



# CFD-Based Thermohydrodynamic Analysis of Vegetable Oil Lubricants in Journal Bearings

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**Abstract.** This study investigates the thermohydrodynamic performance of journal bearings lubricated with palm trimethylolpropane (TMP) ester as a biolubricant, compared to conventional engine oil, using computational fluid dynamics (CFD) in ANSYS Fluent. The objective is to evaluate the influence of lubricant type on pressure distribution, load carrying capacity, friction force, and cavitation behavior. The results show that palm TMP ester generates higher hydrodynamic pressure while maintaining a similar pressure distribution pattern to engine oil. The load carrying capacity increases significantly by approximately 493% at 48 rad/s and 343% at 68 rad/s compared to engine oil. However, this improvement is accompanied by an increase in friction force of about 280% and 234% at the respective speeds due to higher viscosity. In addition, the vapor volume fraction ranges from 0.69 to 0.73, indicating cavitation, with palm TMP ester showing a slightly higher tendency. These findings demonstrate a trade-off between enhanced load support and increased friction, highlighting the potential of palm TMP ester as an environmentally friendly lubricant for hydrodynamic bearing applications.

**Keywords:** journal bearing, biolubricant, load-carrying capacity

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## 1. Introduction

Thermohydrodynamic (THD) lubrication considers the effect of temperature variation on lubricant viscosity within the hydrodynamic film, influencing the overall lubrication performance [1]. A thermohydrodynamic analysis of journal bearings lubricated with aerated oil was conducted by coupling the Reynolds, energy, and heat conduction equations. The results showed that air bubbles slightly affect pressure and temperature fields, while noticeably reducing lubricant density and effective viscosity [2]. A numerical study on two- and three-lobe journal bearings demonstrated that appropriate temperature boundary conditions and zero viscous dissipation in cavitated regions provide good agreement with

experimental results[3]. Dal et al. [4] studied thermohydrodynamic lubrication accounts for the interaction of pressure, temperature, and viscosity in the lubricant film affecting journal bearing performance. Chasalevris et al. [5] proposed a bearing design procedure for turbine-generator shaft trains using thermohydrodynamic lubrication and dynamic analysis, showing that nonlinear models provide more accurate rotor dynamic predictions than linear models. Nikolic et al. [6] investigated the temperature distribution in the oil film of a short journal bearing by deriving an analytical temperature field equation and validating it against experimental data, as well as by coupling the energy equation with the Reynolds equation to obtain a solvable partial differential equation for predicting temperature distribution. Fillon and Bouyer [7] studied the impact of wear on the thermo-hydrodynamic behavior of journal bearings by evaluating parameters including hydrodynamic pressure, temperature distribution at the film–bush interface, lubricant flow rate, power dissipation, and oil film thickness. Dousti and Allaire [8] investigated thermohydrodynamic behavior of single- and double-film floating disk thrust bearings using Reynolds and energy equations, showing that double-film configurations can reduce power loss compared to single-film bearings. Lin et al. [9] investigated the thermohydrodynamic cavitating flow lubrication of high-speed water-lubricated spiral groove thrust bearings by developing a model that includes cavitation, inertia, and turbulence effects, showing that inertia and cavitation reduce load carrying capacity and friction torque, while turbulence increases them. Li et al. [10] developed a thermohydrodynamic lubrication model for misaligned journal bearings considering the axial movement of the journal by solving the generalized Reynolds, heat conduction, and energy equations, showing that axial motion significantly affects lubrication performance, particularly at low speeds, large inclination angles, and high eccentricity. Chun [11] analyzed the influence of variable density and specific heat on high-speed journal bearing performance and found that these thermal properties significantly affect bearing load and frictional power loss. Tauviqirrahman et al. [12] demonstrated that omitting cavitation in CFD analysis causes significant performance overestimation, with peak pressure discrepancies up to 79%. Their study concluded that mass-conservative modeling is essential for achieving accurate hydrodynamic and vortex predictions in journal bearings.

