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THE PROBLEMS OF HYDRODYNAMIC NON-ISOTHERMAL LUBRICATION

PROBLEMY HYDRODYNAMICZNEGO NIEIZOTERMICZNEGO SMAROWANIA

Key words:

liquid viscosity, changes in thin gap height direction, temperature, adhesion, or phospholipids, analytical model, micro-bearings, joints applications, initial results

Słowa kluczowe:

lepkość cieczy, zmiany po grubości cienkiej warstwy, temperatura, adhezja, fosfolipidy, model analityczny, mikrołożyska, stawy, wstępne rezultaty

Abstract

The classical hydrodynamic theory of slide bearing lubrication has been constituted on the assumption of constant pressure and viscosity perpendicular to the thin oil layer thickness. These fundamental assumptions are in contradiction to contemporary achievements connected with new devices such as micro-bearing, nano-bearing, magnetic bearings, artificial joints in humanoid robots, micro-motors. Therefore, new methods of measurements and calculations using AFM and a new mathematical computer programs are

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needed. Energy conservation equations after boundary layer simplifications confirm the fact that temperature gradient variations across the film thickness have the same order of magnitude as the variations in longitudinal or circumferential directions. The fact that temperature gradient variations across the bearing gap height can be significantly large are evident, despite the temperature differences across the film thickness that are negligibly small. This statement cannot be compliant with the assumption of a constant viscosity value in the gap height direction.

It has been proven that hydrodynamic pressure is not constant across the film thickness for non-Newtonian oils with Rivlin Erickson constitutive equations.

For pseudo-plastic non-Newtonian oils, the apparent dynamic viscosity significantly decreases with shear rate increases. However, for pseudo-plastic oils, the shear rate increments during the oil flow are strictly connected with the average flow velocity increments. Therefore, the apparent dynamic viscosity depends strongly on the oil velocity gradients. It is evident that flow velocity gradients across the film thickness have intensive variations, particularly in regions where gap height attains the least value. In these places, the dynamic viscosity attains the largest variations in gap height directions. If gap height in micro-bearing is smaller than one micrometre, than the largest oil dynamic viscosity increments caused by the velocity variations across the film thickness are located near the superficial layer of the movable journal surfaces in the case of the hydrodynamic lubrication by rotation, but in the neighbourhood where each of two come near lubricated surfaces during the squeezing. Hence, in these places, dynamic viscosity increases across the film thickness and attains the local maximum values. A gap height smaller than one micrometre has the largest oil dynamic viscosity increments caused by the adhesion force variations across the film thickness located near the motionless sleeve surfaces. In a similar manner, the influences on the viscosity variations caused by the cluster points of concentrations of nano particles as oil inhibitors or oil additives smaller than 5 nm occurring in micro-bearing gaps and the cluster concentration regions of collagen fibres occurring in human joint gap are observed. This paper describes and comments on the above-mentioned problem of oil viscosity changes in the gap height direction, and it presents the apparent dynamic viscosity functions for Newtonian and non-Newtonian oils as well indicates the largest viscosity variations in bearing gap height direction and gives examples of initial calculation results.

BASIC EQUATIONS IN A VIEW OF OIL VISCOSITY VARIATIONS

The total oil dynamic viscosity has the following dimensional form [L. 1]:

$$\begin{aligned}
 \eta_p(\alpha_1, \alpha_2, \alpha_3, t) &= \eta_0 \eta_1(\alpha_1, \alpha_3, t) \eta_{1\pi}(\alpha_1, \alpha_2, \alpha_3), \\
 \eta_\pi(\alpha_1, \alpha_2, \alpha_3) &\equiv \eta_{IT}(\alpha_1, \alpha_2, \alpha_3) \eta_{IAD}(\alpha_1, \alpha_2, \alpha_3) \eta_{ISA}(\alpha_1, \alpha_2, \alpha_3) \times \\
 &\quad \times \eta_{IV}(\alpha_1, \alpha_2, \alpha_3) \eta_{IPH}(\alpha_1, \alpha_2, \alpha_3) \eta_{IWe}(\alpha_1, \alpha_2, \alpha_3), \\
 \eta_T(\alpha_1, \alpha_2, \alpha_3) &\equiv e^{-\delta T(\alpha_1, \alpha_2, \alpha_3)}.
 \end{aligned}
 \tag{1}$$

