



# **REDUCING WEAR AND POWER CONSUMPTION IN TRIBOLOGICAL SYSTEMS USING CARBON-BASED NANO-LUBRICANTS: AN EXPERIMENTAL STUDY**

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**<https://doi.org/10.30572/2018/KJE/160318>**

## **ABSTRACT**

This study presents a novel approach for producing carbon-based nano-lubricants, which avoids exposure to dry nanopowders usually used in production processes, thereby minimizing the health risks associated with nanoparticles. Furthermore, it adheres to green chemistry principles, as it does not involve toxic solvents or surfactants. In this approach, glucose, the most abundant and cost-effective monosaccharide in most crops, was subjected to hydrothermal carbonization to produce carbon-based aqueous nanofluid. The nanofluid was then mixed with a base oil (SAE 15W-40) at calculated volume ratios. The resulting mixtures were heated to evaporate the water, resulting in 5, 10, 15 and 20 g/l (i.e., 0.25 %, 0.5 %, 0.75 % and 1 % volumetric concentration) stable carbon-based nano-lubricants. In addition to the characterizations of the nano-lubricants, including viscosity and thermal conductivity, power consumption and wear measurements of a tribological system were conducted. The findings revealed linear relationships between nanoparticle concentration and viscosity, thermal conductivity, power reduction, and wear reduction. The maximum thermal conductivity enhancement and viscosity increase were 6 %, and 9.95 % for a 20 g/l nano-lubricant, respectively. Additionally, the power and the wear reductions were 16.66 % at full load, and 52.5 % for the 20 g/l nano-lubricant.



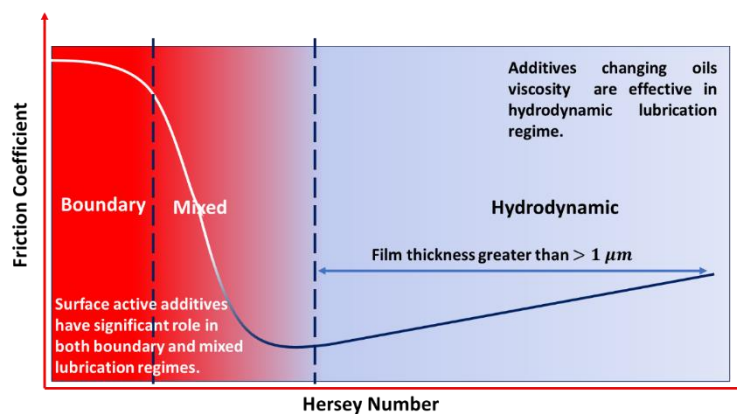
**KEYWORDS**

Hydrothermal carbonization, Carbon nanoparticle, Power consumption, Wear, Thermal conductivity, Viscosity.

## 1. INTRODUCTION

The global interest in developing efficient transportation systems and industrial practices stems from growing concerns regarding sustainability of energy and environment. Friction is roughly responsible for 23 % of the global energy consumption and approximately 33 % of the energy used in transportation (Holmberg et al., 2017, 2019). Additionally, it has been concluded that reducing frictional losses can lead to a threefold improvement in the fuel economy of passenger cars and 2.5-fold improvement for heavy-duty vehicles (Holmberg et al., 2014, 2012). This conclusion has motivated the Research and Development in the vehicle industry, as well as academia.

Lubricants play pivotal roles in tribological systems, aiming mainly to reduce friction, wear, and energy losses. In addition, lubricants play another important role as heat transfer media. These roles critically ensure smooth, reliable and durable operation of mechanical systems. Lubrication can be divided into three main regimes, as shown in Fig. 1: hydrodynamic thick film lubrication, which is characterized by low friction coefficients; mixed regime, which is a transition region from lower friction coefficients to higher ones, and boundary regime, which is characterized by broken thin films with high friction coefficients (Szeri, 1998). Therefore, researchers have paid attention and effort to reduce the high friction coefficient in the latter regime (Al-Jeboori et al., 2020, 2018a, 2018b).



**Fig. 1. Lubrication regimes.**

Lubrication depends on two crucial properties: the viscosity, which is essential in the hydrodynamic regime, and lubricity, which plays a key role in the boundary regime. Presence of a thin layer of lubricant reduces friction forces from 2 to 10 times compared to dry friction conditions, which may reduce wear by up to 100 times (Frycz and Labuda, 2021). The strength of this surface layer relies not only on the presence of active molecules in the lubricant but also on their quantity and physicochemical properties. The crucial role of these molecules can be fulfilled by carbon nano-additives. In general, adding nanoparticles to lubricants reduces the

friction coefficients and increases the load-carrying capacity of friction pairs as nanoparticles can treat the tribological surfaces and modify the lubricant viscosity (Frycz and Labuda, 2021). Similar to nonfluids, nano-lubricants are lubricants containing dispersed nanoparticles, which can be different in type such as ceramic nanoparticles (e.g.,  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$ ), metal nanoparticle (e.g., Cu and Ag), inorganic compounds (e.g.,  $\text{MoS}_2$  and  $\text{WS}_2$ ), and carbon-based nanoparticles (e.g., graphene and CNT) (Sui, 2021a). Nano-lubricants have recently received high levels of attention from industry and academia worldwide. This increasing interest is owing to the potential benefits of improving the efficiency and lifespan of machines, and consequently decreasing their pollution.