Neta et al. [13] studied that along with the increasing demand for sustainable technologies, biolubricants derived from renewable resources have emerged as promising alternatives due to their environmentally friendly characteristics and lower ecological impact. Hussain et al. [14] have shown that the use of biolubricants in hydrodynamic journal bearings can result in lower friction and wear while providing comparable or even improved load-carrying capacity, particularly when vegetable oils are chemically modified and enhanced with suitable additives. Rasep et al. [15] investigated the use of biolubricants in journal bearings and reported that they have significant potential as substitutes for mineral-based lubricants due to their ability to reduce friction and wear while providing competitive load-supporting capability. Rasep et al. [16] investigated the combination of vegetable oil-based lubricants as potential replacements for mineral oils and the modification of surface texture in journal bearings has the potential to significantly enhance bearing performance while simultaneously promoting the use of environmentally friendly lubricants. Hammza et al. [17] studies have investigated the effect of blending biolubricant oils with mineral oils on the dynamic behavior of rotor–bearing systems using analytical and numerical approaches. The results showed that the use of biolubricants can significantly reduce the dynamic response of the system, with reductions of up to 37.3%, while lubricant blends also provide moderate improvements in dynamic performance. Quinchia et al. [18] studies reported that different vegetable oils exhibit varying lubrication performance, where castor oil shows superior film-forming capability and lower friction and wear compared to other vegetable oils, while viscosity modifiers can further improve lubrication in boundary and mixed regimes. Mohammed et al.[19] conducted a thermo-hydrodynamic (THD) analysis comparing ionic liquids with conventional oils. Their findings revealed that while ionic liquids reduced the load-carrying capacity by 35.5% , they successfully lowered the maximum operating temperature by 16.13%. Kamarapu et al. [20] demonstrated that a bio-based nanolubricant blend reinforced with multiwall carbon nanotubes (MWCNTs) can achieve a 37% reduction in operating temperature and a 69% reduction in wear debris size compared to traditional mineral oil. Xie et al. [21] introduced a plant-based lubricant derived from

plant extracts that exhibits superior load-carrying capacity and thermal stability. Natural ingredients within the extract function as built-in additives that promote the formation of a protective layer on metal surfaces, significantly enhancing both smoothness and wear resistance. Pawar et al. [22] demonstrated that biolubricants derived from *Jatropha* and *Karanja* oils exhibit superior performance compared to synthetic PAO4 in crankshaft bearing applications. The study found that these biolubricants can reduce the coefficient of friction (COF) by up to 25% and decrease the specific wear rate (SWR) by up to 18%. This enhanced protection is attributed to the formation of stable, carbon-rich protective tribofilms on the bearing surfaces.

However, despite the widespread use of CFD-based thermohydrodynamic analyses in journal bearing studies, most previous works have focused on conventional mineral oils or general vegetable-based lubricants. The application of palm trimethylolpropane (TMP) ester, particularly under varying operating conditions, remains limited. Furthermore, the combined evaluation of load carrying capacity, friction force, and cavitation behavior within a unified computational framework is still insufficiently addressed. Therefore, this study investigates the thermohydrodynamic performance of journal bearings lubricated with palm TMP ester and engine oil using CFD in ANSYS Fluent.

## 2. Methods

### 2.1. Geometry Modelling and Fluids Properties

The geometry used in this simulation comprises the following: plain journal bearings (see figure 1 and table 1). The journal bearing geometry used to simulate fluid flow in this final project validation adopts the geometry of the journal bearing Taghipour et al. [23], fluid properties of engine-oil also used research references from Taghipour et al. [23], and the properties of palm trimethylolpropane ester adopts from Heikal et al. [24].

