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Progression of Mineral Transformer Oils, Including Nanotechnology and Property Evaluation Techniques

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ABSTRACT

Mineral transformer oil has long been the industry standard for insulating and cooling power transformers due to its favorable dielectric strength, thermal conductivity, and cost-effectiveness. This paper provides a structured review comprising four main elements: (i) the historical evolution of mineral transformer oils, (ii) standard testing methods for evaluating their dielectric (AC, and Impulse breakdown voltages), thermal, and physicochemical properties, (iii) advancements achieved through the incorporation of nanoparticles such as Al_2O_3, TiO_2, SiO_2, $Fe_3O_4@SiO_2$ Core / Shell, AlN, CQD, MWCNT, Zinc Ferrite, Fe_3O_4, etc.., (iv) a comparative analysis of nanofluids in terms of breakdown voltage, thermal conductivity, and long-term performance. The review highlights that nanofluid formulations offer significant improvements in key operational parameters; however, challenges remain, including nanoparticle sedimentation, optimization of particle concentration, viscosity management, and the risk of accelerated oil degradation. This manuscript concludes by outlining essential steps for future research to establish reliable, standardized, and durable nanofluid-based transformer oils.

1. Introduction

Electrical power systems are designed to generate, transmit, and distribute electricity efficiently over long distances. Power transformers are employed to step up voltage levels at generation stations to high transmission levels, often in hundreds of kilovolts, to minimize energy losses during transmission. Conversely, at the distribution end, these transformers step down the voltage to levels suitable for end users. This voltage conversion process is fundamental for the economical and reliable delivery of electrical energy [1].The insulation system is among the critical components in power transformers, which ensures electrical isolation, structural support, and efficient thermal management. Oil-filled transformers, widely used in high-voltage applications, consist of copper windings, magnetic cores, and a comprehensive insulation and cooling system. The insulation system integrates various materials: solid insulation such as bushings, gaseous insulation like air for overhead lines, and liquid insulation—primarily insulating oil—due to its excellent dielectric strength and thermal conductivity. This oil not only insulates but also acts as a coolant by circulating within the transformer to dissipate heat from active components [1, 2] . Additionally, cellulose-based materials like pressboard and paper are used to insulate windings and provide mechanical support [3, 4].Given the crucial role of insulating oil in transformer performance and longevity, recent research has focused on enhancing its properties using advanced materials such as nanoparticles. These modifications aim to improve the dielectric and thermal behavior of the oil, ultimately contributing to safer and more efficient transformer operations. This review is structured to provide a comprehensive overview of the development and advancement of mineral transformer oils. First, the composition of mineral oil is discussed, which includes three main categories: paraffinic, naphthenic, and aromatic hydrocarbons, along with trace amounts of sulfur, nitrogen, and oxygen compounds. Each component influences performance differently: paraffins often lead to sludge formation and possess lower thermal stability;

naphthenics enhance low-temperature behavior; and aromatics affect dielectric stability. The second section describes the production stages of mineral transformer oil, involving refining processes designed to achieve the purity and chemical stability required for high-voltage applications. Crude oil undergoes distillation to separate its fractions. It is followed by dewaxing to improve low-temperature performance, solvent extraction to remove polar and reactive compounds, and optional finishing steps—such as activated clay treatment or hydrogenation—to enhance oxidation stability. Subsequently, the review addresses the key challenges faced by mineral oils in operation, including dielectric breakdown, fire risks, environmental hazards, and waste toxicity arising from degradation products and heavy metal contamination. The following section discusses the various modifications introduced to enhance insulating oil properties and their limitations. Initially, paraffinic oils were used due to their high dielectric strength, thermal conductivity, and low cost; however, their high pour point and tendency to form sludge upon oxidation limited their service life. To address cold-weather challenges, naphthenic oils were developed, offering lower pour points and better oxidation stability, though they exhibited low fire resistance. In the 1930s, halogenated dielectric fluids, including askarel-based compounds, were introduced, providing high fire safety but later faced restrictions due to the toxicity and Persistence of Polychlorinated Biphenyls (PCBs). Subsequent advancements included High-Molecular-Weight Hydrocarbons (HMWHs), which improved fire points and dielectric properties but exhibited higher viscosity, reducing heat transfer efficiency. Chlorofluorocarbon-based fluids were also explored, offering excellent insulation and non-flammability, yet their low boiling points limited their practical use. Today, commercial transformer oils are produced through advanced refining processes to achieve high dielectric strength, improved oxidation stability, and efficient thermal performance across various operating conditions. The review then outlines the primary property testing methods. These include AC and impulse breakdown voltage tests to evaluate dielectric strength under steady-state and transient overvoltage, partial discharge tests to detect early-stage insulation defects, and thermal conductivity assessments to ensure efficient heat dissipation. Additionally, flash and fire point measurements determine the flammability thresholds critical for operational safety. These evaluations are based on widely adopted international standards such as IEC 60156, IEC 60897, and ASTM D1816.Finally, the motivation for publishing this scientific paper was to clarify the fundamental aspects that researchers in this field may rely upon, by providing a simple explanation and an introduction to the components of mineral insulating oils, their historical background, the developments they have undergone, and the key tests that are currently the focus of the industry. It also highlights the advancements achieved by adding nanoparticles. It outlines some of the materials used in the past and the type of improvements resulting from their incorporation.

2. Mineral Oil State of Art: Composition, Manufacturing, History, And Challenges.

2.1. Mineral Oil Composition

Mineral oil, derived from the distillation of crude petroleum, has been used extensively as an insulating medium in power transformers for over a hundred years. Its popularity stems from several beneficial properties, including strong dielectric performance, effective thermal management, and economic viability [5]. The oil is refined to meet specific insulation and heat transfer standards to ensure suitability for electrical applications. Power generation and distribution network transformers are typically expected to function efficiently and dependably for up to four decades. Achieving this long-term performance is closely linked to the condition and characteristics of the insulating oil used within the transformer [6].Mineral oil primarily comprises hydrocarbon molecules, classified into three main categories: paraffinic, naphthenic, and aromatic. In addition to these, it contains trace amounts of other elements—such as Nitrogen (N), Sulfur (S), and Oxygen (O)—which are typically associated with the aromatic fraction [7]. Fig. 1 shows basic hydrocarbon structures in mineral oil molecules. Table 1 summarizes the mineral oil composition molecules, advantages, and limitations.

TABLE 1

Mineral Oil Composition, Advantages, and Disadvantages.

