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# INFLUENCE OF MAGNETIC PARTICLES CONCENTRATION IN FERRO-OIL ON VALUES OF FRICTION FORCE AND COEFFICIENT OF FRICTION OF SLIDE JOURNAL BEARING

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***Abstract***

*This article has been focused on the analysis of changes in friction force as well as coefficient of friction of slide journal bearing in terms of the concentration of magnetic particles in the lubricating ferro-oil. There has been present an analytical and numerical calculation model based on experimentally determined physical quantities describing the dependence of ferro-oil's viscosity on fundamental parameters such as temperature, pressure or external magnetic field in the paper. Numerical calculations of the dimensionless friction force as well as the dimensionless friction coefficient were performed by solving the Reynold's type equation using the finite difference method using Mathcad 15 and own calculation procedures. The obtained results has been presented in the form of a series of graphs that take into account: the influence of external magnetic field, corrections related to the influence of pressure changes, corrections related to the influence of temperature changes and finally corrections related to non-Newtonian ferro-oil properties. An analysis of the obtained characteristics has been made so the observations and conclusions were drawn regarding optimum magnetic particle content in the ferro-oil lubricating the sliding journal bearing*

***Keywords:*** *ferro-oil, dynamic viscosity, magnetic particles concentration, friction force, friction coefficient*

## 1. Introduction

When deciding on the use of a particular oil, including ferro-oil, in the process of lubrication of slide bearings, numerous features are taken into consideration, including the choice of rheological properties and, in particular, its viscosity. This property is mainly dependant on the basic parameters of work – temperature, pressure as well as shear rate. Other significant parameters include the oil chemical composition as well as the internal structure expressed, among others, in the concentration of the magnetic particles $n_{cs}$. In addition, in case of ferro-oils, the presence and characteristics of the external magnetic field, varying depending on the type, direction or the induction value, play the key role in their viscosity.

Following the research work carried out over the past few years, presented in numerous publications, including [4-8], it has been created by the author a mathematical-physics model of changes in viscosity of ferro-oils in terms of the concentration of magnetic particles, taking into account changes in pressure, temperature, shear rate as well as influence of the external magnetic field $\eta_{ncs}=\eta_{ncs}(B,p,T,\theta)$. It has been designated, by the way of the experimental tests, the actual values of the major coefficients $\delta_B$, $\delta_p$ and $\delta_T$ of changes in viscosity of ferro-oil in terms of the above-mentioned physical parameters [5, 6, 8]. On the basis of obtained viscosity models, further analytical-numerical studies have been possible to determine the influence of magnetic particle concentration on the flow- and operating- parameters of journal slide bearings lubricated with ferro-oils. It has been used analytical-numerical model created by A. Miszczak, presented in [10] and previously used in the other works of authors, e.g. in [4]. This model has been modified to adapt above mentioned viscosity models as well as experimentally determined actual values of magnetic susceptibility coefficients $\chi$ [7] or determined material constant $\alpha$ and $\beta$ of ferro-oil taking into account its viscoelastic properties [11].

Physic-chemical properties of oils and in particular their rheological properties are directly attributable to tribological properties of friction nodes described by flow parameters, including in particular: hydrodynamic pressure distributions, component values of lubricant flow velocity vectors as well as operating parameters, among which the most important are temperature distributions, load carrying capacity, friction force, friction coefficient or minimum height of oil gap. Operation of journal slide bearing in the range of optimal values of these parameters provides the conditions for proper operation of the device and consequently its high reliability or durability.

This work has been focused on the analysis of changes in friction force as well as coefficient of friction of slide journal bearing in terms of the concentration of magnetic particles in the lubricating ferro-oil. These values represent important operating parameters for slide bearings. Their value depends on how much heat is emitted in the oil film gap and what will be the efficiency of bearing operation. The ability to control the rheological properties of the lubricant by altering the influence of the external magnetic field or by optimizing the magnetic particle concentration creates an analogous ability to control bearing operation and consequently opens up prospects for the possibilities which are not available for conventional lubricants, ie. bearing operation in intelligent mode. This means that adjustment of the operating parameters of the bearing with respect to changing operating conditions, capable of maintaining the oil film in the bearing under extremely adverse environmental conditions or finally provide specific functional reserve in the aspects of reliability and safety.

