TEMPERATURE DISTRIBUTION IN THE GAP OF SLIDE JOURNAL BEARINGS LUBRICATED WITH FERROFLUIDS FOR DIFFERENT CONCENTRATION OF MAGNETIC PARTICLES

In this paper author presents the results of numerical calculations of temperature distribution, load carrying capacities, friction forces and coefficient of friction in the gap of ferrofluid-lubricated slide bearing for different concentrations of magnetic particles. Reynolds-type equation has been derived from the equations of momentum and continuity of the stream for laminar, steady and isothermal flow so viscoelastic model Rivlin-Ericksen type of lubricant has been adopted. It has been adopted also that the dynamic viscosity depends generally on the magnetic field. Reynolds-type equation by which the hydrodynamic pressure distributions can be determined has been solved numerically using program - Mathcad 14 Professional. On the base of these calculations has been designated values of the friction forces and coefficient of friction, and temperature distributions in the oil gap of sliding journal bearing which is presented in the form of graphs.

Keywords: temperature distributions, ferrofluid, magnetic field, numeric calculation.

INTRODUCTION

The rheological characteristics of temperature-viscosity are fundamental properties used to describe the quality of used lubricating oils. On this basis it is possible to determine the other, important from operational point of view, properties of the oils in particular their behavior in the friction nodes. Change of the lubricating oil’s viscosity caused by temperature changes may adversely result in case of operation of mechanical devices. The resulting disturbance of the lubrication process can lead ultimately to friction over of the elements in the nodes of friction and consequently to the destruction of the device.

The purpose of this paper is to present the impact of the concentration of magnetic particles on the temperature distribution on the surface of the slide journal bearing’s sleeve ferro-oil’s lubricated.

Thermal parameters have a major impact on the slide journal bearing operation. Temperature changes in the sliding friction node can affect in two ways on the bearing structure, including a lubricating oil, which is also regarded structurally.

First of all temperature increase contributes to a decrease of the lubricating oil viscosity. In previous work of the author, among others in [2, 3] has been studied and analyzed the effect of temperature on the ferro-oils dynamic viscosity with
different concentrations of magnetic particles in the absence of an external magnetic field. It has been shown that the differences between the viscosity of base oil and ferro-oil with 8% concentration of the magnetic particles ranged from about 2 to 8 times for the results of the shear rate’s value of several hundred thousand s⁻¹ and from about 3 to 15 times for the shear rate’s value to 200 s⁻¹. The larger differences have been cases of lower temperatures, i.e., 0°C, 10°C and 20°C and the smaller ones have been cases of temperatures above 100°C, 110°C and 120°C.

Second, temperature changes in the oil film may change the height of the oil gap due to the bearings pan’s temperature deformation and possibly also the deformation of the bearing journal. These deformations lead to a change in the height of oil gap and cause appropriate changes in the value of hydrodynamic pressure, which also results in deformation of the bearing pans. As a consequence, there is another adjustment to the temperature values, which again results in a change of the viscosity of the lubricant and deformations in the bearing oil gap [5, 6, 7].

The essence of the importance of the temperature dependence on physical parameters of oil let illustrate the fact that even the temperature difference of a few degrees can cause a local change of the ferro-oil’s dynamic viscosity up to several tens of percent at temperatures close to the nominal bearing operating conditions, to even several hundred in the case of temperatures near start-up state [2, 3]. As it has been shown in [6] precisely of such temperature changes we face in the nodes of the sliding journal friction bearings ferro-oil’s lubricated. The temperature difference in the direction of the oil gap’s height varies on average in the range a few degrees °C with a rather large gradients of temperature changes. Furthermore, local temperature differences occurring between the pan’s inner surface and the outer surface of the bearing bush also achieve significant values. While the temperature on the surface of the bearing journal is rapidly equalized during the operation owing to the performance of its rotation, it cannot be neglected very significant temperature changes on the inner surface of the pan with a change in the direction of an angle of wrap. Large temperature gradients in this direction relate particularly points of supplying a fresh oil which has much lower temperature than the oil already used in the oil gap. Very large temperature fluctuations can also be seen on the inner surfaces of the bearing’s pans in the longitudinal direction to the axis of the shaft. The temperature gradients are mainly depend on the size and design of the sliding bearing construction.