Many studies have been conducted to elucidate the mechanisms of improvement. Roll bearing mechanism was explained by Rapoport L. et al. (Rapoport et al., 2002), Wu Y. et al. (Wu et al., 2007), Chinas-Castillo F. and Spikes H. (Chinas-Castillo and Spikes, 2003) and Tao X. et al. (Tao et al., 1996). In this mechanism, the dispersed spherical nanoparticles, such as fullerenes, in lubricating oils play the role of rolling balls between friction surfaces. As the friction surfaces in relative motion come into contact, the nanoparticles get trapped between the surfaces, rolling instead of sliding, and this rolling behavior reduces friction significantly compared to sliding. Protective film mechanism was demonstrated by Ginzburg B. et al. (Ginzburg et al., 2002), Hu Z. et al. (Hu et al., 2002) and Zhou J. et al. (Zhou et al., 1999). In this mechanism, 2D planar nanoparticles can produce a protective film (i.e., quasi-crystalline boundary layer) on the friction surfaces. A similar effect can be obtained using 1D nanoparticles, such as carbon nanotubes, if their chemical properties allow them to form ciliary layers on the friction surfaces. Mechanisms of repairing and filling defects were presented in several papers (Gulzar et al., 2016; Liu et al., n.d., 2019; Shang et al., 2018b, 2018a). These mechanisms depend on the ability of certain nanoparticles to adhere tightly to the friction surfaces, compensating the material loss from them. Polishing mechanisms presented by Tao X. et al. (Tao et al., 1996) and Nunn N. et al. (Nunn et al., 2015) depend on ability of certain nanoparticles to polish the surfaces.

Researchers demonstrated the beneficial influences of dispersing fullerenes in lubricants. Adding fullerenes and graphite into lubricating oils effectively improved friction conditions during the tests and confirmed the creation of permanent anti-wear layers on the friction surfaces (Huang et al., 2006). Furthermore, experimental studies (Ettfaghi et al., 2013; Ku et al., 2010) showed the negligible effect of adding fullerenes on the effective viscosities of the resulting nano-lubricants. For nanoparticle concentrations up to 0.2 wt.%, the change in the kinematic viscosity did not exceed  $1 \text{ mm}^2/\text{s}$ , regardless of the oil type. Moreover, fullerenes

have another positive impact on the nano-lubricants, which is the flash point enhancement. Etefaghi E. et al. (Etefaghi et al., 2013) showed that the flash point of SAE 20W-50 oil increased by 20 °C and 26 °C with the addition of fullerene C<sub>60</sub> at concentrations of 0.1 wt.% and 0.2 wt.%, respectively. However, these concentrations may be considered low, and fullerenes are the most expensive nano-additives comparing to others. In addition, these influences are not exclusive to fullerenes, but similar benefits can be achieved by dispersing inorganic chemical compounds of fullerene-like structures, such as tungsten disulphide (IF-WS<sub>2</sub>) and molybdenum disulphide (IF-MoS<sub>2</sub>). Huang et al. (Huang et al., 2005) highlighted the positive impact of using IF-MoS<sub>2</sub> on the anti-wear properties of the prepared nano-lubricant. Xie H. et al. (Xie et al., 2016) also found that using MoS<sub>2</sub> nanoplatelets can reduce the friction coefficient by 40 % as compared to the base oil.

Several studies investigated the tribological properties of carbon-based particles suspended in lubricants. Lv X. et al. (Lv et al., 2020) produced carbon spheres with an average diameter of ~ 400 nm by heating a mixture, which was synthesized via the hydrothermal carbonization of a glucose solution, to 80 °C for more than 6 hours. They then prepared a 0.5 wt.% of carbon spheres in the baseline oil (SAE 5W-30). The results of the friction and wear tests clearly demonstrated the positive impact of the carbon spheres. Unlike the baseline oil, the optical observations showed a narrow and smooth wear track for the carbon spheres-oil mixture. Alazemi A. et al. (Alazemi et al., 2020) also dispersed carbon spheres with diameters ranging from 200 nm to 700 nm in SAE 5W-30 baseline oil to prepare a 3 wt.% mixture. The production of these carbon spheres involved: first, producing a mixture of sphere-shaped polymer resins through an accelerated copolymerization of resorcinol with a formaldehyde solution, and second, converting the sphere-shaped polymer resins to carbon spheres via heat treatment up to 900 °C for 4 hours in an argon atmosphere. They compared the rheological and wettability properties of the oil with and without submicron carbon spheres. Their findings revealed a negligible viscosity change (less than 4 %) over the temperature range of 5 – 60 °C. Furthermore, relying on the contact angle measurements, they concluded that adding carbon spheres has negligible effect on the wettability of the baseline oil. Pu Wu et al. (Wu et al., 2021) highlighted graphene as a promising material for use as a lubricant additive to reduce friction and wear. They developed a dispersing method that combines chemical modification of graphene, along with an effective dispersant. This method achieved remarkable dispersion stability, maintaining 0.5 wt.% graphene in PAO-6 baseline oil for up to 120 days, with 1 wt.% dispersant. The experimental results showed that the modified graphene-PAO-6 oil reduced the friction coefficient and wear depth by 44 % and 90 %, respectively, as compared to pure PAO-

6 lubricant, demonstrating significant improvement in tribological performance for a steel ball-to-plate tribo-system under a normal load of 2 N. However, producing this modified graphene required an extensive process. First, graphene oxide (GO) was synthesized via modified Hummer's method, involving careful treatment of graphite with sulfuric acid, sodium nitrate, potassium permanganate and hydrogen peroxide. The resulting solid particles were washed with hydrogen chloride and deionized water, then dried in a vacuum oven at 60°C for 8 hours. The final GO was chemically treated with octadecylamine and dicyclohexylcarbodiimide at 120 °C for 12 hours. The final black sediment particles were then washed five times with deionized water and ethanol, respectively, and dried again in a vacuum oven. This production method is neither green chemistry nor cost-effective.

