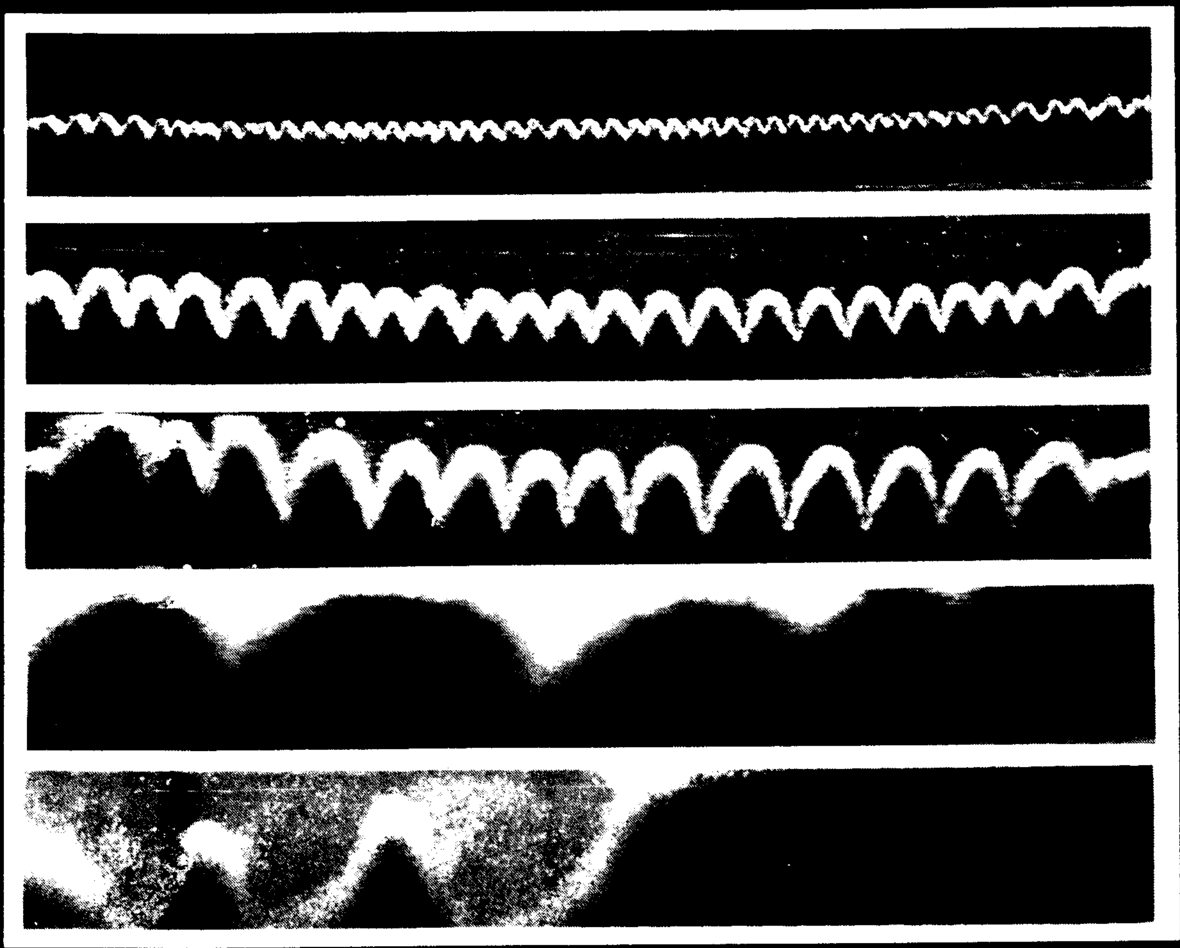
HYDROMECHANICS AND HEAT/ MASS TRANSFER IN MICROGRAVITY



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Hydromechanics and Heat/Mass Transfer in Microgravity

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THE INFLUENCE OF THERMOMAGNETIC CONVECTION ON HYDRODYNAMICAL DRAG IN A WEIGHTLESSNESS STATE

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ABSTRACT

The hydrodynamical drag of the cylinder, coated with a layer of magnetic fluid which is kept on the solid surface by magnetic field, is studied numerically. It was found earlier that the low-viscous magnetofluid coating reduces a drag 2-3 times. The subject of present investigation is how to decrease the drag at zero-g by means of the thermomagnetic convection phenomenon in the coating layer. Drag reduction in this case is attained due to flow intensification at the magnetic-nonmagnetic fluid interface by the convective mechanism. It is shown that the drag value may fall off to zero with increasing magnetic Grashof number.

