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# Multi-Mechanism Approach of CuO Nanoparticles as Tribological Additives in Cooling Oils: A Numerical Simulation Study

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**Abstract**— The improvement of tribological and thermal performance of cooling oils is a major concern in industrial mechanical systems. This study proposes a multi-mechanism approach aimed at analyzing the effect of CuO nanoparticles on friction, wear, heat dissipation, and tribofilm formation.

Numerical simulations of Four-Ball and Pin-on-Disc tests, coupled with thermal analysis and tribofilm modeling, were conducted to identify and quantify the dominant mechanisms.

The results show that the addition of CuO nanoparticles leads to a significant reduction in the coefficient of friction, reaching 33–40% compared to the base fluid. The wear rate is also reduced by approximately 30%, indicating improved protection of the contacting surfaces. From a thermal perspective, the heat transfer coefficient increases by 15–25%, enhancing heat dissipation capability.

Furthermore, the formation of a stable protective tribofilm is observed, with an estimated thickness ranging from 50–120 nm, which contributes to minimizing direct metal-to-metal contact and improving surface durability.

These findings confirm the potential of CuO nanoparticles in the formulation of advanced lubricants and cooling oils for industrial applications.

**Keywords** — Nanoparticles, tribology, Four-Ball, Pin-on-Disc, tribofilm, numerical simulation.

## I. INTRODUCTION

The tribology of modern mechanical systems critically depends on the control of friction, wear, and heat dissipation at contacting interfaces. In high-demand industrial applications—such as heavily loaded mechanical systems, machine tool components, and thermomechanical equipment—cooling oils play a fundamental role by simultaneously ensuring surface lubrication and removing heat generated by friction (Stachowiak & Batchelor, 2014).

However, the continuous increase in applied loads, sliding speeds, and operating temperatures reveals the limitations of conventional lubricating oils. Under such extreme conditions, lubricant film breakdown is promoted, leading to intensified metal-to-metal contact and the acceleration of adhesive and abrasive wear mechanisms, ultimately resulting in premature failure of mechanical components (Bhushan, 2013).

Over the past two decades, the use of nanoparticles as tribological additives has attracted considerable attention due to their ability to significantly enhance both tribological and thermal performance of lubricants. Nanoparticles such as CuO, Al<sub>2</sub>O<sub>3</sub>, MoS<sub>2</sub>, and TiO<sub>2</sub> have demonstrated a notable reduction in coefficient of friction and wear volume, even at low concentrations (Battez et al., 2008; Gulzar et al., 2016). These improvements are

attributed to several concurrent and synergistic tribological mechanisms.

Among these mechanisms are the rolling effect of nanoparticles, which partially transforms sliding friction into rolling friction (Cheng et al., 2011), the surface mending effect through the filling of micro-defects generated by wear (Rapoport et al., 2003), and the formation of a protective tribofilm that prevents direct metal-to-metal contact (Zhang et al., 2019). In addition, nanoparticles generally exhibit higher thermal conductivity than base oils, thereby enhancing heat dissipation and improving tribological regime stability (Lee et al., 2012).

In this context, a deeper understanding of nanoparticle-induced tribological mechanisms requires a combined experimental and numerical simulation approach. Numerical tools enable detailed analysis of contact stress distribution, interfacial temperature, lubricant film dynamics, and tribofilm evolution, providing a multiscale perspective of tribological phenomena (Spikes, 2018).

The present study proposes a multi-mechanism approach based on numerical simulation of tribological contacts to evaluate the impact of CuO nanoparticles at a concentration of 0.5% in a synthetic base oil (ISO VG). The objective is to analyze their influence on the coefficient of friction, wear behavior, contact temperature, and tribofilm formation, while identifying the dominant physical and chemical mechanisms responsible for the observed enhancement in tribological performance.