Composition Molecule	Description	Advantages	Disadvantages
Paraffinic hydrocarbons [7].	Paraffinic hydrocarbons consist of molecules that may be either straight-chained or branched. The straight-chain variants, known as normal alkanes, are often called waxes.	• Widely available and cost-effective. • Good dielectric properties for basic insulation needs.	• Poor low-temperature performance due to wax-like straight-chain variants. • Limited solubility for water and oxidation by-products, promoting sludge formation. • Lower thermal stability compared to naphthenic and aromatic hydrocarbons.
Naphthenic hydrocarbons [7].	Naphthenic hydrocarbons, or cycloalkanes, consist of rings typically containing 5–7 carbon atoms, with six-membered rings predominating.	• Excellent low-temperature behavior, enhancing cold climate performance. • Better solvency power than paraffins. • Good dielectric properties suitable for transformer applications.	• Slightly lower oxidation stability compared to optimized paraffinic types. • Limited availability compared to paraffinic hydrocarbons.
Aromatic molecules [7].	Aromatic hydrocarbons contain at least one benzene-like ring of six carbon atoms with alternating double and single bonds.	• Good electrical properties and oxidation stability. • High gas absorption capacity (beneficial for certain operational conditions).	• Polyaromatic compounds may negatively impact impulse breakdown and streaming charging.
Nitrogen-containing molecules [7].	Present in the original crude oil are naturally occurring heteroatomic compounds.	• Some act as oxidation inhibitors, extending oil life. • It can serve as passivators, protecting copper and metallic components.	• Certain nitrogen species act as charge carriers, degrading dielectric properties. • Others may promote oxidation, depending on their chemical nature.
Sulfur-based compounds [7].	Naturally occurring in crude oil is organosulfur compounds.	• Certain sulfur species neutralize reactive oxidation products (e.g., peroxides). • Can enhance oxidation resistance when present in minimal concentrations.	• Some sulfur compounds are corrosive to metallic parts (e.g., copper). • Need for precise refining to minimize corrosive sulfur while retaining beneficial ones.
Oxygen Compounds [7].	The oxygen chemically bonded to hydrocarbon molecules in mineral oil is relatively low.	• Phenolic byproducts can act as natural oxidation inhibitors.	• Oxidation over time increases oxygen content, producing acids and ketones that degrade oil. • Dissolved oxygen gas can accelerate degradation if not properly degassed.

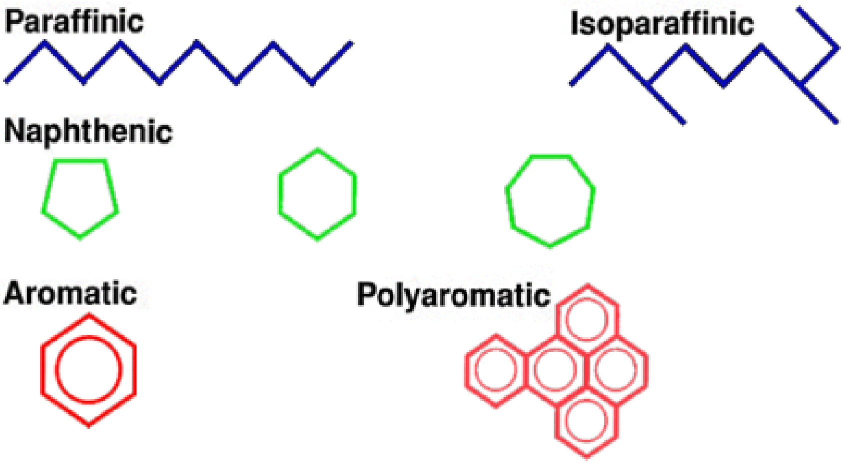


Fig.1: Basic hydrocarbon structures in mineral oil molecules [7].

2.2. Manufacturing Stages of Mineral Transformer Oil

Crude oil is usually subjected to a refining process to be changed to transformer oil. The following steps summarize the refining process, which can be divided into physical and chemical processes, and refining is usually a mixture of the two types of processes [7].

a. Raw material extraction.

Crude oil, sourced from regions such as the Middle East, Venezuela, and the North Sea, varies significantly in density and chemical composition. It is typically classified as either light or heavy, with further distinctions based on its hydrocarbon content—mainly naphthenic or paraffinic. Naphthenic crude, which contains higher levels of asphalt and heavy distillates, is generally categorized as heavy. In contrast, paraffinic crude, rich in lighter fractions like gasoline and gas oil, is considered light. Large deposits of wax-free naphthenic oil are currently available, and exploration continues to uncover additional reserves across the globe. The specific characteristics of the refined product, including its carbon type distribution, are influenced by the nature of the original crude oil.

b. Distillation

Refining crude oil begins with distillation, a process in which the crude is separated into various fractions based on differences in boiling points. This is achieved through fractionation. For light crude oils, distillation is typically carried out at atmospheric pressure. In contrast, heavy crude or the further processing of heavy residues requires vacuum distillation, which lowers the boiling points of hydrocarbons, effectively separating heavier components. This process occurs in a fractionating column, where multiple distillates are continuously and simultaneously produced. Although different oils may fall within the same boiling point range, they can exhibit varying viscosities. Generally, paraffinic oils boil at higher temperatures for a given viscosity than other types.

c. Dewaxing

Naphthenic crude generally contains low concentrations of normal alkanes, making dewaxing unnecessary in most cases. In contrast, paraffinic crude requires dewaxing to improve its performance at low temperatures. Conventional dewaxing techniques are not fully effective, as they may leave residual waxes below the targeted dewaxing temperature. The process typically involves mixing the oil with a solvent, followed by cooling to induce crystallization of the normal alkanes. These crystallized waxes are then removed through filtration, and the remaining solvent is subsequently separated from the oil by distillation.

d. Extraction

Extraction is one of the earliest refining methods to remove reactive, dark-colored, and polar compounds from oil. The oil is treated with a selective solvent—Sulfur Dioxide (SO_2) or furfural. This results in two distinct phases: the raffinate phase, which is primarily purified oil, and the extract phase, which is enriched with aromatic and heteroaromatic compounds containing elements such as sulfur, nitrogen, and oxygen. Polyaromatic hydrocarbons are predominantly concentrated in the extract phase. If furfural is used as the solvent, small residual amounts may occasionally remain in the treated oil.

e. Acid clay treatment

Acid clay treatment is now obsolete, primarily due to the environmental impact of its waste products. While activated clay remains in use among a few refiners as a final processing step to eliminate trace impurities adsorbed on the clay surface, the quantity of clay employed for this finishing is minimal.

f. Hydrogenation

Hydrogenation is a chemical process that transforms molecules into desired ones by employing a catalyst, hydrogen, and operating under high-pressure and high-temperature conditions. In this process, polar compounds, aromatics, and heteroatomic molecules interact with hydrogen on the catalyst surface, facilitating reactions. Generally, the catalyst comprises a porous inert mineral infused with catalytically active metals, enabling the adsorption of polar molecules and catalyzing their reaction.

2.3. Mineral Oil Challenges

a. System failure

Throughout many studies on mineral oils over the past decades, several challenges have emerged regarding their use, prompting further investigation to achieve optimal solutions. Transformer failures resulting from insulation system breakdown are considered one of the most challenging aspects of mineral oil design and enhancement. Transformer failures occur due to contaminated oil, and these problems are generally caused by insulation oil degradation, overload, thermal stress, humidity in oil or paper, and defects on the bushing [8].In paper [9]The authors discuss the failure of the cooling oil and mention that the failure can stem from two main factors: malfunctioning oil circulation or insufficient heat transfer to the secondary cooling circuit. This leads to increased oil viscosity within the transformer and excessively high temperatures in the secondary cooling circuit. Moisture and oxygen, in conjunction with heat, are the primary culprits of oil contamination, leading to the formation of conducting particles. Consequently, the internal temperature of the transformer rises, and if the oil insulation fails, it may result in a short circuit. Electrical factors, such as transient or overvoltage conditions, lightning and switching surges, and partial discharge, can also contribute to transformer failures if the insulating oil cannot manage them effectively. Failure modes have been accounted for between 2004 and 2009, and it was concluded that dielectric and thermal failures are considered two of the root causes of transformer [10]. Fig. 2 Shows the failure modes percentage.