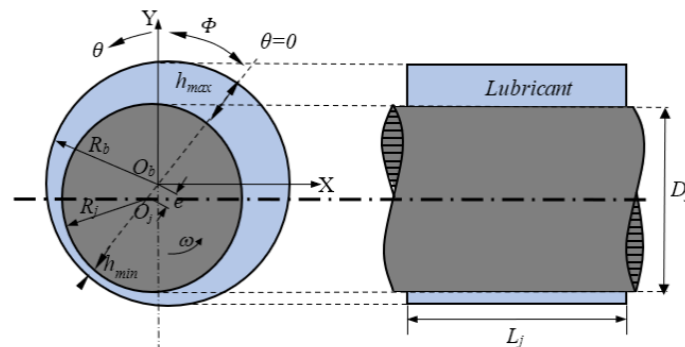


Figure 1. Schematic of journal bearing

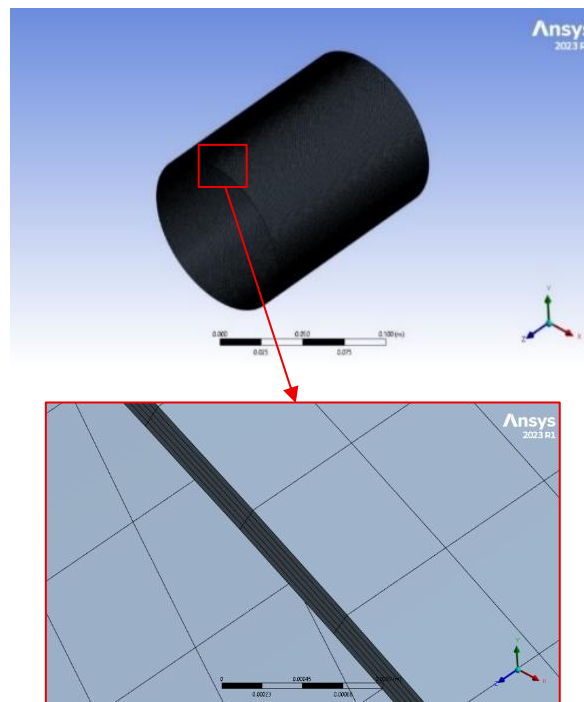
Table 1. Simulation Parameter

Journal Bearing Parameters	Symbol	Value	Unit
Journal Diameter	$D_j$	100	mm
Journal length	$L_j$	133	mm
Radial clearance	$c$	0.145	mm
Eccentricity Ratio	$\varepsilon$	0.6	-
Shaft rotating speed	$\omega$	48, 68	rad/s
Attitude Angle	$\varphi$	0	degree
Engine Oil Parameters	Symbol	Value	Unit
Liquid oil density	$\rho_l$	840	kg/m <sup>3</sup>
Liquid oil viscosity	$\mu_l$	0.0127	Pa·s
Vapor pressure	$P_{sat}$	20,000	Pa

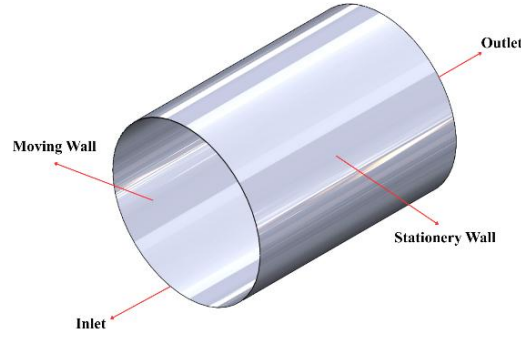
<b>Journal Bearing Parameters</b>	<b>Symbol</b>	<b>Value</b>	<b>Unit</b>
Oil vapor viscosity	$\mu_v$	$2 \times 10^{-5}$	Pa·s
Bubble diameter	$D_b$	0.01	mm
<b>Palm Trimethylolpropane Ester Parameters</b>	<b>Symbol</b>	<b>Value</b>	<b>Unit</b>
Liquid oil density	$\rho_l$	913.4	kg/m <sup>3</sup>
Liquid oil viscosity	$\mu_l$	0.0476	Pa·s
Vapor pressure	$P_{sat}$	100	Pa
Oil vapor viscosity	$\mu_v$	$2 \times 10^{-5}$	Pa·s
Bubble diameter	$D_b$	0.01	mm

