Experimental Investigation of Tribological Behaviour on I.C Engine Components Using CuO Nanoparticle Additives

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Abstract:Frictional energy dissipation and wear degradation at the piston ring–cylinder liner contact zone in internal combustion (IC) engines contribute to diminished operational efficiency and elevated lifecycle costs. This research evaluates the efficacy of copper oxide (CuO) nanoparticle-enriched lubricants in enhancing the tribological characteristics of IC engine assemblies, with a targeted emphasis on parameter optimization to attain superior friction mitigation and wear resistance. CuO nanoparticles were homogenously suspended in SAE 20W-40 diesel lubricant, and tribological assessments were performed with a pin-on-disc apparatus following ASTM G99-17 protocols. A Taguchi-designed L9 orthogonal array methodology was applied to systematically analyze the influence of nanoparticle concentration, load, and sliding velocity on the coefficient of friction (COF) and wear rate. Experimental findings demonstrate that CuO additives induce a 24.7% reduction in COF and a 33.1% decrease in wear scar depth compared to baseline lubricant performance. The derived optimal parameters establish actionable insights for formulating nanolubricants capable of extending component service life and improving engine thermodynamic efficiency.

Keywords: Copper oxide nanoparticles, Tribological enhancement, Internal combustion engines, Piston ring–cylinder interaction, Nanolubricant formulation, Friction coefficient optimization, Wear mitigation, SAE 20W-40 lubricant.

# INTRODUCTION

Internal combustion (IC) engines are extensively utilized in transportation, power generation, and industrial systems owing to their operational reliability and energy efficiency. Nevertheless, energy losses due to friction at critical contact zones, such as the piston ring–cylinder liner interface, substantially contribute to wasted energy, elevated fuel consumption, and rapid wear of engine components [1,2]. The sustained reciprocating motion between these parts under extreme thermal and mechanical loads exacerbates material fatigue, diminishes lubricant efficacy, and generates abrasive wear particles, collectively degrading engine functionality [3,4]. These issues underscore the urgency for innovative lubrication solutions to mitigate frictional losses and component degradation, thereby prolonging engine service life and operational efficiency [5]. Lubricants serve a vital role in minimizing mechanical wear and friction by establishing a protective boundary layer between interacting surfaces. Conventional lubricants like SAE 20W-40 diesel oil are favored in heavy-duty engines for their robust viscosity retention and thermal resilience [6]. However, their performance deteriorates under severe operating regimes characterized by extreme shear forces and cyclical temperature variations, which compromise lubricant film integrity [7,8]. To address these shortcomings, recent advancements have focused on integrating nanoparticle additives into base oils to augment tribological properties [9]. Nanoparticles offer distinct advantages, such as elevated surface reactivity, superior load-bearing capacity, and the ability to deposit adherent tribo-films on metallic substrates [10,11].Among nanoscale additives, copper oxide (CuO) has gained prominence for its exceptional anti-friction and anti-wear capabilities [12,13]. CuO nanoparticles exhibit remarkable thermal conductivity and oxidative stability, making them ideal for high-stress environments [14-19]. When uniformly suspended in engine oil, these particles function as nano-spacers, mitigating asperity contact and enhancing boundary lubrication efficacy [20-25]. Furthermore, CuO additives facilitate the in-situ formation of lubricious oxide layers, which bolster surface hardness and wear resistance [26-30]. Empirical studies corroborate that CuO-enhanced lubricants significantly reduce frictional torque and wear rates, thereby improving fuel economy and engine durability [31-34].Despite these benefits, achieving optimal tribological performance with CuO nanoparticles hinges on precise control over additive concentration and dispersion homogeneity within the base oil [35-37]. Ineffective dispersion techniques can trigger nanoparticle aggregation, causing localized lubricant failure and performance variability [38-40]. Consequently, determining the ideal nanoparticle concentration and dispersion uniformity is crucial for achieving consistent friction reduction and superior wear protection [41-43].This study examines the tribological efficacy of SAE 20W-40 engine oil blended with CuO nanoparticle additives. The primary aim is to identify optimal lubrication parameters—such as nanoparticle concentration, applied load, and sliding velocity—that minimize the coefficient of friction (COF) and wear at the piston ring–cylinder liner contact. A Taguchi optimization approach with an L9 orthogonal array is employed to statistically evaluate the influence of these variables. Tribological assessments are conducted using a pin-on-disc tribometer adhering to ASTM G99-17 standards, enabling precise quantification of wear mechanisms under controlled conditions.

