Effect of lubricant viscosity on gear wear and power loss

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Abstract—**Lubricant viscosity is an important factor affecting the performance, efficiency, and durability of gear systems. This study investigates the effect of lubricant viscosity on gear wear and power loss under different operating conditions. Low-viscosity lubricants reduce friction and power consumption but may increase gear wear due to insufficient film thickness. High-viscosity lubricants provide better wear protection by forming a thicker lubricating film; however, they can increase power loss because of higher fluid resistance. The research analyzes the relationship between viscosity, friction, wear rate, and transmission efficiency to determine the optimum lubricant selection for gear applications. The study concludes that proper viscosity selection improves gear life, reduces maintenance, and enhances overall mechanical efficiency.**

Index Terms—**Gear Wear, Lubricant Viscosity, Power Loss, Tribology, Gear Lubrication, Friction, Transmission Efficiency, Wear Rate, Mechanical Efficiency**

I. INTRODUCTION

Gear transmission systems serve as essential power transfer mechanisms in automotive, aerospace, industrial, and heavy engineering applications due to their capability to deliver reliable and efficient power under diverse operating conditions. The overall performance, longevity, and dependability of these systems are closely associated with the lubrication quality at the gear tooth contact zones. Among the many factors influencing lubrication effectiveness, lubricant viscosity is particularly significant because it directly affects wear resistance, frictional performance, thermal regulation, and power efficiency. By governing the formation and stability of the lubricating oil film between interacting tooth surfaces, viscosity plays a major role in minimizing friction, preventing surface damage, and maintaining system efficiency.[1] During gear meshing, tooth surfaces are continuously subjected to rolling and sliding interactions under elevated loads, pressures, and temperatures. These severe operating conditions generate heat, friction, and mechanical stresses that may cause abrasive wear, scuffing, pitting, or even premature gear failure when lubrication is insufficient. Effective lubrication is therefore necessary to prevent direct surface contact between mating gears. Properly selected lubricant viscosity ensures adequate film thickness, which separates microscopic surface asperities, minimizes wear mechanisms, and reduces frictional losses. When viscosity is too low, the lubricant film may become inadequate, increasing surface interaction, accelerating wear, and raising operating temperatures. In contrast, excessively viscous lubricants can increase fluid drag, churning losses, and internal resistance, ultimately lowering gearbox efficiency. Consequently, selecting an optimal viscosity is vital for balancing mechanical efficiency with wear protection.[2]

Traditional investigations into gear wear have largely been based on Archard's wear equation, which estimates material loss through parameters such as load, hardness, and sliding distance. Although this model has been useful in understanding basic wear progression, it often overlooks the influence of lubricant film formation and elastohydrodynamic lubrication (EHL) behavior. As a result, its predictive accuracy is limited under real-world operating environments, especially in heavily loaded or high-speed systems where lubrication conditions strongly affect gear interactions. Earlier studies primarily emphasized material properties and contact stress while underestimating the critical contribution of lubricant viscosity and oil film behavior to long-term wear control.[3]

To overcome these limitations, contemporary tribological research increasingly focuses on elastohydrodynamic lubrication principles. EHL theory offers a more advanced representation of gear lubrication by incorporating pressure-dependent viscosity changes, elastic deformation of contacting surfaces, and the generation of high-pressure lubricating films. Modern studies have further examined the effects of thermal conditions, transient squeeze behavior, non-Newtonian lubricant properties, micro-scale roughness, and surface morphology. These investigations consistently demonstrate that lubricant viscosity strongly influences film thickness, frictional characteristics, contact temperature, and load-bearing performance. Higher-viscosity lubricants generally provide stronger protective films and improved wear resistance, although they may increase viscous drag and energy losses. Lower-viscosity lubricants, while improving energy efficiency, may weaken lubrication integrity under demanding conditions and accelerate wear.[4]

Temperature effects are especially important in high-speed gear applications because rising temperatures can lower lubricant viscosity, weaken the oil film, and increase the risk of scuffing, pitting, and surface deterioration. Maintaining suitable viscosity under thermal stress is therefore essential for preserving lubrication performance and minimizing frictional losses. Recent developments in lubricant technology, including advanced additives and nanoparticle-enhanced lubricants, have shown considerable promise in improving viscosity stability, thermal conductivity, and anti-wear properties. Nanolubricants, in particular, offer improved lubrication performance under extreme operating environments while reducing energy dissipation and temperature rise.[5]