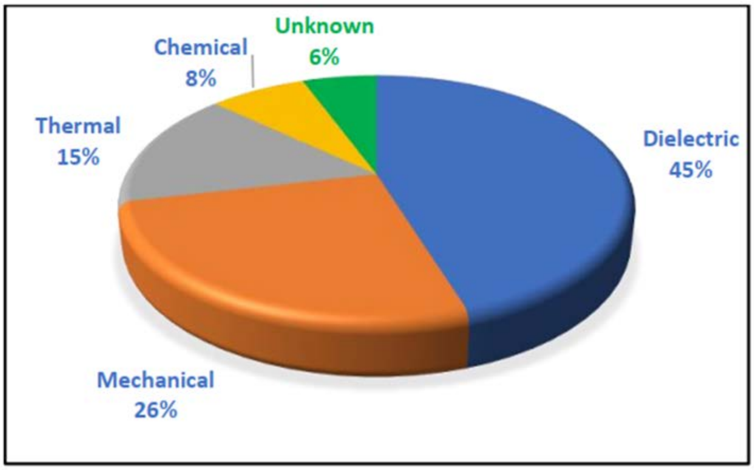


Fig.2: Classified failures according to failure modes [10].

b. Mineral oil waste

- **Waste source**

Mineral oil contains compounds of hydrocarbons, naphthene, aromatics, and paraffins, and other additives such as flame retardants and antioxidants to improve the quality and performance [11]. During operations, electrical, thermal, and environmental conditions are the leading causes of mineral oil degradation. Under operating conditions, the decomposition of mineral oil can be observed over a long period, resulting in increased acidity and the formation of solid materials that can catalyze reactions in the oil, involving complex blends of hydrocarbons, oxygen, and other chemicals, particularly at high temperatures, adversely affecting its insulating properties. Therefore, mineral oil degrades rapidly at higher temperatures and in the presence of moisture, leading to its conversion to waste and necessitating its disposal after prolonged use. Besides oil degradation, which results in the formation of waste oil that needs replacement with new oil, other factors contributing to waste formation include transformer oil spills occurring in the environment when a power transformer is damaged, as well as the generation of waste transformer oil during overhaul, maintenance, electrical equipment replacement, and other related activities [11].

- **Oil waste toxicity**

Waste transformer oil could contain different types of pollutants that harm the surrounding environment, and humans are dealing with it. Polychlorinated Biphenyls (PCBs), heavy metals, Polycyclic Aromatic Hydrocarbons (PAHs), and hazardous gases are the types of pollutants that could increase oil toxicity [11].

- **Polychlorinated Biphenyls (PCBs)** fall under the Persistent Organic Pollutants (POPs), synthetic compounds. These chemicals are known for being stable when exposed to heat, resistant to acids, and photodegradation. They are often added to coolants and insulating liquids in power transformers. Because PCBs linger in the environment for a long time, they can harm human health and wildlife [11].
- **Hazardous gases** released from waste mineral oil may be emitted during regular operations because of chemical reactions or during disposal activities. During operation, chemical reactions occur in the mineral insulating fluids and the materials they come into contact with. Additionally, gases are present due to thermal, mechanical, and electrical stresses. The different stresses on the mineral oil cause the oil breakdown, and release of hydrogen and carbon, and these gases then react with each other and form hydrocarbons such as Methane (CH_4), Ethane (C_2H_6), Acetylene (C_2H_4), Hydrogen (H_2). Additionally, the decomposition of cellulose and insulating paper materials is induced by low-energy sparks, corona (partial discharge), and insulation overheating within a transformer. Carbon

Dioxide (CO_2) and Carbon Monoxide (CO) gases are produced as glucose ring chains break down through depolymerization, dissolving in the oil in varying amounts. Oxygen atoms in cellulose form CO, CO_2, and Water (H_2O) [11].

- **Polycyclic Aromatic Hydrocarbons (PAHs),** which are the Persistent Organic Pollutants (POPs) that remain present in transformer oil. The presence of PAHs in oil in service could lead to undesirable electrical properties and pose a carcinogenic threat. PAHs are composed solely of carbon and hydrogen and are known or suspected carcinogens. There is substantial epidemiological evidence linking oil exposure to cancer [12].
- **Heavy metals** are another source of contamination in mineral oil. Various heavy metals could exist in the transformer oil, such as Iron (Fe), Aluminum (Al), Silver (Ag), Lead (Pb), Copper (Cu), Tin (Sn), And Zinc (Zn). These metals find their way into the transformer oil because of components within the transformer that contain them. Specifically, copper is present in transformer windings, iron is found in the transformer tank and core, lead is present in soldered connectors and joints, aluminum is found in ceramic insulators and coils, and peripheral components contain tin, zinc, and silver [11].

c. Other challenges

In addition to the previous issues, the following are other challenges of mineral oil [5, 13]:

- Breakdown voltage decrease: Mineral oil breakdown voltage decrease is one of the most common problems during mineral oil aging.
- Low Fire Point: Mineral oils have a relatively low fire point (approximately 150°C), making them prone to catching fire at elevated temperatures, which poses a significant fire risk in transformer applications.
- Environmental Impact: Mineral oils are derived from petroleum and can cause serious environmental problems if they leak. Due to their low biodegradability, mineral oil leaks can lead to soil contamination, impacting ecosystems and groundwater.
- Resource Scarcity: Mineral oils are derived from finite petroleum reserves, and the dwindling availability of these resources is expected to lead to severe shortages in the future. This scarcity could drive up prices and create supply chain challenges for industries reliant on mineral oils.
- Regulatory Compliance: Increasing environmental regulations and concerns pressure industries to transition from mineral oils due to their adverse environmental impact, necessitating compliance with stricter standards.
- Cost: The anticipated scarcity of mineral oil resources will likely drive up prices, making mineral oil-based products more expensive and economically less viable in the long term.
- Health Risks: Exposure to mineral oils can pose health risks, including skin irritation and respiratory issues, especially when handling and maintaining equipment containing mineral oil.
- Maintenance Challenges: Mineral oil-filled equipment requires specialized maintenance procedures and precautions due to its inherent fire risk and potential environmental impact, adding complexity and cost to operations.

Based on the previous points, researchers have directed their efforts towards finding solutions to these obstacles, including using alternative oils with different properties or incorporating additives to enhance important characteristics within oils.

2.4. Mineral Oil History

The oil-filled power transformer was introduced in 1890 [14], utilizing mineral oil for both insulation and cooling across various transformer components. Over the years, mineral insulating oil has undergone numerous attempts at development to improve performance and mitigate the flaws that arise in each stage. Table 2 illustrates the development stages, advantages, and limitations.

TABLE 2

The Mineral Oil Development Stages, Advantages, and Limitations.

Stage	Discussion
Paraffinic Oil [14]	It was introduced as the first insulating and cooling medium employed in power transformers. • **Advantage:** - Excellent dielectric strength, ensuring reliable insulation. - High thermal conductivity, promoting efficient heat dissipation. - Proven performance, availability, and relatively low cost compared to alternatives. • **Limitations:** - High pour point and sludge formation from oxidation reduced efficiency and service life.
Naphthenic Oil [14]	It was developed as an alternative to low-viscosity paraffinic oils. • **Advantage:** - Lower pour point temperatures, enabling better performance in cold climates. - Higher oxidation stability, enhancing long-term reliability. • **Limitations:** - low fire resistance, which limits their safety in high-risk environments.
Halogenated Dielectric Fluids [15].	In the 1930s, non-flammable insulating liquids such as halogenated dielectrics and askarel-based compounds were introduced as alternatives to traditional mineral oils. • **Advantage**: - High fire points (above 300 °C), significantly enhancing fire safety. - Better suitability for indoor transformers and distribution systems near consumers. • **Limitations**: - By 1976, concerns arose due to the toxic and hazardous nature of Polychlorinated Biphenyls (PCBs), leading to restrictions on their use.
High-Molecular-Weight Hydrocarbons (HMWHs) [16].	High-Molecular-Weight Hydrocarbons (HMWHs) were introduced as substitutes for oils contaminated with PCBs. They share chemical similarities with conventional petroleum-derived mineral oils. • **Advantage**: - Higher boiling points and molecular weights, resulting in significantly elevated fire points. - Good dielectric properties and effective lubricating performance. - Classified as paraffinic oils, mainly composed of saturated, elongated linear structures. • **Limitations**: - The high viscosity lowers heat transfer efficiency, limiting cooling performance
Chlorofluorocarbon-based Fluids [10].	• **Advantage**: - Strong electrical insulation properties. - Non-flammable nature, enhancing operational safety. • **Limitations**: - The low boiling point makes them susceptible to vaporization under normal operating temperatures.
Current Mineral Oil	Current commercial electrical insulating oils are manufactured from highly refined mineral oil to offer good dielectric properties, good oxidation stability, and provide efficient heat transfer even at low temperatures.

