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CFD ANALYSIS OF NANO-LUBRICATED JOURNAL BEARING CONSIDERING VARIABLE VISCOSITY AND ELASTIC DEFORMATION EFFECTS

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Abstract

The main objective of the present work is to study the behavior of Nano-lubricated journal bearing considering elasticity and variable viscosity effects. A mathematical model for a journal bearing is employed using three-dimensional computational fluid dynamics. The study is implemented for a journal bearing with laminar flow and smooth surfaces lubricated with pure oil as well as lubricants containing different concentrations of Al_2O_3 Nano-particles. The dependence of the oil viscosity on the temperature is considered by using the modified Krieger Dougherty model. Pressure, temperature and elastic deformation in addition to the bearing load-carrying capacity of the bearing working under different eccentricity ratios (0.1-0.6) have been studied. The mathematical model is confirmed by comparing the results of the pressure and temperature distributions obtained in the current work with those obtained by Ferron et al.(1983) for a bearing lubricated with pure oil. Also, the pressure obtained for the Nano-lubricated bearing of the present work is validated with that obtained by Solighar (2015). The results are found in good agreement with a maximum deviation not exceeding 5%. The obtained results show that the oil film pressure increases by about 17.9% with a slight decrease in oil film temperature and friction coefficient.

Keywords: hydrodynamic journal bearings, computational fluid dynamics, thermo-hydrodynamic lubrication, nano-lubricant, elastic deformation.

1. INTRODUCTION

The safe and smooth operation of rotating machines is limited by the reliability of the bearings. Hydrodynamic bearings are extensively used due to their simplicity, improved damping properties, high precision and high loads. It can be used in marine propellers, turbo and electric generators and IC Engines. The increasing journal bearing operating speeds leads to a higher range of temperature distribution that adversely impact the viscosity of the lubricant and the performance of the bearing. Different works have been implemented considering the thermal performance of various types of hydrodynamic bearings. The effect of bearing misalignment on thermo-hydrodynamic performance of journal bearing was extensively studied by [1-3]. Numerical results indicated that the influence of journal axial motion on the performance of the bearing is maximum when the thermal effect is taken into account. Thermal performance of journal bearings with various number of axial grooves has been investigated by [4-6].It was found that the bearing with twin axial grooves deteriorate when the bearing working under high loads in comparison with the single groove one. The combined effect of oil film temperature and the elastic deformation on its performance characteristics of the journal bearing was extensively studied by many workers [7-8]. The obtained results show an increase in maximum oil film pressure and load carrying capacity with sharp increase in oil film temperature due to journal misalignment when considering the elastic deformation of the bearing. The oil containing dispersed nano particles shows a higher viscosity in comparison with the base oil and hence influences the oil film temperature and the overall bearing performance. Different types of nano particles were used as an additives to the base oil such as TiO_2 [10-11], Si,SiO_2, Al, Al_2O_3,Cu, and CuO[12], Al_2O_3 and ZnO[13], Al_2O_3 [14-15]. Different viscosity models were used to include the effect of the dispersed nano particles on the viscosity of the base lubricant. Krieger Dougherty is found to be the most accurate viscosity model used in such works. As the bearing is lubricated with nano lubricant, the load caried by the bearing increases.
Few studies dealt with the combined impact of nano lubrication and thermal effects on journal bearing performance. In all of the work previously mentioned, the energy equation was solved simultaneously with the classical Reynolds equation. However, extensive work has been implemented using fluid structure interaction with computational

fluid dynamics to analyse the performance of the journal bearings considering elastic deformation [16-22]. These works recommended using CFD-FSI technique for hydrodynamic and elasto-hydrodynamic lubrication analysis of rotor bearings due its accuracy. It was found that the elastic deformation has a considerable effect on the performance of rotor-bearing system. However, these works deal mainly with the performance of journal bearings lubricated with pure oil.
It can be concluded from the above presentation that the combined effects of oil film temperature and elastic deformation on the performance of nano lubricated cylindrical journal bearings is rarely studied which is the main purpose of the current work. So, the present work is an attempt to analyse the thermo-elastohydrodynamic performance of journal bearing lubricated with pure and Al_2O_3 nano-lubricant by using fluid structure interaction with CFD technique.

2. MATHEMATICAL MODEL

The perfectly aligned cylindrical journal bearing with the geometry and coordinates system shown in figure 1 is analysed in the current study. It consists of a rotating journal with radius R and fixed bearing with radius R_b with oil filled the gap and assumed to flow laminarly between smooth surfaces. The external applied load 'W' affecting vertically and assumed to be constant which is balanced by the load induced by the oil film pressure generated.