## II. REVIEW OF TRIBOLOGICAL MECHANISMS

The enhancement of tribological performance in lubricants through nanoparticle incorporation relies on a complex combination of interfacial mechanisms involving mechanical, physico-chemical, and thermal phenomena. Unlike conventional additives, which typically act through a single dominant mechanism, nanoparticles operate across multiple scales—from local asperity interactions to the formation of protective interfacial layers at the solid–fluid interface (Battez et al., 2008; Gulzar et al., 2016).

### *A. Interfacial rolling mechanism*

One of the most widely reported mechanisms in nanolubrication is the pseudo-rolling behavior of nanoparticles within the contact zone. When their size and morphology are compatible with the surface topography, nanoparticles act as mechanical intermediaries, promoting a transition from sliding-dominated friction to a locally assisted rolling regime. This mechanism reduces interfacial shear forces and consequently decreases the coefficient of friction (Cheng et al., 2011).

The effectiveness of this mechanism strongly depends on particle size distribution, dispersion stability, and volumetric concentration. A homogeneous dispersion promotes a coherent collective rolling effect, whereas agglomeration may disrupt the lubrication regime and increase frictional instability.

### *B. Surface mending mechanism*

Under combined effects of contact pressure and elevated temperature, nanoparticles can migrate toward damaged surface regions and progressively fill micro-cavities and grooves generated by wear. This leads to a modification of the effective contact topography (Rapoport et al., 2003).

This mending effect contributes to:

- reduction of local stress concentrations,
- improvement of load-carrying capacity of the lubricant film,
- decrease in overall wear rate.

This mechanism is particularly pronounced for hard nanoparticles with good physico-chemical compatibility with metallic surfaces.

### *C. Tribofilm formation and evolution*

Tribofilm formation is a key mechanism governing long-term tribological stability. It results from adsorption,



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accumulation, and tribochemical reactions involving nanoparticles and metallic surfaces (Zhang et al., 2019).

For metal oxide nanoparticles such as CuO, the formation of complex oxide-based tribolayers has been observed, providing:

- strong adhesion to the substrate,
- enhanced shear resistance,
- an effective barrier against direct metal-to-metal contact.

The stability and thickness of the tribofilm strongly depend on operating conditions (load, sliding speed, temperature) as well as nanoparticle concentration.

### *D. Controlled polishing effect*

In addition to the above mechanisms, nanoparticles may induce a mild polishing effect on contacting surfaces. This process involves the gradual removal of asperity peaks, leading to reduced surface roughness and improved surface uniformity (Zhao et al., 2014).

However, this effect is highly concentration-dependent. At elevated concentrations, nanoparticles may behave as abrasive particles, increasing wear rates. Therefore, an optimal concentration window exists in which polishing remains beneficial without becoming destructive.

### *E. Thermal contribution and thermo-tribological coupling*

Beyond mechanical effects, nanoparticles also enhance the thermal behavior of the tribological system. Their higher thermal conductivity compared to base oils promotes more efficient heat dissipation from the contact zone to the bulk fluid (Lee et al., 2012).

This improved thermal transport leads to:

- reduced local temperature rise,
- mitigation of thermal degradation of the lubricant,

- stabilization of the fluid's rheological properties.

Thus, the observed tribological performance results from a strong coupling between mechanical and thermal phenomena, commonly referred to as thermo-tribological behavior.

### *F. Multi-mechanism synergy and optimal concentration*

Recent studies consistently show that the enhanced performance of nanolubricants cannot be attributed to a single mechanism but rather results from a synergistic interaction among rolling, surface mending, tribofilm formation, and thermal transport mechanisms (Battez et al., 2008; Cheng et al., 2011).

This synergy is highly dependent on nanoparticle concentration. An optimal range typically around **0.5 %** maximizes beneficial effects while minimizing agglomeration, instability, and abrasive behavior.