## 2. Analytical-numerical computational model

An analytical model of magnetohydrodynamic lubrication of slide journal bearings was derived from fundamental equations, ie equations of momentum conservation, equations of flow continuity, equations of energy conservation as well as Maxwell's equations [1-3, 9, 10, 12-14]. The non-isothermal bearing lubrication model was assumed with a laminar and steady lubricant flow rate and the external magnetic field was adopted as stationary, transverse to the ferro-oil flow in the bearing gap.

As the constitutive equation for ferro-oil was adopted non-Newtonian viscoelastic model of Rivlin-Ericksen' fluid. This relationship describes the relationship between stress tensor coordinates and the tensor of shear rate of the ferro-oil. The details of these equations and the relationships between them are presented in the work [10].

The dependence of the dynamic viscosity of the ferro-oil on magnetic induction, temperature and pressure $\eta=\eta(B,T,p)$ was taken into account. Whereas the material coefficients $\alpha$, $\beta$ were assumed to be constant [11]. The function of dynamic viscosity is presented in the form of the ratio of members dependent on particular physical parameters:

$$\eta = \eta_o \cdot \eta_1;\ \eta_1 = \eta_{1B} \cdot \eta_{1p} \cdot \eta_{1T},\ \eta_{1p}(\varphi, z) = a_p \cdot e^{\delta_p \cdot p_o \cdot p_1} = a_p \cdot e^{\delta_{p1} p_1},$$

$$\eta_{1T}(\varphi, z, r) \equiv a_T \cdot e^{-\delta_T (T - T_o)} = a_T \cdot e^{-Q_{Br} T_1},\ \eta_{1B}(\varphi, z) = a_B (B_0 \cdot B_1)^{\delta B} = a_B (B_1)^{\delta B1}, \tag{1}$$

where:

- $\eta_1$ – total dimensionless dynamic viscosity,
- $\eta_o$ – characteristic dimensionless dynamic viscosity,
- $\eta_{1p}$ – dimensionless dynamic viscosity depended on pressure,
- $\eta_{1T}$ – dimensionless dynamic viscosity depended on temperature,
- $\eta_{1B}$ – dimensionless dynamic viscosity depended on magnetic induction,
- $\delta_B$, $\delta_{B1}$ – dimensional and dimensionless material factors taking into account viscosity changes from the magnetic field,

$\delta_p$, $\delta_{p1}$ – dimensional and dimensionless material factors taking into account viscosity changes from the hydrodynamic pressure,
$\delta_T$ – dimensional material factor taking into account viscosity changes from the temperature,
$a_B$ – proportionality ratio,
$\kappa_o$ – ferro-oil heat transfer coefficient,
$\omega$ – angular velocity of journal,
$B_o$ – dimensional value of magnetic field induction,
$B_1$ – dimensionless value of magnetic field induction,
$Q_{Br} = R^2\omega^2\eta_o\delta_T/\kappa_o$ – dimensionless coefficient of viscosity change from temperature,
$R$ – radius of journal,
$p_1$ – dimensionless hydrodynamic pressure,
$p_o$ – dimensional value of hydrodynamic pressure.

Equations of motion have been substituted for constitutive relationships between stress tensor coordinates and shear rate tensor coordinates. There were omitted nonstationary units and units of inertia forces in equations of momentum. Such omission is reasonable in the slow and medium speed bearings. It can be obtained the full set of equations of motion for the classical, steady flow of lubricating oil in this way.

The next step in solving the system of equations is its equalization and the estimation of the order of values of the individual members. For this purpose, the dimensional and dimensionless marks and numbers [10], known in the literature have been assumed. A system of equations in the dimensionless form contains units of the order of a unity and members negligibly small order of radial relative clearance $\psi \approx 10^{-3}$. By neglecting the members of the row of radial relative clearance, that is about a thousand times smaller than the values of the other members, a new simplified system of equations is obtained [10].

For further analysis of the basic equations, it has been assumed that the dimensionless density $\rho_1=1$ of the lubricant is constant and independent of both temperature and pressure.

In order to determine the function of the desired values such as velocity vector components, hydrodynamic pressure, load carrying capacity, frictional force and friction coefficient, the *small parameter method* was used. This method consists in converting the sought dimensionless quantities to convergent series with respect to small parameters.

In order to determine the hydrodynamic pressure in the ferro-oil, the Reynolds boundary condition was taken.