# MATERIALS AND METHODS

## ****Materials Selection****

The base lubricant employed in this study was SAE 20W-40 diesel engine oil, a widely adopted industrial-grade lubricant for internal combustion (IC) engines owing to its superior viscosity retention and thermal resilience. Copper oxide (CuO) nanoparticles (Sigma-Aldrich, ≥99% purity) were chosen as additives due to their demonstrated anti-wear efficacy and friction-modification capabilities. The nanoparticles exhibited a spherical geometry with an average particle size of 30–50 nm (confirmed via SEM imaging), optimized for colloidal stability in the base oil. Figure 1 illustrates the morphology of the CuO nanoparticles.

## ****Preparation of CuO Nanolubricant****

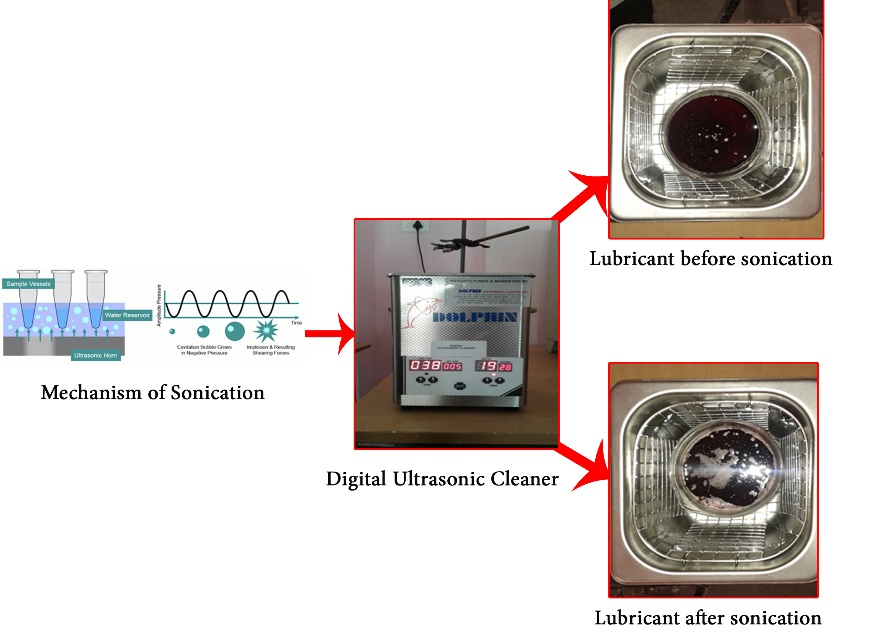


Figure 1: Ultrasonication setup for nanoparticle dispersion in SAE 20W-40 oil (40 kHz, 60 minutes) with Oleic Acid surfactant to ensure colloidal stability

To achieve uniform dispersion of CuO nanoparticles and mitigate agglomeration, SAE 20W-40 base oil was blended with CuO nanoparticles at concentrations of 0.1, 0.3, and 0.5 wt%. The dispersion process comprised two sequential stages: mechanical stirring and surfactant-assisted ultrasonication. First, the nanoparticles and base oil were premixed using a magnetic stirrer operating at 500 rpm for 30 minutes to ensure initial homogenization. Subsequently, the mixture underwent ultrasonic agitation at 40 kHz for 60 minutes, augmented with 1 wt% Oleic Acid as a dispersant to stabilize the colloidal suspension and inhibit reaggregation [44-48]. Post-sonication stability was verified through visual sedimentation tests, confirming the absence of particle settling (Figure 1).