In order to make numerical calculations of distribution of temperature, the Reynolds-type equation has been derived from the ground up with the fundamental equations namely equations of momentum and equations of stream's continuity. There have been also used Maxwell's equations for the ferrofluid in the case of stationary magnetic field's existence. It has been assumed stationary and laminar flow of lubricant liquid and the isothermal model for lubrication of slide bearings. As the constitutive equation has been used Rivlin-Ericksen one. The temperature distribution has been obtained from the conversion of the energy conservation
equation. The cylindrical journal bearing of finite length with the smooth sleeve of whole angle of a belt has been taken into consideration.

In a thin layer of oil film has been assumed constancy of the oil density with temperature changes and the independence of the oil's thermal conductivity coefficient from thermal changes. The viscosity of the oil depends mainly on the magnetic field.

1. BASIC EQUATIONS

Analysis of magnetohydrodynamic lubrication of the cross sliding bearings for a stationary, laminar, nonisothermal flow involves the solution of fundamental equations, namely equations of conservation of momentum, continuity of the stream and conservation of energy in the following form [1, 4, 5, 6, 8]:

\[ 0 = \text{Div} \, S + \mu_0 (N \cdot \nabla) H + \frac{1}{2} \mu_0 \text{rot} (N \times H), \]
\[ \text{div}(\rho v) = 0, \]
\[ \text{div}(\kappa \text{grad} \, T) + \text{div}(\mathbf{v} S) - \mathbf{v} \text{Div} \, S - \mu_0 T \frac{\partial N}{\partial T} \frac{d \mathbf{H}}{d t} + \Omega = \rho \frac{d(c_v \, T)}{d t}, \]
\[ \text{rot} \, \mathbf{H} = 0, \text{div} \, \mathbf{B} = 0, \mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{N}), \mathbf{N} = \chi \cdot \mathbf{H} \]

where:

- \( \mathbf{B} \) – vector of ferrofluid magnetization [T],
- \( \mathbf{H} \) – vector of magnetic field strength in ferrofluid [A·m\(^{-1}\)],
- \( \mathbf{N} \) – vector of ferrofluid magnetization [A·m\(^{-1}\)],
- \( T \) – temperature [K],
- \( S \) – ferrofluid stress tensor with components \( t_{ij} \) for \( i,j = f,r,z \) [Pa],
- \( \mathbf{v} \) – ferrofluid's velocity tensor [m·s\(^{-1}\)],
- \( c_v \) – specific heat at constant volume [J·kg\(^{-1}\)·K\(^{-1}\)],
- \( \nabla \) – Nabla's operator,
- \( \Omega \) – dimensionless heat from external sources applied to the ferrofluid,
- \( \mu_0 \) – vacuum magnetic permeability [H·m\(^{-1}\)],
- \( \rho \) – density of ferrofluid [kg·m\(^{-3}\)],
- \( \kappa \) – coefficient of thermal conductivity [W·m\(^{-1}\)·K\(^{-1}\)],
- \( \chi \) – magnetic susceptibility factor of ferrofluid.

It has been assumed a constant value of magnetic susceptibility coefficient, varies for different values of concentration of magnetic particles in ferro-oil.