Using the continuity equation and previously calculated peripheral and longitudinal components, after integrating the equation and applying appropriate boundary conditions, a velocity vector radial component and a Reynold's type equation are obtained in the following form [10]:

a) for the first set of equations – which takes into account the Newtonian properties and the influence of the magnetic field:

$$\frac{\partial}{\partial\phi}\left[\frac{h_{p1}^3}{\eta_{1B}}\left(\frac{\partial p_1^{(0)}}{\partial\phi}-M_1\right)\right]+\frac{1}{L_1^2}\frac{\partial}{\partial z_1}\left[\frac{h_{p1}^3}{\eta_{1B}}\left(\frac{\partial p_1^{(0)}}{\partial z_1}-M_3\right)\right]=6\frac{\partial h_{p1}}{\partial\phi}, \tag{2}$$

b) for the second set of equations – it takes into account the influence of temperature on viscosity:

$$\frac{\partial}{\partial\phi}\left[\frac{h_{p1}^3}{\eta_{1B}}\left(\frac{\partial p_{10}^{(1)}}{\partial\phi}\right)\right]+\frac{1}{L_1^2}\frac{\partial}{\partial z_1}\left[\frac{h_{p1}^3}{\eta_{1B}}\left(\frac{\partial p_{10}^{(1)}}{\partial z_1}\right)\right]=$$

$$=12\left\{\frac{\partial}{\partial\phi}\left[\left(\int_0^{h_{p1}}\left(\int_0^{r_1}T_1^{(0)}\frac{\partial v_1^{(0)}}{\partial r_1}dr_1\right)dr_1-\int_0^{h_{p1}}\frac{r_1}{h_{c1}}\left(\int_0^{h_{p1}}T_1^{(0)}\frac{\partial v_1^{(0)}}{\partial r_1}dr_1\right)dr_1\right)\right]+\right.$$

$$+\frac{1}{L_1^2}\frac{\partial}{\partial z_1}\left[\int_0^{h_{p1}}\left(\int_0^{r_1} T_1^{(0)}\frac{\partial v_3^{(0)}}{\partial r_1}dr_1\right)dr_1-\int_0^{h_{p1}}\frac{r_1}{h_{c1}}\left(\int_0^{h_{p1}} T_1^{(0)}\frac{\partial v_3^{(0)}}{\partial r_1}dr_1\right)dr_1\right]\Bigg\}, \tag{3}$$

c) for the third set of equations – it takes into account the influence of pressure on viscosity:

$$\frac{\partial}{\partial\phi}\left[\frac{h_{p1}^3}{\eta_{1B}}\left(\frac{\partial p_{11}^{(1)}}{\partial\phi}\right)\right]+\frac{1}{L_1^2}\frac{\partial}{\partial z_1}\left[\frac{h_{p1}^3}{\eta_{1B}}\left(\frac{\partial p_{11}^{(1)}}{\partial z_1}\right)\right]=$$

$$=12\left\{\frac{\partial}{\partial\phi}\left[\int_0^{h_{p1}}\frac{r_1}{h_{c1}}\left(\int_0^{h_{p1}} p_1^{(0)}\frac{\partial v_1^{(0)}}{\partial r_1}dr_1\right)dr_1-\int_0^{h_{p1}}\left(\int_0^{r_1} p_1^{(0)}\frac{\partial v_1^{(0)}}{\partial r_1}dr_1\right)dr_1\right]+\right.$$

$$\left.+\frac{1}{L_1^2}\frac{\partial}{\partial z_1}\left[\int_0^{h_{p1}}\frac{r_1}{h_{c1}}\left(\int_0^{h_{p1}} p_1^{(0)}\frac{\partial v_3^{(0)}}{\partial r_1}dr_1\right)dr_1-\int_0^{h_{p1}}\left(\int_0^{r_1} p_1^{(0)}\frac{\partial v_3^{(0)}}{\partial r_1}dr_1\right)dr_1\right]\right\}, \tag{4}$$

d) for the forth set of equations – it takes into account the influence of non-Newtonian properties on viscosity:

$$\frac{\partial}{\partial\phi}\left(\frac{h_{p1}^3}{\eta_{B1}}\frac{\partial p_{1p}^{(1)}}{\partial\phi}\right)+\frac{1}{L_1^2}\frac{\partial}{\partial z_1}\left(\frac{h_{p1}^3}{\eta_{B1}}\frac{\partial p_{1p}^{(1)}}{\partial z_1}\right)=$$

$$=12\left\{\frac{\partial}{\partial\varphi}\left(\frac{1}{\eta_{B1}}\int_0^{h_{p1}}\int_0^{r_3}\int_0^{r_2}F(\varphi,r_1,z_1)dr_1dr_2dr_3-\frac{h_{p1}}{2\eta_{B1}}\int_0^{h_{p1}}\int_0^{r_2}F(\varphi,r_1,z_1)dr_1dr_2\right)+\right.$$

