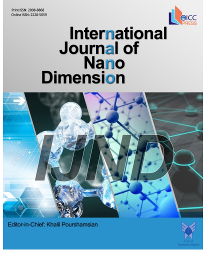

Volume 16, Issue 2, 162510 (1-9)

International Journal of Nano Dimension (IJND)

https://doi.org/10.57647/j.ijnd.2025.1602.10

Synthesis and experimental study of TiO_2 nanofluids for transformer applications

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Original Research

Received:
29 August 2024
Revised:
22 November 2024
Accepted:
8 December 2024

Abstract:

Transformers are essential in an electrical power system, and their efficiency and reliability are vital. The cooling and insulating properties of the fluids used in them are able to influence the performance of transformers drastically. The acceleration of Titanium Oxide (TiO_2) nanoparticles in thermal and dielectric properties suggests promising advantages as a fashionable ingredient for the enhancement in characteristics of oil-base fluids to provide new-generation transformer oils. This study involves the production of TiO_2 nanoparticles through the sol-gel method. The synthesized TiO_2 nanoparticles have been characterized using XRD and SEM analysis. The produced nanoparticles are introduced into base fluids using two-step process. The transformer oil is selected as base fluid, to investigate the thermophysical and dielectric properties at different concentrations typically 0.35, 0.45, and 0.55 wt.% of titanium oxide (TiO_2) nanoparticles with average particle diameter 37 nm. Additionally, assessments are performed on the thermal conductivity, density, and dielectric values of transformer oil. The improvement of 36.84% at 2.5 mm and 36.36% at 4 mm electrode gap, respectively, in Breakdown Voltage (BDV) was identified when using TiO_2 concentration at 0.45 wt% concentration. The maximum thermal conductivity enhancement shown at 0.55 wt% is 23.41%.

Keywords: Dielectric; Nanofluids; Thermo-physical; Titanium dioxide; Transformer oil