## 2.2. Mesh Generation and Boundary Condition

Meshing is performed prior to the simulation to discretize the fluid domain geometry, as shown in Figure 2. The fluid domain (Figure 2) is discretized using ANSYS Meshing. A structured hexahedral mesh is generated with a body sizing of 0,8 mm, while face meshing is applied at the inlet and outlet with five inflation layers to capture near-wall flow behavior. The minimum skewness value of the mesh is  $2,8315 \times 10^{-3}$ . The simulation is considered converged when the residuals of continuity, velocity, and turbulent kinetic energy fall below  $10^{-4}$ , while the energy residual is reduced below  $10^{-6}$ . Figure 3 and Table 2 present the boundary conditions applied in the simulation, including the inlet, outlet, stationary walls, and moving walls. The numerical solution was performed using a pressure–velocity coupling scheme based on the SIMPLE algorithm. Spatial discretization was applied using the least squares cell-based method for gradient evaluation and the PRESTO! scheme for pressure interpolation. The momentum and energy equations were discretized using the second-order upwind scheme to ensure higher accuracy. Meanwhile, the turbulent kinetic energy and turbulent dissipation rate were discretized using the first-order upwind scheme for improved numerical stability. The volume fraction equation was solved using the QUICK scheme to accurately capture phase distribution.



**Figure 2.** Meshing of journal bearing



**Figure 3.** Boundary condition of journal bearing

**Table 2.** Boundary Condition Parameters

Boundary Condition	Condition for momentum
Inlet	0 MPa, 300K
Outlet	0 MPa, 300 K
Moving Wall	0 MPa, 300 K, 48 rad/s, 50 W/m <sup>2</sup> K, 300 K
Stationery Wall	50 W/m <sup>2</sup> K, 300 K
Inlet	0 MPa, 300K

### 2.3. Governing Equations

In this study, a computational fluid dynamics (CFD) model is employed to analyze the lubricant flow, pressure generation, and heat transfer within the fluid domain. The behavior of the lubricant is described using the fundamental principles of fluid mechanics through the continuity and momentum equations for a continuous fluid medium. The governing equation for mass conservation can be expressed as follows:

$$\nabla \cdot \vec{v} = 0 \quad (1)$$

The momentum conservation equation reads:

$$\rho(V \cdot \nabla)V = -\nabla p + \nabla \cdot (\mu \nabla V) \quad (2)$$

where  $V$  is the fluid velocity vector,  $\rho$  is the fluid density,  $p$  is the fluid hydrodynamic pressure, and  $\mu$  is the fluid viscosity.

Temperature-dependent viscosity is considered in this work and modelled in accordance with Hughes W.F. [25].

$$\mu_1 = \mu_0 e^{\alpha(P-P_0)} e^{\beta(T-T_0)} \quad (3)$$

where  $\mu_1$  is the dynamic viscosity of the liquid lubricant,  $\mu_0 = 0.0127$  Pa.s is the reference dynamic viscosity,  $\alpha = 2.3 \times 10^{-8}$  Pa<sup>-1</sup> is the viscosity specification in constant pressure, and  $\beta = -0.03$  K<sup>-1</sup> is the viscosity specification in constant temperature.  $\mu_0 = 0.0476$  Pa.s is the reference dynamic viscosity of the palm TMP ester lubricant,  $\alpha = 2.8 \times 10^{-8}$  Pa<sup>-1</sup> is the pressure-viscosity coefficient at constant temperature, and  $\beta = -0.015$  K<sup>-1</sup> is the temperature-viscosity coefficient at constant pressure. The reference temperature and pressure are  $T_0 = 313$  K and  $P_0 = 101325$  Pa, respectively, while  $P$  [Pa] and  $T$  [K] denote the pressure and temperature.

Journal bearing performance was assessed based on three primary parameters: load-carrying capacity and frictional force. The load-carrying capacity corresponds to the integrated pressure distribution over the bearing surface and the total supported load. Mathematically, it can be expressed as [26]:

$$W = \iint_A p dA \quad (4)$$

where A is the total bearing area and p is the amount of hydrodynamic pressure created along the journal bearing's surface.