Keywords: Cylinder, Magnetofluid Coating, Drag Reduction, Zero-g, Thermomagnetic Convection, Numerical Modelling.

1. INTRODUCTION

Works (Refs.1-3) deal with numerical modelling of separated flow past a solid cylinder coated with a magnetic fluid layer kept on the solid surface by a nonuniform magnetic field. It is found that the low-viscous magnetofluid coating reduces a cylinder drag 2-3 times at the Reynolds numbers of 50-100 (Ref.1). If such a coating has high thermal conductivity, then heat transfer from a heated cylinder is increased as many as 2-3 times (Ref.2). These effects manifest themselves the stronger, the higher is the Reynolds number.

In (Ref.3), it is shown that fluid magnetization as a function of temperature in a nonuniform magnetic field may induce, in the coating layer, the so-called thermomagnetic convection capable to change substantially the structure of separated flow around a heated cylinder at zero-g.

This study is an attempt to use the thermomagnetic convection phenomenon for reducing the drag at zero-g. Thermal conditions have been developed so that the convective motion direction at the magnetic-nonmagnetic fluid interface would coincide with the external flow one. Drag reduction in this case is attained due to interface flow augmentation caused by the convective mechanism, but not to decreasing of coating viscosity.

2. MATHEMATICAL MODEL

Consider an infinite viscous nonmagnetic fluid flow, having a constant temperature T_* and moving in the straight direction with a constant velocity U , past a long transverse cylindrical conductor of radius R which is kept at a constant temperature $T_c > T_*$ and coated with a magnetic fluid layer immiscible with the flow liquid. A conductor current strength I is assumed to be sufficiently high so that the magnetic-nonmagnetic fluid interface may be considered to be a circumference $a > R$ in radius (Ref.1).

Under these conditions and with no gravitation, in the coating layer there appears circulation due to thermomagnetic convection, whose direction at the interface is opposite to the external flow (Ref.3). In this situation shear stresses grow, so the drag increases. To change an unfavourable convective flow direction, a thin nonconducting plate-fin is placed at the cylinder leading edge. A plate width is equal to a coating thickness and its temperature, with respect to cylinder one, is T_c.

Introduce dimensionless variables by choosing, as measuring units of a distance, velocity, and temperature, a cylinder radius R, undisturbed flow velocity U, and a temperature drop $\Delta T = T_c - T_*$, respectively. Use a polar coordinate system r, φ with a pole on the cylinder axis. If necessary, denote by subscript 1 the quantities referring to a magnetic fluid and by subscript 2, external flow.

To simplify the mathematical model, we use the inductionless approximation which enables us to neglect the effect of magnetic fluid nonisothermity on a magnetic field. In such a case, there is no need to solve the Maxwell equations as their solution for a magnetic field of a cylindrical conductor is known. Applicability of the inductionless approximation for thermomagnetic convection problems is shown elsewhere (Refs.4,5).

Under the assumptions made, two-dimensional steady-state thermomagnetic convection in the layer $1 \le r \le \delta = a/R$ and nonmagnetic fluid flow outside it ($r \ge \delta$) are described by the dimensionless equations (Refs.2-4):

$$\frac{1}{r}\frac{\partial(\psi_i, T_i)}{\partial(\varphi, r)} = A_i \nabla^2 T_i,$$

$$\frac{1}{r}\frac{\partial(\psi_i, \omega_i)}{\partial(\varphi, r)} = B_i \nabla^2 \omega_i + F_i,$$

$$\nabla^2 \psi_i + \omega_i = 0; \quad i = 1,\ 2;$$

where

$$A_1 = \gamma / Re\, Pr\, \sigma \lambda, \quad A_2 = 1/Re\, Pr,$$

$$B_1 = \mu / Re\, \lambda, \quad B_2 = 1/Re,$$

$$F_1 = -B_1^2\, Gr_m \frac{1}{r^3} \frac{\partial T_1}{\partial \varphi}, \quad F_2 = 0;$$

