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Static Characteristics of Two-Axial Groove Journal Bearing Operating on TiO_2 Nanolubricant Using a Temperature Dependent Viscosity Model

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Abstract An empirical temperature dependent viscosity model for TiO_2 nanolubricant is used in conjunction with Reynolds equation to obtain the theoretical static performance characteristics of a Two-Axial groove journal bearing operating on TiO_2 nanolubricant. The modified Reynolds equation is non-dimensionalised and solved numerically by finite difference method satisfying the Reynolds boundary condition. The obtained performance characteristics for different lubricant temperatures and nanoparticle additive concentrations are compared with plain engine oil. It is observed that, the usual reduction in load carrying capacity and friction force with increasing temperature of the oil film is lower for nanolubricant in comparison to plain engine oil. The presence of nanoparticle additives therefore arrests the decrease in viscosity with increasing temperature and hence improves the static performance of journal bearings.

Keywords Hydrodynamic journal bearing, Nanoparticles, Tribology, Viscosity model, Static characteristics, Nanolubricant, TiO_2

1. Introduction

The use of nanoparticles as additives to modify the flow behaviour of base fluids have been attempted in many applications [1-10]. One such application is in lubrication; where, a new class of lubricant termed as *nanolubricant* is synthesised by dispersing nanoparticles in base oils [11-13]. The use of nanolubricants have found to decrease friction and wear of tribo-surfaces in boundary lubrication characterized by thin oil films; with the particles playing a physical role in the lubrication process [14, 15]. Few studies have also demonstrated positive impact of using nanoparticles are lubricant additives in hydrodynamic lubrication characterized by thick oil films separating the tribo-surfaces [16-19].

The benefit of using nanoparticle additives in thick film lubrication is the associated increase in viscosity of base fluid, which in turn has demonstrated a ~40% increase in load carrying capacity [20]. However, publications of these findings do not consider the variation in lubricant viscosity with operating conditions. Significant increase in temperature can be observed in loaded journal bearings [21-23]. The current study is therefore an attempt to simulate bearing performance characteristics by using a temperature-viscosity model for TiO_2 nanoparticle dispersions in engine oil [24].

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2. Theoretical

The governing equation for this analysis is the modified Reynolds equation; integrated with empirical temperature dependent viscosity model to simulate the influence of temperature variation on the performance of journal bearings operating on TiO_2 nanolubricants. The governing equation is presented as equation-1 below.

$$\frac{\partial}{\partial\theta}\left[\bar{f}\left(\bar{h},\bar{d}\right)\frac{\partial\bar{p}}{\partial\theta}\right]+\left(\frac{R^2}{L^2}\right)\frac{\partial}{\partial\bar{z}}\left[\bar{f}\left(\bar{h},\bar{d}\right)\frac{\partial\bar{p}}{\partial\bar{z}}\right]=6\bar{\mu}\bar{u}\frac{\partial\bar{h}}{\partial\theta} \quad (1)$$

Where, $\bar{f}\left(\bar{h},\bar{d}\right)=\bar{h}^3-12\bar{d}^2\left[\bar{h}-2\bar{d}\tanh\left(\frac{\bar{h}}{2\bar{d}}\right)\right]$

In solving the above Reynolds equation to obtain the static bearing performance characteristics, the temperature adjusted nanolubricant viscosities at different concentrations are utilized. The final viscosities considered for analysis will the difference of viscosities simulated using modified Krieger-Dougherty Model and viscosities simulated using a temperature dependent empirical model published by Spoorthi et al. [24] for TiO_2 dispersions in Engine oil. The viscosity models utilized in the study are described in detail below.

2.1. Modified Krieger-Dougherty Viscosity Model

The modified Krieger-Dougherty (K-D) model is expressed as equations 2 and 3 shown below.

$$\mu_{nf} = \mu_{bf}\left(1-\frac{\phi_a}{\phi_m}\right)^{-2.5\phi_m} \quad (2)$$

$$\text{Where, } \phi_a = \phi\left(\frac{a_a}{a}\right)^{3-D} \quad (3)$$

The above general equation for nanofluids was customised for TiO_2 nanolubricants by Binu et al. [25] by measuring the aggregate to primary particle size ratio (a_a / a) for TiO_2 nanolubricants using DLS particle size analysis. For primary particle size of 100 nm, the obtained ratio was 7.77.

