Green Tribology: Biodegradable oil Enhancement Techniques

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Abstract—Tribology is a fundamental aspect of engineering, playing a critical role in reducing friction, wear and energy losses in mechanical systems. Green tribology focuses on developing sustainable and environmentally friendly solutions to reduce friction, wear, and energy losses in mechanical systems. While lubrication plays a crucial role in enhancing machine efficiency, many conventional lubricants contribute to environmental pollution due to their non-biodegradable nature and toxic byproducts.This study aims to analyze the current landscape of biodegradable lubricants, assessing their efficiency and feasibility as sustainable alternatives. Furthermore, the research explores the enhancement of lubricant viscosity through the incorporation of nanoparticles and examines their tribological performance under varying temperature conditions[3]. By investigating these factors, this study contributes to the advancement of green tribology by promoting eco-friendly lubrication technologies that balance performance and sustainability.

Keywords—*Green tribology, Biodegradable lubricants, Friction, Wear, Nanoparticles*

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1. Introduction

Tribology is the science and engineering of friction, wear, and lubrication between interacting surfaces in relative motion. It is a highly interdisciplinary field that combines physics, chemistry, materials science, biology, and engineering.[11] Lubrication is the process of reducing friction between two surfaces in relative motion by introducing a lubricant. This practice is essential for improving the efficiency, reliability, and lifespan of mechanical systems. Lubrication serves multiple purposes, including:

- **Reducing Friction:** Minimizes resistance between moving surfaces, thereby lowering energy loss.
- **Preventing Wear:** Protects surfaces from damage caused by continuous contact.
- **Corrosion Protection:** Shields surfaces from oxidation and rust.

Lubrication is crucial across a wide range of applications. In the automotive industry, motor oils help reduce engine wear and improve fuel efficiency.[8] In industrial operations, greases are used to protect machinery during high-friction processes such as metal cutting or forming.[11] In biomedical engineering, biolubricants are employed in artificial joints to mimic the body's natural lubrication, ensuring smooth articulation and reduced wear. Furthermore, eco-friendly lubricants are increasingly utilized in renewable energy systems, including wind turbines and solar panels, where reducing friction and minimizing environmental impact are equally important.

Types of Lubricants

Lubricants can be classified into several categories based on their composition and application:

Liquid Lubricants

- **Mineral Oils**: Derived from crude oil; classified into groups (I-V) based on properties like viscosity index and sulfur content.
- **Synthetic Oils**: Includes polyalphaolefins (PAO), esters, and polyalkylene glycols (PAG), offering superior performance in extreme conditions.
- **Biolubricants**: Made from renewable sources like vegetable oils; biodegradable and eco-friendly.[12]

Solid Lubricants

Examples include graphite, molybdenum disulfide, tungsten disulfide, and polymeric films like PTFE. These are used in high-temperature or high-pressure applications where liquid lubricants fail.

Gaseous Lubricants

Air or other gases used in specialized applications, such as fluid bearings.

Aqueous Lubrication

Utilizes water-based systems with hydrated brush polymers to achieve low friction at liquid-solid interfaces.

Pollution due to Lubricants

Pollution caused by lubricants is a significant environmental concern due to their widespread use in industries, transportation, and machinery. Below are the key points regarding the environmental and health impacts of lubricant pollution:

1. **Improper Disposal**: Lubricants are often disposed of improperly, such as being dumped into sewage systems or water bodies, especially in regions with weak environmental regulations. This contaminates water sources and harms aquatic ecosystems.
2. **Leakage and Spillage**: Lubricants often leak from machinery, vehicles, or during storage and transportation. Approximately 70–80% of hydraulic fluids are lost through leaks or spills.
3. **Use in Open Systems**: Machines with open cutting systems, like chainsaws or harvesters, release lubricants directly into the environment, contaminating soil and vegetation.
4. **Contamination During Use**: Lubricants can become contaminated with dust, water, or other chemicals during use, reducing their effectiveness and increasing their environmental impact when disposed of.[6]

Impact on Enviornment

1. **Water Contamination**:
   - A small amount of lubricant can contaminate large volumes of water. For instance, one liter of oil can render one million liters of drinking water unfit for consumption.[4]
   - Contaminated aquatic life consumed by humans or animals poses long-term health risks .
2. **Soil Degradation**:
   - Petroleum-based lubricants clog soil pores, reducing aeration and water infiltration.
   - They alter the soil's chemical composition, harming microorganisms and vegetation .
3. **Toxicity**:
   - Base oils and additives in lubricants are toxic to plants, aquatic organisms, and wildlife.
   - Oxidation products formed during lubricant use can be more harmful than the original compounds.
4. **Marine Pollution**:
   - The maritime sector contributes significantly to lubricant pollution due to leaks and improper disposal.
   - Over 265,000 kiloliters of petroleum products enter marine environments annually [4].

