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SURFACE MODIFICATION OF NANOPARTICLES USING PLASMA TECHNOLOGY TO ENHANCE THE INSULATION PROPERTIES AND STABILITY OF NANOFLUIDS: A REVIEW

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Abstract

The literature has shown that introducing nanoparticles into mineral oil is a potential approach to improving the liquid insulation's thermal and electrical performance. Nanoparticles' fundamental characteristics, such as conductivity and permittivity, can improve the relaxation time constant, thereby improving electrical performances, while the nanoparticles' Brownian motion may enhance the nanofluids' thermal conductivity. This manuscript includes a detailed analysis of the research on transformer oil-based nanofluids. Besides, a critical issue has been discovered: nanoparticle dispersion in transformer oil may result in sedimentation and agglomeration, affecting the stability and performance of nanofluids. The most typical approach for improving nanofluid dispersion and reducing sediment is to add a surfactant, but selecting the most effective surfactant remains challenging. An excess of surfactant added could cause an overabundance of change in nanofluid characteristics which is thermal conductivity and viscosity, which would be a concern in nanofluid applications. Therefore, many recent studies on plasma treatment for nanoparticle surface modification have been published. Plasma treatment, which is suitable for mass production, environmentally friendly, and easily operated, has emerged as the preferred method for modifying the surface of nanoparticles. This treatment may additionally eliminate the need for surfactants or other chemical dispersants to improve nanofluid stability and dispersion. There is currently a scarcity of research on plasma treatment in transformer oil-based nanofluids. Therefore, this manuscript reviews the non-conventional method of nanoparticle surface treatment known as atmospheric pressure plasma treatment, in an effort to improving the electrical, thermal, and the characteristics of transformer oil for power transformer applications, while also highlighting the culmination of the future direction of this non-conventional method of surface treatment for nanofluids.

Keywords: Nanofluids; atmospheric pressure plasma treatment; surface modifications; nanoparticles; transformer oils; breakdown strength; partial discharge; thermal conductivity.

1.0 INTRODUCTION

For many electrical equipment, including power transformers, mineral oil has served as the primary supply of insulating material. Because of its promising electrical insulating capabilities, self-healing behaviour, low relative permittivity, low dissipation factor (tan delta), and low viscosity, mineral oil made from refined petroleum makes an excellent material. Additionally, mineral oil is used extensively worldwide for the creator of HV transformers since it's affordable and superior heat transfer rate compared to comparable solid insulating materials.

Complex combinations of hydrocarbons make up the majority of the chemical components of mineral oil. To further minimise product size and weight, mineral oil's electrical and thermal qualities must be enhanced. Nanoparticle addition has recently enhanced heat transmission and electrical breakdown strength of mineral oils. Table 1 displays the mineral oil's characteristics.

Table 1. The mineral oil's characteristics according to datasheet [1].

Characteristics	Test Method	Value
Density [20°C, g/ml]	ISO 12185	0.893
Viscosity [at 40°C]	ISO 3104	9.06
Pour Point, °C	ISO 3016	-51
Water Content, PPM	IEC 60814	<10
Flash Point, °C	ISO 2719	146
Breakdown Voltage, kV	IEC 60156	>30

The word "nanofluid" is created by researchers at the Argonne National Laboratory to describe a two-phase mixture in which the liquid phase serves as the base fluid and contains spread-out nanoparticles [2]. A heat-transfer fluid is referred to as a "nanofluid" if it contains a little quantity of nanoscale materials (nanoparticles, nanofibers, nanotubes, nanowires, nanorods, or nanosheets) that steadily suspended in regular heat-transfer fluid [3]. In high voltage engineering, nanofluids could be used as transformer oil, particularly for lubrication, insulating, cooling, and arcing suppression. Researchers have previously looked into nanofluids' thermal conductivity at varied nanoparticle concentrations with diverse nanoparticle materials, particle sizes and particle volume fractions [4].

Karthik *et al.* [5] evaluated the improvement of crucial features of transformer oil using nanoparticles with modifications in terms of the nanoparticles' particle volume fraction. The viscosity, flash point, and pour point all significantly improved as a result. Dong *et al.*'s [6] thorough investigation of the conductivity electricity of an AlN nanofluid based on transformer oil revealed greater electrical conductivity compared to pure transformer oil. However, the purpose of this study was to validate the novel model that was developed during the authors' research. In order to understand how the transformer oil based nanofluids' improved dielectric characteristics under the influence of dispersants, Mansour *et al.* [7] examined the dielectric characteristics of nanofluids based on transformer oil utilising Titania (TiO_2) nanoparticle. The findings indicated that failure voltage increased as titania nanoparticle concentration rose.

Characteristics of mineral oil-based silica nanofluids were studied by Jin *et al.* [8]. The outcomes demonstrated the inclusion of SiO_2 nanoparticles enhanced the mineral oil's AC breakdown voltage. Meanwhile, Mansour and Elsaeed [9] found that adding modest amounts of alumina nanoparticles to alumina-mineral oil based nanofluids has improved heat transfer. The study of Al_2O_3-based nanofluids by Sridhara and Satapathy [10] indicates that alumina nanofluid can also be used to increase the dielectric strength and longevity of transformer oil. They also asserted that using alumina additions can considerably enhance the heat transfer characteristics of transformer oil [10].

2.0 OVERVIEW OF NANOFLUIDS APPLICATIONS

Nanotechnology has been used in numerous areas in order to create energy supply and usage that is more effective, cleaner, and better. Excellent characteristics of nanofluids could make them helpful in a variety of applications. Transformer oil, engines, electronics, solar water heaters, diesel generators, chillers, and refrigeration systems are examples of heat-exchanging equipment are only a few examples of the industrial uses of nanofluids for heat transmission [11].

A lack of theoretical support for understanding the mechanisms, a lack of consensus among researchers, and inadequate characterization of nanofluids have all contributed to the slow progress of recent studies, which have reported extensive data on the thermo-physical characteristics and heat transfer characteristics of various nanofluids. This difference may have resulted from the use of various techniques and preparations for nanofluids. The evaluation of the nano-suspension's long-term stability is crucial in order to create economically viable nanofluids. To assure nanofluids' long-term stability, more theoretical and experimental research must be explored [11]. Research on nanofluids delves into suspensions of tiny particles within base fluids, showcasing improved thermal and physical characteristics. However, the theoretical foundations and underlying mechanisms are still areas of active research, and a complete consensus among researchers might not exist due to the complexity involved. Yet, several theories and mechanisms have been proposed to explain the behaviour of nanofluids. Multiple theories aim to elucidate their behaviour, often pinpointing heightened thermal conductivity as a key enhancement owing to nanoparticle presence. The Maxwell-Garnett and effective medium theories, classic in this realm, endeavour to capture this enhancement by examining how nanoparticles interact with the base fluid. Wang *et al.* [12] underscored that nanoparticle aggregation significantly impacts nanofluid thermal conductivity. It was observed that as the fractal dimension of aggregation decreases, the thermal conductivity of nanofluids rises, particularly evident in aggregations with more nanoparticles, holding volume fraction and particle size constant. Moreover, smaller nanoparticles prove advantageous in augmenting nanofluid thermal conductivity in cases of aggregation. Furthermore, comprehending the mechanisms behind nanofluids is linked to the idea of Brownian motion. Within fluids, nanoparticles undergo this motion, leading to collisions and interactions with molecules in the base fluid. This motion significantly influences the transport characteristics of nanofluids, thereby affecting their overall properties [13].

Additionally, the dispersion of nanoparticles within the fluid and their inclination to either aggregate or remain uniformly dispersed have a notable impact on the traits of nanofluids. The stability of the suspension and the surface chemistry of the nanoparticles are crucial factors influencing their properties [14]. Moreover, nanoparticles have the potential to create interfacial layers at the interface between solids and liquids, which can modify the fluid's thermal and rheological properties [15]. The characteristics and thickness of these interfacial layers can vary based on the material of the nanoparticles and their surface attributes. Another crucial theoretical explanation for the mechanism of nanofluids involves the modification of the thermal boundary layer. Nanoparticles have the capacity to change the thermal boundary layer in close proximity to heated surfaces, thereby impacting heat transfer mechanisms and convective heat transfer coefficients [16]. Nevertheless, there is not a unanimous agreement on a singular dominant mechanism that dictates the behaviour of nanofluids. This is because their behaviour tends to rely on diverse factors like nanoparticle size, shape, concentration, surface chemistry, and the specific type of base fluid employed. Consequently, ongoing research in this field seeks to enhance existing theories and discover novel mechanisms to precisely elucidate and forecast the behaviour of nanofluids.

3.0 NANOPARTICLES IN NANOFLUIDS

Nanofluids typically demonstrate superior stability compared to conventional fluids containing larger solid particles for several reasons. The smaller size of nanoparticles leads to more pronounced Brownian motion, effectively preventing their aggregation and settling [17]. This constant motion acts as an obstacle against particle clumping, contrasting the weaker Brownian motion observed in larger particles that makes them more susceptible to settling. Furthermore, nanoparticles possess a higher surface area-to-volume ratio, enabling better interaction with the base fluid [18]. The surface charges on nanoparticles often repel each other, minimizing aggregation and enhancing stability. Additionally, due to their smaller size, nanoparticles disperse more uniformly within the fluid, reducing particle agglomerations [18]. This uniform distribution significantly contributes to increased stability compared to larger particles, which tend to aggregate. Moreover, nanoparticles create interfacial layers at solid-liquid interfaces, establishing barriers that impede particle aggregation and deposition, further enhancing stability [19]. These collective factors significantly bolster the stability of nanofluids, ensuring the sustained uniform dispersion of nanoparticles within the fluid. This stability surpasses that of conventional fluids with larger solid particles, which are more prone to deposition and aggregation.

The selection of nanoparticles is quite challenging especially when the focus on enhancement of dielectric and thermal properties. Typically, basic characteristics like conductivity and permittivity are the first things considered when choosing nanoparticles. Numerous nanoparticles had been examined in an effort to enhance the liquid insulation's dielectric properties [7], [20], [21]. Conductive nanoparticles (Fe_3O_4, ZnO, and SiC), insulating nanoparticles (SiO_2, Al_2O_3), and semiconductive nanoparticles (TiO_2, CuO, and Cu_2O) are some notable nanoparticles that are frequently utilised in solid-liquid work [22].

