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SHORT COMMUNICATIONS

Thermoconvective Flow Velocity in a High-Speed Magnetofluid Seal After it Has Stopped[1]

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Abstract—Convective flow is investigated in the high-speed (linear velocity of the shaft seal is more than 1 m/s) magnetofluid shaft seal after it has been stopped. Magnetic fluid is preliminarily heated due to viscous friction in the moving seal. After the seal has been stopped, nonuniform heated fluid remains under the action of a high-gradient magnetic field. Numerical analysis has revealed that in this situation, intense thermomagnetic convection is initiated. The velocity of magnetic fluid depends on its viscosity. For the fluid with viscosity of 2×10^{-4} m^2/s the maximum flow velocity within the volume of magnetic fluid with a characteristic size of 1 mm can attain a value of 10 m/s.

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INTRODUCTION

During the 11th International Conference on Magnetic Fluids, Dr. R.E. Rosensweig paid attention to the fact that after the complete stoppage of a high-speed magnetofluid shaft seal (MFSS), radial flow is seen at a free surface, but the cause of it is not clear [1]. It is well known that magnetic fluid in the MFSS is strongly heated due to viscous friction. The temperature distribution in the fluid volume is nonuniform. The magnetic field in the MFSS is also nonuniform and the strength gradient is very high ($\sim 10^9$ A/m^2). Under these conditions, in the magnetic fluid volume, there must appear very intense thermomagnetic convection that can be the cause of magnetic fluid flow at the free surface in spite of a motionless shaft. Of fundamental importance is the question: what is the value of the convective flow velocity and can it be registered when observing the free surface of the magnetic fluid in the MFSS.

GOVERNING EQUATIONS

Let R be the shaft radius and a be the width of the gap between the shaft and the pole of the MFSS. As for the MFSS, where usually $R \gg a$, an axisymmetrical flow in the plane r–z could be considered as plane. It is possible to use a stream function ψ as $v_r = -\partial\psi/\partial z$, $v_z = \partial\psi/\partial r$ and a vortex $\omega = \operatorname{curl}\vec{v}$. Then, the system of dimensionless equations for axisymmetric flow and temperature in the meridional plane in Boussinesq approximation can be written as:

$$\omega = -\Delta\psi, \qquad (1)$$

$$\frac{\partial\psi}{\partial z}\frac{\partial\omega}{\partial r} - \frac{\partial\psi}{\partial r}\frac{\partial\omega}{\partial z} = \frac{\partial^2\omega}{\partial z^2} + \frac{\partial^2\omega}{\partial r^2} - \mathrm{Gr}_m[\nabla \times (MT\nabla H)]_\varphi, \qquad (2)$$

$$\mathrm{Pr}\left(\frac{\partial\psi}{\partial r}\frac{\partial T}{\partial z} - \frac{\partial\psi}{\partial z}\frac{\partial T}{\partial r}\right) = \Delta T, \qquad (3)$$

where ν/a, $T_0 = 1$K, and a are used as scales for velocity, temperature, and distance, $\mathrm{Pr} = \nu/\kappa$ is the Prandtl number, $\mathrm{Gr}_m = \mu_0\beta_\rho T_0 H_0 M_S a^2/\rho_0\nu^2$ is the magnetic Grashof number, μ_0 is the magnetic permeability of vacuum, β_ρ is the coefficient of fluid thermal expansion, ν, ρ_0, and κ are viscosity, density, and thermal diffusivity of the magnetic fluid, H_0 is the maximum strength of a magnetic field under the pole of the MFSS, $M = M(H, T)$ is the magnetic fluid magnetization, the state equation is assumed to be $M(H, T) = M^*(H)[1 - \beta_\rho(T - T^*)]$, $M^*(H) = M_S H/(H_T + H)$, the equilibrium values are marked by symbol "*", M_S is the magnetic fluid magnetization saturation, and H_T is the experimental value of the magnetic field strength at which fluid magnetization is equal to half of the magnetization saturation (for magnetic fluids used in MFSS $H_T \approx 50 - 100$ kA/m).