Lubricants play a crucial role in ensuring the smooth operation of industrial machinery. However, conventional lubricants, which are predominantly petroleum-based, pose significant environmental challenges due to their non-biodegradable nature and potential toxicity. Their disposal and degradation contribute to long-term ecological harm.

Given these concerns, there is a pressing need to transition towards environmentally friendly alternatives—specifically, biodegradable lubricants derived from natural sources.This field of study in a border perspective is called as **Green Tribology**. In this research paper, we explore the potential of such bio-based lubricants as sustainable replacements for traditional oils. Our study investigates the performance of natural oils under varying temperature conditions and examines how their tribological properties—particularly the coefficient of friction—can be enhanced through the incorporation of nanoparticles.

In the concluding section, we present a comparative analysis between the developed biodegradable lubricants and conventional non-biodegradable lubricants. This evaluation aims to assess their industrial applicability and highlight their potential as eco-friendly substitutes without compromising on performance and also present some other Biodegradable lubricants which are in current research and development.[10]

2. Theortical Background

Green tribology is a subdiscipline of tribology focused on minimizing environmental impact while addressing the tribological aspects of friction, wear, and lubrication. It integrates principles of sustainability, ecological balance, and environmental protection into tribological practices, making it an essential field for fostering sustainable development in science and industry [9].

Principles of Green Tribology

1. Minimization of friction.
2. Reduction of wear.
3. Elimination or reduction of lubrication (including self-lubrication).
4. Use of natural lubricants.
5. Adoption of biodegradable lubricants.
6. Application of sustainable chemistry and engineering practices.

Biodegradable lubricants are being enhanced through chemical modifications, genetic engineering of raw materials, and innovative formulations to improve performance and environmental compatibility. These advancements address key challenges such as oxidative stability, temperature sensitivity, and cost-effectiveness while maintaining biodegradability.[7]

Chemical Modification

- **Estolide synthesis**: *Orychophragmus violaceus* seed oil's natural triacylglycerol estolide structure inspired synthetic castor oil estolides, reducing the coefficient of friction by 30–50% compared to unmodified castor oil **pmc**.
- **Transesterification**: Modifying vegetable oils (e.g., castor oil) through esterification of hydroxyl groups enhances viscosity and pour points **wiley**, **pmc**.
- **Branching and oxidation resistance**: Alkyl-branched fatty acids and antioxidant additives mitigate oxidation issues in soybean and canola oils **wiley**, **machinery**.

Formulation Strategies

- **Blends**: Combining vegetable oils with biodegradable synthetic esters (e.g., polyalkylene glycols) improves cold-flow properties while maintaining over 51% bio-based content[7].
- **Additive development**: Low-toxicity antiwear additives and viscosity modifiers are being designed to meet OECD 301B biodegradability standards and reduce aquatic toxicity [1].

Building upon the advancements in biodegradable lubricant technologies and performance enhancers such as estolides, high-oleic oils, and synthetic ester blends, this study aims to explore the tribological behavior of eco-friendly formulations using solid lubricants.[1]

Specifically, we propose to investigate the effect of incorporating molybdenum disulfide (MoS_2)—a well-known solid lubricant—into mineral oil, which serves as a biodegradable base lubricant. By adding MoS_2 in controlled concentrations, we aim to assess its influence on the coefficient of friction (CoF) under varying thermal conditions.

The coefficient of friction will be experimentally measured at two different temperatures to evaluate the temperature sensitivity and performance consistency of the MoS_2-enhanced mineral oil blend. This investigation is expected to provide insights into optimizing environmentally friendly lubricants for use in temperature-variable applications while maintaining low friction and wear characteristics.

Mineral Oil

Mineral oil, a byproduct of crude petroleum refining, is a cost-effective and versatile substance widely used in industrial and commercial sectors. Its physicochemical stability and hydrophobic nature make it suitable for lubrication, insulation, and moisture resistance applications [3].

Key Characteristics

- **Viscosity & Density**: Exhibits a broad viscosity range (temperature-dependent) and typical density of 0.8–0.87 g/cm^3, lighter than water
- **Pour Point**: Varies by composition—naphthenic oils have lower pour points than paraffinic oils, favoring cold climates
- **Thermal Performance**: Adequate heat dissipation and moderate temperature stability; widely used in transformers and hydraulic systems **Boiling Point: 300-600°C (572-1112°F)** and a **flash point :above 180°C (356°F)**
- **Chemical Stability**: Inert, non-polar, and water-repellent; resists oxidation moderately well.
- **Lubricity**: Forms a protective film to reduce wear under high pressure and varying temperatures
- **Types**: Paraffinic (thermally stable, higher pour point), and naphthenic (better solubility, low-temp performance)
- **Applications**: Used in lubricants, transformers, corrosion protection, and food/pharma-grade formulations.