Typically, nanofluid is made up of smaller than 100 nm-sized solid particles and suspended in various base fluids or liquid media. In addition to having great thermal conductivity, this solid-liquid composite material also possesses interesting technical features for improving heat transmission. Due to the liquid's nanoparticles' Brownian motion and size effect, nanofluids have higher and improved stability compared to micrometre- or millimeter-sized solid particles in conventional fluids. Consequently, the ultrafine nanoparticles in the microchannel, nanofluids can travel and flow there without becoming clogged. The size of the heat transfer system can also be reduced contribute to nanofluids with great heat transfer efficiency.

4.0 NANOFLUIDS PREPARATION

The preparation of nanofluids for high-voltage applications encompasses various methods, all directed toward improving the dielectric characteristics while preserving insulation integrity. The common method utilized to prepare nanofluids is known as two-step dispersion, which involves the process of mixing pre-synthesized nanoparticles into transformer oil. Improvement lies in optimizing the dispersion technique to ensure uniform distribution and stability of nanoparticles within the oil. Advanced surface modification techniques and surfactants are employed to enhance dispersion and prevent particle agglomeration. Zhang *et al.* [23] applied a surface modification technique to prepare γ-glycidoxypropyltrimethoxysilane (GPTMS) modified TiO_2/water nanofluids. It has been discovered that the thermal conductivity of nanofluids increases by introducing surfactants.

Ultrasonication stands out as a favoured technique for nanofluid preparation. It entails exposing the nanofluid blend to ultrasonic waves to disperse particle clusters and attain a more uniform distribution. Continuous enhancements concentrate on refining ultrasonication parameters to guarantee reliable and efficient dispersion without adversely affecting the oil or compromising its insulating properties. Farade *et al.* [24] investigated the effect of sonication time on dispersion stability, dielectric properties, and heat transfer of graphene-based green nanofluids. It was revealed that improving nanoparticle dispersion led to an increased number of dispersed nanoparticle sheets within a given volume, generating additional trapping sites throughout the fluid. These sites contribute to higher AC breakdown strength. Furthermore, the heightened dispersion, by increasing trapping sites, reduces the mobility of charge carriers, resulting in elevated resistivity. Additionally, in terms of Brownian motion and interparticle interactions, both thermal conductivity factors exhibit direct proportionality to the nanoparticle count, emphasizing the advantage of dispersing nanosheets for longer durations during ultrasonication. Chemical stabilization stands as an alternative approach investigated to stabilize nanoparticles within the oil using stabilizing agents or additives. Ongoing studies seek stable additives that prevent particle sedimentation, sustain dispersion, and elevate nanofluid thermal conductivity without affecting the dielectric properties of transformer oil. Ji *et al.* [25] found that incorporating expanded graphite as a stabilizing additive enhanced the thermal conductivity of nanofluids.

In-situ synthesis, a method involving the preparation of nanoparticles within transformer oil, is continuously refined to regulate the synthesis process for attaining desired nanoparticle sizes and distributions without compromising the oil's dielectric properties. Koutras *et al.* [26] employed this technique to prepare TiO_2 nanofluids based on natural ester oil. The study revealed that varying volume fractions of nanoparticles prepared via in-situ synthesis affected the nanofluids' thermal conductivity and electrical insulation properties. This outcome was attributed to trapping and de-trapping mechanisms within shallow traps, diminishing streamer propagation and elevating breakdown strength in the nanofluids. The interfacial zone's role, bolstered by increased nanoparticle loading, potentially captured high-mobility electrons, boosting resistance to partial discharge. Furthermore, optimal thermal stability in the nanofluids was achieved at specific nanoparticle loading levels, notably at a dispersion volume of 0.02%. [26]. Enhancements in these preparation techniques are centred on attaining improved dispersion, stability, and harmonization of nanoparticles within transformer oil. The primary objective is to boost heat transfer efficiency without compromising the oil's insulation properties or causing adverse effects on transformer performance. Further explorations are also required to acquire comprehensive testing methodologies for assessing the long-term stability, dielectric strength, thermal conductivity, and overall performance of nanofluids within transformers under various operating conditions.

The preparation of the nanofluids themselves is the most crucial step in the experimental study of nanofluids. In particular, steady suspension, long-term stability, the absence of particle agglomeration, and no chemical alteration of the fluid characteristics are required. Agglomeration of nanoparticles will lead to poor stability of nanofluids. The two methods—one-step and two-step—are primarily employed in the manufacture of nanofluids. The goal of the one-step procedure is to reduce agglomeration by suspending the nanoparticles in the base liquid without drying, storing, or transporting them. This improves the stability of nanofluids and the suspension of the nanoparticles. Unfortunately, the one-step process is expensive and inappropriate for mass production [27].

The one-step method's further flaw is that the nanofluids contain unreacted or unstable reactants. Without removing this impurity impact, it is challenging to understand the nanoparticle effect. Yu and Xie [28] and Haddad *et al.* [29] examined the one-step procedure for making nanofluids. In Hwang *et al.*'s [30] synthesis of Ag-Silicon oil nanofluids using the one-step approach and modified magnetron sputtering methods, direct condensation of the Ag vapour produced by magnetron sputtering resulted in the creation of Ag nanoparticles.

The nanoparticle synthesis processes previously scaled up to commercial production levels, making the two-step procedure the most advantageous and inexpensive method for producing nanofluids on a large scale. In this process, the nanoparticles are first created individually as dry powders using both chemical and physical means. By reducing the diameter of agglomerated nanoparticle clusters, utilising a range of physical treatment methods such the stirrer, ultrasonic bath, ultrasonic disruptor, and high-pressure homogenizer, the produced nanoparticles are distributed in the base fluid.

Because of their wide range of nanoparticles application, which is appropriate and low cost, compared to the one-step procedure, this two-step approach is more frequently utilised. Nevertheless, since there is a lot of surface activity, agglomeration or sedimentation of nanoparticles may happen during the steps in two-step method [27], [28], [30]. Mansour *et al.* [7] and Atiya *et al.* [31] compose mineral oil-based nanofluids with TiO_2 nanoparticles as an additive by using two-step method, incorporated with various physical treatment techniques. Jin *et al.* [8] applied the two-step procedure to create SiO_2 nanofluids based on mineral oil as well.

5.0 APPLICATION OF NANOFLUIDS IN TRANSFORMER

The transformer, which changes voltage and transports energy, is the most crucial part of an electric power network. The lifetime of the transformer essentially depends on the insulation material. There have been uses for mineral oils as insulating and cooling materials for more than a century because of its remarkable insulating and thermal features. Nonetheless, the more advance industries nowadays demands a transformer with high voltage rate, small size, as well as enhanced dielectric and thermal characteristics, therefore some works and modification on insulation oil are required [22]. In power transformer applications, nanometer-sized particles are frequently added to mineral oil as an additive because they can enhance the dielectric characteristics and boost heat conductivity. The use of nanoparticles has considerably improved transformer oils' capacity for heat transfer. Low thermal conductivity exists in the transformer oil itself; hence previous researchers produced transformer oil-based nanofluids, using different nanoparticles suspended in the base fluids to improve electrical and thermal conductivity.

Several researchers tested nanoparticle suspensions and discovered a considerable increase in heat conductivity at 1% volume fraction of very small particles; which is indeed an enhancement compared to base fluids [32]. Choi *et al.* [33] produced and assessed nano-alumina powder dispersions in transformer oil using a modest amount of oleic acid as a dispersant in a prior study. However, because the transformer oil had a very low thermal conductivity, thermal failure from immediate overload commonly occurred. The transformer oil's improved thermal conductivity was therefore intended to boost cooling capacity and extend the lifespan of the transformer. The researchers were able to create nanofluids that outperformed pure oil considering of properties of natural convection, thermal conductivity, and convective heat transfer, and these fluids were subsequently considered alternatives for the upcoming wave of heat transfer mediums [33].

6.0 AC BREAKDOWN VOLTAGE OF TRANSFORMER OIL-BASED NANOFLUIDS

In order to decrease the volume and mass of transformer, it is most appropriate to increase the dielectric strength of insulating oil by dispersing the nanoparticles. Furthermore, it's very necessary to check the quality of the nanofluids for power transformer application. AC breakdown voltage is one of the compulsory tests that are usually used to measure the quality of transformer oil. Until now, more publications and research works on nanofluids have been published, highlighting on their breakdown voltage characteristics [27], [34], [35].

Jin *et al.* [8] looked at the viscosity and AC breakdown strength of SiO_2 nanofluids based on mineral oil. The SiO_2 nanoparticles had different diameters, ranging from 10 to 20 nm. The examined nanofluids' mass fractions ranged from 0.005% to 0.02%. Researchers looked at how moisture content and nanoparticle concentration affected breakdown strength. The results of the test for AC breakdown were analysed using the Weibull statistical distribution. Rafiq *et al.*'s [36] research of the mineral oil-based nanofluids' AC breakdown performance at varied moisture levels used SiO_2 nanoparticles. The results of this experiment showed that nanofluids have better breakdown strength than base transformer oil.

Other researchers generated silica nanofluids with mass fractions of 0.005%, 0.01%, 0.02%, and 0.1% for analyses, studies, and testing on the thermal conductivity, viscosity, and AC breakdown voltage. According to the findings, mineral oil with a larger concentration of silica nanoparticles had a higher breakdown strength. Even with higher moisture contents and lower failure probability, the mineral oil-based silica nanofluid's improvement in AC breakdown strength was more notable. Since the silica nanoparticles had hydrophilic surface, it played an important role to absorb water in the nanofluids, as the breakdown strength depended on the moisture content in the nanofluids. The nanoparticles had little impact on the mineral oil's thermal conductivity for concentrations of silica nanofluids up to 0.1% [3].

Many researchers used nanoparticles in the study of oil-based nanofluids is alumina (Al_2O_3). Alumina nanoparticles have been used in numerous studies to examine the dielectric and thermal characteristics of nanofluids. On their study of the impact of Al_2O_3 on transformer oil, Mansour *et al.* [9] discovered that the improvement in breakdown strength was reliant on the moisture content. In addition, according to Sridhara and Satapathy [10], scattering Al_2O_3 nanoparticles in an alumina nanofluid can extend the dielectric strength and life of transformer oil. They also came to the conclusion which is adding Al_2O_3 nanoparticles to the base fluid, ranging in size from 13 to 302 nm, increased thermal conductivity by 2% to 36%. The outcomes also showed that adding alumina to transformer oil had greatly improved its heat transfer characteristics.