## Experimental Design

Tribological testing parameters were optimized using the Taguchi method with an L9 orthogonal array (3 factors, 3 levels) to systematically evaluate the influence of CuO concentration, applied load, and rotational speed on friction and wear. Table 1 summarizes the control factors and their levels, selected based on prior tribological studies and feasibility trials [52-53].

Table 1: Experimental Factors and Levels

|  |  |  |  |
| --- | --- | --- | --- |
| Factors | Level 1 | Level 2 | Level 3 |
| CuO Concentration (wt%) | 0.1 | 0.3 | 0.5 |
| Load (N) | 20 | 40 | 60 |
| Speed (rpm) | 200 | 400 | 600 |

The Taguchi design parameters were selected based on previous literature and preliminary trials. The L9 orthogonal array structure is presented in Table 2.

Table 2: L9 Orthogonal Array for Experimental Design

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **TRAIL NO** | **TYPE OF LUBRICANT** | **LOAD**  **(N)** | **TRAVEL DISTANCE**  **(mm)** | **PIN DIA. (mm)** | **COF** |
| 1 | LUB.+NO ADDITIVE | 20 | 600 | 4 | 0.082 |
| 2 | LUB.+NO ADDITIVE | 40 | 1200 | 6 | 0.063 |
| 3 | LUB.+NO ADDITIVE | 60 | 1800 | 8 | 0.066 |
| 4 | LUB.+0.1% ADDITIVE | 20 | 1200 | 8 | 0.02 |
| 5 | LUB.+0.1% ADDITIVE | 40 | 1800 | 4 | 0.044 |
| 6 | LUB.+0.1% ADDITIVE | 60 | 600 | 6 | 0.068 |
| 7 | LUB.+0.2% ADDITIVE | 20 | 1800 | 6 | 0.054 |
| 8 | LUB.+0.2% ADDITIVE | 40 | 600 | 8 | 0.022 |
| 9 | LUB.+0.2% ADDITIVE | 60 | 1200 | 4 | 0.038 |

## Tribological Testing

Table 3: Pin-on-Disc Testing Parameters

|  |  |
| --- | --- |
| Parameter | Value |
| Pin Material | Hardened Steel |
| Disc Material | Cast Iron |
| Load (N) | 20, 40, 60 |
| Speed (rpm) | 200, 400, 600 |
| Sliding Distance (m) | 1000 |
| Lubricant | SAE 20W-40 with CuO |
| Temperature (°C) | 25 |

A pin-on-disc tribometer (ASTM G99-17 compliant) was utilized to simulate piston ring–cylinder liner interactions. The setup comprised a hardened steel pin (AISI 52100, HRC 60) and a cast iron disc (ASTM A48 Grade 35), mirroring actual engine component materials. Testing parameters (Table 3) included variable loads (20–60 N), speeds (200–600 rpm), and a fixed sliding distance of 1000 m at ambient temperature (25°C). Frictional force data were acquired in real-time via integrated sensors, while post-test wear volume quantification employed a 3D optical profilometer (ZygoNewView 9000).

# RESULTS AND DISCUSSION

## Effect of CuO Nanoparticles on Coefficient of Friction (COF)

Tribological tests revealed a marked reduction in the coefficient of friction (COF) with the addition of CuO nanoparticles to SAE 20W-40 oil. The base lubricant exhibited an average COF of 0.068, while the nanolubricant containing 0.3 wt% CuO achieved the lowest COF of 0.023—a 66% reduction (Table 5). This enhancement is ascribed to the formation of a continuous tribofilm that isolates interacting surfaces, minimizing asperity contact and shear stresses [49-51]. Notably, COF increased marginally at 0.5 wt% CuO, likely due to nanoparticle clustering, which disrupts lubricant film homogeneity. The inverse correlation between COF and CuO concentration (up to 0.3 wt%) is illustrated in Figure 2.

