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A comparative study on stability, thermal conductivity, and rheological properties of nanolubricant using carbon-based additive

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KEYWORDS

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Rheology
Stability
Viscosity
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ABSTRACT

This study investigates different thermophysical properties of lubricants added with fullerene, graphene, single-walled carbon nanotubes, double-walled carbon nanotubes, and multi-walled carbon nanotubes nanoparticles, with engine oil 10W-30 as the basic fluid. The samples of nanoparticles were prepared in 0.1wt% using two stages synthesis method. Further, we examined the nanoparticle's morphology, as well as the nanolubricants stability, viscosity, and thermal conductivity. Results show that the SWCNT has the smallest particle size then other nanoparticles. All nanolubricants stable after 3 days sonication. The dynamic viscosity test results show that the lubricant with MWCNTs has the highest viscosity, because the entangled structure of MWCNTs increases surface interaction, when dispersed in the fluid. The results of the thermal conductivity test on fullerene, graphene, SWCNT, DWCNT, and MWCNT nanolubricant indicate increasing thermal conductivity compared with base oil. The shape and size of nanoparticles affect thermal conductivity, cylindrical (Single-walled Carbon Nanotubes, Double-walled Carbon Nanotubes, and Multi-walled Carbon Nanotubes) and buckyball (Fullerene) structures have better thermal conductivity enhancement compared to platelet structure (Graphene). The shape, structure and size of the particles have an influence on stability, viscosity and thermal conductivity.

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1.0 INTRODUCTION

The issues of material and energy conservation are essential, especially at the current moment. The loss of energy caused by friction in mechanical systems can be decreased through lubrication. Besides, lubrication also prevents rust and functions as an isolator in the vehicle engines. Further, it also operates as a shield from dirt, dust, and water. Lubricants perform several important functions in addition to reducing wear, including reducing friction, heat dissipation, sealing critical areas and various other important properties to maintain optimal engine performance (Ahmed Ali et al., 2019). The effectiveness and efficiency of vehicle engine performance is greatly influenced by the condition of the lubricants used, the selection of lubricants is generally done by adjusting the needs of motorcycle engines with lubricant specifications (Suprayitno & Ruslan, 2021). An excellent lubricant has high viscosity index, high boiling point, normal stability, low freezing point, corrosion prevention capacity, and high oxidation resistance (Mobarak et al., 2014).

Improving lubricant performance can be achieved by adding nano-sized additive particles called nanolubricants (Irawansyah et al., 2018). The addition of nanoparticles as an additive to lubricants can improve thermophysical properties (thermal conductivity, density, viscosity, etc.) (Kumar et al., 2015; Gong et al., 2021). In addition, thermophysical properties (thermal conductivity, density, viscosity, etc.) are also affected by variations in volume, shape and dimensions, as well as the concentration of nanoparticles (Kotia et al., 2019). According to Mousavi et al., (2019) the addition of nanoparticles to lubricants results in higher thermophysical properties because of nanoparticle additives. The addition of nanoparticles can improve the tribological properties of lubricants by settling in the contact area and forming a protective layer (Puspitasari et al., 2023; Zulkifli et al., 2013).

Peng et al., (2009) describe four roles of nanoparticles in their addition to oil. First, the nanoparticle can interact with the friction contact surface to form the surface-protecting filament easily. Second, the small spherical nanoparticle has a greater tendency to roll between surfaces, altering the friction force. Third, voltage concentration related to high contact pressure can be reduced by applying abundant nanoparticles which can endure pressure. Fourth, the nanoparticle precipitated on the surface form a physical tribo-film that compensates for the loss of mass, known as repairing effects. These four mechanisms describe the excellent friction and wear feature of nanoparticles added into the basic fluid.

The usage of nanoparticles as an additive of lubricant should consider several factors, including the size, shape, hardness, and weight of nanoparticles. On average, the nanoparticle's size ranges between 2-120 nm (Rudnick, 2006). Further, Wu et al., (2007), on modification of copper nanoparticles with dialkyl dithiophosphate (DDP) as an additive on liquid paraffin, reported that a smaller nanoparticle size has a greater tendency to interact with friction pair surface, forming a surface protective layer to enhance its anti-wear ability. Rapoport et al., (2005) uncovered that the inorganic fullerene-like (IF) particle friction within oil offers the benefit of the IF ball shape, generating a possibility for an effective rolling friction mechanism. Hu et al., (2000) added amorphous lanthanum borate nanoparticle size 20-40 nm into a mineral base oil, resulting in excellent wear resistance of Boron trioxide (B_2O_3) and ferro boron (FeB). Ganesh & Prabhu S., (2022) added micro graphite, multi-walled carbon nanotubes (MWCNT) and zinc oxide (ZnO) into cutting fluid oil, showing that the oil with 0.1% wt MWCNT had the best wear resistance.