T, ψ, and ω are a dimensionless temperature, stream-function, and vorticity;

$\gamma = k_1 : k_2$, $\sigma = c_1 : c_2$, $\lambda = \rho_1 : \rho_2$, $\mu = \eta_1 : \eta_2$ are the ratios of the magnetic and nonmagnetic fluid thermal conductivity, specific heat, density, and dynamic viscosity, respectively;

$Re = U R \rho_2 / \eta_2$ is the Reynolds number; $Pr = \eta_2 c_2 / k_2$ is the Prandtl number;

$Gr_m = \mu_o K_1 I \Delta T \rho_1 R / 2\pi \eta_1^2$ is the magnetic Grashof number, μ_o is the magnetic permeability of vacuum, K is the pyromagnetic coefficient.

In the case i=1 these equations are determined on the coating ring region $1 \le r \le \delta$, and in the case i=2, on the outer region $r \ge \delta$. The numbers Re, Pr, Gr_m and ratios δ, γ, σ, λ, μ are determining parameters of the problem.

When a numerical method is applied the determination domain must be assigned finite, and the flow is therefore considered undisturbed at rather a great distance from the cylinder $r \ge r_* \gg \delta$. Moreover, let us assume a solution to be symmetric by confining to the angular coordinate range $0 \le \varphi \le \pi$. On the solid surface of a cylinder and a fin, the attachment conditions are stated and at the interface, continuity conditions for a velocity and temperature, the conditions for surface permeability, shear stress and heat flux balances. The mathematical formulation of the boundary conditions is of the form:

$$r=1:\ T=1,\ \psi=0,\ \partial\psi/\partial r=0;$$

$$r=r_*:\ T=0,\ \psi=r_*\sin\varphi,\ \omega=0;$$

$$\begin{matrix} r\ge 1,\ \varphi=0 \\ r>\delta,\ \varphi=\pi \end{matrix}:\ \partial T/\partial\varphi=0,\ \psi=0,\ \omega=0;$$

$$1\le r\le\delta,\ \varphi=\pi:\ T=1,\ \psi=0,\ \partial\psi/\partial\varphi=0;$$

$$r=\delta:\ T_1=T_2,\ \gamma\,\partial T_1/\partial r=\partial T_2/\partial r,\ \psi=0,\ \partial\psi_1/\partial r=\partial\psi_2/\partial r,$$

$$\mu\left(\omega_1+\frac{2}{\delta}\frac{\partial\psi_1}{\partial r}\right)=\omega_2+\frac{2}{\delta}\frac{\partial\psi_2}{\partial r}.$$

A dimensionless magnetofluid-coated cylinder drag is calculated by the formula from (Ref.1):

$$W=\delta\,\mathrm{Re}\int_0^{\pi}\left(\mathrm{Re}\left(\frac{\partial\psi}{\partial r}\right)^2\cos\varphi+2\,\delta^2\frac{\partial}{\partial r}(\omega_2/r)\sin\varphi\right)\Big|_{r=\delta}d\varphi.$$

3. COMPUTATIONAL ALGORITHM

The problem was solved by the finite-difference method. Constructing of a grid in the coating layer and in the outer semi-ring region was made in the same manner as in Refs.1-3 . A dimensionless "infinity" radius r_* was chosen equal to 20 radii of a conductor, i.e. $r_*=20$. In terms of a polar angle the grid step was assigned equal to $\pi/40$ and in terms of a radius the uniform grid was constructed in the coating layer with 10 partitions in number, and within the range $\delta \le r \le r_*$ the nonuniform grid was constructed with a step growing in the geometrical progression and with 20 partitions in number. In this case, the first step of the nonuniform grid was equal to the radial one of the internal uniform grid.

The differential equations were approximated by a monotonic conservative difference scheme having, on a regular grid pattern, the second approximation order and on an irregular one, the first one (Ref.6). Solid wall vorticity was predetermined by the approximate Woods condition. Boundary condition derivatives were second-order approximated on a minimum grid pattern. A solution to the obtained difference problem was found using the iteration-relaxation method (Ref.6).

