).
15. Z. P. Shul'man, B. M. Khusid, and Z. A. Shabunina, Inzh.-Fiz. Zh., 45, No. 2, 245-250 (1983).

NUMERICAL MODELING OF THERMODYNAMIC PROCESSES IN A COOLED MAGNETIC-FLUID SEAL

V. A. Novikov, A. K. Sinitsyn, and V. E. Fertman

UDC 62-762:538.4

The results are given from numerical computations of the velocity and temperature fields in a magnetic-fluid sealing layer under one tooth of a cooled multistage magnetic-fluid seal.

The use of magnetic-fluid (MF) seals in power-generating and industrial equipment is motivated by a number of advantages that they have over conventional sealing techniques [1]. The MF in a magnetic-fluid seal moves in the narrow clearance (δ = 0.1-0.2 mm) formed by the pole piece and the rotating shaft. The performance and time to first overhaul of the high-speed MF seal depends largely on the thermodynamic processes in the sealing layer [2]. The diagnosis of the hydrodynamic and temperature fields in a MF sealing layer is complicated by the small width of the working clearance and the capacity of the MF. It is particularly important, therefore to consider numerical modeling of the thermo- and hydrodynamic processes in the working clearance of MF seals under conditions as close as possible to the actual working environment. Studies of a one-dimensional model of the MF seal have been reported in a number of papers, in which data have been obtained on the velocity and temperature fields in a MF layer whose motion in the clearance obeys Newton's friction law. It is well known, however, that concentrated MF's exhibit non-Newtonian properties, even when the carrier liquid is Newtonian [3].

In the present article we investigate the thermo- and hydrodynamic processes in a multistage MF seal with magnetic-field concentrators in the form of identical teeth on the pole piece. The position of a tooth in the pole piece is specified by the conditions for the temperature at its boundaries.

Radio-Engineering Institute, Minsk. A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 51, No. 3, pp. 368-375, September, 1986. Original article submitted June 14, 1985.

0022-0841/86/5103-1010$12.50

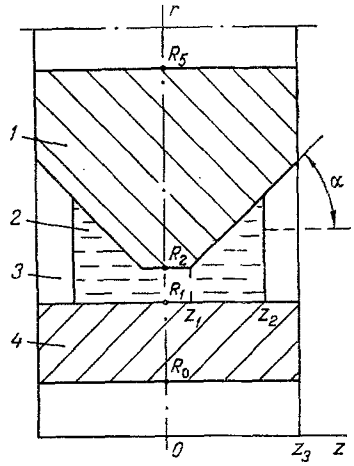

Fig. 1. Computational domain. 1) Pole piece; 2) magnetic fluid; 3) air; 4) shaft; R_0 is the radius of the cooling duct on the shaft, R_1 is the radius of the shaft, $R_2 - R_1 = \delta$ is the working clearance, and R_5 is the radius of the cooling duct on the pole piece; r and z are in m.

We consider one tooth of a MF seal with cooling ducts on the shaft and the pole piece; the cross section of the seal is shown in Fig. 1. It is assumed that the flow of the MF in the working clearance takes place in concentric circles situated in planes perpendicular to the axis of the shaft. The influence of the magnetic field $H = H(r, z)$ in the clearance on the MF flow is taken into account entirely through the value of the dynamic viscosity η. The curvature of the free surface of the MF layer and the asymmetry of the tensor of viscous stresses in the MF are disregarded. The medium filling the space 3 (Fig. 1) is assumed to be inviscid; viscous dissipation is disregarded in it, and the velocity gradients in the MF layer along the normal to the boundary are assumed to be equal to zero.

The variation of the temperature field in the computational domain is analyzed as a function of the time for instantaneous stabilization of the velocity field, since the rate of change of the temperature field is several orders of magnitude smaller than the rate of change of the velocity field throughout the entire domain.

We give the results of computations for the basic MF seal configuration and make special note of all deviations from the basic configuration. Following are the parameters of the basic configuration: $R_0 = 20\cdot10^{-3}$ m; $R_1 = 40\cdot10^{-3}$ m; $\delta = 0.2\cdot10^{-3}$ m; $R_5 = 70\cdot10^{-3}$ m; $z_1 = 0.25\cdot10^{-3}$ m; $z_2 = 0.34\cdot10^{-3}$ m; $z_e = 2\cdot10^{-3}$ m, $\alpha = 45°$.

