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Influence of metal particles shape on direct current voltage electric properties of nanofluids

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ABSTRACT

It is widely recognized that the application of nanoparticles has the potential to improve the dielectric properties of transformer oil. Nevertheless, there is a scarcity of studies that have utilized pure nanofluids, and in practical applications, it is inevitable for transformer oil to become contaminated. Therefore, this study conducted tests to investigate how the shape and size of metal contaminants impact the dielectric performance of Fe_3O_4 nanofluids. The findings from the levitation voltage test indicate that as the size and diameter of the particle increase, the levitation voltage value measured also increases, and conversely. Moreover, a higher concentration of nanoparticles leads to a higher measured levitation voltage value. On the other hand, the breakdown voltage test results demonstrate that larger and sharper particles result in lower measured breakdown voltage values, and vice versa. The simulation outcomes regarding electric field distribution reveal that larger and sharper particles correspond to higher measured electric field values, while the opposite is true for smaller and less sharp particles.

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1. INTRODUCTION

Transformers play a crucial role in transmission and electric power distribution systems. One of the essential components of transformers is transformer oil, which serves as both an insulation material and a coolant [1]. However, transformer oil is prone to contamination, which can lead to a reduction in its dielectric strength. Consequently, various endeavors have been undertaken to enhance the performance of insulating oil.

Researchers are currently exploring the potential of incorporating nanoparticle materials into oil-insulating materials to create nanofluids as a solution to the issue. Nanofluids are widely accepted as ideal liquid media due to their dielectric properties and heat-exchange efficiency [2]–[4]. This approach aims to enhance the dielectric strength, thereby delaying the spread of streamers. Nanoparticles utilize various mechanisms to impede the advancement of streamers, effectively trapping electrons by generating charges and functioning as electron-absorbent materials if the rate of charge relaxation surpasses the rate of streamer growth [5], [6].

Numerous studies have been conducted to assess the impact of nanoparticle additives on the dielectric properties of nanofluids. Chen *et al.* [7] discovered that the introduction of Al_2O_3, Fe_3O_4, and TiO_2 nanoparticles resulted in an increase in the lightning impulse breakdown voltage value at a 50% probability. Specifically, the breakdown voltage values for pure mineral oil increased by 15.68%, 7.25%, and 44.52% respectively. Furthermore, a study involving the combination of two types of nanoparticles revealed that a mixture comprising 20% Fe_3O_4 nanoparticles and 80% nanoparticles of SiO_2 led to a significant 92.78% increase in the breakdown voltage value of mineral oil [8].

Typically, investigations pertaining to nanofluids are primarily focused on their pure state, while transformer oil remains vulnerable to impurities under current circumstances. Among the various contaminants, metal particles pose a significant concern, originating from various sources such as deteriorating windings, iron core, transformer body, or particles introduced during installation or maintenance procedures [9]–[11]. Various research investigations have delved into the influence of metal particles on the electrical properties of transformer oils. The primary emphasis of these studies was on the partial discharge (PD) and breakdown properties of spherical particles when subjected to a uniform or quasi-uniform electric field within mineral oil. Li *et al.* [12] conducted a study to examine the effect of steel balls of varying sizes, with radius of 0.5, 0.75 and 1 mm under quasi-uniform electric field. The findings of the study revealed that the discharge amplitude significantly increases with the applied voltage, particularly for the larger particles. Research also conducted by Wang *et al.* [13] proved that the alternating current (AC) breakdown voltage value decreases linearly by 11% as the size of the metal particles increases. Sarathi and Archana [14] examined the PD activity by utilizing a 2 mm diameter aluminum ball immersed in oil. The experimental setup involved a sphere serving as the top electrode and a slightly concave dish acting as the bottom electrode. The findings of this investigation revealed that the voltage necessary for the particle to levitate and induce PD exhibited a positive correlation with the applied frequency.

This research paper emphasizes the lack of studies that specifically investigate nanofluids and their impact on transformer oil contaminants, particularly in terms of variations in shape and size. The main objective of this research was to examine the electrical properties of Fe_3O_4 nanofluids containing metal particles by subjecting them to direct current (DC) voltage. The primary objective of this study was to gain insight into how the presence of metal particles affects the electrical characteristics of mineral oil that has been modified with Fe_3O_4 nanoparticles. The experimental findings encompassed the breakdown voltage of the nanofluid as well as the initial voltage at which particle-initiated movement (levitation voltage) occurred. Additionally, simulations were conducted using finite element method (FEM) software to ascertain the distribution of the electric field in nanofluids contaminated with metal particles. The findings supporting this correlation have been presented and analyzed in a scholarly manner.

