Air Conditioning Compressor Oil Enhancement using Carbon-based Nano-lubricants

Hessah ALTHALAB[1], Naser ALI[2], Shikha A. EBRAHIM[1], Ammar M. BAHMAN[1,*]

[1]Kuwait University, College of Engineering and Petroleum, Mechanical Engineering Department, Kuwait City, Kuwait
h.althalab@ku.edu.kw, shikha.ebrahim@ku.edu.kw, a.bahman@ku.edu.kw

[2]Kuwait Institute for Scientific Research, Nanotechnology and Advanced Materials Program, Energy and Building Center, Kuwait City, Kuwait
nmali@kisr.edu.kw

* Corresponding Author

ABSTRACT

The evolution of air conditioning systems, alongside new refrigerants, highlights the importance of studying compressor lubricants. Employing nanolubricants in heating, ventilation, and air conditioning (HVAC) systems will result in improvement in heat transfer, reduction in energy consumption, and overall system performance enhancement, thereby advancing efficiency in HVAC systems operations. In this work, we integrated short single-walled carbon nanotubes (Short-SWCNTs), short multi-walled carbon nanotubes (Short-MWCNTs) as well as graphene into POE32 oil to enhance the overall thermophysical and tribological properties of the mixture for compressors applications. Stability characteristics such as dispersion stability and sedimentation behavior were assessed using the two-step method to ensure the uniform dispersion of nanoparticles within the oil and enhance the homogeneity of nanolubricant. In this study, the investigated nanoparticles were analyzed at various volume fractions (0.01, 0.025, 0.05, and 0.1 vol.%) to identify the concentration for optimal stability performance. The experimental results showed that the samples have long term stability with short-MWCNT that has the highest stability. In summary, this study is pivotal for optimizing nanofluid stability in energy-efficient air conditioning compressors.

1. INTRODUCTION

Nanofluids have earned significant attention in recent years due to their promising enhancement to various industrial related applications, especially in heating, ventilation, and air conditioning (HVAC) systems (N. Ali et al., 2021). In general, they are categorized as advanced types of suspensions since the host liquid contains dispersed nanoparticles that have an average apparent particle size of 1nm to 100 nm. The basefluid itself can be of any type, *e.g.,* water, oil, ethylene glycol, etc. As such, the basefluid should not chemically react with the particles nor cause them to dissolve into forming a solvent (*i.e.,* should maintain a suspension form). Furthermore, the dispersed particles can be of metallic, metal oxides, or carbon-based origin as well as their combinations or alloy form. Carbon-based nanomaterials in specific are known for their tremendous thermal and tribological properties. For instance, one of the commonly used nanoparticles for fabricating nanofluids are multi-walled carbon nanotubes (MWCNTs) due to their notably high thermal conductivities and surface lubrication effect. The nanofluids can be produced using devices for mixing or growing the nanoparticles, or recently via effervescent tablets (N. Ali et al., 2023; Alsayegh et al., 2024).

Many studies have shown the positive impact of carbon-based nanomaterials on the thermophysical properties and tribological performance of the basefluid. For instance, Ahmadi et al. (2013) evaluated the effect of MWCNTs on engine oil, and their results showed that the thermal conductivity increased with the increase of concentration, reaching a 22.7% enhancement with only 0.5 wt.% of the dispersed carbon-based nanomaterial. P. G. Kumar et al. (2017) investigated the addition of MWCNTs to ethylene glycol (EG) used in solar collector system, resulting in an improvement of 30.59% in thermal conductivity at a concentration of 0.6 vol.%. N. Ali (2022) evaluated the effect of preparation temperature, surfactant ratio and concentration on the thermal conductivity as well as the stability of graphene nanoplatelets (GNP) dispersed in water, at a concentration of 0.1 vol.%. The results showed that the thermal conductivity increased more than double that of the basefluid, reaching an increase of 125%. Yarmand et al. (2016) reported that temperature increase had a dominant effect on the increase of thermal conductivity. They also showed that increasing the concentration of functionalized GNP dispersed in water lead to an improvement in the property up to 19.68%, when using 0.1 wt.% with mixture temperature at 40°C. Harish et al. (2012) evaluated the enhancement of thermal conductivity of single-walled carbon nanotubes (SWCNTs)/ EG nanofluid. The 0.21 vol.% sample resulted in a 14.8% increase in thermal conductivity over that of the hosting liquid. Sandhu & Gangacharyulu (2017) analyzed the effect of temperature on thermal conductivity of MWCNT dispersed in water/EG mixture. The change in water to EG ratio was also investigated, showing that the maximum increase in thermal conductivity can reach up to 28%, when a ratio of 50:50 water/EG was employed with a fixed temperature of 50°C. Iranmanesh et al. (2016) investigated the effect of varying both the concentration and temperature of GNP nanofluid on the thermal property of the suspension. The concentration was varied from 0.05 wt.% to 0.1 wt.%, while the temperature was explored from 20 to 60°C. The results showed that the GNP nanofluid at 60°C and a concentration of 0.1 wt.% had the highest thermal conductivity increase equivalent to 30.7%. Xing et al. (2016) evaluated three types of CNTs (short-SWCNTs, long-SWCNTs, and long-MWCNTs) dispersed in deionized water while varying both temperature and concentration of the nanofluid. The outcome illustrated that all three types of carbon-based nanomaterials caused an increase in the thermal conductivity. However, the highest increase was found at temperature of 60°C and concentration of 0.1 wt.%, at which the thermal property improved by 16.2%, 8.1% and 5% for the long-SWCNT, short-SWCNT and long-MWCNT, respectively. Zhang et al. (2016) compared the results of three types of carbon-based nanoparticles (SWCNTs, graphene and graphite) dispersed in ionic liquid. The authors used a temperature range of 20 to 45°C along with two mass fractions (*i.e.,* 0.005 and 0.01%). Their results indicated that the highest thermal conductivity was obtained when 0.01% mass fraction of graphene was dispersed in the basefluid.