Gearbox power losses are generally categorized into load-dependent and load-independent components. Sliding friction between gear teeth primarily contributes to load-dependent losses, whereas churning, windage, and viscous drag account for load-independent losses. Lubricant viscosity directly influences both forms of energy loss. While higher-viscosity lubricants can reduce wear through superior film formation, they may also increase no-load losses due to greater fluid resistance. Conversely, lower-viscosity lubricants may improve efficiency but can compromise wear resistance when lubrication films become insufficient. Therefore, careful viscosity selection is essential to optimize both wear control and power efficiency. Overall, lubricant viscosity is a critical parameter that governs not only lubrication effectiveness but also the tribological, thermal, and energetic behavior of gear systems. Its impact extends to gear durability, efficiency, operational cost, and long-term reliability. A thorough understanding of viscosity-related lubrication behavior is therefore fundamental for improving gear system design, optimizing performance, and promoting sustainable mechanical operation. Figure 1 illustrates the frictional interaction between gear and pinion surfaces.

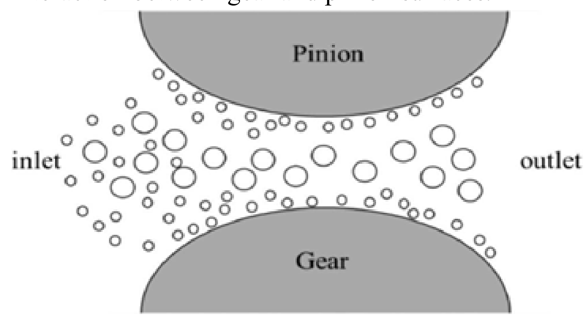


Fig.1 The friction coefficient of teeth surface

II. TYPES OF LUBRICANTS

1. Bio lubricants:

Bio lubricants are increasingly recognized as environmentally sustainable alternatives to conventional petroleum-based lubricants due to their biodegradability, lower toxicity, and reduced environmental impact. Their adoption supports the reduction of carbon emissions while offering safer disposal options. As industries shift toward greener technologies, bio lubricants are becoming essential for addressing ecological concerns associated with fossil fuel-derived lubricants and supporting sustainable automotive and industrial development.

2. Palm Oil-Based Lubricants:

Palm oil has gained significant attention as a renewable and widely available raw material for bio lubricant production. Its natural properties make it suitable for lubricant synthesis, particularly in applications focused on sustainability. Research has shown that incorporating nanoparticles such as graphene, carbon nanotubes, and metal oxides into palm oil-based lubricants substantially enhances their tribological and thermal properties. These additives improve wear resistance, reduce friction, and increase thermal conductivity by forming protective layers on metal surfaces. Such improvements make palm oil-derived lubricants particularly promising for electric vehicle systems, where effective heat dissipation and component durability are critical.[6]

3. Nanoparticle-Enhanced Palm Oil Bio lubricants:
The integration of nanoparticles into palm oil-based lubricants significantly improves their operational performance, especially under demanding conditions. These advanced lubricants demonstrate enhanced oxidation resistance, lower frictional losses, and improved anti-wear characteristics. In electric vehicles, they can increase drivetrain efficiency, reduce maintenance requirements, and extend component lifespan. Although these developments are promising, further research is necessary to optimize formulation strategies and ensure large-scale practical implementation.

4. Palm Stearin Methyl Ester (PSME):
Palm stearin methyl ester represents another promising bio-based lubricant alternative. Under optimized synthesis conditions, including controlled methanol ratios, catalyst concentrations, and reaction temperatures, PSME can achieve high production yields. Compared to mineral lubricants, PSME offers superior oxidation resistance, improved viscosity characteristics, and enhanced tribological performance, positioning it as a viable sustainable lubricant for industrial applications.

5. Olive Oil-Based Lubricants:
Olive oil has also demonstrated potential as a renewable lubricant due to its naturally favorable frictional properties. Studies indicate that olive oil can reduce wear and friction more effectively than some mineral oils, largely because of its lower coefficient of friction and reduced wear scar formation. While its oxidation stability may require enhancement through additives, olive oil remains a strong candidate for bio-lubrication, particularly in heavy-duty mechanical systems.