Molybdenum disulfide (MoS_2) is a widely used solid lubricant known for its exceptional friction-reducing and anti-wear properties, especially under extreme conditions.

Molybdenum disulfide (MoS_2)

Physical and Chemical Properties

- **Crystal Structure**: Hexagonal lamellar structure enables easy interlayer sliding, contributing to its lubricating effect.
- **Chemical Stability**: Chemically inert and insoluble in water and most acids; reacts only with strong oxidizing agents.
- **Thermal Resistance**: High melting point makes it suitable for high-temperature applications.
- MoS_2 provided by SRL
- Molecular Weight: 160.07 g/mol
- Average Particle Size: 90 nm

Tribological Properties

- **Low Friction**: Exhibits a coefficient of friction as low as 0.03–0.06, independent of ambient gases or absorbed films.
- **Protective Film Formation**: Adheres to metal surfaces to form a solid film that reduces wear and prevents surface contact.
- **Extreme Pressure (EP) Performance**: Effective under high load and pressure conditions, making it ideal for EP lubricant formulations.[2]

Applications

- **Industrial Lubricants**: Used in greases, oils, and dry coatings to enhance performance and longevity.
- **Aerospace and Automotive**: Applied in engines, transmissions, and mechanical assemblies requiring high-temperature and load resistance.
- **Electronics**: Employed in transistors and electrical contacts due to its semiconducting and conductive properties.

Unique Features

- **Humidity Resistance**: Performs reliably in moist environments.
- **Corrosion Inhibition**: Protects metal surfaces from oxidation and corrosion.
- **Thermal Conductivity**: Aids in heat dissipation in frictional systems.

MoS_2 remains a critical component in high-performance lubrication systems, combining durability, efficiency, and adaptability across diverse industrial applications.

Behavior of MoS_2 in Mineral Oil

MoS_2 (Molybdenum Disulfide) is not soluble in mineral oil but can be dispersed within it, forming a colloidal suspension. This enhances the lubricating properties of the oil, especially under high-stress conditions.

Key Characteristics

- **Insoluble, but Dispersible:** MoS_2 retains its solid form and suspends as fine particles.
- **Colloidal Suspension:** Nano-sized MoS_2 particles provide better dispersion and longer suspension time.
- **Stirring Requirements:** To maintain homogeneity:
  - Hand stirring
  - Magnetic stirring
  - Ultrasonic agitation
- **Lubrication Effect:** Forms a low-shear, friction-reducing film on surfaces.
- **Thermal Stability:** Remains effective at temperatures up to 400–450°C.

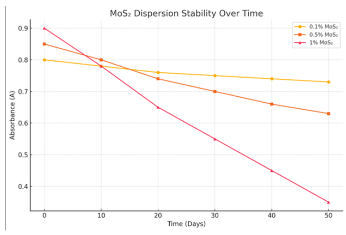

Figure 1. Solubility of $MoS_2 inmineraloil$

Comparison of Mineral Oil and Mustard Oil

Mustard Oil Composition (Approximate)

- Erucic Acid (C22:1): 42–50%
- Oleic Acid (C18:1): 12–20%
- Linoleic Acid (C18:2): 15–20%
- Alpha-linolenic Acid (C18:3): 6–10%
- Palmitic and Stearic Acids: 5–7%
- Allyl Isothiocyanate: Trace amounts

Flash Point and Smoke Point

Type of Oil	Flash Point (°F)	Smoke Point (°F)
Mustard Oil	~482	489

The flash point is the lowest temperature at which an oil emits enough vapor to ignite in the presence of a spark or flame.

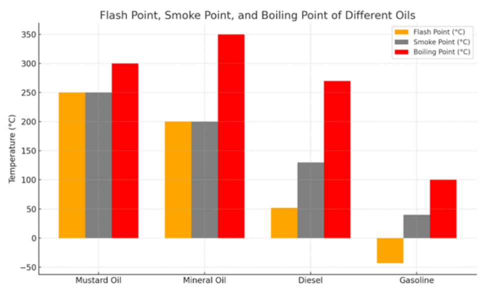

Figure 2. Comaprision of Different Oils

3. Methadology

Linear Friction Tribometer

Overview

A linear friction tribometer is a device used to measure friction and wear between two surfaces under controlled conditions. It simulates real-world contact where materials slide against each other, helping us understand how different lubricants affect wear and friction.