A number of studies have proposed several mechanisms for identifying the performance of nanoparticles as additives in oil material functioning to lower friction and wear (Rahman et al., 2023). Chinas-Castillo & Spikes (2000) investigates the mechanism of solid colloid nanoparticles on lubricant oil. This study observed the ability of nanoparticles to pass through rolling contacts by forming filaments at low speeds, the filaments formed by colloids have a size similar to the particle size or twice the particle size. Besides, at high speed, the filament of the nanoparticle cannot be re-formed on its surface, especially when the filament is thicker than the particle's diameter.

This study aims to compare the stability, conductivity, and rheology of nano lubricants based on Fullerene, Graphene, SWCNT, DWCNT, and MWCNT. After we prepared the nanofluid, its stability, conductivity, and rheology were measured. Further, the variation of viscosity of nanofluid was also investigated as a sliding rate function toward the temperature. Then, the nanofluid rheology characteristic was also compared.

1.0 EXPERIMENTAL

2.1 Material

This study used 10W-30 engine oil as the base lubricating oil. Meanwhile, Fullerene, Graphene, SWCNT, DWCNT, and MWCNT nanoparticle were used as the additive and purchased from Nanomaterials Company in China. The detailed information on each nanoparticle is presented in Table 1.

Table 1: Details of material used in this present.

Name	Supplier/Product Code	Purity [%]	Density [g/cm^3]
Engine oil	Shell advance 10W-30	-	-
Fullerene C60	XFNano	99,5	-
Graphene KNG-150	KNano	98	~0.15~0.2
SWCNT	XFNano	>95	~0.14
DWCNT	XFNano	>95	~0.15
MWCNT	XFNano	>95	~0.19

2.2 Nanolubricant Preparation

In this study, we used two stages method for the nanolubricant synthesis, as illustrated in Figure 1. The nanoparticle with 0.1 wt% concentration mixed with 200 ml of base oil using a magnetic stirrer at 1200 rpm for 15 minutes, nanoparticle concentration of 0.1 wt% was chosen because it has the best performance for reducing wear in engine oil (Alqahtani et al., 2022; Wang et al., 2019). This two-stage method involves a set of techniques for improving the stability of the nanoparticle within the basic fluid, such as the sonication technique for 15 minutes using a KG-MT3N sonicator.

2.3 Physical Properties Measurement

Scanning electron microscopy (SEM) is an analysis technique for measuring the size and morphology of an additive nanoparticles (Pramono et al., 2023; Schatten, 2014). In this study, we conducted SEM analysis using SEM with FEI brand type Inspect-S50. Data stability was obtained through lubricant sedimentation at 0, 12 and 24 hours after sonication. This technique accelerates the acquisition of results while showing clear agglomeration and sedimentation of the sample in the vial.

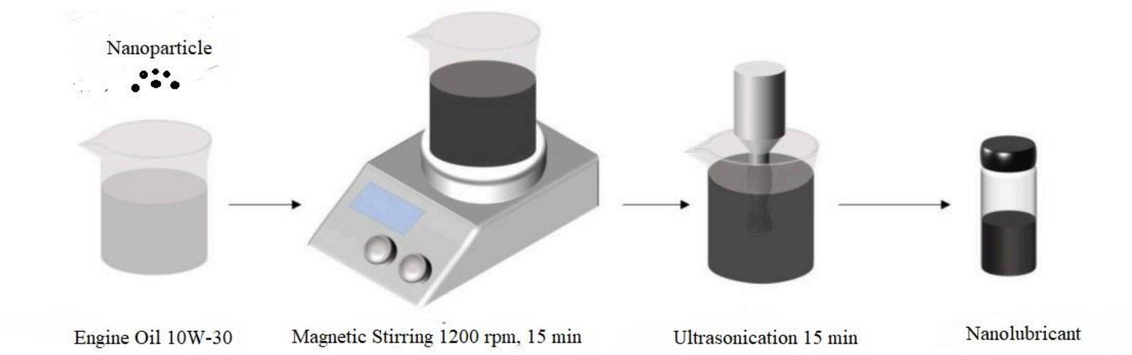


Figure 1: Preparation of nanolubricant.