In the modified Krieger-Dougherty model presented in equation 2, ϕ_m is the maximum particle packing fraction in the suspension, which is dependent on the extent of shear. For high-shear applications, 0.605 is the prescribed value and for low shear applications ϕ_m is taken as 0.5 [26]. The fractal index D is generally taken as 1.8 for nanofluids [26]. The modified Krieger-Dougherty model therefore reduces to equation 4, presented below.

$$\overline{\mu} = \frac{\mu_{nf}}{\mu_{bf}} = \left(1-\frac{\phi}{0.605}\left(\frac{a_a}{a}\right)^{1.2}\right)^{-1.51} \quad (4)$$

2.2. Empirical Temperature Dependent Viscosity Model

The empirical temperature dependent viscosity model for TiO_2 dispersions in engine oil used in this study is obtained from Spoorthi et al. [24]. The model used was observed to simulate viscosities in agreement with experimental viscosities. The model is expressed as below:

$$\mu = A + B/T \quad (5)$$

Where, A and B are constants and T is the operating temperature.

Values of the constants A and B for various concentrations of TiO_2 nano particle additives are provided in Spoorthi et al. [24] and used accordingly in this study.

The modified Reynolds equation is thus equipped to include the temperature adjusted effective viscosities of nanolubricants at different TiO_2 nanoparticle concentrations with a primary particle size of 100 nm (BET) and an aggregate particle size of 777 nm [25]. The governing equation 1 is solved numerically using finite difference scheme to obtain the pressure distributions. The pressure distributions are then used to compute the load carrying capacity and friction force.

2.3. Load Carrying Capacity

Load carrying capacity of the bearing is obtained by integrating nodal hydrodynamic pressures across the bearing surface. The two components of generated oil film force, along the line of center and perpendicular to the line of center, are computed using the pressure integration equations given below.

$$\overline{W}_r = \frac{W_r C^2}{\mu_{bf}\omega R^3 L} = -\int_0^{\theta_m}\int_0^1 \overline{p}\cos\theta \, d\theta \, d\overline{z} \quad (6)$$

$$\overline{W}_t = \frac{W_t C^2}{\mu_{bf}\omega R^3 L} = \int_0^{\theta_m}\int_0^1 \overline{p}\sin\theta \, d\theta \, d\overline{z} \quad (7)$$

2.4. Friction Force

The friction force generated within the oil film thickness, due to its continuous shearing by the surface motion of journal, is computed by integrating the shear stresses induced around the journal surface. The effective viscosity of TiO_2 nanolubricants with considerations to both volume fraction and aggregate particle size influences the friction force. The shear stress developed at the journal surface is given by the equation 8 stated below [25].

$$\tau = \mu \left.\frac{\partial u}{\partial y}\right|_{y=h} - \eta \left.\frac{\partial^3 u}{\partial y^3}\right|_{y=h} \quad (8)$$

Substituting for u using conventional theory, the shear stress is obtained as [25]:

$$\tau = \mu\left(\frac{U}{h} + \frac{h}{2\mu}\frac{\partial p}{\partial x}\right) \quad (9)$$

The non-dimensional friction is then obtained by the integration of shear stress equation as [25]:

$$\overline{F}_f = \frac{F_f C}{R^2 L \mu_{bf}\omega} = \int_0^1\int_0^{2\pi}\left[\frac{\overline{\mu}}{\overline{h}} + \frac{\overline{h}}{2}\frac{\partial \overline{p}}{\partial\theta} - \overline{d}\frac{\partial \overline{p}}{\partial\theta}\tanh\left(\frac{\overline{h}}{2\overline{d}}\right)\right] d\theta \, d\overline{z} \quad (10)$$

The standard friction parameter is then computed as:

$$f\left(\frac{R}{C}\right) = \frac{\overline{F}_f}{\overline{W}_R} \quad (11)$$

3. Results and Discussions

The modified Krieger-Dougherty viscosity model explained in section 2.1 is used to simulate viscosities of TiO_2 nanolubricants at room temperature (28°C) for nanoparticles concentrations expressed in volume fractions as ϕ = 0, 0.005, 0.01, 0.15 and 0.02 [25]. The values are presented in Table-1.

Table 1. Nanolubricant Viscosities using K-D Model at room temperature

TiO_2 Concentration Volume fraction ϕ	μ_{nf} (Pa-s)
Plain engine oil, 0	0.1036
Nano-oil, 0.005	0.1193
Nano-oil, 0.01	0.1398
Nano-oil, 0.015	0.1677
Nano-oil, 0.02	0.2076

It is observed from Table-1 that, addition of TiO_2 nanoparticles increases the viscosity of base engine oil. This increase in viscosity will however decrease due to the increase in oil temperature during operation of the bearing. This effect of decrease in viscosity is not modelled in modified Krieger-Dougherty viscosity model. A more realistic approach should consider the effect of temperature viscosities during analysis. This decrease in viscosity is simulated using the temperature dependent empirical viscosity model discussed in section 2.2. Table-2 provides the viscosities obtained at TiO_2 nanoparticle concentration of $\phi = 0.005$ for operating temperatures of 28°C, 40°C, 50°C and 60°C.