The temperature dependence of the thermophysical characteristics are approximated by the general relation

$$\Pi_i = \Pi_{0i}\,[1 - \delta\Pi_i\,(T - T_{0i})], \tag{1}$$

in which $i = \rho$ for the density, $i = c$ for the specific heat, and $i = \lambda$ for the thermal conductivity.

The thermophysical characteristics of the gas 3 and the materials of the shaft 4 and the pole piece 1 are assumed to be independent of the temperature; the following parameters are used for the material of the shaft and the pole piece (steel St3): $\lambda_{st} = 48$ W/m·K; $\rho_{st}c_{st} = 3.75\cdot10^6$ J/K·m³, and for the gas (air); $\lambda_a = 2.44\cdot10^{-2}$ W/m·K; $\rho_a c_a = 1.29\cdot10^3$ J/K·m³.

In light of the experimental results [3], the MF is assumed to be a pseudoplastic fluid, whose effective viscosity decreases with increasing shear rate. An analysis of exhaustive experimental data on the viscosity of pseudoplastic fluids shows that for large shear rates the spatial structure in the fluid is completely broken down by shear flow, and flow with a minimum viscosity η_{min} that no longer depends on the shear rate is observed under isothermal conditions. This tendency has been observed [3] for a hydrocarbon-base MF at $\dot{\gamma} \gtrsim 10^3$ sec⁻¹. It is obvious that the minimum viscosity of a MF in a magnetic field cannot be lower than the effective viscosity of the MF at the same shear rates in the absence of the field. The experimental data of [4], which refer to a MF with the same hydrocarbon base, correspond to

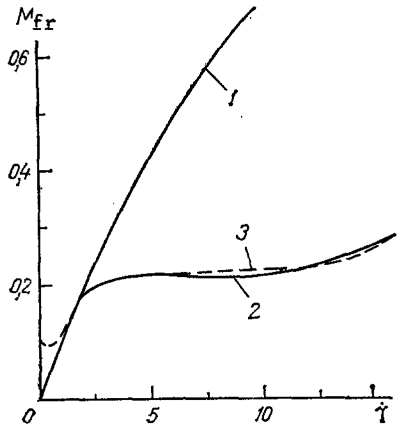

Fig. 2. Friction torque of the MF seal vs shear rate in the working clearance for $\alpha_0 = \alpha_3 = 0$, $\alpha_1 = \alpha_5 = 10^3$ W/m²·K, $T_0 = T_1 = T_5 = 20$°C; the magnetic fluid is the type MMt-60. 1) $K(\dot{\gamma}) \equiv 1$; 2) $K(\dot{\gamma}) \to K(0)/K(\infty) = 4$; 3) experimental [5]; M_{fr} in N·m; $\dot{\gamma}$ in 10^4 sec^{-1}.

a decrease by approximately one half in the effective viscosity in transition to the flow regime with minimum Newtonian viscosity. However, data obtained from a MF seal modified for measurement of the friction torque [5] evince a reduction in the effective viscosity by roughly 75%. It must be noted at this point that the experiments of [5] were carried out without a reliable thermostatting system for the MF layer, and it was possible for the temperature dependence of the effective viscosity to contribute to the observed dependence of the friction torque on the shaft rotation speed. We use the data of [5] as the basis for numerical modeling of the thermo- and hydrodynamic processes in the working clearance of the MF seal, and we assume the simplest kind of function

$$\eta = \eta(T) K(\dot{\gamma}), \tag{2}$$

in which $\eta(T)$ and $K(\dot{\gamma})$ are specified by approximate tables, where $\eta(T) = B \exp(A/T)$ [6] and $K(\dot{\gamma} = 0) \equiv 1$, $K(\dot{\gamma} \to \infty) \in [0, 1]$.

The hydrodynamic and thermal processes in the working regime of the MF seal ($10^3 \lesssim \dot{\gamma} \lesssim 10^5$ sec^{-1}) are of the greatest practical interest in high-speed seals, and so the MF is regarded as a Newtonian fluid for the computations in the interval $\dot{\gamma} < 10^3$ sec^{-1}.