2.4 Thermophysical Properties Measurement

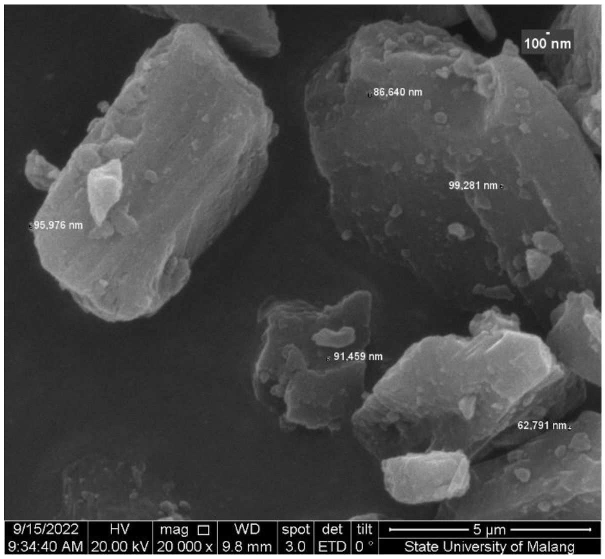
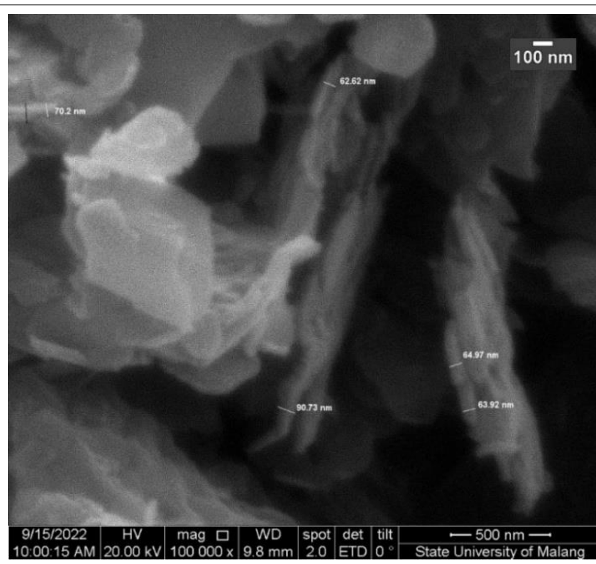
In this study, the thermal conductivity test on nanolubricant samples used the KD2-Pro instrument. The dynamic viscosity was attained using the viscometer by placing the liquid into the rotor selected based on the types of liquid. In this study, we used a viscometer NDJ-8S with one rotor, suitable for the oil-based fluid. This viscosity measurement was carried out at 20 – 60°C temperature with a shear rate of 22.2 s^{-1} – 111.2 s^{-1}.

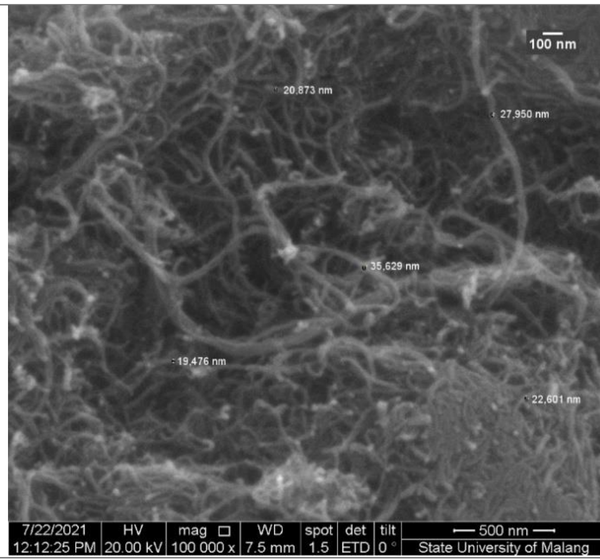
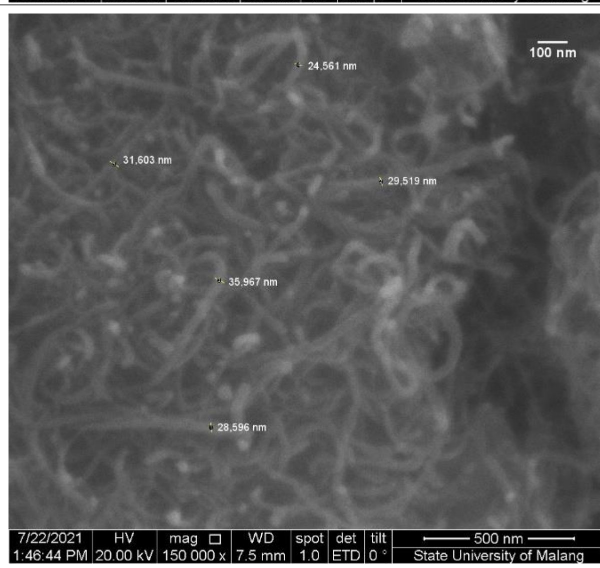
2.0 RESULTS AND DISCUSSION