In summary, all the reviewed studies used nanoparticles in powder form by mixing a pre-calculated mass of powder with a certain mass or volume of lubricant to produce a nanolubricant. This method, known as the two-step method, faces challenges regarding the cost-effectiveness of producing carbon-based nanoparticles for industrial applications, such as the lubricant industry, which necessitates the integration of substantial quantities of nanoparticles into conventional lubricants. Although physical production methods can produce high purity nanomaterials, some of these methods are cost-effective but present challenges in controlling the nanomaterial parameters. Other production methods are costly as they require expensive high-technology equipment. On the other hand, chemical production methods are suitable for mass production, but they require additional processes such as washing and purification, which increase the final cost (Sui, 2021b). Moreover, apprehensions exist about the potential adverse effects of these nanoparticles on health of humans and animals, especially when handling dry nanopowders. Owing to their low density, these nanoparticles can become airborne, inhaled, and subsequently accumulate in the lungs. Additionally, they can settle on the eyes and skin, potentially causing severe health problems. The toxic and carcinogenic potentials of carbon-based nanomaterials were reported in previous studies. Depending on the dose, CNTs and/or associated contaminants are responsible for oxidative stress, inflammation, apoptosis, pulmonary inflammation, fibrosis, and granuloma in lungs (Francis and Devasena, 2018). When they reach lungs, CNTs are significantly more toxic than carbon black and quartz (Lam, 2003). Similarly, Liu J. et al. (Liu et al., 2015) reported the toxic effects of GO on laboratory mice. Functionalizing graphene with dextran can reduce the toxicity, but not eliminate it. However, the same toxic signs were reported at higher dosages.

This study aims to overcome the aforementioned challenges by proposing a novel approach suitable for mass production. In this approach, glucose—the most abundant and cost-effective

extractable monosaccharide in most crops—undergoes hydrothermal carbonization, which is a process often used in synthesizing carbon spheres in an aqueous solution to produce green carbon-based aqueous nanofluid (Liang et al., 2021). The resulting nanofluid is then mixed with a base oil at calculated volume ratios to create emulsions. A heating process is subsequently used to evaporate water molecules from the emulsion samples, resulting in carbon-based nano-lubricants. Characterizations, including viscosity and thermal conductivity measurements, as well as power consumption and wear measurements, are conducted on the prepared nano-lubricants. This method eliminates the exposure to dry nanopowders, thereby reducing the negative health impacts associated with nanoparticles, and it can be considered as green chemistry since it does not use toxic solvents or surfactants.

## 2. MATERIALS AND METHODS

### 2.1. Nano-lubricant preparation

Firstly, green biodegradable carbon-based aqueous nanofluid was produced via the hydrothermal carbonization, which is presented by (Chen et al., 2009; Karna et al., 2017; Sun et al., 2004), of medical grade aqueous glucose solution (5 wt./vol.%), which costed ID 1500 per 500 ml. The production procedure, which can be considered as green chemistry since it does not use toxic solvents or surfactants, followed the following steps:

The glucose solution, contained in a Teflon-lined steel autoclave, was placed in a well-controlled electrical furnace and maintained at 200 °C for 4 hours to complete the hydrothermal carbonization process.

After cooling to the room temperature, the sample was filtered to remove any impurities and large clusters. It was then sonicated using probe ultrasonic device (MTI company, model MSK-USP-3N, 300 W power, 20 kHz frequency) for 15 minutes at 30 % of its maximum power with an operating sequence of 2 seconds on and 2 seconds off.

Assuming complete conversion of the precursor (glucose) into carbon particles, the concentration of the synthesized carbon-based aqueous nanofluid was 20 g/l. The cost of 20 g carbon-based nanoparticles was ID 3000. Fig.2 shows a TEM image, which reveals the existence of carbon nanospheres (CNs) in the prepared aqueous nanofluid. Using ImageJ tool, the minimum and maximum size of the CNs were 3.59 nm and 24.12 nm respectively, and the average size was determined as 9.62 nm with a standard deviation (SD) of  $\pm 5.90$  nm.

Secondly, nano-lubricants were prepared according to the following steps, as presented schematically in Fig. 3:

The prepared nanofluid was mechanically mixed with the base lubricant (Al-Rasheed oil, SAE 15W-40, Doura Oil Refinery Plant) at volume ratios of 1:1, 0.75:1, 0.5:1 and 0.25:1.

The mixtures were heated to 80 °C to evaporate all water molecules, producing carbon-based nano-lubricants of 20, 15, 10 and 5 g/l (i.e., 1 %, 0.75 %, 0.5 % and 0.25 % volumetric concentration) respectively, as shown in Fig.4. One Liter of the higher concentration of the nano-lubricant costed ID 3000 higher than cost of the base lubricant. This extra cost is very low if compared to the cost of dispersing 20 g of carbon-based nanoparticle (purchased from any commercial company or supplier) in 1 Liter of the based lubricant. Table 1 shows prices of carbon-based nanopowders from the well-known supplier (SIGMA ALDRICH, <https://www.sigmaaldrich.com/>)