Rivlin-Ericksen formula describing the relationship between the coordinates of the stress tensor \( S \equiv \|\tau_{ij}\| \) and the deformation rate tensor coordinates of ferrofluid can be presented in the following form [6, 9, 10, 11]:

\[ S = -p \, I + \eta A_1 + \alpha A_1 A_1 + \beta A_2. \]  \tag{5}

Deformation rate tensors can be defined by the following relation [6, 9, 10]:
\[ A_1 \equiv L + L^T, \quad A_2 \equiv \text{grad} \, a + (\text{grad} \, a)^T + 2L^T \cdot L, \]  \tag{6}

where the acceleration vector is given by:
\[ a \equiv L \cdot v, \quad L \equiv \text{grad} \, v, \]  \tag{7}

where:
- \( A_1 \) – the first one deformation rate tensor [s\(^{-1}\)],
- \( A_2 \) – the second one deformation rate tensor [s\(^{-2}\)],
- \( I \) – unit tensor,
- \( L \) – tensor of gradient taken from the velocity tensor [s\(^{-1}\)],
- \( a \) – accelerating vector [m·s\(^{-2}\)],
- \( p \) – hydrodynamic pressure [Pa],
- \( \alpha, \beta \) – materials pseudo-viscosity coefficients determining the viscoelastic properties of ferrofluid [Pa·s\(^2\)],
- \( \eta \) – dynamic viscosity coefficient [Pa·s].

Pseudoviscosity coefficients \( \alpha, \beta \) of the lubricant liquid multiplied by the deformation tensor components denote the additional stresses arising from the viscoelastic, non-Newtonian ferrofluid nature. In case of acceptance of material's coefficients \( \alpha, \beta \) equal to zero can be obtained the classical Newtonian relationship between stress tensor and deformation rate tensor.

Ferrofluid's dynamic viscosity depends mainly on the magnetic induction \( \eta = \eta(T,B) \) and the material's coefficients \( \alpha, \beta \) were taken as constants.

The amount of base of oil gap \( h_p \) depends on the relative eccentricity \( \lambda \) and nonparallelity of shaft and sleeve axis with an angle of \( \gamma \).
\[ h_{p1} = \left[ 1 + \lambda \cdot \cos \phi + a_{\gamma} \cdot z_1 \cdot \cos(\phi) \right], \quad a_{\gamma} = \frac{L_1}{\Psi} \cdot \tan(\gamma). \]  \tag{8}

where:
- \( h_{p1} \) – basic dimensionless height of the oil gap,
- \( \lambda \) – relative eccentricity,
- \( z_1 \) – dimensionless longitudinal coordinate,
- \( \phi \) – peripheral coordinate,
- \( a_{\gamma} \) – misalignment coefficient,
- \( L_1 \) – dimensionless bearing length,
- \( \Psi \) – relative radial clearance,
- \( \gamma \) – misalignment.

The constitutive relations (5) between the coordinates of the stress tensor \( \tau_{\phi\phi}, \tau_{rr}, \tau_{zz}, \tau_{\phi\phi}, \tau_{\phi\phi}, \tau_{rr} \) and the coordinates of the deformation rate tensor are substituted for the equations of motion (1) - (3). So nonstationary units as the forces of inertia in the equations of momentum shall be ignored. This kind of ignoring is justified
in the slow and medium speed bearings. The whole set of equations of motion for classical steady flow of lubricating oil can be obtained in this procedure.

To estimate the magnitude of units in the system of equations and ignore small units of a higher order the making dimensionless and estimating the magnitude of units in the system of equations has been done. For this the following dimensional and dimensionless marks and numbers have been assumed [6, 9, 10]:

\[
\begin{align*}
    r &= R(1 + \psi r_1), \quad z = bz_1, \quad h_p = \varepsilon \cdot h_{p1}, \quad T = T_0 + T_0BrT_1, \quad p = p_0p_1, \quad v_\phi = Uv_1, \\
    v_t &= U\psi v_2, \quad v_z = UL_1^{-1} v_3, \\
    H_\phi &= H_oH_1, \quad H_r = H_oH_2, \quad H_z = H_oH_3, \quad N_\phi = N_oN_1, \quad N_t = N_oN_2, \quad N_z = N_oN_3, \\
    \eta &= \eta_o\eta_1, \quad \kappa = \kappa_o\kappa_1, \quad \nu = \nu_o\nu_1, \quad \rho = \rho_o \cdot \rho_1, \quad \alpha = \alpha_o\alpha_1, \quad \beta = \beta_o\beta_1.
\end{align*}
\]  
(9)