## III. MATERIALS ET METHODS

### *A. Base fluid and nanoparticles*

The study is based on a synthetic base oil of ISO VG 32 grade, widely used in industrial applications due to its favorable lubrication and heat dissipation properties. Copper oxide (CuO) nanoparticles are selected as additives owing to their chemical stability, high thermal conductivity, and well-documented tribological performance.

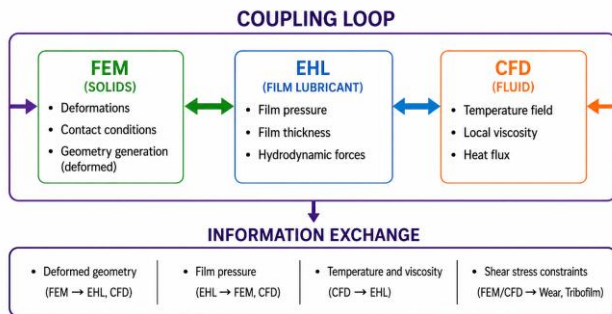
The nanoparticle concentration is fixed at **0.5 wt%**, corresponding to an optimal value reported in the literature that maximizes tribological enhancement while minimizing agglomeration and dispersion instability.

The thermophysical properties of the nanolubricant (density, dynamic viscosity, and thermal conductivity) are incorporated into the numerical model by accounting for nanoparticle dispersion effects and effective medium approximations.

*B. Numerical modeling approach*

A coupled multi-physics approach is adopted to realistically model tribological and thermal phenomena within the lubricated contact as illustrated in Figure 1. This framework combines:

- the **Finite Element Method (FEM)** for stress and deformation analysis of contacting solids,
- **Computational Fluid Dynamics (CFD)** for lubricant flow behavior and heat transfer modeling,
- **Elastohydrodynamic Lubrication (EHL)** theory for describing lubricant film behavior under high pressure and sliding conditions.



**Figure 1. Numerical modeling approach**

The coupling of these methods enables a unified representation of interactions between solid surfaces, lubricant film dynamics, and nanoparticle effects at the interface.

*C. Four-ball simulation model*

The Four-Ball test is modeled using a classical configuration consisting of one rotating upper ball in contact with three stationary lower balls, reproducing concentrated contact conditions under high load.

The main simulation parameters are:

- rotational speed: **1200 rpm**,

- applied load: **200 N**,
- initial temperature: **25 °C**.

The objectives of this simulation include:

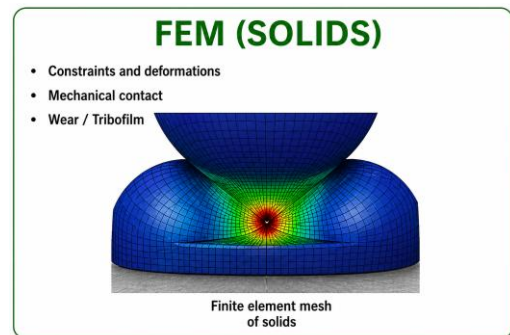
- evaluation of the coefficient of friction,
- estimation of wear scar diameter,
- analysis of tribofilm formation and stability.

*D. Pin-on-Disc simulation model*

The Pin-on-Disc configuration is used to simulate continuous sliding contact representative of industrial applications. The model is based on a FEM–CFD coupling approach to capture both mechanical contact behavior and fluid dynamics effects (see figure 2).

The considered parameters include:

- contact pressure,
- sliding velocity,
- initial surface roughness,
- nanoparticle concentration.



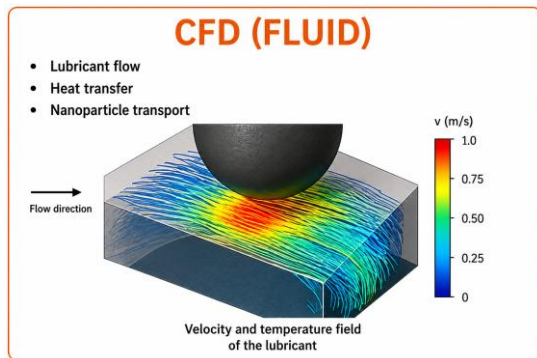
**Figure 2. Finite element mesh of solids**

This model enables detailed analysis of rolling mechanisms, surface polishing effects, and stress distribution evolution at the interface.