$$\left.+\frac{1}{L_1^2}\frac{\partial}{\partial z_1}\left(\frac{1}{\eta_{B1}}\int_0^{h_{p1}}\int_0^{r_3}\int_0^{r_2}G(\varphi,r_1,z_1)dr_1dr_2dr_3-\frac{h_{p1}}{2\eta_{B1}}\int_0^{h_{p1}}\int_0^{r_2}G(\varphi,r_1,z_1)dr_1dr_2\right)\right\}, \tag{5}$$

where:

$$v_1^{(0)}(r_1,\varphi,z_1)=\frac{1}{2\eta_{1B}}\left(\frac{\partial p_1^{(0)}}{\partial\phi}-M_1\right)\left(r_1^2-r_1h_{p1}\right)+1-\frac{r_1}{h_{p1}},\ v_3^{(0)}(r_1,\varphi,z_1)=\frac{1}{2\eta_{1B}}\left(\frac{\partial p_1^{(0)}}{\partial z_1}-M_3\right)\left(r_1^2-r_1h_{p1}\right),$$

$$T_1^{(0)}(r_1,\varphi,z_1)=1+\frac{1}{2}\eta_{1B}(1-2s)-q_{1c}^{(0)}h_{p1}s-\frac{1}{2}\Omega_1\left(h_{p1}s\right)^2-\frac{1}{6}h_{p1}^2\left(\frac{\partial p_1^{(0)}}{\partial\varphi}-M_1\right)s\,(3-3s+s^2)+$$

$$-\frac{1}{2}\eta_{1B}\left[\left(v_1^{(0)}\right)^2+\frac{1}{L_1^2}\left(v_3^{(0)}\right)^2\right]+\frac{1}{24\eta_{1B}}h_{p1}^4\left[\left(\frac{\partial p_1^{(0)}}{\partial\varphi}-M_1\right)^2+\frac{1}{L_1^2}\left(\frac{\partial p_1^{(0)}}{\partial z_1}-M_3\right)^2\right]s^3(s-2),$$

$$M_1=R_f\chi\left[H_1\frac{\partial H_1}{\partial\varphi}+\frac{1}{L_1}H_3\frac{\partial H_1}{\partial z_1}\right],\ M_3=R_fL_1\chi\left(H_1\frac{\partial H_3}{\partial\varphi}+\frac{1}{L_1}H_3\frac{\partial H_3}{\partial z_1}\right),$$

$$F(\varphi,r_1,z_1)\equiv\left(1+2\frac{\beta_o}{\alpha_o}\right)\left(\frac{\partial X_1}{\partial\varphi}+\frac{1}{L_1^2}\frac{\partial Z_1}{\partial\varphi}\right)-\frac{\partial X_1}{\partial\varphi}-\frac{1}{L_1^2}\left(\frac{\partial X_2}{\partial r_1}+\frac{\partial X_3}{\partial z_1}\right)-\frac{\beta_o}{\alpha_o}\left(\frac{\partial X_4}{\partial r_1}+2\frac{\partial X_5}{\partial r_1}\right),$$

$$G(\varphi,r_1,z_1)\equiv\left(1+2\frac{\beta_o}{\alpha_o}\right)\left(\frac{\partial X_1}{\partial z_1}+\frac{1}{L_1^2}\frac{\partial Z_1}{\partial z_1}\right)-\frac{1}{L_1^2}\frac{\partial Z_1}{\partial z_1}-\left(\frac{\partial Z_2}{\partial r_1}+\frac{\partial Z_3}{\partial\varphi}\right)-\frac{\beta_o}{\alpha_o}\left(\frac{\partial Z_4}{\partial r_1}+2\frac{\partial Z_5}{\partial r_1}\right),$$

$$X_1\equiv\left(\frac{\partial v_1^{(0)}}{\partial r_1}\right)^2,\ X_2\equiv\frac{\partial v_3^{(0)}}{\partial r_1}Y_4-2\frac{\partial v_1^{(0)}}{\partial r_1}\frac{\partial v_3^{(0)}}{\partial z_1},\ X_3\equiv\frac{\partial v_1^{(0)}}{\partial r_1}\frac{\partial v_3^{(0)}}{\partial r_1},\ Y_1\equiv\frac{\partial v_1^{(0)}}{\partial\phi},\ Y_2\equiv\frac{\partial v_2^{(0)}}{\partial r_1},$$