Other researchers have produced transformer oil-based nanofluids using magnetic nanoparticles in addition to alumina and silica, but they have discovered that the methodologies and development processes required to prepare magnetite nanoparticles are rather expensive. The researchers concluded that the magnetic nanoparticles suspended in transformer oil could be one of the potential fluids and has good dielectric characteristics using nanoparticles of the appropriate size and volume content [37]. Lee and Kim [38] used magnetic nanoparticles distributed in transformer oil to create nanofluids to study the dielectric breakdown voltage. The findings demonstrated that pure transformer oil had a dielectric breakdown voltage that was three times higher. Since electron scavengers in electrically strained transformer oil-based nanofluids transformed the rapid electron into slowly negatively charged nanoparticles, it was anticipated that the additional conductive nanoparticles were impacted.

Meanwhile Du *et al.* [39] prepared Fe_3O_4 nanofluid from transformer oil and investigated the effect of breakdown strength. They came out with conclusion that the breakdown voltage of nanofluid will be drastically reduced when using increased level of nanoparticle concentration. This behaviour was considered since the agglomeration of Fe_3O_4, it can cause the breakdown voltage to drop. Besides Fe_3O_4 nanoparticle, TiO_2 has also become a common nanoparticle in nanofluids preparation for power transformer application. By dispersing TiO_2 nanoparticles into transformer oil, Fan *et al.* [40] created a nanofluid that had an improvement over pure transformer oil for the mean breakdown voltage of 15% to 43%.

Lv *et al.* [35] studied the effect of nanoparticles on breakdown strength by generating transformer oil-based nanofluids with insulating metal oxide nanoparticles (INPS), semi-conductive metal oxide nanoparticles (SNPS), and conductive metal oxide nanoparticles (CNPS) at concentrations of 0.05 g/L each. They asserted that the oil's dielectric performance had been enhanced by the addition of those nanofluids. The conductive, insulative and semi-conductive nanoparticles produced shallower traps in oil, hence capturing fast electrons and rapidly releasing them. In 2016, Jianzhuo *et al.* [41] dispersed SiO_2 nanoparticles in the transformer oil to produce nanofluids and investigated the breakdown strength and broadband dielectric response. The findings showed that the breakdown voltage of nanofluids based on transformer oil rose up to 0.1 weight percent concentration, but then decreased with 0.2 wt% nanoparticle concentration. The increase and uptrend behaviour in breakdown voltage value could be due to the electric double layer structure of nanofluids.

7.0 PARTIAL DISCHARGE OF TRANSFORMER OIL

Partial discharge (PD) is also known as local breakdown. By examining the inception voltage, total discharge magnitude, and number of PDs, the pre-breakdown phenomenon in transformer oil may be further understood by measuring PD behaviour. The presence of voids, impurities and air bubbles could be the reasons of decreasing performance and degradation of transformer oil. Besides, this kind of test is essential to identify early symptom and diagnostic before any insulation failure happens [42], [43].

A streamer, which typically comprises of a positive and a negative streamer, causes a liquid insulator to dissolve. Often, streamer in transformer oil is triggered by electrons produced by field emission at the needle tip. These electrons would then cause the immediate area to expand and form a low-density form. Charge causes the ionisation process to appear multiplied and accelerates electron motion, which aids in the expansion of the discharge channel. It's important to highlight which the emergence of low-density zones unpredictable and results in various propagation trajectories. There develops a positive space charge zone, going per the space charge theory and grows as a result of the stark contrast in ion and electron mobility. The earlier distribution of the electric field in the oil is altered by these positive space charges, weakening the electric field at the needle tip. Streamer channels under positive excitation are more likely to extend towards the ground than under negative excitation because of the greater electric field at the top of the ionised zone [44]. The ionisation moves along faster as a result of this improved electric field.

Meanwhile, it was discovered that negative polarity PDs take place obviously more frequently than the positive polarity PDs while examining the PD pattern in oil. According to earlier researchers, the corona-like needle electrode is always surrounded by PD with negative polarity. According to the space charge hypothesis, the ionisation close to the needle tip produced positive ions and free electrons. The positive ions in the oil travel rather slowly, which causes them to assemble around the negative tip, greatly enhancing and forcing the electric field between the positive ions, which causes PD to happen much more frequently. A negative charge layer with pierced distribution is created as a result of the free electron that results from ionisation growth being more inclined to extend along the electric field line [45]. After considering the aforementioned explanations, it is obvious that the space charge effect is principally caused by significant disparities in the mobility of ions and electrons. [44].

The moisture level, acidity, and contaminants brought on by oxidation can induce a detrimental influence on mineral oil's dielectric strength, according to a study by Yuzhen *et al.* [38]. The pulse repetition rate is more susceptible to such additions than PD magnitude. Mineral oil has additional nanoparticles added, which can absorb the additives and hold them on their surface. This explains why there are less PDs in silica and alumina nanofluids compared to mineral oil. According to the overall findings, it is possible to improve PD features by lowering the total discharge magnitude when compared to pure mineral oil by using plasma-treated nanoparticles in nanofluids rather than untreated samples.

To investigate the partial discharge (PD) behaviour of silica oil- and mineral oil-based nanofluids, Jin *et al.* [46] employed needle-plane electrodes. The findings indicate that compared to using pure mineral oil, silica/mineral oil nanofluids had a 20% higher inception voltage and a smaller overall discharge magnitude. Other researchers provided a model to explore the effects of nanoparticles with various conductivities, and they arrived to the conclusion that since conductive nanoparticles trap electrons at the particle surface, they can slow the pace of the positive streamer propagation in mineral oil. The results showed a 60% reduction in silica nanofluid discharge magnitudes when compared to utilising pure mineral oil [47].

The partial discharge properties of palm fatty acid ester (PFAE) oil were studied by Ramli *et al.* [48]. Their analysis revealed that the PD patterns of PFAE and mineral oil during the ageing period were comparable. Other researchers investigated partial discharge characteristics using mineral and vegetable oils, and they compared various insulating oils relative to the occurrence of PD. The results showed that mineral oil had fewer repetitions and a lower average PD charge, and achieved better performance than vegetable oils, but only for certain time of aging [49].

Using needle-plane and rod-plane electrode designs, Prasad and Chandrasekar [43] investigated the effects of silica nanoparticles on the partial discharge characteristics of FR3 transformer oil. 0.01, 0.05 and 0.1% concentrations by weight were added into the transformer oil for preparing the nanofluids. The study's findings demonstrated that, when compared to pure FR3 oil, nano-silica/FR3 oils considerably increased both the partial discharge inception voltage and the steady PD formation voltage. The 0.01%wt silica FR3 oil-based nanofluids showed a better performance compared with other weight percentage concentrations. Additionally, it was found that silica nanoparticles added in modest quantities to the FR3 oil might enhance its PD performance characteristics in nanofluids.

Makmud *et al.* [42] looked at the characteristics of transformer oil-based Fe_2O_3 nanofluid partial discharge under AC voltage. When compared to using pure transformer oil, they discovered that the PD inception voltage (PDIV) of their nanofluids had increased. However, PDIV of the nanofluids decreased when the nanoparticles concentration increased since the deteriorated electron trapping effect. The nanofluid with the lowest concentration showed the least amount of PD in the positive cycle but increased with the increase of Fe_2O_3 concentration. When the nanoparticle dispersed, the electron trapping effect was because of the applied electric field. The trapping and de-trapping process was influenced by the added nanoparticles. With higher volume concentration, the nanoparticles agglomerated and deteriorated the electron trapping effect. In nanofluids, PD activities occur frequently in negative cycle. However, at the lowest concentration nanofluid, it still showed the least amount of PD even in the negative cycle. More PD activities in negative cycle are attributable to greater negative electrode surface area which authorizes higher ionization process.

A needle-plane electrode arrangement with TiO_2 and $BaTiO_3$ were used to evaluate the PD properties of MO-based nanofluids by Muangpratoom and Pattanadech [50]. The PDIV of nanofluid was found to be closely correlated with needle tip radius, and the dominating PD value of oil insulation occurred in the positive cycle, according to their findings. The increase of PDIV value of nanofluids was due to higher nanoparticle concentration, which was the same reason for the increased breakdown voltage value. In this research study, nanoparticles with high dielectric constant achieved higher PDIV value, which means that the nanofluids showed better PD characteristics as opposed to using pure mineral oil.

The study also catered research into the PD behaviour of transformer oil with conductive and semiconductive nanoparticles using needle-plane electrode system. In comparison to pure transformer oil, nanofluids experienced fewer PD events, a lower total charge, mean charge, and maximum charge magnitude. The reduced electron mobility and PD activities in nanofluids were caused by electron capture on the surface of the nanoparticles. Consequently, the ground electrode's increased surface area enhancing electron production, there were more PD activities during the negative cycle. The higher nanoparticle concentration also influenced PD characteristics because the electric interaction between nanoparticles also increased, leading to agglomeration [51].

A transformer oil-based titania nanofluid was prepared by Rafiq *et al.* [52] to enhance the insulating properties and partial discharge of the nanofluid. PDIV tests had been carried out, and they found that nanofluids resulted in higher PDIV value compared to the base oil. The pulse number and mean of discharge magnitude in nanofluid also indicated a better enhancement. They came to the conclusion that the transformer oil's dielectric strength may be increased by adding nanoparticles. By employing parallel plate electrodes at various gap distances, Herchl *et al.* [53] examined the PD properties of transformer oil utilising Fe_3O_4 nanoparticles coated with oleic acid. The findings showed that the PD current in the nanofluids initially decreased as the quantity of nanoparticles rose, and later increased at all tested gap distances. Jin [54] produced mineral oil-based nanofluid with 0.01 wt% fullerene nanoparticle and investigated the PDIV under DC positive voltages. In comparison to using pure mineral oil, the PDIV of nanofluid showed a higher value with fewer pulses and a larger mean discharge magnitude. The created nanofluid's PD properties improved, which might be related to the nanoparticles' relaxation time constant, which was too long for them to catch any electrons in the oil.

8.0 STABILITY EVALUATION METHODS OF NANOFLUIDS

Before using nanofluids in whatever application, it's crucial to select a method to assess their stability. The use of UV-Vis spectroscopy and Transmission Electron Microscopy is advised by a thorough review of the literature to ascertain the relative stability of nanofluid [30], [55].