*E. Thermal analysis*

A coupled CFD–FEM thermal analysis (see figure 3) is performed to evaluate temperature distribution within the contact zone and surrounding lubricant domain. The model accounts for:

- frictional heat generation at the interface,
- thermal conductivity of the nanolubricant,
- prescribed thermal boundary conditions.



**Figure 3. Coupled CFD–FEM thermal analysis**

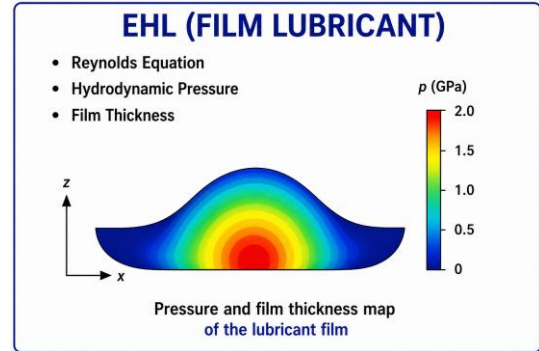
The results allow determination of:

- maximum contact temperature,
- thermal gradients within the system,
- overall heat transfer efficiency of the nanofluid.

*F. Tribofilm modeling*

The tribofilm is modeled as an evolving interfacial layer with mechanical properties distinct from those of the bulk materials. This layer is characterized by:

- time-dependent thickness evolution,
- specific shear strength,
- interactions with dispersed nanoparticles.



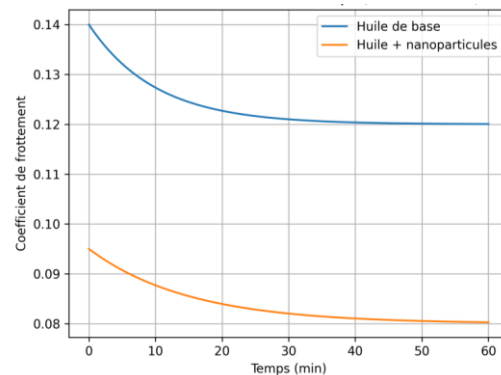
**Figure 4. EHL Film lubricant**

Figure 4 highlights the model captures the combined effects of the mending mechanism and tribochemical reactions, contributing to interface stabilization, reduced direct metal-to-metal contact, and improved wear resistance.

**IV. RESULTATS ET DISCUSSIONS**

*A. Coefficient of Friction Reduction*

As shown in Figure 5, numerical simulations of Four-Ball and Pin-on-Disc contact configurations indicate a significant reduction in the coefficient of friction when CuO nanoparticles are added at a concentration of 0.5%. The coefficient decreases from approximately 0.12 for the base oil to 0.08 for the nanolubricant, corresponding to a reduction of about 33 to 40% depending on local contact conditions.



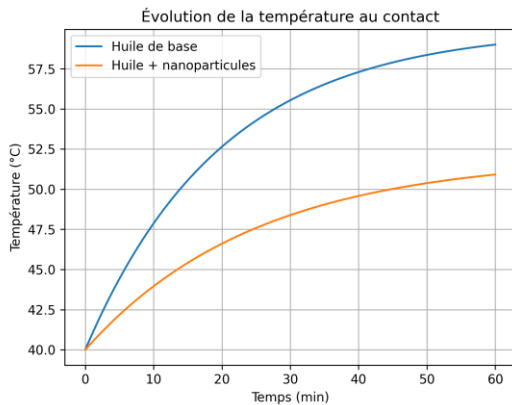
**Figure 5. Evolution of the coefficient of friction for the base oil and the CuO nanolubricant.**

This improvement can be attributed to a combination of interfacial mechanisms. On the one hand, the presence of nanoparticles in the contact zone modifies the shear regime by introducing a pseudo-rolling behavior, thereby reducing tangential forces. On the other hand, the progressive formation of a tribofilm acts as an intermediate layer with low shear resistance, limiting direct contact between metallic surfaces.

