Transformer Oil Nanofluids by Two Dimensional hexagonal Boron Nitride Nanofillers

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ABSTRACT

This paper explores the fascinating properties of two-dimensional (2D) nanofillers based transformer oil (TO) nanofluids. Nanofluids of 2D hexagonal boron nitride (h-BN) nanosheets in TO demonstrate stable dispersion with improved dielectric breakdown strength and superior thermo physical properties like thermal conductivity, viscosity and stability. An appreciable augmentation in AC breakdown voltage (BDV) is observed compared to the state-of-the-art boron nitride (BN) particles. This enhancement in BDV is elucidated by the role of the greater surface area of Maxwell-Garnet 'oil-sheet' interfacial region of the 2D morphology in charge trapping perspective. The faster rate of heating and cooling along with noteworthy enhancement in thermal conductivity is due to the interfacial heat transfer via 2D nanoadditives prompting good phonon transport which agrees with Maxwell's forecasts. Addition of 2D nanofiller at diluted concentration exhibits better stability and high thermal efficiency compared to its particle counterpart. Hence, 2D nanofillers are better choices for next generation transformer oil nanofluids, due to their high surface area, lower filler fraction and better stability.

Index Terms — **nanotechnology, oil insulation, dielectric breakdown, cooling**

1 INTRODUCTION

RATING of power transformers are greatly influenced by the temperature rise and breakdown strength of liquid insulation. Currently the changing dynamics of power systems with ample use of power electronics converters has put additional challenges on operation and thermal management of transformers. Traditional way to combat such challenges via proposal to increase the accessible zones or areas for radiating heat from such equipment have been inefficient as it imposes an adverse surge by making the entire system unnecessarily bulky and uneconomic [1]. Hence, there is need for newer approaches to combat these multifaceted stresses.

One such way to do so is to improve the cooling and insulating performance of transformer oil (TO) which serves as the power blood of transformers via proper engineering approach.
The perception of Nanotechnology can be taken as a key here.

Nanomaterials (1-100 nm) have emerged to assist impetus in numerous technological sectors due to their faster response to perturbation, higher thermal conductivity, mechanical strength, chemical inertness, surface to volume ratio [2]. Thereafter, designs of plethora of nanomaterials for a wide range of applications have flourished linearly with the growing demand of mankind. Similarly, in the current problem, development of nanofluids by dispersing high thermal conductive and electrically insulating nanofillers in TO to develop nanodielectric fluids i.e. electrically insulating thermal nano-engineered transformer oil have been found to be very effective and efficient over conventional TO. Thus nanofluidic TO have become an emerging field of research in the global perspective for boosting the overall rating and capacity of transformers and is extremely important to meet up the need of the modern power systems.

Last decade registered exponential research on nanodielectric fluids with multiple tailormade nanomaterials; metallic, non-metallic, or ceramic with various sizes, morphologies and shapes due to their attractive properties. Prior reports suggest that suspending several kinds of crystalline nanoparticles such as CuO, Al_2O_3, SiO_2, Ag on SiO_2, Fe_3O_4, TiO_2, ZrO_2 of 1-100 nm size in TO greatly enhanced either thermal conductivity [3, 4] or breakdown voltage (BDV) [5] levels but most of the investigations failed to include both. Again, for optimized efficiency, the

nanoadditives need to be evenly distributed in the liquid base, but in practice, to decrease the greater surface energy, they intend to agglomerate and custom lengthy assemblies of connected nanoparticles and agglomerates [4] causing blockage of networks in the heat-handover arrangements. This declines the net thermal conductivity and overall operating efficiencies. Again, fillers that typically increase thermal conductivity without increasing electrical conductivity are ceramic [6] and known ceramics often have dispersal or relaxing difficulties and are not usually well dispersible. To overcome these barriers which blocks the industrial adoption of nanofluids, focused treating methods, such as surface hydrogenation [7] or surfactant imbuement have been attempted but the resultant nanofluids still found to suffer from below-par sustainability in terms of lifetime. To circumvent the above pitfalls, searching for newer types of nanofillers that are able to address both the challenges at relatively lower filler fractions appears to be a viable approach.

Recent development of two-dimensional (2D) materials presents a unique opportunity to address several of the aforementioned problems. Properties of these 2D materials range from metallic (NbS_2, VSe_2), conducting (graphene), semi-metallic (WTe_2, $TiSe_2$), semiconducting (MoS_2, WS_2) to insulating (h-BN, HfS_2); and their properties can even be tailored to suit specific base fluids to design optimum solution [8]. Owing to their two-dimensional nature, these 2D material based nanofillers have very high surface to volume ratio and thus they can be operated on relatively much lower filler fractions. Among the materials described above, highly insulating h-BN or white graphene unveils more multipurpose assets such for example outstanding thermal conductivity, first-rate mechanical steadiness, and prominent chemical dullness. Du *et al* [9] demonstrated that BN nanoparticle improves thermal responses, electrical insulation and BDV of the transformer oil. However, BN particles agglomerate easily leading to lowering of vital properties. Here chemically exfoliated hexagonal boron nitride (h-BN) nanosheets have been used owing to their large surface area of (002) lattice planes, with the alluring appeal as better 2D nanofiller of choice in both thermal and insulating aspects with improved stability for designing next-generation transformer oils.