Working Principle

1. **Two Contacting Surfaces:**
   - One surface is the test specimen (SS304 rectangular flat plate in our case).
   - The other surface is the counter body (AISiE 51200 steel ball).
   - A controlled load (force) is applied to press them together.
2. **Reciprocating Motion:**
   - The steel ball moves back and forth over the SS304 plate in a linear motion.
   - This motion mimics real-world sliding conditions, such as engine parts, bearings, or metal contacts in machinery.
3. **Friction Force Measurement:**
   - A sensor continuously records the friction force between the two surfaces.
   - This data helps calculate the coefficient of friction (COF), which tells us how slippery or resistant the material is.
4. **Wear Measurement:**
   - After the test, we inspect the wear track (the mark left by the steel ball on the SS304 plate).
   - Wear is measured by looking at track width, depth, and material loss using a microscope or profilometer.
5. **Temperature Control:**
   - The tribometer allows us to heat the setup to 80°C to see how lubrication changes with temperature.
   - This helps us understand whether MoS_2 improves or worsens the lubrication under heat.

Machine Specifications

- **Cooling Chamber:** Low temperature reciprocating tribology testing from -50°C.

Figure 3. Cooling Chamber

- **Heating Chamber:** High temperature reciprocating tests up to 1200°C.

Figure 4. Heating Chamber

- **Wear with Capacitive Sensor:** Fast reciprocating drive module allows for multiple test setups.

Figure 5. Wear with Capacitive Sensor

- **Liquid Container:** Anti-splash high-speed liquid containers.

Figure 6. Liquid Container

- **Sample Holder:** Universal sample holder to mount samples with ease.

Figure 7. Sample Holder

- **Tribocorrosion:** Several application-specific modules mount on the reciprocating drive.

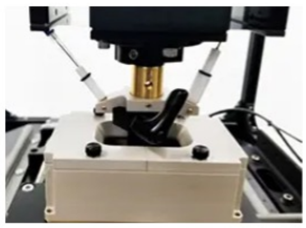

Figure 8. Tribocorrosion

Advantages of Using a Linear Friction Tribometer

- Allows precise control over friction and wear conditions.
- Helps compare pure mustard oil vs. MoS-mixed oil.
- Provides quantifiable data to analyze lubrication performance at different temperatures.

4. Procedure

Apparatus Used

Magnetic Stirrer

A magnetic stirrer is a handy lab tool that helps mix liquids smoothly and effortlessly. It works by using a spinning magnetic field to move a small magnetic stir bar inside a container, creating a consistent swirling motion.

Some parameters to note:

- Temperature = 30°Celsius
- Time = 20 Minutes

Ultrasonic Shaker

An ultrasonic shaker is like a high-tech mixer that uses sound waves instead of a spoon. It sends out super-fast vibrations that create tiny bubbles in a liquid, and when those bubbles pop, they create powerful mixing forces. **Some parameters to note:**

- Temperature = 44°Celsius
- Time = 10 Minutes

Polishing Machine with Water Lubrication

Components:

- **Rotating Disc** – Operates at 200 RPM for uniform polishing.
- **Abrasive Paper** – Two grit levels:
  - 320-grit (coarse) – For initial surface smoothing.
  - 1200-grit (fine) – For final polishing.
- **Water Lubrication System** – Prevents overheating and washes away debris.
- **Motorized Base** – Powers the rotation of the polishing disc.
- **Drain System** – Removes excess water and debris from the polishing surface.

Purpose behind doing this: Used for surface preparation, metallographic sample polishing, and fine finishing of materials like metals, ceramics, and stones.

AISiE 51200 Ball

High-carbon, high-chromium steel ball used for wear resistance testing or material evaluation.

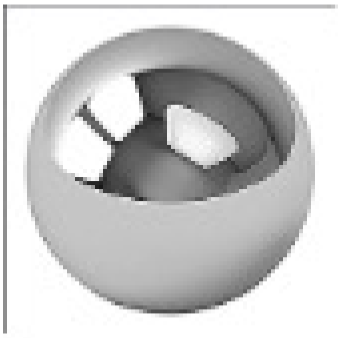

Figure 9. AISiE 51200 Ball

SS304 Rectangular Flat Plate

Stainless steel specimen.

Figure 10. SS304 Rectangular Flat Plate

Molybdenum Disulfide (MoS_2) Lubricant

For observation of solid lubricant's behavior in liquid lubricant mustard oil.

Figure 11. $MoS_2 Lubricant$

Mustard Oil

Used as a natural lubricant for comparative tribological analysis.

Figure 12. Mustard Oil

Experimental Setup

Preparation of Lubricant Solutions

To test how MoS_2 (Molybdenum Disulfide) and mustard oil work together as lubricants, we carefully mixed them step by step. We ensured that the MoS_2 powder was evenly distributed to obtain reliable results.

