Nano-oil with high thermal conductivity and excellent electrical insulation properties for transformers

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Water, ethylene glycol (EG) and mineral oil (MO) play a vital role as heat-transfer agents in automotive and heavy-duty engines, energy production and supply, nuclear systems cooling and also in many other fields, including space, defence, biomedical and magnetic sealing. High thermal conductivity and low viscosity are the important characteristics of these heat-transfer fluids. To cool an electrical transformer during its operation, it is filled with transformer oil. This oil is customarily a highly refined MO and employed in transformers as a coolant because of its high stability at elevated temperatures and excellent electrical insulating properties. Insulation is essential as the winding inside has to be separated to prevent voltage from leaking or shorting. As the thermal conductivity of MO is low, it is not uncommon to experience thermally driven failures from instantaneous overload. Therefore, to achieve significant extension in transformer lifetime and increment in load/cooling capacity, it is pertinent to increase the thermal conductivity of the transformer oil. Obviously in the right choice of materials, one essentially will search for suitable dispersants in oils that take heat away, yet remain electrically neutral without increasing the viscosity of the oil.

In this context, the addition of nanomaterials having higher thermal conductivity to an industrial coolant fluid like water, EG and MO was found to enhance heat-transfer capabilities\(^1\). The presence of nanoparticles with large surface area cannot only be expected to enhance the heat-transfer, but also to increase the stability of the suspension. Suspensions prepared by dispersing nanometre-sized solid particles, rods or tubes in the base fluids are called nanofluids\(^1\). These are found to possess enhanced thermophysical properties such as thermal conductivity, thermal diffusivity and convective heat transfer coefficients compared to those of base fluids like oil or water. In many cases the viscosity of the nanofluids is also considerably reduced.

Eastman \textit{et al.}\(^1\) demonstrated that Cu nanoparticles dispersed in EG resulted in a 40% increase in the thermal conductivity of EG at a very low particle loading (0.3 vol%). This enhancement is much higher than for the same fluid containing the same volume fraction of dispersed oxide nanoparticles\(^1\). Because of their large intrinsic thermal conductivity and low density, carbon nanomaterials have been employed as the solid phase in nanofluids. Choi \textit{et al.}\(^2\) also established significant enhancement in thermal conductivity of a dispersion of carbon nanotubes in EG. Some more experimental results also demonstrated that other carbon materials, such as graphite nanoparticles, exfoliated graphite and graphene oxide nanosheets are good candidates for use in nanofluids\(^3\). In many of the studies no surfactant was employed for the stabilization of solid phase in liquid.

Recently, Baby and Ramprabhu\(^4\) prepared CuO decorated on hydrogen-induced exfoliated graphene (CuO/HEG)-dispersed nanofluids both in deionized water and EG-based fluids without any surfactant. According to these authors, the thermal conductivity of CuO/HEG dispersed in a water-based nanofluid exhibited an enhancement of ~ 28% at 25°C for a volume fraction of 0.05%. In an earlier related work, the same authors reported an enhancement of thermal conductivity by ~ 14% for a volume fraction of 0.056% in the nano-fluid.

![Figure 1](image1.png) **Figure 1.** \(a\), Schematic of liquid exfoliation of h-BN crystals into 2D h-BN nanosheets using sonication and centrifugation. IPA (green spheres in figure) is used for liquid exfoliation. \(b\), TEM image of h-BN (corresponding SAED pattern is shown in the inset) showing few layered sheets. SAED pattern shows the crystallinity of the exfoliated nanosheets with the adjacent nanosheets having rotational disorders. Reprinted with ACS permission from Taha-Tijerina \textit{et al.}\(^10\). Copyright (2012) from the American Chemical Society.

![Figure 2](image2.png) **Figure 2.** (Left) Photographs of pure MO and various suspensions of h-BN/MO and graphene/MO in a white background. (Right) Schematic of two layers (h-BN/graphene) in MO stabilized via Brownian motion and interactions with MO. Reprinted with ACS permission from Taha-Tijerina \textit{et al.}\(^10\). Copyright (2012) from the American Chemical Society.
obtained by dispersion of thermally exfoliated graphene in water\(^6\). Nanofluid containing graphene nanosheets displayed substantial enhancement in thermal conductivity at low concentration and also the dependence of thermal conductivity on temperature differed from nanofluids containing carbon nanotubes or graphene oxide\(^6\). Thermal conductivity and heat-transfer measurements suggest that these nanofluids can be used for coolant applications. Further, the low enhancement in electrical conductivity of nanofluids is likely to inspire its use as an insulating fluid. Studies on the thermal conductivity of EG-based nanofluids containing oxides, including MgO, TiO\(_2\), ZnO, Al\(_2\)O\(_3\) and SiO\(_2\) nanoparticles have also established that MgO–EG nanofluid possesses superior features with the highest thermal conductivity and lowest viscosity\(^3,7\).