2. METHOD

2.1. Oil specifications

The parameters examined in the oil specifications include density, viscosity, flash point, pour point, and breakdown voltage. Each of these parameters is associated with the standards employed during the testing process. Furthermore, each specification parameter is linked to the performance of the oil as an insulator within transformers. The mineral oil specifications for this study are outlined in Table 1.

Table 1. Oil specifications

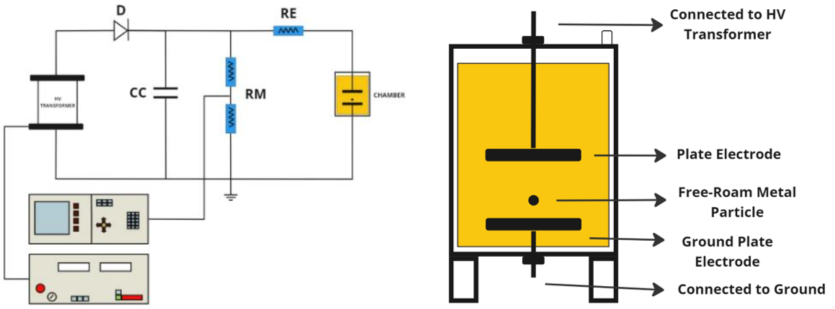
Properties	Standard	Value	Unit
Density	ISO 3675	0.866	Kg/m^3
Viscosity	ISO 3104	21	cSt
Flash point	ISO 2719	146	°C
Pour point	ISO 3016	-34	°C
Breakdown voltage	IEC 60156	30	kV

2.2. Testing setup

The research involved conducting levitation voltage and breakdown voltage tests under high DC voltage conditions. Figure 1(a) illustrates the configuration of the test setup employed in this study. To assess the impact of metal contaminants, nanofluids were tested using specialized test media, as depicted in Figure 1(b).

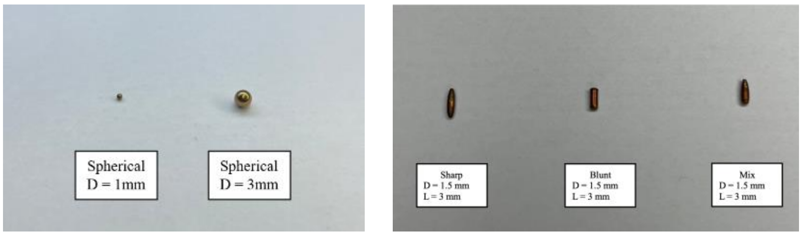
The objective of this experiment was to ascertain the influence of the shape and size of the metal particles on the electrical properties of the nanofluids. Spherical metal particles with diameters of 1 and 3 mm were utilized, along with cylindrical particles of varying sharpness, including sharp, blunt, and mixed types with a diameter (D) of 1.5 mm and a length (L) of 3 mm. Figure 2 presents an image of the metal particles employed in the study. Flat electrodes were used for the tests. A separation distance of 10 mm was maintained between each electrode to facilitate the visual observation of the metal particles within the oil.

Figure 2(a) shows two metal particles that are spherical in form, exhibiting a difference in diameter. In contrast, Figure 2(b) depicts three metal particles characterized by a cylindrical shape, each featuring distinct ends. The test procedure involved gradually increasing the supply voltage applied to the terminal electrode, while connecting the other electrode to the ground. The supply voltage was raised until the metal particles began to levitate, ultimately leading to the occurrence of a spark in the oil.



(a) (b)

Figure 1. Testing (a) circuit scheme and (b) chamber



(a) (b)

Figure 2. Metal particle (a) spherical and (b) cylinder

2.3. Preparation of Fe_3O_4 nanofluids

The nanofluid manufacturing process consisted of three main stages: mineral oil preconditioning, nanoparticle preconditioning, and nanofluid manufacturing. The first stage involves filtering mineral oil to remove contaminants that may affect its dielectric strength. Following the oil filtering process, the heated mineral oil was placed in a vacuum oven for 24 hours at a temperature of 100 °C to remove water and bubbles from the oil [15].