The total dimensional apparent dynamic viscosity η_p is defined in the form of dimensional oil dynamic viscosity function $\eta_0\eta_1$ multiplied by the dimensionless viscosity correction function $\eta_{1\pi}$. We denote η_0 -characteristic dimensional oil dynamic viscosity value, $\eta_1(\alpha_1, \alpha_3, t)$ – dimensionless oil dynamic viscosity independent of the gap height direction α_2 but additionally dependent on the time t . The dimensionless dynamic viscosity correction function $\eta_{1\pi}$ describes the product of various dimensionless influences, namely [L. 1–4] η_{IT} , η_{IAD} , η_{ISA} , η_{IV} , η_{IPH} , η_{IWe} , caused by the temperature, adhesion, synthetic & bio-additions (impurities, inhibitors, nano-particles, collagen fibres), and velocity gradients, i.e. shear rate, hydrogen ion concentration consistency, wet-ability of porous surfaces, respectively. These dimensionless influences of various factors on the oil dynamic viscosity are functions of three orthogonal co-ordinates $(\alpha_1, \alpha_2, \alpha_3)$. Constant dimensional coefficient δ in $[K^{-1}]$ describes the influences of dimensional temperature T on the oil dynamic viscosity.

Putting dependence (1) into conservation of momentum, continuity and energy equations, and neglecting the terms of body, inertia, and convective forces, we obtain the following non-linear system of basic equations in the curvilinear orthogonal co-ordinates $(\alpha_1, \alpha_2, \alpha_3)$ [L. 1] after layer boundary simplifications:

$$0 = -\frac{1}{h_1} \frac{\partial p}{\partial \alpha_1} + \frac{\partial}{\partial \alpha_2} \left[\eta_p(\alpha_1, \alpha_2, \alpha_3) \frac{\partial v_1}{\partial \alpha_2} \right],
 \tag{2}$$

$$0 = \frac{\partial p}{\partial \alpha_2},
 \tag{3}$$

$$0 = -\frac{1}{h_1} \frac{\partial p}{\partial \alpha_1} + \frac{\partial}{\partial \alpha_2} \left[\eta_p(\alpha_1, \alpha_2, \alpha_3) \frac{\partial v_1}{\partial \alpha_2} \right],
 \tag{4}$$

$$0 = \frac{1}{h_1} \frac{\partial v_1}{\partial \alpha_1} + \frac{\partial v_2}{\partial \alpha_2} + \frac{1}{h_1 h_3} \frac{\partial}{\partial \alpha_3} (h_1 v_3),
 \tag{5}$$

$$\frac{\partial}{\partial \alpha_2} \left(\kappa \frac{\partial T}{\partial \alpha_2} \right) + [\eta_p(\alpha_1, \alpha_2, \alpha_3)] \left[\left(\frac{\partial v_1}{\partial \alpha_2} \right)^2 + \left(\frac{\partial v_3}{\partial \alpha_2} \right)^2 \right] = 0, \quad (6)$$

where the length, width and gap- height directions, are limited by: $0 < \alpha_1 \leq 2\pi$, $-b_m \leq \alpha_3 \leq b_s$, $0 \leq \alpha_2 \leq \varepsilon_T$. Apparent oil viscosity has the following form [L. 5–8]:

$$\eta_p(\alpha_1, \alpha_2, \alpha_3, t) = \eta_p(n, p_H, We, T, t, E, E_x) \equiv \frac{\gamma(p_H, We, T, E_x, t)}{\delta_v v_0} \left(\frac{\left(\frac{v_0}{\varepsilon_0} \right)^2}{\left(\frac{\partial v_1}{\partial \alpha_2} \right)^2 + \left(\frac{\partial v_3}{\partial \alpha_2} \right)^2} \right)^{l-n}. \quad (7a, b)$$

$$\gamma(p_H, We, T, E_x, t) = \gamma_{max} + kA^{-1}T \ln L, \quad 0 < L(K_a, K_b, a_H^+) < l.$$

