Enhancing the thermophysical properties of PAG lubricant using graphene nano-sheets.

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Abstract. One of the most attractive methods to improve the thermo physical and heat transfer properties of conventional coolants and lubricants is the use of nanoparticles in it. Nanofluids are stable colloidal suspensions of nanoparticles and base fluids. The nanofluids exhibit superior thermal performance compared to conventional heat transfer fluids and this leads to the best hope for lubricants based nanofluids as well. Nanolubricant is a new class of lubricant produced by dispersing nano-sized particles of metals, metal oxides, carbon and its allotropes into conventional lubricating oils. In the present study, experiments were conducted to measure the thermophysical and rheological properties of polyalkyleneglycol (PAG) refrigerant compressor oil suspended with graphene nano-sheets. The effect of particle concentration and temperature on thermal conductivity and viscosity of nanolubricant were elucidated. The volume fraction is varied from 0.05 to 0.8% and the temperature range is from 15°C to 85°C. The rheological properties have been investigated at various shear rates, particle concentrations, and temperatures. Furthermore, a correlation is proposed to predict the thermal conductivity of Graphene-PAG nanolubricant. The results revealed that the thermal conductivity and viscosity of the nanolubricant is strongly depends on the volume fraction and temperature. The nanolubricant exhibits higher thermal conductivity and viscosity compared to the PAG oil. Unlike in the case of pure lubricant, the shear rate has a crucial impact on the behavior of nanolubricant. Interestingly, the pure lubricant, which is a Newtonian fluid, is transformed into non-Newtonian when nanoparticles are appended with it. From the studies, it was observed that the nanolubricant having graphene particle concentration of 0.05% is optimum for refrigeration application.

1. Introduction

Exponentially growing energy demands necessitate high efficient heat transfer fluids and lubricants in diverse thermal systems. The performance of lubricants directly affects global energy consumption. For this reason, enhancing the thermo-physical and tribological properties lubricants is imperative. The addition of chemical compounds is a well-known practice to enhance the thermal and tribological capabilities of coolants and lubricants. The development of various nanoparticles has opened up new avenues in various fields including cooling, lubrication, medicine, composite etc. Metallic and metal oxide nanoparticles, carbon and its derivatives (fullerenes, onions, nanotubes, and graphene), have been used now a days to develop nano-coolants and nanolubricants.
In the year 1995, Choi coined the term nanofluids and found that nanoparticles can offer anomalous enhancement of thermal conductivity to the base fluids [1]. Since 1995, research in this area has diversified tremendously into many disciplines. A series of breakthroughs were witnessed when Choi and Eastman et al. and Das et al. observed more than 40% enhancement in thermal conductivity by using 0.3% Cu particles of 10 nm size and 150% increase by using multi-walled carbon nanotubes (MWCNT) in engine oil [2,3]. In 2008 Baltez et al. studied anti-friction properties of CuO, ZrO$_2$ and ZnO nanoparticles. Interestingly, another wave of serious interest evolved among researchers when single-atom-thick graphene was successfully extracted from bulk graphite in 2004. Few reports have been published on graphene based nanolubricants and nanofluids by Rasheed et al., and Senatore et al. in 2013 and 2015 [4, 5]. However, comprehensive studies focusing on graphene based nanolubricants are scarce. It is imperative to understand the anti-friction behavior, enhanced thermal transport phenomenon, rheological and tribological characteristics of graphene based nanofluids and nanolubricants owing to its different nature from other nanoparticles.

This study mainly focuses on the thermal and rheological characterization of graphene-Polyalkylene glycol (PAG) nanolubricant. Specifically, to determine the thermo-physical properties like thermal conductivity and viscosity of graphene based nanolubricant at different composition and temperatures. Furthermore, efforts are taken to propose a regression model to predict the thermal conductivity of graphene based nanolubricant.

2. Methodology

2.1. Preparation of nanolubricant

Preparation of nanolubricant is the key step in the experimental studies. Nanofluids are not mere solid to fluid suspensions. Graphene-PAG nanolubricants were prepared at different volume fractions (0.05, 0.1, 0.15, 0.3, 0.5% and 0.8vol %). The stable nanolubricants were prepared thorough magnetic agitation and ultra-sonication. No evidence of sedimentation or coagulation was noticed after 5 days of preparation. The properties of graphene nano-sheet are summarized in table 1.

| Properties        | Values        |
|-------------------|---------------|
| Purity            | >99%          |
| Thickness         | 5-10nm        |
| Length            | 4-8 micron    |
| Surface area      | 190m$^2$/g    |
| Thermal conductivity | $\approx$3000 W/mK |
| Tensile modulus   | >1000GPa      |

2.2. Determination of thermal conductivity

The thermal conductivity of base lubricant and nanolubricants were measured with KD2-Pro thermal property analyzer (Decagon devices, Inc., USA). The principle of operation of the device is transient hot wire method and the maximum deviation is ±5.0%. The probe of the instrument consists of a needle with a heater and temperature sensor inside it. Electric current is supplied through the heater and the temperature of the probe is measured over time. The apparatus meets the standards of ASTM D5334. A refrigerated and heating circulator (F-25, Julabo, Germany) with an accuracy of 0.01°C was used to maintain the temperature of the sample constant. The thermal conductivity of nanolubricant at different particle volume concentrations was measured in the temperature range of 15°C to 45°C.