1. Introduction

Electrical grid stability depends on power transformers operating effectively and dependably. Transformers are used in the distribution and transmission of electrical energy and are components that determine the overall efficiency of electrical energy delivery systems. The efficient dissipation of heat produced during transformer operation is one of its most important components. Conventional transformer oils are used as insulators and coolants; these are usually mineral oils. However, the heat dissipation and thermal conductivity of these oils are limited. The use of nanofluids with basic fluids containing suspended nanoparticles has gained attraction as a possible way to improve the thermal performance of transformer oils. The thermal conductivity and heat transfer capabilities of the base fluid can be greatly enhanced by adding high-conductivity nanoparticles like titanium dioxide (TiO_2) to transformer oils. This improvement may result in lower operating temperatures, increased cooling efficiency, and longer transformer life spans. Abdullah Bin Afzal et al. [1] reported nanofluids based on mineral oils, enhanced with nanoparticles like MgO, TiO_2, and Fe_3O_4, improve electrical and thermal properties and show potential for transformer applications in insulation. A. J. Amalanathan et al. [2] studied that nanofluids affect the transformer by enhancing its attributes, such as thermal conductivity and stability, but their consequences, including aging, are specific to some types of nanoparticles. Rohith Sangineni et al. [3] Nanofluids with conducting, semi-conducting, and insulating nanoparticles show potential for transformer applications due to their superior electrical and thermal properties. Cristian, Olmo et al. [4] Nanofluids show promise as dielectric cooling liquids for power transformers, enhancing thermal conductivity and dielectric strength and potentially improving the safety and lifespan of transformers. R. H. M. Ali et al. [5] studied that nanofluids enhance the thermal conductivity and electrical properties of transformer oils, improving insulation resistance and dissipation factors, making them beneficial for transformer applications. N. Kishore et al. reported that transformer oil nanofluids containing Al_2O_3 and CuO nanoparticles were synthesized and applied to transformer cooling heat exchangers [6]; when the volume concentration of the nanofluids was increased, the thermal conductivity also increased. A. Mikhail et al. [7] reported nanofluids are utilized in transformer applications due to their enhanced heat transfer properties, making them beneficial for improving efficiency and performance in power engineering systems. Wagd Adnan Ajeeb et al. [8] The characterization of SiC and BN nanofluids in the study shows enhanced thermophysical properties like thermal conductivity and electrical conductivity, indicating potential for transformer applications. Suhaib Ahmad Khan et al. [9] studied that Ester-based nanofluids with graphene oxide and TiO_2 nanoparticles enhance the thermal conductivity and viscosity of oils, crucial for improved insulation cooling in transformers. K. N. Koutras et al. [10] TiO_2 and SiC nanofluids in natural ester oil show enhanced thermal conductivity and lightning impulse breakdown voltage, making them promising for transformer applications. Waleed Iqbal et al. [11] stated that the sol-gel process offers the advantage of synthesizing TiO_2 nanoparticles in more than one structure, such as a core-shell, and these structures would enhance the operation of nanoparticles in different uses. According to W. Jamshed et al. [12], the Maxwell-Eucken model explains the research on the thermal conductivity of the nanofluids and finds that Cu-water-based nanofluids have more thermal conductivity than TiO_2-based nanofluids. Rahmat et al. [13] conducted the study. Nanofluids containing TiO_2 and Fe_3O_4, which are based on rice bran oil, have improved dielectric characteristics suitable for use in transformers. These nanofluids present a viable substitute for conventional transformer oils. Zaid et al. [14] found that the dispersion of graphene oxide in natural ester-based nanofluids improves their dielectric characteristics. This makes them a feasible option for transformer insulation since they exhibit higher breakdown voltage and enhanced relative permittivity compared to traditional oils. The paper by Miloš et al. [15] examines the application of oxide-based nanofluids, specifically Al_2O_3, TiO_2, Fe_2O_3, and Fe_3O_4, in improving the performance of dielectric fluids in power transformers. The study primarily focuses on the properties of these nanofluids and their environmental implications. In their study on the magnetic characteristics of nanofluids Deepak et al., we utilized copper oxide (CuO) and titanium oxide (TiO_2) nanoparticles that were dispersed in mineral oil (MO) to improve the insulating qualities for transformer applications [16]. The review by Mehmet et al. [17] focuses on dielectric nanofluids for transformers and emphasizes their improved breakdown voltage, thermal conductivity, and physicochemical characteristics. However, it does not particularly address nanofluids based on oxides. Xinsheng Yang et al. [18] examine the effects of Al_2O_3 nanofluids on power transformers and determine that a concentration of 0.01% is the most effective in lowering the size of the transformer. The Maxwell-Eucken model plays a crucial role in measuring the thermal conductivity of nanofluids due to its ability to predict the enhanced thermal conductivity resulting from nanoparticle aggregation and elongated structures [19, 20]. Nanofluids, which consist of base liquids and nanoparticles, exhibit significantly improved thermal conductivity compared to conventional fluids, making them a subject of intense research interest. Kelvii et al. [21] research presents useful design insights specifically for oil-based transformers. The Maxwell-Eucken model serves as a valuable tool in advancing the understanding and application of nanofluids in various fields, including thermal engineering, nuclear heating, and safety in technological equipment [22]. Density testing for transformer nanofluids is crucial, as it provides insights into the composition and behavior of the nanofluid. Research has shown that the density of nanofluids remains relatively constant even with the addition of nanoparticles, as observed in both virgin and naturally aged transformer oils [23, 24]. Nanofluids possess improved electrical and thermal characteristics, rendering them highly promising as liquid dielectrics for power transformers. It has the possibility of improving effectiveness and productivity for the use of transformers. The synthesis of gold nanocomposite on hydroxyl propyl cellulose (HPC) by using $NaBH_4$ has been done effectively. Reflecting the properties by X-ray diffraction, TEM, SEM, and TGA, the Au/HPC nanocomposite had a FCC crystal structure below 22 nm [25]. The work also reports a technique for producing silver nanoplates with the aid of PVA and DMF with a reduction of silver nitrate. Babak Sadeghi et al. [26] represents absorption spectra of the nanoplates are dissimilar to those of spherical silver nanoparticles because of their shape and possibly because of the reaction between silver ions and hydroxide groups. Pouya Barnoon et al. [27] investigate non-Newtonian nanofluid flow and heat transfer in a permeable enclosure with two cylinders embedded in a cavity with and without thermal radiation effect. Simulations are conducted for different Rayleigh numbers, Darcy numbers, volume fraction, radiation parameter, and emission coefficient ranges. Pouyan Talebi zadeh sardari et al. [28] investigates the impact of a magnetic field on the rheological behavior of water-carbon nanotube/magnetite nanofluid. Stabilized with TMAH and GA, the nanofluid was characterized using SEM, DLS, and XRD methods. Rostami et al. [29] proposes an artificial neural network (ANN) algorithm to predict the thermal conductivity of SiO_2 /water-ethylene glycol (50:50) nanofluid. After generating experimental data points for different nanoparticle volume fractions and temperatures, the algorithm finds the best architecture and correlation coefficient of 0.9919. Xiaowei Yang et al. [30] was used an Artificial Neural Network (ANN) to predict thermal conductivity in water/ethylene glycol hybrid nanofluid containing MWCNTs-titania-Zinc oxide. Yanfang Zhu et al. [31] investigates the effect of temperature and volume fraction of nanoparticles on the dynamic viscosity of MWCNT - WO_3 /water - Ethylene glycol (80:20) nanofluid. The nanofluids are synthesized using a two-step method by dispersion of nanoparticles in the base fluid.