The problem was studied numerically in the geometry as presented in [2, 3] for the shape of the pole of the MFSS described by a hyperbola with an angle between asymptotes 2β. For an adequate description

[1]The article was translated by the authors.

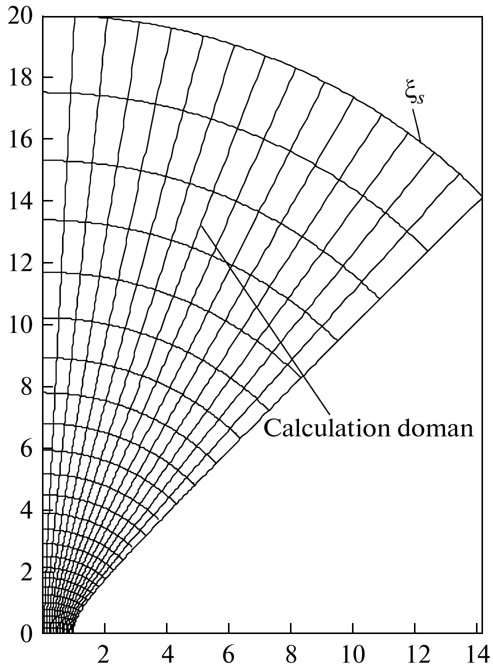

Fig. 1. Calculation doman.

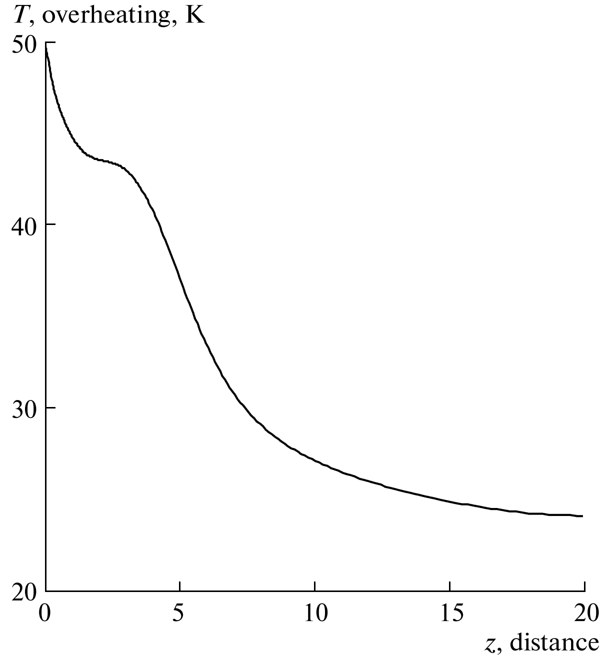

Fig. 2. Temperature variation along the shaft of the MFSS.

of the problem one used the system of η, ξ coordinates of the elliptic cylinder so that the coordinate line $\eta = \beta$ coincided with the pole surface, the line η coincided with the shaft surface, and the coordinate lines ξ were normal to them (Fig. 1). A finite-difference scheme based on the control volume method is used for the solution of Eqs. (1)–(3). In the frames of this method the linear interpolation function was used for the stream function and exponential Patankar function [4] for the vortex, which gives one the possibility to take into account both the direction and intensity of flow in the control volume.

The analysis used the typical values of magnetic fluid properties and MFSS parameters: $a = 2 \times 10^{-4}$ m, angle between the pole surface and plane symmetry $\beta = 45°$, thermal diffusivity $\kappa = \lambda/\rho_0 c_p = 0.2/(1.2 \times 10^3 \times 1.7 \times 10^3) = 10^{-7}$ m^2/s, coefficient of thermal expansion $\beta_\rho = 10^{-3}$ K^{-1}, maximum magnetic field strength in the MFSS gap $H_0 = 2 \times 10^6$ A/m, magnetic fluid magnetization saturation $M_S^* = 4 \times 10^4$ A/m, and density of magnetic fluid $\rho_0 = 1.2 \times 10^3$ kg/m^3.