To further understand the effect of nanomaterials on air conditioning compressor's oil, researchers investigated the thermophysical properties of lubricant basefluids. For instance, Sharif et al. (2016) investigated the thermal conductivity of nanolubricants containing Al_2O_3 nanoparticles dispersed in PAG oil. The results showed that the thermal conductivity increased for higher volume concentrations with an enhancement of 4% for concentrations up to 1.0%. Aljuwayhel et al. (2023) examined the increase of thermal conductivity in nanodiamonds (NDs) mixed with POE32 oil. The thermal conductivity of the nanolubricant was calculated while varying the temperature and ND volume concentration. They found that thermal conductivity increased with both temperature and ND volume fraction, reaching a peak of 15% at a concentration of 0.5 vol.% and a temperature of 10°C. Redhwan et al. (2017) studied the dispersion of Al_2O_3 and SiO_2 in PAG oil. The results of the study showed that the thermal conductivity of both Al_2O_3/PAG and SiO_2/PAG nanolubricants increased with the volume concentration but decreased with the temperature. The highest thermal conductivity recorded was for Al_2O_3/PAG nanolubricant at 1.0 vol.%, with a 4% increase over that of the base lubricant, while SiO_2/PAG nanolubricant exhibited slightly lower thermal conductivity compared to the previous type of nanolubricant. In addition, the thermal conductivity tends to decrease with the raise in suspension temperature.

Although the aforementioned literature demonstrated how dispersed nanomaterials in a basefluid can highly improve its thermophysical performance, the optimum harvesting of these materials' potential in a liquid can only be achieved once they are homogenously dispersed and physically stable. This was confirmed by N. Ali et al. (2021), Almurtaji et al. (2020), and Azman & Samion (2019) for properties such as the viscosity, thermal conductivity, and tribological performance, respectively. Figure 1 demonstrates the effect of suspension stability on its properties. In terms of tribological performance, the clustered nanomaterial in an unstable nanolubricant bounds their free motion, and thus causes them to be easily pushed out from the microstructure of the rubbing surface. As such, this would prevent the penetration of the nanomaterial to the rubbing surface, and consequently causes the coefficient of friction (COF) to increase (M. K. A. Ali et al., 2016; Kogovšek & Kalin, 2014).

From the previous literature, it can be concluded that understanding the different factors affecting the thermophysical properties and dispersion stability of nanolubricants is crucial for optimizing their performance towards addressing the challenges in modern engineering applications. This will also pave the way for more sustainable systems across various industries, especially for HVAC applications. As such, this research work explores the dispersion stability of three types of carbon-based nanolubricants, namely graphene, short-SWCNTs, and short-MWCNTs dispersed in POE oil with concentration range of 0.01 to 0.1 vol.%. In addition, the as-prepared nanolubricants were characterized in terms of their dispersion physical stability using three methods, ultraviolet-visible (UV-Vis) spectrophotometer, zeta potential measurement, and image capturing approach. The outcome of this study would provide an insight on how different carbon-based nanomaterials influences the physical stability of nanolubricants once fabricated in a similar

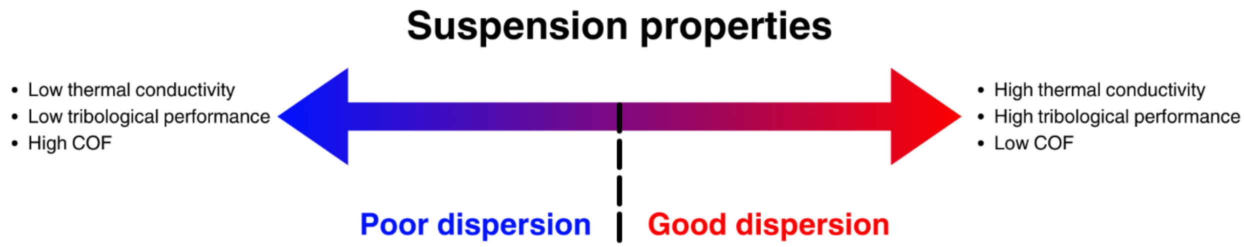

Figure 1: Effect of nanomaterial dispersion stability on the suspension thermophysical and tribological properties.

route of production for implementation in air conditioning compressors.