The state of the art in transformer oil research emphasizes the integration of TiO_2 nanoparticles to enhance the performance of transformer fluids, with ongoing studies focused on optimizing these nanofluids for practical applications in electrical power systems. The study explores the potential use of TiO_2 nanofluids in the transformers anticipating the better performance of the transformer. It discusses its use as dielectric cooling liquid, insulating fluid, better thermal management and replacement of conventional oils.

2. Materials and methods

2.1 Selection of base oil

Transformer oil specifications are crucial for guaranteeing the optimal and reliable performance of transformers. The factors encompass insulation, cooling, chemical stability, moisture content, purity, material compatibility, and aging. Insulation and prevention of short circuits are ensured by a high dielectric strength. High thermal conductivity facilitates the dispersion of heat, while low viscosity improves the effectiveness of cooling.

Oxidation stability safeguards against harm to insulation and impediments to oil circulation. Insulation requires a minimal amount of moisture. Purity inhibits the formation of corrosive chemicals. Material compatibility ensures that there are no chemical interactions that could lead to leaks. Regular testing aids in evaluating the state of the oil and strategizing maintenance tasks. These requirements guarantee the durability and dependability of transformer oil. In this research study the selected transformer oil specifications as per IS: 335:1993 performance levels are indicated in Table 1.

2.2 Synthesis of TiO_2 nanoparticles

There are different ways in which TiO_2 nanoparticles are prepared: chemical, physical, and biological. Chemical methods include the use of hazardous chemicals, while physical methods include methods like irradiation through gamma rays, exposure to which results in high-energy particles. In this process, the sol-gel process is adopted due to its adaptability, cost-effectiveness, and capacity to manufacture a diverse array of materials with customized properties.

Table 1. Detail of Transformer oil [32].

Parameter	Specification
Appearance	Clear and Bright
Density	Approx. 872 kg/m^3 at 29.5 °C
Kinematic Viscosity at 27 °C	16.46 cSt
Kinematic Viscosity at 27 °C	11 cSt
Interfacial Tension	0.044 N/m at 27 °C.
Flash Point	172 °C
Pour Point	−18 °C
Neutralization Value	Nil
Corrosive Sulphur	Non-corrosive
Dielectric Dissipation Factor	0.00025 at 90 °C.
Resistivity at 27 °C	11300×10^{12} Ωcm
Resistivity at 40 °C.	750×10^{12} Ωcm

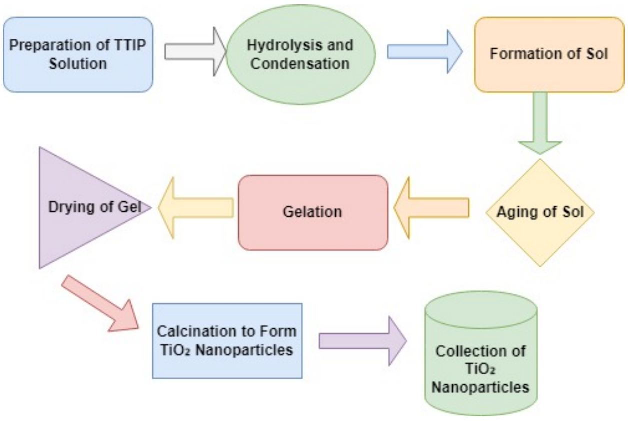

Figure 1. Flow chart of Synthesis of TiO_2 Nanopowder.

This method enables the production of nanoparticles and advanced materials at temperatures close to room temperature, ensuring uniformity and affordability.

The sol-gel method is a commonly employed technology because of its capacity to generate nanoparticles with exceptional purity and consistent size. The sol-gel method's versatility and effectiveness render it a desirable technology in many domains, such as materials science and environmental chemistry.