In the current study we explore experimentally the result of fine distributed exfoliated h-BN nanosheets in TO and its augmented results of thermo-physical and dielectric properties. Achieved outcomes displayed extraordinary surge in dielectric and thermo physical characteristics of the transformer oil. Observations on stability show that nanofluids having low filler concentration are stable over long period. Hence, 2D nanosheets are anticipated to be the future orientation of TO nanofluids with great potential for high voltage industrial applications.

The following sections discuss the methods employed and the experiments performed. The outcomes of the results are discussed elaborately with suitable references. Schematics are used to discuss the mechanisms involved.

2 PREPARATION OF 2D H-BN BASED NANOFLUID

Transformer oil (TO) with a batch number, 15L865TD03 supplied by Savita oil technologies with a maximum moisture content of 50 ppm have been used as a base fluid in this study [10]

Nanofluids were prepared following conventional two-step procedure [4, 10, 20] at weight percentage (Wt. %) of 0.005, 0.01, 0.05 and 0.1 respectively without usage of surfactant. The process is shown schematically in Figure 1.

Figure 1. Schematic of nanofluid preparation.

Amount of nanofiller required to prepare each Wt. % of
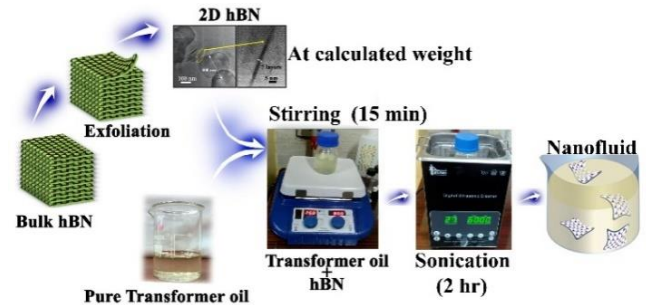
nanofluid is calculated by Equation (1) on the basis of the volume of nanofluid sample required for different tests done in this work as shown in Table 1. The nanofluids are prepared in air tight Pyrex bottles so that no moisture could enter during the sonication process. The prepared nanofluids are shown in Figure 2.

$$Wt.\% = \frac{\text{Weight of nanosheets}}{\text{Weight of (nanosheets} + \text{TO)}} \times 100\% \quad (1)$$

Table 1. Details of Nanofluid sample prepared.

Sl No.	Experiment	Sample Required (mL)
1.	AC BDV	500
2.	Tandelta loss and	100
3.	Resistivity	30
3.	Thermal conductivity	70
4.	Thermal imaging Viscosity and Tyndall Scattering	200

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Figure 2. (a) 2D h-BN nanopowder and (b) prepared nanofluids with various weight percentages
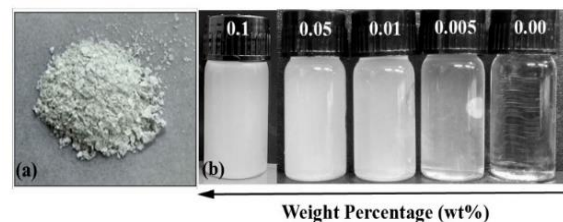
2.1 MATERIAL SYNTHESIS

h-BN nanosheets were synthesized by hydrothermal method [11] In a typical experiment, 0.05 M sodium hydroxide (NaOH) with 0.04 M potassium hydroxide (KOH) pellets were grounded superbly followed by addition of 10 mM h-BN powders. The blend was further grounded for half an hour until it was an even mix by natural moisture absorption. Afterward, this similar mix was moved into Teflon container, covered by stainless steel jacket,

heated to 180 °C for a duration of 2 h, and permitted to cool down normally to room temperature. The white colored precipitate was collected afterward by centrifugation followed by dehydrating at 60ºC in an oven.

2.2 CHARACTERIZATION

The phase purity of the synthesized samples was studied by recording X-ray diffraction (XRD) pattern (Bruker D-8 Advance, 40 kV at 40 mA) using Cu-Kα emission. Classification and identification of the functional groups were achieved by Shimadzu IR PRESTIGE 21 spectrometer having a range of 500-4000 Cm^{-1}. Raman spectra was recorded by WITec Raman spectrometer, Nd:YAG laser having an excitation wavelength of 532 nm. The samples were further characterized using high-resolution transmission electron microscope (HRTEM) JEOL 2100 for defining its nanostructures.

Figure 3a illustrates the representative XRD form of the sample. Diffraction peaks observed at 26.2° and 42.8° were assigned to diffraction originating from (002) and (100) planes of h-BN. From relative intensity ratio it can be concluded that the samples are having (002) preferred orientation. Two noticeable bands in FTIR spectra occurs at 814 and 1389 Cm^{-1} which rises to owe to in-plane stretching and out-of-plane bending vibrations of B-N bond and are correspondingly shown in Figure 3b. Characteristic Raman spectra of synthesized nanosheets displays the main peak at the position of 1374 Cm^{-1}, which corresponds to the elevated frequency E_{2g} kind (Figure 3c). The position of full width at half maximum (FWHM) of obtained Raman peak states that the exfoliating route transfers no injury to the arrangement and crystallinity.
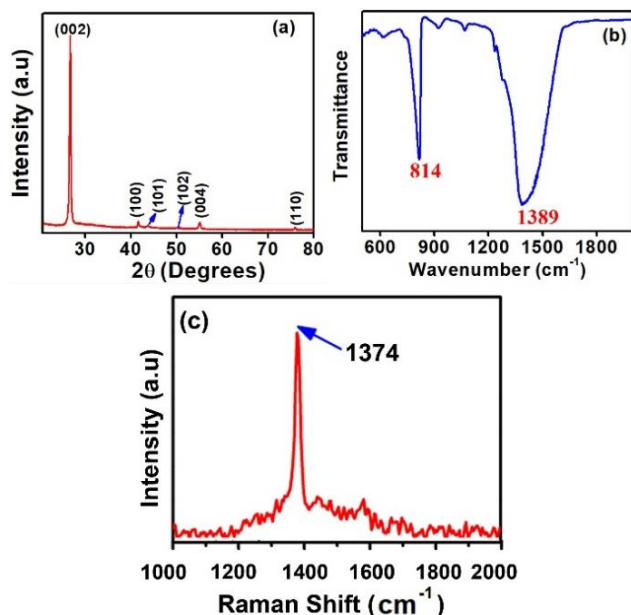