Under the stated assumptions and restrictions, the distributions of the MF velocity and temperature are determined from the respective equations

$$\frac{\partial}{\partial z}\left(\eta \frac{\partial v}{\partial z}\right) + \frac{\partial}{\partial r}\left(r\eta \frac{\partial}{\partial r}\left(\frac{v}{r}\right)\right) + 2\eta \frac{\partial}{\partial r}\left(\frac{v}{r}\right) = 0, \tag{3}$$

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r \frac{\partial T}{\partial r}\right) + \eta\left(\frac{\partial v}{\partial z}\right)^2 + \eta\left[r \frac{\partial}{\partial r}\left(\frac{v}{r}\right)\right]^2 \tag{4}$$

subject to the velocity boundary conditions

$$v_1 = \begin{cases} 0 & t \leqslant 0, \\ W & t > 0, \end{cases} \quad v_2 = 0, \quad \frac{\partial v(r, z_2)}{\partial z} = 0 \tag{5}$$

and the temperature boundary conditions

$$\frac{\partial T(R_0, z)}{\partial r} = \frac{\alpha_1}{\lambda}(T(R_0, z) - T_1), \quad \frac{\partial T(R_5, z)}{\partial r} = \frac{\alpha_5}{\lambda}(T_5 - T(R_5, z)),$$
$$\frac{\partial T(r, 0)}{\partial z} = \frac{\alpha_0}{\lambda}(T(r, 0) - T_0), \quad \frac{\partial T(r, z_3)}{\partial z} = \frac{\alpha_3}{\lambda}(T_0 - T(r, z_3)). \tag{6}$$

The problem (3)-(6) is solved numerically by a differencing procedure. A nonuniform rectangular rz computing grid is chosen in such a way as to guarantee a maximum 5% temperature error.

Equation (3) is approximated by the finite-difference scheme [7]:

$$2\eta\left(\frac{v}{r}\right)_{\overset{\circ}{r}}+\left[r\eta\left(\frac{v}{r}\right)_{\bar r}\right]_r+(\eta v_{\bar z})_z=0, \tag{7}$$

and Eq. (4) is approximated by the alternating-direction finite-difference scheme

$$\text{a)}\quad \rho c\,\overline{T}_{\bar t}=\frac{1}{r}\,(\lambda r\overline{T}_{\bar r})_r+(\lambda T_{\bar z})_z+\eta\left[r\left(\frac{v}{r}\right)_{\overset{\circ}{r}}\right]^2+\eta\,(v_{\overset{\circ}{z}})^2;$$

$$\text{b)}\quad \rho c\overline{T}_t=\frac{1}{r}\,(\lambda r\,\overline{T}_{\bar r})_r+(\lambda\hat{T}_{\bar z})_z+\eta\left[r\left(\frac{\bar v}{r}\right)_{\overset{\circ}{r}}\right]^2+\eta\,(\bar v_{\overset{\circ}{z}})^2, \tag{8}$$

where F, $\overline{F}$, and $\hat{F}$ are the values of F at t, t + τ/2, t + τ, respectively.

In the solution of the system of different equations (7) with the boundary conditions (5) for a fixed viscosity field η^k, a simple iteration procedure is used with velocity relaxation at each node of the spatial grid according to the equation

$$v_{ij}^{n+1}=\omega_v v_{ij}^n+(1-\omega_v)\,\tilde{v}_{ij}^{n+1}, \tag{9}$$

where $\tilde{v}$ is the velocity field obtained after simple iteration. The relaxation parameter ω_v is stipulated by the condition of best convergence of the iteration process; this condition is presumed to exist when

$$\varepsilon_{vn}=\max_{i,j}|v_{ij}^n-\tilde{v}_{ij}^{n+1}|<\varepsilon_v.$$

After the velocity field v^{n+1} has been determined, the shear-rate field $\dot\gamma^{k+1}$ is determined and is used to find $K^{k+1}(\dot\gamma)$ and then the viscosity field $\tilde\eta^{k+1}(T,\dot\gamma)$ for a fixed temperature field T^m. Next, the viscosity field is relaxed:

$$\eta_{ij}^{k+1}=\omega_\eta\tilde{\eta}_{ij}^{k+1}+(1-\omega_\eta)\,\eta_{ij}^k,$$

and a test for convergence is made:

$$\varepsilon_{\eta k}=\max_{i,j}|1-\eta_{ij}^k/\eta_{ij}^{k+1}|<\varepsilon_\eta. \tag{10}$$

If condition (10) is not satisfied, the system of difference equations (7) is solved again with the viscosity field $\eta^{k+1}(T,\dot\gamma)$; otherwise, the resulting velocity field is taken as the solution of the difference equation (7) with the boundary conditions (5). The relaxation parameter ω_η is stipulated by the condition of best convergence of the iteration process.

In the solution of the system (8) with the boundary conditions (6), the temperature is relaxed at each node of the grid in conjunction with the double-sweep method (modified Gaussian elimination) along the coordinate r [Eq. (8a)] according to Eq. (9) with the relaxation parameter ω_T.