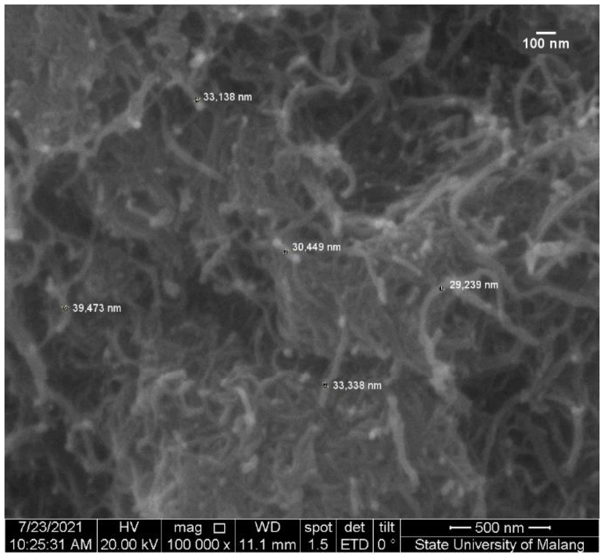
3.1 Characterization of Nanoparticles

The obtained morphology of nanomaterial with different magnifications is summarized in Table 2. Table 2 shows that Fullerene nanoparticles have an angular particle shape with an average grain size of 87.229 nm, Graphene nanoparticles have a platelet particle shape with an average grain size of 70.488nm, while additive nanoparticle SWCNT, DWCNT and MWCNT have a waved cylinder particle shape and there are agglomerations with an average particle size of 25.306nm, 30.049nm and 33.127nm (Ivanov et al., 2012; Ku et al., 2010; Zhang & Li, 2009; Clara et al., 2020).

Table 2: Results of SEM on nanoparticles.

<table>
<tr><th>Nanoparticle</th><th>SEM Characterization</th><th>Average Grains</th></tr>
<tr><td>Fullerenece C60</td><td>
</td><td>87,229 nm</td></tr>
<tr><td>Graphene KNG-150</td><td>
</td><td>70,488 nm</td></tr>
</table>

SWCNT		25,306 nm
DWCNT		30,049 nm

MWCNT		33,127 nm

3.2 Stability of Nanolubricant

Analysis of the stability and dispersion characteristics of nanoparticles is essential for enhancing the nanofluid’s heat transfer capacity (Iacobazzi et al., 2019). Che Sidik et al. (2017) describe that nanofluid tends to agglomerate, resulting in the loss of efficient heat transfer ability. The sediment on nanofluid is induced by numerous factors, such as the nanofluid’s pH, potential Zeta between nanoparticles, nanoparticle’s shape and size, nanoparticle’s concentration in primary fluid, and forces on those particles, such as the gravitational force, Van der Waals force, buoyant force, and electrostatic repulsion force (Al-Janabi et al., 2021a). Ghadimi et al. (2011) describe that sedimentation particle caused by robust Van der Waals force between the nanoparticle and basic fluid is a central challenge in the homogeneous fluid. Aside from lowering the effective thermal conductivity, particle agglomeration also causes blockage on the micro lines (Li et al., 2019).