Ideal transformer oil shall possess low viscosity for facilitating continuous flow of oil, high thermal conductivity and excellent electrical insulating properties. Botha et al.\(^8\) prepared nano-oil containing silver nanoparticles with particle size distribution of 5.5 ± 2.4 nm supported on silica, and this nanofluid enjoyed all the qualities stated above for an ideal nano-oil\(^8\). However, a silver–silica nanocomposite dispersed in transformer oil without the use of surfactant was found to be stable only for about 1 h. Since the reported thermal conductivity values and also stability of nanofluids are far from satisfactory for practical use, several groups have been pursuing research on nanofluids involving novel nanomaterials with the objective to improve the thermal properties.

Zhi et al.\(^5\) were the first to examine the suitability of boron nitride nanotubes (BNNT) and boron nitride nanospheres (BNNS) as nano-fillers to improve the thermal conductivity of a nanofluid with water as the base fluid\(^4\). To stabilize boron nitride (BN) nanomaterials, polydiallyldimethylammonium chloride was used as a surfactant. The authors observed perceptible enhancement of thermal conductivity of water. For the addition of 6 vol% fraction of BNNT and BNNS, thermal conductivity improvement was ~2.6-fold and 1.6-fold, respectively. A mixture of BNNT and BNNS fillers resulted in a significant improvement of the fluid thermal conductivity while keeping its viscosity relatively low\(^2\).

A further development on the use of BN/MO has been reported recently by Taha-Tijerina et al.\(^9\), who suggest the 2D hexagonal boron nitride nanosheets (h-BN)/MO fluids as the most likely next-generation thermal nano-oils. These authors obtained nanosheets of h-BN by the exfoliation of micrometre-sized layered h-BN crystals in isopropyl alcohol (IPA) by sonication (Figure 1 a) as 2D fillers. The h-BN nanosheets were characterized by TEM image studies (Figure 1 b), and selected area electron diffraction in addition to XRD and Raman studies of dried h-BN nanosheet powders.

In Figure 2 the photographs of various nano-oils containing different concentrations of h-BN or graphene MO are shown. Nano-oil containing h-BN is highly stable in MO for more than three months. The high stability of the suspension has been attributed to the strong interaction of oleophilic layer (2D h-BN) with the MO as evidenced by dynamic light-scattering studies, viscosity measurements, theoretical modelling and pour point evaluations\(^10\). The performance of 2D h-BN-dispersed MO has been compared with that of graphene dispersion.

While the thermal conductivity of MO is independent of temperature, all the
other nanofluids show a temperature-dependent variation (Figure 3a) in thermal conductivity, indicating the role of Brownian motion on thermal conductivity. The observed enhancement in thermal conductivity is ~ 76% for the nanofluids containing 0.1 wt% h-BN/MO. As h-BN and graphene are insulator and electrically conducting nanomaterial respectively, the observed electrical resistivity of the nanofluids decreases in the expected order h-BN/MO > MO > graphene.

Studies on the influence of temperature on shear viscosity measurements indicate that in general the viscosity of MO, graphene/MO and h-BN/MO (at different concentrations of h-BN) decreases with temperature (Figure 4a). This is a desirable quality of the nano-oil for the smooth circulation of fluid in the transformers at high temperature. However, at 298 K and 0.35 wt% of 2D h-BN, the viscosity increases. Taha-Tijerina et al. 10 also calculated the viscosity of various nanofluids using the theory of Hinch and Leal 11 and the enhancement observed is in agreement with the theoretical predictions 10.

The pour point (the minimum temperature at which a liquid, particularly a lubricant, will flow) is the lowest for h-BN/MO among the three nanofluids (Figure 4b). This is another additional advantage to use 2D h-BN as the solid phase in MO. A comparison of these results for h-BN/MO with the reported literature on various nanofillers with different morphology (table 1 in the supporting information of Taha-Tijerina et al. 10) clearly suggests that 2D h-BN is highly qualified to be used as the nanodispersant in MO.


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