The key chemicals used in synthesis process includes titanium tetra-isopropoxide (TTIP) (CAS number: 546 – 68 – 9, manufactured by Lobachemie and purity 98%) used as reagent in solvent and oleic acid extra pure (CAS number: 112-80-1, manufactured by Lobachemie, Mumbai). The detailed flowchart for the synthesis of TiO_2 nanoparticles is shown in figure 1 indicates the sol-gel process makes use of TiO_2 nanosol particles prepared by dissolving titanium tetra-isopropoxide (TTIP) in a solvent.

The steps that ensue include reactions of hydrolysis and condensation, which see the creation of a number of intermediate species and a sol. The sol forms nanoparticles in a liquid, and the further process of mounding and development forms a more stable structure. The sol transforms into a gel with a soluble network and a liquid phase entrapped within it. The gel is dried to obtain xerogel, which is calcined to get TiO_2 nanoparticles, or titania. The collected product with TiO_2 nanoparticles is obtained at the end of the calcination stage. The prepared nanopowder is indicated in figure 2.

Figure 2. Titanium dioxide Nanopowder.

2.3 Synthesis of nanofluids

The production of nanofluids is essential for their successful use in diverse industries, with various technologies providing differing levels of efficiency. The process of preparing nanofluids, which involves ultra-sonication in two steps, is commonly utilized. They include the choice of the proper synthesis techniques for the nanofluids, the stability of the nanofluids, and the characterization of the prepared nanofluids. The one-step technique combines the synthesis and dispersion of nanoparticles in the base fluid into a single procedure.

There are several alternate approaches to this procedure. The direct evaporation technique, also described as a one-step method, is a technique for producing nanofluid by solidifying nanoparticles into a liquid state. The preparation process of nanofluids starts with the direct suspension of nanomaterials into the base fluid. Initially, nanomaterials are produced, and then they are added to the base fluid as the second step. The two-step process is often applied to prepare carbon nanotube-based nanofluids.

The figure 3 schematic illustrations indicates the process of preparing a nanofluid involves weighing the nanopowder, preparing the base fluid, adding a surfactant, mixing the mixture, stirring, and sonicating. This ensures an even distribution of nanoparticles in the base fluid. The final product is a stable suspension of nanoparticles evenly distributed in the base fluid.

2.4 Characterization

2.4.1 XRD analysis

The analysis of X-ray diffraction (XRD) has a pivotal role in the characterization of nanomaterials, which is concerned with identifying crystalline phases and measuring crystal sizes and lattice parameters, as well as evaluating the degree of crystallinity and inferring internal strains or stresses inside materials. It also has the ability to detect impurities and secondary phases that can affect material quality, performance, and durability. They are utilized in quality control to ensure consistency and reliability in industrial applications. You can read more about X-ray diffraction (XRD) here. It also helps in establishing the synthesis conditions required for obtaining desired properties during both application and processing. XRD, in general, is a versatile technique for understanding the unique properties of these nanomaterials. The utilization of X-ray diffraction (XRD) analysis is essential in the characterization of TiO_2 nanoparticles, as it offers important insights into the structural features of these materials. X-ray diffraction (XRD) examination enables the identification of crucial parameters, including crystallite size, phase composition, and crystal structure. These parameters are vital for comprehending the behavior and performance of TiO_2 nanoparticles. Figure 4 represents the observed XRD pattern for titanium dioxide (TiO_2). The highest peak is observed at around 25 degrees 2θ. Additional prominent peaks can be found at around 37°, 48°, and 54° in terms of 2θ. The prominent feature observed at an angle of 25° is indicative of the presence of the anatase phase of TiO_2 [33].

2.4.2 SEM analysis

Scanning electron microscopy (SEM) study of TiO_2 nanoparticles aids in identifying their crystalline structure and their propensity to agglomerate. An analysis of TiO_2 nanoparticles through SEM pictures provides useful insights into their size, structure, and propensity for aggregation. The particles exhibit predominantly spherical shapes, with average particle diameter 37 nm. Aggregation is easily detectable and is expected in samples that contain nanoparticles. The smooth surfaces and various sizes of the discovered particles align with the characteristic features of TiO_2 nanoparticles that are extensively used in a wide range of applications, such as photo catalysis and pigment production.