The viscosity of magnetic fluids used in the MFSS is in the range from 3×10^{-5} to 1.5×10^{-3} m^2/s. Calculations were made on the grid with 251×151 nodes only for viscosities greater than or equal to 2×10^{-4} m^2/s, for which steady temperature fields in the seal with the moving shaft, are found in [3]. These temperature fields were used as boundary conditions when solving Eq. (3). The examples of the temperature distribution for one of the versions are illustrated in Figs. 2 and 3. Here, the temperature T is the difference of the absolute temperature and the cooling system temperature. So, the temperature on the solid boundaries of the magnetic fluid volume was assumed to be defined and was taken from the calculations of high-speed MFSS with the rotating shaft [3]. The heat flux through the magnetic fluid free

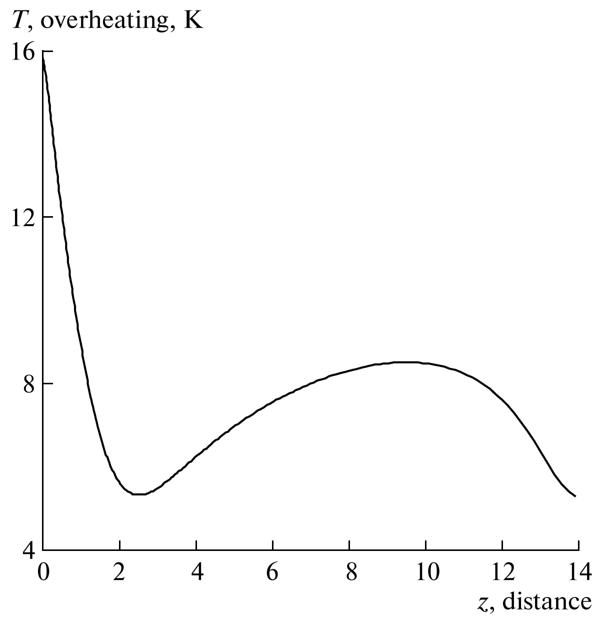

Fig. 3. Temperature variation along the pole of the MFSS.

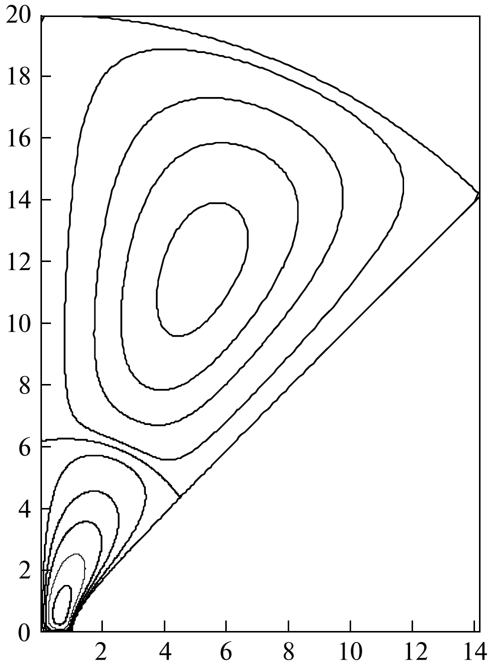

Fig. 4. Convective flow streamlines. Pr = 2040, Gr_m = 0.0838, $\nu = 2 \times 10^{-4}$ m^2/s, T_{max} = 47 K. ψ_{max} = 0.0369, ψ_{min} = –0.00225. The same flow structure exists for all viscosities.