Figure 3.(a) X-ray diffraction pattern; (b) FTIR spectra and (c) Raman spectra.

TEM micrograph (Figure 4a) indicates puckered sheet-like structure similar to graphene structure with average size approximately 100-450 nm in breadth and having a few layers as thickness. Figure 4b shows presence of about 10-20 layers of the material, obtained by HRTEM studies.
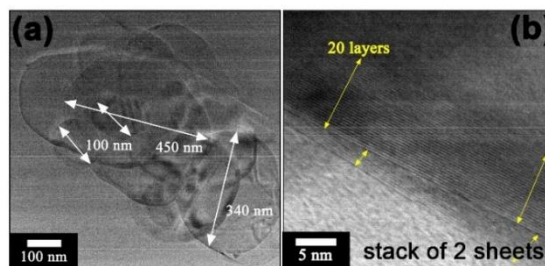

Figure 4. (a) TEM Image of exfoliated h-BN nanosheets; (b) HRTEM images shows several sheets of different dimensions with 20 layers of thickness,

3 IMPACT ON DIELECTRIC INSULATION SYSTEMS

In addition to the role of heat transfer, transformer oil acts as the electrically insulating medium among the high voltage windings. Hence, the impact of the nano agents on the dielectric breakdown strength, resistivity, dielectric loss of the liquid insulation system are very important. Following sections pronounce these important electrical properties of the transformer oil nanofluids under study that were measured by ELTEL ADTR 2K Plus tester.

3.1 ELECTRICAL RESISTIVITY AND RELATIVE PERMITIVITY AND DIELECTRIC LOSS

Nanofluid containing h-BN nanosheets exhibited higher resistivity compared to base oil, as h-BN is a highly insulating material. However, the variation of relative permittivity is small as the nanofillers (h-BN) has the relative permittivity in the order of 2.7 [12], very close to the base oil. The experimentally obtained relative permittivity have good agreement with theoretical prediction at different volume fractions, as obtained by Maxwell-Garnet formula [12]. These comparisons are presented in Figure 5a. Whereas the resistivity variation is shown in Figure 5b. Nevertheless, the loss component of the nanofluid is low and it varies inversely with the temperature in Figure 5c.

The reason behind the rise in resistivity is due to the fact that h-BN sheets are capable of trapping charged entities injected in the oil during the measurement procedure. This will lead to the decrease of mobile charges and make the oil more resistive [9], which is reflected in the decrease of dielectric loss.
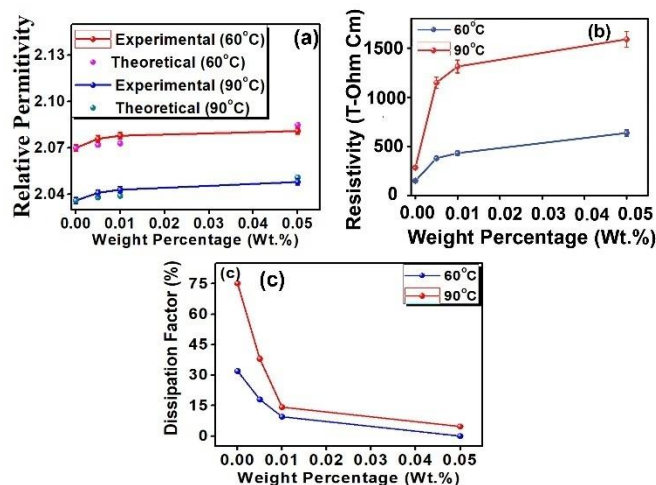
3.2 AC BREAKDOWN VOLTAGE

The AC breakdown Voltage (BDV) of the TO nanofluids were measured according to ASTM D877 standard using spherical electrodes at 2.5 mm gap distance. Neo-TeleTronix made 120 kV, 50 Hz automatic breakdown voltage testing set have been used for this purpose. The applied voltage was increased in steps starting from zero with a degree of 2 kV/s till the breakdown happened. The mean Breakdown voltages of the nanofluids under test with a minimal dispersion of nanofiller showed a significant increment as shown in Table 2 & Figure 6a. For each mean value, 30 independent readings were recorded.

Table 2. Breakdown voltages of nanofluids.