The time step is varied automatically to attain the required computational precision in T^m, on the one hand, and to diminish the computing time for the steady-state temperature field, on the other.

The fundamental results of the numerical computations are shown in Fig. 2, from which it is evident that the bending of the friction-torque curve near $\dot\gamma = 10^4$ sec^{-1} (curve 2) cannot be attributed entirely to the temperature dependence of the effective viscosity of the MF (curve 1). The abrupt drop in the effective viscosity at $\dot\gamma \sim 10^4$ sec^{-1} was absolutely unaccountable in [5]. A microscopic foundation for the "cutoff" of interaction between the MF and the external magnetic field under the conditions of a sufficiently high rotation speed of the field is given in [8]. This mechanism has been used to predict the drop in the effective viscosity of a MF as a result of a decrease in the contribution of the rotational viscosity to the internal friction [9, 10]. We note that the combined influence of the shear rate and the temperature on the effective viscosity affords a good description not only of the bend in the experimental curve 3 at $\dot\gamma \sim 10^4$ sec^{-1}, but also of the bend at $\dot\gamma \sim 10^5$ sec^{-1}. On the other hand, a definite quantitative disparity exists between the maximum and minimum effective viscosities that have been obtained from viscometric studies, fitted to the computational model, and evaluated according to the data of [5]. Clearly, additional viscometric tests at shear rates $\dot\gamma \sim 10^4$ sec^{-1} are needed in order to obtain reliable information on the effective viscosity of MF's.

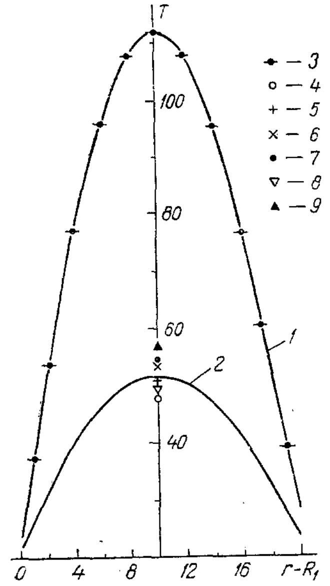

Fig. 3. Temperature profiles in the cross section $z = 0$ of the working clearance for $W = 40$ m/sec, $\alpha_1 = \alpha_3 = \alpha_5 = 10^9$ W/m²·K, $T_1 = T_5 = T_0 = 20°C$, $\alpha_0 = 0$; the MF is the type MMt-60: $\Pi_{0\lambda} = 0.165$ W/m·K. 1) $K(\dot{\gamma}) \equiv 1$; 2) $K(\dot{\gamma}) \to K(0)/K(\infty) = 4$, $\lambda_a = 48$ W/m·K; 3) one-dimensional model; 4) $\lambda_a = 48$ W/m·K, $\alpha_0 = 10^9$ W/m²·K; 5) $\alpha_0 = 10^9$ W/m²·K; 6) $\alpha = 60°$; 7) $\alpha = 30°$; 8) $\Pi_{0\lambda} = 0.19$ W/m·K; 9) $\Pi_{0\lambda} = 0.14$ W/m·K; T in °C; $r - R_1$ in 10^{-2} mm.

The maximum temperature in the working clearance of the MF seal is directly related to the value of the effective viscosity of the MF.

Figure 3 shows the temperature profiles in the cross section where $T(r, z) = T_{max}$. The profiles are shown without any dependence of the effective viscosity on the shear rate $[K(\dot{\gamma}) \equiv 1]$ and with $K(0)/K(\infty) \sim 4$. It is evident from the figure that the maximum temperature in the working clearance decreases by roughly one third when $K(\dot{\gamma})$ is taken into account. Also shown for comparison are the values of T_{max} for other geometrical parameters of the MF seal and for various MF's.

It must be noted that the thermal conductivity of the MF has the same influence as the viscosity on the value of T_{max} in the working clearance, but this characteristic of the MF is known with sufficient accuracy [6].

The geometrical parameters of the MF seal, which have been varied in the computations in accordance with typical structures, essentially do not have any influence on the value of T_{max}. A comparison of the values obtained for T_{max} with the results of computations according to the one-dimensional model (Fig. 3) indicates the validity of the engineering procedure for the computation of T_{max} according to the much simpler one-dimensional model, in which, however, the functions $\lambda(T)$, $\eta(T)$, and $K(\dot{\gamma})$ must be taken into consideration.