6. Pentaerythritol (PE) Ester Lubricants with Refrigerants:
PE ester lubricants are widely studied for refrigeration applications due to their favorable low-temperature lubrication properties and low pour points. Although they possess characteristics comparable to commercial polyol esters, compatibility issues with refrigerants such as HFC R134a may arise because of limited miscibility. The use of surfactants can improve refrigerant compatibility, thereby enhance compressor performance and maintain system reliability in refrigeration cycles.[7]

7. Palm Oil Methyl Ester (PME) and Trimethylolpropane (TMP) Lubricants:
Bio lubricants synthesized from palm oil methyl ester and trimethylolpropane through microwave-assisted methods exhibit excellent physicochemical properties and production efficiency. This process significantly reduces activation energy compared to traditional synthesis techniques, while also lowering energy consumption, carbon emissions, and chemical waste. Such advantages make PME-TMP lubricants attractive for sustainable industrial applications

8. Sustainable Lubricants and Global Environmental Goals:
The advancement of sustainable lubricants contributes directly to broader global sustainability initiatives. Renewable lubricants, especially those derived from bio-based feedstocks and enhanced with advanced additives, support reduced fossil fuel dependence, lower greenhouse gas emissions, and improved energy efficiency. These benefits align closely with Sustainable Development Goals related to clean energy, responsible production, and climate action, emphasizing the growing importance of sustainable lubrication technologies in future industrial systems.

2.1 Additives
Additives are specialized chemical substances blended into lubricants to improve their functional properties and enhance overall performance under various operating conditions. Their primary purpose is to strengthen lubrication quality by improving friction reduction, minimizing wear, increasing thermal and oxidative stability, preventing corrosion, and extending lubricant lifespan. In bio-based lubricants, particularly palm oil-derived formulations, additives are essential for modifying specific characteristics such as viscosity behavior, oxidation resistance, and anti-wear performance to meet industrial application requirements. The inclusion of additives is often determined by the desired operational characteristics of the lubricant and the environment in which it will be used. Common additive categories include viscosity modifiers, oxidation inhibitors, anti-wear agents, and friction reducers.
These components help create more durable, efficient, and sustainable lubricant systems. Although some bio lubricants may function without additives, their strategic incorporation significantly enhances

performance and allows formulations to be customized for specific mechanical demands. Recent tribological studies, including those by Chan et al. (2018), emphasize the growing importance of environmentally friendly additive technologies in sustainable lubricant development. These additives may include plant-derived compounds, ionic liquids, layered materials, and nanoparticles. Effective lubricant design requires not only selecting an appropriate base stock but also ensuring that additive packages complement the viscosity range, lubrication regime, and tribofilm stability required for specific applications. Strong tribofilm formation and surface adhesion are particularly important for improving wear resistance and maintaining long-term lubrication effectiveness.[8]

Naturally derived compounds such as cystine Schiff base esters have demonstrated considerable promise as multifunctional additives because of their anti-friction, anti-wear, and anti-corrosion capabilities. Their molecular structures allow them to form protective surface films that reduce direct metal contact under boundary lubrication conditions. Similarly, polymeric additives such as ethylene-vinyl acetate (EVA) and ethyl cellulose (EC) are widely used to enhance viscosity characteristics. Even at low concentrations, these modifiers can substantially increase base oil viscosity, improving lubrication strength and temperature adaptability.

Conventional anti-wear additives such as Zinc dialkyldithiophosphate (ZDDP) remain widely used due to their proven ability to form protective tribofilms on metal surfaces, thereby reducing wear and friction under severe pressure conditions. Boron-containing additives, including borate esters and boron nitride, also offer effective wear protection by creating durable surface barriers that limit metal-to-metal interaction. Under extreme temperature and pressure conditions, conventional lubricants may fail due to breakdown of the lubricating film. To address this limitation, nanomaterial additives have emerged as advanced solutions. These additives can enhance lubrication by converting sliding interactions into rolling mechanisms at the microscopic level, thereby significantly reducing friction, improving wear resistance, and maintaining lubricant performance under demanding conditions. As a result, additive technology continues to play a central role in advancing both conventional and sustainable lubricant systems.

2.2 Viscosity

Viscosity is one of the most important parameters in lubricant formulation because it directly controls fluid flow behavior and lubrication effectiveness. In palm oil-based bio lubricants, viscosity significantly influences the lubricant's ability to maintain protective films, reduce friction, and perform efficiently under varying mechanical conditions. Adjusting viscosity through formulation strategies or additives is often necessary to ensure that the lubricant meets the demands of specific applications.