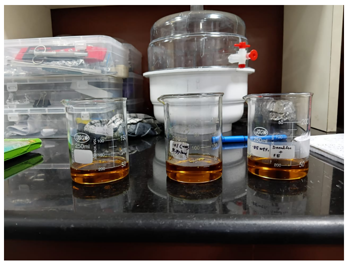

Figure 13. Lubricatin before adding MoS_2

Hand Stirring (Initial Mixing)

- Measured 50 ml of mustard oil into a beaker for each solution.
- Added MoS_2 powder in different amounts:
  - 0.05g for 0.1% solution.
  - 0.25g for 0.5% solution.
  - 0.5g for 1% solution.
- Stirred manually for 2-3 minutes to begin the mixing process.

Magnetic Stirring (Homogeneous Mixing at 30° C for 10 Minutes)

- Placed the beaker on a magnetic stirrer and set the temperature to 30°C.

- Allowed stirring at a steady speed for 10 minutes to break up clumps and mix the MoS_2 uniformly.

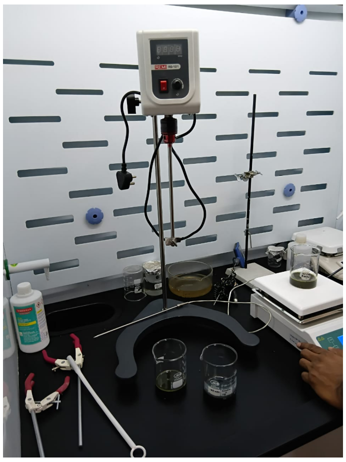

Figure 14. Magnetic Stirrer

Ultrasonic Shaking (Final Dispersion at 44° C for 20 Minutes)

- Transferred the mixture into an ultrasonic shaker and set the temperature to 44°C.
- Shook the mixture for 20 minutes, ensuring even dispersion of MoS_2 particles in the oil.

Figure 15. Ultrasonic Shaker

Final Check and Storage

- Verified that the solution appeared smooth and well-blended.
- Stored in sealed containers wrapped with aluminum foil to prevent contamination.

Figure 16. Sample after adding additative

Preparation of SS304 Specimen

To ensure the SS304 rectangular flat plate was ready for testing, a careful polishing and cleaning process was followed to provide a smooth and contamination-free surface for accurate tribological evaluation.

Figure 17. SS304 Specimen

Polishing the Specimen

- Used a wet polishing machine operating at 200 RPM.
- Performed initial polishing with a 320-grit abrasive to remove roughness.
- Followed with a 1200-grit abrasive for fine polishing to achieve a smoother surface.

Cleaning the Specimen

- Cleaned the polished specimen using acetone to remove residual abrasives, oil, and contaminants.
- Ensured a clean surface to prevent errors in friction and wear testing.

Final Check

- Conducted a visual inspection to confirm a smooth and debris-free surface.
- Once verified, placed the SS304 specimen into the linear reciprocating tribometer for testing.

How We Conducted the Tribometer Experiments

Once the SS304 specimen and lubricant solutions were prepared, we carefully set up the linear reciprocating tribometer to run our tests. Our goal was to analyze how different MoS_2 concentrations and temperatures affected friction and wear.

Placing the Specimen in the Tribometer

- Secured the polished SS304 rectangular plate in the sample holder of the tribometer.
- Mounted the AISiE 51200 steel ball on the upper holder as the counter body.
- Checked the alignment to ensure proper contact between the steel ball and the SS304 plate.

Setting the Test Parameters

The tribometer was configured with the following fixed parameters for all tests:

- Load Applied: 5N (to simulate real contact pressure).
- Frequency: 4 Hz (steel ball moves back and forth 4 times per second).
- Sliding Length: 2 mm (short-distance reciprocating motion).
- Test Duration: Fixed time for each test.

Running the Tests

Since we had four different lubricant solutions and tested each at two different temperatures, a total of eight separate tests were conducted. **For each test:**

- The selected lubricant was applied between the steel ball and SS304 specimen.
- The tribometer was run for the set duration while continuously recording friction force.

- If the test was at 80°C, we allowed the setup to reach the required temperature before starting.
- After completion, we cleaned the sample area with acetone before moving to the next test.

Test No.	Lubricant Solution	Temperature
1	Pure Mustard Oil	Room Temp (~30°C)
2	0.1% MoS_2 in Mustard Oil	Room Temp (~30°C)
3	0.5% MoS_2 in Mustard Oil	Room Temp (~30°C)
4	1% MoS_2 in Mustard Oil	Room Temp (~30°C)
5	Pure Mustard Oil	80°C
6	0.1% MoS_2 in Mustard Oil	80°C
7	0.5% MoS_2 in Mustard Oil	80°C
8	1% MoS_2 in Mustard Oil	80°C

Table 1. Test conditions for lubricant evaluation in the tribometer.

5. Data Pocessing

The following Python code was implemented.