2.5 Experimentation

2.5.1 Thermal conductivity

The KD2-Pro thermal analyzer is used to test the thermal conductivity of nanofluids and establish accurate relationships for calculating thermal conductivity at different temperatures and concentrations. The thermal conductivity of transformer oil is a crucial determinant in ensuring efficient cooling of transformers, hence impacting their longevity and maintenance costs. Studies suggest that a mere re-

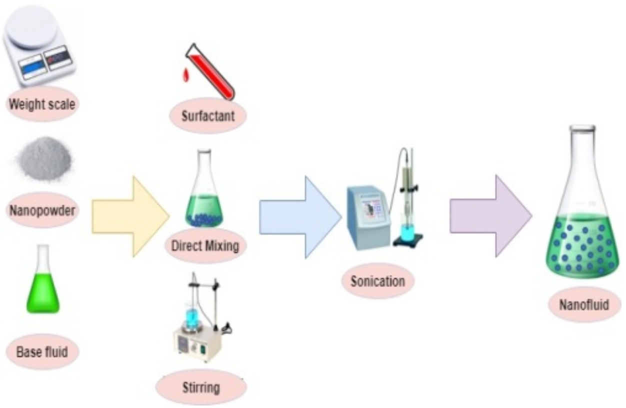

Figure 3. Preparation of nanofluids.

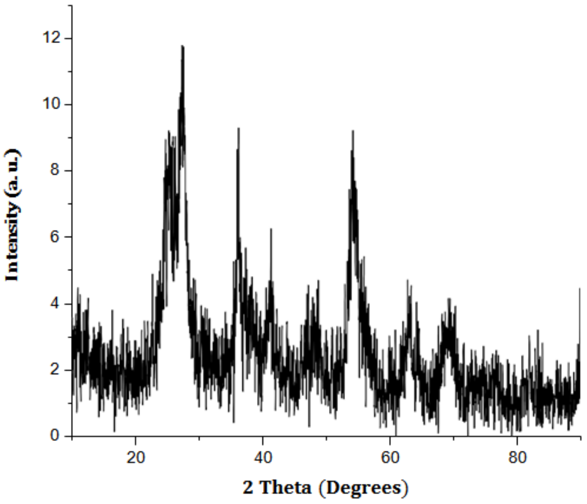

Figure 4. XRD pattern of TiO_2 nanoparticles.

duction of 1 °C in the core temperature can increase the lifespan of the transformer by 10%. Improving the thermal conductivity of transformer oil, for example, by including functionalized nanodiamond particles or semiconducting zinc oxide nanoparticles, enhances its ability to transport heat, resulting in more efficient cooling. Thermal property has been measured using the KD2 Pro analyzer as per the ASTM D5334 standard and the schematic representation in figure 5.

2.5.1.1 Maxwell-Eucken model

The Maxwell-Eucken model is essential for quantifying the thermal conductivity of nanofluids and composite materials. The estimation of the effective thermal conductivity of heterogeneous materials is based on traditional theories proposed by Maxwell and Eucken. The model postulates that nanofluids are uniform substances with thermal conductivity that is affected by both the base fluid and the nanoparticles. The Maxwell-Eucken model offers a mathematical equation for determining the effective thermal conductivity (k_{eff}) of a nanofluid.

$$k_{eff} = k_m \times \frac{k_p + 2k_m + 2\phi(k_p - k_m)}{k_p + 2k_m - \phi(k_p - k_m)} \tag{1}$$

where, k_{mis} the thermal conductivity of the base fluid (matrix), k_p represents the thermal conductivity of the nanoparticles, and ϕ represents the proportion of the volume occupied by the nanoparticles.

Maxwell-Eucken model is applied for heat exchangers, cooling systems, and electronic thermal management relies on it. Nevertheless, the model is limited in its ability to account for factors such as particle size, shape, and cluster formation. However, it is crucial to design and optimize nanofluid formulations for specific thermal management applications.

2.5.2 Density calculation using rule of mixtures

The rule of mixtures is crucial for measuring the density of nanofluids, as it provides a theoretical framework to predict the effective density of these complex fluids. Studies have shown that the rule of mixtures is used to calculate the effective density of nanofluids based on the mass fractions of the solvent, nanoparticles, and any compressed phases present around the nanoparticles [25]. For calculate the density of a nanofluid as per the rule of mixtures:

$$\rho_{nf} = \phi\rho_s + (1-\phi)\rho_w \tag{2}$$

where,
ρ_{nf} is the density of the nanofluid.
ϕ is the volume fraction of the nanoparticles in the nanofluid.
ρ_s is the density of the solid nanoparticle (TiO_2)
ρ_w is the density of the base fluid (Transformer oil).