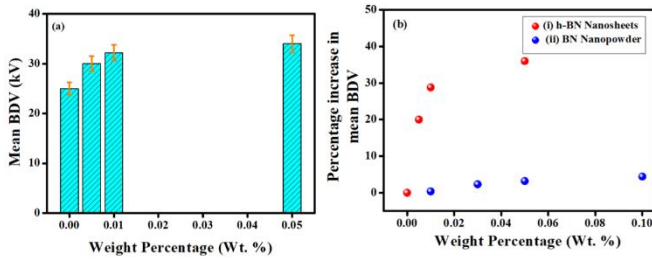| Sample (Wt. %)	Mean BDV (kV)	Standard Deviation (±5 %)	Percentage Enhancement
0.00	25	1.25	0
0.005	30	1.51	20
0.01	32.2	1.60	28.8
0.05	34	1.70	36

Figure 6. Impact on breakdown voltage of TO nanofluid. Plot (b) (ii) data reused from [9], 978-1-4799-2063-1 $31.00 ©2014 IEEE.

The percentage enhancement of the breakdown voltage has increased progressively with an increment of Wt. % of nanofiller. A maximum improvement of ~ 36% was observed for 0.05 Wt. % of h-BN nanosheets. Figure 6b shows relative comparison of performance of the nanofluids between the present work and that reported by Du *et al* [9]. The theoretical emphasis on the breakdown phenomena of the nanofluids has been clarified by statistical analysis using the Weibull distribution function [10], which for any random variable say "x" (BDV in the present study) is defined as [10]:

$$f(x) = 1 - \exp(-\frac{x}{\alpha})^{\beta} \qquad (2)$$

Where α and β denote the scale and shape factor respectively. The scale factor α resembles BDV at the probability of 63.2%, whereas shape factor β is linked with the degree of failure [10]. The calculated scale and shape factors of experimentally obtained BDVs at various filler fractions are furnished in Table 3. The corresponding voltage endurance with 63.2% and 5% breakdown probability along with its Weibull distribution are presented in Table 4 and Figure 7 respectively.

It is self-explanatory from the statistical analysis that 2D h-BN dispersed nanofluid possesses highly improved dielectric breakdown strength. The less scattering of the breakdown data from the mean value indicated absence of impurities as well as free moisture [13]. The possible justification of the superior

breakdown voltages due to the dispersal of 2D nanofillers is explained in the next paragraph.

Table 3. Scale and shape factor of nanofluids.

Sample (Wt. %)	Scale parameter, α	Shape parameter, β
0.00	22.58	17.82
0.005	31.15	16.73
0.01	32.87	19.28
0.05	40.9	9.5

Table 4. Statistical analysis of breakdown voltages.

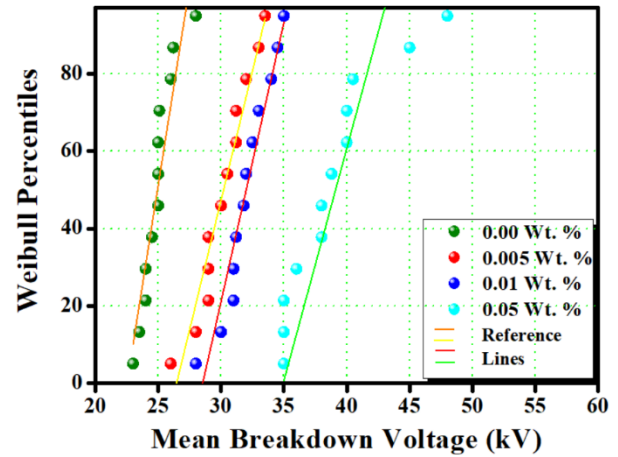| Sample (Wt. %)	Mean BDV (kV) at 5% Prob,	Mean BDV (kV) at 63.2 % Prob,
0.00	21.03	25.58
0.005	25.2	31.15
0.01	27.41	32.87
0.05	28.28	40.9

Figure 7. Cumulative probability curves of nanofluids; (a) 0.00 Wt. %, (b) 0.005 Wt. % (c) 0.01 Wt. % and (d) 0.05 Wt. %.

Streamers mediate electrical breakdown in nanofluids [10]. 'Streamers' in virgin oil are created due to near-field ionization of oil under high electrical stresses and are oriented uniformly in the continuous oil media of constant conductivity (σ) and permittivity (ε). Presence of foreign material in the oil would cause an interruption in the continuous streamer orientation and effectively lead to significant changes in the breakdown phenomena. The conductivity and permittivity of the dispersed fillers have an important role to attract free charges, to trap and store them [5]. The appearance of nanomaterial with dissimilar resistivity and permittivity in base oil would lead to the formation of an incoherent interfacial region. This heterogeneous or discontinuous region is called Maxwell-Garnet (M-G) region [12] and plays a crucial protagonist in governing the electrical breakdown phenomena in nanofluids. According to the physics of polarization, these domains can attract traversing charges of streamers and trap them. Apparently, the velocity of charge propagation in the oil media decreases. Hence, this would lead to a decrease in space charge density and propagation delay of streamers to short the electrodes. These eventually enhances the breakdown voltage. Apart from the conductivity and permittivity, scavenging of free charges greatly depends on the surface area of the