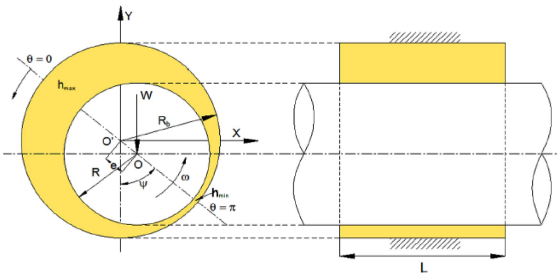


Fig. 1. Geometry of the Hydrodynamic journal bearing system [20]

Pressure distribution in journal hydrodynamic bearings is controlled by solving the modified conservation equations with the following assumptions using ANSYS-FLUENT 2019 R3 Software: compressible, laminar flow with negligible heat conduction, no-slip at the bearing surfaces, steady-state operating conditions, elastic bearing material and the oil viscosity is a function of temperature.

2.1. Mass conservation equation [20]:

$$\frac{\partial \rho}{\partial t} + \Delta(\rho \cdot \vec{v}) = 0 \qquad (1)$$

where
$\vec{v}$ is the velocity vector of fluid, ρ is the density of the nanofluid.

2.2. Momentum conservation equation [20]:

$$\frac{\partial}{\partial t}(\rho \cdot \vec{v}) + \nabla(\rho \cdot \vec{v} \cdot \vec{v}) = -\nabla P + \nabla(\bar{\tau}) + \rho \cdot \vec{g} + \vec{F} \quad (2)$$

where:
$\bar{\tau}$ is the stress tensor which could be written as:

$$\bar{\tau} = \mu\left[(\nabla \cdot \vec{v} + \nabla \cdot \vec{v}^T) - \frac{2}{3}\nabla \times \vec{v} \cdot I\right] \qquad (3)$$

where:
μ the viscosity of the fluid, which can be taken as a function of temperature.
I unit tensor, and the dilation effect is on the right side of the second term.
P the static pressure, $\vec{F}$ and $\rho.\vec{g}$ are the body and gravitational force vectors.

The above equations can be used for steady state operation of journal bearing by switching off the $\partial/\partial t$ terms.

2.3. Energy equation [20]

The distribution of the oil film temperature in the journal bearing can be attained by solving the following three-dimensional energy equation:

$$\rho C_p\left(u \cdot \frac{\partial T}{\partial x} + w \cdot \frac{\partial T}{\partial z}\right) = \frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right) + \mu\left[\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2\right] \qquad (4)$$

The energy transfer by convection represented by the left term of equation (4) while the conduction and viscous heat dissipation represented by the right-side term.

2.4. Elasticity equation

The following three- dimensional elasticity equation used to evaluate the elastic deformation of the bearing surface.

$$[k]\{d\} = \{f\} \qquad (5)$$

where
$\{d\}$ vector of all nodal displacements.
$\{f\}$ vector of nodal force.
$[k]$ stiffness matrix

3. RHEOLOGICAL AND PHYSICAL PROPERTIES OF NANO-LUBRICANT

The most important rheological properties of Nano-lubricant is the oil viscosity which can be modelled by using the following Krieger-Dougherty shear viscosity equation for particle dispersion as [24]:

$$\mu_{nf} = \mu\left[1 - \frac{\varphi}{\varphi_m}\right]^{-[\eta]\varphi_m} \qquad (6)$$

where:
η is the intrinsic viscosity with standard value of 2.5 for monodisperse, as defined by [24];
φ_m is the maximum fraction of particle packing, which is about 0.605 at elevated shear rates, as stated in[24];
φ is the solid nanoparticles' volume fraction;
μ is the viscosity of the base oil.

By applying the values of η and φ_m equation (6) can be rewritten as:

$$\mu_{nf} = \mu\left(1 - \frac{\varphi_a}{\varphi_m}\right)^{-2.5\varphi_m} \qquad (7)$$

where:

$$\varphi_a = \varphi\left(\frac{a_a}{a}\right)^{3-D} \quad (8)$$

D the fractal index for nanofluids with a standard value of 1.8.

$\frac{a_a}{a}$ represents the radii of aggregate to primary particle size ratio taken as 7.77.

The effect of oil film temperature on the oil viscosity can be taken as:

$$\mu = \mu_{nf} \exp\left[-\beta(T - T_i)\right] \quad (9)$$

where:

β is the lubricant's viscosity-temperature index equal to 0.032.

(ρ_{nf}) The density of the nano-lubricant which can be evaluated as[26]:

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_p \quad (10)$$

By defining $C_{p,nf}$ as the thermal power of the Nano-fluid, then [26]

$$\rho_{nf} C_{p,nf} = (1-\varphi)\left(\rho C_p\right)_f + \varphi\left(\rho C_p\right)_p \quad (11)$$

Subscripts *p*,*f*, and *nf* refer to particle, the base fluid, and nanofluid, respectively. Furthermore, the nanofluid thermal conductivity can be determined by using the following Maxwell-Garnett's model [26]:

$$k_{nf} = k_f\left[\frac{(k_p+2k_f)-2\varphi(k_f-k_p)}{(k_p+2k_f)+\varphi(k_f-k_p)}\right] \quad (12)$$

4. BEARING PERFORMANCE PARAMETERS

The following are the main performance parameters.