3. Properties Test Methods

3.1. AC Breakdown Voltage Test

The breakdown voltage is considered the most critical property of insulating oils, as it directly reflects their capacity to withstand electrical stress. A reduction in this value can significantly impair transformer reliability and operational safety. To ensure consistent assessment, international standards such as IEC 60156 and ASTM D1816 are commonly applied in breakdown voltage testing. According to the IEC 60156 procedure, the measurement uses horizontally mounted electrodes with hemispherical or mushroom-shaped ends, typically manufactured from brass, bronze, or austenitic stainless steel. The electrodes are spaced 2–2.5 mm apart, and the test voltage is increased gradually at a rate of 0.5–2 kV/s until dielectric breakdown occurs. To enhance the reliability of results, at least six consecutive readings are required for each oil sample, with a recovery period of 1–2 minutes allowed between successive measurements [17-26]. The ASTM D1816 method differs slightly in its design and operational parameters. It employs polished brass electrodes with spherical caps placed 1–2 mm apart. The test cell capacity depends on the electrode spacing, approximately 0.95 L ± 5% for a 2 mm gap and 0.5 L ± 5% for a 1 mm gap. The voltage rise rate is maintained within the range of 0.5–2 kV/s, and the oil sample is allowed to rest for about 5 minutes before testing begins. Similar to the IEC approach, a minimum of six breakdown measurements is performed for each sample, with 1–2 minutes between tests, and the oil is stirred after each breakdown to maintain homogeneity [27-33]. Previous researchers tend to change the design of the electrodes to test the oil performance at different degrees of uniformity of the electric field, as the shape and area of the electrodes affect the field uniformity [34]. Also, the test device manufacturers have declared some precautions regarding the test temperatures and the limitations for each standard method [35]. Tables 3 to 5 summarize the precautions recommended by previous researchers and the corresponding test cell designs used for AC breakdown voltage measurements.

TABLE 3

Experimental Conditions for AC Breakdown Voltage Tests of Transformer Oil.

Ref.	**Applied Standard**	**Gap Distance (mm)**	**Voltage Ramp Rate (kV/s)**	**Number of Shots**	**Recovery Time (minute)**	**Device Name**	**Electrodes Shape & Material**	**Remarks**
[36]	IEC 60156	2.5 & 5	2	10	1	-	Brass - mushroom electrodes	-
[19]	IEC 60156	2.5	-	10	-	Baur DPA 75C	Stainless steel-semispherical electrodes	Electrodes having a body diameter of 7.8 mm, and a tip radius of 4 mm.
[26]	IEC 60156	1, 2.5, 4 & 5	2	20	1	-	Brass - mushroom electrodes	-
[33]	ASTM D1816	2	2	30	1	Portable Jiantong Oil Tester 6801	Brass-spherically capped electrodes	Initial standing time = 5 minutes.

TABLE 4

Experimental Conditions for AC Breakdown Voltage Tests of Transformer Oil (Continued).

Ref.	**Applied Standard**	**Gap Distance (mm)**	**Voltage Ramp Rate (kV/s)**	**Number of Shots**	**Recovery Time (minute)**	**Device Name**	**Electrodes Shape & Material**	**Remarks**
[25]	IEC 60156	2.5	2	10	-	Oil Tester	Mushroom electrodes	-
[37]	IEC 60156	2.5	2	10	-	Oil Tester	-	-
[38]	IEC 60156	2.5	2	6	-	BAUR DTA 100 C	Mushroom electrodes	-

[32]	ASTM D1816	2	0.5	20	1	Tester model OC60D (220/60 kV)	Mushroom electrodes	Electrodes 36 mm in diameter
[31]	ASTM D1816	2.5 & 1.5	0.5	10	-	Oil Tester	-	-
[30]	ASTM D1816	2	0.5	10	1	Oil Tester	Mushroom electrodes	
[39]	ASTM D–877	5	2	10		Customized equipment	Hemispherical electrodes of 5mm diameter	-
[29]	ASTM D1816	2	0.5	10	2	-	-	-
[40]	IEC 60156	2.5	2	18	-	OPG-100A	Spherical brass electrodes	-
[22]	IEC 60156	2.5	2	18	-	OPG-100A	Spherical brass electrodes	-
[41]	IEC 60156	1.5, 2.5 & 3.5	2	50	-	-	Mushroom electrodes	Initial standing time = 2 minutes.
[20]	IEC 60156	-	2	50	2	DTA 100C BAUR	Mushroom electrodes	Initial standing time = 2 minutes.
[18]	IEC 60156	2.5	2	50	2	BAUR automatic 50 Hz tester	Bi-spherical electrodes	Initial standing time = 2 minutes.
[17]	IEC 60156	2	2	30	1	Jiantong 6801	Brass - spherically-capped electrodes	Initial standing time = 5 minutes.

TABLE 5

Experimental Conditions for AC Breakdown Voltage Tests of Transformer Oil (Continued).

Ref.	**Applied Standard**	**Gap Distance (mm)**	**Voltage Ramp Rate (kV/s)**	**Number of Shots**	**Recovery Time (minute)**	**Device Name**	**Electrodes Shape & Material**	**Remarks**
[23]	IEC 60156	-	-	18	-	OPG-100A	-	-
[42]	IEC 60156	-	-	30	-	Jiantong 6801	-	-
[43]	IEC 60156	2.5	2	5	-	Oil test kit	Spherical electrodes	-
[44]	IEC 60156	2.5	2	-	-	BAUR DTA-100C	-	-

3.2. Impulse Breakdown Voltage Test

The impulse breakdown voltage test is conducted to replicate the conditions of a lightning strike during thunderstorms or to simulate transient overvoltage events that may occur in power systems [10]. This test is essential for evaluating the ability of insulating oils to withstand short-duration high-voltage surges. Standardized procedures for impulse testing are outlined in IEC 60897, IEC 60060-2, and ASTM D3300, which guide test parameters and safety precautions. in a typical setup, the test cell employs either needle-to-sphere or needle-to-plane electrode configurations, with the electrode gap adjusted to the desired value depending on the test objectives. The standard 1.2/50 µs lightning impulse waveform is generally applied. Parameters such as the incremental rise in applied voltage, the number of shots per test, the resting interval between successive impulses, and the recovery period before repeating tests are determined according to the selected standard and, in many cases, the practices reported by different researchers. Tables 6 and 7 summarize the precautions highlighted by previous researchers and the test cell designs they employed for measuring lightning impulse breakdown voltage.