Table 3 shows the comparative images of the samples in 0, 12, 24 and 72 hours. These results definitely depict no sedimentiation in every nanolubricant sample during the investigation period, decrease in sedimentation speed of the nanoparticles and improvement of nanofluid stability (Ghadimi et al., 2011). Nanolubricant is claimed to be stable if it does not agglomerate and has no slow particle deposition (Zainon & Azmi, 2021). In this study, the Fullerene, Graphene, SWCNT, DWCNT, and MWCNT are the non-polar compounds, carrying positive influences when mixed with the akin basic fluid. Our findings from visual analysis are linear with the results reported by Rahman et al. (2022); Sarsam et al., (2016); Wang et al., (2021); Xie et al., (2021) and Xing et al., (2014) which show that Graphene, SWCNT, DWCNT, MWCNT and Fullerene nanoparticles have good stability when used as additives to oil.

Table 3: Visual stability of nanofluids at different times after sonication.

Sample Name	0 hour	12 hours	24 hours	72 hours
Oil + Graphene 				
Oil + SWCNT 				
Oil + DWCNT 				
Oil + MWCNT 				
Oil + Fullerene 				

3.3 Dynamic Viscosity

The viscosity data of 10W-30 engine oil and the carbon-based nanofluid samples toward shear rate and temperature variations show tendencies of decreasing viscosity following the higher temperature, as illustrated in Figure 2. It occurs due to the more speedy movement of kinetic energy or molecular heat within its area, which reduces the binding energy between molecules, decreasing the viscosity (Igwe, 2004). The expansion of temperature boosts the distance between the molecules of the nanoparticle and the basic fluid, lowering the durability of nanolubricant flow and viscosity (Harchaoui et al., 2023). In general, the maximum viscosity index was identified from the MWCNT nanolubricant, because the entangled structure of the MWCNT increases the surface interactions, when it is dispersed in the fluids. The increased surface interactions could also contribute to the increase in the viscosity of the nanofluids (Kumaresan & Velraj, 2012). The high viscosity index characterizes excellent lubricant (Mobarak et al., 2014).

It can be seen in Figure 2 that the carbon nanotubes (CNT) based nanolubricant sample has the highest viscosity value when compared to Fullerene and graphene nanolubricants, this is because CNT-based nanoparticle additives have a smaller particle size when compared to Fullerene and Graphene (can be seen in table 3). Based on research from Esfe & Rostamian (2019) and Sergis & Hardalupas (2011) shows that the viscosity value of the nanolubricant sample is influenced by the size of the nanoparticle additive, the smaller the particle size, the more the viscosity value of the lubricant increases. However, the effect of particle size again depends on the particle shape. If the particle size or diameters are the same but the shape is different as being spherical and cylindrical, then viscosity and other properties will different (Koca et al., 2018).

At 20°C temperature, the Fullerene and DWCNT nanolubricant can be treated as a Newtonian fluid. However, at 30°C - 60°C temperature, all nanolubricant samples have a non-Newtonian attitude. Further, the increase in shear rate increases the viscosity, known as shear thickening flow behavior, which can be caused by nanoparticle rotation and different molecular sizes on the nanolubricant. The more significant number of fluid rotations tends to generate a shear-thickening flow, the opposite of shear thinning flow (Mezger, 2015).

The base oil and Graphene nanolubricant at temperature 60°C can be treated as a Newtonian fluid because has a linear viscosity. This is because base oil and graphene nanolubricant has more rotational motion due to its shape. The more rotational motion the fluid has the more it tends to be shear-thickening flow behaviour, which is the opposite of shear-thinning flow behaviour (Al-Janabi et al., 2021b).