Table 2. Nanolubricant Viscosities using K-D Model at different temperatures

Temperature °C	μ_{nf} (Pa-s)
28	0.2442
40	0.1397
50	0.0910
60	0.0585

From Table 2, it is seen that increase in temperature significantly decreases the nanolubricant viscosities. To consider this effect in bearing analysis, effective nanolubricant viscosities obtained from modified K-D model is corrected by deducting proportionately the decrement in viscosity observed using the empirical temperature dependent viscosity model considered in section 2.2. The final considered effective viscosities are provided below in Table 3.

Table 3. Temperature corrected Effective Viscosities at different temperatures and concentrations

Temperature °C	μ_{nf} (Pa-s)				
	ϕ = 0	ϕ = 0.005	ϕ = 0.01	ϕ = 0.015	ϕ = 0.02
28	1	1.075	1.174	1.309	1.501
40	0.448	0.701	0.815	0.805	1.002
50	0.294	0.336	0.647	0.569	0.747
60	0.00001	0.179	0.535	0.413	0.576

It is observed from Table 3 that, while the effective viscosities of lubricant decrease with increasing temperature, the decrement of effective viscosities is smaller for nanolubricants in comparison to plain engine oil. These temperature corrected viscosities are then used in the journal bearing governing equation to obtain the pressure distribution and other static characteristics described in sections 3.2 and 3.3. The maximum non-dimensional pressure, load carrying capacity and friction force are calculated for different temperatures and TiO_2 nanoparticle concentrations.

Fig. 1 compares the maximum non-dimensional pressure computed for plain oil with maximum pressures for TiO_2 nanolubricants at different TiO_2 nanoparticle concentrations and different operating temperatures. As seen in the Fig. 1, the maximum hydrodynamic pressure at the bearing mid-plane is observed to increase with TiO_2 nanoparticle concentration. For TiO_2 nanolubricant concentration of ϕ = 0.015, a 30% increase in maximum pressures is observed in comparison to plain oil at room temperature of 28°C and a 79% increase in maximum pressure at 40°C. It is also found that pressure decreases with increase in temperature for plain oil and this decrease in values are lowered by adding TiO_2 nanoparticle additives to plain oil. A similar observation is also made about load carrying capacity illustrated in Fig. 2. Pressure and load carrying capacity drops drastically as temperature increases and this decrement could be arrested by increasing the nanoparticle additive concentration. A corresponding behaviour is also observed for non-dimensional friction force as illustrated in Fig. 3. Fig. 4 shows the beneficial increment of hydrodynamic pressure developed for different concentrations of TiO_2 nanoparticles at 50°C and the corresponding load carrying capacity and friction forces are also illustrated in Figs. 5 and 6.

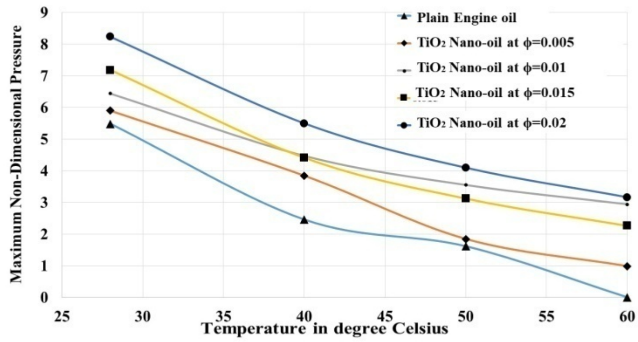

Figure 1. Maximum non-dimensional pressure for plain oil compared with maximum pressures for different concentrations of TiO_2 nanolubricants at different temperatures

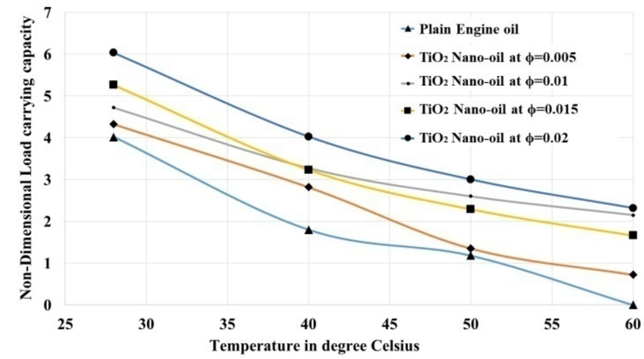

Figure 2. Maximum non-dimensional load for plain oil compared with maximum load for different concentrations of TiO_2 nanolubricants at different temperatures

Figs. 4 to 6 demonstrates an improvement in static characteristics of journal bearings operating on TiO_2 nanolubricants in comparison to plain engine oil. The decrement in performance due to increase in temperature is arrested to an extent due to the addition of nanoparticles as additives. A peculiar characteristic of the above distributions illustrated in Figs. 4 to 6 is the abrupt decrease in performance characteristics at a TiO_2 nanoparticle concentration of ϕ=0.015. This decrease could be a characteristic feature of the empirically derived viscosity model expressed in section 2.2. This is an indication of inconsistency present in the model and a more rigorous mode is essential for better simulations.