The integral of the shear stress along the journal bearing's surface is used to determine frictional force. Mathematically the frictional force that occurs in the journal bearing can be expressed as equation 5 below [27]:

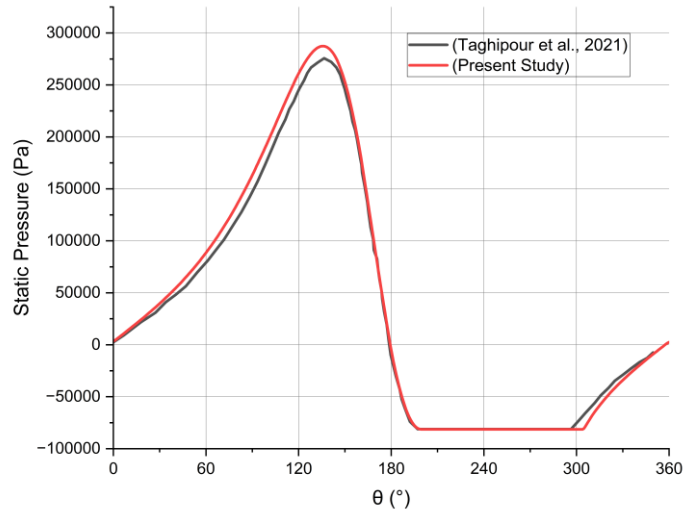
$$F_f = \iint_A \tau dA \quad (5)$$

### 3. Results and Discussion

The results of the case studies are discussed in the following section. CFD simulations are performed to analyze thermo-hydrodynamic lubrication in plain journal bearings.

#### 3.1. Validation

To ensure the validity of the research methodology, the present results were compared with the baseline data reported by Taghipour et al. [23]. Specifically, the maximum hydrodynamic pressure and bearing deformation values were compared. At a shaft speed of 48 rad/s, the difference in the maximum pressure (Pmax) is 3,4%. In addition, the minimum pressure obtained from the present simulation shows good agreement with the reference data reported by Taghipour et al. [21], with a deviation of 1.68%, further confirming the validity and reliability of the numerical model. The details of the validation results are presented in Figure 4.



**Figure 4.** Comparison of journal bearing pressure value at  $\varepsilon = 0.6$  Taghipour et al. [23]. with present study on shaft speed of 48 rad/s.

**Table 3.** Mesh Independence Test

Mesh Type	Face Layers	Mesh Elements	Mesh Nodes	Max Pressure (Pa)	Min Pressure (Pa)	Max Dev (%)	Min Dev (%)
Coarse	3	196,212	263,192	264,683.66	-81,325	–	–

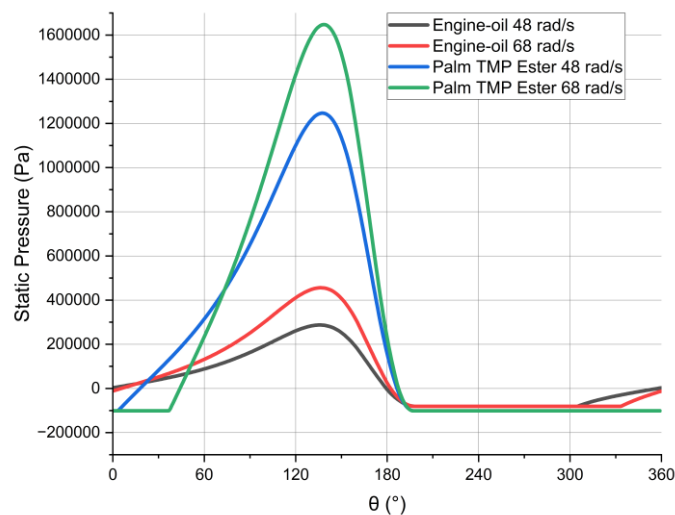
Medium	4	261,616	328,990	273,250.59	-81,325	3.24	0.0
Fine	5	327,020	394,788	280,522.47	-81,325	2.66	0.0

Table 3 presents the grid-independence study, indicating how maximum hydrodynamic pressure converges with increasing mesh density. Four mesh layers were ultimately selected to balance computational cost and accuracy, and this configuration was applied in all subsequent simulations to ensure consistent, reliable evaluation.