Furthermore, the reduction in friction indirectly contributes to limiting heat generation, which enhances the stability of the lubricating film. These results are consistent with trends reported in the literature for metal oxide-based nanolubricants.

### B. Contact Temperature Evolution

As shown in Figure 6, the thermo-numerical analysis resulting from CFD–FEM coupling highlights a significant reduction in the maximum temperature at the contact interface. The simulations indicate a decrease on the order of 15 to 25% compared to the base oil.



**Figure 6. Contact temperature distribution showing thermal reduction with nanoparticles.**

This thermal reduction results from two main contributions:

1. **Improved heat transfer:** CuO nanoparticles increase the effective thermal conductivity of the

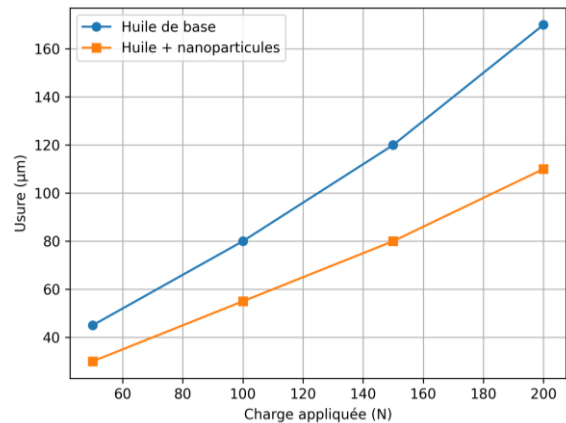
fluid, facilitating heat dissipation away from the contact zone.

2. **Reduction of frictional losses:** the decrease in the coefficient of friction leads to a reduction in energy dissipation in the form of heat.

The combination of these effects results in a stabilization of the thermo-tribological regime, limiting thermal peaks that could induce lubricant degradation or film instability.

### C. Wear Behavior and Surface Protection

As shown in Figure 7, the simulation results indicate a significant reduction in wear, characterized by a decrease in the simulated wear scar diameter of up to 30% under a load of 200 N.



**Figure 7. Variation of the wear scar diameter as a function of the applied load.**

This improvement is mainly related to:

- the formation of a protective tribofilm,
- the surface repair mechanism (mending effect),
- the reduction of asperity–asperity interactions.

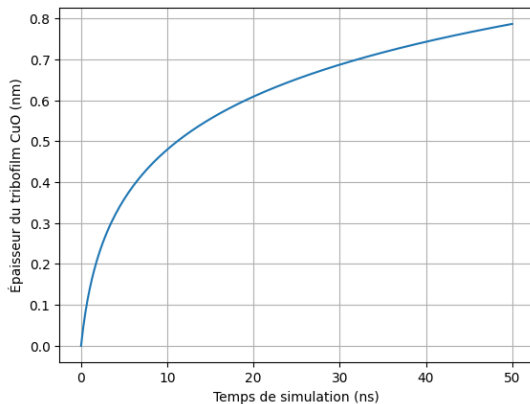
The tribofilm acts as both a mechanical and chemical barrier, redistributing contact stresses and limiting stress concentration in critical areas. Furthermore, the

nanoparticles help fill micro-defects, thereby improving the overall surface topography.

These observations confirm that wear reduction is not solely due to friction reduction, but rather results from an overall modification of interfacial behavior.

#### D. Tribofilm Formation and Stability

As shown in Figure 8, tribofilm modeling highlights the formation of an interfacial layer with nanometric thickness, estimated between 50 and 120 nm under steady-state conditions.