TABLE 6

Experimental Conditions for Lightning Impulse Breakdown Voltage Tests of Transformer Oil.

Ref.	Applied Standard	Impulse Voltage Std.	Gap Distance (mm)	Voltage Ramp Rate (kV/s)	Number of Shots	Recovery Time (minute)	Electrodes Shape & Material	Remarks
[26]	IEC 60897	1.2/50 µs	10	-	-	-	Needle-sphere electrode	-
[33]	ASTM D3300	1.2/50 µs	25	-	30	1	Needle-sphere electrode	Needle with a 50 µm radius of curvature. Initial standing time = 5 minutes.
[21]	IEC60897 & IEC 60060-2	1.2/50 µs	25 ± 1mm	10	15	2	Steel needle plane electrode	Plane electrode has 35 mm diameter. Oil sample was 450 mL.

TABLE 7

Experimental Conditions for Lightning Impulse Breakdown Voltage Tests of Transformer Oil (Continued).

<table>
<tr><th>Ref.</th><th>Applied Standard</th><th>Impulse Voltage Std.</th><th>Gap Distance (mm)</th><th colspan="2">Voltage Ramp Rate (kV/s)</th><th>Number of Shots</th><th>Recovery Time (minute)</th><th>Electrodes Shape & Material</th><th>Remarks</th></tr>
<tr><td rowspan="2">[17]</td><td rowspan="2">IEC 60897</td><td rowspan="2">1.2/50 µs</td><td>+ve LI</td><td>25 mm</td><td rowspan="2">2.5</td><td rowspan="2">6</td><td rowspan="2">-</td><td rowspan="2">Needle-sphere electrode</td><td rowspan="2">-</td></tr>
<tr><td>-ve LI</td><td>15 mm</td></tr>
<tr><td>[42]</td><td>IEC 60897</td><td>1.2/50 µs</td><td>-</td><td colspan="2">-</td><td>5</td><td>1</td><td>-</td><td>Initial standing time = 5 minutes.</td></tr>
<tr><td>[45]</td><td>-</td><td>1.2/50 µs</td><td>25</td><td colspan="2">-</td><td>5</td><td>4</td><td>Needle-sphere electrode</td><td>Needle with a 20 µm radius of curvature to sphere electrodes with a 6.5 mm radius of curvature was used.
Initial standing time = 5 minutes.</td></tr>
<tr><td>[46]</td><td>ASTM D 3300 – 85</td><td>1.2/50 µs</td><td>-</td><td colspan="2">-</td><td>3</td><td>-</td><td>Needle-sphere electrode</td><td>-</td></tr>
<tr><td>[47]</td><td>IEC 60897</td><td>1.2/50 µs</td><td>25</td><td colspan="2">-</td><td>6</td><td>1</td><td>Needle-sphere electrode</td><td>Needle with a 50 µm radius of curvature.
Initial standing time = 5 minutes.</td></tr>
<tr><td>[44]</td><td>IEC 60897</td><td>1.2/50 µs</td><td>3</td><td colspan="2">-</td><td>-</td><td>-</td><td>Sphere-sphere electrode</td><td>-</td></tr>
<tr><td>[48]</td><td>IEC 60897</td><td>1.2/50 µs</td><td>10</td><td colspan="2">-</td><td>-</td><td>-</td><td>Needle-sphere & needle-plane electrodes</td><td>-</td></tr>
</table>

[49]	IEC 60897	1.2/50 µs	15	-	-	-	Steel needle-sphere electrode	Ball electrode has 13 mm-diameter.
[50]	IEC 60897	1.2/50 µs	15	-	-	-	Needle-sphere electrode	The needle has a curvature of 40 µm, while the ball electrode has a diameter of 13 mm.
[51]	-	1.2/50 µs	25	2	20	10	Brass needle-plane electrode	The needle has a curvature of 50 µm radius, while the plane electrode has a diameter of 2 cm.

3.3. Partial Discharge/Corona Discharge

Partial discharge (PD), or corona discharge, occurs in insulating oils primarily due to micro-sized impurities such as air bubbles, dust, ionic contaminants, and other pollutants. Additionally, surface discharges may develop at the interfaces between oil and solid insulating materials like pressboards or composite insulators, where localized electric stress becomes concentrated [26]. An example of a partial discharge test setup, as presented in [26], is illustrated in Fig. 3. A typical partial discharge test setup consists of an oil container, a pair of needle-to-plane electrodes with a defined gap, a high-voltage transformer connected to an AC power supply, and a detection and control unit. In several studies, the electrode gap was maintained at 5 mm to ensure consistent measurement conditions [48, 52]. The Partial Discharge Inception Voltage (PDIV) is a widely used non-destructive method for assessing the ability of insulating liquids to withstand high electric stress. Unlike AC breakdown voltage, which is strongly influenced by external contaminants such as moisture and suspended particles, PDIV is more sensitive to the intrinsic composition of the oil [47]. In practice, the applied voltage is gradually increased at a rate of 0.5 kV/s until the first partial discharge pulse is detected by the measurement system, at which point the voltage is defined as the PDIV [26]. In alternative configurations, a needle-to-sphere electrode arrangement with a 25 mm gap has also been employed to evaluate the discharge behavior under different field intensities. Further investigations reported AC voltages increasing at a rate of 2 kV/s to stress the samples, where PDIV was defined as the point at which the discharge reached 100 pC. Under this approach, each sample was tested five times, and the mean value of the results was taken as the PDIV [45]. In other studies [47, 53] Researchers adhered to the IEC 1294:1993 standard, employing a needle-to-sphere configuration with a 50 mm gap. These tests raised the voltage at 1 kV/s to determine the inception voltage.

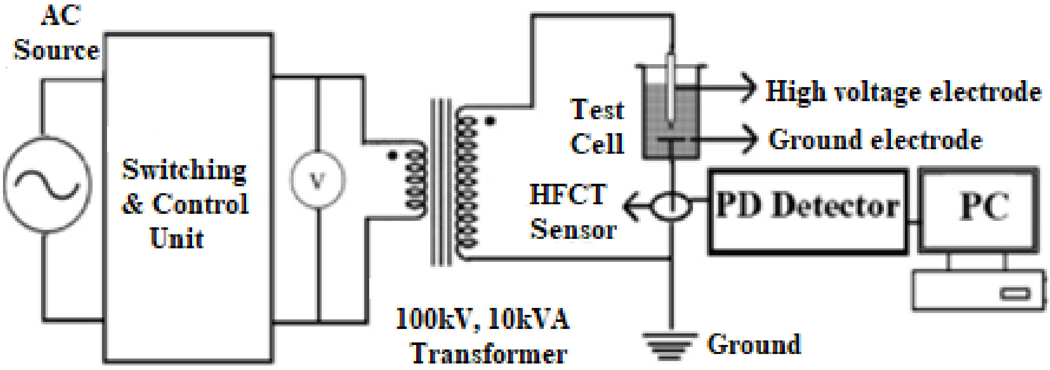
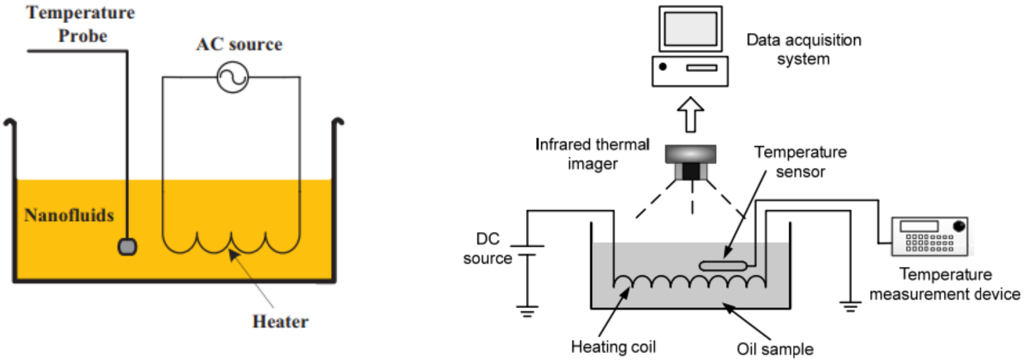


Fig.3: Schematic diagram of the partial discharge test setup [26].