Calculating density is essential for transformer nanofluid in order to verify cooling effectiveness and preserve the performance of the base oil without being influenced by the dispersion of nanoparticles. This is particularly important for the operation of high-voltage transformers.

2.5.3 Break down voltage

The dielectric strength of transformer oil, commonly known as the breakdown voltage (BDV), refers to the point at which the oil loses its ability to insulate when exposed to significant electrical stress between two electrodes. The minimum breakdown voltage refers to the threshold at which the transformer oil can be safely utilized. Typically, the accepted standard value for this threshold is 30 KV. The typical BDV measuring device is selected as per ASTM D1816, which includes an oil beaker. The BDV Testing Apparatus includes an electrode system, voltage supplier unit, control system, current controlling unit, test measuring device, sample container, temperature controlling unit, and safety accessories. A conductive material, AC high voltage sources, a control box, current control apparatus, a digital or analog oscilloscope or voltmeter, and insulated gloves or goggles are required. The process involves preparing a sample, setting up electrodes, adjusting temperature, applying voltage, recording results, and repeating the test multiple times to ensure reliability and consistency. The oil to be tested is placed between two mushroom-shaped electrodes, with a gap of 2.5 mm between them. This setup is utilized for measuring the breakdown voltage. The oil between the electrodes experiences electrical stress when a high voltage is applied between the electrodes at a rate of 2 kilovolts per second. The dielectric fluid is a crucial element of electrical transformers. It serves two essential roles: providing dielectric insulation and acting as a cooling medium. The method follows ensuring the insulating liquid is free of contaminants and air bubbles, positioning electrodes correctly, and monitoring the voltage throughout the test.

The test cell is used to collect a sample of transformer oil, as depicted in the circuit diagram in figure 6. The test cell consists of transparent glass. The container has a volume of

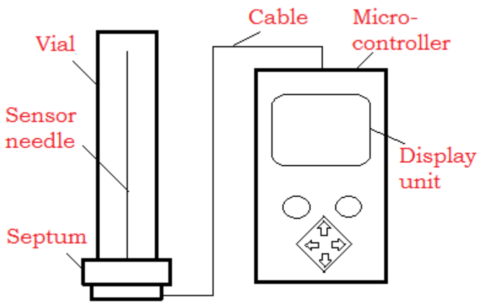

Figure 5. Schematic diagram of KD-2 Pro Analyzer.

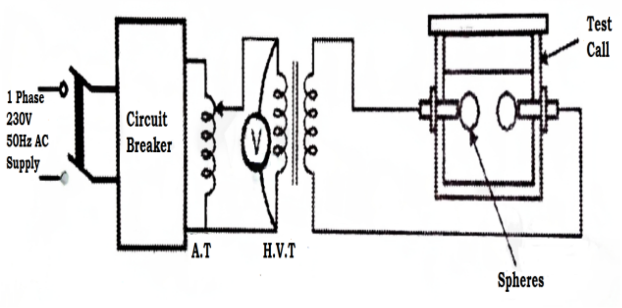

Figure 6. Circuit diagram of BVD measuring device.

approximately 500 mL and is equipped with a lid on the top. Two polished stainless steel electrodes, shaped like spheres with a diameter of 12.5 mm, are positioned in the test cell. The electrodes are separated by a gap of 2.5 mm and 4 mm. They are linked to the high-voltage secondary of the transformer. The high-voltage transformer's primary is provided with a changeable voltage from an autotransformer. The autotransformer is linked to the standard 230 volt alternating current (A.C.) 50 Hz power source. To ensure safety, an appropriate circuit breaker is installed between the power supply and the autotransformer. The test spherical electrodes are positioned in such a way that their axis is immersed in oil at a depth of approximately 40 mm. The distance between them is set at 2.5 mm and 4 mm, which may be verified with a filling gauge.

Inspection of errors in BDV testing necessitates calibrating tools while ensuring the integrity of electrodes. Regulated temperature fluctuations have been handling samples carefully to maintain a steady voltage application, and performing multiple tests in a controlled atmosphere to prevent disruptions from moisture or heat changes. This leads to reliable results and keeps statistical integrity preserved.