We denote the following: T [310 K] – temperature, γ [mJ/m²] – interfacial energy defined by extended Young-Kelvin-Laplace equation, k – Boltzmann constant $1.38054 \cdot 10^{-23}$ [J/K], K_a [J] – the area compression modulus (how much energy is needed to stretch the – layer of nano-particles additions), K_b [J] – bending modulus (how much energy is needed to bend or flex the above layer), a_H [J] – coefficient describing the hydrogen ion concentration activities, We – wet-ability of a porous surface for interval from 30° for hydrophilic to 100° for hydrophobic superficial layer, v_0 – characteristic value of linear velocity of lubricated surface, δ_v – dimensionless coefficient introduced by author in range ($2 < \delta_v < 6$) identifying the cluster regions of concentration of nano-meter synthetic or bio-additions or impurities in oil from $\delta_v = 2$ for $c_c = 1\,000\,000$ mol/mm³ to $c_c = 100$ mol/mm³ and less for $\delta_v = 6$, E_x – modulus or modules of elastic or hypo-elastic or hyper-elastic bearing superficial layer, and the flow index $0.70 < n < 1.0$, which is dependent on oil non-Newtonian features [L. 8, 9, 10]. We denote the following: v_{11} , v_{31} – dimensionless velocity component in α_1 , α_3 curvilinear coordinate directions, respectively, and $\alpha_{21} = \alpha_2/\varepsilon_0$, ε_0 – characteristic dimensional value of joint gap height. Oil density has a value of $\rho = 800$ kg/m³. The system of equations (2)–(6) contains the following dimensional unknowns: pressure $p(\alpha_1, \alpha_3)$, temperature $T(\alpha_1, \alpha_2, \alpha_3)$, three oil velocity components $v_i(\alpha_1, \alpha_2, \alpha_3)$, for $i = 1, 2, 3$ in three curvilinear, orthogonal dimensional directions: $\alpha_1, \alpha_2, \alpha_3$. The Lamé coefficients are as follows: $h_1(\alpha_3)$, $h_3(\alpha_3)$ for rotational ultra-thin surfaces and non-monotone curvatures in general. Total gap height ε_T changes in direction α_2 . If lubricant flow in the bearing gap is generated by rotation of a rotational, curvilinear journal surface, boundary conditions for lubricant velocity components have the form [L. 1]:

$$v_1 = \omega h_1 \text{ for } \alpha_2 = 0, \quad v_1 = 0 \text{ for } \alpha_2 = \varepsilon_T, \tag{8}$$

$$v_2 = 0 \text{ for } \alpha_2 = 0, \text{ and } v_2 = 0 \text{ for } \alpha_2 = \varepsilon_T, \tag{9}$$

$$v_3 = 0 \text{ for } \alpha_2 = 0, \quad v_3 = 0 \text{ for } \alpha_2 = \varepsilon_T. \tag{10}$$

In the case of squeezing, the lubricated non-rotational upper (or lower) surface moves with the uniform velocity U_{VM} from the opposite side of the lower (or upper) motionless surface. Thus boundary conditions for oil velocity components are as follows [L. 1]:

$$v_1 = 0, v_2 = 0, v_3 = 0 \text{ for } \alpha_2 = 0, \text{ and } v_1 = 0, v_2 = -U_{VM}, v_3 = 0 \text{ for } \alpha_2 = \varepsilon_T, \\ \text{or } v_1 = 0, v_2 = U_{VM}, v_3 = 0 \text{ for } \alpha_2 = 0, \text{ and } v_1 = 0, v_2 = 0, v_3 = 0 \text{ for } \alpha_2 = \varepsilon_T. \tag{11}$$