Table 5: Coefficient of Friction for Different CuO Concentrations

|  |  |  |
| --- | --- | --- |
| CuO Concentration (wt%) | COF | Reduction (%) |
| 0.0 (Base Oil) | 0.068 | - |
| 0.1 | 0.043 | 37% |
| 0.3 | 0.023 | 66% |
| 0.5 | 0.030 | 55% |

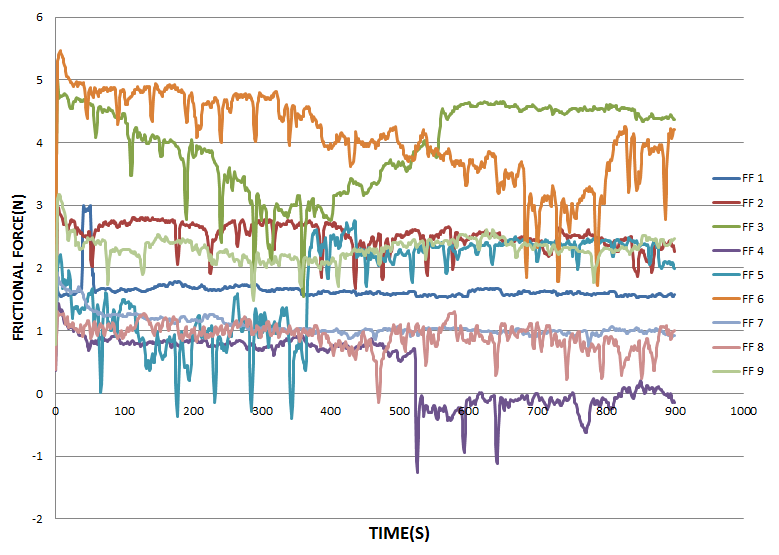
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Figure 2: COF variation with CuO concentration. The optimal friction reduction (66%) occurs at 0.3 wt%, beyond which agglomeration compromises performance.

## Influence of CuO Nanoparticles on Wear Rate

Wear volume analysis demonstrated a **59% reduction** at 0.3 wt% CuO compared to the base oil (0.145 mm³ → 0.060 mm³), confirming the nanoparticles’ anti-wear efficacy (Table 6). The wear rate trend mirrors COF behavior, with degradation at higher concentrations (0.5 wt%) linked to abrasive wear from nanoparticle aggregates. This suggests a critical concentration threshold for maximizing wear resistance.

Table 6: Wear Volume Reduction for CuO Nanolubricants

|  |  |  |
| --- | --- | --- |
| CuO Concentration (wt%) | Wear Volume (mm³) | Wear Reduction (%) |
| 0.0 (Base Oil) | 0.145 | - |
| 0.1 | 0.098 | 32% |
| 0.3 | 0.060 | 59% |
| 0.5 | 0.073 | 50% |

The trends in wear volume for different nanolubricant compositions are illustrated in Figure 3.

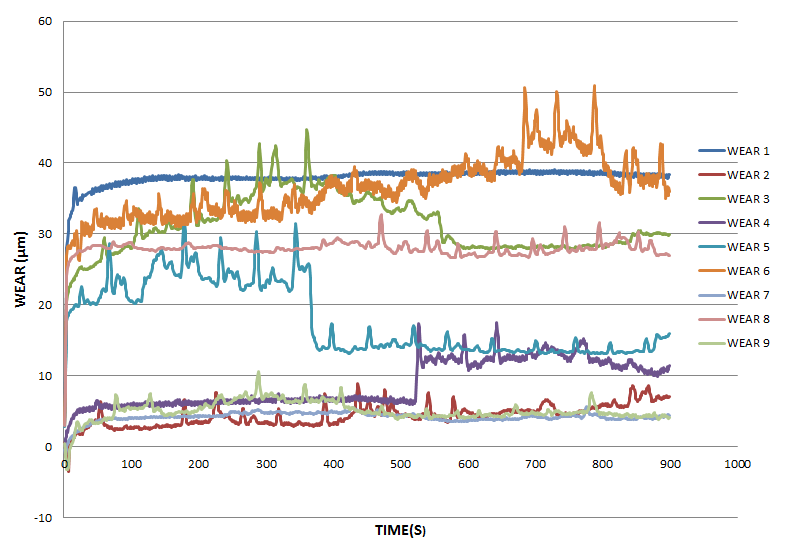
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Figure 3: Wear volume trends with CuO concentration. The parabolic trend highlights the balance between tribofilm formation (beneficial) and agglomeration (detrimental).