$$Y_3 \equiv \frac{\partial v_3^{(0)}}{\partial z_1},\ Y_4 \equiv \frac{\partial v_3^{(0)}}{\partial \varphi} + \frac{\partial v_1^{(0)}}{\partial z_1},\ Z_1 \equiv \left(\frac{\partial v_3^{(0)}}{\partial r_1}\right)^2,\ Z_2 \equiv \frac{\partial v_1^{(0)}}{\partial r_1} Y_4 - 2\frac{\partial v_3^{(0)}}{\partial r_1}\frac{\partial v_1^{(0)}}{\partial \varphi},\ Z_3 \equiv \frac{\partial v_1^{(0)}}{\partial r_1}\frac{\partial v_3^{(0)}}{\partial r_1},$$

$$X_4 \equiv \frac{\partial}{\partial r_1}\left(v_1^{(0)}\frac{\partial v_1^{(0)}}{\partial \varphi} + v_2^{(0)}\frac{\partial v_1^{(0)}}{\partial r_1} + \frac{1}{L_1^2} v_3^{(0)}\frac{\partial v_1^{(0)}}{\partial z_1}\right),\ X_5 \equiv \frac{\partial v_1^{(0)}}{\partial \phi}\frac{\partial v_1^{(0)}}{\partial r_1} + \frac{1}{L_1^2}\frac{\partial v_3^{(0)}}{\partial \varphi}\frac{\partial v_3^{(0)}}{\partial r_1},$$

$$Z_4 \equiv \frac{\partial}{\partial r_1}\left(v_1^{(0)}\frac{\partial v_3^{(0)}}{\partial \phi} + v_2^{(0)}\frac{\partial v_3^{(0)}}{\partial r_1} + \frac{1}{L_1^2} v_3^{(0)}\frac{\partial v_3^{(0)}}{\partial z_1}\right),\ Z_5 \equiv \frac{\partial v_1^{(0)}}{\partial r_1}\frac{\partial v_1^{(0)}}{\partial z_1} + \frac{1}{L_1^2}\frac{\partial v_3^{(0)}}{\partial z_1}\frac{\partial v_3^{(0)}}{\partial r_1},$$

$$h_{p1} = [1 + \lambda\cdot\cos\varphi + a_\gamma\cdot z_1\cdot\cos(\varphi)],\ a_\gamma = \frac{L_1}{\psi}\tan(\gamma),$$

$$0 \le r_1 \le h_{p1},\ 0 \le \varphi < \varphi_k,\ -1 \le z_1 < +1,\ s \equiv r_1/h_{p1},\ 0 \le s \le 1,\ 0 \le r_1 \le r_2 \le r_3 \le h_{c1},$$

$a_\gamma$ – misalignment factor,
$v_1, v_2, v_3$ – dimensionless velocity vector components of ferro-oil,
$r_1$ – dimensinless radial coordinate,
$q_{1c}^{(0)}$ – dimensionless density of heat stream,
$z_1$ – dimensionless longitudal coordinate,
$\phi$ – peripheral coordinate,
$\gamma$ – angle of misalignement,
$\lambda$ – relative eccentricity,
$\chi$ – magnetic susceptibility coefficient of ferro-oil,
$\psi$ – dimensionless value of radial relativ clearence,
$\Omega_1$ – dimensionless heat supplied from outside sorces to ferro-oil,
$H_1, H_2, H_3$ – dimensionless vector components of magnetic field strength,
$\alpha_o, \beta_o$ – dimensional values of ferro-oil material coefficients,
$L_1$ – dimensionless lenght of bearing,
$R_f$ – magnetic pressure number.

The total dimensional friction force $Fr_\Sigma$ and total dimensionless friction force $Fr_1$ in the journal slide bearing gap are shown in the following relation [10]:

$$Fr_\Sigma = Fr\cdot(bR\eta_o\omega)/\psi\ .\ Fr_1 = Fr_1^{(0)} + Q_{BR}Fr_{10}^{(1)} + \varsigma_p\cdot Fr_{11}^{(1)} + De\cdot Fr_1^{(1)}\ . \tag{6}$$