Thus, the failure to allow for either the temperature dependence or the shear-rate dependence of the effective viscosity of the MF leads to incorrect values of T_{max} in the working clearance of the MF seal in the computations.

We also investigate the influence of asymmetry of the viscous stress tensor in the MF on the temperature distribution in the working clearance of the MF seal in laminar flow. The computations for an asymmetrical MF model in the quasiequilibrium magnetization approximation [8] have shown that the temperature fields in the sealing layer of a MF seal of the investigated design are determined with a high degree of accuracy from computations according to a symmetrical model in which the effective viscosity of the MF is evaluated in the field $H \perp \nabla \times v$. The justification for this approach lies in the condition $\partial v/\partial z \ll \partial v/\partial r$, which holds in conventional MF seal disigns, so that the main factor contributing to viscous dissipation is the velocity gradient along the radial coordinate.

An analysis of the computed temperature field in the pole piece and the shaft shows that: 1) large temperature gradients are observed only near the boundaries of the working clearance, and the wall temperature is practically equal to the coolant temperature at a distance ~5 mm from the boundaries; 2) the profile in the cross section of maximum temperature depends on the width of the magnetic mirror and is close to the profile obtained according to the one-dimensional model, in which the energy equation contains a source to simulate the withdrawal of heat in the direction of the z axis; 3) in connection with heat withdrawal from the sealing zone along the shaft, the maximum temperature of the MF always occurs in the fluid layer and cannot exist at the boundary of the working clearance as stated in [11]; 4) the temperature of the boundary of the working clearance can be measured with high accuracy by placing temperature sensors on the solid boundaries of the MF layer in such a way as to bring the sensor into contact with the MF, because the total temperature difference between the clearance and the cooling ducts is insignificant, being equal to 10-15°C for v_1 = 40 m/sec.

In conclusion we consider the conditions for the loss of stability of the laminar MF flow in the working clearance. Taking into account the geometry of the clearance space, we can partition the sealing layer into two regions: the region under the working tip of the tooth and the region formed by the sidewalls of the tooth (see Fig. 1). An analysis shows that the flow under the tip of the tooth is close to Couette flow, so that we can make use of the well-known results on flow stability between concentric rotating cylinders. The threshold for the onset of Taylor instability in this case, under the assumption of an isothermal fluid and the absence of eccentricity, is given by the value of the modified Reynolds number $Re^* = (\rho v\delta/\eta)\sqrt{\delta/4}$ equal to 41.17. After the inception of Taylor vortices and with the transition to more complex motions of the MF in the clearance, the maximum temperature must drop, because the thermal resistance of the MF layer decreases. This raises the limiting rotation speeds of the shaft in the MF seal.

Estimates of the number Re in numerical modeling under the experimental conditions of [5] for T = 20°C at the boundaries of the clearance, v = W = 40 m/sec, δ = 0.2 mm, R_1 = 40 mm, and ρ = 1800 kg/m^3 yield Re* = 27 with allowance for the function $K(\dot{\gamma})$. These estimates of Re* are obtained from the effective viscosity of the MF averaged over the entire clearance according to the expression

$$\eta = \frac{M_{fr}\delta\cdot 1000}{2\pi R_1^2 v},$$

where M_{fr} is the friction torque per millimeter along the MF layer.

The values obtained for Re* are much lower than the critical value R^*_{cr} for an isothermal layer. Well-known results have been obtained from an investigation of Taylor instability of nonisothermal Couette flow for ordinary fluids [12], indicating a possible reduction of the critical number R^*_{cr} by approximately one half, i.e., to R^*_{cr} ~ 20. The value obtained for Re* in this case is close to the critical value.

In the region under the sidewalls of the teeth, instability of the MF must set in at much smaller circumferential speeds of rotation of the shaft than in the region under the tips of the teeth. However, the influence of the onset of instability in this region on the maximum temperature in the clearance can be modeled by specifying a constant temperature equal to the temperature T_0 at the boundary z_1 of the region under the tip of the tooth. This case corresponds to the ultimate withdrawal of heat through the fluid along the axis of the shaft. Numerical computations show that T_{max} is diminished at most by 15% under these conditions. It is therefore inopportune to analyze the flow stability of the MF in the region under the sidewalls of the tooth, owing to the inconsequential influence of heat transfer from the free surface of the MF layer on the maximum temperature in the working clearance.