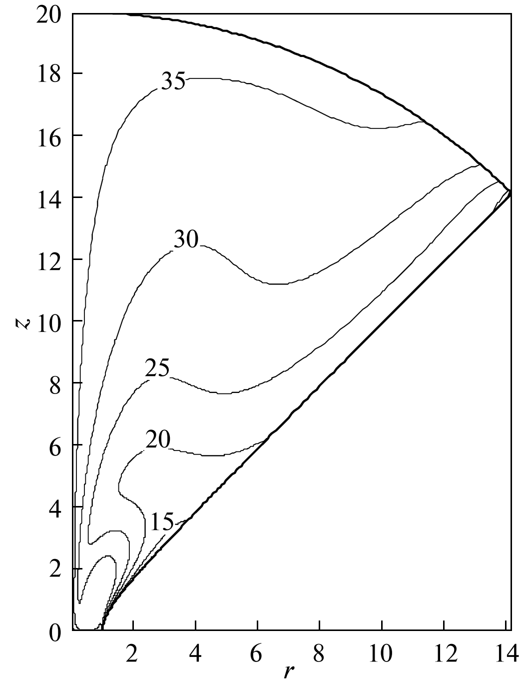

Fig. 5. Temperature profiles in the magnetic fluid volume. Pr = 2040, Gr_m = 0.0838, $\nu = 2 \times 10^{-4}$ m^2/s, T_{max} = 42.7 K.

surface and plane symmetry was assumed to be equal to zero.

RESULTS

Numerical solutions to Eqs. (1)–(3) show that in the calculation domain two convective cells are formed with the flow in the small cell being much more intense than in the large one (Fig. 4). The largest velocity of convective flow is observed in the small cell in the vicinity of the pole tip. The intensity of fluid flow is so high that isotherms are essentially distorted (Fig. 5), though usually thermal conductivity prevails in the volume of the small part of a millimeter size and isotherms coincide with volume boundaries. It could be seen from the presented pattern that the fluid moves counter clockwise in the inner cell and clockwise in the outer one; i.e., the external observer has to see the fluid movement at the free surface from shaft to pole. The flow velocity at the free surface is minimal near the shaft and the pole and has a maximum. Figure 6 plots the maximum fluid flow velocity in the volume and the maximum velocity at the fluid surface as a function of maximum overheating temperature of the shaft surface. As it should be expected, the intensity of the convective flow increases with growing overheating temperature. Calculations were made for the viscosity values of $\nu = 15 \times 10^{-4}$ m^2/s (Fig. 6), $\nu = 5 \times 10^{-4}$ m^2/s (Fig. 7), and $\nu = 2 \times 10^{-4}$ m^2/s (Fig. 8). Of the greatest interest are the values of the surface velocity of a magnetic fluid drop that can be compared to the experimental data. It is seen that at T = 50 K the maximum velocity at the free surface of the magnetic fluid varies with decreasing viscosity from 0.15 mm/s for the vis-

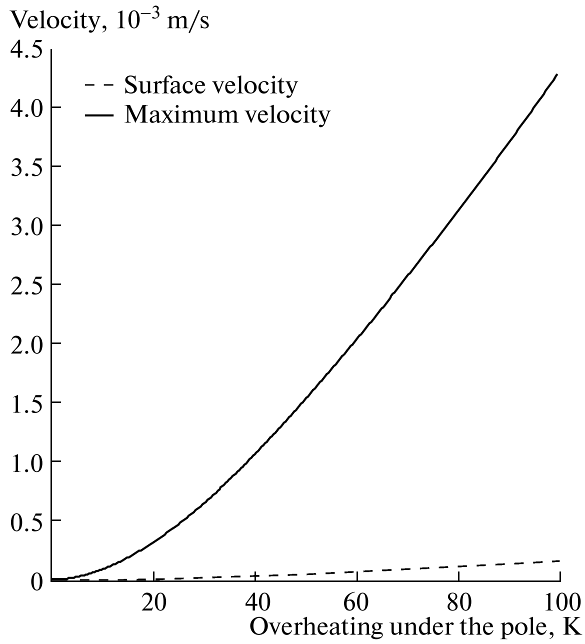

Fig. 6. Variation of the maximum fluid flow velocity and surface velocity vs. the overheating temperature of the pole. $\nu = 15 \times 10^{-4}$ m^2/s.