In both cases, the hydrodynamic pressure acts in contrary to the human joint load W . Moreover, the hydrodynamic pressure equals the atmospheric pressure p_A on the boundary $\bar{\Omega}$ of lubrication region $\Omega_L = \Omega(\alpha_1, \alpha_3)$ resting on the contact area of cartilage (or bearing surface) surface. Hence the following [L. 1]:

$$p(\alpha_1, \alpha_3) = 0, \quad \text{for } (\alpha_1, \alpha_3) \in \bar{\Omega}. \tag{12}$$

Decrements or increments above the characteristic environmental temperature T_0 have constant value f_c on the journal and variable unknown values $f_p(\alpha_1, \alpha_3)$ on the sleeve surface. Hence, boundary temperature values are as follows [L. 1]:

$$T(\alpha_1, \alpha_2, \alpha_3) = T_0 + f_c \text{ for } \alpha_2 = 0, \text{ and } T(\alpha_1, \alpha_2, \alpha_3) = T_0 + f_p(\alpha_1, \alpha_3) \\ \text{for } \alpha_2 = \varepsilon_T. \tag{13}$$

Heat flux density is transferred from the rotational journal (lubricant) into lubricant (rotational journal) or from the lubricant (sleeve surface) to the sleeve surface (lubricant); hence, we obtain the boundary condition in the following form:

$$\kappa \frac{\partial T}{\partial \alpha_2} = -q_c, (= +q_c) \text{ for } \alpha_2 = 0 \text{ or } \kappa \frac{\partial T}{\partial \alpha_2} = -q_p, (= +q_p) \text{ for } \alpha_2 = \varepsilon_T. \tag{14}$$

Thermal conductivity is denoted by [W/mK].

Symbols q_c and q_p , in W/m^2 denote dimensional heat flux density values between journal and lubricant, or between lubricant and sleeve.

INITIAL OBSERVATIONS CALCULATIONS AND REMARKS

Initial considerations implied from Y-K-L equations (6–7) are restricted to the examination of the initiated influences of interfacial energy actions on the necessity to include oil viscosity variations across the film thickness [L. 11].

Temperature

Negligibly small are lubricant dynamic viscosity variations caused by very small temperature variations (from 3K to 5K) across the thin layer film thickness, despite the fact of viscosity decreases with temperature increments. Because the temperature gradients (the first derivatives respect to the gap height direction coordinate) can be significant large; therefore, there are the large differences in dynamic viscosity across the thin layer film thickness.

Heat flux inflow from the journal surface through lubricant to the sleeve gives the larger oil temperature near to the journal surfaces than the oil temperature in proximity of the sleeve surface. From this fact, it follows that the oil dynamic viscosity near to the sleeve surfaces is larger than the oil dynamic viscosity in proximity of the journal surface. Heat flux inflow from the sleeve surface through lubricant to the journal gives the larger oil temperature near the sleeve surfaces than the oil temperature in the proximity of the journal surface. Therefore, the oil dynamic viscosity near to the journal surfaces is larger than the oil dynamic viscosity in proximity of the sleeve surface.

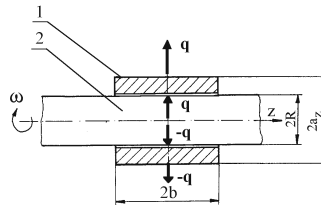


Fig. 1. Heat flux density q out-flowing from journal 2 through the oil into the sleeve 1

Rys. 1. Strumień ciepła o gęstości q wypływający z czopa 2 poprzez olej do panewki 1

Oil velocity distributions and shear rates

The flow of the lubricant in bearing gap is essentially caused by the pressure effect (Poiseuille's flow) and by the moving of bearing surfaces, i.e. the journal or sleeve (Couette's flow). For bearing surface lubrication by rotation, we also have Poiseuille's and Couette's flow. For squeeze film lubrication only Poiseuille's flow occurs. The initial calculations of oil velocity components in α_1 direction across the film thickness in bearing gap obtained by virtue of (2), (4), (7) and presented in **Figs. 2a, b, c** will have confirmed the corollaries presented below.