8.1 UV-Vis Spectroscopy

The use of nanofluids based on transformer oil presents a significant difficulty, and the stability of the nanofluid is a vital factor in this research. Some requirements include long-term stability, steady suspension, no nanoparticle aggregation, and no chemical alteration of the fluid's characteristics. One of the easiest methods to assess and explain the properties of colloidal stability of the dispersions is UV-Vis spectroscopy, primarily due to its simplicity of use and quick analysis results. Previous studies employed UV-Vis spectroscopy in solid-liquid operations to observe the maximum absorbance obtained and track the stability of nanofluids. A UV-Vis spectroscopy modifies the light's intensity by absorbing light that is travelling through a fluid and scattering light from that light. The UV-Vis spectrophotometer is frequently used to examine different fluid dispersions since it can detect the liquid's absorption at wavelengths in the 200-900 nm range. This technique uses scanning to determine the dispersed nanoparticles' peak absorbance at highly diluted suspension [56].

The first to utilise a UV-Vis spectrophotometer to estimate sedimentation for nanosuspensions were Jiang *et al.* [57], who prepared stable and homogeneous dispersions of carbon nanotubes. The results from UV-Vis spectroscopy in this work have become a guideline in choosing suitable surfactant for nanofluid. Shukla and Aiyer [58] investigated the stability of transformer oil-based with functionalized nanodiamond using UV-Vis in the range of 300-800 nm. They measured the absorbance values of the nanofluids up to three months and found that no change was observed in absorbance value until 960 hours, which means the nanofluids were in steady state conditions. Other researchers reported that the UV-Vis is an effective method to analyze absorption capability of nanofluids [29], [59]. Meanwhile, Ghadimi *et* *al.* [60] examined the consistency of nanofluids in the periods of 24, 48, 168, and 720 hours right after sample preparation. They noticed that the sample with low surfactant concentration resulted in high absorbance value. Sagadevan and Shanmugam [61] studied the stability of ZnO nanofluids using UV-Vis spectroscopy and discovered the greatest absorbance at 345 nm wavelength.

It is also possible to use UV-Vis spectroscopy to evaluate variations of sedimentation time from the absorbed spectrum [62]. Using UV-Vis, Sadeghi *et al.* [63] assessed the stability and dispersion properties of alumina nanofluid and discovered that the outcomes were dependent on the ultrasonic mixing time. The maximal absorbance rose as the concentration of nanoparticles and the duration of ultrasonic mixing were increased up to 30 minutes. The absorbance value decreased as the cluster size of nanoparticle in nanofluid was increased. They concluded that the size of nanoparticle clusters and nanoparticle concentration had influenced the absorbance in UV-Vis. In other studies, the researcher created copper oxide, copper nanoparticles, copper oxide, and transformer oil-based nanofluids. They asserted that aside from such nanofluids, pure transformer oil should have a low absorption. The outcomes revealed that the bandwidth spectra had increased as the particle volume of nanoparticles was increased [5].

Due to its simplicity and efficiency, UV-Vis spectroscopy was utilised by Mansour *et al.* [64] to evaluate the resilience of nanofluids based on transformer oil. The sediment time versus sediment value can be used to calculate the suspension stability. To evaluate the stability of nanofluids, the absorbance of a sample was compared to the absorbance of pure transformer oil. The concentration of nanoparticles was connected to variations in absorbance peaks. After nanofluid preparation, the absorbance of the sample had been measured directly because the rate of sedimentation occurred very slowly. The nanoparticle left the upper part of the sample in a cuvette cell due to the effect of gravity, hence achieving the maximum absorbance in UV-Vis spectroscopy. The agglomeration of nanoparticle in nanofluid was simply related to the lower value of absorbance value. The researchers then compared the nanofluids sample between 0 hour and 24 hours after sample preparation. The outcomes revealed that the maximum absorbance value was higher for nanofluids at 0 hour compared to the sample after 24 hours preparation. The same downtrend was shown by nanofluid sample with surfactant, which shows that adding surfactant alone will not greatly increase the stability of nanofluid.

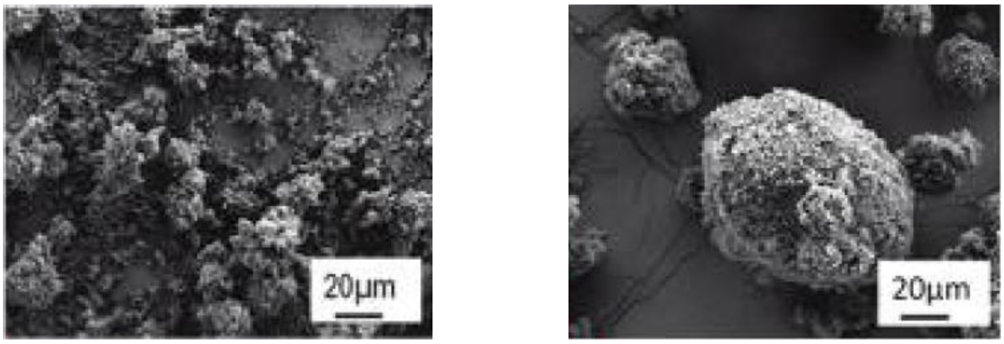
8.2 Transmission Electron Microscopy (TEM)

Transmission electron microscopy (TEM) is a popular yet essential tool for evaluating the size, shape, and dispersion behaviour of nanoparticles in nanofluids. By using this instrument, a very fine and nano-scale size objects can be examined, thanks to the use of beam of energetic electrons in the instrument. In TEM equipment, the sample is shot by electrons, and measurement is done to know how the sample's scattering affects the electron beam. Apart from dispersion behaviour characterized by TEM analysis, this equipment can be used to observe how physical manipulation affects suspended nanoparticles in nanofluids. Several researchers have used TEM pictures to confirm that the creation of nanofluids was stable. Through TEM, the nanoparticles' size in the nanofluid is measured while images are periodically taken throughout time.

The stability of nanofluids can be estimated by looking at the sizes of the nanoparticles. Lower stability results from larger nanoparticles agglomerating in nanofluids. The instability of the nanofluid will increase with agglomeration. However, there are a few restrictions to the benefit of being able to see how nanoparticles behave in nanofluid. Because dried samples of the nanofluid are employed for the measurements portion, the application of TEM does not accurately reflect the behaviour and circumstances of nanoparticles in the nanofluid. Effective characterisation of nanoparticles requires the appropriate choice of magnification, image type, and analytic approach [56]. Nanofluid samples are initially combined in a 1:10 volume ratio with distilled water for sample preparation for TEM [30]. Sagadevan *et al.* [61] characterized ZnO nanoparticles using TEM images, and the researchers discovered that the nanoparticles' particle size distributions fell between 15 and 30 nm. Meanwhile, Atiya *et al.* [31] used TEM to study the dispersion behaviour of TiO_2 nanoparticles, and the captured image showed that the main particles were roughly shaped like big spherical agglomerations.

8.3 Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy is another common instrument apply by researchers to analyze stability, shown through SEM images, in which stable nanofluids would have different shapes after preparation [65]. Yan *et al.* [66] used SEM to analyze plasma treated silica nanoparticles. The SEM images of plasma-treated and untreated silica were displayed in Figure 1.



(a) (b)

Figure 1. SEM images of (a) untreated silica, and (b) plasma-treated silica [21].

They came to the conclusion that the treated nanoparticles self-organized into quasi-spherical agglomerates with diameters ranging from 10 to 100 µm on the basis of the obtained results. On the other hand, no noticeable morphological change was observed in untreated silica. Agglomeration most likely developed as a result of the plasma-treated nanoparticles' enhanced surface energy [66]. Other work reported that through SEM analysis, the spherical shaped nanoparticles with homogenous dispersion can be proven [61].

9.0 HEAT TRANSFER PROPERTIES OF TRANSFORMER OIL-BASED NANOFLUID

Their study on the heat transfer characteristics of Al_2O_3 nanoparticle suspensions in transformer oil, Mansour *et al.* [9] discovered that the weight % of the surfactant as well as the nanoparticle concentration had a profound impact on the coefficient of heat transfer. They noted that for surfactant weight percentages of 0.1% and 1%, the largest enhancement of heat transfer coefficient occurred at intermediate nanoparticle concentrations and low nanoparticle concentrations, respectively. The heat transfer coefficient in nanofluids can be significantly influenced by the weight and concentration of surfactants due to their direct impact on nanoparticle dispersion, stability, and interactions within the fluid [67]. Surfactant weight profoundly influences nanofluid behaviour, primarily through its role in nanoparticle dispersion and stabilization. Greater surfactant weight can enhance dispersion by mitigating particle aggregation, ensuring a more uniform distribution of nanoparticles within the fluid [17]. This uniformity facilitates heightened interaction between nanoparticles and the fluid medium, thereby augmenting heat transfer efficiency. However, excessive surfactant weight might pose challenges, potentially leading to increased fluid viscosity, which can impede heat transfer, counteracting the expected enhancement [17]. Concurrently, nanoparticle concentration significantly influences heat transfer properties. Increasing nanoparticle concentration intensifies the chances of nanoparticle collisions, enhancing thermal conductivity due to increased particle-to-particle interactions [68]. This increased concentration contributes to more efficient heat transfer paths and enhances the overall heat transfer coefficient of the nanofluid. Nevertheless, excessively high concentrations may induce particle agglomeration, offsetting the envisaged improvement in heat transfer efficiency.

According to Singh *et al.* [69], transformer oil-based nanofluids have the potential to have better heat transfer properties than standard transformer oils used for cooling. Meanwhile, better heat transfer rates are achieved by mineral oil, according to Rafiq *et al.* [34]. The synergy between surfactant weight and nanoparticle concentration thus dictates nanofluid behaviour and subsequent heat transfer characteristics. Optimal surfactant weight and nanoparticle concentration synergize to achieve superior dispersion, minimizing aggregation and promoting uniform distribution. This harmonious balance is pivotal for maximizing the heat transfer coefficient without compromising fluid properties. An excessive surfactant weight or nanoparticle concentration may lead to diminished thermal performance due to increased viscosity or particle agglomeration [17], [68]. In essence, the judicious selection of surfactant weight and nanoparticle concentration in the nanofluid formulation is paramount. This balance ensures effective dispersion, stability, and enhanced heat transfer properties, culminating in an augmented heat transfer coefficient. Achieving this delicate equilibrium offers significant potential for advancing heat transfer technologies while mitigating adverse effects on fluid properties. Hence, understanding and optimizing the interplay between surfactant weight and nanoparticle concentration stand as crucial facets in harnessing the full potential of nanofluids for enhanced heat transfer applications.