2. MATERIALS AND METHODS

2.1 Starting Materials

Three carbon-based nanomaterials in the form of powders were used in this study. This includes commercial graphene, short-SWCNTs, and short-MWCNTs nanopowders. The graphene nanomaterial used was obtained from XFNANO Co., and consist of 3 to 8 layers, 3 nm to 6 nm thickness, and 2 µm to 7 µm diameter. Furthermore, the short-SWCNTs were purchased from US Research Nanomaterials Inc., and had 98 wt.% purity, 1 nm to 2 nm outer diameter, 0.8 nm to 1.6 nm inner diameter, and 1 µm to 3 µm length. Moreover, the short-MWCNTs were received from US Research Nanomaterials Inc. with purity of 97 wt.%, outer diameter of 30 nm to 50 nm, inner diameter of 5 nm to 12 nm, and length of 0.5 µm to 2 µm. The glassware that host the suspensions were purchased from Glass Solutions Ltd., and had dimensions of 4 cm outer diameter, 9.5 cm height, and 0.33 cm thickness. The lubricant that was used as a basefluid was polyolester (POE) oil of type SL32 synthetic refrigeration oil (referred to as POE32), and it was purchased from Suniso Company.

2.2 Feedstock Characterization

Three characterizations were performed to the as-received powders. The first is the X-ray diffraction (XRD) analysis through an XRD system of type SmartLab that was provided by Rigaku Co. This test was performed at 9 kW working power to confirm the elements in the different powders via comparing the generated 2θ diffraction angle peaks (or Bragg's peaks) to that of the system database. The second analysis is the one concerned with the morphological structure of the as-received nanomaterials, which was performed via a field emission scanning electron microscopy (FE-SEM) device of type JSM-IT700HR (supplied by JEOL Co.). As for the third characterization test, it was performed using an energy dispersive X-ray spectroscopy (EDS) system that is integrated with the FE-SEM device. The previous test is used to reveal the purity of the as-obtained nanomaterials. It is to be noted that the sample in both FE-SEM and EDS analyses was placed at a working distance of 10 mm, and it was exposed to 10 kV of accelerating voltage. This was done to ensure an ideal system performance while eliminating potential system damages from the sample (N. Ali et al., 2019b).

2.3 Nanolubricant Production

The nanolubricants were prepared using the two-step method (Alsayegh & Bahman, 2022). As such, the nanopowders were initially weighed to ensure correct particle concentration of 0.01, 0.025, 0.05 and 0.1 vol.%, which corresponds to 100 mL of basefluid. Afterwards, the nanoparticles were added to the POE32 oil (100 mL), then magnetic stirred for 5 min. Next, the mixture was subjected to intensive mixing via a bath sonicator for one hour to ensure sufficient nanomaterial dispersion throughout the hosting liquid. Finally, the as-prepared nanolubricant was removed from the bath sonicator and set for further analysis. Figure 2 shows the suspension production process conducted in this research.

2.4 Dispersion Stability

The dispersion stability of the as-fabricated nanolubricants was determined via three means, namely the ultraviolet-visible (UV-Vis) analysis, zeta potential measurement, and image capturing approach. In the UV-Vis method and image capturing approach, the dispersion stability is determined via comparing the samples after their preparation and following a selected duration of time (in this case 1 week). As such, the dispersion stability in the first method is

Figure 2: Two-step production approach used to fabricate the nanolubricants of different concentrations.

determined through the reduction in the light absorption, whereas in the second approach the nanomaterial separation from the basefluid illustrate the level of physical stability. Furthermore, the UV-Vis analysis was performed at a spectral range of 200 nm to 800 nm with an interval of 0.5 nm. On the other hand, the zeta potential measurement was performed using a Zetasizer Nano ZS90 (supplied by Malvern Co.). The samples were first collected using a syringe, then injected into the DTS1070 folded capillary cell. All dispersion analysis were performed and measured at room temperature to ensure consistency.