4.1. Load-Carrying Capacity

The bearing load components in vertical direction can be evaluated as:

$$\left(F_p\right)_y = \iint_{A_i} P_j \cdot \cos\theta \cdot \left(dA_j\right) = -W \quad (13)$$

And, the component of the load in horizontal direction can be evaluated as :

$$\left(F_p\right)_x = \iint_{A_j} P_j \cdot \sin\theta . \left(dA_j\right) = 0 \quad (14)$$

The load carried by the bearing can be calculated as:

$$W = \sqrt{(F_p)_x^2 + (F_p)_y^2} \quad (15)$$

The attitude angle can be evaluated as :

$$\phi = \tan^{-1}\left(\frac{F_{py}}{F_{px}}\right) \quad (16)$$

4.2. Friction Force

The friction force can be calculated as:

$$\left(F_{fr}\right) = \iint \tau \cdot (dA) \quad (17)$$

The coefficient of friction can be expressed as:

$$f = \frac{F_{fr}}{W} \quad (18)$$

4.3.Side leakage of the flow

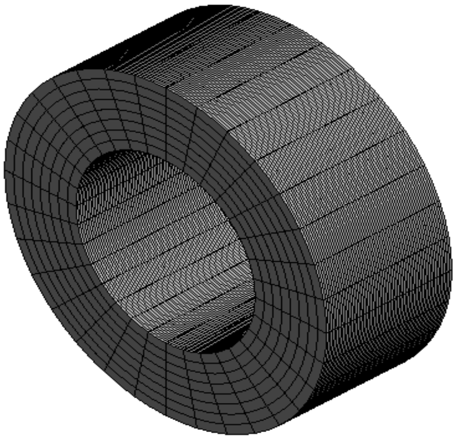
The oil side leakage flow can be expressed as:

$$Q_s = \int_{\theta_1}^{\theta_2} \frac{h^3}{12\mu}\frac{\partial P}{\partial z}\, d\theta \qquad at\ z = 0\ and\ L \quad (19)$$

5. MODEL DESCRIPTION

The current work deals with the steady-state thermal analyses of the Nano-lubricated circular journal bearing using CFD approach. The problem is modeled using ANSYS FLUENT software which can be used to simulate different problems. The bearing structure and fluid film domain have been modeled in three dimensions as shown in figure 2 a ,b. The fluid film was modeled by FLUENT using hexahedral elements while the bearing solid structure was modeled using the ANSYS with hexahedral elements. The numerical analysis is implemented for a bearing with grid size of $100\times 500 \times 3$ elements in the axial, circumferential, and radial directions, respectively with 150000 total number of elements. Grid independence is ensured by extensive mesh testing for a bearing lubricated with pure oil.

(a) Fluid domain



(b) Solid domain

Fig. 2. Mesh generation for fluid and solid domains of the bearing

6. BOUNDARY CONDITIONS

The following thermal boundary conditions are adopted:

- Constant shaft temperature since the speed of the journal does not allow conduction heat transfer through the shaft material.

$$T_s = T_i$$

- $T_f = T_b$ (Continuity of the temperature)
- The heat transfer continuity for conduction at the interface of the bearing fluid. $r=R_b$

$$k_{nf}\frac{\partial T_f}{\partial y} = k_b\frac{\partial T_b}{\partial y}$$

– The continuity of conduction and convection heat transfer at the outside of the bearing surface:

$$k_b \frac{\partial T_b}{\partial y} = -hc(T_b - T_a)$$

– Atmospheric pressure at the ends of the bearing.
– At the fluid solid interfaces, the displacement of fluid is equal to the displacement of the solid, i.e.

$$d_{nf} = d_s$$

– At the fluid solid interfaces, the shear stress of fluid is equal to the shear stress of the solid, i.e.

$$\tau_{nf} = \tau_s$$

7. RESULTS AND DISCUSSION

The bearing with geometrical and physical properties shown in Table1. is analyzed in the present work. The bearing lubricating oil dispersed with different volume fractions of Al_2O_3 nano-particles with the physical and thermal properties shown in Table 2. The numerical model is verified, by examining the oil film temperature distribution obtained in the current work for a cylindrical journal bearing lubricated with pure oil with that obtained by Ferron et al.[23]**,** as can be seen in figure 3. This figure clearly shows that the findings are in reasonable agreement with an overall deviation not exceeding 5%.