In the second stage, the nanoparticles underwent a drying process for 120 min at 200 °C to reduce the humidity. Once dried, the nanoparticles were weighed and mixed with the mineral oil using a stirring process. This ensured that the nanoparticles were evenly distributed throughout the oil. The stirring process was carried out for 60 min at a temperature of 50 °C to achieve a thorough mixture without introducing bubble contamination [16]. Table 2 displays the different concentrations of Fe_3O_4 nanoparticles blended with mineral oil.

Table 2. Nanoparticle concentration variations

Nanoparticle Concentration (g/l)	Oil Volume (ml)	Mass of Fe_3O_4 Nanoparticle (mg)	Sample Code
0	300	0	MO
0.1	300	30	MO/Fe-1
0.3	300	90	MO/Fe-2
0.4	300	120	MO/Fe-3

The final stage involved sonication, in which ultrasonic waves were utilized to enhance the dissolution and stability of the nanoparticles in the oil. This prevents the agglomeration of the nanoparticles. The sonication was performed for 120 min at a temperature of 30 °C [17]. The entire nanofluid production process is illustrated in Figure 3.

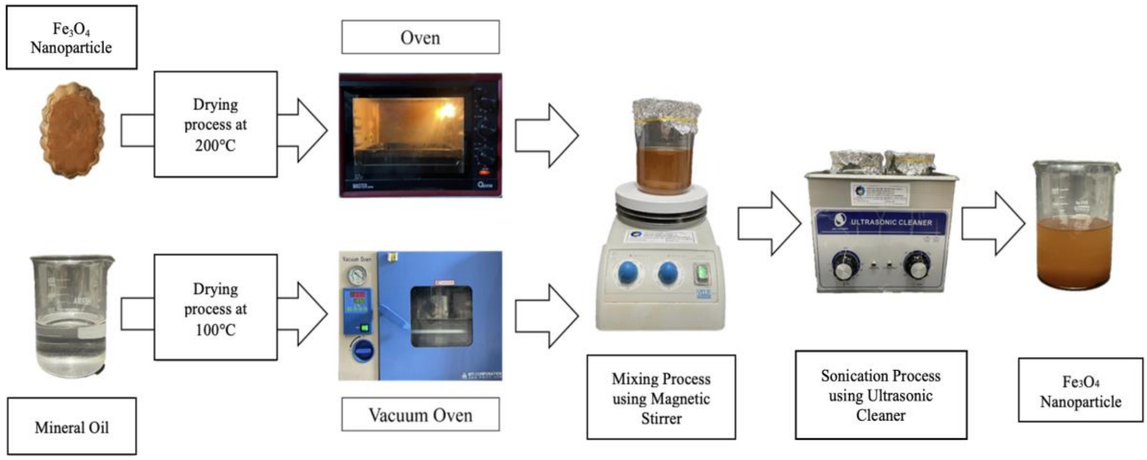


Figure 3. Fe_3O_4 nanofluid production process

2.4. Simulation setup

The impact of the form of contaminants on the breakdown voltage of oil was examined by investigating the electric-field distribution in nanofluids containing metal particles. Simulations were conducted on both spherical and cylindrical particles to gain a deeper understanding of how the intensity of the electric field influences the breakdown voltage. This study aimed to provide a more detailed analysis of the relationship between the form of contaminants and the breakdown voltage in nanofluids. FEM-based software was used to conduct these simulations. To accurately determine the electric field distribution, the required material parameter values should include mineral oil, nanofluids, electrodes, and metal particle contaminants [18].

The electrostatic module was utilized to generate physical quantities by arranging the aforementioned elements in a specific manner. This module simulated the electric fields, electric field displacements, and dielectric potential distributions of the materials employed.

$$F_e = kqE \tag{1}$$

Where q indicates the total charge quantity distributed on the particle surface, E is the applied field [19], [20].

The governing equations and boundary conditions play a crucial role in establishing the foundation of the model configuration, dictating the manner in which the physical phenomena are replicated within the specified geometric constraints and under prescribed circumstances. The formulations of the governing equation in this study are as (2):

$$\nabla . D = \rho_v \tag{2}$$

Maxwell's equation elucidates the correlation between the electric potential (V) and the electric flux density (D). This equation can be deduced from the interconnection between electric flux (D) and electric field strength (E).

$$\nabla . D = \rho_v \tag{3}$$

The relationship between the electric field (E) and the electric potential (V) in electrostatics is represented by the expression, where charges are stationary and there are no time-varying magnetic fields. The electric field is determined by the gradient of the electric potential, with the negative sign indicating that the electric field E moves towards decreasing electric potential V. Essentially, the electric field lines flow from areas of higher potential (positive charges) to lower potential (negative charges or regions where the potential decreases along the gradient) [21], [22].