3. RESULTS AND DISCUSSION

3.1 XRD Analysis

The conducted XRD analysis for the powders took place at a range of 20 to 80°, step size of 0.1°, and scanning speed of 0.1°, as shown in Figure 3. Carbon-based nanomaterials in the form of powders were used in this study. This includes commercial graphene, short-MWCNTs, and short-SWCNTs. The outcome of the analysis showed that the as-obtained powders agreed with the manufacturer claims. This was confirmed via comparing the generated Bragg's peaks from the samples to that of the device database. In specific, the Bragg's peaks produced from analyzing the short-SWCNTs, short-MWCNTs, and graphene powders was found to correspond to that of the data in PDF files no. 00-058-1638, 96-101-1061, and 00-041-1487, respectively. The XRD outcomes of the previous nanomaterials also agrees well with the available literature (Alghamdi & Rajeh, 2022; Borzooeian et al., 2018; Siburian et al., 2018).

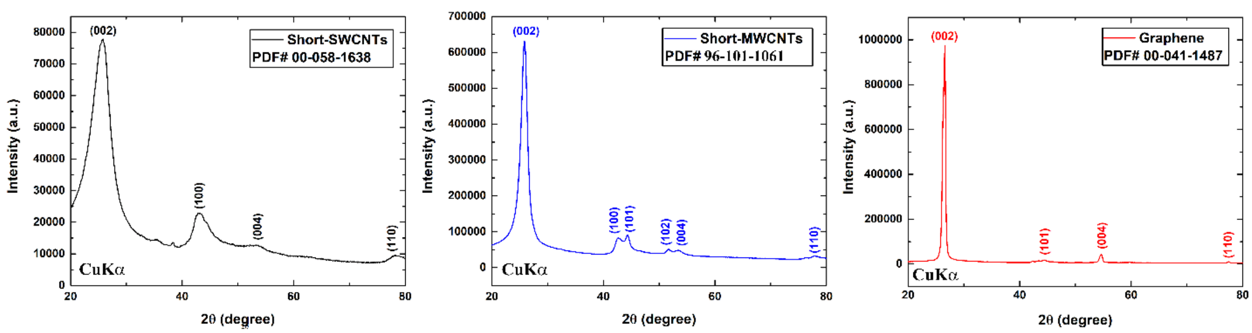

Figure 3: XRD analysis of the as-received powders, where (left to right) shows the as-obtained diffraction pattern of short-SWCNTs, short-MWCNTs, and graphene nanomaterials, respectively.

3.2 FE-SEM and EDS Characteristics

Morphological and elemental analysis were conducted by using the FE-SEM and EDS systems, as shown in Figure 4. It can be seen from the FE-SEM images in Figures 4(a) and 4(c) that the structure of the nanomaterial is of tube-like. Also, the output of the EDS analysis in Figures 4(b) and 4(d) demonstrated that both nanomaterials were made of pure carbon. As a result of both previous findings, it can be confirmed that the examined materials are carbon nanotubes (CNTs). In addition, the diameter of the CNTs was found to be within the range of the manufacturer specification, as shown in Figures 4(a), 4(c) and 4(e). As such, it can be concluded that the as-received CNTs powders agree with the supplier claims. On the other hand, the FE-SEM image in Figure 4(e) has a sheet-like morphological structure, whereas its EDS analysis showed that these sheet-like materials are of pure carbon, as shown in Figure 4(f). Since graphene is known to have such morphological structure and of carbon element, it can be confirmed that this material is indeed graphene. The average dimensions of the aforementioned carbon-based material are a bit larger than what is provided by the supplier. However, this is likely due to the agglomeration between the nanosheets with each other, which can be caused from absorbing some of the air humidity while preparing the sample for the characterization test.