interfacial region. Hence, the morphological changes of the nanofillers have great impact to influence the BDV. Among common morphologies of nanofillers, 2D structure provides highest surface exposal and surface energy that leads to form the maximum M-G interfacial area [5, 12]. More the area of the interfacial layer, more charge accumulation would take place leading to rising slope of BDV. The effect of interfacial layer in scavenging the free charges for spherical (particle) and 2D morphologies of the nanofillers are presented in Figure 8.
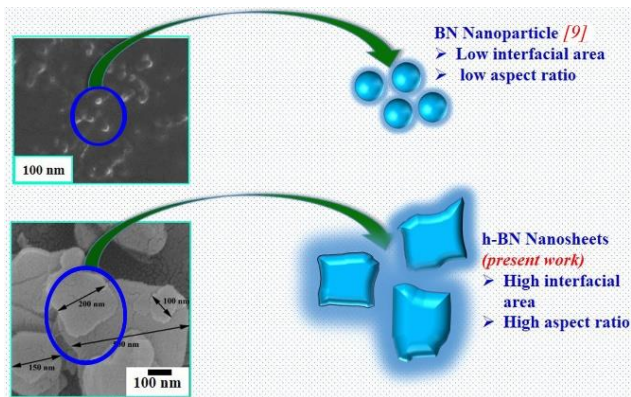

Figure 8. Morphology dependent interfacial region. (a) Image reused from [9], 978-1-4799-2063-1 $31.00 ©2014 IEEE. (b) SEM image of h-BN nanosheets

Previously reported BN particle of 50 nm size [9] and presently used h-BN nanosheets (2D) have almost similar resistivity and conductivity. However, with the same volume fraction, 2D nanosheets of h-BN provide a huge area of the interfacial layer and high aspect ratio resulting into more trapping of free electrons and create noteworthy augmentation of BDV as compared to the spherical morphology of BN family, as furnished in Figure 6b.

4 IMPACT ON THERMOPHYSICAL PROPERTIES

Improved thermal management and the heat transfer capability of nanofluids have opened a new horizon in front of liquid insulation. However, corroboration of nanofillers not only improves the thermal conductivity but also at the same time creates an adverse effect like increased viscosity, agglomeration of nanofillers. In this investigation impact of 2D nanofillers, on these correlated thermo-physical properties have been investigated to consider the overall performances of the TO nanofluids under study.

4.1 THERMAL CONDUCTIVITY

The temperature dependent thermal conductivity of the nanofluids(k_f) along with base TO (k) were measured at 35°C, 45°C and 55°C respectively by KD2 pro analyzer [14]. The results has been presented in Figure 9. Every experiment have been repeated 4 times with 10 min gap. The percentage increment is presented in Table 5. At lower filler fraction (0.005-0.05 Wt. %), sharp increase and linear relationship with thermal conductivity have been achieved. Beyond this concentration, a small negative slope of thermal conductivity have been observed.

Further, to validate the enhanced thermal conductivity of nanofluids, surface temperature of the nanofluids were recorded at different instances of heating time (in 15 min interval) by an Infrared thermal camera (RAYCAM 1886). From the thermographs (Figure 10), it was observed that the higher
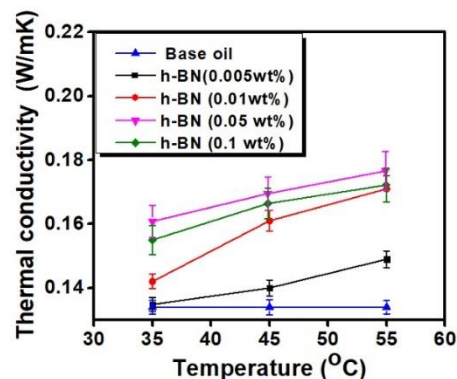
temperature region extends with the Wt. % of nanofluids and also with heating time. Hence, addition of h- BN nanosheets in TO supports tranquil dissipation of formed heat via the surface of the oil.

Figure 9. Temperature dependent thermal conductivity of TO nanofluids.

Table 5. Percentage enhancement in thermal conductivity of nanofluids.

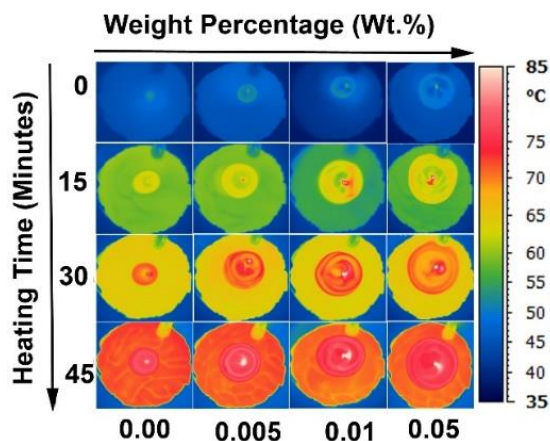| Sample (wt. %)	At 35°C	At 45°C	At 55°C
0.00	0	0	0
0.005	0.06	4.4	11
0.01	6	20	28
0.05	20	26	31
0.1	17	24	28

Figure 10. Infrared images of nanofluid surfaces.

The heat transport mechanism in nanofluid is a multifaceted one and depends on many attributes like nanomaterial's composition, shape and size, morphology, surface charge, the nature of interface as well as fluid temperature, concentration, [15]. It is well known that Brownian motion and convection helps to drag heat by generating a long-range velocity field in the medium. But effective contribution of Brownian motion is restricted to 10% with high nanofiller concentrations and high

temperatures [16]. In case of layered materials (with nanometric layer), liquid-layering interface and percolation channel formation plays most dominant role in the overall heat transfer in the medium [14]. The degree of heat transfer via these zones is restricted by the inherent thermal resistance faced at the interface; i.e, the Kapitza resistance, which depends on the nature of the interface, whether it is oil-wetting or not. In case of lipophobic dispersants, large Kapitza resistance and heat constraint exists and amphibilic agents or surfactants are required to create a smooth bond between oil and nanofiller [17]. Further, in case of layered materials in a recent study, it is found that Kapitza resistance increases if the layer number becomes less than 5 but remains comparatevely lesser if the layer number is more than 10 [18].