Boundary conditions are set by defining the electric potential or electric field at the edges of the model geometry. The permittivity value, as indicated in Table 3, was used to characterize the material. Subsequently, mesh modeling was conducted, as illustrated in Figure 4, to enhance the resolution of spatial changes in the electric potential and improve the accuracy of calculating the electric field. Lastly, the fixed potential on the electrode was established by determining the voltage difference between the voltage electrode (with a specified voltage input) and the ground electrode (set at a voltage value of 0).

Table 3. Electric field values for spherical and cylindrical particles

Particle	Electric Field (kV/mm)
1 mm Spherical	6.318
3 mm Spherical	6.357
Sharp Cylinder	23.653
Blunt Cylinder	8.026
Mix Cylinder	24.335

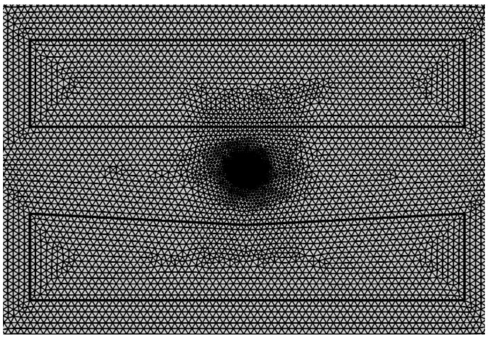


Figure 4. Mesh images of test objects

3. RESULTS AND DISCUSSION

3.1. Levitation voltage testing

The voltage at which metal particles in oil start to float or become suspended is known as the levitation voltage. This voltage represents the point at which the electrostatic force between the particle and the surrounding oil can counteract the gravitational force acting on the particle. To determine the levitation voltage, a series of tests was conducted on each particle using different nanoparticle concentrations. The tests were repeated five times and the average levitation voltage for each particle at varying concentrations was calculated.

Figure 5 illustrates a comparison between the average levitation voltages of spherical and cylindrical particles. The levitation voltage of the particles in the nanofluid oil was higher than that of the particles in the pure mineral oil. The levitation voltage values, arranged in descending order, were as follows: 3 mm spherical particles had the highest levitation voltage, followed by blunt cylinder particles, mixed cylinder particles, sharp cylinders, and finally, 1 mm spherical particles with the lowest levitation voltage. This indicates that there is a direct relationship between particle size and levitation voltage. Larger particles require greater force to counteract the gravitational force, resulting in higher levitation voltages. This observation aligns with the theoretical forecasts made by Tobazeon [23], which elucidate the correlation between the lifting fields (E_d) and the radius (R) of the particles.

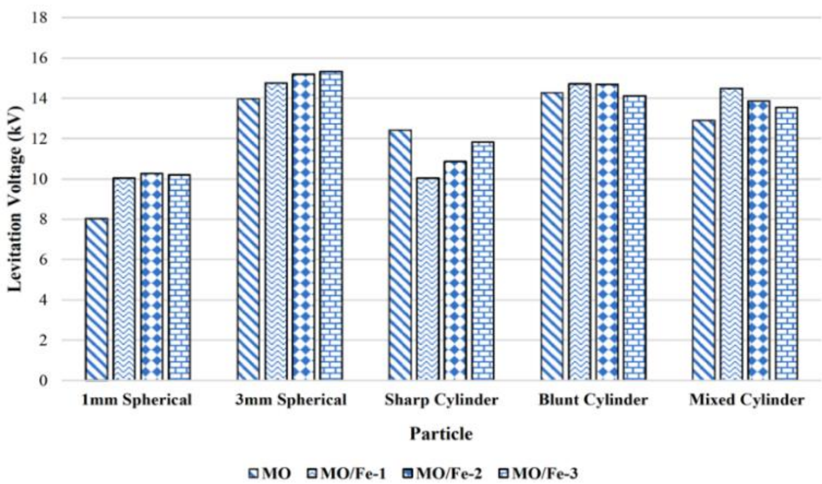


Figure 5. Comparison of average levitation voltages of spherical and cylindrical particles

$$E_d = 0.494\sqrt{(\frac{R(\rho_s - \rho_l)g}{\varepsilon})} \quad (4)$$

The density of the particles, denoted as ρ_s, and the density of the oil, denoted as ρ_l, are important factors in the given context. The gravitational acceleration, represented by g, and the permittivity of the particle, denoted as ε, also play significant roles. The provided formula illustrates the proportional connection between lifting fields (E_d) and particle radius (R). It indicates that as the particle size increases, a higher lifting field is necessary to achieve the desired effect.