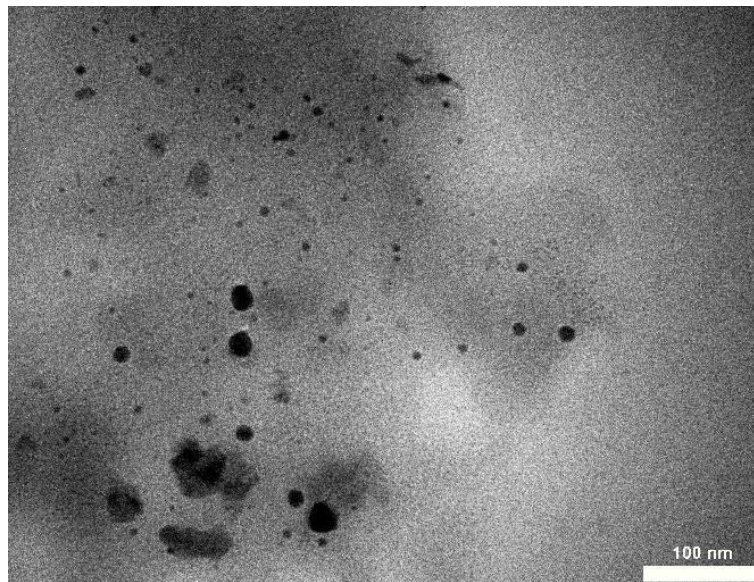


Fig.2. TEM image of the carbon spheres in the prepared aqueous nanofluid

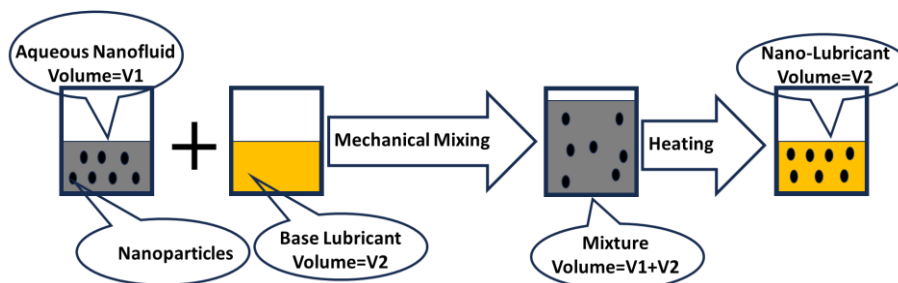


Fig. 3. Schematic diagram of the nano-lubricant preparation

The resulting nano-lubricants were stable, as no sediment was observed by flipping the samples up down during a month of shelf storage at temperature of 25-26 °C. Moreover, since the size of nanoparticles affects certain physical properties of nano-lubricants, such as thermal

conductivity and viscosity, these two properties were used as indicators of the aggregation ratio. Both the thermal conductivity and viscosity of the nano-lubricants were measured multiple times over the course of a month of storage, and negligible changes were detected.

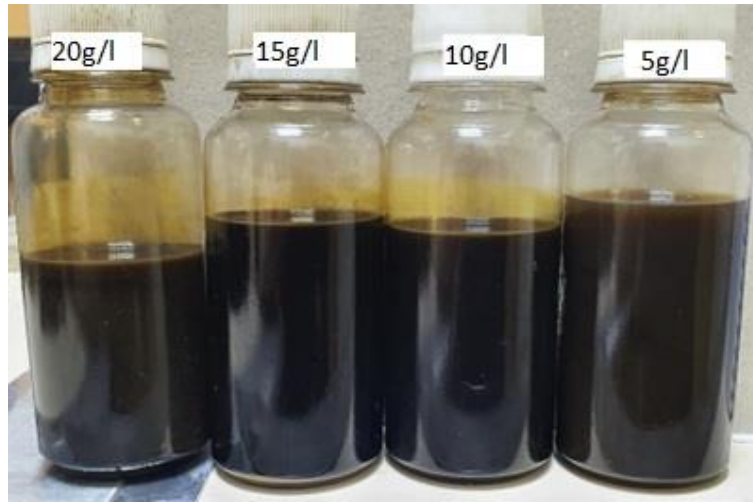


Fig.4. Photographic picture of the carbon-based nano-lubricants

Table 1: Prices of carbon-based nanopowders

Nanopowder	CAS	Pack	Price
Carbon nanotube, single-walled	308068-56-6	5 g	€692.00
Graphene	1034343-98-0	0.5 g	€552.00
Carbon, mesoporous	1333-86-4	5 g	€215.00
Graphene quantum dots	7440-44-0	50 mg	€298.00

## 2.2. Thermal conductivity and viscosity measurements

A well-calibrated thermal properties analyser device (KD2 Pro from Decagon Devices, Inc., USA) with a KS-1 sensor was used to measure the thermal conductivity of the base lubricant and the prepared nano-lubricants. The thermal conductivity of each sample was measured 3 times, and the average and standard deviation were calculated as illustrated in Eq. 1.

$$SD = \pm \sqrt{\frac{\sum_{i=1}^N (X_i - \bar{X})^2}{N}} \quad (1)$$

where:

$SD$ - Standard deviation.

$X_i$ -the value in the data distribution.

$\bar{X}$ - The sample average value.