There has been adopted the following criterion numbers:

\[
\begin{align*}
    p_o &\equiv \frac{RU\eta_o}{\varepsilon^2}, \quad \psi \equiv \frac{\varepsilon}{R} \cong 10^{-3}, \quad L_1 \equiv \frac{b}{R}, \quad R_f \equiv \frac{\mu_oN_oH_o}{p_o}, \quad Re \equiv \frac{U\rho_o}{\varepsilon}, \\
    \Omega_l &\equiv \frac{\Omega \cdot \varepsilon^2}{U^2\eta_o}, \quad De_\alpha \equiv \frac{\alpha_oU}{\eta_oR}, \quad De_\beta \equiv \frac{\beta_oU}{\eta_oR}, \quad 0 < |De_\alpha| < 1, \\
    Nu &\equiv \frac{\nu\varepsilon}{\kappa}, \quad Br \equiv \frac{U^2\eta_o}{\kappa_oT_o}, \quad 0 < Q_{Br} \equiv BrT_\delta T < 1.
\end{align*}
\]  
(10)

where:

- \(Br\) – dimensionless Brinkman number,
- \(De_\alpha, De_\beta\) – Deborah numbers as dimensionless small parameters,
- \(H_o\) – dimensional vector value of magnetic field strength [A·m\(^{-1}\)],
- \(H_1, H_2, H_3\) – dimensionless vector components of magnetic field strength,
- \(H_\phi, H_r, H_z\) – vector components of magnetic field strength [A·m\(^{-1}\)],
- \(L_1\) – dimensionless bearing length,
- \(N_o\) – dimensional value of magnetization vector [A·m\(^{-1}\)],
- \(N_1, N_2, N_3\) – dimensionless components of magnetization vector,
- \(N_\phi, N_t, N_z\) – components of magnetization vector [A·m\(^{-1}\)],
- \(Nu\) – Nusselt number,
- \(Q_{Br}\) – dimensionless coefficient of viscosity on temperature changes,
- \(R\) – journal radius [m],
- \(R’\) – shell radius [m],
- \(R_f\) – dimensionless number of magnetic pressure,
- \(Re\) – Reynolds number,
- \(T_0\) – dimensional value of temperature [K],
- \(T_1\) – dimensionless value of temperature,
- \(U = \omega \cdot R\) – dimensional value of the peripheral velocity [m·s\(^{-1}\)],
- \(a_s\) – dimensionless misalignment ratio,
- \(2b\) – bearing length [m],
- \(h_{c1}\) – dimensionless total height of the oil gap,
The system of equations in dimensionless form contains the units with order of elementary magnitude are visible as units of the negligible order like the relative radial clearance \( \psi \approx 10^{-3} \). Omitting units of the order of the relative radial clearance that means about a thousand times smaller than the value of other units, a new simplified set of equations has been obtained \[6\].

For further analysis of the basic equations it has been assumed that the dimensionless density \( \rho_1 = 1 \) of lubricant is constant and not depend on temperature and pressure \[5, 8\].
In order to solve the problem of hydrodynamic lubrication, which determine the size of the functions sought, such as: components of velocity, hydrodynamic pressure, load-bearing forces and friction forces the classical method of small parameter has been used. This method uncouples of nonlinear partial differential equations, forming three linear equations. The first set of equations allows to determine the flow parameters for the classical isothermal, Newtonian lubrication with the magnetic field effect on the change in viscosity. The second one allows to determine the so-called velocity components corrections, hydrodynamic pressure as resulting of temperature effect on viscosity. The third one allows to determine the adjustments follow from the consideration of non-Newtonian properties.