On the contrary, particles that have pointed ends tend to display lower levitation voltages. This observation aligns with the theoretical framework established by Fahmi *et al.* [24], who found that as the surface area of the particle diameter increased, there was a corresponding rise in the average discharge current. The decrease in particle diameter leads to an uneven distribution of the electric field around the tip and top area of the particle, resulting in a more nonuniform electric field. Consequently, a higher electric field intensity is generated on the larger cross-sectional area of the particle, leading to ionization. This ionization process triggers an increase in the field value, subsequently amplifying the levitation force. As a result, sharp-edged particles exhibit lower levitation voltage values compared to blunt particles.

3.2. Breakdown voltage testing

The minimum voltage required to induce electrical conductivity in an insulating material, thereby allowing current to pass through, is known as the breakdown voltage of a nanofluid. This phenomenon is characterized by the occurrence of a spark or sudden surge in current between the two electrodes. To determine the breakdown voltage, a voltage was applied to the electrodes and was gradually increased until the dielectric strength of the nanofluid was surpassed by the electrical stress caused by the high voltage. In order to assess the breakdown voltage, a series of tests were conducted on individual particles, with the concentration of nanoparticles being varied systematically. The breakdown voltage test was repeated five times, and data were collected on each occasion.

Figure 6 illustrates the graph depicting the average breakdown voltage for spherical and cylindrical particles. The breakdown voltage in oil follows a descending order from highest to lowest as 1 mm spherical particle contamination, 3 mm spherical particle contamination, mixed cylinder particles, blunt cylinder particles, and sharp cylinder particles. This indicates that larger particle sizes resulted in lower breakdown voltages. The spherical particles exhibited higher breakdown voltages than the cylindrical particles. Specifically, cylindrical particles with sharp edges lead to lower breakdown voltages.

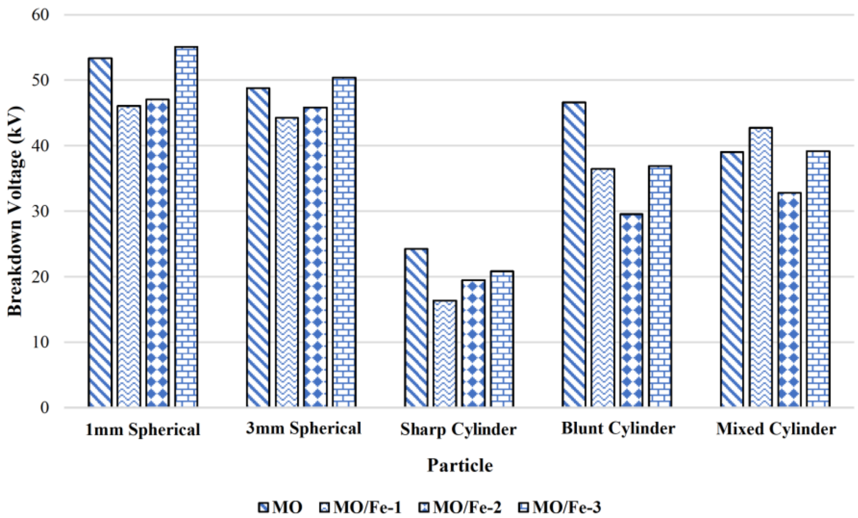


Figure 6. Comparison of average breakdown voltages of spherical and cylindrical particles

The breakdown voltage of MO/Fe-1 oil generally decreased for all particles compared to that of MO oil. However, with an increase in the nanoparticle concentration, there is an increase in the breakdown voltage of the oil, as evidenced by the concentrations of MO/Fe-2 and MO/Fe-3. The breakdown voltage of oil containing spherical particles tended to increase in the MO/Fe-3 concentration when compared with MO oil. This suggests that the presence of spherical particles in the nanofluid oil only enhanced the breakdown value, particularly at the MO/Fe-3 concentration. On the other hand, oil containing cylindrical particles tends to exhibit a decline in performance for nanofluid oil, including MO/Fe-1, MO/Fe-2, and MO/Fe-3, as indicated by a lower breakdown voltage value in comparison to MO oil. This indicates that the impact of cylindrical particles on the nanofluid oil leads to a reduction in the breakdown voltage.

