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INFLUENCE OF RHEOLOGICAL PROPERTIES OF A LUBRICANT ON POWER CONSUMPTION AND HEAT TRANSFER IN A HYDROSTATIC LUBRICATING LAYER

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The influence of rheological properties of lubricants on power consumption for pumping the lubricant in a hydrostatic lubricating layer and heat transfer of the lubricant with the supporting surfaces of a bearing is studied.

In modern mechanical engineering wide use is made of hydrostatic friction pairs, operating in the regime of a liquid lubricant. In high-precision and heavily loaded machines minimization of the heat releases and power consumption in a lubricating layer is the most important criterion that characterizes the operating regime of the supports. One manages to solve this problem by applying rheologically complex lubricants, in particular, plastic lubricants. In this connection new investigations based on rheological models that approximate with a sufficient degree of detail experimental data over a wide range of shear rates are needed for rational, scientifically substantiated use of a variety of lubricants. These requirements are satisfied by a rheological equation with an exponential dependence of plastic viscosity on stress intensity proposed by the authors of [1], which can be written for pure shear as

$$\tau = \tau_0 + \eta_0 \exp\left(- \frac{I_\tau - \tau_0}{G_0} \right) \gamma . \tag{1}$$

The rheological constants of Eq. (1) for some plastic lubricants are given in [2, 3].

We can represent Eq. (1) in reduced form as follows:

$$\bar{\tau} = 1 + \exp\left[- (\bar{I}_{\bar{\tau}} - 1)/L \right] \bar{\gamma} , \tag{2}$$

where L is the rheological parameter that characterizes the abnormal viscosity properties of the lubricant.

In [2–4] the authors solved the hydrodynamic and thermal problems for radial flow of a plastic lubricant described by the rheological equation (1) in a hydrostatic thrust bearing. Expressions were obtained for determining velocity and temperature profiles as well as the lubricant flow rate. The carrying capacity of a hydrostatic support was determined numerically. However, for justified use of a variety of lubricants, we need to analyze the relationship between the basic dimensionless parameters that characterize the hydrostatic lubricating layer and are given in [5, 6] and rheological properties of the lubricants described by the set of constants of Eq. (1).

To characterize the parameters of the hydrostatic lubricating layer, we use the coefficient of carrying capacity ω_f and the coefficient of pumping power H_f, determined, according to [5, 6], by the formulas

$$\omega_f = \frac{F}{\pi r_{11}^2 p_{\text{ch}}} , \tag{3}$$

$$H_f = \frac{N_{\text{p}} \eta_0}{4\pi p_{\text{ch}}^2 h^3} . \tag{4}$$

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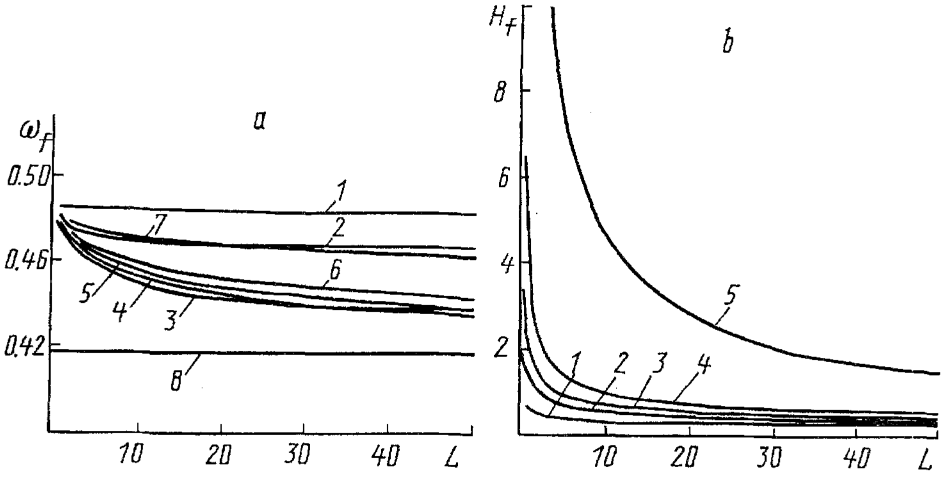

Fig. 1. Dependence of the coefficient of carrying capacity of a support ω_f (a) and the pumping power coefficient H_f (b) on the rheological parameter L for different values of I: a: 1) I = 100; 2) 10; 3) 1; 4) 0.33; 5) 0.2; 6) 0.1; 7) 0.01; 8) dependence for a Newtonian lubricant; b: 1) I = 1; 2) 0.33; 3) 0.2; 4) 0.1; 5) 0.01.

The coefficient of carrying capacity of a support characterizes the uniform pressure distribution in the hydrostatic lubricating layer in the radial direction and the coefficient for pumping power characterizes the energy consumption on pumping the lubricant at a certain flow rate and pressure in the central chamber of the bearing. These two coefficients enable us to establish the influence of rheological properties of the lubricant on the basic parameters of the hydrostatic lubricating layer.