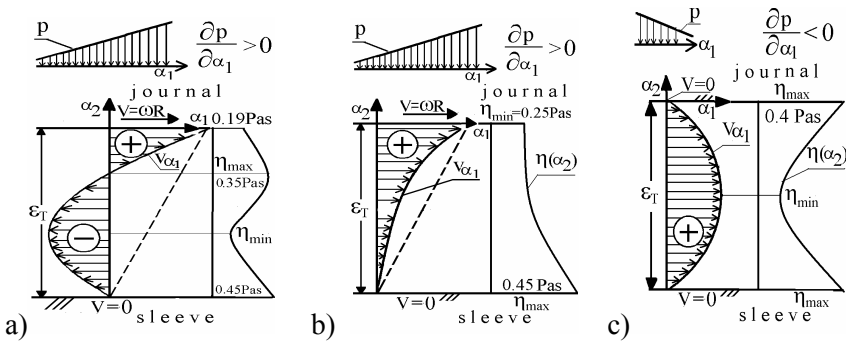


Fig. 2. Comparison of the oil velocity changes in gap height direction for components in α_1 direction with its dynamic viscosity distributions across the film thickness between journal and sleeve surfaces in cylindrical joint gap, for constant temperature 310 K, $\epsilon_T = 0.02\text{mm}$, short bearing $b/R = 0.75$, non-Newtonian oil with nano particles additions concentration $v_0\delta_v = 6.0 \text{ m/s}$ where are considered the following cases after own elaboration: a) the lubrication by rotation inside the region of hydrodynamic pressure increments, when the pressure influences on the oil velocity effects are larger than the effects of journal rotations on the oil speed, b) the lubricating caused by rotation inside the region of hydrodynamic pressure increments, when the pressure influences on the oil velocity effects are smaller than the effects of journal speed, c) the bearing surface lubrication with oil caused by squeezing effects inside the region of hydrodynamic pressure decreases.

Rys. 2. Porównania zmian po kierunku grubości filmu składowych obwodowych prędkości przepływu oleju z odpowiadającymi im zmianami rozkładów lepkości dynamicznej w kierunku wysokości szczeliny pomiędzy powierzchnią czopa i panewki w poprzecznych łożyskach walcowych dla nienewtonowskiego czynnika smarującego charakteryzującego się wskaźnikiem dodatków $v_0\delta_v = 6,0 \text{ m/s}$ w stałej temperaturze oleju 310 K, dla średniej wysokości szczeliny $\epsilon_T = 0,02 \text{ mm}$, w łożysku krótkim $b/R = 0,75$ dla następujących przypadków: a) smarowanie odbywa się na zasadzie ruchu obrotowego czopa w rejonie wzrostu ciśnienia, przy czym efekty prędkości oleju wywołane ciśnieniem są większe od prędkości powodowanych ruchem obrotowym, b) smarowanie odbywa się na zasadzie ruchu obrotowego czopa w rejonie wzrostu ciśnienia, przy czym efekty prędkości oleju wywołane ciśnieniem są mniejsze od prędkości powodowanych ruchem obrotowym, c) smarowanie poprzez wyciskanie w rejonie spadku ciśnienia hydrodynamicznego

Because velocity increments of the lubricant denote shear rate increments, the denominator in formula (7a) increases and fraction defining the viscosity decreases, i.e. viscosity decreases. This fact confirms the well-known law for pseudo plastic liquids about viscosity decrements with shear rate increments. The lubricant dynamic viscosity varies significantly across the bearing gap limited by the journal and sleeve surfaces. The gap height attains average values from 10 to 200 micrometres. From fluid mechanics of non-Newtonian pseudo-plastic liquids it follows that the places of maximal values across the gap height of the lubricant velocity component profiles in the α_1 direction coincide with the points where the lubricant has large shear rates and attains the minimal dynamic viscosity values. It is visible in **Figs. 2a, b, c**, that the places of

maximal values of oil velocity component profiles in the α_1 direction coincide with the points where the oil dynamic viscosity across the film thickness attains the minimal values. Moreover, the minimal values of the oil velocity component profiles in the α_1 direction are corresponding to the local maximum values of dynamic viscosities occurring in gap height direction.