3.4. Thermal Conductivity and Heat Transfer

Thermal conduction is the energy transfer process from high-energy particles to those with lower energy through direct interactions within a medium. In solids, this occurs mainly via lattice vibrations or through the movement of free electrons. At the same time, in gases and liquids, the mechanism relies on the random motion of molecules followed by collisions, resembling a diffusion process. Based on kinetic theory, molecules move freely until they encounter others, with the mean free path defined as the average distance traveled between successive collisions [54]. In power transformers, insulating oil serves a dual role as insulators and coolants, making its thermal conductivity a crucial parameter in fluid selection. A higher thermal conductivity enhances the oil's ability to dissipate heat effectively, thereby improving cooling efficiency. This improvement not only helps maintain transformer reliability but also enables the design of more compact transformer units [55, 56].Previous research has adopted different methods and setups to investigate the thermal conductivity of transformer oils. The main approaches are summarized as follows:

- **<u>Hot Wire Method</u>**
  - Based on a fine wire acting both as a linear heat source and a temperature sensor when immersed in the test liquid [57].In one setup, 25 ml of oil was tested by heating the wire for 2 seconds at a rate of 2 °C/s, and the resulting temperature changes were used to calculate thermal conductivity [50] A system developed in [22] Followed the ASTM D2717 standard, using a platinum wire heated with constant voltage. Due to the surrounding oil's thermal properties, the wire's resistance variation produced a voltage drop that enabled conductivity determination.
  - The measurement time was less than 800 ms, minimizing errors from convection effects.
- **<u>Heating and Cooling Method</u>**
  - A heating coil immersed in oil samples was energized at 5 W for 50 minutes to simulate transformer winding heating [58].The starting temperature was set at 15 °C, and temperature rise and distribution were recorded every 5 minutes using an infrared thermal imager. During cooling, initially at 75 °C, the coil was immersed in the oil for 5 minutes, with surface temperatures monitored using a tightly attached sensor. Another study [29] Tested 500 ml oil samples in a glass beaker heated by a 20 W heater. Temperatures were measured at 10-minute intervals for 60 minutes during heating and under similar conditions during cooling from 80 °C.
  - The experimental arrangements are shown in Fig. 4
  - .



(a) **(b)**

Fig.4: Schematic diagram for (a) thermal test system [29], (b) heating and cooling test cell [58]

3.5. Flash And Fire Point

The flash point is the lowest temperature at which vapors above a liquid form a flammable mixture that ignites in an external flame. In contrast, the fire point is the minimum temperature at which the vapor–air mixture sustains combustion even after the ignition source is removed [36]. Several standardized methods are available for measuring these properties. The IEC 60296 standard recommends the use of the Pensky–Martens closed cup apparatus [7], while ASTM standards such as ASTM D3487 [7], ASTM D3828 [59], and ASTM D93 [60] specify procedures that include the Cleveland Open Cup and other closed-cup methods. In [43] The Pensky–Martens Closed Cup Tester was employed following the ASTM D93 procedure to determine both flash and fire points. The measurement steps were as follows:

- The oil sample was poured into a brass test cup.
- The sample was heated using an electric heater controlled by a temperature regulator.
- The flash point was recorded when vapors ignited briefly upon introducing a small test flame onto the oil surface.
- The fire point was determined when sustained combustion occurred under the same conditions.

The Pensky–Martens apparatus used for these tests is shown in Fig. 5.

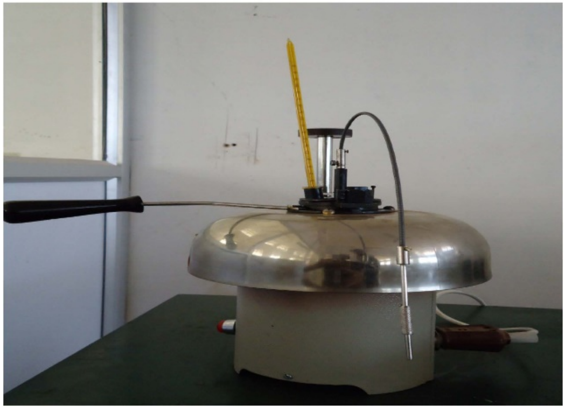


Fig.5: Pensky-Martins flash point device [43].

4. Insulating Oil Modification with Nano-Additives

In 1994, Lewis proposed the concept of “nano-dielectrics,” which suggests that the properties of nanoscale dielectrics depend significantly on the interface between the nanoscale dielectric material and its substrate. This interface effect is crucial in determining the electrical characteristics of nanoscale dielectrics. In 1995, Choi introduced the concept of “nanofluids”. Due to their large surface area, nanoscale additives within these fluids exhibit high thermal conductivity and resistance to settling in a liquid medium. These advancements have ushered in a new era in modifying mineral insulating oils. Nanoparticles are now extensively utilized to enhance mineral insulating oils, representing a novel class of materials with improved properties [61]. Also, from an environmental perspective, adding nanoparticles to insulating oils is considered negligible, as they are introduced in minimal concentrations that do not significantly alter the chemical composition or generate harmful residues. Furthermore, these concentrations are typically well below the thresholds that could pose environmental or health-related risks, ensuring that the modified oils remain safe for both industrial application and ecological sustainability.

4.1. Nanotechnology

Nanotechnology can be defined as the ability to convert nanoscience theories, including matters at the nanometer scale, to practical applications. It is considered one of the most promising technologies of the 21st century. Nanomaterials are defined as materials with a size range from 1 to 100 nanometers, and the synthesis of nanostructures follows one of the two approaches:

The top–down approach involves breaking down bulk materials to obtain nano-sized particles. This can be accomplished by utilizing advanced techniques such as precision engineering and lithography, which have been refined and perfected by industry over recent decades. Precision engineering is vital in supporting most of the microelectronics industry throughout the production process. Achieving high performance requires a combination of enhancements, including using advanced nanostructures based on diamond or cubic boron nitride and sensors for size control. These are complemented by numerical control and advanced servo-drive technologies. In lithography, a surface is patterned by exposure to light, ions, or electrons, followed by the deposition of material onto that surface to generate the desired material [62]

The bottom–up approach entails the construction of nanostructures from scratch, at the atomic or molecular level, utilizing both physical and chemical methods within the narrow nanoscale range of 1 nm to 100 nm. This process hinges on precisely manipulating the self-assembly of atoms and molecules. Chemical synthesis serves as a cornerstone technique in this methodology, facilitating the production of raw materials that can be directly integrated into products or utilized in their bulk, disordered state. Self-assembly, a fundamental aspect of the bottom-up approach, involves spontaneously organizing atoms or molecules into structured nanostructures through chemical-physical interactions. Positional assembly represents a unique technique wherein individual atoms, molecules, or clusters can be meticulously positioned individually [62]

4.2. Previous Trials Using Nano-Additives

A nanofluid refers to an insulating oil infused with a small concentration of nanoparticles, which significantly alter its physical and thermal behavior. Unlike their bulk counterparts, nanoparticles exhibit distinctive properties that can enhance the base fluid's dielectric strength, thermal conductivity, and overall stability. The concept of nanofluids was first introduced by Choi and colleagues at Argonne National Laboratory to describe a colloidal system in which nanoparticles are uniformly suspended within a liquid medium [22]. Tables 8 to 11 summarize the key findings reported in the literature regarding the use of various types of nanoparticles in transformer insulating oils. Equations 1 and 2 show the conversion equation from the different concentrations to wt% to unify the concentration units.