It is of interest to analyze calculated values of the coefficients of carrying capacity and pumping power for the hydrostatic lubricating layer, obtained with the use of the rheological equation (2) for different values of the rheological parameter L.

Calculations were performed with the use of relations obtained in [3] for a hydrostatic support that has the following design parameters: $\bar{r}_1 = 0.35$ and $s = 1.5 \cdot 10^{-3}$.

Figure 1 gives calculated dependences of the coefficient of carrying capacity of a hydrostatic support (a) and the pumping power coefficient (6) on the rheological parameter L for different values of the Il'yushin number I for the hydrostatic lubricating layer.

Figure 1a shows that with a change in L from 50 to 0.3, which corresponds to increase in the abnormal viscosity properties of the lubricant, the coefficient of carrying capacity of the support increases 0.4–11.5%, depending on I, which is due to a more uniform pressure distribution over the support's working surface in the radial direction. At large values of I (I > 100) and small ones (I < 0.01) the value of ω_f is practically independent of L and has a maximum value. At I = 0.1–3.0 the dependence of ω_f on L is most pronounced. The dependence of the coefficient of carrying capacity ω_f on the Il'yushin number has an extremal character. The minimum of ω_f values also lies in the region of values I = 0.1–3.0. From Fig. 1a it also follows that using viscoplastic lubricants enables us to increase the coefficient of carrying capacity of the support by 4–16% compared to a Newtonian lubricant, depending on abnormal viscosity properties, characterized by the parameter L.

Figure 1b shows that with a decrease in L from 50 to 0.3 the pumping power coefficient H_f increases by a factor of 3–12, depending on I, which is due to an increase in the lubricant flow rate at fixed pressure in the central chamber as a consequence of a decrease in its effective viscosity. With a decrease in I the pumping power coefficient H_f increases, which is also due to an increase in the lubricant flow rate. The increase in the lubricant flow rate causes a corresponding increase in energy consumption on its pumping.

The calculated and experimental values of the coefficient of carrying capacity ω_f for viscoplastic lubricants, produced by thickening spindle AU, IGP-30, and IRP-75 oils with ceresin-65 in an amount from 2.5 to 5 wt. %, are, according to data of [2], from 0.45 to 0.47, i.e., they indicate a 7–12% increase in ω_f for viscoplastic lubricants compared to industrial oils, for which $\omega_f = 0.418$.

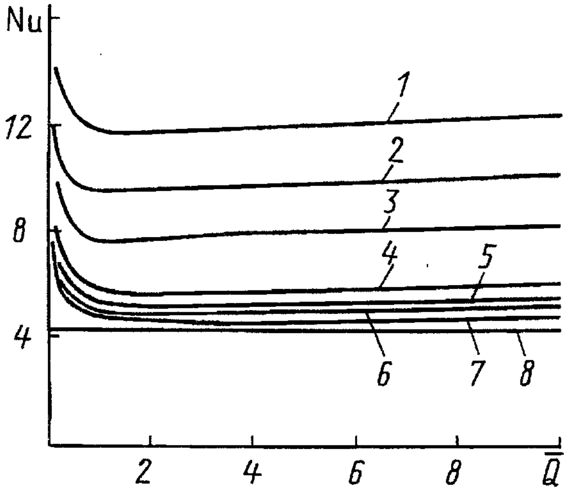

Fig. 2. Average value of Nu for a supporting surface vs lubricant flow rate $\bar{Q}$ for different values of the rheological parameter L: 1) $L = 0.3$; 2) 0.5; 3) 1; 4) 5; 5) 10; 6) 20; 5) 50; 8) Newtonian lubricant.

We need to analyze the influence of rheological properties of the lubricant on the characteristics of the hydrostatic lubricating layer, taking into account estimates of dissipative heat releases in the lubricating layer and conditions of heat transfer with the supporting surfaces of the bearing.

From the solution of [4], we calculated numerically the average dimensionless temperature of the lubricant in the running clearance of the bearing, the dimensionless density of the heat flux to the supporting surfaces, and the value of the Nusselt number for the supporting surface of the bearing.

To determine the average lubricant temperature in the bearing, we divided the half-height of the running clearance $\bar{h}$ into k equal segments with the number i and the height $\Delta\bar{h}_i$, and for each we calculated the value of the dimensionless temperature $\bar{T}_i$ by the formulas given in [4]. The average lubricant temperature for each annular element with the number j was calculated by the formula

$$\bar{T}_j^m = \frac{\sum\limits_{i=1}^{k} \bar{T}_{ij}\Delta\bar{h}_i\bar{v}_{ij} + \bar{T}_{0j}\bar{h}_{0j}\bar{v}_{0j}}{\sum\limits_{i=1}^{k} \Delta\bar{h}_i\bar{v}_{ij} + \bar{h}_{0j}\bar{v}_{0j}}. \tag{5}$$

For each annular element we also determined the value of the dimensionless heat flux density $\bar{q}_j$ by the formulas of [4].