### 3.2. Effect of Biolubricant on Journal Bearing with Variation Shaft Speed

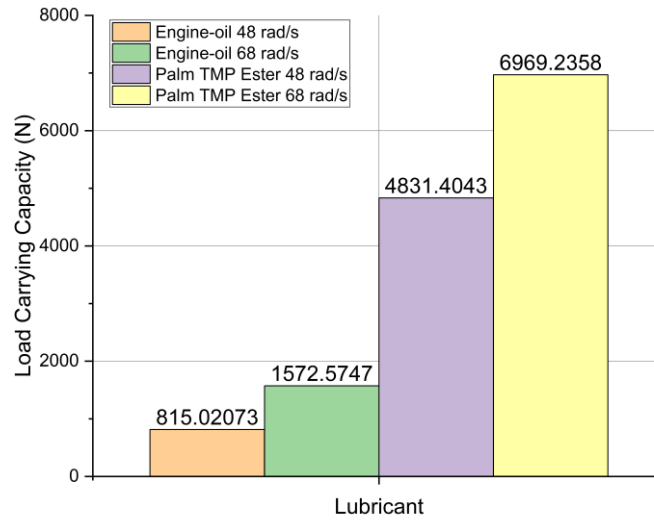
The calculation results from the case studies will be explained in the following discussion. Each case is solved using CFD software to address thermo-hydrodynamic lubrication problems on plain journal bearings. The improvements discussed are pressure, load carrying capacity and friction force.

Figure 6 shows the static pressure distribution along the circumferential direction for different lubricants and shaft speeds. The pressure profiles of biolubricant-lubricated journal bearings are comparable to those of conventional oil-lubricated plain journal bearings. The pressure profiles of the biolubricant-lubricated journal bearing show similar distribution patterns to those lubricated with conventional oil, while providing higher pressure generation capability.



**Figure 5.** Pressure distribution in palm trimethylolpropane ester and engine-oil lubricated journal bearings at shaft speed of 48 rad/s and 68 rad/s.

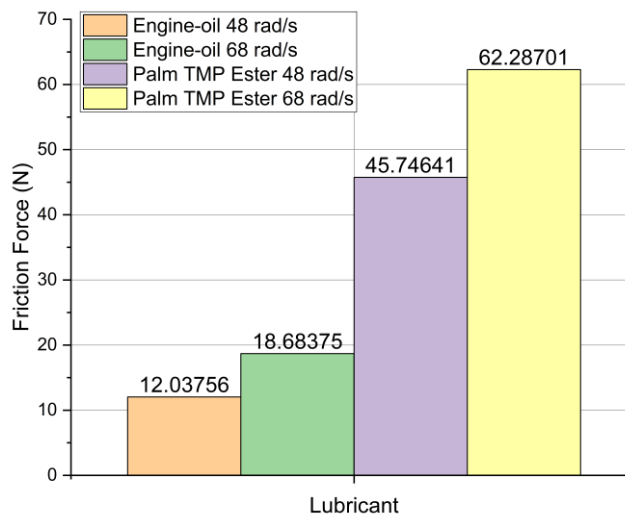
This behavior indicates that the higher viscosity characteristics of palm TMP ester enhance the hydrodynamic pressure generation within the lubricant film, thereby improving the load-carrying capacity of the journal bearing. The superior pressure profile of Palm TMP Ester can be scientifically attributed to its high viscosity index and molecular polarity. Unlike mineral-based engine oils, the ester molecules form a more resilient boundary layer that resists thermal degradation under high shear conditions. From a tribological perspective, this heightened pressure distribution implies a significantly lower eccentricity ratio for a given load, which enhances the stability of the journal bearing. This finding confirms that the biolubricant not only serves as an eco-friendly substitute but also provides a functional advantage in maintaining hydrodynamic lift under demanding thermohydrodynamic regimes. Figure 7 shows load carrying capacity between biolubricant and engine-oil lubricated journal bearings.



**Figure 6.** Load carrying capacity in palm trimethylolpropane ester and engine-oil lubricated journal bearings at shaft speed of 48 rad/s and 68 rad/s.