TABLE 8

Key Findings on the Use of Different Nanoparticles in Transformer Insulating Oils.

Ref.	Nanoparticles	Concentrations	Main Findings
[33]	- Titania	- 0.075 vol%	• AC Breakdown Voltage (BDV) increased by 20%. • Impulse breakdown voltage increases by 24%. Additionally, the breakdown time for nanofluids is extended by 53% compared to the base oil. • Negative DC breakdown voltage increases by 28%, but the positive DC breakdown voltage is slightly lower than the base oil. • At a 5% probability, the PDIV for the nanofluid is 1.18 times higher than the base oil. • The resistivity is lower than the base oil but meets the required quality standards. • The relative permittivity is significantly higher, which helps achieve a more uniform electric field.
[63]	- Alumina	- 0.01-0.05 vol%	• AC BDV improved for all concentrations. • At a 0.01 vol% concentration, the positive polarity lightning impulse dielectric strength increased. However, no increase was observed at 0.03% and 0.05% concentrations. • The negative polarity lightning impulse voltage at all concentrations showed higher dielectric strength than the base oil.
[64]	- Magnetite - Alumina	- 0.05-0.4 g/l	• The AC breakdown voltage of Fe_3O_4 and Al_2O_3 nanofluids is higher than that of the base oil. The improvement depends on the nanoparticle concentration, size, and type • Smaller nanoparticles provide a more significant enhancement. • Fe_3O_4 results in a higher improvement in dielectric strength compared to Al_2O_3. • With Fe_3O_4 nanoparticles, the breakdown voltage can exceed twice that of mineral oil, while Al_2O_3 increases the BDV by more than 76%.

TABLE 9

Key Findings on the Use of Different Nanoparticles in Transformer Insulating Oils (Continued).

Ref.	**Nanoparticles**	**Concentrations**	**Main Findings**
[19]	- Magnetite - Graphene oxide - Silicone dioxide	- 0.1-0.5 g/l	• In quasi-uniform electric fields, dielectric performance shows noticeable improvement at a nanoparticle concentration near 0.2 g/l. • When exposed to divergent fields under AC, partial discharge behavior demonstrates enhanced characteristics. • Under DC conditions, silica-based nanofluids outperform conventional mineral oil, whereas the other two nanofluid types exhibit inferior performance.
[65]	- Alumina - Titania	- 0.01-0.04 g/l	• Alumina and titania nanofluids increased PDIV by 18% and 12%, respectively, compared to the base oil. • Under equivalent applied voltage, both PD repetition rate and magnitude were lower in the nanofluids, with Al_2O_3-based nanofluids exhibiting the most effective PD suppression. • The observed enhancement in PD behavior is primarily attributed to the Electric Double Layer (EDL) role, which captures charge carriers and delays PD charge accumulation across the oil gap.
[66]	- Al_2O_3 Sphere - Al_2O_3 Fiber - A1N	- 0.5-4 vol%	• The thermal conductivity increases with both the particle volume fraction and the intrinsic thermal conductivity of the nanoparticles. • AlN nanoparticles at a 0.5% volume fraction can improve the thermal conductivity of transformer oil by 8% and the overall heat transfer coefficient by 20%. • Natural convection tests using a prototype transformer confirm that nanofluids improve the cooling effect on the heating element and the oil. • Excessive surfactant quantities harm viscosity, thermal properties, and chemical stability, highlighting the importance of carefully managing surfactant addition.
[67]	- Functionalized nanodiamonds	- 0.01-1 wt%	• Functionalized nanodiamonds improved stability and thermal conductivity. At a 0.12 wt% concentration, thermal conductivity increased by 14.5%, and this enhancement further increased with temperature. • The base oil's electrical resistivity, dissipation factor, and dielectric properties remained unchanged. • The viscosity of the nanofluid remained almost unchanged with up to 1% nanodiamond loading. • AC BDV enhanced for all concentrations.
[68]	- Zinc oxide		• The thermal conductivity increased at 25 ºC compared with the base oil. Also, the improvement increased with the nanoparticle's concentration. • Thermal conductivity increased by 4.61% at 0.05% volume fraction and 11.53% at 1% volume fraction. • The dynamic viscosity of the nanofluid has witnessed the highest improvement at the maximum volume fraction of nanoparticles across all temperatures.

Table 10

Key Findings on the Use of Different Nanoparticles in Transformer Insulating Oils (Continued).

Ref.	Nanoparticles	Concentrations	Main Findings
[25]	- BT+ (Silica, Alumina, and Titania)	BT 0.005 g/l Silica 0.01 g/l Alumina 0.01 g/l Titania 0.01 g/l	• Using BT nanoparticles has only improved heat transferability by about 33%, but the dissipation factor and BDV were degraded. • Using BT and titania hybrid nanofluid has improved the heat transferability by about 33% and increased the BDV by about 43%. • The enhancement was repeated using silica nanoparticles but reversed using alumina nanoparticles.
[36]	- Surface-treated silica with CQD	- 0.01 wt%	• Nanofluid exhibited better insulation and dielectric properties than base oil. • Nanofluid viscosity has a slight decrease compared with the base oil. • The flash point and fire point of CQD nanofluid were found to be 10°C higher than pure mineral oil, indicating better thermal stability. • tan delta value of CQD nanofluid was approximately 10 times lower than pure mineral oil.
[32]	- CdS quantum dots.	- 0.02-0.5 g/l	• The addition of CdS quantum dots significantly increased the breakdown strength of transformer oil by about 81% compared to the base oil. • CdS quantum dots slightly increased the relative permittivity of the transformer oil. • The presence of CdS quantum dots significantly decreased the dissipation factor of the transformer oil. • The presence of CdS quantum dots significantly decreased the dissipation factor of the base oil.
[58]	- BN	- 0.01-0.1 wt%	• Incorporating BN nanoparticles enhances BDV relative to the base oil, with further improvement observed as BN concentration increases. • The inclusion of BN particles leads to a marked rise in the thermal conductivity of transformer oil. • Oils containing higher BN concentrations exhibit more efficient heat dissipation. • Improvements in relative permittivity and dissipation factor suggest enhanced dielectric behavior.
[22]	- Silica	- 0.005-0.1 wt%	• Silica nanofluids improve the AC breakdown voltage of mineral oil, especially at higher moisture content. • Surface-modified silica nanoparticles (hydrophobic) negatively affect breakdown strength. • Thermal conductivity of silica nanofluids has a negligible effect on mineral oil, even with up to 0.1% silica nanoparticles. • Viscosity of mineral oil's viscosity is negligibly affected by adding up to 0.1% silica nanoparticles.

TABLE 11

Key Findings on the Use of Different Nanoparticles in Transformer Insulating Oils (Continued).