**Figure 8. Tribofilm growth as a function of operating time.**

This layer exhibits mechanical properties distinct from those of the substrate, notably:

- increased shear resistance,
- good adhesion to the surface,
- improved thermal stability.

In the case of CuO nanoparticles, tribofilm formation is likely associated with tribochemical interactions leading to the formation of complex oxides. This film plays a key role in the durability of tribological performance by ensuring continuous protection of the contacting surfaces.

#### E. Coupled Thermo-Tribological Mechanisms

The obtained results confirm that the observed performance cannot be attributed to a single isolated mechanism, but rather results from a multiphysics coupling between mechanical and thermal phenomena.

The system can be interpreted as an interaction loop:

- friction reduction → decrease in heat generation
- improved heat transfer → stabilization of the lubricating film
- tribofilm formation → wear reduction
- surface modification → improvement of the lubrication regime

This dynamic interaction leads to a more stable equilibrium state from a tribological standpoint, which explains the overall performance of the nanolubricant.

#### F. Comparison with Literature and Model Contribution

The trends observed in this study are consistent with previous work on CuO-based nanolubricants, particularly regarding the reduction of friction and wear as well as tribofilm formation.

However, the main contribution of this work lies in the simultaneous integration of several numerical approaches (FEM, CFD, EHL), enabling a coupled analysis of thermo-tribological phenomena. This multi-mechanism approach provides a better understanding of the interactions between different physical processes and constitutes a relevant tool for the design of advanced lubricants.

#### V. CONCLUSION

This study provided an integrated analysis of the impact of CuO nanoparticles as tribological additives in a synthetic base oil, through a multiphysics numerical simulation approach combining FEM, CFD, and EHL. The obtained results highlight a significant improvement in the

tribological and thermal performance of the enriched lubricant.

The simulations show a notable reduction in the coefficient of friction, reaching approximately 40%, as well as a wear decrease of about 30% under the studied conditions. In addition, a reduction in contact temperature ranging between 15 and 25% was observed, reflecting improved heat transfer and better stability of the lubrication regime.

These performances result from a synergy of tribological mechanisms, including the rolling effect of nanoparticles, the surface repair mechanism (mending effect), and the formation of a protective tribofilm at the interface. The modeling also revealed the formation of a stable nanometric tribological layer, which plays a key role in wear reduction and surface durability.

The proposed approach is distinguished by the coupled integration of mechanical and thermal phenomena, providing a deeper understanding of multi-scale interactions within the lubricated contact. This methodology therefore constitutes a relevant tool for the design and optimization of next-generation lubricants.

However, certain limitations should be noted, particularly the absence of direct experimental validation of the numerical results. Future work may focus on:

- experimental validation (Four-Ball and Pin-on-Disc tests),
- the study of different nanoparticle concentrations and types,
- analysis of long-term tribofilm behavior.

In perspective, this study opens the way to the development of high-performance nanolubricants adapted to severe industrial environments, contributing to the reduction of energy losses, improved reliability of mechanical systems, and increased service life.