Here, dispersed 2D h-BN being layered, possesses large specific surface area which has enabled to create a large interfacial region. Again, owing to its (002) plane dominance (hexagonal phase) and being similar to graphitic plane, it possesses highest thermal conductivity (>600W/mK) among all other phases [19]. Moreover, the long time stability and moderate number of layers (20 layers, from TEM image) have indicated that the thin, high specific surface area h-BN nanosheets are perfectly oil-wet (lipophilic) which have enabled the formation of a perfect contact with oil without usage of any surfactant. Hence, the intra-sheet heat propagation with a larger mean free path of phonon occurs which faces lower Kapitza resistance and lower thermal losses.

In addition to this, cluster formation due to less inter-particle distance in a nanofluid medium leads to formation of percolation network and acts as a conductive path for propagation of heat. When a cluster is formed, an overlap of interfacial regions of two or more sheets occurs resulting in a continious Kapitza region with reduced vibrational density of states of phonons [18] which is a characteristic feature of high concentration based nanofluids. In the present case, the total length occupied by the h-BN sheets (300*300*10 nm^3), in a sample nanofluid (say 0.1Wt. %) hypothetically arranged longitudinally or laterally along the length of the experimental cell (10 Cm long, 3 Cm diameter) of thermal conductivity measurement is roughly calculated to exceed far from the length (10 Cm) of the cell. This proves indeed there exists a percolating network even in such diluted concentrations which have played a contributory role in favorable phonon transfer and a ballistic heat transfer. Further the differences in the thermal images of base transformer oil and nanofluid shows that the region of high temperature gets spreaded with loading of h-BN sheets. This directly proves that a percolating network exists.

With the increase in temperature and filler concentration the velocity and number of participatory phonons increases and hence the overall thermal performance surges too. Nevertheless, the improvement in thermal conductivity cannot be infinite simply by increasing the filler concentration. Because beyond a certain limit (here, 0.05 Wt. %), the increasing concentration would intensify the gravitational agglomeration of discrete nanomaterial due to the strong van der Waals force in close vicinity of nanofillers, causing

drooping characterictics. This saturation or drooping characteristics are more prominent in high temperature with high filler concentration, due to high phonon scattering [4] and high potential agglomeration [4]. Additionally, the long measuring time of thermal conductivities lead to visible agglomeration and make it puroposely insignificant.

The overall heat transport in nanofluids via interfacial region is shown in Figure 11. Propagation of heat via sheets with large interfacial area enhances heat propagation. These results are better at lower concentrations than other recently studied nanofillers such as TiO$_2$ [20] or ZnO [21] and are comparable to the results of graphene or copper nanofluids.
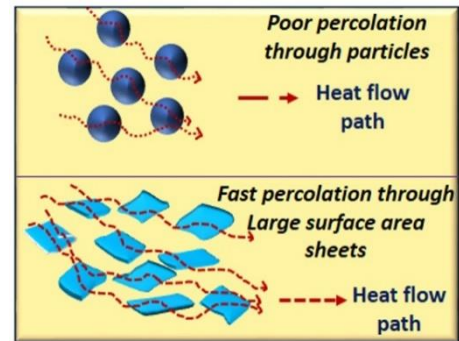

Figure 11. Schematic overview of heat propagation in nanofluids.

4.2 VISCOSITY

Viscosity is the internal resistance of fluid flow and depends on both filler geometry, surface properties and filler concentration [22]. Temperature-dependent viscosity (η) of the prepared TO-2D h-BN nanofluid at different concentration have been measured using Brookfield viscometer and depicted in Figure 12 along with its base value (η_0). The viscosity increases with the Wt. % of the nanofillers but decreases with temperature.
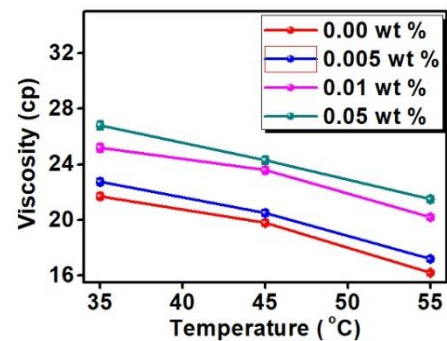

Figure 12. Temperature dependent viscosity of nanofluids.

On the context of viscosity and thermal conductivity, overall thermal efficiency (C_η/C_k,), for the nanofluids are computed using the following equations [22] which is furnished in Table 6.

$$C_\eta = \quad \eta/\eta_o - 1 \qquad (3)$$

$$C_k = k/k_o - 1 \qquad (4)$$

And the thermo-efficiency of the nanofluids is defined by:

$$C_\eta/C_k \leq 4 \qquad (5)$$

Where C_η and C_k are viscosity and thermal conductivity enhancement coefficients, determined from experimental viscosity and thermal conductivity ratios.

Table 6. Thermo effeciency of nanofluids.