2.3. Determination of rheological behaviour

Rheological behaviour was evaluated in the temperature range of 25-85°C at varying shear rates and particle dosing levels. A Brookfield LVDV-II +Pro, plate-and-cone rheometer together with a constant temperature circulator (JULABO F-25, Germany) was used for the measurements. All the measurements were performed under steady state conditions within the torque range of 10-100%.

Table 1. Properties of graphene nano-sheet.
3. Results and discussion

3.1. Thermal conductivity

Figure 1 shows the variation of thermal conductivity with respect to volume fraction and temperature. From the figure it is evident that, as graphene concentration in the PAG lubricant increases, the thermal conductivity increases first then slightly decreases. The maximum value of thermal conductivity is obtained as 0.167 W/mK at a particle concentration of 0.05vol%, which is 9.86% greater than that of pure lubricant. The major contributing factor for this enhancement is increased Brownian motion and subsequent thermal interaction and higher thermal conductivity of nano-sheets.

![Figure 1. Variation of thermal conductivity with volume fraction.](image1)

The temperature dependent thermal conductivity of graphene-PAG nanolubricant is shown in figure 2. As temperature increases thermal conductivity decreases. However, it is observed that for 0.05% particle concentration, the value of thermal conductivity is always greater than that of pure lubricant. According to the study, the most suitable concentration as an alternative lubricant for the refrigerant compressor is 0.05vol%.

![Figure 2. Temperature dependent thermal conductivity variation.](image2)

3.2. Viscosity

The viscosity of the nanolubricant is measured at different shear rates and temperatures. Figures 3-8 represent the variation in viscosity with respect to shear stresses at different temperatures. The figure
shows that the viscosity of nanolubricant at all particle concentrations and temperatures displays non-Newtonian behaviour, especially at lower shear rates and temperatures. That is the viscosity varies with respect to shear rates. Interestingly, as the temperature and shear rate increases, the nanolubricant displays Newtonian behaviour.

**Figure 3.** Shear stress vs viscosity at a volume fraction of 0.05% (at different temperatures).

**Figure 4.** Shear stress vs viscosity at a volume fraction of 0.1vol% (at different temperatures).

**Figure 5.** Shear stress vs viscosity at a volume fraction of 0.15vol% (at different temperatures).
Figure 6. Shear stress vs viscosity at a volume fraction of 0.3vol% (at different temperatures).

Figure 7. Shear stress vs viscosity at a volume fraction of 0.5vol% (at different temperatures).

Figure 8. Shear stress vs viscosity at a volume fraction of 0.8vol% (at different temperatures).
Figure 9 shows the variation in viscosity of graphene based nanolubricant with respect to temperature and volume fraction.

![Figure 9. Temperature dependent viscosity.](image)

The viscosity of pure lubricant and nanolubricant decreases with the intensification of temperatures at all particle concentrations. This is due to the weak van-der Waals force of attraction between the molecules. However, graphene-PAG nanolubricant at lower particle concentration (0.05vol %) exhibits a slight decrease in viscosity than that of pure PAG oil, especially at elevated temperature. This may be an added advantage since reduced viscosity significantly saves the pumping power.

3.3. Correlation to predict the thermal conductivity

From the experimental data, a correlation is proposed for predicting the thermal conductivity of graphene-PAG nanolubricant at different concentrations and temperatures, which is shown in equation 1.

\[ k = -0.001T - 0.014\varphi + 0.166 \]  

(1)

where T is the temperature in °C, \( \varphi \) is the particle concentration and k is the thermal conductivity in W/m K. The regression model with an R-squared value higher than 0.98, well predicts the thermal conductivity of nanolubricant in the temperature region of 15-80°C and volume fraction between 0.05 to 0.8vol%, as shown in Figure 10.

![Figure 10. Experimental data vs model predictions.](image)
4. Conclusions

Thermal conductivity and viscosity of the graphene-PAG nanolubricant have been experimentally determined. The experimental results show that the addition of nanoparticle to the lubricant oil enhances the thermal conductivity. The thermal conductivity was 9.86% higher than that of pure PAG lubricant at a particle concentration of 0.05vol%. Similar to thermal conductivity, the volume concentration and temperature have significant effects on the viscosity of nanolubricants as well. As the particle concentration increases, the viscosity also increases. In the case of particle concentration 0.05vol%, the nanolubricant displays slight detrimental effect on viscosity than that of pure PAG lubricant. The nanolubricant exhibits non-Newtonian behaviour especially at lower shear rates. The proposed correlation well predicts the thermal conductivity of nanolubricant. It is concluded that, among the particle concentration considered for the investigation, the optimum concentration of graphene nanoparticle is 0.05vol%.

References

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