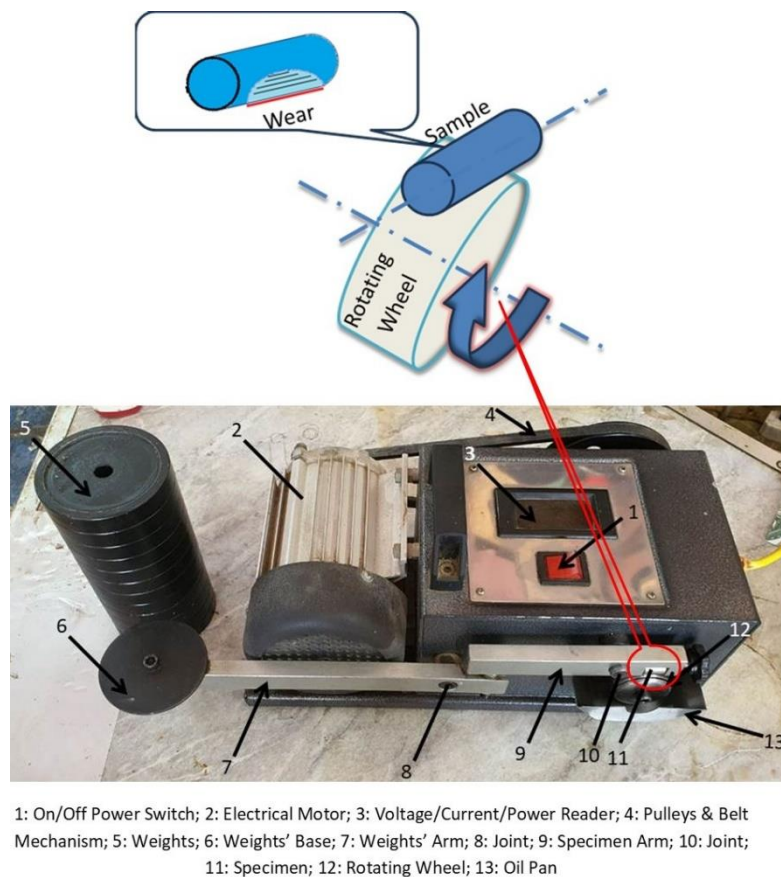
$N$ - Total number of measurements.

The viscosity of each sample was measured 3 times using a well-calibrated rotational viscometer (ONE model from Fungilab S.A., Spain), and the average and standard deviation values were calculated using Eq. 1.

## 2.3. Power consumption and wear analysis experimental setup

Fig.5 illustrates the wear-producing apparatus used in this study, which is based on ASTM-D5001-19. It mainly consists of an electric motor (2) that generates rotational motion, pulleys

and belt mechanism (4), which transfers this rotational motion to the rotating wheel (12). The rotating wheel, which rotates inside the oil pan (13), transfers the lubricant to a specimen (11) of standard steel, which is made of carbon steel of grade Ck50. Ten pieces of weight (5), each weighing 600 g, can be placed one on the top of the other on the weight base (6) to generate a pressure load, which is transferred to the specimen through the arms-joints mechanism (7, 8, 9, 10). The design of this apparatus ensures hydrodynamic lubrication at no load, and mixed and boundary lubrication with loads. The electrical power consumption of the motor, which is proportional to the friction force between the specimen and the rotating wheel, can be monitored using a power reader (3) of maximum error of  $\pm 0.5\%$ . The schematic inset diagram of the rotating wheel and the steel specimen shows the shape of the wear scar observed in the specimen with length presented by the red line. For each lubricant, the experiment was conducted under identical conditions, i.e., same volume of lubricant in the oil pan and the same weight load for the same time period to ensure a fair comparison.



**Fig.5. Wear generating device**

For each lubricant, the power consumed by the electric motor was recorded when the power reader (3) reaches a steady-state reading at each load. A 0% load means that no weight is placed on the weight's base, a 10% load means that one weight piece is placed on the base, a 20% load means two weight pieces are placed on the base, and so forth.

A DigiMicro Mobile Microscope (CMOS image sensor of 5 megapixels, magnification from 10 to 500x, from dnt®, Germany) was used to capture images of the resulting scars on the worn specimens. The length of the wear was determined using a standard-length measuring scale (with a resolution of ½ mm) and the ImageJ tool, which can calculate the length of each pixel. The wear length of each specimen was determined three times using the ImageJ, and the average value and standard deviation were then calculated using Eq. 1.

### 3. RESULTS AND DISCUSSION

#### 3.1. Thermal conductivity and viscosity results

As mentioned earlier in subsection 2.2, the thermal conductivity was measured 3 times for each sample, and the average and standard deviation values were calculated using Eq.1. The obtained data are listed in Table 2. It is obvious that low standard deviations were achieved with maximum value of 0.0026 W/m.K.

Similarly, the viscosity of each sample was measured 3 times, and the average and standard deviation values were calculated using Eq.1. The obtained data are listed in Table 3, and the maximum deviation was 1.152 cP.

To study the trend of the change of any property of the nano-lubricants, property ratios ( $r$ ) were used to compare the results of nano-lubricants with respect to that of the base oil. The thermal conductivity ratios of the nano-lubricants to that of the base lubricant were calculated and presented in Fig.6 as functions of the nano-lubricant concentration. The maximum thermal conductivity enhancement was 6 % for the sample with 20 g/l concentration. This enhancement may play crucial role in heat transfer in tribological systems. Also, the linearity of ( $r$ ) is clear, where ( $r$ ) increases as the concentration of carbon-based nanoparticles in the nano-lubricants increases. These results are consistent with many previous studies, which demonstrate that the effective thermal conductivity of a nanofluid increases with the rise in the concentration of the dispersed nanoparticles due to their higher thermal conductivity compared to that of the base fluid, such as (Arear et al., 2021; Sadiq Al-Baghdadi et al., 2020; Zeiny et al., 2022, 2019).