10.0 THERMAL CONDUCTIVITY OF TRANSFORMER OIL-BASED NANOFLUID

Incorporating nanoparticles into a base fluid can significantly boost the nanofluid's thermal conductivity due to various factors. Nanoparticles possess a high surface area-to-volume ratio, which this surface area allows for more effective interactions with heat and enhances thermal conductivity [70]. Additionally, nanoparticles in the fluid experience Brownian motion, leading to collisions that facilitate more efficient heat transfer [17]. This motion contributes to an improved effective thermal conductivity within the nanofluids. Moreover, the presence of nanoparticles results in the formation of interfacial layers at the solid-liquid boundary, modifying the thermal characteristics of the fluid [19]. These layers play a role in enhancing thermal conductivity by facilitating improved heat transfer throughout the fluid. Besides, effective dispersion of nanoparticles within the fluid prevents clustering and enables a more even spread [18]. This uniform distribution creates enhanced heat transfer routes, thereby elevating thermal conductivity. The cumulative impact of nanoparticles in nanofluids leads to a considerable rise in thermal conductivity compared to the base fluid. Yet, ensuring the appropriate dispersion and stability of nanoparticles within the fluid is pivotal to effectively obtain these improvements. Thermal conductivity and viscosity, two crucial thermo-physical characteristics that potentially influence how well nanofluids transport heat, were examined by Singh and Kundan [69]. The thermal conductivity and viscosity of Al_2O_3 transformer oil-based nanofluids were examined in relation to varied weight fractions of nanoparticles ranging from 0.1, 0.3, and 0.5% volume. The viscosity and thermal conductivity of the nanofluids were strongly influenced by volume fraction and temperature. Their research showed that up to 40°C, thermal conductivity increased with temperature, but as the temperature increased, brownian motion of the nanoparticles led to some differences. Additionally, it was noted that at higher concentrations (0.4–0.5%), volume fraction had an impact on thermal conductivity; nevertheless, the thermal conductivity has been decreased by the aggregation of nanoparticles in the nanofluids. In their analysis, they found that transformer oil-based nanofluid can serve as a good substitute for conventional transformer oil, but further testing is required to accurately forecast its thermal performance.

However, the rise in alumina nanofluids' thermal conductivity is not constant, since different researchers have reported conflicting results and the underlying causes have not been adequately discussed in the literature [9],[10]. As nanoparticle size decreases, thermal conductivity of nanofluids often rises, while Brownian motion depends on the temperature and size of nanoparticles [63], [71]. Brownian motion is induced if the nanoparticle size reduced. Smaller size of nanoparticles will delay and resist early sedimentation, which is one of the big issues and challenge in nanofluids. Brownian motion is more intense if low nanoparticles percentage fraction is used at higher temperature, otherwise nanoparticles tend to agglomerate if high percentage fraction is used. Higher fraction of nanoparticles will contribute to agglomerated nanoparticles and increased viscosity, which then impacts the performance of thermal conductivity in nanofluids [72]. Thus in the future, more researches on thermal conductivity are required for better understanding [9].

11.0 SURFACE MODIFICATION BY USING SURFACTANT

The main concern in nanofluid preparation is to get homogeneous suspension and improved nanoparticle dispersion in the base fluid, by reducing or eliminating the agglomerated nanoparticles and avoiding early sedimentation. According to earlier studies, surface modification of nanoparticles employing an appropriate dispersion or surfactant can enhancement of nanofluids' stability. The agglomerated nanoparticles will lower the thermal conductivity and contribute to the poor stability of nanofluids. The stability of the nanofluid and how evenly the nanoparticles are distributed throughout the base fluid determine its quality. However, the amount and selection of the surfactant that could stabilize the nanofluids should be carefully chosen beforehand.

Yu *et al.* [28] reported that, previous researchers added some kind of surfactant to improve the nanofluid stability, which increased the interaction between two materials in two-phase system. Adding surfactant into the base fluid is a simple and affordable solution; however, the most crucial step in the process is choosing an appropriate surfactant. Surfactant may increase the thermal resistance between the base fluid and lower thermal conductivity as a result. Besides, surfactants could be cationic, anionic, nonionic and amphoteric. Generally, the surfactant can be selected according to the type of base fluid used in the procedure of preparing the nanofluid. Water-based surfactants are suitable with polar solvent base fluid, otherwise, oil-soluble ones should be selected [28].

How soluble a surfactant is can be assessed using the hydrophilic-lipophilic balance, or HLB, value. The surfactant can be chosen using the HLB value. Higher HLB numbers indicate that the surfactants are more water-soluble, whereas lower HLB numbers indicate that they are more oil-soluble. HLB = 20* (Mh/M), where Mh is the hydrophilic group's molecular weight and M is the surfactant's molecular weight, can be utilised to calculate the HLB value [52]. A surfactant can enhance the dispersion of nanoparticles in nanofluids, but it also has the potential to generate a number of issues. As an illustration, adding surfactants can contaminate the heat transfer medium. Heat exchange systems frequently involve heating and cooling, which can cause surfactants to form foams. The thermal barrier between surfactant molecules and the base fluid may increase when they adhere to nanoparticle surfaces, which could impede the development of effective thermal conductivity [28]. Salt and oleic acid [30], sodium dodecylsulfate (SDS) [57], [73], SDBS [74], cetyltrimethylammoniumbromide (CTAB) [29], [55], [75], [76], dodecyl trimethylammonium bromide (DTAB), and sodium octanoate (SOCT) [77] are a few surfactants that have been employed in literature. Surfactant can be added to nanoparticle surfaces to change them and improve their interactions with the base fluid [7]. Figure 2 illustrates what will happen if there is an excess of surfactant at the surface of nanoparticles: double chains will develop, having an adverse effect.

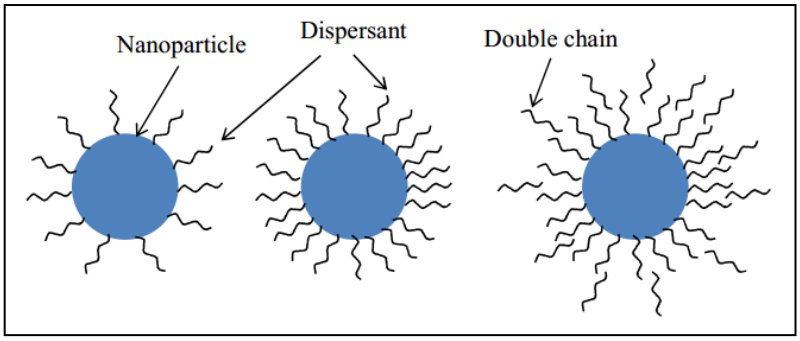


Figure 2. Effect of surfactant on surface modification of nanoparticles [7].

Cetyltrimethylammoniumbromide (CTAB) is one of the favorable surfactants among the researchers [29], [55], [75], [76]. Silica and alumina nanofluid sedimentation is typically avoided by using CTAB. CTAB was chosen because it has an oil-in-water emulsion that may be mixed with oil and has an HLB value of 12.3. The CTAB reagent is cationic. Figure 3 depicts the structure of the CTAB molecule. Timofeeva *et al.* [78] tested cationic surfactant, CTAB as surfactant to disperse 15 nm silicon dioxide in synthetic oil. The researchers came out with the suspension with no surfactant having significantly large agglomerate, while adding CTAB just provided some reduction in the average agglomerated size. Atiya *et al.* [31] used CTAB surfactant in nanofluid preparation to enhance the dispersion behaviour. Regarding the results obtained, they examine the dispersion of nanoparticles using various concentrations of CTAB and found that the addition of CTAB had improved the dispersion of nanoparticles in nanofluids. In comparison to examples without surfactant or with excessive amounts of surfactant, lower CTAB concentrations led to less agglomerated nanoparticles and a good degree of dispersion.

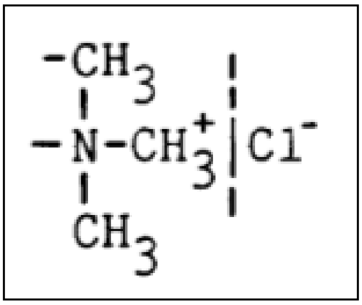


Figure 3. Molecule structure of Cetyl Trimethyl Ammonium Bromide (CTAB) [79].

12.0 SURFACE MODIFICATION BY USING COLD ATMOSPHERIC PRESSURE PLASMA TREATMENT

Low-ionization, non-equilibrium plasmas, also known as cold plasmas or low-temperature plasmas, are predominantly made up of electrons, ions, free radicals, and electronically excited atomic and molecular species [80]. Cold atmospheric pressure plasmas (APP) are applied in many areas, such as the generation of nano-sized nanoparticles treatment. They have also recently attracted a lot of interest and are frequently utilised in technologies like thin-film deposition and surface treatment [81], [82]. Previous research established that the structure of the materials is not significantly altered by the plasma. Earlier, many researchers used low-pressure plasma (LPP) treatment for surface modification. Unfortunately, due to the expensive vacuum and pump systems, aside from complicated procedures, there have been some rapid developments mainly over the last two decades. Since non-equilibrium cold atmospheric plasmas are now an alternative to proven low-pressure plasma systems, expensive equipment is no longer required for vacuum-based plasma treatment [83]. A portion of the gas particles in a neutral gas can be transformed (ionised) into charged particles to create plasma when power is applied to the gas. Plasmas can be created under a variety of circumstances, and it is interesting that one of the crucial factors in plasma treatment is gas pressure. The type of power and gas consumption affects the characteristics of plasmas, such as the energy and densities of charged particles.

The most widely used cold atmospheric plasma source is dielectric barrier discharge (DBD), which combines non-equilibrium plasma features with straightforward atmospheric-pressure operation. Streamers can be suppressed and prevented by a dielectric barrier at one or both electrodes in conjunction with high frequency power. Since more than a century ago, it has been acknowledged that alternative designs, architectures, electrode shapes, and dielectric barriers can be used with DBD sources for varied applications [84].