Thus, numerical modeling of the thermodynamic and hydrodynamic processes makes it possible to obtain detailed information about the structure of the hydrodynamic and temperature fields in the working clearance of a MF seal and to determine the limits of applicaiblity of cooled MF seals for the sealing of rotating shafts.

NOTATION

H, magnetic field; $\dot{\gamma}$, shear rate; η, dynamic viscosity; v, linear velocity; T, temperature; Re*, modified Reynolds number; M_{fr}, friction torque; λ, thermal conductivity; c, specific heat; ρ, density.

LITERATURE CITED

1. L. P. Orlov and V. E. Fertman, Magnetic-Fluid Seals for Rotating Shafts (Preprint of the A. V. Lykov Institute of Heat and Mass Transfer of the Academy of Sciences of the Belorussian SSR, No. 8) [in Russian], ITMO AN BSSR, Minsk (1979).
2. L. P. Orlov, A. K. Sinitsyn, and V. E. Fertman, Inzh.-Fiz. Zh., 42, No. 1, 58-65 (1982).
3. A. N. Veslovich, S. A. Demchuk, V. I. Kordonskii, and V. E. Fertman, in: Abstr. All-Union Symp. Hydrodynamics and Heat Physics of Magnetic Fluids [in Russian], Salaspils (1980), pp. 97-104.
4. R. E. Rosensweig, R. Kaiser, and G. Miskolszy, J. Colloid Interface Sci., 29, No. 4, 580-585 (1969).
5. V. A. Chernobai, Problems of the Mechanics of Magnetic Fluids [in Russian], Minsk (1981), pp. 110-116.
6. G. É. Kronkalns, M. M. Maiorov, and V. E. Fertman, Magn. Gidrodin., No. 2, 38-42 (1984).
7. A. A. Samarskii, Theory of Difference Schemes [in Russian], Moscow (1983).
8. B. M. Berkovskii, A. N. Vislovich, and B. É. Kashevskii, The Magnetic Fluid as a continuum with Internal Degrees of Freedom (Preprint of the A. V. Lykov Institute of Heat and Mass Transfer of the Academy of Sciences of the Belorussian SSR, No. 4) [in Russian], ITMO AN BSSR, Minsk (1980).
9. V. A. Novikov, A. K. Sinitsyn, and V. E. Fertman, in: Proc. Third All-Union School-Sem. Magnetic Fluids (Ples, 1983) [in Russian], Moscow (1983), pp. 186-187.
10. V. A. Novikov, A. K. Sinitsyn, and V. E. Fertman, in: Abstr. Eleventh Riga Conf. Magnetohydrodynamics [in Russian], Vol. 3, Salaspils (1984), pp. 119-122.
11. V. A. Chernobai, "Thermal and hydrodynamic processes in high-speed magnetic-fluid seals: structural design," Author's Abstract of Candidate's Dissertation, Engineering Sciences, Moscow (1984).
12. L.-H. Lee, Probl. Treniya, 100, No. 2, 132-142 (1978).

HYDRAULIC DRAG IN TURBULENT COOLANT FLOW IN A POROUS CABLE

V. A. Babenko

UDC 532.517.4+536.48

The hydrodynamics and heat transfer in the cooling of an electrical cable by radical coolant filtration are studied.

The constructional scheme of the cable is shown in Fig. 1. There are two coolant channels, of circular and annular cross section. Attachments that completely or partially cover the channel force the coolant to filter in the radial direction through the permeable structure formed by the current-carrying strands, the porous insulation, and the supporting base.

The model of a porous body with equivalent permeability, heat conduction, and heat liberation is used for mathematical modeling of the hydrodynamic and thermal processes in the permeable structure. The current-conducting part is cooled on account of heat transfer at the surfaces and intrapore heat transfer.

The hydrodynamics in the heat exchanger is modeled using channel-averaged equations of mass and momentum balance.

The momentum-balance equation is written for the tube

$$\frac{d}{dx^*}\left(\beta_T \bar{\rho}_T^* \bar{u}_T^{*2} S_T^* + P_T^* S_T^*\right) = -\tau^{a^*} 2\pi a^* \quad (1)$$

and for the annular channel

$$\frac{d}{dx^*}\left(\beta_C \bar{\rho}_C^* \bar{u}_C^{*2} S_C^* + P_C^* S_C^*\right) = -\tau^{b^*} 2\pi b^* - \tau^{c^*} 2\pi c^*. \quad (2)$$

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 51, No. 3, pp. 375-383, September, 1986. Original article submitted May 5, 1985.

0022-0841/86/5103-1016$12.50