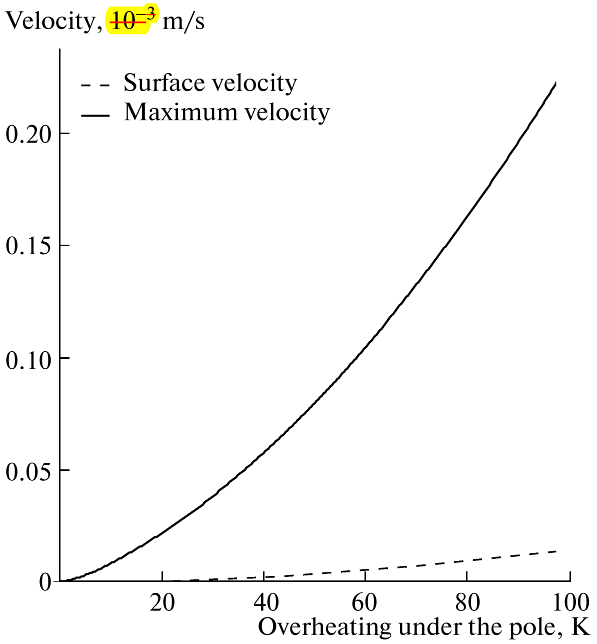

Fig. 7. Variation of the maximum fluid flow velocity and surface velocity vs. the overheating temperature of the pole. $\nu = 5 \times 10^{-4}$ m^2/s.

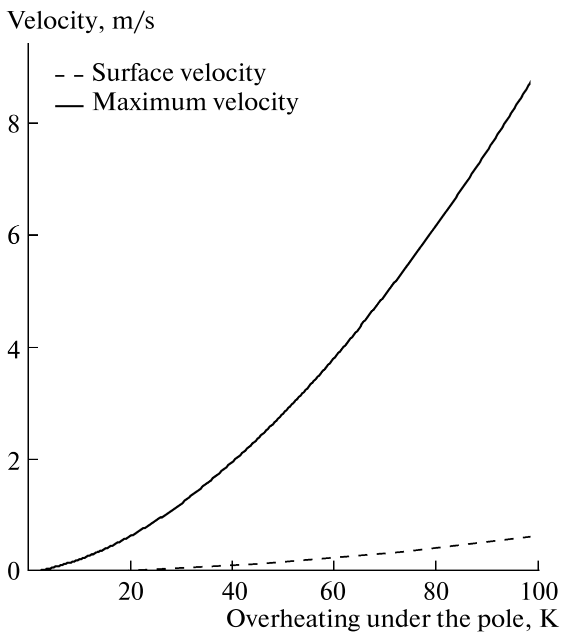

Fig. 8. Variation of the maximum fluid flow velocity and the surface velocity with the overheating temperature of the pole. $\nu = 2 \times 10^{-4}$ m^2/s.

cosity $\nu = 15 \times 10^{-4}$ m^2/s to 16 cm/s for the fluid viscosity $\nu = 2 \times 10^{-4}$ m^2/s.

Thus, natural thermomagnetic convection in the volume of the magnetic fluid, due to its heating during the operation of high-speed MFSS, can appear to be the cause of the motion of this fluid after the MFSS has been stopped.

CONCLUSIONS

The magnetic fluid in the high-speed MFSS is strongly heated due to viscous friction. After the seal has been stopped, nonuniform heated fluid is under the action of a high-gradient magnetic field. Numerical analysis has revealed that in this situation, intense thermomagnetic convection is initiated. The velocity of the magnetic fluid depends on its viscosity. For the fluid with viscosity of 2×10^{-4} m^2/s the maximum flow velocity within the volume of magnetic fluid in the MFSS with a characteristic size of 1 mm can attain a value of 10 m/s, and the free surface velocity attains a value about 30–50 cm/s and could be seen visually. Thus, natural convection in the volume of the magnetic fluid due to its heating during the operation of high-speed MFSS can appear to be the cause of the motion of this fluid after the MFSS has been stopped.

SPELL:OK

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