The average dimensionless temperature of the lubricant in the running clearance and the average density of the heat flux to the supporting surface of the bearing were calculated by the expressions

$$\bar{T}^m = \sum_{j=1}^{k-1} \bar{T}_j \frac{\bar{r}_{j\,\mathrm{ext}}^2 - \bar{r}_{j\,\mathrm{int}}^2}{1 - \bar{r}_{\mathrm{I}}^2}, \tag{6}$$

$$\bar{q}^m = \sum_{j=1}^{k-1} \bar{q}_j \frac{\bar{r}_{j\,\mathrm{ext}}^2 - \bar{r}_{j\,\mathrm{int}}^2}{1 - \bar{r}_{\mathrm{I}}^2}. \tag{7}$$

The average Nusselt number for the supporting surface was calculated by the formula

$$\mathrm{Nu} = \frac{\bar{q}^m}{\bar{T}^m}. \tag{8}$$

With the use of relations (5)-(8) and the formulas obtained in [4] we performed numerical calculations of heat transfer in the hydrostatic lubricating layer as a function of rheological properties of the lubricant and its flow rate.

Figure 2 shows the calculated dependence of the average Nusselt number Nu for the supporting surface on the dimensionless flow rate $\overline{Q}$ for different L. It is evident from the graph that with decreasing L the Nusselt number Nu increases. This is due to an increase in the height of the quasisolid core and the corresponding restructing of the temperature profile. The dependence of Nu on $\overline{Q}$ has an extremal character, as does the dependence of ω_f. The minimum values of Nu correspond to $\overline{Q} = 0.5-3.0$ or the values of $\mathrm{I} = 0.33-2.0$, which coincides with the region of the minimum ω_f values. For viscoplastic lubricants the value of Nu changes from 4.6 to 14.0 with a change in L from 50 to 0.3, and for a Newtonian lubricant the value Nu, calculated by formula (8) is independent of the flow rate of the lubricant and its viscosity and is equal to 4.38. The calculated values of Nu for the investigated viscoplastic lubricants produced by thickening industrial oils with ceresin-65 lie in the range 4.9–5.7.

Therefore, use of viscoplastic lubricants enables us to intensify heat transfer from the lubricant to the supporting surfaces compared to a Newtonian lubricant and to a decrease thereby the temperature in the lubricating layer.

Consequently, to enhance the carrying capacity of the hydrostatic lubricating layer and to decrease energy consumption on pumping, we need to use viscoplastic lubricants with the maximum possible limiting shear stress τ_0 and a more pronounced abnormality of viscosity properties. Their use ensures a decrease in the temperature in the lubricating layer and intensifies heat transfer to the supporting surfaces of the bearing.

NOTATION

τ_0, η_0, G_0, rheological constants; τ, $\dot{\gamma}$, shear stress and shear rate, respectively; $\overline{\tau} = \tau/\tau_0$, $\overline{\dot{\gamma}} = \dot{\gamma}\eta_0/\tau_0$, dimensionless tangential stress and shear rate; I_τ, stress intensity; ω_f, coefficient of carrying capacity of a support; H_f, pumping power coefficient; F, carrying capacity of a support; $N_\mathrm{p} = p_\mathrm{ch}Q$, power consumption on pumping; p_ch, lubricant pressure in the central chamber of a bearing; r_II, external radius of disks of a hydrostatic support; r_I, central chamber radius; $\overline{r} = r/r_\mathrm{II}$, dimensionless radial coordinate; $\overline{r}_{j\mathrm{ext}}$ and $\overline{r}_{j\mathrm{int}}$, external and internal radii of the annular element with the number j; h, half-height of the clearance between disks; L_0, half-height of the quasisolid core; $L = G_0/\tau_0$, $s = h/r_\mathrm{II}$, dimensionless parameters; Q, lubricant flow rate; $\overline{Q} = Q\eta_0/4\pi\tau_0 h^2 r_\mathrm{II}$, dimensionless flow rate; $\mathrm{I} = 1/\overline{Q} = 4\pi\tau_0 h^2 r_\mathrm{II}/Q\eta_0$, Il'yushin number for the hydrostatic lubricating layer; $\overline{v} = v\eta_0/\tau_0 h$, dimensionless velocity of the lubricant; $\overline{v}_0$, dimensionless velocity of the quasisolid core; $\overline{T} = (T - T_s)\lambda\eta_0/\tau_0^2 h^2$, dimensionless temperature; T_s, temperature of the supporting surfaces; $\overline{T}_0$, dimensionless temperature of the quasisolid core; $\overline{q} = -\partial\overline{T}/\partial\overline{z}$, dimensionless heat flux to the supporting surfaces; $\overline{z} = z/h$, dimensionless transverse coordinate; z, transverse coordinate; $I_\tau = \{1/6[(\tau_{rr} - \tau_{zz})^2 + (\tau_{zz} + \tau_{\theta\theta})^2 + (\tau_{\theta\theta} - \tau_{rr})^2] + \tau_{z\theta}^2 + \tau_{\theta r}^2\}^{1/2}$, stress intensity; G_0, nonlinearity exponent of the flow curve.

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