The ratios of the viscosity of the nano-lubricants to that of the base lubricant were also calculated and presented in Fig.6 as functions of the nano-lubricant concentration, with maximum value of 1.095 at a concentration of 20 g/l. The linearity of ( $r$ ) is obvious, where ( $r$ ) increases as the concentration of carbon-based nanoparticles in the nano-lubricants increases. It is evident that the slope of the viscosity line is steeper than that of the thermal conductivity line, indicating that adding carbon-based nanoparticles affects the viscosity of the lubricant more than its thermal conductivity. These results are consistent with many previous studies,

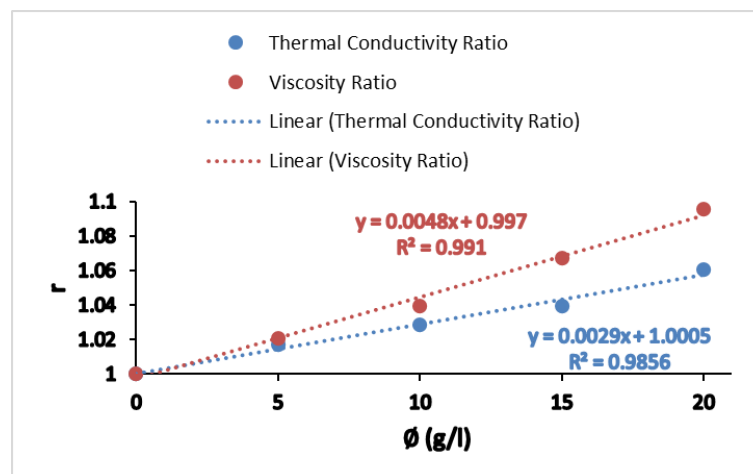
which demonstrate that the effective viscosity increases as the nanoparticle concentration increases due to the higher flow resistance caused by the presence of nanoparticles in the base fluid, such as (Arear et al., 2021; Sadiq Al-Baghdadi et al., 2020; Zeiny et al., 2022, 2019).

**Table 2: Measurements of Thermal Conductivity of Nano-lubricants**

Nano-lubricant's Concentration (g/l)	Measurements Reading (W/m.K)			Average ( $\bar{X}$ )	Standard Deviation ( $\pm SD$ )
	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>		
	reading	reading	reading		
0	0.267	0.272	0.273	0.271	0.0026
5	0.273	0.275	0.278	0.275	0.0021
10	0.277	0.278	0.28	0.278	0.0013
15	0.280	0.282	0.282	0.281	0.0009
20	0.290	0.287	0.284	0.287	0.0025

**Table 3: Measurements of Viscosity of Nano-lubricants**

Nano-lubricant's Concentration (g/l)	Measurements Reading (cP)			Average ( $\bar{X}$ )	Standard Deviation ( $\pm SD$ )
	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>		
	reading	reading	reading		
0	181.1	180.3	180.4	180.600	0.356
5	184.3	184.2	184.5	184.333	0.125
10	186.8	187.6	188.7	187.700	0.779
15	191.3	193.4	193.5	192.733	1.014
20	199.4	196.6	197.7	197.900	1.152



**Fig.6. Ratios of the thermal conductivity and viscosity of the nano-lubricants to the base lubricant**

### 3.2. Power consumption and wear results

The data of the power consumption of the electric motor for each prepared nano-lubricant under different loads are presented in Fig.7. The results show that there is no noticeable effect of the carbon-based nanoparticles on the power consumed by the electric motor at no load. Also, for a certain lubricant's concentration, the results clearly reveal that increasing the load results in an increase in the power consumption. This phenomenon can be interpreted physically relying on the analysis of the applied forces on the tribological system, as depicted schematically in

Fig.8, which shows a thin layer of lubricant surrounding the rotating wheel. Fundamentally, the power consumed by the motor is equal to.

$$P = F * R * \omega * \eta^{-1} \tag{2}$$

where:

$P$  – power [W]

$F$  – couple force [N]

$R$  – rotating wheel’s radius [m]

$\omega$  – rotational speed [rad/s]

$\eta^{-1}$ – reciprocal of motor efficiency

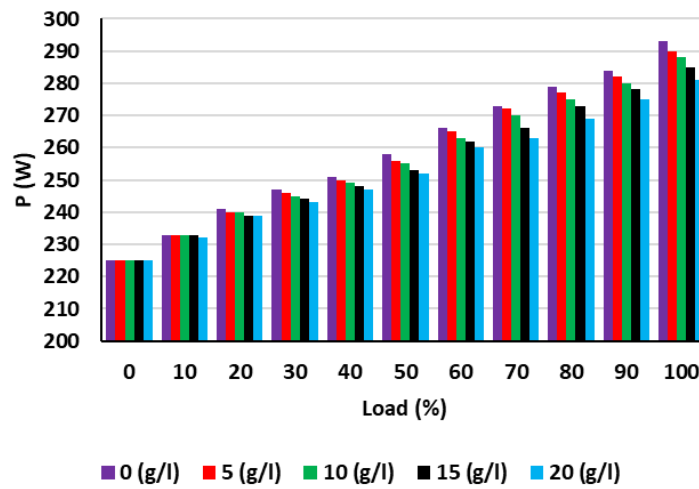


Fig.7. Power consumption vs. load for different concentrations of the nano-lubricant