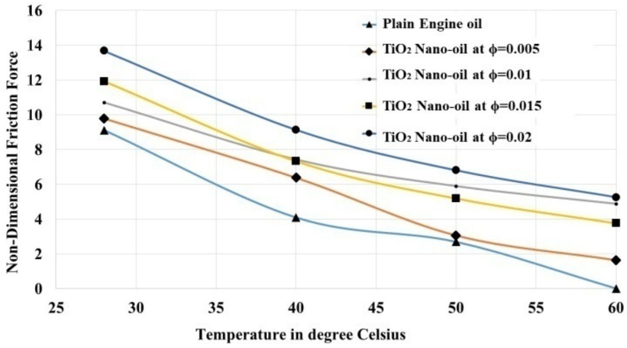

Figure 3. Non-dimensional friction force for plain oil compared with friction force for different concentration of TiO_2 nanolubricants at different temperatures

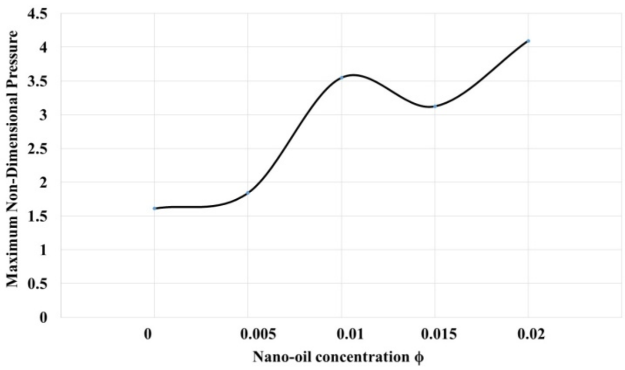

Figure 4. Maximum non-dimensional pressures at different TiO_2 nanoparticle concentrations at a temperature of 50 °C

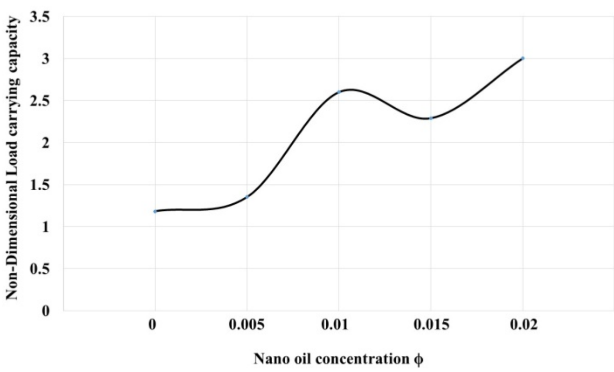

Figure 5. Load carrying capacity at different TiO_2 nanoparticle concentrations at a temperature of 50 °C

4. Conclusions

The results obtained in this study confirms the beneficial influence of adding nanoparticles as lubricant additives in journal bearings. The study demonstrates that the decrease in lubricant viscosities due to increasing operating temperature is arrested to an extent due to the presence of nanoparticle additives. This decrement in loss of viscosity results in improved bearing performance characteristics at elevated temperatures. However, the extreme subjective nature of nanofluid formulation necessitates experimental validation of the results obtained.

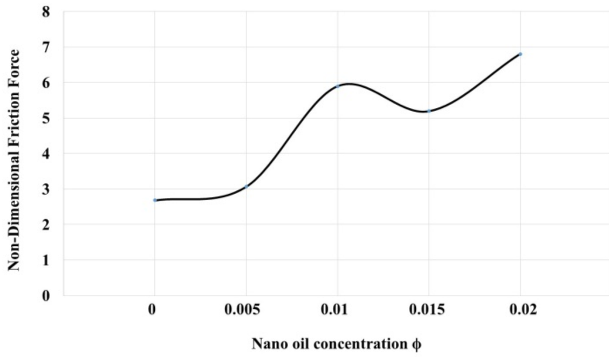

Figure 6. Friction force at different TiO_2 nanoparticle concentrations at a temperature of 50°C

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