Analogously, the total contractual coefficient of friction for ferro-oil taking into account the influence of magnetic field, pressure temperature and non-Newtonian properties on the change of dynamic viscosity is determined from the following formula [10]:

$$\left(\frac{\mu}{\psi}\right)_\Sigma = \frac{Fr_\Sigma}{\psi\cdot C_\Sigma} = \left(\frac{\mu}{\psi}\right)_1^{(0)} + Q_{BR}\left(\frac{\mu}{\psi}\right)_{11}^{(1)} + \varsigma_p\left(\frac{\mu}{\psi}\right)_{11}^{(1)} + De\cdot\left(\frac{\mu}{\psi}\right)_1^{(1)}, \tag{7}$$

where:
$C_\Sigma$ – dimensional value of load carrying capacity of bearing,
$\mu$ – magnetic permeability of ferro-oil,
b – half the length of the bearing,
$\zeta_p$ – dimensionless piezocoefficient of ferro-oil,
De – Deborah's number.

## 3. Results of modelling

Numerical calculations of the dimensionless friction force and the dimensionless friction coefficient were performed by solving the Reynold's type equation using the finite difference method using Mathcad 15 and own calculation procedures. Numerical calculations were performed for the relative eccentricity and dimensionless bearing length $L_1$=1 for six chosen magnetic particle concentrations in ferro-oil: 0%, 1%, 2%, 4%, 6% and 8%.

The components of the magnetic field strength was determined by analytical and numerical solution of Maxwell's equations [12]. The components of the magnetic field vector developed in the paper of Authors [4] were used.

Values of material coefficients $\chi$, $\delta_B$, $\delta_T$ and $\delta_p$ were determined on the basis of the results of experimental research published in [5, 6, 8]. The dimensions and dimensionless values were adopted for all calculations: misalignment angle $\gamma$=0,000°, dimensionless density of heat stream $q_{1c}^{(0)} = -0{,}5$, radius of journal R=0,015m, angular velocity of the journal $\omega$=300s$^{-1}$, ferro-oil heat transfer coefficient $\kappa_o$=0,15W·m$^{-1}$·K$^{-1}$. Dimensional characteristic dynamic viscosity $\eta_o$ was determined at temperature t=90°C.

Table 1 below shows the empirically determined and assumed values of coefficients: $\chi$, $\delta_p$, $\delta_B$, $\delta_T$ for the different concentration of magnetic particles in the ferro-oil.

*Tab.1. Values of viscosity coefficients and magnetic susceptibility coefficient*

| | 0% | 1% | 2% | 4% | 6% | 8% |
|---|---|---|---|---|---|---|
| $\eta_o^{(90°C)}$ [Pa·s] | 0.015471 | 0.015628 | 0.019393 | 0.02598 | 0.065505 | 0.092299 |
| $\chi$ [-] | 0 | 0.047523 | 0.060073 | 0.082272 | 0.117637 | 0.143877 |
| $\delta_p$ [Pa$^{-1}$] | $4.594\cdot10^{-8}$ | $5.889\cdot10^{-8}$ | $6.531\cdot10^{-8}$ | $6.639\cdot10^{-8}$ | $5.834\cdot10^{-8}$ | $6.149\cdot10^{-8}$ |
| $a_p$ [-] | 1.352213 | 1.516317 | 1.605946 | 1.684889 | 1.755983 | 1.928807 |
| $\delta_B$ [-] | 1 | 0.251396 | 0.246007 | 0.254334 | 0.216903 | 0.210347 |
| $a_B$ [T$^{-1}$] | 1 | 0.207057 | 0.571693 | 0.783821 | 1.096772 | 1.380766 |
| $\delta_T$ [T$^{-1}$] | -0.048053 | -0.050638 | -0.052605 | -0.053772 | -0.054196 | -0.057493 |
| $a_T$ [-] | 0.9353 | 0.7950 | 0.7372 | 0.7279 | 0.6887 | 0.6732 |

The obtained distributions of the dimensionless friction force for selected relative eccentricities and concentrations of magnetic particles in the ferro-oil are shown in Fig.1. and the dimensionless coefficient of friction is shown in Fig. 2. In both figures, mark **a)** refers to the results of Newtonian properties of oils subjected to the influence of external magnetic fields. Mark **(b)** refers to the corrections of the quantities represented from the effect of pressure changes on ferro-oils. Symbol **c)** denotes corrections resulting from temperature changes and finally **d)** means corrections from non-Newtonian properties.