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt

RT1 = pd.read_csv('80_1.csv')
print(RT1.head())
mu = np.array(RT1['COF'])
f = np.array(RT1['Reciprocating.Frequency (Hz)'])
t = np.array(RT1[' Timestamp'])
sd = np.zeros(len(f))
sd[0]=f[0]*t[0]*2*0.001
for i in range(1,len(f)):
  if np.isnan(f[i]):
    sd[i]=sd[i-1]
  else:
    sd[i]=sd[i-1]+f[i]*(t[i]-t[i-1])*2*0.001

print("Sliding Distance: ",sd[len(f)-1]," m")

plt.xlabel('Time (in s)')
plt.ylabel('Coefficient of Friction')
plt.plot(t,mu,color='tab:orange')
plt.xlim(left=0)
plt.ylim(bottom=0)
plt.show()

\\Rounding Average


filtered_mu = np.array(RT1['COF'].rolling(50).mean())
filtered_t = np.array(RT1[' Timestamp'].rolling(50).mean())

filtered_mu1 = [m for s, m in zip(filtered_t, filtered_mu) if s >= 800]

mean_mu = np.mean(filtered_mu1)

plt.xlabel('Time (in s)')
plt.ylabel('Coefficient of Friction (COF)')
plt.plot(filtered_t,filtered_mu,color='tab:orange')
plt.axvline(x=800, color='tab:blue', linestyle=':', label='x = 800')
plt.text(x=850, y=0.02,
          s=f'Avg. COF = {mean_mu:.6f}',
          color='blue', fontsize=10)
plt.xlim(left=0)
plt.ylim(bottom=0)
plt.show()
```

Pure Mustard Oil

At Room Temperature

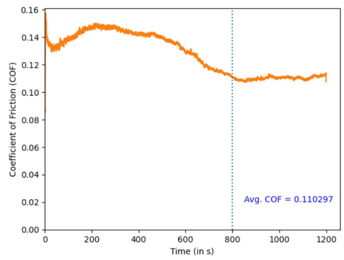

Figure 18. Room Temperature (Pure Mustard Oil)

Coefficient of Friction and Sliding Distance

Average Coefficient of Friction = 0.110297
Sliding Distance = 9.6 m.
Stabalization Time = 800 s.

At High Temperature = 80°C

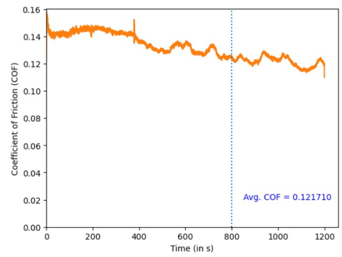

Figure 19. High Temperature (80°C) - Pure Mustard Oil

Coefficient of Friction and Sliding Distance

Average Coefficient of Friction = 0.121710
Sliding Distance = 9.6 m.
Stabalization Time = 800 s.

Mustard Oil with 0.1% (w/v)

At Room Temperature

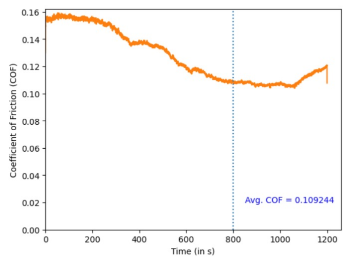

Figure 20. Room Temperature (0.1%)

Coefficient of Friction and Sliding Distance

Average Coefficient of Friction = 0.109244
Sliding Distance = 9.6 m.
Stabalization Time = 800 s.

At High Temperature = 80°C

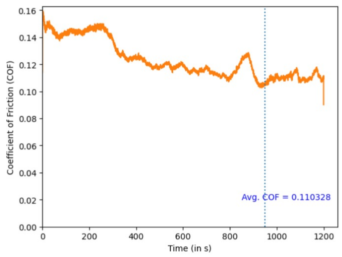

Figure 21. High Temperature (80°C) - 0.1% Mustard Oil

Coefficient of Friction and Sliding Distance

Average Coefficient of Friction = 0.110328
Sliding Distance = 9.6 m.
Stabalization Time = 950 s.

Mustard Oil with 0.5% (w/v)

At Room Temperature

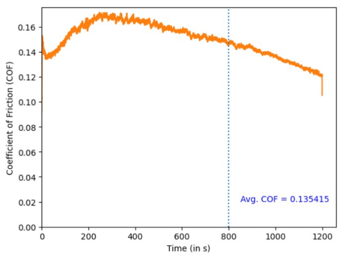

Figure 22. Room Temperature (0.5%)

Coefficient of Friction and Sliding Distance

Average Coefficient of Friction = 0.135415
Sliding Distance = 9.6 m.
Stabalization Time = 800 s.

At High Temperature = 80°C

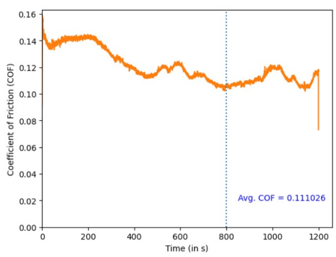

Figure 23. High Temperature (80°C) - 0.5% Mustard Oil

Coefficient of Friction and Sliding Distance

Average Coefficient of Friction = 0.110328
Sliding Distance = 9.6 m.
Stabalization Time = 950 s.

Mustard Oil with 1% (w/v)

At Room Temperature

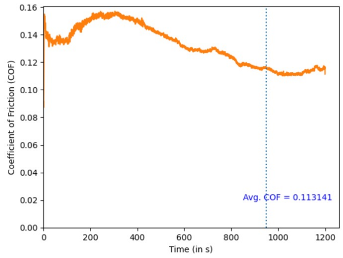

Figure 24. Room Temperature (1%)

Coefficient of Friction and Sliding Distance

Average Coefficient of Friction = 0.113141
Sliding Distance = 9.6 m.
Stabalization Time = 950 s.

At High Temperature = 80°C

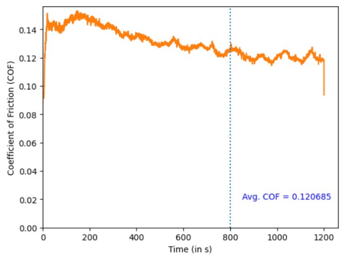

Figure 25. High Temperature (80°C) - 1% Mustard Oil

Coefficient of Friction and Sliding Distance

Average Coefficient of Friction = 0.120685
Sliding Distance = 9.6 m.
Stabalization Time = 800 s.

6. Conclusion

Average CoF	wt% MoS_2	Temperature (°C)	Stabilization Time (s)
0.110297	0 (Pure)	30 (RT)	800
0.109244	0.1	30 (RT)	800
0.135415	0.5	30 (RT)	800
0.113141	1.0	30 (RT)	950
0.121710	0 (Pure)	80	800
0.110328	0.1	80	950
0.111026	0.5	80	800
0.120685	1.0	80	800

Table 2. Summary of Results Obtained

Plotted Graphs and Codes