12.1 Surface Modification using Atmospheric Pressure Plasma in High Voltage Application

In high voltage application, Yan [85] developed atmospheric-pressure plasma (APP) system by modifying the surface of the silica nanoparticles generated by gaseous discharges in order to fabricate nanocomposites with advanced dielectric and electrical insulation properties. Additionally, the APP provided an effective, economic, and environmentally friendly approach for surface modification. The researcher stated that plasmas are electrically neutral but conductive as a whole and exhibits collective behaviors. In such processes, electrical field is applied to ionize the working gases. Electrons can accelerate quickly since they have much lesser weight, resulting in increased kinetic energy which is faster than ions, henceforth can obtain lower ion temperature.

Additionally, Yan *et al.* [66] revealed that silica nanoparticles' surface energy and reactivity can be successfully increased by cold atmospheric-pressure plasmas, thus will lead to a better dispersion uniformity of nanoparticles, reduction of weak bonds, and stronger chemical bonds between the base material and treated nanoparticles. Another research, conducted by Musa *et al.* [86] also showed the same result. In comparison to the other surface treatment techniques that were used in the study, the plasma treated samples showed the best results in nanocomposites. Besides, it was proven that plasma-treated samples contribute to less and smaller number of agglomerated nanoparticles. Thus, atmospheric-pressure plasmas can replace existing treatment methods which use chemical substances and whose procedures are complicated hence not suitable for mass production by high voltage applications.

12.2 Previous Works on Plasma Treatment of Nanoparticles in Nanofluids

In order to generate a stable suspension, plasma-treated nanoparticles with desired surface functions engage aggressively along the molecules of the base fluid. Figure 4 shows the impact of non-equilibrium plasma treatment on the surfaces of materials. Low-temperature plasmas can be utilized to treat nanoparticles for use in nanofluids. The most difficult and important problems in nanofluids are nanoparticle agglomeration and nanoparticles' poor stability during dispersion in base fluid, which will gradually reduce the final product's quality, including its reliability, thermal conductivity, electrical properties, and viscosity. Because of their propensity to clump together, aggregated nanoparticles decrease the stability of the suspension of nanofluids.

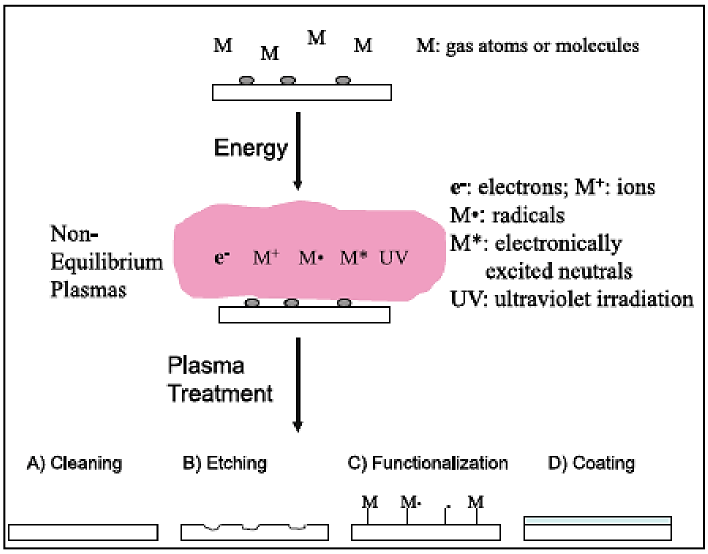


Figure 4. Plasma treatment effects on materials surfaces [80].

Prior researchers were successful in achieving homogeneous dispersion and stable nanoparticle suspension by using a range of surfactants [87]. However, a substantial problem could arise if the excess surfactants considerably change the viscosity and thermal conductivity of the nanofluids. By treating the surface of the nanoparticles without the use of surfactants, plasma treatment of nanoparticles offers a novel and promising method for the production of well-dispersed and stable suspension heat transfer nanofluids [80].

By using a plasma arc nanoparticle synthesis apparatus, Teng *et al.* [88] investigated the production and characterisation of carbon nanofluid. This project produced a nanofluid of carbon nanoparticles suspended in distilled water using plasma arc technology. In one phase of the synthesis, carbon was heated and vaporised simultaneously in the chamber. The carbon vapour and particles were moved to a collector, where they were cooled to create the required carbon/water nanofluid. A light-scattering size analyser, a SEM, and a TEM were used to determine the particle size and shape. The produced nanofluid behaved well in suspension, therefore there was no obvious need for dispersants. At different temperatures, viscosity, density, and electric conductivity were all tested. In comparison to pure water, the carbon/water nanofluid's thermal conductivity rose to roughly 25 % at 50 °C. They came to the conclusion that the manufacturing device may eventually generate nanofluid made of a range of materials.

Chang *et al.* [89] produced an Al_2O_3 nanofluid with good suspension stability using a modified plasma arc method. This technology uses a plasma arc system's high temperature to heat and vaporise the bulk metal. The induction mechanism introduces the vaporised metallic gas into the collection piping. The consistency of the nanofluid Al_2O_3 in suspension at various pH values was examined in the study using zeta potential. Using a UV-Vis spectrophotometer, the Al_2O_3 nanofluid's absorption characteristics were studied. The study produced a number of findings, chief among them the fact that the nanofluid created using this technique can last for longer than six months. As a result, the nanofluid is already electrostatically stable before utilising the solution to change its pH value. Additionally, it was shown that when combined with 92 octane unleaded gas, aluminium oxide powder with smaller particle size might produce a better combustion efficacy. Applying a 3% concentration will improve combustion performance.

Aluminium-oxide brake nanofluids were prepared using plasma charging system by Kao *et al.* [90]. As to produce plasma electric arc continuously, argon was the source of plasma gas, because it only requires low voltage, and it can easily be ionized. The alumina nanoparticles were vaporized using plasma system with high temperature from the instantly extracted plasma electric arc. The prepared nanofluids contributed to increase of boiling point and higher thermal conductivity, along with stable and uniform dispersion of nanoparticles in base fluid. Other researchers investigated copper-oxide brake nanofluid with synthesized CuO nanoparticles, and found that the nanofluid had improved the overall performance [91].

Ambrico *et al.* [92] produced plasma-treated alumina-based nanofluid and studied its electrical properties. The alumina nanoparticles were dried for 1 hour at temperature of 1073 K and then left for 24 hours at room temperature. Small amount of alumina nanoparticles was placed on the ceramics plasma area and covered with alumina plate to avoid them from being blown by the plasma gas in the chamber. Three types of plasma gas were used, which were He:N_2 mixture with input power of 300 W, and N_2 and Ar with input power of 60 W. They concluded that the thermally activated process, which had an impact on the plasma-generated electron traps, was the cause of the glow peak. The suspension of AC impedance, conductivity, and permittivity of nanofluids can be modified by DBD plasma treatment using selected plasma gas as mentioned above.

Kim *et al.* [93] treated the surface of nanoparticles and nanotubes of carbon using cold plasma. This simple plasma treatment was utilised to create a very thin plasma coating and then modify the surface properties. They asserted that plasma-treated nanoparticles with desirable surface functions might interact significantly with water molecules, improving nanofluid suspension stability and dispersion characteristics. The surface functionalities of plasma-treated nanoparticles can be determined using FTIR. This work also reported that higher treatment time than 60 minutes resulted in decreased thermal conductivity. This can be as a result of the effects of excessive plasma therapy. The researchers also claimed there was no phase separation in the nanofluid with plasma-treated nanoparticle after 45 days of sediment test. The settling time of plasma-treated nanofluid showed very little change compared to the untreated nanofluid although with that significant decreasing trend. Nonetheless, it is noteworthy that the well-dispersed plasma-treated nanoparticles in nanofluids had improved the thermal conductivity owing to the polar surface functions are introduced by plasma treatment.

13.0 CONCLUSION

Physical and chemical properties of nanoparticle surfaces can be altered by plasma, and these properties may be used to improve how well nanofluids insulate. There is a wide range of possible industrial uses for atmospheric-pressure plasmas. Plasma treatment could result in a more powerful interaction between the base material and the nanoparticles. It encourages addressing agglomeration problems in nanomixtures by altering the surface of the nanofillers using thermal non-equilibrium atmospheric-pressure plasma. A stable suspension can be created by strong interactions between plasma-treated nanoparticles with appropriate surface functions and liquid molecules that have been more effectively disseminated into the base fluid. In order to improve the surface of the nanoparticles' compatibility with mineral oil and to provide a better connection between the nanoparticles and transformer oil, cool atmospheric pressure plasma is frequently applied. Additionally, the use of surfactants can be reduced or removed, enhancing one of the key characteristics of transformer oil-based nanofluids. To increase the thermal and electrical properties, such as breakdown strength and partial discharge characteristics, the performance of transformer oil based on plasma-treated nanoparticles must be studied.

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References

[1] Fluids for Electrotechnical Applications - Unused Mineral Insulating Oils for Transformers and Switchgear, IEC 60296:2012, *International Electrotechnical Commission*, Geneva, Switzerland, Feb. 20, 2012.

[2] R. Wiken, "Plasma Treatment of Microparticles and Nanoparticles at Atmospheric Pressure Permits New Materials and Applications," *Annual Report of Advanced Materials (IFAM)*, pp. 109-113, 2010.

[3] H. Jin, T. Andritsch, I. A. Tsekmes, R. Kochetov, P. H. F. Morshuis, and J. J. Smit, “Properties of Mineral Oil based Silica Nanofluids,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 3, pp. 1100–1108, 2014.

[4] M. Mehrali *et al.*, “Investigation of Thermal Conductivity and Rheological Properties of Nanofluids Containing Graphene Nanoplatelets,” *Nanoscale Res. Lett.*, vol. 9, no. 1, 2014.

[5] R. Karthik, T. S. R. Raja, and R. Madavan, “Enhancement of Critical Characteristics of Transformer Oil Using Nanomaterials,” *Arab. J. Sci. Eng.*, vol. 38, no. 10, pp. 2725–2733, 2013.

[6] M. Dong, L. P. Shen, H. Wang, H. B. Wang, and J. Miao, “Investigation on the Electrical Conductivity of Transformer Oil-Based Aln Nanofluid,” *J. Nanomater.*, vol. 2013, pp. 1–7, 2013.

[7] D.-E. A. Mansour, E. G. Atiya, R. M. Khattab, and A. M. Azmy, “Effect of Titania Nanoparticles on the Dielectric Properties of Transformer Oil-Based Nanofluids,” in *2012 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, 2012.