An appropriate viscosity level allows the lubricant to flow efficiently while maintaining sufficient film thickness between contacting surfaces. This balance is essential for reducing wear, supporting thermal stability, and optimizing mechanical performance. Viscosity modifiers are therefore frequently incorporated into bio lubricant formulations to tailor their properties for different operational requirements. The viscosity index is another important factor because it reflects how consistently a lubricant maintains its viscosity across temperature changes. A higher viscosity index indicates better thermal adaptability, enabling the lubricant to perform effectively over a broader temperature range. This characteristic is particularly valuable in industrial systems where temperature fluctuations are common. Consequently, both viscosity and viscosity index are critical considerations in the design of efficient and versatile bio-based lubricants.[9]

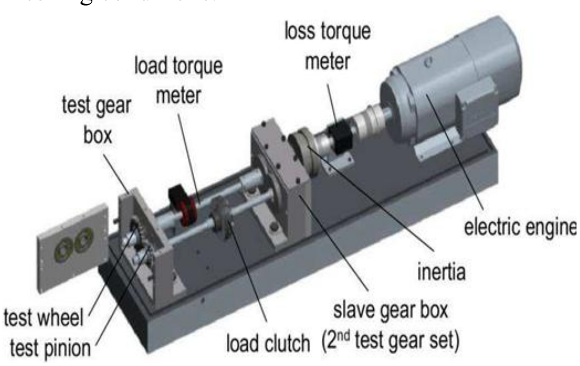
Experimental evaluations of bio lubricants derived from sources such as sunflower oil, soybean oil, Jatropha oil, and waste oils consistently show that viscosity decreases as temperature rises. This reduction occurs because elevated temperatures weaken intermolecular forces, including hydrogen bonding and van der Waals interactions, which normally resist fluid motion. As molecular interactions become weaker, lubricant flow resistance decreases, leading to lower viscosity.

In some cases, prolonged exposure to high temperatures may also cause molecular degradation, further reduce viscosity and potentially affect lubricant performance. Therefore, understanding the temperature-viscosity relationship is essential for predicting lubricant behavior under real operating conditions. This thermal sensitivity highlights the importance of selecting or formulating lubricants with suitable viscosity characteristics to maintain consistent tribological performance, system reliability, and operational efficiency.

III. EXPERIMENTAL PROCEDURE

A. Preparation of Test Gears

The experiment begins with the selection of standard FZG Type-A spur gears fabricated from case-carburized steel, chosen for their suitability in gear performance and wear studies. Before installation, the gear tooth surfaces are thoroughly cleaned to remove any contaminants that could interfere with lubrication or wear measurements. The initial mass of each gear is then accurately measured using a precision balance to establish baseline wear data. Surface roughness measurements are also recorded prior to testing to document the original condition of the gear surfaces. After these preliminary evaluations, the gears are securely mounted in both the test gearbox and slave gearbox to ensure proper alignment and consistent meshing conditions.



B. Lubrication System Setup

A selected lubricant, which may include ISO VG 68, 100, 150, or 220 grades in either mineral or synthetic form, is introduced into the lubrication system. The oil circulation unit consisting of a pump, filtration system, heater, and cooling components is then activated to maintain stable lubrication conditions. The lubricant temperature is carefully regulated within the required operating range of 60–90°C. Additionally, the oil flow rate is maintained between 1 and 2 liters per minute to ensure effective lubrication. Depending on the testing requirements, either splash lubrication or forced lubrication is employed.

C. Test Rig Configuration

The electric motor is initiated to drive the gear system under controlled conditions. Desired loading conditions are established by adjusting the torque loading clutch to apply torque values ranging from 50 to 300 Nm. Gear rotational speed is set according to the experimental design, varying between 300 and 3000 rpm. Prior to testing, all measurement instruments including thermocouples, torque sensors, and speed sensors are calibrated to ensure data accuracy. The data acquisition system is then activated for real-time monitoring and recording of operational parameters.3.4 Test Operation. The FZG back-to-back test rig functions according to the power recirculation principle, which minimizes external energy requirements while allowing precise measurement of transmission losses. During operation, the gears run continuously under predetermined speed, load, and temperature conditions. Critical operating parameters such as torque, rotational speed, lubricant temperature, and power loss are continuously monitored and recorded throughout the test.