In this paper has been analyzed only that first set of equations. The other systems will be considered in future works.

Integrating twice after the radial variable corresponding momentum equation and applying boundary conditions circumferential and longitudinal component of the velocity vector has been obtained.

Boundary conditions for components of velocity vector of oil with Newtonian properties are as follows:

\[
\begin{align*}
\nu_1 &= 0, \quad \nu_2 = 0, \quad \nu_3 = 0 \quad \text{on sleeve } r_1 = h_{pl}, \\
\nu_1 &= 1, \quad \nu_2 = 0, \quad \nu_3 = 0 \quad \text{on journal } r_1 = 0. \quad \text{(11)}
\end{align*}
\]

where \(\nu_1, \nu_2, \nu_3\) – dimensionless velocity vector’s components of the lubricant agent.

These conditions indicate that the peripheral speed of the oil in contact with the journal assumes a value of peripheral speed of the journal and zero on the stationary sleeve, because the liquid lubricant is a viscous liquid, and it does not take into account the vibration of the shaft and the sleeve, or slips. For these reasons, the longitudinal velocity component of the oil is zero. The radial velocity component of the oil on the journal and sleeve is zero because the material is porous and it’s assumed that the journal and sleeve do not perform transverse vibration.

Dimensionless components: the circumferential and the longitudinal of the velocity vector for Newtonian oil in the magnetic field takes the following form:

\[
\begin{align*}
\nu_1(r, \varphi, z) &= \frac{1}{2 \eta_B} \left( \frac{\partial \rho_1}{\partial \varphi} - M_1 \right) \left( r_1^2 - r_1 h_{pl} \right) + 1 - \frac{r_1}{h_{pl}}, \\
\nu_3(r, \varphi, z) &= \frac{1}{2 \eta_B} \left( \frac{\partial \rho_1}{\partial z} - M_3 \right) \left( r_1^2 - r_1 h_{pl} \right).
\end{align*}
\]

For the distribution of hydrodynamic pressure in the oil with Newtonian properties Reynolds boundary conditions have been adopted in the following form [9, 10, 11]:
\[ p_1 = 0 \text{ for } \phi = \phi_p, \quad p_1 = 0 \text{ for } \phi \geq \phi_k, \]
\[ \frac{\partial p_1}{\partial \phi} = 0 \text{ for } \phi = \phi_k, \quad p_1 = 0 \text{ for } z_1 = +1 \text{ and } z_1 = -1, \quad (13) \]

where:
\[ \phi_p \] – beginning of the oil film coordinate,
\[ \phi_k \] – end of the oil film coordinate.

These conditions mean that the value of hydrodynamic pressure is equal to the ambient pressure (atmospheric pressure) equal to zero compared with the developed pressure in the bearing. Adoption a value of zero applies the site \( \phi = \phi_p \), ie the initial coordinate equal to approximately 4° in the direction of the journal movement on the front end of the line which connecting centers of journals and sleeves is usually the place to bring the oil into the gap and at the site \( \phi = \phi_k \), ie coordinate the end of the oil film. This value is unknown in terms of Reynolds, but it is known that it lies outside the rear end of the line which connecting centers of journals and sleeves.

Using the continuity equation and the previously evaluated components: the longitudinal and circumferential and after integrating equation and imposing the appropriate boundary conditions we obtain the radial component of velocity and Reynolds-type equation which has the form [6]:
\[
\frac{\partial}{\partial \phi} \left[ \frac{h_{pl}^3}{\eta_{IB}} \left( \frac{\partial p_1}{\partial \phi} - M_1 \right) \right] + \frac{1}{L_1^2} \frac{\partial}{\partial z_1} \left[ \frac{h_{pl}^3}{\eta_{IB}} \left( \frac{\partial p_1}{\partial z_1} - M_3 \right) \right] = 6 \frac{\partial h_{pl}}{\partial \phi}, \quad (14)
\]

where:
\[ M_1 = R_f \chi \left[ H_1 \frac{\partial H_1}{\partial \phi} + \frac{1}{L_1} H_3 \frac{\partial H_1}{\partial z_1} \right], \quad M_3 = R_f L_1 \chi \left[ H_1 \frac{\partial H_3}{\partial \phi} + \frac{1}{L_1} H_3 \frac{\partial H_3}{\partial z_1} \right] \]