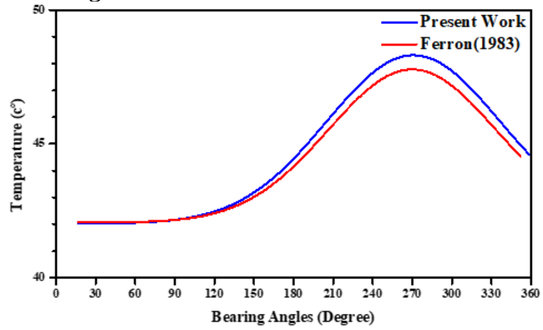


Fig. 3. Validation of temperature results with that obtained by Ferron et al. [23]

A further validation is made by comparing the thermal pressure distribution of the bearing lubricated with Al_2O_3 Nano-lubricant studied in the current work with the data published by Solighar[25] as presented in figure 4. This figure clearly shows the closeness between the results with little deviation due to the different mathematical approaches used in both works. The finite difference approach was used by Solighar to solve the two dimensional Reynolds and energy equations while CFD approach was used to solve three dimensional model in the present work.

Figure 5 shows the effect of dispersing 5%by volume of Al_2O_3 nanoparticles in the base oil on the oil film pressure. This figure clearly indicates that the overall oil film bearing pressure rises by 17.9% when the bearing is lubricated with such nano-lubricant compared to that lubricated with pure oil. This can be explained by the fact that the viscosity of the base oil becomes higher when it dispersed by the nano-particles in comparison with that of pure oil. It is well known that the oil viscosity is the most important physical property which responsible of the oil film pressure generation This figure also shows that the maximum oil film pressure increases from 7.8MPa. to 9.1 MPa when the bearing lubricated with the nano-lubricant. The increase in oil film pressure accompanied with slight increase in the maximum oil film temperature as can be seen in figure 6. This can be attributed to the increase in the lubricant's thermal conductivity when Al_2O_3 nanoparticles are applied to the base oil due to the higher surface area of such nanoparticles.

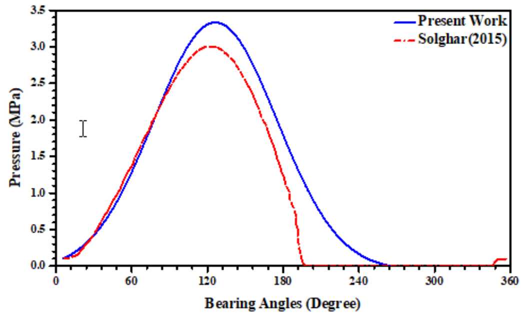


Fig. 4.Validation of pressure with that published in [25]

Table 1. Geometrical and operating parameters [28]

Parameter	Symbol	Value
Length/Diameter	L/D	0.7
Radius of the shaft	R_s	50mm
Bearing Inner radius	R_i	50.05mm
bearing Outer radi-us	R_o	90mm
eccentricity ratio	ε	0.1-0.9
attitude angle	ϕ	77°
Rotational speed	N	3000rpm
Inlet oil temperature	T_i	40°C
Clearance	C	0.05mm
Viscosity at 40°C	μ_i	0.0192Pa.s
Viscosity temperature index	β	0.032°C^{-1}
Oil density	ρ_{oil}	860kg/m^3
Oil specific heat	C_{poil}	1970kJ/kg.K
Oil thermal conductivity	k_{oil}	0.135W/m.°C
Bearing thermal conductivity	k_B	50W/m.°C
Material heat trans-fer coefficient	h_B	50W/m.°C

Table 2.Thermal and physical properties(Al_2O_3)

Parameter	Symbol	Value
Specific heat	C_p	765J/kg.°C
Density	ρ	3970kg/m^3
Thermal conductivity	K	40W/M.°C

The maximum temperature of the oil film at the mid plane of the bearing with the eccentricity ratio for Al_2O_3 nano-lubricated journal bearing with different concentrations of particles is presented in

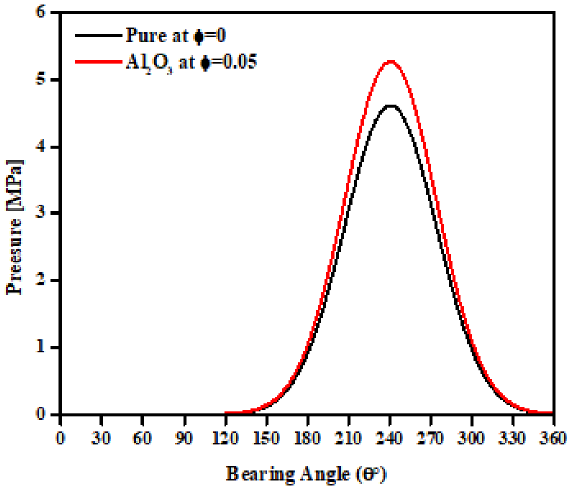


Fig. 5. Circumferential pressure distribution for a bearing lubricated with pure oil and Nano-lubricant