Cluster points of nano particles concentration

After notations for the formulas (7ab), it follows that the small values of the coefficient δ_v are identified with the cluster point's concentrations with many nano-particle additions in the form of inhibitors, impurities, or contaminations. Formula (7) indicates that, in the places for small coefficient δ_v , the dynamic viscosity of lubricant attains larger and larger values, because the denominator (fluid velocity) of the fraction presenting the dynamic viscosity has smaller and smaller values. Usually, we often observe the localization of cluster-regions of nano particle concentrations near the bearing surfaces. Therefore, by virtue of this fact, it follows that impurities and various nano particle additions give the intensive increments of dynamic viscosity in the proximity of the journal and bearing surface and attain maximal values in these places. Therefore, by virtue of these observations and from hydro-mechanic laws, we deduce that the velocity distribution of the lubricant during the lubrication rotation flow in bearing gap usually has a parabolic profile (shape) with maximum values in neighbourhood of bearing upper and lower bearing surfaces.

CONCLUSIONS

By virtue of estimations of initial interfacial energy and oil viscosity and calculations using Y-K-L-equations connected with a new model represented by fundamental equations (1–7) with boundary conditions (8–14), the following conclusions are formulated as follows [L. 11]:

1. Temperature increments in interval of $308\text{K} < T < 317\text{K}$ across the film thickness, in bearing gap height direction between two cooperating elastic, hyper-elastic, anisotropic, non-homogeneous bodies, lubricated by rotation or squeezing, can only indirectly determine the real decrements of apparent dynamic viscosity values in the gap height direction, because the temperature differences are too small. The oil viscosity decrements can be demonstrated by the increments of temperature gradients and concentration activities of nano-particle additions ($< 5\text{nm}$) in an indirect way. The abovementioned increment of concentration activities with identified parameters from $v\delta_v = 4 \text{ m/s}$ to 6 m/s , $c_c = 5 \cdot 10^5 \text{ mol/m}^3$, leads to the oil dynamic viscosity decreases in

- interval $0.30 \text{ Pas} > \eta > 0.03 \text{ Pas}$, for $We = 40^\circ$, $T = 310 \text{ K}$, $pH = 6$ across the film thickness. In the general case, we have $0.60 \text{ Pas} > \eta > 0.03 \text{ Pas}$.
2. Power Hydrogen ion concentration in oil across the film thickness from about 4 to 10 in lubricant, for constant temperature 310 K and constant wet-ability about 40° of porous soft, hyper-elastic material on the lubricated bearing surfaces, decreases the lubricant apparent viscosity in the gap height direction from about 0.500 to 0.003 Pas.
 3. Wet-ability We of porous solid bearing material (in range from 80° for hydrophobic – to 30° for hydrophilic) for isotropic, homogeneous, elastic, constant Young modulus E from 12 to 50 MPa, during the rotation and squeeze film lubrication, leads to the oil viscosity η decrements across the film thickness in interval $0.40 \text{ Pas} > \eta > 0.03 \text{ Pas}$ for $pH = 6$, $T = 37^\circ\text{C}$, $v\delta_v = 6 \text{ m/s}$, $c_c = 5 \cdot 10^5 \text{ mol/m}^3$.
 4. The well-known law for liquids about viscosity decrements with shear rate increments is valid for all pseudo plastic non-Newtonian lubricants. Therefore, the large decrements across the film thickness of the oil velocity components near to the squeezing bearing surfaces leads to the intensive viscosity increments in the gap height direction. Additionally, the large increments of the oil velocity components in the gap height direction near the rotational moving bearing surfaces lead to indicated places with significant viscosity decrements across the film thickness.
 5. Increments of additions of inhibitors or impurities in the form of nano particles concentration for $v\delta_v = 6 \text{ m/s}$, in porous solid bearing material with isotropic, homogeneous features, and for elastic, constant Young modulus E from 12 to 50 MPa, during the rotation and squeeze film lubrication, implies that the oil viscosity variations in the gap height direction indicated in interval $0.03 \text{ Pas} < \eta < 0.40 \text{ Pas}$, if $10 < c_c < 10^6 \text{ mol/mm}^3$, ($8 > \delta_v > 2$), for $3.7 < pH < 12$, $70^\circ > We > 50^\circ$.
 6. In these bearing gaps ($< 1 \mu\text{m}$), the maximum value of adhesion forces occur near to the sleeve surface and especially in the points of the local maximum values of the sleeve profile line curvature. In these places, the oil viscosity attains maximum values in gap height direction.