Dimensional value of the lift force \( C_\Sigma \) in the cross slide bearing is determined from the known formula [6]:
\[ C_\Sigma = C_1 \cdot b R \eta_\omega \omega / \psi^2. \quad (15) \]

Dimensionless value of the lift force \( C_1 \) of cross sliding bearing lubricated by ferromagnetic fluid with viscoelastic properties is calculated from the relation [6]:
\[
C_1 = \sqrt{\int_{-1}^{+1} \left( \int_{0}^{\phi_k} p_1 \cos \gamma \sin \phi \, d\phi \right) \, dz_1 \left( \int_{0}^{+1} \left( \int_{0}^{\phi_k} p_1 \cos \gamma \cos \phi \, d\phi \right) \, dz_1 \right)^2}, \quad (16)
\]

where the symbol \( \gamma \) is the misalignment angle.

The total dimensional friction in the gap the cross slide bearing shows the following relationship:
\[ F_r = F_{r1} \cdot b R \eta_\omega \omega / \psi. \quad (17) \]
Dimensionless value of friction force for the classical Newtonian oil including the influence of the magnetic field to change the dynamic viscosity is calculated from the following relationship:

\[
\text{Fr}_1 = \int_{-1}^{1} \int_{0}^{\phi} \left( \eta_{IB} \frac{\partial v_1}{\partial r_1} \right) \, d\phi \, dz_1 + \int_{-1}^{1} \int_{0}^{\phi} \left( \eta_{IB} \frac{\partial (r_1^2 - \eta h_{pl})}{\partial \eta} \right) \, d\phi \, dz_1 + \int_{-1}^{1} \int_{0}^{\phi} \left( \eta_{IB} \frac{\partial (r_1^2 - \eta h_{pl})}{\partial \eta} \right) \, d\phi \, dz_1
\]

The function of peripheral velocity consists of a velocity caused by gradient of pressure and the velocity caused by peripheral movement of the journal (shear flow) and the magnetic field.

Total conventional coefficient of friction for the classical Newtonian oil including the influence of the magnetic field to change the dynamic viscosity is determined from the following formula:

\[
\left( \frac{\mu}{\psi} \right) = \frac{\text{Fr}_1 \cdot b R \eta_0 \omega}{C_1 \cdot b R \eta_0 \omega} = \left( \frac{\mu}{\psi} \right) = \frac{\text{Fr}_1}{C_1},
\]

The temperature distribution should be obtained from the equation of conservation of energy being disregarded derived permeability with temperature.

Energy dissipation units should be replaced with property units obtained from the transformed momentum equation [6]:

\[
\eta_{IB} \left( \frac{\partial v_1}{\partial \eta} \right)^2 = \frac{1}{2} \eta_{IB} \frac{\partial^2}{\partial r_1^2} (v_1)^2 - v_1 \left( \frac{\partial p_1}{\partial \phi} - M_1 \right),
\]

\[
\eta_{IB} \frac{1}{L_1^2} \left( \frac{\partial v_3}{\partial \eta} \right)^2 = \frac{1}{2L_1^2} \eta_{IB} \frac{\partial^2}{\partial r_1^2} (v_3)^2 - v_3 \frac{1}{L_1^2} \left( \frac{\partial p_1}{\partial z_1} - M_3 \right).
\]

The resulting dependence is twice integrated over the variable \( r_1 \).