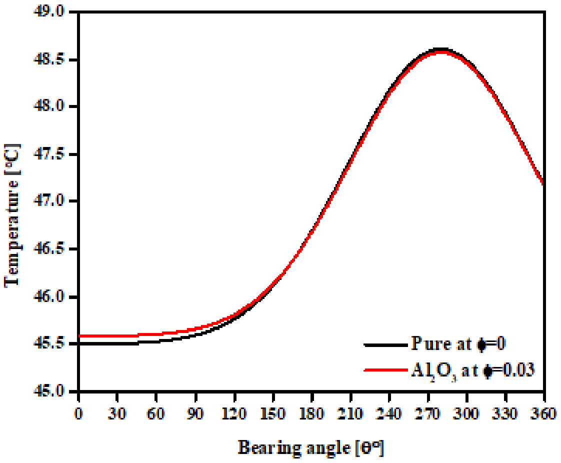


Fig. 6. Oil film temperature vs. angular position

Figure 7. This figure illustrates that the maximum temperature of the oil film grows up as the bearing operates at greater eccentricity ratio. This can be demonstrated by the fact that, the distance between the journal and the bearing becomes smaller as the bearing works at higher eccentricity ratio, resulting in a higher shear rate and higher friction force which was converted to heat used to increase the oil film temperature. It can also be seen from this figure that the overall oil film temperature of the bearing is slightly lower when the bearing is lubricated with nano-lubricant that has higher volume fraction of Al_2O_3 nano particles due to the higher thermal conductivity of the nano-lubricant. The decrease in maximum oil film temperature becomes higher in comparison with the pure oil when higher particle concentrations of such particles were dispersed in the base oil due to the higher surface area of such nanoparticles.

Figure 9 demonstrates the variation of the bearing material elastic deformation with the eccentricity ratio when the bearing lubricated with an oil dispersed with Al_2O_3 nanoparticles with different concentrations. It was found that the bearing material deformation becomes higher when the bearing working at higher eccentricity ratio or lubricated with oil dispersed with nano-particles. This related to the higher oil film pressure generated when the bearing acts under this situation. However, a higher increase in elastic deformation can be noticed with more Al_2O_3 nanoparticles dispersed in the base oil for the same above discussed reasons.

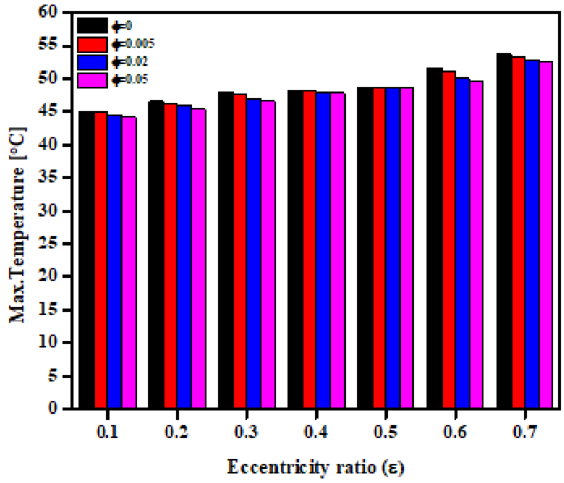


Fig. 7. Variation of Maximum oil film temperature with eccentricity ratio and nanoparticle concentration

Figure 8 demonstrates the maximum bearing pressure for a bearing works at different eccentricity ratios lubricated with oil dispersed with different volume fractions of Al_2O_3.This figure clearly depicts that the maximum oil film pressure increases when the bearing works at higher eccentricity ratios due to the smaller oil film thickness in this case. The growth of the maximum pressure becomes greater when the bearing lubricated with nano-lubricant has higher volume fraction of Al_2O_3 nanoparticles due to the increase of the oil viscosity.

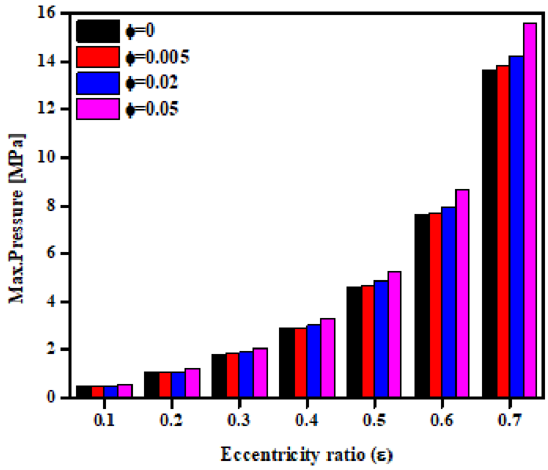


Fig. 8. Variation of Maximum oil film pressure with eccentricity ratio and nanoparticle concentration

The effect of the nanoparticle volume fractions on the load carrying capacity of the bearing working at different eccentricity ratios is clarified in fig.10. It was observed that the bearing supports higher load when it works at higher eccentricity ratios and lubricated with nano-lubricant that has higher concentration of Al_2O_3 nano particles. This can be revealed by the higher oil film pressure generated in this case as has been noticed in previous figures.