The higher load carrying capacity generated by palm TMP ester is mainly attributed to its higher viscosity, which enhances hydrodynamic pressure formation within the lubricant film. At a shaft speed of 48 rad/s, the load carrying capacity using engine oil is 815.02 N, while palm TMP ester reaches 4831.40 N. When the shaft speed increases to 68 rad/s, the load carrying capacity increases to 1572.57 N for engine oil and 6969.24 N for palm TMP ester. This indicates that both lubricant type and rotational speed have a significant influence on the load carrying capacity of the journal bearing. Based on hydrodynamic lubrication theory, pressure generation increases with both viscosity and surface velocity, resulting in a stronger pressure wedge effect for higher-viscosity lubricants.

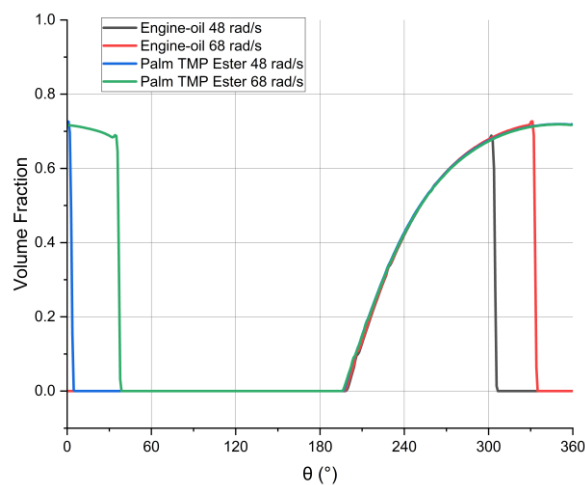
When the shaft speed increases to 68 rad/s, the load carrying capacity increases significantly. This trend is consistent with the Reynolds equation, where hydrodynamic pressure increases with sliding velocity. The non-linear increase suggests a coupled effect between viscosity and shear-driven flow, highlighting that viscosity plays a more dominant role than speed in enhancing the load carrying capacity under the studied conditions.



**Figure 7.** Friction force in palm trimethylolpropane ester and engine-oil lubricated journal bearings at shaft speed of 48 rad/s and 68 rad/s.

Figure 8 shows friction force between biolubricant and engine-oil lubricated journal bearings. The results indicate that the friction force increases with increasing rotational speed for both lubricants. At a shaft speed of 48 rad/s, the friction force produced by engine oil is 12.04 N, while palm TMP ester generates a higher value of 45.75 N. When the shaft speed increases to 68 rad/s, the friction force rises to 18.68 N for engine oil and 62.29 N for palm TMP ester. These results indicate that the higher viscosity of palm TMP ester leads to greater shear resistance in the lubricant film, resulting in higher friction force compared to conventional engine oil. The observed increase in friction force for Palm TMP Ester is a direct consequence of its higher dynamic viscosity, which enhances the internal shear resistance within the lubricant film. According to Newton's law of viscosity, the shear stress is proportional to the fluid's viscosity and the velocity gradient; thus, at higher rotational speeds, the viscous dissipation becomes more pronounced.

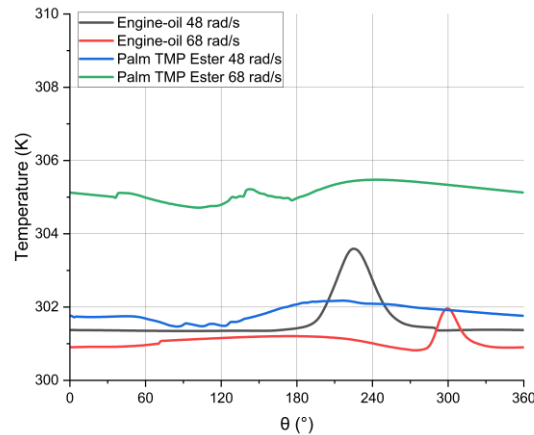
However, this higher friction force represents a critical tribological trade-off. While the viscous drag is increased, it is fundamentally linked to the significantly higher hydrodynamic pressure reported in Figure 6. The robust molecular structure of the palm TMP ester prevents excessive film thinning, ensuring that the bearing operates deep within the hydrodynamic regime even under high loads. Consequently, the higher friction force is an acceptable compromise for the substantial 4.9-fold increase in load-carrying capacity, which effectively minimizes the risk of asperity contact and mechanical wear. The volume fraction of vapor is a thermohydrodynamic lubrication parameter used to identify the presence and intensity of cavitation phenomena in the lubricant film of journal bearings. The comparison of the vapor volume fraction distribution for biolubricant and engine oil lubricated journal bearings. is presented in Figure 9.