To determine the temperature distribution in the oil having Newtonian properties, that has been adopted the following boundary conditions:

\[ T_1 = f_{1c} \text{ for } r_1 = 0, \quad T_1 = f_{1p} \text{ for } r_1 = h_{pl}, \]
\[
\frac{\partial T_1}{\partial r_1} = \text{Nu} \left( T_1 - f_{1c} \right) \equiv -q_{1c} \quad \text{for} \quad r_1 = 0,
\]

\[
\frac{\partial T_1}{\partial r_1} = \text{Nu} \left( f_{1p} - T_1 \right) \equiv -q_{1p} \quad \text{for} \quad r_1 = h_{p1}.
\]

In order to designate integration’s constants the boundary conditions for adjusted temperature \( f_{1c} = 1 \) on the journal are adopted and assumes a known dimensionless heat flux density \( q_{1c} = 0.5 \) on the journal \( r_1 = 0 \). There is a known dimensionless temperature \( f_{1p} \) on the sleeve surface.

Finally, after simplification of expressions the function of oil temperature in the magnetic field is obtained as [6]:

\[
T_1 (r, \varphi, z_1) = 1 + \frac{1}{2} \eta_{1B} (1 - 2s) - q_{1c} h_{p1} s - \frac{1}{2} \Omega_1 (h_{p1} s)^2 - \frac{1}{6} h_{p1}^2 \left( \frac{\partial p_1}{\partial \varphi} - M_1 \right) s (3 - 3s + s^2) - \frac{1}{2} \eta_{1B} \left[ (v_1)^2 + \frac{1}{l_1^2} (v_3)^2 \right] + \frac{1}{24 \eta_{1B}} h_{p1}^4 \left[ \left( \frac{\partial p_1}{\partial \varphi} - M_1 \right)^2 + \frac{1}{l_1^2} \left( \frac{\partial p_1}{\partial z_1} - M_3 \right)^2 \right] s^3 (s - 2).
\]

for \( s = r_1 / h_{p1} \), \( 0 \leq s \leq 1 \).

2. NUMERICAL CALCULATIONS

Numerical calculations of the load carrying capacities, friction force, friction coefficient and temperature distribution are performed in Mathcad 14 Professional Program by virtue of the equation (16), (17), (18), (19), (23) by means of the finite difference method (see Fig.1, 2, 3, 4, 5, 6, 7). On the ground of pressure distributions are calculated the load carrying capacities (see Fig.1). The frictional force is shown in Figure 2 and the apparent friction coefficient in Figure 3. Figures from 4 to 7 shows temperature distributions for the sliding journal bearings sleeves.

The numerical calculations have been performed for the relative eccentricity: \( \lambda = 0.1 \); \( \lambda = 0.2 \); \( \lambda = 0.3 \); \( \lambda = 0.4 \); \( \lambda = 0.5 \); \( \lambda = 0.6 \); \( \lambda = 0.7 \); \( \lambda = 0.8 \); \( \lambda = 0.9 \) and the dimensionless length of bearing \( L_1 = 1/4 \) at four concentrations of magnetic particles of ferrofluid: 0% (classic lubricating oil), 1%, 3% i 6%.

The components of the magnetic field strength have been determined by analytical-numerical solution of Maxwell's equations [5].

For all calculations, the following dimensional and dimensionless parameters have been assumed: angle of misalignment \( \gamma = 0.00^\circ \); magnetic susceptibility corresponding to different concentrations of magnetic particles \( \chi = 2.0 \), \( \chi = 2.5 \), \( \chi = 3.0 \); the number of magnetic pressure \( R_f = 0.5 \); dimensionless coefficient describing the effect of magnetic induction on the dynamic viscosity suitable for different concentrations of magnetic particles \( \delta_{B1} = 0.100 \); \( \delta_{B1} = 0.175 \); \( \delta_{B1} = 0.225 \).
For determining the distribution of hydrodynamic pressure boundary conditions of Reynolds have been adopted.