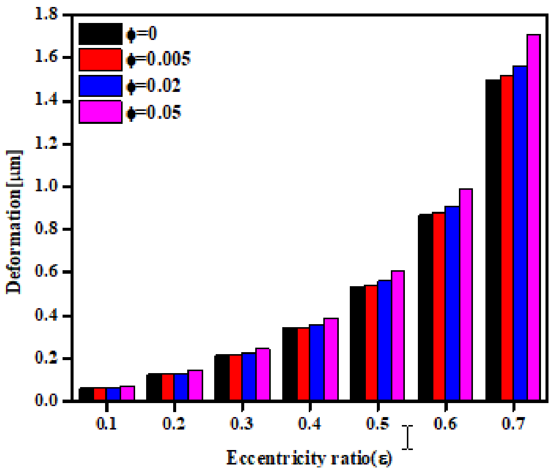


Fig. 9. Variation of the bearing deformation with the eccentricity ratio and particle concentration of Al_2O_3.

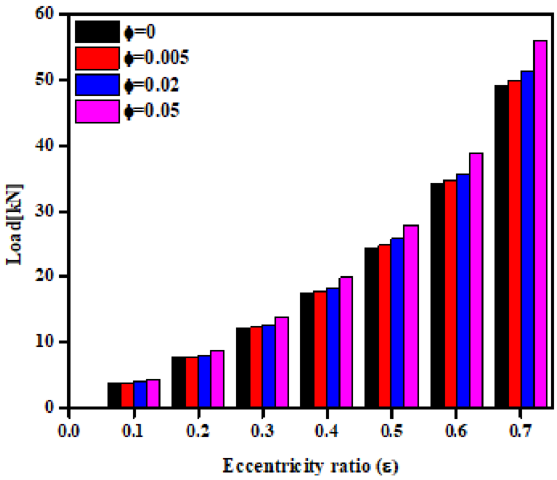


Fig. 10. Variation of load carrying with an eccentricity and particle concentration ratio of Al_2O_3

Figure11 depicts that the induced friction force grows up for the bearing with higher eccentricity ratio since the journal becomes closer to the bearing in this case resulting in higher shear rate. It becomes higher when the bearing lubricated with oil that has higher concentrations of nano- particles. This can be explained by understanding that the dispersion of nanoparticles in the base oil enhanced the oil viscosity which causes an increase in shear stress of the lubricant layers thus increases the friction force. However, figure 12 shows that the friction coefficient decreases as the bearing operates at the same above circumstances. It was observed that the coefficient of friction was unaffected by the addition of the nano particles to the base oil since it represents the ratio between the friction force and the load carried by the bearing which increase simultaneously in this case.

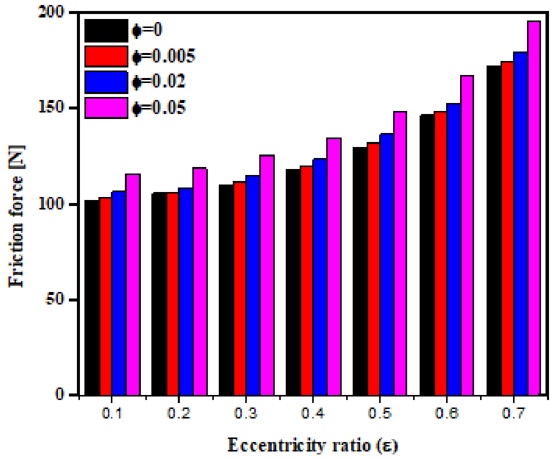


Fig. 11. Variation of friction force with eccentricity ratio and nanoparticle concentration

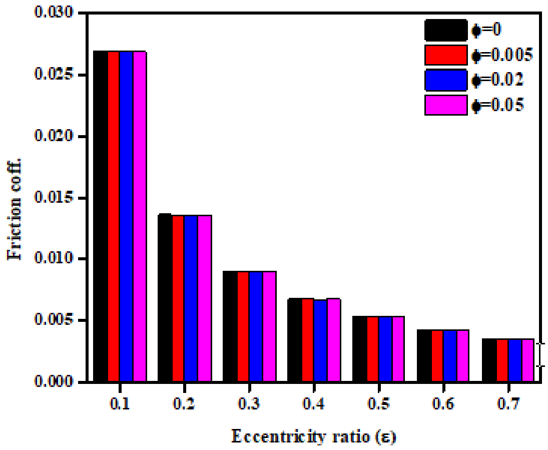


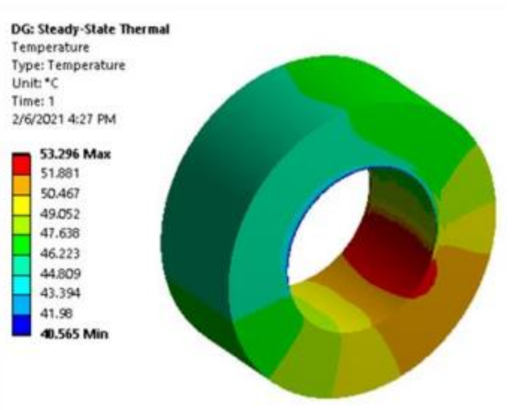
Fig. 12. Variation of friction coefficient with eccentricity ratio and nanoparticle concentrations

Figure 13 shows the contour plot of the bearing surface temperature when the bearing operates at two different eccentricity ratios (0.4 and 0.6) and lubricated with oil dispersed by 5% volume fraction of Al_2O_3 nanoparticles. This figure clearly depicts that there is a little effect on the bearing surface temperature when the bearing works in such circumstances. The maximum surface temperature increases from 53.296ºC to 54.799ºC when the eccentricity ratio increases from 0.4 to 0.6.

