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# Transformer oils-based graphene quantum dots nanofluid as a new generation of highly conductive and stable coolant

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ABSTRACT

Transformer oil-based graphene quantum dots (GQD) nanofluid with superior colloidal stability has great potentials as a new generation of high performance transformer oil. To this end, graphene quantum dots were initially synthesized with a novel and cost-effective exfoliation approach. To eliminate the acidity, a covalently-functionalization process was employed to change GQD to amine-treated graphene quantum dots (AGQD). The morphological analysis confirmed that the diameter and average height of the mono-layered AGQD were mostly in the range of 5–17 nm and <1 nm, respectively. Transformer oil-based AGQD nanofluid at very low weight fraction has been shown experimentally to have substantially higher positive voltage breakdown, thermal conductivity, natural and forced heat transfer rate, and flash point levels compared to that of pure transformer oil. A comprehensive rheological and electrical analysis of the transformer oil-based AGQD nanofluid showed no significant enhancement in its viscosity compared to pure transformer oil, which is a great advantage of this new generation of transformer oil. Case studies showed that the transformer oil-based AGQD nanofluid has a superior colloidal stability, offering improved high voltage equipment performance and reliability.



## 1. Introduction

Transformer oil (TO), a pure mineral oil which are stable at high temperatures, commonly shows low thermal conductivity, which is the main obstacle for upgrading the performance of transformers [1]. Note that a suitable transformer oil should exhibit an outstanding electrical resistance and a superior thermal conductivity [2,3]. According to [1,4], a small enhancement in the thermal conductivity of TO can result in a significant frugality in cost and performance. To this end, researchers synthesized different type of novel TO-based nanofluids with appropriate voltage insulation, thermal and dielectric properties. They concluded that the higher thermal conductivity of TO means the higher rate of heat transfer, leading to smaller size transformers, more desirable lifetime and greater performance [1]. To address this issue, various nanoparticles and carbon nanostructures were used for preparing nanofluids [2,5–7].

Over the last decade, the researches on efficient, scalable and economical ways to produce highly-dispersive TO-based metal or TO-based metal oxide nanofluids have encountered different problems including drop in the breakdown voltage, high level of sedimentation rate, and change in TO acidity. To solve the aforementioned problems, significant efforts have been made on the preparation of TO-based carbon nanostructures nanofluids, which typically employs different covalent and non-covalent functionalizations to overcome the poor stability of additives in TO [3].

Among different carbon nanostructures, graphene (*Gr*) and carbon nanotubes (CNT) are promising additives for future heat transfer equipment due to the superior thermal and mechanical properties as well as their chemical stability [8–14]. Due to the high specific surface area, superior thermal conductivity, and suitable stability in the presence of covalent and non-covalent functionalization, graphene-based materials have attracted numerous researchers across the globe [3,15–17]. In particular, few layer Grs are the two-dimensional sheets with $sp^2$-hybridized carbons in a hexagonal lattice with unique properties [18–20]. While the graphene-based materials have unique desirable properties including a thermal conductivity of the order of 5000 W/mK [21], the challenge remains on producing long-term colloidal stability of *Gr* suspension in transformer oil and also the superior electrical conductivity of *Gr* spoils the insulation property of TO. In this context, it has been highly desirable to develop materials with the capability of functionalization for preparing stable colloidal suspension with high

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**Nomenclature**

| | |
|---|---|
| *Nu* | Nusselt number |
| $T_c$ | average temperature of walls, °C |
| h | heat transfer coefficient, W/m$^2$ K |
| k | thermal conductivity, W/m K |
| L | length, m |
| $T_h$ | average temperature of oil, °C |
| Q | input power, W |
| A | heat transfer area |
| V | voltage, V |
| GQD | graphene quantum dots |
| AGQD | amine-treated graphene quantum dots |
| TO | Transformer Oil |
| I | current, A |

thermal conductivity while being electrically-semiconductive for use as effective transformer oil.

The semiconductor quantum dots (SQD) opened a new gateway to address all the above-mentioned targets. Due to the promising two-dimensional feature, large specific surface area, and favourable electronic properties, graphene quantum dot (GQD) is a promising candidate for use as additives in TO. Applications that require semiconductive additive, superior thermal conductivity and ultra-high electrical resistivity will benefit immensely from GQD, which has been demonstrated to show remarkable thermophysical and physicochemical properties. Note that acidity of additive is also harmful and can be the source of numerous issues in transformers. The more the acidity, the more the solubility of water in the TO, which reduces the insulation property and depreciates transformer [3,22]. So, the synthesized GQD should not include the acidic groups.

In this study, a novel and cost-effective synthesis approach for preparing amine-treated GQD (AGQD) was developed. The morphological study confirmed the presence of AGQD at sub-17 nm sizes. The resulting suspension shows that the TO-based AGODs nanofluid is a promising and unique alternative coolant for use in transformer.