**Fig. 1.** The dimensionless load carrying capacities \( C_i \) in cylindrical sliding journal bearings

**Fig. 2.** The dimensionless friction force \( F_{ri} \) in cylindrical sliding journal bearings

**Fig. 3.** The apparent friction coefficient \( \frac{\mu}{\psi} \) in cylindrical sliding journal bearings
Fig. 4. The temperature distribution in the gap of sliding journal bearing lubricated with ferrofluids for relative eccentricity $\lambda = 0.1$–0.9
Fig. 5. The temperature distribution in the gap of sliding journal bearing lubricated with 1% ferro-oil for relative eccentricity $\lambda = 0.1–0.9$
Fig. 6. The temperature distribution in the gap of sliding journal bearing lubricated with 3% ferro-oil for relative eccentricity $\lambda = 0.1–0.9$
Fig. 7. The temperature distribution in the gap of sliding journal bearing lubricated with 6% ferro-oil for relative eccentricity $\lambda = 0.1-0.9$
CONCLUSIONS

Increase in the number of magnetic particles causes an increase of load carrying capacities with the presence of the same value of external magnetic field. This increase is in the range: \( T_{\lambda=0.1} - 90_{\lambda=0.9} \)% relating to the lubricating oil without the magnetic particles.

Increase in the number of magnetic particles results in a slight increase in friction force. This increase is in the range 0.2–7%.

With a large increase in load carrying capacities and a slight growth in friction force, conventional friction coefficient decreases with increasing concentration of magnetic particles in ferrofluid. This decrease is in the order of \( 44_{\lambda=0.1} - 2_{\lambda=0.9} \)%. The presence of magnetic particles in ferrofluid reduces the maximum temperature in the gap of slide journal bearing. This decrease is around \( 20_{\lambda=0.1} - 30_{\lambda=0.9} \) degrees. There is a noticeable effect of the presence of magnetic particles to change the temperature gradient.

It should be clear that the quoted values are the result of computer simulation. The actual value of changes of temperature, load carrying capacities, friction force and friction coefficient will depend on the type of magnetic particles, the type of base fluid, the concentration of magnetic particles, the value of an external magnetic field, temperature and value of ferrofluid's hydrodynamic pressure, which depends inter alia on the load bearing, rotational speed, radial clearance, and the geometric dimensions of the bearing.

REFERENCES

ROZKŁAD TEMPERATURY W SZCZELINIE POPRZECZNEGO ŁOŻYSKA ŚLIZGOWEGO SMAROWANEGO FERROCIECZĄ O RÓŻNYM STĘŻENIU CZĄSTEK MAGNETYCZNYCH

Streszczenie

W pracy autor przedstawia wyniki obliczeń numerycznych rozkładu temperatury, siły nośnej, siły tarcia i współczynnika tarcia w szczelinie poprzecznego lożyska ślizgowego smarowanego ferrocieczą o różnym stężeniu cząstek. W analityczno-numerycznym modelu przyjęto równania typu Reynoldsa wyprowadzone z równań pędu i ciągłości strugi dla przepływu laminarnego, ustalonego i izotermicznego oraz lepkosprężysty model cieczy smarującej typu Rivlina-Ericksena. Przyjęto również, iż lepkość dynamiczna zależy głównie od pola magnetycznego. Równanie typu Reynoldsa, na podstawie którego można wyznaczyć rozkłady ciśnienia hydrodynamicznego, rozwiązano numerycznie przy wykorzystaniu programu Mathcad 14 Professional. Na podstawie tych obliczeń wyznaczono wartości siły nośnej i tarcia oraz współczynnika tarcia, a także rozkłady temperatur w szczelinie lożyska ślizgowego, które przedstawiono w formie wykresów.

Słowa kluczowe: rozkład temperatury, ferrociecz, pole magnetyczne, obliczenia numeryczne.