2.5.3.1 The process of doing transformer oil test

Once the electrodes are correctly positioned, a test sample of transformer oil is carefully poured into the test cell using a dry and clean glass rod to prevent the formation of gas bubbles during the pouring process. The environment should be devoid of dust, grime, and dampness, with a temperature ideally ranging from 15 to 35 °C, preferably 27 °C. Ramp up the voltage gradually using an autotransformer at a rate of 2 kV per second, starting from zero, until a breakdown occurs between the spheres. During the breakdown, the circuit breakers are tripped. The voltage at which breakdown occurs is recorded. The test is conducted a minimum of six times. These breakdown tests are conducted at five-minute intervals. Each occurrence of the breakdown voltage is documented. The average of the six readings is computed. This pertains to the electrical insulating capacity of the oil under examination. The oil should display the allowable thresholds as indicated in Table 2.

Table 2. Permissible limits of transformer oil.

Equipment's rated voltage (kV)	Breakdown voltage in test (kV)
Less than 70	Above 30
70 to 170	Above 40
Above 170	Above 50

3. Results and discussions

3.1 Thermal conductivity

Figure 7 shows that both the Maxwell-Eucken model and actual data demonstrate a positive correlation between the concentration of the additive and the thermal conductivity, indicating that as the concentration increases, the thermal conductivity also increases. This implies that the addition of the chemical enhances the thermal conductivity of the base fluid. When the concentration of BF is smaller (0.35 wt.%), the experimental values closely align with the model predictions. At elevated concentrations (0.45 wt% and 0.55 wt.%), there are minor discrepancies between the empirical data and the model forecasts, with the empirical values tending to be slightly lower than the model projections.

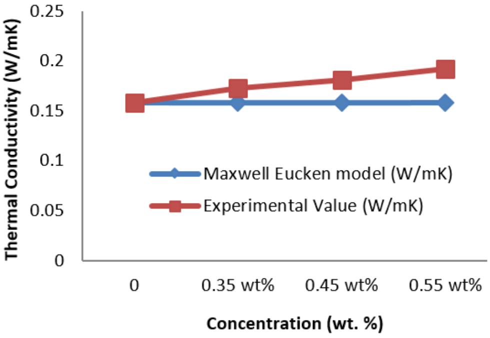

Figure 7. Thermal conductivity *vs* Concentration.

According to the thermal conductivity values depicted in the graph, it seems that the material improves thermal conductivity as the BF concentration increases. This indicates the potential viability for transformer applications, assuming that the other necessary qualities (such as electrical insulation and material compatibility) are also satisfied. However, the acceptability of these specific conclusions would be contingent upon the precise thermal management requirements of the transformer under consideration. If the desired thermal conductivity for the transformer application is approximately 1.0 W/mK or less, then these findings may be deemed satisfactory.

3.2 Density of nanofluid

The density of nanofluid-based transformer oil has been estimated using the simple rule of mixtures. The utilization of this model is essential in the computation of nanofluid density, a fundamental characteristic required for further thermal and fluid dynamic investigations. The calculated results are shown in Table 3. The density of TiO_2 nanoparticles are 4.23 g/cm^3 at an average particles size of 37 nm [34].

The density values obtained for transformer oil containing TiO_2 nanoparticles up to a concentration of 0.55 wt% exhibit relatively minimal increases compared to the baseline. The observed modifications fall within the permitted range for transformer applications, indicating that the inclusion of TiO_2 nanoparticles in these modest quantities does not have a substantial impact on the oil's fundamental functions of insulation and cooling. Hence, the density of transformer oil with 0.45 wt.% TiO_2 may be considered the optimum

Table 3. Calculated results of density of nanofluid.

Sample	Density (g/cm^3)
Transformer oil (TO)	0.872
TO + 0.35 wt%	0.874
TO + 0.45 wt%	0.875
TO + 0.55 wt%	0.875

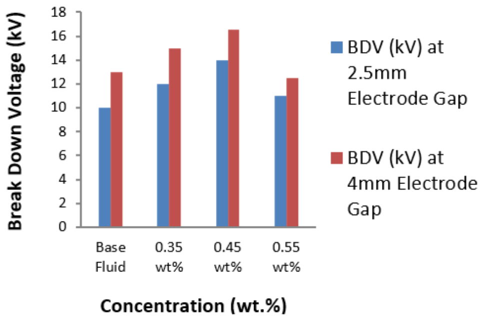

Figure 8. BDV (kV) vs Concentration (wt%).

value since the significant improvement in BDV is observed at this concentration.