## 2. Experimental

### 2.1. Preparation of AGQD

Herein, a modified Hummers method was employed to prepare the graphite oxide sheets from natural graphite powder [23]. For GQD synthesis, the method presented by Zhang et al. [23] with slight modification was used. Typically, 2.0 g of the graphite oxide were oxidized in the concentrated $HNO_3$ (60 mL, 38 wt%) and $H_2SO_4$ (180 mL, 98 wt%) for 48 h under mild ultrasonication. After cooling, the mixture was diluted with 1200 mL of deionized water and subsequently was centrifuged at 4000 rpm to separate the un-exfoliated material. The supernatant was then diluted with the deionized water. The colloidal suspension was then dialyzed using a dialysis bag (Mw cut off: 3500 Da) overnight.

To remove the acidic groups decorated on the edge of GQD, 100 mL of colloidal solution was mixed with deionized water (100 mL) and ammonia solution (120 mL) in a vessel. The resulting suspension was sonicated in a 300 W probe-sonicator for 30 min. The mixture was then stirred for 4 h at 100 °C. After cooling to room temperature, the resulting black suspension centrifuged at 25000 rpm and the supernatant was collected. After performing the reaction step, the majority of oxidized GQD changed to the amine-treated GQD (AGQD). Finally, a rotary evaporator was used to concentrate the AGQD solution at 50 °C, which is followed by drying in a vacuum oven to obtain the dried AGQD powder.

### 2.2. Preparation of nanofluid

In order to prepare TO-based AGQD nanofluid, the AGQD was sonicated in transformer oil for 30 min. As mentioned before, the AGQD were decorated with the amine groups. Therefore, the easily-miscible amine functionalities on the edges of AGQD may cause great colloidal stability of suspension as well as the superior solubility of the AGQD in transformer oil media.

### 2.3. Experimental apparatus

Fig. 1 shows a schematic diagram of the experimental setup, which was designed based on an industrial transformer. There is a good agreement between the size and materials of the experimental set-up and the oil-25 KVA transformer. It can be seen that the experimental transformer used in the present study is an oil based-transformer and comprises of a 203 × 100 × 221 mm$^3$ reservoir. To provide input power for heating the working fluid, a cylindrical heating element was installed at the top of reservoir. The average temperatures of working fluids at different locations in the reservoir were measured by PT-100 thermocouples. To provide accurate data on average temperatures of the walls, four thermocouples were installed on the top of the reservoir with another 4 thermocouples installed at different sides of the transformer's walls. To have force convection heat transfer, a 55 W blower was installed at a constant distance of 5 cm from the transformer. Ammeter, voltmeter and the thermocouples, respectively, had the measurement uncertainties of 0.001 A, 0.1 V and 0.1 °C. According to the Holman technique [24], the total uncertainty for calculating the natural and forced heat transfer coefficients were <2.1%. Atomic force microscopy (AFM, ScanAsyst mode, frequency 1 Hz, Bruker) was also used to investigate the surface morphology of AGQD.

Brookfield LVDV-III rheometer and $KD_2$ thermal analyzer (Decagon Devices, Inc., USA) were used, respectively, to measure the viscosity and thermal conductivity of resulting nanofluid. Also, the flash point was evaluated experimentally by a seta semi-automatic Cleveland open cup flash point tester, which works on the basis of American Society for Testing and Materials (ASTM) D-92 [25]. Also, Mugger's automatic laboratory oil tester was used to measure the dielectric breakdown with the setting of ASTM D-92 standard.

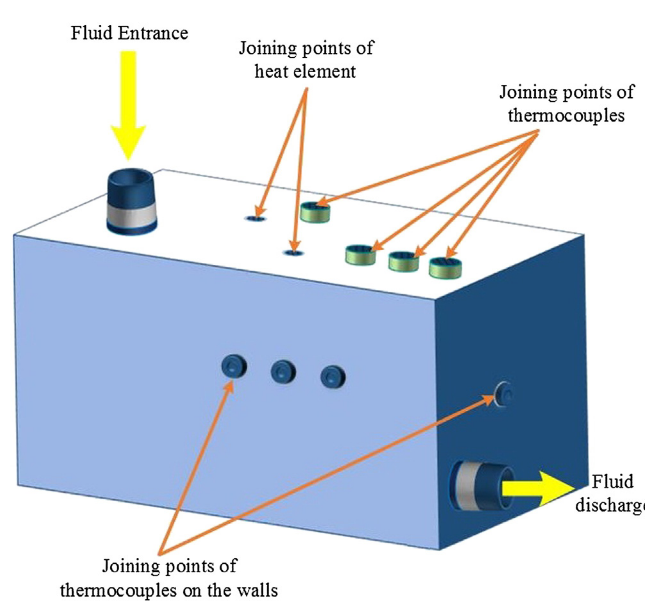


**Fig. 1.** Schematic diagram of the experimental set-up.