Temperature (^{0}C)	0.005 Wt. %	0.01 Wt. %	0.05 Wt. %
35	8.1	2.7	1.17
45	0.79	0.98	0.87
55	0.55	0.89	1.04

It is clear from the above tabulation that at lower filler fraction the nanofluids are more thermal efficient, particularly at higher temperature. This is because at a greater concentration, increase in viscosity decreases the effective thermal conductivity [23]. Hence, the nanofillers, which can provide high thermal conductivity at lower filler concentration, are the new orientation of nanofluidic research. In this context, 2D structures are the promising candidates due to their high surface to volume ratio.

4.3 STABILITY

Stability of a nanofluid is a critical factor to determine its industrial applicability. According to DLVO theory, in a nanofluid, two type forces, namely electrostatic repulsive force and van der Waals attractive force interplays due to close particle interaction and decides the stability [24]. In a diluted nanofluid, less van der Waals force acts due to less inter-particle interaction. Additionally, nanofillers with small size and light weight can resist gravitational sedimentation too. In this context, lightweight and ultrathin nature of 2D h-BN nanofillers have encouraging future.

Here, the stability of the nanofluid of 0.005 Wt. % was checked by Tyndall scattering using a red laser beam of 650 nm. The digital photographs were taken just after the preparation of the nanofluid and after 7 days of preparation and are shown in Figure 13. The scattered intensity of light by nanofluid shows there is no much alteration. The prepared nanofluid was observed to remain stable over several weeks without any surfactant. This enhancement is achieved due to the lightweight and large surface area of the 2D nanofillers.
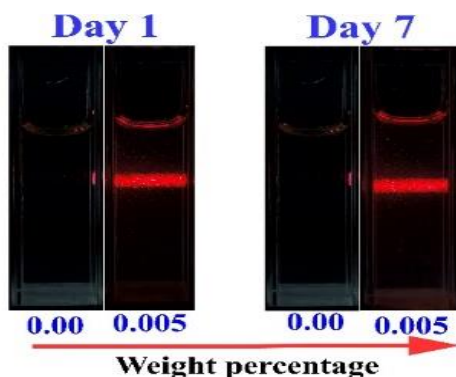

Figure 13. Stability study of TO nanofluids at 0.005Wt. %

It is to be pointed out that the stability study have been carried out after keeping the fluid in the lab environment without any type of disturbance. However, in practical scenario, TO is not kept stationary during the operating conditions. In a transformer, the average speed of oil movement is 1Cm/s according to industrial experience. This speed times the cross section of the tube in which oil is circulated to be around 19 ml/min [13]. Hence, under force convection, the dispersed nanofillers will maintain their stability much better as continuous force hinders the possibility of agglomeration. Also the particle agglomeration in the operational environment can be solved by increasing the convection speed of nanofluid and by lipophobic coating as well.

4.4 TO NANOFLUIDS: PARTICLE VS 2D NANOFILLERS

Finally, the overall performances of the developed nanofluid with 2D h-BN nanofillers with its state-of-the-art counterpart as reported by Du *et. al.* [9] have been compared and furnished in Table 7. It clearly indicates the outstanding performances of 2D nanoadditives in the framework of both thermo-physical and electrical properties of liquid insulation like transformer oil. Large surface to volume ratio of the 2D nanostructure has the key role behind these improved performances

Table 7. Comparative performance of transformer oil nanofluids: BN nanoparticle vs. h-BN 2D nanosheets.

Sl. No	Morphology of nanofiller	Electrical Property BDV ENHANCEMENT (0.05 WT. %)	Thermo-Physical Properties		
			Thermal Properties	Thermal Efficiency (equation (4))	Stability
[9], 2015	BN Nanoparticles (50 nm)	4.5 kV (3.2 % at 2 mm electrode distance)	Improved thermal Response	-	A couple of days
[25], 2018	BN Nanoparticles (40 nm)	-5 kV (17 % decrease at 0.25 vol %)	Not studied	Not studied	Not studied
Present Work	h-BN *Nanosheets*	*9 kV (34 % at 2.5 mm electrode distance)*	Superior thermal Response with *30%* enhancement in thermal conductivity (0.05 Wt. % at 55 ^{0}C)	*0.55-1.04* (at 55 ^{0}C)	*A couple of Weeks*

5 CONCLUSIONS

The advent of nanotechnology has opened a new prospect in the area of multifunctional fluid like transformer oil. However, for achieving the optimum performances the choices of the nanomaterials and their morphologies have great influences. State-of-the-art nanoparticles can improve the thermal and electrical responses but their stability in the oil is poor. To overcome these limitations, 2D layered materials are gaining

importance in this area. Two-dimensional nanomaterials can be the good choices as nanofillers in transformer liquid insulation, due to their high surface area, surface to volume ratio and of course for better stability. In the present investigation, 2D nanomaterial of chemically exfoliated h-BN nanosheets have been developed. Simple and cost elective bulk production of 2D nanofiller shows a promising future for efficient thermal management and augmentation of BDV of the high voltage insulating fluid. The novelty of this research exertion lies on the opening of a new direction of nano-engineered transformer oil with 2D nanofillers to combat with ever-increasing stresses of power industries.

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REFERENCES

[1] P.P. Verma *et al*, "A review of uncertainty handling techniques in smart grid," Int. J. Uncertain. Fuzziness Knowl.-Based Syst., vol. 26, no. 3, pp. 345-378, Jun. 2018.