Figure 7 provides a visual representation of the ability of Fe_3O_4 nanoparticles to enhance the dielectric strength of mineral oil. When subjected to an electric field, the Fe_3O_4 nanofluids exhibit a phenomenon where positive ion charges accumulate on the surface of the Fe_3O_4 nanoparticles. These positive charges then attract negative ions, resulting in the formation of an electric double layer (EDL). The compact layer, located near the Fe_3O_4 surface, consists of negatively charged ions that are trapped and drawn towards the Fe_3O_4 surface. As the distance from the Fe_3O_4 surface increases, the charge density in the compact layer gradually decreases until it reaches zero in the electrically neutral region of the fluid. The ions present in this region are known as the diffuse layer, which experiences less influence from electrostatic interactions with the Fe_3O_4 nanoparticles [25].

Due to the incorporation of conductive Fe_3O_4 nanoparticles, the transformation of these nanoparticles into microparticles takes place, resulting in an augmentation of the atomic size of the metal particles, as depicted in Figure 8. This phenomenon is attributed to the interchange of valence electrons among the particles, leading to the thickening of the layer of electrons surrounding the metal particles. Consequently, this has repercussions on enhancing the conductivity of the specimen under examination, thereby causing a reduction in the breakdown voltage value of the insulating oil when certain conditions are met.

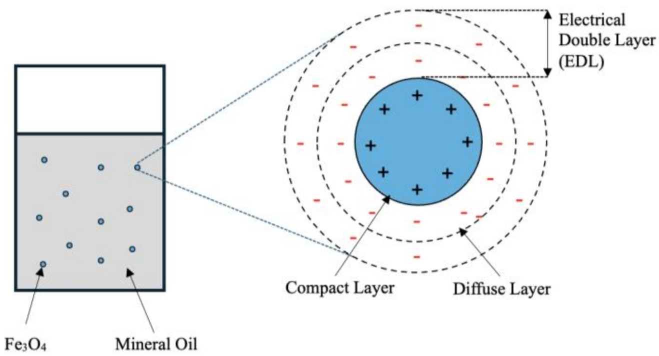


Figure 7. Breakdown mechanism in Fe_3O_4 nanofluid

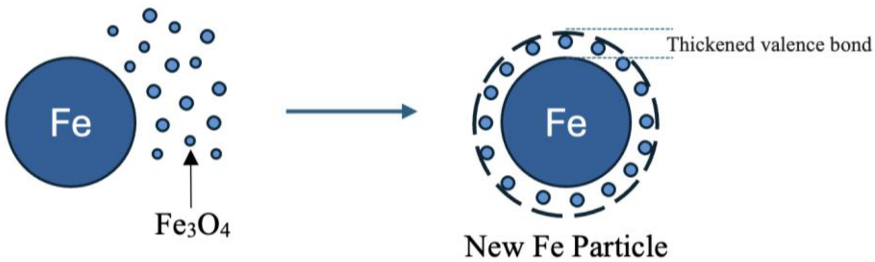


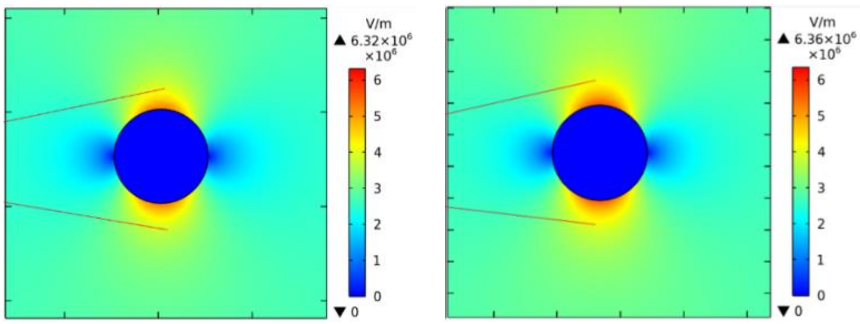
Figure 8. Formation of new FE microparticles by Fe_3O_4 nanoparticles

3.3. Electric field distribution simulation

The FEM-based software COMSOL 5.6 was utilized to conduct simulations on the distribution of electric fields. Variations in the concentration of nanoparticles resulted in discrepancies in the values of the Relative Permittivity parameter for the nanofluid. These specific parameter values were incorporated into the software through material definition. The metal particles were positioned between the two electrodes at the center. Pure mineral oil and nanofluid served as the insulating materials surrounding the electrodes and metal particles. A voltage of 30 kV was applied to the terminal electrode, which was determined by averaging the smallest Breakdown Voltage values obtained from various tests with different variations. Subsequently, the other electrode was connected to the ground.