DISCUSSION ABOUT SOME OBTAINED RESULTS

A new hydrodynamic model described in (1–7) enables one to deliver numerous parameters in an analytical way that refers to the non-isothermal synthetic as to the biological lubricants for non-conventional bearing lubrication connected with bearing solid material properties. Some of them, without influences of adhesion forces, are illustrated in **Table 1** for $0 < Re < 1$. On the basis of obtained lubricant dynamic viscosities and by virtue of a new model

Table 1. The variations of dynamic viscosity function for non-isothermal, synthetic and biological oils connected with various kinds and features of co-operating bearing materials as the interactions of sleeve solid body after Author's calculation

Tabela 1. Zmiany wartości funkcji lepkości dynamicznej syntetycznego i biologicznego oleju powiązanej z różnymi rodzajami i właściwościami współpracującego materiału łożyskowego, jak też ciała stałego panewki wg własnych obliczeń autora

No	Non – Newtonian lubricant (or Synovial) in bearing Not damaged gap (or natural sound human joint))	Features of non-damaged bearing solid material on the sleeve (or cartilage) assigned to the successive parameters or its tendencies of changes	Kind of lubrication assigned to the successive parameters	
	The phenomenon of such parameters as: lubricant viscosity, temperature, wet-ability, hydrogen ion concentration and its changes	The values of intervals of successive parameters or its variation tendencies		
1	Wettability We of solid body (in range from 80° for hydrophobic - to 30° for hydrophilic)	$70^\circ > We > 50^\circ$	Isotropic, homogeneous elastic, constant Young modulus E_x from 12 to 50 MPa	Rotation, squeezing
2	Viscosity η decrements along wet-ability grade interval indicated in v. 1	$0.40 \text{ Pas} > \eta > 0.03 \text{ Pas}$ for: pH=6, T=310K, $v\delta_v=6\text{m/s}$, $c_c=5 \cdot 10^5 \text{ mol/m}^3$	Isotropic, homogeneous elastic, constant Young modulus E_x from 12 to 50 MPa	Rotation, squeezing
3	Two regions of Hydrogen ion concentration pH in lubricant (synovial fluid)	a): $2 < \text{pH} < 3.7$, b): $3.7 < \text{pH} < 12.0$,	Isotropic, homogeneous, elastic, constant Young modulus E_x from 12 to 50 MPa	Rotation, squeezing
4	Viscosity: a) increments, b) decrements, with pH index increases indicated in versus no.3	a): $0.30 \text{ Pas} < \eta < 0.55 \text{ Pas}$ if: $2.0 < \text{pH} < 3.7$, b): $0.55 \text{ Pas} > \eta > 0.20 \text{ Pas}$ if: $3.7 < \text{pH} < 12$, for a,b: $We=40^\circ, T=37^\circ\text{C}$, $v\delta_v=6\text{m/s}, c_c=5 \cdot 10^5 \text{ mol/m}^3$	Isotropic, homogeneous Elastic, constant Young modulus E from 12 to 50 MPa	Rotation, squeezing
5	Viscosity η decrements with shear rate values Θ increments for lubricant and other pseudo-plastic oils lubricants	$0.30 \text{ Pas} > \eta > 0.03 \text{ Pas}$, if: $5 \text{ s}^{-1} < \Theta < 10^4 \text{ s}^{-1}$, for : $We=40^\circ, T=37^\circ\text{C}$, $v\delta_v=6\text{m/s}, c_c=5 \cdot 10^5 \text{ mol/m}^3$ $2 < \text{pH} < 12.0$,	Isotropic, homogeneous elastic, constant Young modulus E_x from 12 to 50 MPa	Rotation, squeezing
6	Viscosity η decrements of non-treated lubricant (or SF) during the time increases in years after statistical observation	$\eta(t=t_0) \text{ Pas} > \eta > \eta(t=t_1) \text{ Pa s}$, if: $(t_0=0) < t < (t_1=10 \text{ years})$	Anisotropic, non-homogeneous, Hyper-elastic, 21 various hyper-elastic modules E_x from 12 to 60 MPa	Rotation, squeezing