[8] H. Jin, T. Andritsch, P. H. F. Morshuis, and J. J. Smit, “AC Breakdown Voltage and Viscosity of Mineral Oil Based SiO_2 Nanofluids,” in *2012 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, 2012.

[9] D.-E. A. Mansour and A. M. Elsaeed, “Heat Transfer Properties of Transformer Oil-Based Nanofluids Filled with Al_2O_3 Nanoparticles,” in *2014 IEEE International Conference on Power and Energy (PECon)*, 2014.

[10] V. Sridhara and L. N. Satapathy, “Al_2O_3-based Nanofluids : A Review,” *Nanoscale Res. Lett.*, vol. 6, no. 1, 2011.

[11] R. M. Mostafizur, R. Saidur, A. R. Abdul Aziz, and M. H. U. Bhuiyan, “Thermophysical Properties of Methanol-based Al_2O_3 Nanofluids,” *Int. J. Heat Mass Transf.*, vol. 85, pp. 414–419, 2015.

[12] R. Wang, S. Qian, and Z. Zhang, “Investigation of the aggregation morphology of nanoparticle on the thermal conductivity of nanofluid by molecular dynamics simulations,” *Int. J. Heat Mass Transf.*, vol. 127, pp. 1138–1146, 2018.

[13] M. Borzuei and Z. Baniamerian, “Role of nanoparticles on critical heat flux in convective boiling of nanofluids: Nanoparticle sedimentation and Brownian motion,” *Int. J. Heat Mass Transf.*, vol. 150, no. 119299, p. 119299, 2020.

[14] F. Yu *et al.*, “Dispersion stability of thermal nanofluids,” *Prog. Nat. Sci.*, vol. 27, no. 5, pp. 531–542, 2017.

[15] O. Arthur and M. A. Karim, “An investigation into the thermophysical and rheological properties of nanofluids for solar thermal applications,” *Renew. Sustain. Energy Rev.*, vol. 55, pp. 739–755, 2016.

[16] A. Zaraki, M. Ghalambaz, A. J. Chamkha, M. Ghalambaz, and D. De Rossi, “Theoretical analysis of natural convection boundary layer heat and mass transfer of nanofluids: Effects of size, shape and type of nanoparticles, type of base fluid and working temperature,” *Adv. Powder Technol.*, vol. 26, no. 3, pp. 935–946, 2015.

[17] S. Shrestha, B. Wang, and P. Dutta, “Nanoparticle processing: Understanding and controlling aggregation,” *Adv. Colloid Interface Sci.*, vol. 279, no. 102162, p. 102162, 2020.

[18] J. S. Basha and R. B. Anand, “Applications of Nanoparticle/Nanofluid in Compression Ignition Engines - A Case Study.,” *International Journal of Applied Engineering Research*, vol. 5, no. 4, pp. 697–708, 2010.

[19] Y. Zhai, Y. Li, Z. Xuan, Z. Li, and H. Wang, “Determination of heat transport mechanism using nanoparticle property and interfacial nanolayer in a nanofluidic system,” *J. Mol. Liq.*, vol. 344, no. 117787, p. 117787, 2021.

[20] Z. Jian-quan, D. Yue-fan, C. Mu-tian, L. Cheng-rong, L. Xiao-xin, and L. Yu-zhen, “AC and lightning breakdown strength of transformer oil modified by semiconducting nanoparticles,” in *2011 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, 2011.

[21] N. A. C. Sidik, H. A. Mohammed, O. A. Alawi, and S. Samion, “A review on preparation methods and challenges of nanofluids,” *Int. Commun. Heat Mass Transf.*, vol. 54, pp. 115–125, 2014.

[22] M. Rafiq, Y. Lv, and C. Li, “A review on properties, opportunities, and challenges of transformer oil-based nanofluids,” *J. Nanomater.*, vol. 2016, pp. 1–23, 2016.

[23] H. Zhang, S. Qing, J. Xu, X. Zhang, and A. Zhang, “Stability and thermal conductivity of TiO_2/water nanofluids: A comparison of the effects of surfactants and surface modification,” *Colloids Surf. A Physicochem. Eng. Asp.*, vol. 641, no. 128492, p. 128492, 2022.

[24] R. A. Farade *et al.*, “Investigation of the effect of sonication time on dispersion stability, dielectric properties, and heat transfer of graphene-based green nanofluids,” *IEEE Access*, vol. 9, pp. 50607–50623, 2021.

[25] J. Ji, Y. Wang, X. Lin, B. Liu, and X. Zhang, “Fabrication of highly thermal conductive and shape-stabilized phase change materials,” *J. Energy Storage*, vol. 44, no. 103256, p. 103256, 2021.

[26] K. N. Koutras, I. A. Naxakis, A. E. Antonelou, V. P. Charalampakos, E. C. Pyrgioti, and S. N. Yannopoulos, “Dielectric strength and stability of natural ester oil based TiO_2 nanofluids,” J. Mol. Liq., vol. 316, no. 113901, p. 113901, 2020.

[27] Y. Lv, Y. Zhou, C. Li, Q. Wang, and B. Qi, “Recent progress in nanofluids based on transformer oil: preparation and electrical insulation properties,” *IEEE Electr. Insul. Mag.*, vol. 30, no. 5, pp. 23–32, 2014.

[28] W. Yu and H. Xie, “A review on nanofluids: Preparation, stability mechanisms, and applications,” *J. Nanomater.*, vol. 2012, pp. 1–17, 2012.

[29] Z. Haddad, C. Abid, H. F. Oztop, and A. Mataoui, “A review on how the researchers prepare their nanofluids,” *Int. J. Therm. Sci.*, vol. 76, pp. 168–189, 2014.

[30] Y. Hwang *et al.*, “Production and dispersion stability of nanoparticles in nanofluids,” *Powder Technol.*, vol. 186, no. 2, pp. 145–153, 2008.

[31] E. G. Atiya, D.-E. A. Mansour, R. M. Khattab, and A. M. Azmy, “Dispersion behavior and breakdown strength of transformer oil filled with TiO_2 nanoparticles,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2463–2472, 2015.

[32] R. Saidur, K. Y. Leong, and H. A. Mohammed, “A review on applications and challenges of nanofluids,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 3, pp. 1646–1668, 2011.

[33] C. Choi, H. S. Yoo, and J. M. Oh, “Preparation and heat transfer properties of nanoparticle-in-transformer oil dispersions as advanced energy-efficient coolants,” *Curr. Appl. Phys.*, vol. 8, no. 6, pp. 710–712, 2008.

[34] M. Rafiq, D. Khan, and M. Ali, “Insulating properties of transformer oil-based silica nanofluids,” in *2015 Power Generation System and Renewable Energy Technologies (PGSRET)*, 2015.

[35] Y. Lv *et al.*, “Nanoparticle effect on dielectric breakdown strength of transformer oil-based nanofluids,” in *2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, 2013.

[36] M. Rafiq, C. Li, Y. Lv, K. Yi, and I. Arif, “Breakdown characteristics of transformer oil-based silica nanofluids,” in *2016 19th International Multi-Topic Conference (INMIC)*, 2016.

[37] Y. Lv, M. Rafiq, C. Li, and B. Shan, “Study of dielectric breakdown performance of transformer oil based magnetic nanofluids,” *Energies*, vol. 10, no. 7, p. 1025, 2017.

[38] J.-C. Lee and W.-Y. Kim, “Experimental study on the dielectric breakdown voltage of the insulating oil mixed with magnetic nanoparticles,” *Phys. Procedia*, vol. 32, pp. 327–334, 2012.