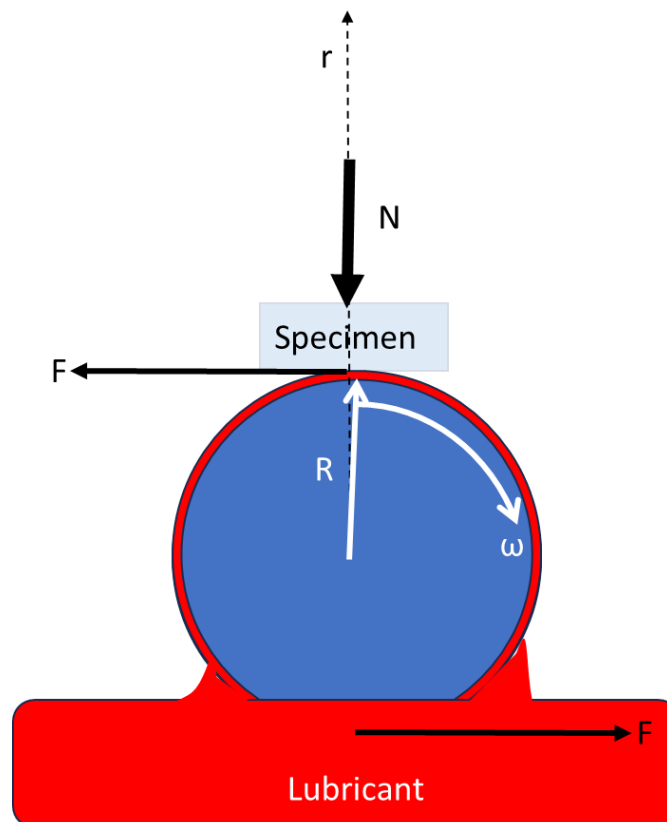


Fig.8. Forces acting on the tribological system

From Eq.2, it is obvious that the change in  $P$  is proportional to the change in  $F$ . In case of no load (i.e.,  $N \approx 0$ ), the change in the power consumption must be proportional to the change in the shear force ( $F_s$ ) acting on the interface between the lubricant and wheel surface. This shear force can be expressed as:

$$F_s = \mu * \frac{du}{dr} * A \quad (3)$$

where:

$\mu$  – dynamic viscosity of the lubricating oil [Pa.s]

$\frac{du}{dr}$  – radial rate change of the flow velocity at the wheel out surface [ $s^{-1}$ ]

$A$  – interface contact surface area of the rotating wheel.

Although the maximum change in the nano-lubricant viscosity ( $\mu$ ) is 9.95 %, the radial rate change of the nano-lubricant flow velocity at the wheel out surface is negligible (i.e.,  $\frac{du}{dr} \approx 0$ ), as the thin layer rotates at the same rotational speed of the wheel (no slip condition), which leads to infinitesimal amount of shear force (i.e.,  $F_s \approx 0$ ) acting on the rotating wheel, causing negligible increase in power consumption, which could not be detected by the power reader.

While in loading case, the friction between the specimen and rotating wheel can be expressed as:

$$F_f = C_f * N \quad (4)$$

where:

$F_f$  – friction force [N]

$C_f$  – friction coefficient

$N$  – normal load [N]

The design of the wear-producing apparatus magnifies the applied weight many times, making the normal force (N) very high, which increases the friction between the specimen and the rotating wheel, and consequently increases the power consumed by the electric motor.

Furthermore, as the load increases, the effect of the carbon-based nanoparticle concentration becomes more pronounced. In the boundary regime, the film thickness is usually less than 1  $\mu\text{m}$  (Holmberg and Erdemir, 2017b; Szeri, 1998); thus, the surface roughness significantly influences friction forces. The presence of carbon nanospheres (CNs) can reduce friction in this regime through the ball-bearing mechanism of spherical particles (Chinas-Castillo and Spikes, 2003; Rapoport et al., 2002; Tao et al., 1996; Wu et al., 2007), repairing and filling defects mechanism (Gulzar et al., 2016; Liu et al., n.d., 2019; Shang et al., 2018b, 2018a), polishing mechanisms (Nunn et al., 2015; Tao et al., 1996). Return to Fig.7, for a certain load (e.g., 100%), power consumption decreases as nanoparticle concentration increases. This is due to the increase in the number of the nanoparticles trapped between the friction surfaces (specimen

and rotating wheel). As the friction surfaces in relative motion come into contact, the nanoparticles roll instead of sliding, and this rolling behavior reduces friction significantly compared to sliding. Also, when the number of the nanoparticles trapped between the friction surfaces increases, the repaired defects via filling increase. Furthermore, polishing of the rough surfaces can be enhanced. All these mechanisms can reduce friction significantly, minimizing power consumption.

To quantify the effects of the load and nanoparticle concentration on the power consumption, the percentage of the power increase was calculated as follows:

$$\text{power increase (\%)} = \frac{P_i - P_0}{P_0} * 100 \Big|_j \quad (5)$$

Load  $i = 0, 10, 20, 30, \dots, 100\%$

Concentration  $j = 0, 5, 10, 15, 20\text{g/l}$

where:  $P_i$  and  $P_0$  – electrical power consumption (W) in case of the ( $i^{\text{th}}$ ) and no load respectively at ( $j^{\text{th}}$ ) nanoparticle concentration.

The results are displayed in Fig.9, which shows the linear relationship between the percentage of power increase and the nanoparticles concentration for each load, except 0% load, which has a slope of zero value. Also, it is clear that the slope of the lines increases (negative slope) as the load increases, indicating the beneficial impact of the presence of the carbon-based nanoparticles in the lubricant. The maximum reduction in the power consumption at full load was 16.66 % in case of using 20 g/l carbon-based nano-lubricant.

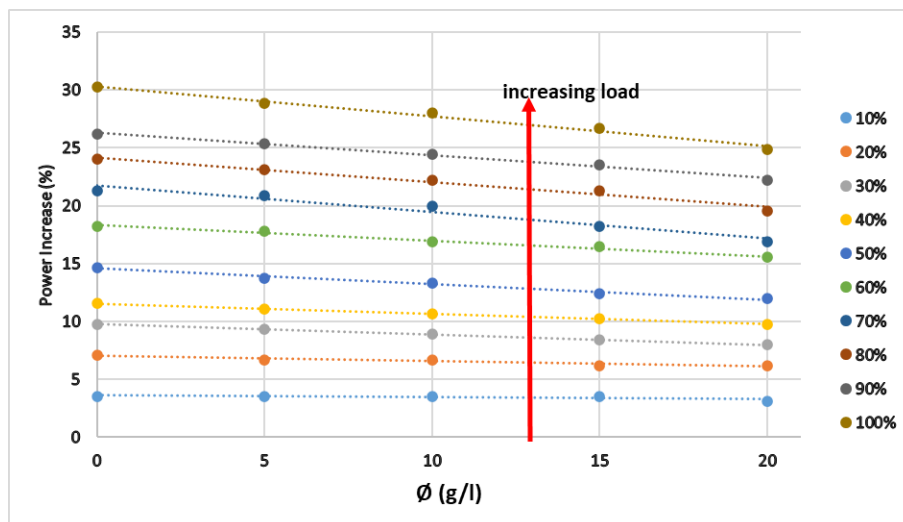


Fig.9. Percentage of the power increase against nanoparticles concentration for different loads