Specific features of the problem are such that the accuracy of its difference solution depends not only on the net construction but also on the "infinity" radius r_* and boundary condition at $r = r_*$. Their choice was based on the methodological conclusions of Ref.7. The comparison of calculated data for a non-coated cylinder (Ref.1) with the known results (Refs.7-10) points to the reliability of the mathematical model and computational algorithm.

4. SOME RESULTS AND CONCLUSIONS

Calculations were made at fixed $\delta = 1.1$, $\lambda = 1$, $\sigma = 1$. Figure 1 plots the drag vs viscosity of a magnetofluid coating in a smooth cylinder, i.e. when a fin is absent. The ratio W/W_0 where W_0 is the non-coated cylinder drag evidences, how much the drag changes due to coating. As we see, decreasing the drag may be attained due to coating viscosity reduction.

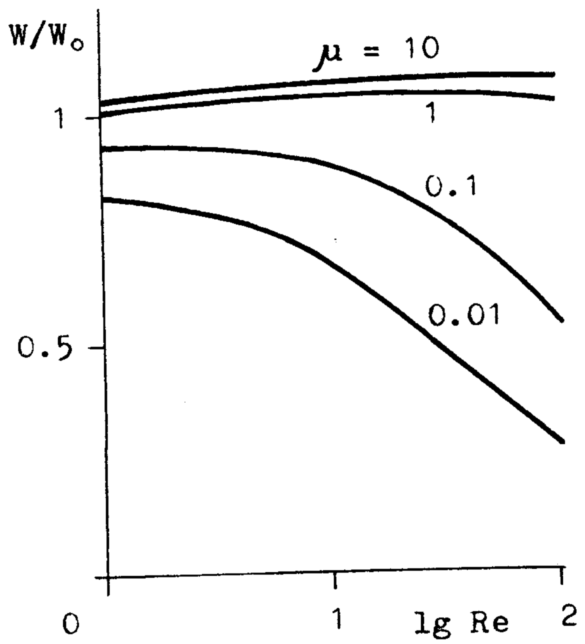

Figure 1: Coated-cylinder drag vs the Reynolds number at different viscosity ratios μ. $Gr_m=0$. A fin is absent.

The existing magnetic fluids possess rather high viscosity: it is not lower than that of water. So, small values of μ which would provide a substantial drag reduction may be practically obtained only at high flow viscosity. In experiment (Ref.11), e.g., to demonstrate the efficiency of a magnetofluid coating, glycerine was chosen as a flow liquid.

Calculation results show that a drag may be reduced not only by decreasing μ but also by thermomagnetic convection.

Figure 2 enables one to judge, how much the convective mechanism may affect the drag. Owing to the presence of a fin two convective cells are formed on the leading edge of a coating which enhance interface motion, thereby reducing a drag. With increasing Gr_m, the drag value falls up to zero, and at rather great Gr_m the inversion of this drag force occurs, i.e. it converts to a thrust force.

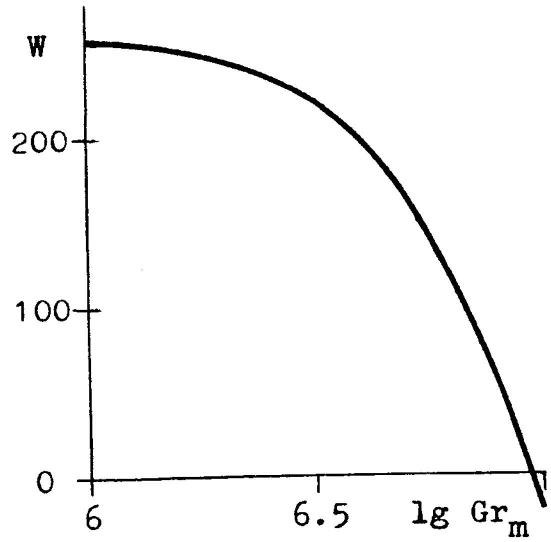

Figure 2: Magnetic Grashof number effect on a drag of a finned magnetic fluid-coated cylinder. $Re=10$, $Pr=1$, $\mu=1$, $\gamma=1$.

Probably, the thermomagnetic convection effect may be more significant in the case of a nonuniform temperature distribution over the cylinder surface, at which the temperature would decrease monotonically from a maximum value on the fin to a minimum one on the rear cylinder edge. The convective motion in this case is formed either in the entire region of a semi-ring or over its greater part.

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