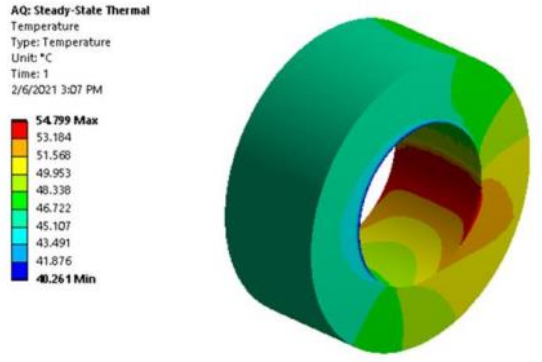
8. CONCLUSIONS

The performance of Thermo-Elasto-Hydrodynamic lubrication of journal bearing lubricated with nano-lubricant dispersed with different volume fractions of AL_2O_3 nanoparticles was studied in the present work. The cavitation effect was considered and the results were compared with the bearing lubricated with pure oil. The study leads to the following conclusions:

1. Using Al_2O_3 nano-lubricant with 5% of nanoparticles increases the oil film by 17.9% .
2. The dispersion of the nanoparticles in the base oil slightly decreases the maximum oil film temperature.



(a) Eccentricity ratio 0.4



(b) Eccentricity ratio 0.6

Fig. 13. Contour map of the temperature in the solid domain with different eccentricity ratios and volume fraction 0f 5%

3. The use of nano additives results in an increase in load carrying capacity of the bearing and a decrease in the friction coefficient.
4. The elastic deformation of the bearing material slightly increases when using nano-lubricant.
5. The surface temperature of the bearing slightly increase as the bearing works at higher eccentricity ratios and lubricated with nano-lubricant.

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Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

REFERENCES

1. Sun J, Deng M, Fu Y, Gui V. Thermohydrodynamic lubrication analysis of misaligned plain journal bearing with rough surface. J. Tribol. 2010,132(1): 011704. https://doi.org/10.1115/1.4000515.
2. He Z-P, Zhang J-H, Xie W-S, Li Z-Y, Zhang G-C. Misalignment analysis of journal bearing influenced by asymmetric deflection, based on a simple stepped shaft model. Journal of Zhejiang University Science A 2012,13(9):647-664. http://dx.doi.org/10.1631/jzus.A1200082.
3. Li B, Sun J, Zhu S, Fu Y, Zhao X, Wang H, et al., Thermohydrodynamic lubrication analysis of misaligned journal bearing considering the axial movement of journal. Tribology International 2019;135:397-407. https://doi.org/10.1016/j.triboint.2019.03.031.
4. Brito F, Miranda A, Claro JCP, Fillon MJT. Experimental comparison of the performance of a journal bearing with a single and a twin axial groove configuration. Tribology International 2012;54:1-8. https://doi.org/10.1016/j.triboint.2012.04.026.
5. Zhang ZS, Yang YM, Dai D, Xie YB. Effects of thermal boundary conditions on plain journal bearing thermohydrodynamic lubrication. Publication Cover. Tribology Transactions 2013; 56(5):759-770. https://doi.org/10.1080/10402004.2013.797531.
6. Brito FP, Miranda AS, Claro JCP, Teixeira JC, Costa L, Fillon M. The role of lubricant feeding conditions on the performance improvement and friction reduction of journal bearings. Tribology International 2014;72: 65-82. http://dx.doi.org/10.1016/j.triboint.2013.11.016.
7. Lambha SK, Kumar V, Verma R. Elastohydrodynamic analysis of couple stress lubricated cylindrical journal bearing. Journal of Physics: Conference Series. 2019. IOP Publishing. http://dx.doi.org/10.1088/1742-6596/1240/1/012165.
8. Zhang Y, Chen G, Wang L. Thermoelastohydrodynamic analysis of misaligned bearings with texture on journal surface under high-speed and heavy-load conditions. Chinese Journal of Aeronautics 2019;32(5):1331-1342. http://dx.doi.org/10.1016/j.cja.2018.08.005.
9. Shenoy BS, Binu KG, Pai R, Rao DS, Pai RS. Effect of nanoparticles additives on the performance of an externally adjustable fluid film bearing. Tribology International 2012;45(1):38-42. http://dx.doi.org/10.1016/j.triboint.2011.10.004.
10. Binu KG, Shenoy BS, Rao DS, Pai R. Static characteristics of a fluid film bearing with TiO2 based nanolubricant using the modified Krieger–Dougherty viscosity model and couple stress model. Tribology International 2014;75:69-79. https://doi.org/10.1016/j.triboint.2014.03.013.
11. Binu KG, Shenoy BS, Rao DS, Pai R. A variable viscosity approach for the evaluation of load carrying capacity of oil lubricated journal bearing with TiO2 nanoparticles as lubricant additives. Procedia Materials Science 2014;6:1051-1067. https://doi.org/10.1016/j.mspro.2014.07.176.
12. Nicoletti R. The importance of the heat capacity of lubricants with nanoparticles in the static behavior of journal bearings. J. Tribol. 2014;136(4). https://doi.org/10.1115/1.4027861.
13. Babu KS, Nair KP, Rajendrakumar PK. Science, and Technology, "Computational analysis of journal bearing operating under lubricant containing Al_2O_3 and ZnO nanoparticles. International Journal of Engineering, Science and Technology 2014;6(1):34-42. https://doi.org/10.4314/ijest.v6i1.4.
14. Gunnuang W, Aiumpornsin C, Mongkolwongrojn M. Effect of nanoparticle additives on journal bearing lubricated with non-Newtonian Carreau fluid. in Applied Mechanics and Materials. 2015;175:137-142. https://doi.org/10.4028/www.scientific.net/AMM.751.137.
15. Solghar AA. Investigation of nanoparticle additive impacts on thermohydrodynamic characteristics of