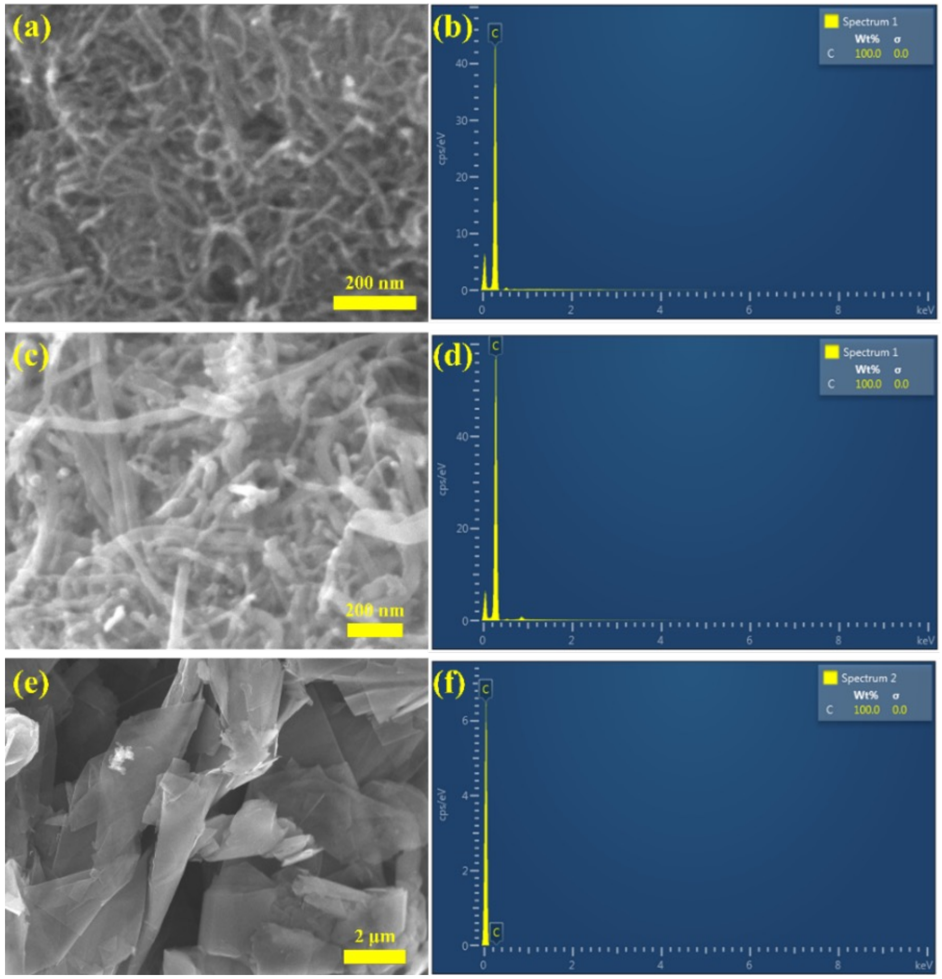

Figure 4: FE-SEM and EDS characterization of the as-received carbon-based powders, where (a), (c), and (e) show the morphological images of short-SWCNTs, short-MWCNTs, and graphene, respectively, while (b), (d), and (f) demonstrate the elemental content percentage of short-SWCNTs, short-MWCNTs, and graphene, respectively.

3.3 Dispersion Physical Stability

As mentioned earlier, the dispersion stability of the nanolubricant plays a key role in improving its viscosity, thermal conductivity, and tribological performance. As such, three characterization approaches were conducted to determine the physical stability of the as-prepared suspensions. To be noted that when dealing with suspensions dispersion stability, two (or more) characterization approaches are used to determine the nanomaterial stability behavior. However, the image capturing approach is considered the most reliable stability analysis method (N. Ali et al., 2019a).

3.3.1 UV-Vis analysis: The UV-Vis measurement for all three types of carbon-based nanolubricants were conducted after preparation and on the fifth day following preparation, as shown in Figure 5. Almost all results showed that when using low nanomaterial concentrations (*i.e.,* 0.01 to 0.025 vol.%), the rate of sedimentation formation tends to be less compared to the other two higher concentrations. On the other hand, it can be noticed from the graphene and short-SWCNTs nanolubricants of 0.1 vol.% that the dispersion process via the two-step mixing approach was more effective compared to the other lower vol.% concentrations of similar nanomaterials. Such behavior was interestingly not observed with the short-MWCNTs, as the deviation between the 0.1 and 0.05 vol.% was minimum. Nevertheless, all carbon-based nanolubricants of 0.1 and 0.05 vol.% were found to have a noticeable reduction in their physical stability after 5 days, except for the short-MWCNTs of 0.05 vol.%.

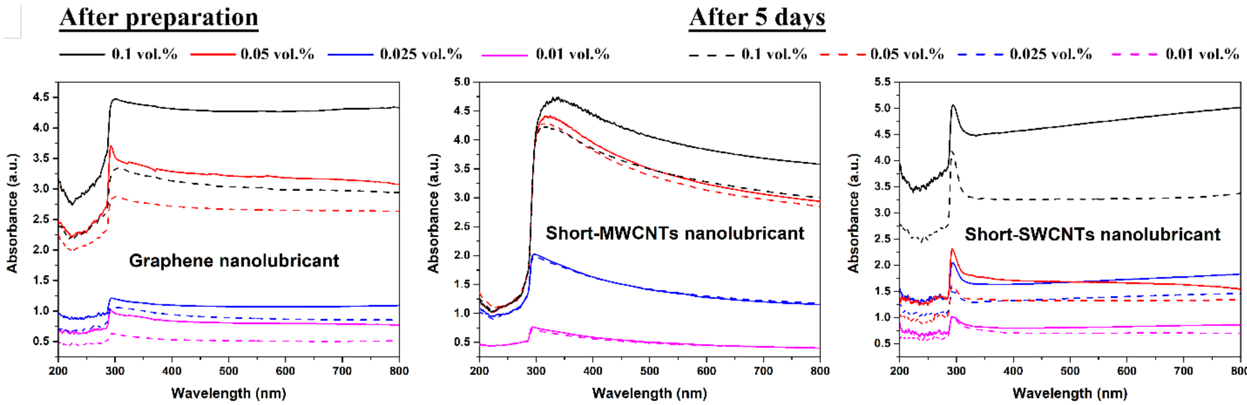

Figure 5: UV-Vis analysis of the graphene, short-MWCNTs, and short-SWCNTs nanolubricants of different concentrations, where (solid line) demonstrate the measurements after preparation, and (dotted line) illustrate the measurements after 5 days.