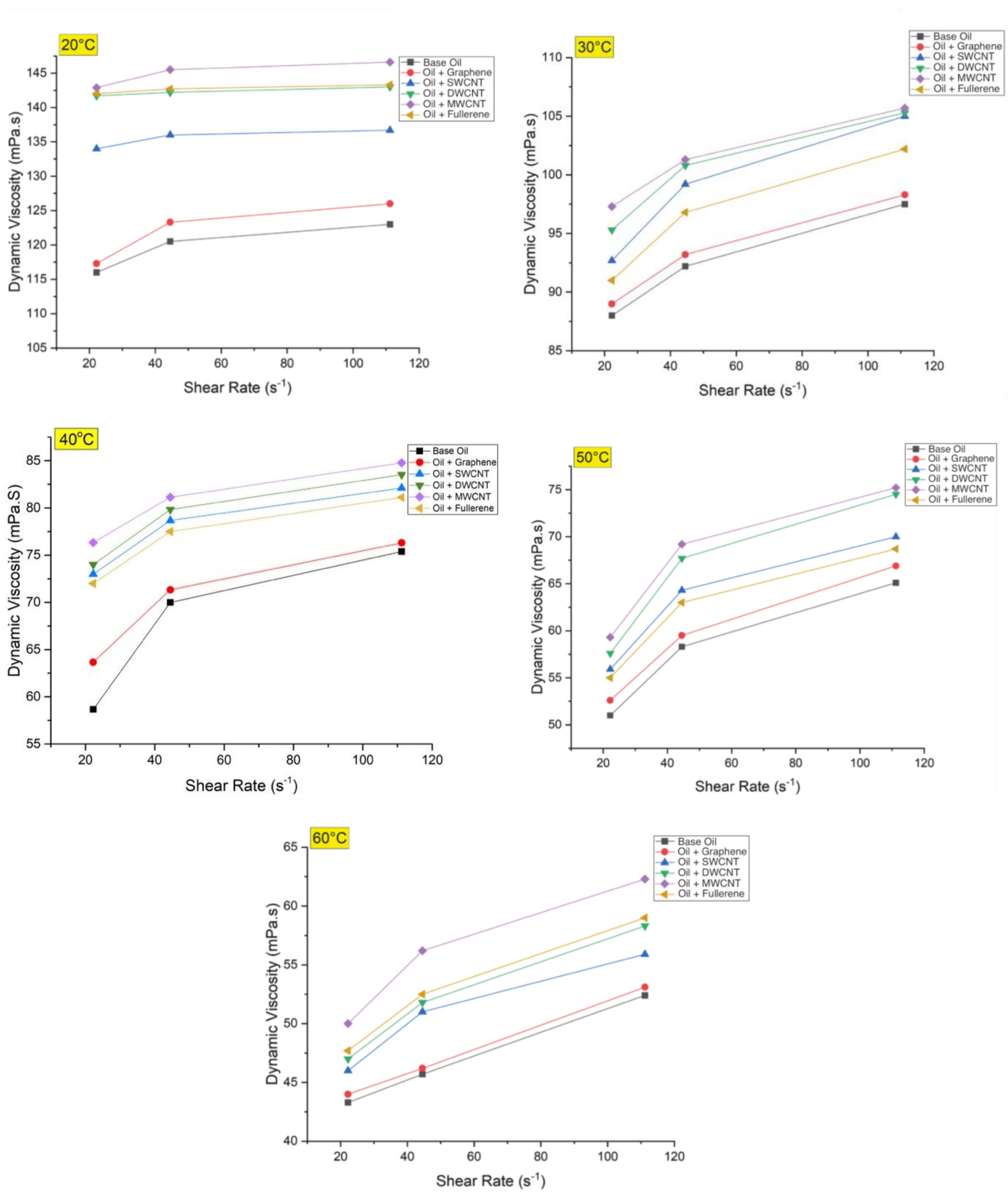


Figure 2: Dynamic viscosity of nano lubricant samples with shear rate variation and different temperature.

3.4 Thermal Conductivity

Figure 3 shows the thermal conductivity for the 10W-30 engine oil (basic fluid) and nanofluid samples based on carbon in W/m.K. In general, the thermal conductivity was found on the basic fluid sample. Meanwhile, the best thermal conductivity of carbon-based nanofluid was identified from the Fullerene and DWCNT nanolubricant samples (0.147 W/m.K), followed by the SWCNT and MWCNT samples (0.146 W/m.K). This occurrence is induced by the surface coating around the nanoparticle formed by the molecule in the basic fluid and the improve thermal conductivity on the nanolayer surface than the basic fluid, resulting in a higher thermal conductivity (Sadri et al., 2017). The addition of nanoparticles into the samples improving thermal conductivity, indicating the crucial role of carbon-based nanoparticles in improving the thermal properties of the lubricant. Similar research conducted by Naddaf & Zeinali Heris (2018) shows that the addition of Graphene nanoparticles and MWCNT to diesel oil can increase the thermal conductivity value compared to pure diesel oil at the constant temperature.