```
    import matplotlib.pyplot as plt

# Data from the table
data = [
    {"cof": 0.110297, "wt": 0, "temp": 30},
    {"cof": 0.109244, "wt": 0.1, "temp": 30},
    {"cof": 0.135415, "wt": 0.5, "temp": 30},
    {"cof": 0.113141, "wt": 1.0, "temp": 30},
    {"cof": 0.121710, "wt": 0, "temp": 80},
    {"cof": 0.110328, "wt": 0.1, "temp": 80},
    {"cof": 0.111026, "wt": 0.5, "temp": 80},
    {"cof": 0.120685, "wt": 1.0, "temp": 80},
]

```

```
# Group data by wt%
grouped = {}
for entry in data:
    wt = entry["wt"]
    if wt not in grouped:
        grouped[wt] = {"temp": [], "cof": []}
    grouped[wt]["temp"].append(entry["temp"])
    grouped[wt]["cof"].append(entry["cof"])

# Define colors by wt%
color_map = {
    1.0: "blue",
    0.5: "green",
    0.0: "orange",
    0.1: "pink"
}

# Plot lines for each concentration
plt.figure(figsize=(8, 5))
for wt, vals in grouped.items():
    color = color_map.get(wt, "gray")
    plt.plot(vals["temp"], vals["cof"], marker='o', label=f"{wt} wt% MoS", color=color)