3.3 Break down voltage

The bar chart displayed in figure 8 represents the breakdown voltage (BDV) in kilovolts (kV) for various concentrations of TiO_2 nanofluid, recorded at two distinct electrode gaps: 2.5 mm and 4 mm. The x-axis represents the weight percentage (wt.%) of TiO_2 nanofluid, ranging from 0 wt% (no TiO_2 content) to increasing concentrations of 0.35 wt%, 0.45 wt%, and 0.55 wt%. The y-axis represents the magnitude of the breakdown voltage in kilovolts. The BDV increases with TiO_2 nanofluid concentration for both electrode gaps, with higher values at 4 mm and 2.5 mm gaps. The highest recorded BDV is 0.45 wt% at 4 mm, while the lowest is for base fluid. 2.5-mm-gap BDV values show less consistency. The greatest improvement in breakdown voltage (BDV) was obtained when using a titanium dioxide (TiO_2) concentration of 0.45 wt% for both electrode gaps. The BDV increased by approximately 36.84% at the 2.5 mm gap and 36.36% at the 4 mm gap. The minimal improvement was noticed at a concentration of 0.55 wt% for both gaps.

According to the breakdown voltage results, the TiO_2 nanofluid with concentrations of 0.35 wt% and 0.45 wt% demonstrates enhanced insulating capabilities compared to the base fluid. This suggests that these concentrations could possibly be appropriate for use in transformers. The findings indicate that the utilization of TiO_2 nanofluid can augment the dielectric strength of the insulating fluid in transformers. Nevertheless, the ultimate approval for transformer applications necessitates thorough testing in real-world settings, encompassing thermal stability, sustained performance, and compatibility with other transformer components. If these supplementary examinations yield appropriate results, then the TiO_2 nanofluid, namely at concentrations of 0.35 wt% and 0.45 wt%, may be deemed suitable for implementation in transformers.

4. Future perspectives

The future prospects of TiO_2 nanofluids in enhancement of transformer applications include thermal and dielectric characteristics. Studies show that using TiO_2 nanofluids leads to an increase in heat transfer coefficient and reduction of electrical conductivity vital for the stability of the transformer. Probably the investigation of other hybrid nanofluids like TiO_2 combined with other oxide based materials like CuO, ZnO, and Al_2O_3 may yield enhanced thermal and electrical advantages. Despite the demonstrated benefits of TiO_2 nanofluids there are still several opportunities to improve formulations and issues with the long-term stability of the nanofluids in transformer applications. The presence of Oleic acid and Span 80 enhance the electrical characteristics of the reformed oil, and the dielectric withstanding strength is improved for lightning impulse voltages over the usual oil. It is noted that there are many questions for further investigations; for instance, the stability of nanoparticle solutions and the influence of the nanoparticles' concentration on the obtained properties and the system's performance are the important topics which demand further exploration.

5. Conclusions

5.1 Break down voltage

Titanium dioxide nanoparticles improve the insulating qualities of oil, especially in aged transformer oil, by reducing space charge buildup, increasing charge dissipation, and altering trap characteristics. The highest breakdown voltage improvement was observed with a 0.45 wt.% TiO_2 concentration for both electrode gaps, with a 36.84% increase at 2.5 mm and 36.36% at 4 mm gaps. The trend indicates that the addition of TiO_2 to the base fluid enhances the breakdown voltage up to a certain degree, and a wider gap between electrodes necessitates a higher voltage to produce breakdown. Nevertheless, there is no direct and consistent relationship, and additional variables may be affecting the BDV at different concentrations and intervals.

5.2 Thermal conductivity

The thermal conductivity increases with additive concentration, with experimental values slightly higher than the Maxwell-Eucken model. The highest conductivity with 23.41% is observed at 0.55 wt% concentration, with the gap between model and experimental values consistent. The experimental values are seen to rise at a significantly higher rate than the theoretical values, suggesting that other factors such as extra processes (interaction of particles, coagulations, or Brownian movements) might be enhancing the thermal conductivity in an actual system. The dispersion of TiO_2 nanoparticles into transformer oil has been demonstrated to enhance the thermal characteristics of the transformer in question, an aspect whose enhancement is important for the successful operation of the transformers. Thus, the possibilities of using TiO_2 nanofluids for increasing the transformers' efficiency are quite high, but the dependent relationship between the nanoparticles' concentration and temperature must be controlled optimally.

5.3 Density

The study calculates the densities of transformer oil with varying weight percentages of TiO_2 nanoparticles using the rule of mixtures method. The baseline density of 0.872 g/cm^3 indicates the oil is suitable for transformer applications. The addition of TiO_2 nanoparticles results in small increases in density, but these are within acceptable limits. The challenges such as stability and long-term performance under operational conditions remain areas for further research.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The authors declare that the data supporting the findings of this study are available from corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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