3.3.2 Image capturing approach: As mentioned earlier, the image capturing approach is one of the most accurate methods for determining the physical stability of nano-based suspensions. Figure 6 illustrates the photographical images of the as-prepared suspension after their production and on the fifth day. It can be seen that the graphene nanolubricant exhibited the highest overall dispersion stability, whereas the short-SWCNTs suspensions had the lowest physical stability. One of the most interesting findings is the two different sediment formation behavior between the short-MWCNTs and the short-SWCNTs nanolubricants, although they are made from the same material and production route. In the short-SWCNTs nanolubricant, the sediment follows a dispersed sedimentation behavior, which means that the sediment tends to form from bottom to top. On the other hand, the sediment formation in the short-MWCNTs suspension can be seen taking the mixed sedimentation mechanism. Further explanation on the different types of sedimentation behaviors can be seen in the literature (N. Ali et al., 2019a).

3.3.3 Zeta potential: The zeta potential is a key concept in colloidal science, particularly in understanding the stability and behavior of suspensions, which includes nanofluids. It represents the measure of the electrostatic repulsion or attraction between particles in a dispersion. Researchers have reported that for nanofluids to be stable, the zeta potential should be at least ±30 mV for moderate stability, ±40 mV for good stability, and greater than ±60 mV would result in excellent stability (N. Ali et al., 2018; A. Kumar & Dixit, 2017). Figure 7 shows the results of the zeta potential test conducted for the different nanolubricant samples. The results have shown that the zeta potential values for all suspension cases were well above the recommended values of ±30 mV, with the lowest obtained zeta potential values found at a concentration of 0.05 vol.% for all three types of carbon-based nanomaterials.

4. CONCLUSIONS

The comprehensive characterization and analysis presented in this study provided valuable insights into the production and stability of carbon-based nanolubricants. Through XRD analysis, FE-SEM, and EDS characterization, the results yield:

- FE-SEM confirmed the structural integrity and purity of the material used.
- The image capturing method showed two different sediment formation behavior between the short-MWCNTs and the short-SWCNTs nanolubricants.
- The zeta potential measurements showed long term suspension stability.
- Through the UV-Vis analysis, it was found that the short-MWCNT nanofluid was the most stable when compared to the remaining carbon-based suspensions.

Future work will evaluate the thermophysical properties (thermal conductivity, viscosity, etc.) to have a better assessment when using nanolubricants in air conditioning compressors. In addition, the optimal concentration has to be

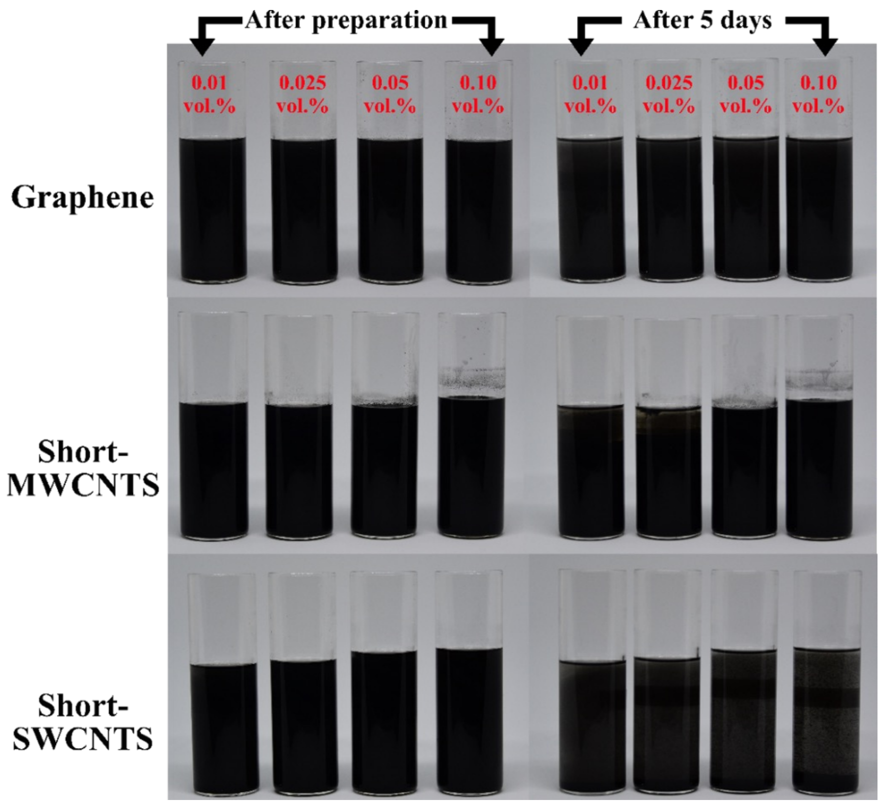

Figure 6: Image capturing of the graphene, short-MWCNTs, and short-SWCNTs nanolubricants of different concentrations, after preparation and on day five.