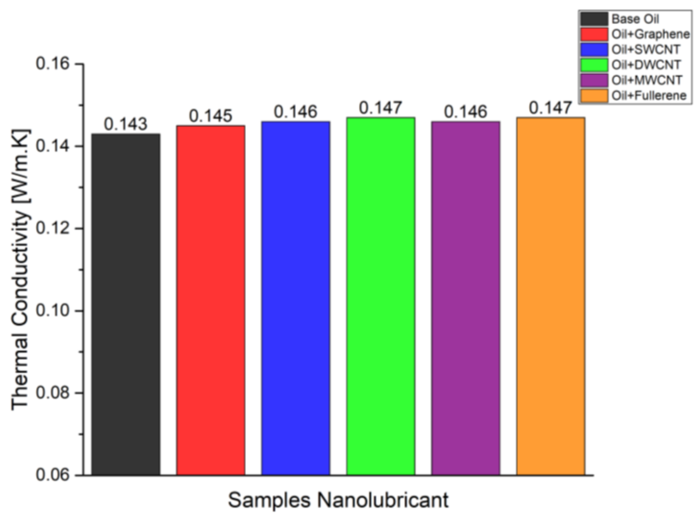


Figure 3: Thermal conductivity of nanolubricant samples at 25°C temperature.

The increase of thermal conductivity from our samples ranges between 1.4 - 2.8%. The low thermal conductivity enhancement is also due to the low fraction of the nanoparticles. For the ordinary solid-liquid mixture, the thermal conductivity increases due to the higher thermal conductivity of solid particles and hence the effective thermal conductivity of nanofluids is some kind of average thermal conductivity of the liquid and solid (Samani et al., 2012). So Larger weight concentration means more solid particles and more Brownian motion (Nabati Shoghl et al., 2016). It is well known that a good dispersion of nanofluid has an important role in its thermal properties.

The SWCNT, DWCNT, and MWCNT appear to have a cylinder shape since it contains a graphene roll sheet (Clara et al., 2020). Meanwhile, the Fullerene C60 has a spherical shape. The structure of Fullerene is similar to graphite, containing of a connected hexagonal ring, but the Fullerene has pentagonal ring (sometimes heptagonal) that prevents transformation of sheet shape into planar. Buckyballs and buckytubes are the terms use to illustrate them, depending on their shape.

Thermal conductivity is strongly associated with the nanoparticle's concentration, size, shape, and type, as well as the temperature and types of basic fluid (Mahamude et al., 2021; Zainon & Azmi, 2021; Sajid & Ali, 2018). Both the particle size and shape have effects on the enhancement of thermal conductivity and viscosity (Jeong et al., 2013), based on research conducted by Timofeeva et al. (2009) that the platelet structure has lower thermal conductivity than the bricks and cylinder's structure, platelet structure ≈ blades < bricks < cylinder. Brick shaped nanoparticles possess higher thermal conductivity than platelet and blade shaped nanoparticle (Kim et al., 2015). The thermal conductivity of nanofluid get improved with the decreased nanoparticle size (Ali & Salam, 2020). If the particles are of small size, Brownian motion becomes prominent. Hence, chaotic movement increases in the base fluid. Hence, thermal conductivity of nanofluid get increased. The surface to volume ratio increases if the size of particle decreases (Kazemi-Beydokhti et al., 2014). Higher thermal conductivity enhances heat transfer coefficient, thermal penetration, and faster thermal distribution (Nabi et al., 2022). The increase in thermal conductivity decreases the operational cost as well as accelerates the thermal efficiency and performance (Aly, 2014).

CONCLUSIONS

In this study, we analyzed the stability, thermal conductivity, and rheology properties of Fullerene, Graphene, SWCNT, DWCNT, and MWCNT nanolubricant. From the results, we obtained a number of conclusions, as described in the following.

a. The result of morphology nanoparticle show that the SWCNT has the smallest particle size then other nanoparticles.
b. The results of the stability test show that all nanolubricant has stable after 3 days sonication.
c. Results of the dynamic viscosity test on show that the lubricant with MWCNT has the highest viscosity, because the entangled structure of the MWCNT increases the surface interactions, when it is dispersed in the fluids.
d. The results of the thermal conductivity test on Fullerene, Graphene, SWCNT, DWCNT, and MWCNT nanolubricant indicate increasing thermal conductivity compared with base oil. The shape and size of nanoparticle influence the thermal conductivity, the cylinder structure (SWCNT, DWCNT, MWCNT) and buckyball (Fullerene) has better thermal conductivity improvement than platelet's structure (Graphene).

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