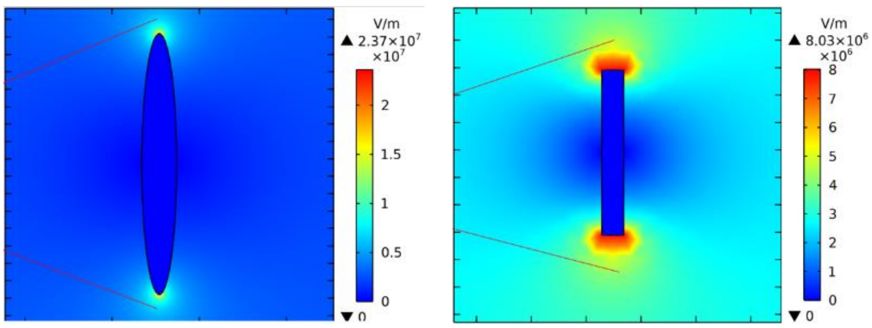
Figures 9 and 10 depict the recorded electric field values in MO oil that has been contaminated with both spherical and cylindrical metal particles. It is observed that the electric field value in the oil containing spherical particles with a diameter of 1 mm shown in Figure 9(a) is comparatively smaller, measuring at 6.32×106 V/m. On the other hand, the electric field value for spherical particles with a diameter of 3 mm as seen in Figure 9(b) is slightly higher, measuring at 6.36×106 V/m. This observation indicates that as the particle size increased, the measured electric field value also increased which leads to lower value of breakdown voltages.

In the case of oil containing cylindrical particles, the electric field value differs depending on the shape of the particles. For sharp cylindrical particles in Figure 10(a), the electric field value was measured at 2.36×10^4 kV/m. Conversely, for blunt cylinder particles as seen in Figure 10(b), the value was 8.03×10^3 kV/m. Furthermore, for the cylinder mix particles depicted in Figure 10(c), the electric field value was recorded as 2.43×10^4 kV/m. This finding demonstrates that cylindrical particles with a sharp tip exhibit a higher electric field value compared to those with a blunt tip. Table 3 presents the electric field values for each particle. It is evident that the electric field value is closely associated with the breakdown voltage, whereby an increase in the electric field value leads to a decrease in the breakdown voltage value of the test sample.

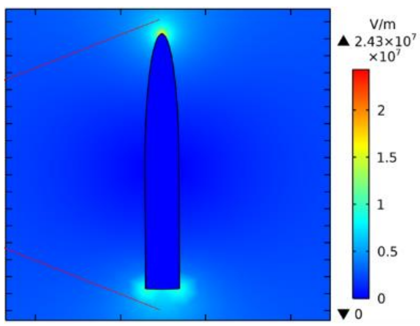


(a) (b)

Figure 9. Electric field of spherical particles (a) 1 mm and (b) 3 mm



(a) (b)



(c)

Figure 10. Electric field of cylindrical particles (a) sharp, (b) blunt, and (c) mixed

4. CONCLUSION

The study on the impact of contaminant shapes on the electrical properties of nanofluid has been completed. The research findings indicate that larger particle sizes necessitate a higher voltage for levitation, whereas sharper particles require a lower levitation voltage. Moreover, the concentration of nanofluid also plays a role in determining the levitation voltage level. On the other hand, the examination of oil contaminated with metal particles using breakdown voltage testing demonstrates an inverse correlation between particle size and breakdown voltage value. Additionally, the breakdown voltage testing of oil contaminated with spherical and cylindrical metal particles reveals that the presence of cylindrical particles in the oil leads to lower breakdown voltage values compared to spherical particles. Results from electric field simulations carried out with specialized software show that the electric field value within oil-containing particles increases with the size of the particle. Furthermore, it has been established that the electric field value on the side of a cylindrical particle with a sharp tip is higher than that on the blunt tip side.

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