The pictures of the wear scar of each specimen are shown in Table 4. The wear length was determined 3 times by ImageJ and the average and standard deviation values were calculated using Eq.1. The reduction percentage of the wear length was calculated as follows:

$$\text{Reduction of wear length(\%)} = \frac{L_b - L_n}{L_b} * 100 \quad (6)$$

where:  $L_b$  and  $L_n$  – the wear length in case of base lubricant and nano-lubricant respectively.

The results are presented in Fig.10. The positive impact of employing carbon-based nanoparticles in lubricants is obvious, with the wear length decreasing as the concentration increases. The maximum reduction in wear edge length was 52.5 % in case of using 20 g/l nano-lubricant. This may be attributed to the ball bearing effect (Chinas-Castillo et al., 2003; Rapoport et al., 2002; Tao et al., 1996; Y. Y. Wu et al., 2007), where the dispersed spherical nanoparticles in lubricating oil play the role of rolling balls between friction surfaces. As the friction surfaces in relative motion come into contact under the applied load, the nanoparticles get trapped between the surfaces, rolling instead of sliding, and this rolling behavior reduces friction significantly compared to sliding. Also, protective film effect (Ginzburg et al., 2002; Hu et al., 2002; Lv et al., 2020; Zhou et al., 1999) can play useful role. In this case nanoparticles usually have charged chemical groups (such as  $OH^-$ ) that can be attracted to the charged friction surfaces making a protective film, which can be replenished continuously. This gain prolongs the life of tribo-systems significantly. Furthermore, the results revealed linear relationship between the percentage of wear reduction and nano-lubricant concentration.

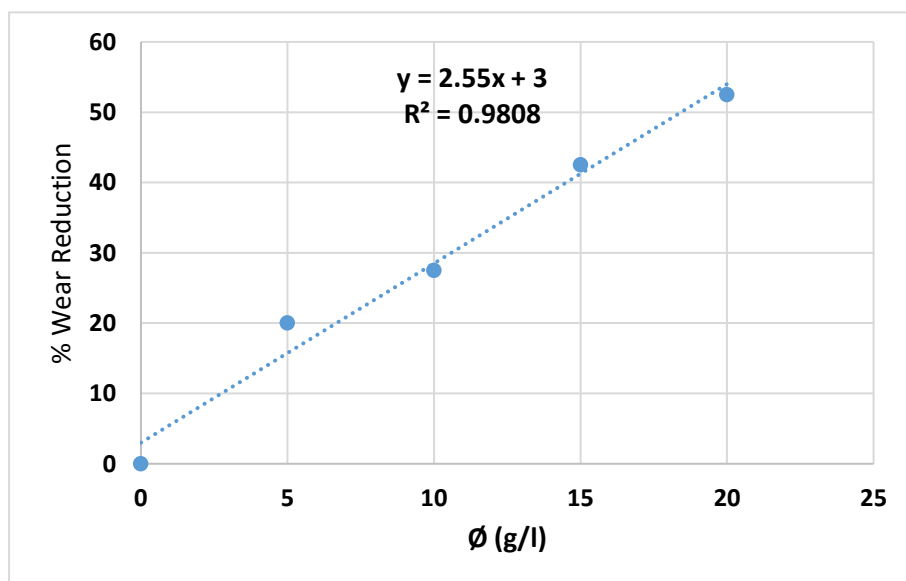
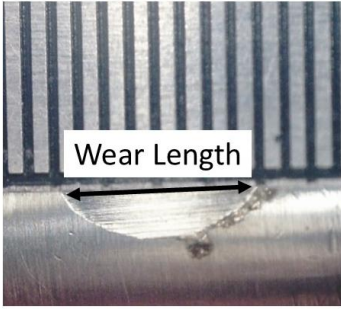
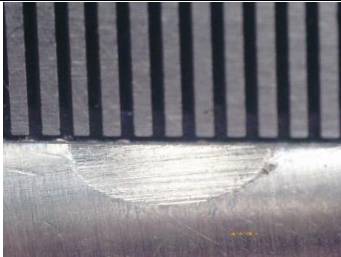





Fig.10. Wear reduction percentage against nano-lubricant concentration

**Table 4: Data of wear tests and calculations**

	Sample's Photo	Wear Length $\pm$ SD (mm)
Nanolubricant Concentration (g/l)	0 	4 $\pm$ 0.021
	5 	3.2 $\pm$ 0.036
	10 	2.9 $\pm$ 0.029
	15 	2.3 $\pm$ 0.012
	20 	1.9 $\pm$ 0.05

#### 4. CONCLUSION

In this study, a cost-effective approach that adheres to green chemistry principles was proposed and examined for the production of stable carbon-based nano-lubricants. The main findings are:

- Replacing conventional lubricants with carbon-based nano-lubricants, which were produced cost-effectively via a novel approach, reduces the electrical power consumption of tribological systems.

- Employing carbon-based nano-lubricants significantly reduces wear of tribological systems.
- Carbon-based nano-lubricants have higher thermal conductivity compared to the baseline lubricant.

This novel approach is a feasible solution to overcome current challenges regarding energy demand and environment issues.

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