**Figure 8.** Vapor volume fraction distribution in palm trimethylolpropane (TMP) ester and engine oil lubricated journal bearings at shaft speeds of 48 rad/s and 68 rad/s.

The results show that the vapor volume fraction ranges from approximately 0.69 to 0.73 under the investigated operating conditions. Palm oil tends to produce slightly higher vapor volume fraction compared to engine oil, indicating a marginally stronger cavitation tendency within the lubricant film. Additionally, the change in shaft speed slightly influences the magnitude of the vapor volume fraction but does not significantly alter the overall cavitation behavior. This is scientifically attributed to the steeper pressure gradient generated by the biolubricant; as the high-pressure film from the convergent zone (see Fig. 6) enters the divergent region, the pressure drops more abruptly below the lubricant's saturation point, triggering vapor formation. Additionally, higher shaft speeds extend the cavitation region due to increased shear rates. Despite this, the overall bearing stability remains superior due to the higher peak pressures that compensate for localized cavitation.

The temperature distribution in the lubricant film is an important parameter in thermohydrodynamic lubrication analysis because it is directly related to heat generation caused by viscous friction and changes in the physical properties of the lubricant during operation. The contour of the temperature distribution is presented in Figure 10.



**Figure 9.** Temperature distribution in palm trimethylolpropane (TMP) ester and engine oil lubricated journal bearings at shaft speeds of 48 rad/s and 68 rad/s.

The results indicate that the temperature slightly increases in the region near the maximum pressure zone and decreases toward the outlet. In addition, palm trimethylolpropane (TMP) ester produces higher temperatures compared to engine oil due to its higher viscosity. The lubricant's higher viscosity increases internal fluid friction (viscous shear), converting mechanical energy into heat, particularly in the high-pressure zone where the oil film is thinnest. This thermal behavior confirms the necessity of the THD model, as the temperature rise directly influences the local viscosity. Despite the higher heat generation, the biolubricant's superior thermal stability prevents excessive thinning, maintaining the structural integrity of the hydrodynamic film under high-speed conditions (68 rad/s).

#### 4. Conclusion

This study investigated the thermohydrodynamic lubrication characteristics of plain journal bearings lubricated with engine oil and palm TMP ester using CFD simulation. Based on the obtained results, the following conclusions can be drawn:

1. The pressure distribution of the biolubricant-lubricated journal bearing shows a similar pattern to that of conventional engine oil, but palm TMP ester generates higher hydrodynamic pressure within the lubricant film.
2. Palm TMP ester significantly improves the load carrying capacity of the journal bearing. Palm TMP ester significantly improves the load carrying capacity, with increases of approximately 493% at 48 rad/s and 343% at 68 rad/s compared to engine oil.
3. The friction force increases with increasing shaft speed for both lubricants. The load carrying capacity increases by approximately 493% at 48 rad/s and 343% at 68 rad/s when using palm TMP ester compared to engine oil. However, the friction force also increases by about 280% at 48 rad/s and 234% at 68 rad/s due to the higher viscosity of the biolubricant.
4. The vapor volume fraction ranges from approximately 0.69 to 0.73 under the investigated conditions, indicating the occurrence of cavitation in the lubricant film. Palm TMP ester shows a slightly higher cavitation tendency compared to engine oil.

Overall, palm TMP ester demonstrates strong potential as an environmentally friendly alternative lubricant for journal bearing applications due to its ability to enhance hydrodynamic pressure and load carrying capacity.

### **Declaration of AI and AI assisted technologies in the writing process**

During the preparation of this work, the authors used ChatGPT to support language refinement, including grammar correction, paraphrasing, and improving the clarity of the manuscript. After using this tool, the authors carefully reviewed and edited the content as needed and takes full responsibility for the final content of the publication.

### **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.

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