## 3. Observations and conclusions

The most important influence on the change in friction force values is caused by changes in ferro-oil temperatures in the bearing gap. These changes reach the order of 100% of the baseline in the whole range of tested relative eccentricities and for each of the tested ferro-oil concentrations. Changes derived from the influence of pressure have a much smaller values, for relative eccentricities $\lambda$=0.1-0.6 do not exceed 2%. Only for higher eccentricities values grow rapidly up to about 20% of the base value. This phenomena is related to the change in the nature of friction from liquid one to mixed in a very narrow clearance of gap. Slightly larger, but also little impact on the friction force exert non-Newtonian lubricant properties. They reduce its value throughout the range of eccentricity changes (for large eccentricities like $\lambda$=0.8 or $\lambda$=0.9 by up to a few percent) and are clearly independent of the concentration of magnetic particles in the ferro-oil.

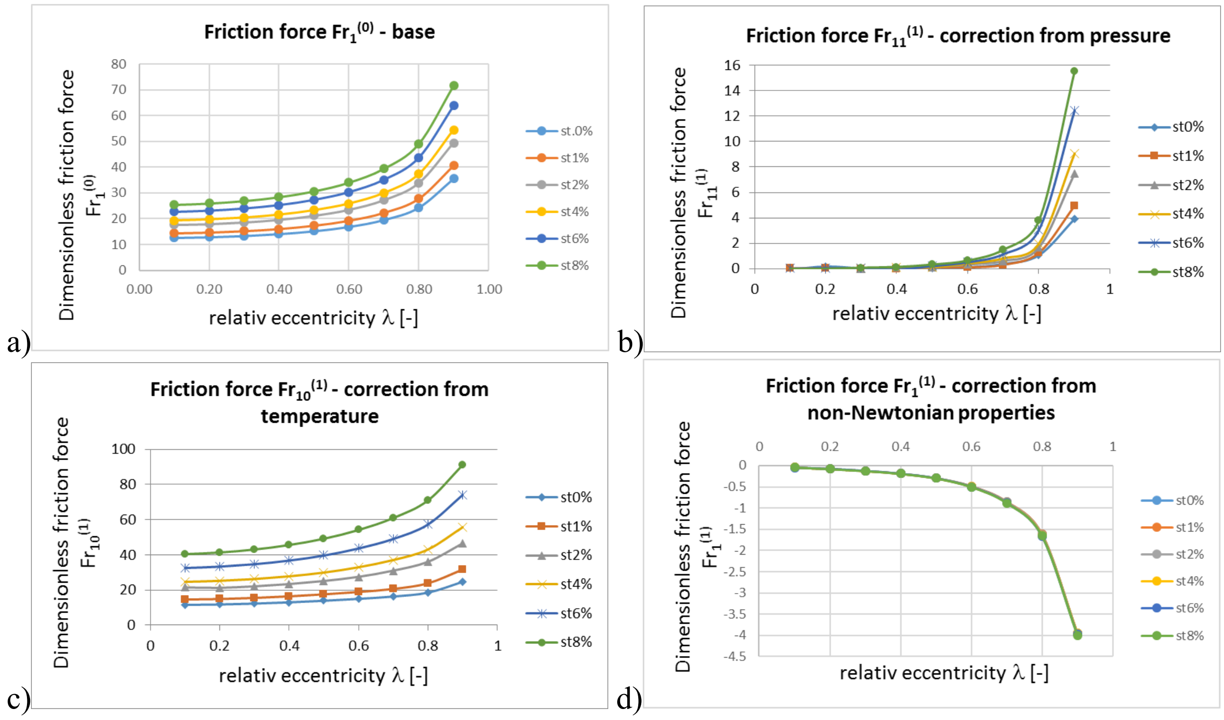



*Fig. 1. Friction force and friction force corrections for different concentrations of magnetic particles in ferro-oil*