D. Test Duration

The experimental duration is selected based on the study objectives and generally ranges from 20 to 100 hours. Throughout this period, lubricant quality and system temperature are regularly monitored to maintain stable operating conditions and ensure consistent test reliability.

E. Post-Test Gear Inspection

Upon completion of the test cycle, the system is shut down following proper safety procedures. The gears are then carefully removed from the gearbox and cleaned to eliminate residual lubricant deposits. Final gear weight measurements are taken to determine material loss, and surface roughness is reassessed to evaluate changes in surface condition resulting from operational wear.

F. Wear Analysis

Wear performance is evaluated using multiple analytical techniques, including weight loss measurements, surface roughness assessments, optical microscopy, and scanning electron microscopy (SEM). These methods allow detailed examination of gear surface degradation and facilitate identification of dominant wear mechanisms such as abrasive wear, adhesive wear, and scuffing.

G. Power Loss and Efficiency Evaluation

Power loss is determined by calculating the difference between input and output power:

$$P_{loss} = P_{in} - P_{out}$$

Gear efficiency is subsequently evaluated for each lubricant viscosity grade. Comparative analysis is conducted to identify the lubricant that provides the most effective wear protection, minimizes power loss, and offers the best balance between durability and mechanical efficiency.

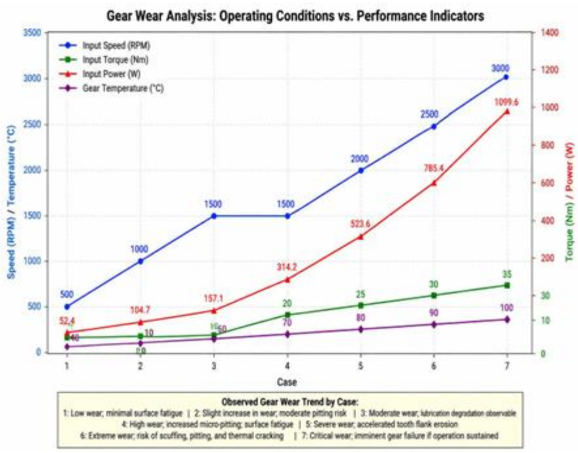


Figure No.1 Gear wear analysis

IV. RESULT AND DISCUSSION

Experimental investigations performed using FZG spur gear test rigs consistently indicate that lubricant viscosity plays a critical role in determining both gear wear characteristics and transmission efficiency. The viscosity of the lubricant directly affects the lubrication regime, frictional performance, and power losses within the gear system. Lubricants with lower viscosity generally reduce churning resistance and internal fluid friction, resulting in improved mechanical efficiency and lower transmission power losses. In contrast, high-viscosity lubricants form thicker elastohydrodynamic lubrication (EHL) films between meshing gear surfaces. This enhanced film strength improves surface separation, significantly reducing direct metal-to-metal contact and minimizing wear, pitting, and scuffing. Therefore, effective lubricant selection requires achieving an optimal compromise between wear protection and energy efficiency. The ideal lubricant viscosity should provide adequate film thickness to protect gear surfaces while avoiding unnecessary power losses caused by excessive viscous resistance.