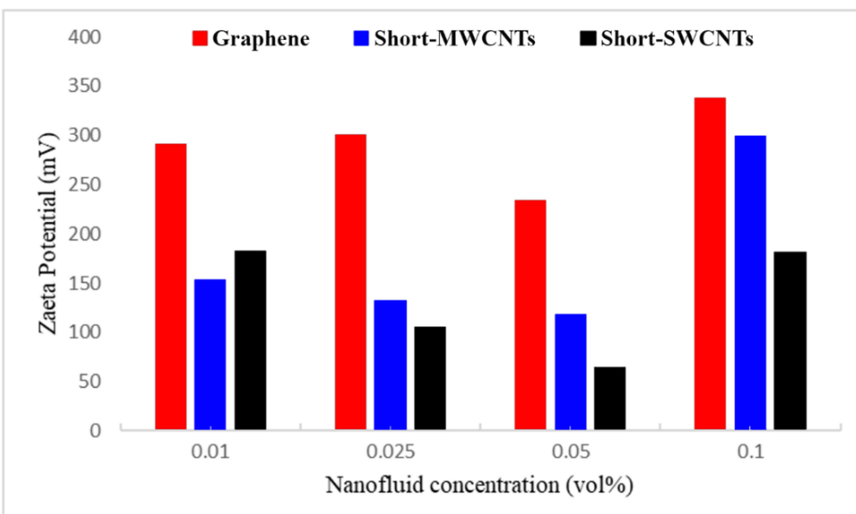

Figure 7: Zeta potential values of the as-prepared graphene, short-MWCNT, and short-SWCNT nanolubricants at different vol.% concentrations.

determined to maximize the tribological properties (*i.e.,* coefficient of friction) before implementing in the air conditioning compressor for experimental testings.

NOMENCLATURE

CNT	carbon nanotubes
EDS	energy dispersive X-ray spectroscopy
EG	ethylene glycol
FE-SEM	field emission scanning electron microscopy
GNP	graphene nanoplatelets
ND	nanodiamond
PAG	polyalkylene glycol
POE	polyolester
MWCNT	multi-walled carbon nanotube
SWCNT	single-walled carbon nanotube
UV-Vis	ultraviolet-visible
V	volt
XRD	x-ray diffraction

REFERENCES

Ahmadi, H., Rashidi, A., Nouralishahi, A., & Mohtasebi, S. S. (2013). Preparation and thermal properties of oil-based nanofluid from multi-walled carbon nanotubes and engine oil as nano-lubricant. *International Communications in Heat and Mass Transfer*, *46*, 142–147.

Alghamdi, H. M., & Rajeh, A. (2022). Synthesis of cofe2o4/mwcnts nanohybrid and its effect on the optical, thermal, and conductivity of pva/cmc composite as an application in electrochemical devices. *Journal of Inorganic and Organometallic Polymers and Materials*, *32*(5), 1935–1949.

Ali, M. K. A., Xianjun, H., Mai, L., Qingping, C., Turkson, R. F., & Bicheng, C. (2016). Improving the tribological characteristics of piston ring assembly in automotive engines using al2o3 and tio2 nanomaterials as nano-lubricant additives. *Tribology International*, *103*, 540–554.

Ali, N. (2022). Graphene-based nanofluids: production parameter effects on thermophysical properties and dispersion stability. *Nanomaterials*, *12*(3), 357.

Ali, N., Bahman, A. M., Aljuwayhel, N. F., Ebrahim, S. A., Mukherjee, S., & Alsayegh, A. (2021). Carbon-based nanofluids and their advances towards heat transfer applications—a review. *Nanomaterials*, *11*(6), 1628.

Ali, N., Bahzad, H., Aljuwayhel, N. F., Ebrahim, S. A., & Hamoud, A. T. (2023). Effervescent tablets for carbon-based nanofluids production. *Journal of Molecular Liquids*, *390*, 123083.

Ali, N., Teixeira, J. A., & Addali, A. (2018). A review on nanofluids: fabrication, stability, and thermophysical properties. *Journal of Nanomaterials*, *2018*.

Ali, N., Teixeira, J. A., & Addali, A. (2019a). Aluminium nanofluids stability: A comparison between the conventional two-step fabrication approach and the controlled sonication bath temperature method. *Journal of Nanomaterials*, *2019*, 1–9.