[2] L. Qiu *et al*, "A review of recent advances in thermophysical properties at the nanoscale: From solid state to colloids," Phys. Rep., vol. 843, pp. 1-81, Feb. 2020.

[3] S.U Ilyas, R. Pendyala, and M. Narahari, "Stability and thermal analysis of MWCNT-thermal oil-based nanofluids," Colloid Surface A., vol. 527, pp. 11-22, Aug. 2017.

[4] G. Shukla and H. Aiyer, "Thermal conductivity enhancement of transformer oil using functionalized nanodiamonds," IEEE Trans. Dielectr. Electr. Insul., vol. 22, no. 4, pp. 2185-2190, Aug. 2015.

[5] V. A. Primo, B. Garcia, and R. Albarracin, "Improvement of transformer liquid insulation using nanodielectric fluids: A review," IEEE Elect. Insul. Mag., vol. 34, no. 3, pp. 13-26, May 2018.

[6] R. Zhang *et al*, "Enhanced mechanical and thermal properties of anisotropic fibrous porous mullite–zirconia composites produced using sol-gel impregnation," J. Alloys Compd., vol. 699, pp. 511-516. Mar. 2017.

[7] O.A. Williams *et al*, "Size-dependent reactivity of diamond nanoparticles," ACS nano, vol. 4, no.8, pp. 4824-4830, Aug. 2010.

[8] N.B Singh, S.K. Shukla, "Properties of two-dimensional nanomaterials," Two-Dimensional Nanostructures for Biomedical Technology, pp. 73-100, 2020.

[9] B. Du, X. Li, and M. Xiao, "High thermal conductivity transformer oil filled with BN nanoparticles," IEEE Trans. Dielectr. Electr. Insul., vol. 22, no. 2, pp. 851-858, Apr. 2015.

[10] M. M. Bhunia *et al*, "Amorphous graphene–Transformer oil nanofluids with superior thermal and insulating properties," Carbon, vol. 139, pp. 1010-1019, Nov. 2018.

[11] G. Zhao et al., "One-Step exfoliation and hydroxylation of boron nitride nanosheets with enhanced optical limiting performance" Advanced Optical Materials, Vol. 4(1), pp.141-146, 2016.

[12] A. Laturia, M.L. Van de Put, and W.G. Vandenberghe, "Dielectric properties of hexagonal boron nitride and transition metal dichalcogenides: from monolayer to bulk," NPJ 2D Mater. Appl., vol. 2, no. 1, pp. 1-7, 2018.

[13] H. Jin, "Dielectric strength and thermal conductivity of mineral oil based nanofluids," 2015

[14] M.M. Bhunia*, et al.*, "2D square nanosheets of Anatase TiO$_2$: A surfactant free nanofiller for transformer oil nanofluids" *Journal of Molecular Liquids*, Vol. *325*, pp.115000, 2021

[15] S. Mohanachandran Nair Sindhu, and S. SankaranarayanaIyer, "Generalized theory of thermal conductivity for different media: solids to nanofluids," J. Phys. Chem. C, vol. 123, no. 37, pp. 23264-23271, Sep. 2019.

[16] A. Gupta, and R. Kumar, "Role of Brownian motion on the thermal conductivity enhancement of nanofluids," Appl. Phys. Lett., vol. 91, no. 22, pp. 223102, Nov. 2007.

[17] K. Wu, and C. Cheng, "Interface charges between insulating materials," IEEE Trans. Dielectr. Electr. Insul., vol. 24, no.4, pp. 2633-2642, 2017.

[18] D. Alexeev *et al*, "Kapitza resistance between few-layer graphene and water: liquid layering effects," Nano lett., vol. 15, no. 9, pp. 5744-5749. Sep. 2015.

[19] Q. Cai *et al*, "High thermal conductivity of high-quality monolayer boron nitride and its thermal expansion," Sci. Adv., vol. 5, no. 6, p.eaav0129, Jun. 2019.

[20] M. Maharana *et al*, "Nanofluid-based transformer oil: effect of ageing on thermal, electrical and physicochemical properties," IET Sci meas Technol., vol. 12, no. 7, pp. 878-885, Oct. 2018.

[21] M. Parvar, S. Saedodin, and S.H. Rostamian, "Experimental study on the thermal conductivity and viscosity of transformer oil-based nanofluidcontaining ZnO nanoparticles," J. of Heat and Mass Transf. Research, 2020.

[22] A. Amiri *et al*, "Transformer oil based multi-walled carbon nanotube–hexylamine coolant with optimized electrical, thermal and rheological enhancements," Rsc Adv., vol. 5, no. 130, pp. 107222-107236, 2015.

[23] M.H. Esfe and M. H. Hajmohammad, "Thermal conductivity and viscosity optimization of nanodiamond-Co$_3$O$_4$/EG (40:60) aqueous nanofluid using NSGA-II coupled with RSM," J. Mol. Liq., vol. 238, pp. 545-552, Jul. 2017.

[24] E.G. Atiya *et al*, "Dispersion Behavior and Breakdown Strength of Transformer Oil Filled with TiO$_2$ Nanoparticles," IEEE Trans. Dielectr. Electr. Insul.**,** vol. 22, no. 5, pp. 2463-2472, Oct. 2015.

[25] Madavan, R., Kumar, S.S. and Iruthyarajan, M.W., 2018. A comparative investigation on effects of nanoparticles on characteristics of natural esters-based nanofluids. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *556*, pp.30-36.

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