[39] B. Du, J. Li, B.-M. Wang, and Z.-T. Zhang, "Preparation and Breakdown Strength of Fe_3O_4 Nanofluid Based on Transformer Oil," in *2012 International Conference on High Voltage Engineering and Application*, 2012.
[40] D. Yue-fan, L. Yu-zhen, Z. Jian-quan, L. Xiao-xin, and L. Cheng-rong, "Breakdown Properties of Transformer Oil-based TiO_2 Nanofluid," in *2010 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, 2010.
[41] D. Jianzhuo, D. Ming, W. Li, L. Yang, and W. Jianyi, "Study on AC breakdown and broadband dielectric response properties of transformer oil-based nanofluids," in *2016 International Conference on Condition Monitoring and Diagnosis (CMD)*, 2016.
[42] M. Z. H. Makmud, H. A. Illias, and C. Y. Chee, "Partial discharge behaviour within palm oil-based Fe_2O_3 nanofluids under AC voltage," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 210, p. 012034, 2017.
[43] D. Prasad and S. Chandrasekar, "Effect of Nano-SiO_2 Particles on Partial Discharge Signal Characteristics of FR3 Transformer Oil," *J. Adv. Chem.*, vol. 13, pp. 6208–6217, 2017.
[44] Y. Li, J. Y. Wen, Y. Liang, J. Wu, S. Qin, and G.-J. Zhang, "Streamer discharge propagation and branching characteristics in transformer oil under AC voltage: Partial discharge and light emission," in *2017 IEEE 19th International Conference on Dielectric Liquids (ICDL)*, 2017.
[45] M. Pompili, C. Mazzetti, and R. Bartnikas, "PD pulse burst characteristics of transformer oils," *IEEE Trans. Power Deliv.*, vol. 21, no. 2, pp. 689–698, 2006.
[46] H. Jin, P. Morshuis, A. R. Mor, J. J. Smit, and T. Andritsch, "Partial discharge behavior of mineral oil based nanofluids," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2747–2753, 2015.
[47] H. Jin, P. H. F. Morshuis, A. R. Mor, and T. Andritsch, "An investigation into the dynamics of partial discharge propagation in mineral oil based nanofluids," in *2014 IEEE 18th International Conference on Dielectric Liquids (ICDL)*, 2014.
[48] M. R. Ramli *et al.*, "Partial discharge characteristics of palm fatty acid ester (PFAE) as high voltage insulating material," in *2nd IEEE Conference on Power Engineering and Renewable Energy (ICPERE) 2014*, 2014.
[49] U. Khayam, Suwarno, A. Susilo, J. Muslim, Y. Z. Arief, and M. Hikita, "Partial discharge characteristics and dissolved gas analysis of vegetable oil," in *Proceedings of 2014 International Symposium on Electrical Insulating Materials*, 2014.
[50] P. Muangpratoom and N. Pattanadech, "Breakdown and Partial discharge characteristics of Mineral oil-based nanofluids," *IET Sci. Meas. Technol.*, vol. 12, no. 5, pp. 609–616, 2018.
[51] M. Makmud, H. Illias, C. Chee, and S. Dabbak, "Partial discharge in nanofluid insulation material with conductive and semiconductive nanoparticles," *Materials (Basel)*, vol. 12, no. 5, p. 816, 2019.
[52] M. Rafiq *et al.*, "Insulating and aging properties of transformer oil-based TiO_2 nanofluids," in *2014 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, 2014.
[53] F. Herchl *et al.*, "Breakdown and partial discharges in magnetic liquids," *J. Phys. Condens. Matter*, vol. 20, no. 20, p. 204110, 2008.
[54] H. Jin, "Dielectric Strength and Thermal Conductivity of Mineral Oil-based Nanofluids," Master dissertation, Delft University of Technology, 2015.
[55] D.-E. A. Mansour and E. G. Atiya, "Application of UV/Vis spectroscopy to assess the stability of oil-based nanofluids," in *2016 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, 2016.
[56] H. Setia, R. Gupta, and R. K. Wanchoo, "Stability of Nanofluids," *Mater. Sci. For.*, vol. 757, pp. 139–149, 2013.
[57] L. Jiang, L. Gao, and J. Sun, "Production of aqueous colloidal dispersions of carbon nanotubes," *J. Colloid Interface Sci.*, vol. 260, no. 1, pp. 89–94, 2003.
[58] G. Shukla and H. Aiyer, "Thermal conductivity enhancement of transformer oil using functionalized nanodiamonds," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 4, pp. 2185–2190, 2015.
[59] S. Mukherjee, "Preparation and stability of nanofluids-A review," *IOSR J. Mech. Civ. Eng.*, vol. 9, no. 2, pp. 63–69, 2013.
[60] A. Ghadimi, H. S. C. Metselaar, and B. LotfizadehDehkordi, "Nanofluid stability optimization based on UV-Vis spectrophotometer measurement," *Journal of Engineering Science and Technology*, vol. 7, no. 1, pp. 32–40, 2015.
[61] S. Sagadevan and S. Shanmugam, "A study of preparation, structural, optical, and thermal conductivity properties of zinc oxide nanofluids," *J. Nanomed. Nanotechnol.*, vol. s6, 2015.
[62] N. Ali, J. A. Teixeira, and A. Addali, "A review on nanofluids: Fabrication, stability, and thermophysical properties," *J. Nanomater.*, vol. 2018, pp. 1–33, 2018.
[63] R. Sadeghi, S. G. Etemad, E. Keshavarzi, and M. Haghshenasfard, "Investigation of alumina nanofluid stability by UV–vis spectrum," *Microfluid. Nanofluidics*, vol. 18, no. 5–6, pp. 1023–1030, 2015.
[64] T. V. Oommen, "Vegetable oils for liquid-filled transformers," *IEEE Electr. Insul. Mag.*, vol. 18, no. 1, pp. 6–11, 2002.
[65] A. Ghadimi, R. Saidur, and H. S. C. Metselaar, "A review of nanofluid stability properties and characterization in stationary conditions," *Int. J. Heat Mass Transf.*, vol. 54, no. 17–18, pp. 4051–4068, 2011.
[66] W. Yan, Z. J. Han, B. T. Phung, and K. Ostrikov, "Silica nanoparticles treated by cold atmospheric-pressure plasmas improve the dielectric performance of organic–inorganic nanocomposites," *ACS Appl. Mater. Interfaces*, vol. 4, no. 5, pp. 2637–2642, 2012.
[67] A. H. Askar, S. A. Kadhim, and S. H. Mshehid, "The surfactants effect on the heat transfer enhancement and stability of nanofluid at constant wall temperature," *Heliyon*, vol. 6, no. 7, p. e04419, 2020.
[68] J. Dong, Q. Zheng, C. Xiong, E. Sun, and J. Chen, "Experimental investigation and application of stability and thermal characteristics of SiO_2-ethylene-glycol/water nanofluids," *Int. J. Therm. Sci.*, vol. 176, no. 107533, p. 107533, 2022.
[69] M. Singh and L. Kundan, "Experimental Study on Thermal Conductivity and Viscosity of Al_2O_3-Nanotransformer Oil," *International Journal on Theoretical and Applied Research in Mechanical Engineering (IJTARME) Nanofluids*, Vol. 2, No. 3, pp. 125-130, 2013.
[70] H. Younes, M. Mao, S. M. Sohel Murshed, D. Lou, H. Hong, and G. P. Peterson, "Nanofluids: Key parameters to enhance thermal conductivity and its applications," *Appl. Therm. Eng.*, vol. 207, no. 118202, p. 118202, 2022.
[71] J. J. Taha-Tijerina, " Multifuctional Nanofluids with 2D Nanosheets for Thermal Management and Tribological Applications," Ph.D. dissertation, Rice University, Houston, USA, 2013.
[72] P. Hu, W.-L. Shan, F. Yu, and Z.-S. Chen, "Thermal conductivity of AlN–ethanol nanofluids," *Int. J. Thermophys.*, vol. 29, no. 6, pp. 1968–1973, 2008.
[73] Y. Hwang *et al.*, "Stability and thermal conductivity characteristics of nanofluids," *Thermochim. Acta*, vol. 455, no. 1–2, pp. 70–74, 2007.
[74] D. Zhu, X. Li, N. Wang, X. Wang, J. Gao, and H. Li, "Dispersion Behavior and Thermal Conductivity Characteristics of Al_2O_3-H_2O Nanofluids," *Curr. Appl. Phys.*, vol. 9, no. 1, pp. 131–139, 2009.
[75] V. Fuskele and R. M. Sarviya, "Recent developments in nanoparticles synthesis, preparation and stability of nanofluids," *Mater. Today*, vol. 4, no. 2, pp. 4049–4060, 2017.
[76] S. M. S. Murshed, K. C. Leong, and C. Yang, "Investigations of thermal conductivity and viscosity of nanofluids," *Int. J. Therm. Sci.*, vol. 47, no. 5, pp. 560–568, 2008.
[77] B. Sohrabi, N. Poorgholami-Bejarpasi, and N. Nayeri, "Dispersion of carbon nanotubes using mixed surfactants: Experimental and molecular dynamics simulation studies," *J. Phys. Chem. B*, vol. 118, no. 11, pp. 3094–3103, 2014.
[78] E. V. Timofeeva, M. R. Moravek, and D. Singh, "Improving the heat transfer efficiency of synthetic oil with silica nanoparticles," *J. Colloid Interface Sci.*, vol. 364, no. 1, pp. 71–79, 2011.

[79] Q. Yu, Y. Ye, and J. D. Miller, "A study of surfactant/oil emulsions for fine coal flotation," in *Advances in Fine Particles Processing*, Boston, MA: Springer US, pp. 345–355, 1990.
[80] Y. J. Kim, Q. Yu, and H. Ma, "Plasma Treatment of Nanoparticles for Nanofluids," in *Encyclopedia of Microfluidics and Nanofluidics*, Boston, MA: Springer US, pp. 1691–1699, 2008.
[81] T. C. Corke, M. L. Post, and D. M. Orlov, "Single dielectric barrier discharge plasma enhanced aerodynamics: physics, modelling and applications," *Exp. Fluids*, vol. 46, no. 1, pp. 1–26, 2009.
[82] Z. Fang, Y. Qiu, and E. Kuffel, "Formation of hydrophobic coating on a glass surface using atmospheric pressure non-thermal plasma in ambient air," *J. Phys. D Appl. Phys.*, vol. 37, no. 16, pp. 2261–2266, 2004.
[83] L. Bárdos and H. Baránková, "Cold atmospheric plasma: Sources, processes, and applications," *Thin Solid Films*, vol. 518, no. 23, pp. 6705–6713, 2010.
[84] U. Kogelschatz, "Dielectric-Barrier Discharges: Their History, Discharge Physics, and Industrial Applications," *Plasma Chem. Plasma Process.*, vol. 23, no. 1, pp. 1–46, 2003.
[85] W. Yan, "Nanocomposite Dielectric Materials for Power System Equipment," Ph.D. Thesis. The University of New South Wales, Australia, 2013.
[86] F. Musa, N. Bashir, M. Ahmad, Z. Buntat, and M. Piah, "Investigating the influence of plasma-treated SiO_2 nanofillers on the electrical treeing performance of silicone-rubber," *Appl. Sci. (Basel)*, vol. 6, no. 11, p. 348, 2016.
[87] C. Gao, F. Lyu, and Y. Yin, "Encapsulated metal nanoparticles for catalysis," *Chem. Rev.*, vol. 121, no. 2, pp. 834–881, 2021.
[88] T.-P. Teng, C.-M. Cheng, and F.-Y. Pai, "Preparation and characterization of carbon nanofluid by a plasma arc nanoparticles synthesis system," *Nanoscale Res. Lett.*, vol. 6, no. 1, 2011.
[89] H. Chang and Y.-C. Chang, "Fabrication of Al_2O_3 nanofluid by a plasma arc nanoparticles synthesis system," J. Mater. Process. Technol., vol. 207, no. 1–3, pp. 193–199, 2008.
[90] M-J. Kao *et al.* "Producing aluminium-oxide brake nanofluids using plasma charging system," *J. Chin. Soc. Mech. Eng.*, vol. 28, no. 2, pp. 195–200, 2007.
[91] M. J. Kao, C. H. Lo, T. T. Tsung, Y. Y. Wu, C. S. Jwo, and H. M. Lin, "Copper-oxide brake nanofluid manufactured using arc-submerged nanoparticle synthesis system," *J. Alloys Compd.*, vol. 434–435, pp. 672–674, 2007.
[92] M. Ambrico, T. Morávek, P. F. Ambrico, and J. Ráhel, "Tuning the water-alumina nanofluids impedance and dielectric relaxation by the diffuse coplanar dielectric barrier discharge," *Powder Technol.*, vol. 340, pp. 570–577, 2018.
[93] Y. J. Kim, Q. Yu, and H. Ma, "Plasma treatment of nanoparticles and carbon nanotubes for nanofluids," in *Encyclopedia of Microfluidics and Nanofluidics*, Boston, MA: Springer US, pp. 1–17, 2013.