# Labels, title, and legend
plt.xlabel("Temperature (C)")
plt.ylabel("Average CoF")
plt.title("Average CoF vs Temperature by MoS Concentration")
plt.legend(title="wt% MoS")
plt.grid(True)
plt.tight_layout()
plt.show()
```

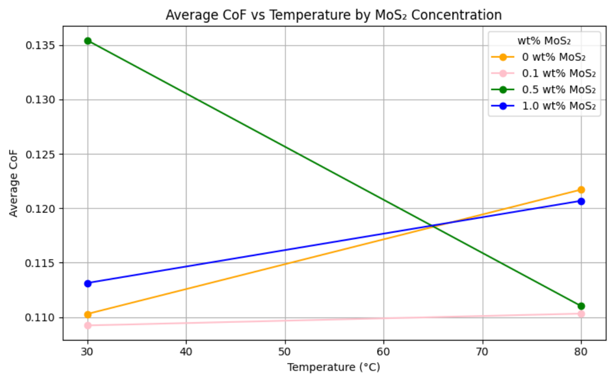

Figure 26. Average COF of different solutions

Reference
The COF between Stailess Steel 304 is 0.5800 and 0.4600 without any lubrication at Room temperature and High Temperature

Results and Observations

The sliding distance in all test cases was maintained at 9.6 meters, as depicted in the accompanying graphs. The blue vertical lines in the graphs denote the stabilization temperature. The stabilization time was determined through visual analysis of the graphs and is defined as the point after which the coefficient of friction (CoF) values tend to stabilize around the average, exhibiting minimal fluctuations.

The average CoF values observed across all test cases ranged from 0.109244 to 0.135415. It was noted that the initial addition of molybdenum disulfide (MoS_2) reduced the CoF for both low- and high-temperature scenarios. However, beyond a specific threshold concentration of MoS_2, the CoF values began to increase again, as evident from the plots.

An anomalous behavior was observed for the sample containing 0.5 wt% MoS_2 at room temperature. Unlike other samples, where the CoF stabilized after a certain period, the CoF in this case exhibited a monotonically decreasing trend throughout the test duration. Several potential explanations for this deviation are considered:

- At 30°C, the dispersion stability of MoS_2 in mustard oil may be insufficient, particularly at intermediate concentrations such as 0.5 wt%. Due to Van der Waals forces, MoS_2 particles may agglomerate, forming clusters that impair lubrication.
- Mustard oil contains a complex mixture of compounds, including sulfur-containing molecules and fatty acids. MoS_2 may chemically interact with these constituents in concentration- and temperature-dependent manners. At 0.5 wt%, it is possible that MoS_2 catalyzes a reaction that alters the oil's viscosity or film-forming properties over time.
- Variations in surface roughness across the specimen might have influenced the results. A localized anomaly in roughness could have disrupted the lubricant film, significantly affecting the friction behavior.
- Environmental disturbances during the experiment, such as unintentional mechanical shocks or vibrations, may have introduced noise into the CoF measurements.
- Improper calibration or malfunction of the tribometer's heating apparatus could have resulted in non-uniform temperature distribution, thereby influencing the CoF trends.

Best Practices to Prevent Erroneous Results

Following best practices could be adopted to get rid of erroneous results:

- Use the sample immediately after preparation to prevent it from settling down. If dispersion is poor, a surfactant may be used to stabilize MoS_2 in oil.
- Conduct tests in a stable environment to prevent noise in CoF readings.
- Ensure that test specimens are correctly aligned to prevent uneven wear of the specimen or measurement noise.
- Ensure the heating system is correctly calibrated to provide consistent performance across all experiments and throughout the surface of the specimen.
- Allow the tribometer to stabilize at the set temperature before starting the experiment.

Recommendations for Improving Experimental Reliability

To minimize the likelihood of such discrepancies in future tests, the following best practices are suggested:

- Utilize the lubricant samples immediately after preparation to prevent settling. If dispersion quality is inadequate, a suitable surfactant may be introduced to enhance the stability of MoS_2 in the oil.
- Conduct experiments in a controlled environment to minimize external disturbances and measurement noise.
- Ensure thorough calibration of the tribometer's heating system to maintain uniform temperature across the contact interface.

Alovera Gel

Aloe vera gel has potential applications as a natural lubricant in various industries, including personal care, pharmaceuticals, and cosmetics. Its unique composition and properties make it suitable for certain uses, although limitations exist depending on the specific application[5]

Potential to be used as a Lubricant
Aloe vera gel's water-based nature makes it compatible with latex and silicone materials. It offers moisturizing benefits and matches the vaginal pH (3.8–4.5), making it suitable for personal lubricants in specific contexts. However, its thinner consistency may limit its effectiveness for applications requiring higher viscosity or cushioning

1. **Chemical Additives:** Many commercial aloe vera gels contain preservatives or chemicals that may irritate sensitive skin or disrupt pH balance
2. **pH Compatibility:** Aloe vera gel's pH (4.5) is unsuitable for applications requiring neutral or alkaline pH levels (e.g., anal lubricants)

3. **Consistency:** Its thin texture may not provide sufficient lubrication for heavy-duty industrial applications requiring higher viscosity

Aloe vera gel can be a viable natural lubricant in industries focused on skincare and personal care due to its hydrating and soothing properties. However, its limitations—such as pH compatibility and consistency—must be considered when exploring broader industrial applications.

Egg-White

Egg white has been explored as a natural lubricant, particularly in fertility contexts, due to its unique properties. Below is an overview of its potential uses, benefits, and limitations.

Advantages

1. **Eco-friendly:**As a natural substance, egg white avoids the environmental concerns associated with synthetic lubricants.
2. **Biocomplexity:**It is safe for use in applications requiring contact with biological systems (e.g., medical or cosmetic uses).
3. **Low-friction Properties:**Egg-derived materials can lower friction and operating temperatures when added to conventional lubricants.
   These lubricants can be enhanced as the same way the mineral oil and we can expect more usage of these Natural lubricants for econ-friendly sustainable development of Industries.

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