Ali, N., Teixeira, J. A., & Addali, A. (2019b). Effect of water temperature, ph value, and film thickness on the wettability behaviour of copper surfaces coated with copper using eb-pvd technique. *Journal of Nano Research*, *60*, 124–141.

Aljuwayhel, N. F., Ali, N., Ebrahim, S. A., & Bahman, A. M. (2023). Experimental investigation of thermophysical properties, tribological properties and dispersion stability of nanodiamond-based nanolubricant for air conditioning systems. *International Journal of Refrigeration*, *145*, 325–337.

Almurtaji, S., Ali, N., Teixeira, J. A., & Addali, A. (2020). On the role of nanofluids in thermal-hydraulic performance of heat exchangers—a review. *Nanomaterials*, *10*(4), 734.

Alsayegh, N., & Bahman, A. M. (2022). *Apparatus for testing the stability of dispersed particles in flowing suspensions.*

Alsayegh, N., Bahzad, H., & Aljuwahel, N. F. (2024). *Tablet-based method of producing nano/micro particle water suspensions and carbon dioxide gas.*

Azman, N. F., & Samion, S. (2019). Dispersion stability and lubrication mechanism of nanolubricants: a review. *International journal of precision engineering and manufacturing-green technology*, *6*, 393–414.

Borzooeian, Z., Taslim, M. E., Ghasemi, O., Rezvani, S., Borzooeian, G., & Nourbakhsh, A. (2018). A high precision method for length-based separation of carbon nanotubes using bio-conjugation, sds-page and silver staining. *PLoS*

One, *13*(6), e0197972.

Harish, S., Ishikawa, K., Einarsson, E., Aikawa, S., Chiashi, S., Shiomi, J., & Maruyama, S. (2012). Enhanced thermal conductivity of ethylene glycol with single-walled carbon nanotube inclusions. *International Journal of heat and mass transfer*, *55*(13-14), 3885–3890.

Iranmanesh, S., Mehrali, M., Sadeghinezhad, E., Ang, B. C., Ong, H. C., & Esmaeilzadeh, A. (2016). Evaluation of viscosity and thermal conductivity of graphene nanoplatelets nanofluids through a combined experimental–statistical approach using respond surface methodology method. *International Communications in Heat and Mass Transfer*, *79*, 74–80.

Kogovšek, J., & Kalin, M. (2014). Various mos 2-, ws 2-and c-based micro-and nanoparticles in boundary lubrication. *Tribology Letters*, *53*, 585–597.

Kumar, A., & Dixit, C. K. (2017). Methods for characterization of nanoparticles. In *Advances in nanomedicine for the delivery of therapeutic nucleic acids* (pp. 43–58). Elsevier.

Kumar, P. G., Kumaresan, V., & Velraj, R. (2017). Stability, viscosity, thermal conductivity, and electrical conductivity enhancement of multi-walled carbon nanotube nanofluid using gum arabic. *Fullerenes, Nanotubes and Carbon Nanostructures*, *25*(4), 230–240.

Redhwan, A., Azmi, W., Sharif, M., & Zawawi, N. (2017). Thermal conductivity enhancement of al2o3 and sio2 nanolubricants for application in automotive air conditioning (aac) system. In *Matec web of conferences* (Vol. 90, p. 01051).

Sandhu, H., & Gangacharyulu, D. (2017). An experimental study on stability and some thermophysical properties of multiwalled carbon nanotubes with water–ethylene glycol mixtures. *Particulate Science and Technology*, *35*(5), 547–554.

Sharif, M., Azmi, W., Redhwan, A., & Mamat, R. (2016). Investigation of thermal conductivity and viscosity of al2o3/pag nanolubricant for application in automotive air conditioning system. *international journal of refrigeration*, *70*, 93–102.

Siburian, R., Sihotang, H., Raja, S. L., Supeno, M., & Simanjuntak, C. (2018). New route to synthesize of graphene nano sheets. *Oriental Journal of Chemistry*, *34*(1), 182.

Xing, M., Yu, J., & Wang, R. (2016). Experimental investigation and modelling on the thermal conductivity of cnts based nanofluids. *International Journal of Thermal Sciences*, *104*, 404–411.

Yarmand, H., Gharehkhani, S., Shirazi, S. F. S., Amiri, A., Alehashem, M. S., Dahari, M., & Kazi, S. (2016). Experimental investigation of thermo-physical properties, convective heat transfer and pressure drop of functionalized graphene nanoplatelets aqueous nanofluid in a square heated pipe. *Energy Conversion and Management*, *114*, 38–49.

Zhang, L., Chen, L., Liu, J., Fang, X., & Zhang, Z. (2016). Effect of morphology of carbon nanomaterials on thermo-physical characteristics, optical properties and photo-thermal conversion performance of nanofluids. *Renewable Energy*, *99*, 888–897.

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