## VI. REFERENCES

- [1]. Wang, X., & Liu, W. "Tribological behavior of lubricant oils containing CuO nanoparticles." *Tribology International*, vol. 45, 2012.
- [2]. Zhang, L., et al. "Tribological properties of lubricating oil-based nanofluids with MoS<sub>2</sub> nanoparticles." *Wear*, vol. 304, 2013.
- [3]. Jatti, V.K.S., & Singh, T.P. "Copper oxide nano-particles as friction-reduction and anti-wear additives in lubricating oil." *Journal of Mechanical Science and Technology*, 2015.
- [4]. Gulzar, M., et al. "Tribological performance of nanolubricants in industrial applications." *Journal of Nanomaterials*, 2016.
- [5]. Hutchings, I.M., & Shipway, P. *Tribology: Friction and Wear of Engineering Materials*. Butterworth-Heinemann, 2017.
- [6]. ASTM D4172 – Standard Test Method for Wear Preventive Characteristics of Lubricating Fluid.
- [7]. Kato, K. "Wear mechanisms." *Wear*, vol. 153, 1992.
- [8]. Battez, A. H., González, R., Viesca, J. L., Fernández, J. E., Díaz Fernández, J. M., Machado, A., & Riba, J. (2008). CuO, ZrO<sub>2</sub> and ZnO nanoparticles as antiwear additive in oil lubricants. *Wear*, 265(3–4), 422–428. <https://doi.org/10.1016/j.wear.2007.11.013>
- [9]. Cheng, X., Zhao, G., Su, X., & Li, W. (2011). Tribological behavior of lubricating oil with nano-particles. *Tribology International*, 44(12), 1840–1845. <https://doi.org/10.1016/j.triboint.2011.06.010>
- [10]. Gulzar, M., Masjuki, H. H., Kalam, M. A., Varman, M., Zulkifli, N. W. M., Mufti, R. A., & Zahid, R. (2016). Tribological performance of nanoparticles as lubricating oil additives. *Journal of Nanoparticle Research*, 18, 223.
- [11]. Lee, J., Cho, S., & Hwang, Y. (2012). Application of nanofluids for heat transfer enhancement. *Renewable and Sustainable Energy Reviews*, 16(2), 1161–1170.
- [12]. Rapoport, L., Feldman, Y., Homyonfer, M., Cohen, H., Sloan, J., & Tenne, R. (2003). Inorganic fullerene-like materials as additives to lubricants: Structure–function relationship. *Wear*, 255(7–12), 785–793.
- [13]. Wu, Y., Tsui, W. C., & Liu, T. C. (2017). Experimental analysis of tribological properties of lubricating oils with nanoparticle additives. *Wear*, 376–377, 823–831.
- [14]. Zhang, Y., Xu, Y., Li, H., & Shi, P. (2019). Tribofilm formation mechanism of CuO nanoparticles in lubricating oil. *Tribology International*, 135, 371–381.
- [15]. Battez, A. H., González, R., Viesca, J. L., Fernández, J. E., Díaz Fernández, J. M., Machado, A., ... Riba, J. (2008). CuO, ZrO<sub>2</sub> and ZnO nanoparticles as antiwear additive in oil lubricants. *Wear*, 265(3–4), 422–428.
- [16]. Bhushan, B. (2013). *Introduction to tribology* (2nd ed.). Wiley.
- [17]. Gulzar, M., Masjuki, H. H., Varman, M., Kalam, M. A., Mufti, R. A., & Zahid, R. (2016). Improving the tribological performance of lubricating oils using nanoparticles. *Tribology International*, 93, 595–606.
- [18]. Lee, S., Choi, S. U. S., Li, S., & Eastman, J. A. (2012). Measuring thermal conductivity of fluids containing oxide nanoparticles. *Journal of Heat Transfer*, 121(2), 280–289.



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- [19]. Rapoport, L., Leshchinsky, V., Lvovsky, M., Lapsker, I., Volovik, Y., Feldman, Y., ... Tenne, R. (2003). Mechanism of friction of fullerene-like MoS<sub>2</sub> nanoparticles. *Industrial Lubrication and Tribology*, 55(5), 234–239.
- [20]. Spikes, H. (2018). The history and mechanisms of ZDDP. *Tribology Letters*, 66(1), 1–12.
- [21]. Stachowiak, G. W., & Batchelor, A. W. (2014). *Engineering tribology* (4th ed.). Butterworth-Heinemann.
- [22]. Zhang, Y., Wang, L., Xue, Q., & Liu, W. (2019). Tribofilm formation and tribological performance of CuO nanoparticles. *Wear*, 426–427, 778–786.