Ref.	Nanoparticles	Concentrations	Main Findings
[69]	- Zinc ferrite	- 0.05-0.2 wt%	• The highest improvement was shown for the following: • Thermal conductivity increased by 6.23% at a concentration of 0.2 wt%. • Nusselt numbers increased by 11.17% at concentration 0.1 wt%. • FCHTC (Free Convection Heat Transfer Coefficient) increased by 14.15% at concentration 0.1wt%. • AC BDV increased by 17.3% at concentration 0.1wt%.
[70]	- MWCNT - GNP	- 0.005 wt%	• Adding GNP has increased by 8.6% and 8.3% for the natural and forced convection factors, respectively, compared with the base oil. • The Nusselt number with adding GNP improved at 60 and 90 W but decreased at 120 and 150 W.

<table>
<tr><td></td><td></td><td></td><td>• The thermal conductivity of MWCNT with transformer oil nanofluid has decreased at 25 °C and 50 ºC but improved at 75 ºC.
• Adding the nanoparticles has decreased the breakdown voltage.</td></tr>
<tr><td>**[71]**</td><td>- Mn-Zn ferrite</td><td>0.03-0.4 g/l</td><td>• AC BDV has improved especially at concentrations of 0.1 and 0.2 g/l but decreased at 0.4 g/l.
• tan δ of the investigated nanofluids has exhibited pronounced dependencies on the nanoparticles concentration for the frequency range from 30 Hz to 1 MHz.
• dielectric loss at 0.1 g/l concentration decreased by 58% compared with the base oil at low frequency.</td></tr>
<tr><td>**[72]**</td><td>- Titanium dioxide doped MWCNT(TC)
- Zinc ferrite (Z)</td><td><table><tr><td>Z</td><td>TC</td></tr><tr><td>0.1 wt%</td><td>-</td></tr><tr><td></td><td>0.1 wt%</td></tr><tr><td>0.075 wt%</td><td>0.025 wt%</td></tr><tr><td>0.025 wt%</td><td>0.075 wt%</td></tr><tr><td>0.05 wt%</td><td>0.05 wt%</td></tr></table></td><td>• Stability: Nanofluids with 0.075 wt% TC and 0.025 wt% Z nanoparticles showed high stability.
• Thermal Properties: 0.1 wt% TC nanoparticles enhanced thermal conductivity and volumetric specific heat.
• Heat Transfer: 0.075 wt% TC and 0.025 wt% Z nanofluids improved convective heat transfer by 15.38% and Nusselt number by 14.4%.
• Breakdown voltage has decreased for all samples except for the (0.1 wt% Z) sample</td></tr>
<tr><td>**[73]**</td><td>- Two-dimensional (2D) hexagonal boron nitride (h-BN) nanosheets</td><td>- 0.005-0.05 wt%</td><td>• 2D layered materials, like h-BN nanosheets, are more stable in oil, offering high surface area and improved stability.
• Nanofluid samples showed efficient thermal management and improved Breakdown Voltage (BDV).</td></tr>
<tr><td>**[74]**</td><td>- $Fe_3O_4@SiO_2$ Core/Shell</td><td>- 0.04-0.1 g/l</td><td>• AC BDV has improved across all concentrations and types.
• The increase in shell thickness has increased the improvement.</td></tr>
</table>

$$\boldsymbol{wt}\% = \boldsymbol{vol}\% * \frac{\boldsymbol{Nanoparticles\ Density}}{\boldsymbol{Insulating\ Oil\ Density}} \tag{1}$$

$$\boldsymbol{wt}\% = \frac{\boldsymbol{Gram}}{\boldsymbol{Liter}} * \frac{\mathbf{1}}{\boldsymbol{Insulating\ Oil\ Density}} \tag{2}$$

Studies have shown that materials such as silica, titania, alumina, etc. can enhance AC BDV. This improvement is mainly attributed to the ability of nanoparticles to act as electron scavengers, capturing free electrons, delaying the breakdown process, and consequently increasing the breakdown voltage [75]. Regarding impulse breakdown voltage, adding nanomaterials such as h-BN, MWCNT, and Zinc Ferrite could reasonably enhance its properties. Previous studies revealed that this enhancement occurs because nanoparticles disrupt the electric field distribution of pure oil, which is typically characterized by homogeneous polarization. They also capture fast electrons through surface polarization, thereby hindering the propagation of streamers. Moreover, a uniform dispersion of nanoparticles in the base fluid facilitates the formation of branched discharge pathways, improving resistance to breakdown [76]. Numerous studies have demonstrated that nanofluids exhibit higher thermal conductivity than pure insulating oils [67, 77, 78]. This improvement is primarily attributed to nanoparticles' inherently high thermal conductivity, which, when dispersed in oil, enhances the thermal transport properties of the resulting nanofluid. Studies have shown that partial discharge (PD) in nanofluids progresses more slowly than in base oils [45]. Electrical and acoustic measurements indicated that nanofluids exhibit significantly higher PD magnitude and pulse counts compared to base oil [79]. Under accelerated aging, while PD inception voltage decreased in both fluids, nanofluids consistently maintained higher inception voltage levels [80].

5. Conclusions, Challenges, And Future Research Directions

5.1. Conclusions

This paper has presented extensive preliminary information about transformer oils and their history and the various measurement methods used to evaluate their multiple properties. In addition, several published studies have been reviewed regarding enhancing transformer oil properties using nanoparticles. The findings demonstrated improvements in various characteristics, such as electrical insulation, by adding materials like Titania, Alumina, Magnetite, Functionalized Nanodiamonds, and CdS quantum dots. Moreover, enhancements in thermal conductivity were observed when incorporating materials such as Zinc Oxide, Al_2O_3 Spheres, Al_2O_3 Fibers, AlN, BN, and Zinc Ferrite. These results highlight the potential of nanoparticles, even when added in minimal concentrations, to significantly improve the properties of insulating oils, representing a fundamental pillar in the advancement of this industry.

5.2. Challenges

- **Long-Term Stability of Dielectric Nanofluids:** Due to Van der Waals forces, nanoparticles tend to agglomerate and sediment, reducing thermal and dielectric performance. Ensuring long-term stability remains a major challenge for practical applications.
- **Viscosity of Dielectric Nanofluids:** Elevated viscosity and density in dielectric nanofluids cause higher pressure drops, limiting energy efficiency in cooling systems.
- **High Production Costs:** The synthesis of nanoparticles and preparation of nanofluids often involve expensive and complex methods, making large-scale industrial production time-consuming and costly.
- **Variation in thermal and dielectric performance:** Experimental findings vary widely because of differences in nanoparticle type, concentration, and preparation methods. The influence of turbulent flow on heat transfer requires further study, and a unified theory explaining breakdown strength enhancement mechanisms across nanoparticle types is still lacking.
- **Incompatibility and Aging:** Nanoparticles may interact adversely with solid insulation materials in transformers, leading to long-term degradation.
- **Environmental and Toxicity Concerns:** Certain nanoparticles are corrosive or toxic, highlighting the need for environmentally friendly alternatives.

5.3. Future Research Directions

- **Stabilization and Dispersion:** Minimizing nanoparticle agglomeration and achieving uniform dispersion remain significant challenges. Surface modification of nanoparticles and surfactants presents promising research directions, provided they also ensure eco-friendly and biodegradable characteristics.
- **Concentration Optimization:** Determining the optimum nanoparticle concentration is crucial to balance enhanced thermo-dielectric properties with minimal increase in viscosity.
- **System Integration:** Examine the performance of dielectric nanofluids in both forced and natural cooling systems, focusing on how nanoparticle volume fraction influences pump power requirements and overall system efficiency.
- **Environmental Impact Assessment:** Evaluate the ecological implications of using dielectric nanofluids.

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