(1–7), the author plans to compare the pressure, temperature, friction coefficients and with results obtained in papers [L. 2–4]. This means of analysis

is typical in tribology. Please notice that there are very interesting and valuable contemporary obtained results in [L. 3], and [L. 12–13] had been constituted on the chemical knowledge only without mechanical law contributions for lubricant viscosity determination, without lubricant or synovial fluid (SF) velocities, flow shear rates, and finally without hyper-elastic properties of bearing sleeve materials (cartilage materials) and mathematical or hydro mechanical lubricant flow analysis [L. 3].

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Streszczenie

W niniejszej pracy wykazano, że lepkość dynamiczna nie-newtonowskiego nieizotermicznego czynnika smarującego zmienia się po kierunku wysokości szczeliny łożyskowej oraz że zmiany te mają istotny wpływ na parametry pracy poprzecznego łożyska ślizgowego łącznie z siłami tarcia, współczynnikami tarcia oraz zużyciem materiału.

Zmiany lepkości nieizotermicznej nienewtonowskiej cieczy smarującej po grubości warstwy czynnika smarującego uzasadnia się poprzez:

- wpływ zmian gradientów temperatury po grubości warstwy smarującej,
- wpływ zmian wartości składowych prędkości nienewtonowskiego, nieizotermicznego oleju po kierunku wysokości szczeliny,
- wpływ lokalizacji w cieczy smarującej obszarów skupienia (clustering regions) nanometrowych cząsteczek i ich liczebności.

Dla wyjaśnienia mechanizmu opisanych wpływów podano komentarze.

1. Zmiany wartości temperatury pomiędzy powierzchnią czopa i panewki są małe i ich wartość osiąga zaledwie od 3 K do 7 K. Dlatego nie mają one wpływu na zmiany lepkości po grubości warstwy, chociaż z równania zachowania energii wynika zmienność wartości temperatury po kierunku wysokości szczeliny łożyska. Jednak zmiany gradientów temperatury po kierunku wysokości szczeliny mogą być znaczące i one wpływają na zmiany lepkości w kierunku wysokości szczeliny.
2. Zmiany wartości składowych prędkości nienewtonowskiego, nieizotermicznego oleju po kierunku wysokości szczeliny są znacząco malejące (rosnące), powodują spadek (wzrost) prędkości deformacji w cieczach nienewtonowskich, a stąd na mocy praw mechaniki cieczy odpowiednio znacząco wzrasta (maleje) lepkość.
3. Obszary skupienia dotyczą: inhibitorów, dodatków polimerowych, zanieczyszczeń solami ołowiu, molekuł magnetycznych o ok. 2–5 nm wielkości cząsteczek w obszarze szczeliny smarnej łożysk mechanicznych oraz chondrocytów, włókien kolagenowych, miceli, liposomów, fosfolipidów o wielkości 5 nm w obszarze cieczy synowialnej wypełniającej szczelinę stawu.

Obszary skupienia lokalizują się na ogół w pobliżu współpracujących powierzchni i tam wywołują znaczne wzrosty lepkości pozornej cieczy smarującej.

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- 4. Siły adhezji w szczelinach łożysk o wysokości poniżej mikrometra osiągają największe wartości w pobliżu współpracujących powierzchni, powodując w tych obszarach największe wzrosty lepkości oleju po kierunku wysokości szczeliny.**