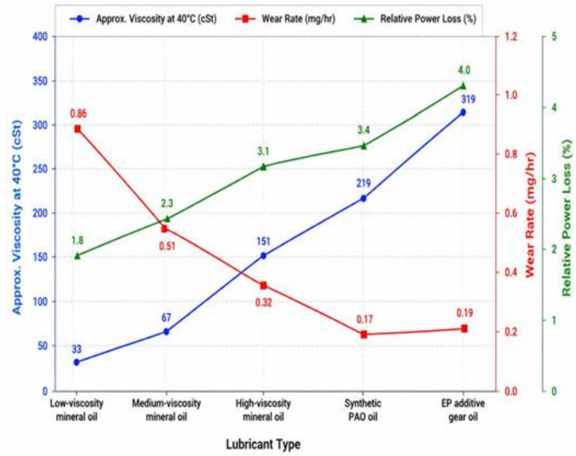


Figure no.2 Effect of lubricant type on spur gear performance

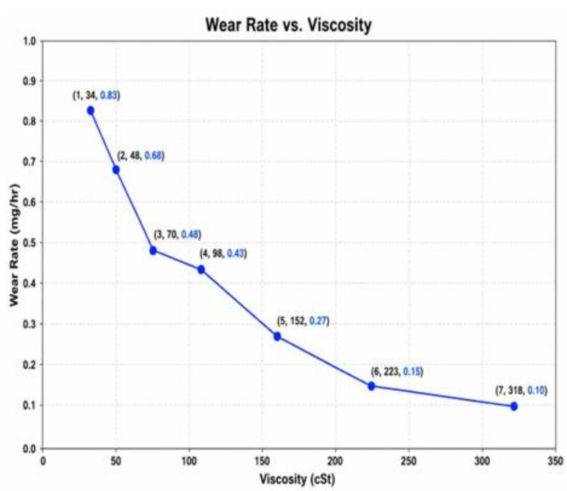


Figure no.3 Line graph showing wear rate with respect to viscosity

A rise in viscosity enhances oil film thickness, which effectively minimizes direct metal-to-metal interaction and reduces surface damage caused by friction and wear. The most substantial improvement in wear reduction is observed within the viscosity range of approximately 32cSt to 150cSt, where increasing viscosity provides considerable protective benefits. Beyond roughly 220cSt, however, the rate of wear reduction becomes less pronounced. Although higher-viscosity lubricants continue to offer wear protection, the additional benefits diminish while power losses increase significantly due to elevated fluid resistance, churning effects, and viscous drag.

Overall, the findings confirm that lubricant viscosity is one of the most critical parameters affecting gear wear progression and power loss in transmission systems. Proper viscosity selection has a direct influence on lubrication quality, tooth surface preservation, gear geometry stability, and overall transmission performance. Selecting an optimal viscosity grade is therefore essential for maximizing gear lifespan while maintaining efficient energy utilization.

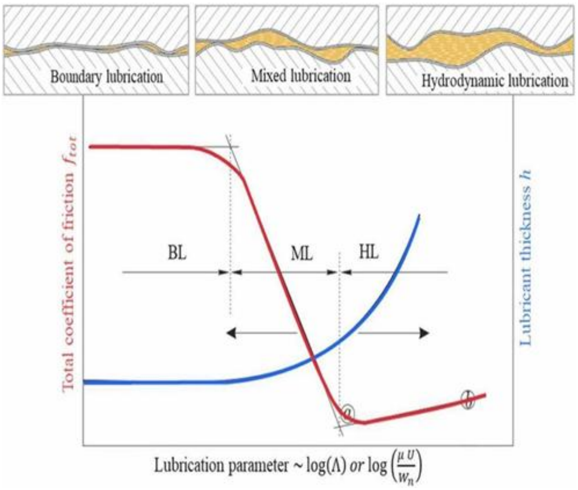


Figure no.4 Curve showing lubricating parameter

V. CONCLUSION

- Lubricant viscosity is a fundamental factor influencing the wear behavior, lubrication quality, and power efficiency of gear transmission systems throughout their operational lifespan.
- During continuous gear operation, progressive tooth surface wear alters lubrication conditions, meshing behavior, and overall system performance. As wear develops over time, changes in gear geometry including reduced curvature radius and entrainment velocity, along with increased sliding parameters can weaken lubrication effectiveness and accelerate surface degradation, particularly when lubricant viscosity is inadequate.
- Lower-viscosity lubricants offer notable advantages in improving fuel efficiency and reducing power losses by minimizing viscous friction, churning losses, and fluid drag. Modern ultra-low-viscosity oils, such as 0W-20 formulations, have demonstrated considerable energy-saving potential across various operating conditions.
- Despite these efficiency benefits, low-viscosity lubricants also present significant challenges. Reduced film thickness can increase direct asperity interaction under heavy loads or elevated temperatures, which may lead to higher wear rates, abrasive damage, and reduced long-term reliability.
- In contrast, higher-viscosity lubricants provide thicker and more robust lubricating films, offering superior wear protection by maintaining better separation between contacting surfaces.
- Emerging lubricant technologies, including nano lubricants, additive-enhanced low-viscosity oils, and environmentally friendly water-based lubricants, are increasingly important in addressing this trade-off. Advanced additives such as calcium phosphate compounds, sulfur-based agents, and specialized anti-wear chemicals promote tribofilm formation, improving surface protection while preserving the efficiency advantages of lower-viscosity lubricants.
- Overall, the selection of an appropriate lubricant viscosity remains essential for maximizing gear durability, maintaining transmission efficiency, reducing operational costs, and improving long-term system sustainability.

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