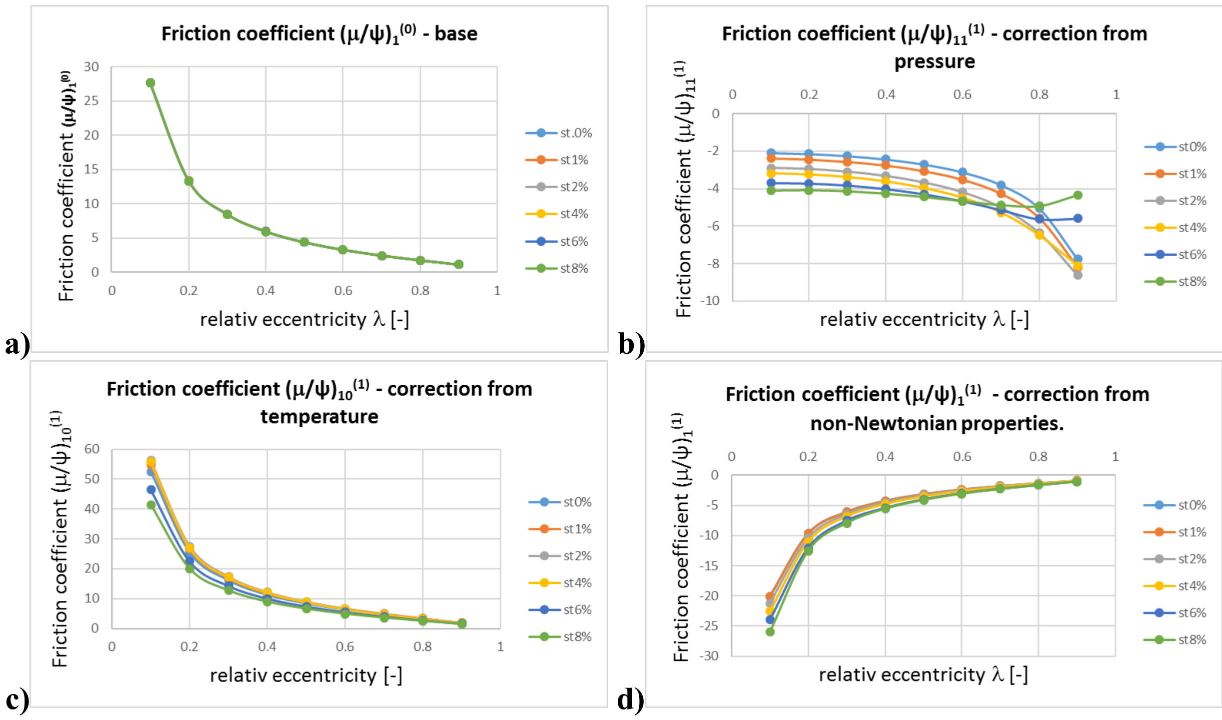
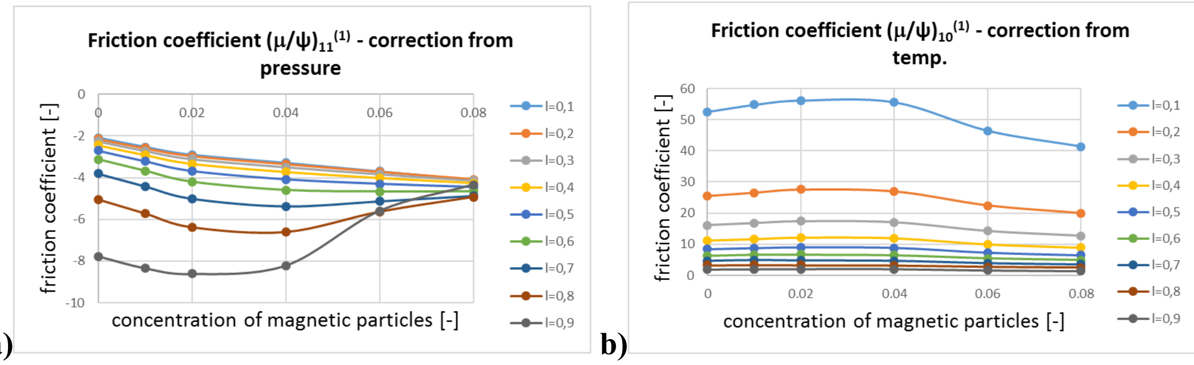



*Fig. 2. Friction coefficient and friction coefficient corrections for different concentrations of magnetic particles in ferro-oil*

Even more interesting observations concern the friction coefficient. Also in this case the corrections from the temperature changes are most significant, but the variation in this case is about 200% for all ferro-oil concentrations. Changes in the coefficient of friction from non-Newtonian properties are of the order of baseline values, lead to its decrease, and depend on the concentration of magnetic particles in the ferro-oil. For changes in coefficient of friction from temperature and pressure, we can observe its local maximum values related to the concentration of magnetic particles. The following characteristics presented in Fig. 3. indicate the existence of an optimum value of the concentration of magnetic particles in the ferro-oil of approx. 2% for which the coefficient of friction reaches its maximum value




a) b)

*Fig. 3. Correction of friction coefficient a) from pressure and from b) temperature due to magnetic particle concentration in ferro-oil for different relative eccentricities*

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