journal bearings. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 2015;229(10):1176-1186. https://doi.org/10.1177%2F1350650115574734.
16. Li Q, Liu S-I, Pan X-H,Zheng S-Y. A new method for studying the 3D transient flow of misaligned journal bearings in flexible rotor-bearing systems. Journal of Zhejiang University SCIENCE A 2012;13(4):293-310. http://dx.doi.org/10.1631/jzus.A1100228.
17. Liu H, Xu H, Ellison PJ, Jin Z. Application of computational fluid dynamics and fluid–structure interaction method to the lubrication study of a rotor–bearing system. Tribology Letters 2010;38(3): 325-336. http://dx.doi.org/10.1007/s11249-010-9612-6.
18. Li Q, Yu G, Liu S, Zheng S. Application of computational fluid dynamics and fluid structure interaction techniques for calculating the 3D transient flow of journal bearings coupled with rotor systems. Chinese Journal of Mechanical Engineering 2012;25(5):926-932. https://doi.org/10.3901/CJME.2012.05.926.
19. Dhandea DY, Pande DW. Numerical analysis of hydrodynamic journal bearing lubrication using computational fluid dynamics and fluid structure interaction approach. Int. J. of Vehicle Structures & Systems 2016;8(4):224-228. http://dx.doi.org/10.4273/ijvss.8.4.08.
20. Dhande DY, Pande DW. A two-way FSI analysis of multiphase flow in hydrodynamic journal bearing with cavitation J Braz. Soc. Mech. Sci. Eng. 2017;39(9):3399-3412. https://doi.org/10.1007/s40430-017-0750-8.
21. Chen Y, Sun Y, He Q, Feng J. Elastohydrodynamic behavior analysis of journal bearing using fluid–structure interaction considering cavitation. Arabian Journal for Science and Engineering. 2019;44(2):1305-1320. https://doi.org/10.1007/s13369-018-3467-9.
22. Kyrkou M-E, Nikolakopoulos PG. Simulation of thermo-hydrodynamic behavior of journal bearings, lubricating with commercial oils of different performance. Simulation Modelling Practice and Theory 2020;104:102128. https://doi.org/10.1016/j.simpat.2020.102128.
23. Ferron J, Frene J, Boncompain R. A Study of the thermo-hydrodynamic performance of a plain journal bearing comparison between theory and experiments. J. of Lubrication Tech. 1983;105(3):422-428. https://doi.org/10.1115/1.3254632.
24. Dang, RK, Chauhan A, Dhami SS. Static thermal performance evaluation of elliptical journal bearings with nanolubricants. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 2020; https://doi.org/10.1177/1350650120970742.
25. Solghar AA. Investigation of nanoparticle additive impacts on thermohydrodynamic characteristics of journal bearings. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 2015;229(10):1176-1186. https://doi.org/10.1177%2F1350650115574734.
26. Gandjalikhan Nassab SA, Moayeri MS. Three-dimensional thermohydrodynamic analysis of axially grooved journal bearings. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 2002;216(1):35-47. https://doi.org/10.1243%2F13506500215438-70.

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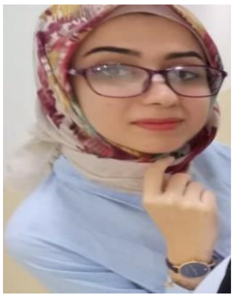

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