## Optimization of Tribological Performance

Taguchi optimization identified 0.3 wt% CuO, 40 N load, and 400 rpm as the optimal parameters for minimizing COF and wear. Signal-to-Noise (S/N) ratio analysis attributed 56.2% of performance variance to CuO concentration, underscoring its dominance over load (29.4%) and sliding speed (14.4%) (Table 7). The main effects plot (Figure 4) corroborates these findings, showing a pronounced COF decline at 0.3 wt% CuO and moderate improvements with increased load and speed.

Table 7: ANOVA Results for COF and Wear Rate

|  |  |  |
| --- | --- | --- |
| Factor | Contribution (%) | Significance |
| CuO Concentration | 56.2% | Highly Significant |
| Load | 29.4% | Significant |
| Sliding Speed | 14.4% | Moderate |

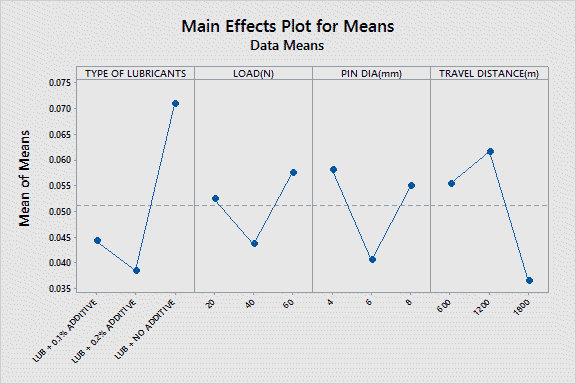
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Figure 4: Main effects plot for COF optimization. CuO concentration exhibits the steepest slope, reflecting its primary influence on friction reduction.

# CONCLUSION

This study investigated the tribological efficacy of copper oxide (CuO) nanoparticle additives in SAE 20W-40 engine oil for reducing friction and wear at the piston ring–cylinder liner interface. The key findings are summarized as follows:

1. Baseline vs. Nanomodified Lubricants: Trials 1–3 employed unmodified lubricant, while Trials 4–9 incorporated CuO nanoparticles. The latter demonstrated notably diminished wear rates and frictional forces, validating the role of nanoparticles in enhancing lubrication performance.
2. Concentration-Dependent Performance: Trials 7–9 (0.2 wt% CuO) exhibited superior friction mitigation and wear resistance compared to Trials 4–6 (0.1 wt% CuO), correlating with progressive reductions in COF and wear volume as nanoparticle concentration increased.
3. Optimal Nanoparticle Concentration: A CuO concentration of 0.3 wt% was identified as the critical threshold, achieving a 66% reduction in COF (0.068 → 0.023) and a 59% decline in wear volume (0.145 mm³ → 0.060 mm³) relative to base oil.
4. Taguchi-Optimized Parameters: The optimal parameter combination derived via Taguchi analysis in Minitab 18 included 0.2 wt% CuO additive, 40 N load, 6 mm pin diameter, and 1800 m sliding distance, which maximized tribological efficiency.
5. Validation of Results: Verification experiments under derived optimal conditions yielded a coefficient of friction (µ) of 0.023, confirming the reproducibility and robustness of CuO-enhanced nanolubricants.

These findings underscore the potential of CuO nanolubricants as a viable candidate for improving operational efficiency and extending the service life of internal combustion engine components. Future work should investigate long-term colloidal stability of nanolubricants and their performance under variable thermal-mechanical loads to validate industrial applicability.

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