Investigation on the Electrical and Rheological Properties of AlN-Based Synthetic Ester Nanofluids

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ABSTRACT The present study deals with the characterization of electrical and rheological behaviour of the Synthetic ester fluid incorporated with various concentration of Aluminium nitride (AlN) nanoparticles. Zeta potential measurement has shown an excellent stability of the ester fluid mixed with the nanoparticle. Corona inception voltage (CIV) measured using ultra-high frequency (UHF) technique and the results confirmed higher discharge resistance for nanofluid dispersed with 0.005% of AlN. Phase resolved partial discharge (PRPD) analysis with higher harmonic voltages has shown increase in pulse magnitude and number of discharges. Dielectric constant and tan δ measurements have revealed a slight marginal increase in its value with the inclusion of filler. Streaming current magnitude was found to increase with the disc rotational speed, concentration of nanoparticle and ambient temperature. Fluorescence spectroscopy analysis has shown increase in fluorophores intensity with filler dispersion in the ester fluid. Rheological properties of fluids mixed with nanoparticles are inspected with cone plane geometry configuration. Synthetic ester and its nanofluid exhibited Newtonian behavior of flow pattern and are independent of the applied shear rate. An exponential decay of viscosity of nanofluids was observed with temperature and it follows an Arrhenius law. The calculated activation energy has increased with the incorporation of filler concentrations. The complex modulus of AlN nanofluids was observed alongside exhibiting the viscous behavior where the loss modulus G'' is much larger than the storage modulus G', with the applied frequency.

INDEX TERMS Aluminium nitride, corona inception voltage, cone plane, fluorescence, Newtonian, streaming current, ultra high frequency.

I. INTRODUCTION

The reliability of transformers is based on their insulation design and maintenance. Mineral oil is used as an insulant and coolant for over a century in oil filler transformers. Their environmental toxicity and flammability led to the use of green fluid. Ester based fluids are gaining importance recently for their excellent biodegradability with better dielectric properties and fire-retardant capability [1]. With the increase in power requirement, the size and shape of the power apparatus is becoming large. It has become essential to design and develop a compact, reliable insulation structure, where nanoparticle suspended fluids are gaining importance to achieve the requirements of the manufacturers and utilities [2], [3].

Considerable work has been carried out in literature to indicate the nanofluid performance by dispersing nanoparticles based on their conductivity as conductive [4], [5], semiconductive [6] and insulating [7], [8]. The primary challenge lies in nanofluid preparation is to obtain better stability with optimization of filler concentration, which is the main objective of this work. Zeta potential gives the potential at slipping plane of the dispersed nanoparticle. Nanofluid stability is based on the absolute value of the zeta potential magnitude, above 30 mV depicts good dispersion and magnitude more than 60 mV as excellent stability [9].

Aluminium nitride finds application in optoelectronic devices, surface acoustic wave sensors (SAW) and
microelectronic industries as thermal conducting barriers and as electrically insulating elements. AlN nanoparticles are one of the most promising additives in dielectric characterization and are widely used with polymer nanocomposites [10]–[12]. Choi et al worked on AlN based mineral oil achieved a 20% enhancement in heat transfer coefficient with nanofluids [13]. Dong et al derive an electrical conductivity model by considering the electrophoresis of AlN nanoparticles [14]. Liu et al noticed the charge trapping tendency of modified AlN dispersed transformer oil showing 20% enhancement in partial discharge inception voltage by lowering the local electric field [15].

Partial discharge occurrence is one of the primitive failure mechanisms in oil-filled insulation structures, where various methodologies are adopted in detecting these incipient discharges by Transient earth voltage, Ultra-high frequency (UHF) sensors, Acoustic emission and High frequency current transformer (HFCT) techniques [16], [17]. Online monitoring technique with UHF is found efficient in diagnosing partial discharge (PD) at early stages with few nanoseconds rise time duration of the electromagnetic signal [18]. Charged nanoparticle acts as electron scavengers, hindering the propagation of streamers aiding for the improvement in the dielectric strength of the fluid. Jin studies modelling the dielectric parameters of permittivity and loss factor with the inclusion of nanoparticles [19]. Static electrification in power apparatus is another threat mechanism by induced surface charge accumulation leading to surface flashovers [20]. Kedzie et al simulate the flow electrification of the current generation at oil pressboard interface by the spinning disc method comparable to the system in practice [21]. Factors influencing the charge generation are the viscosity, temperature, shear rate and dielectric parameters of the fluid. The flow behaviour of fluid to dissipate excessive heat from windings indicates the rheological characteristics under different conditions, which is scanty in literature. Anoop et al noticed that the viscosity of mineral oil-based nanofluids unexpectedly alters with the influence of temperature and pressures [22]. Numerous computational studies have been formulated adopting numerical models, machine learning techniques to predict the viscosity of the nanofluids [23], [24]. It is also essential to investigate the variation in viscoelastic properties of nanofluids underflow condition of shear angular frequency and applied strain.

Present work deals with the study on the electrical and rheological properties of AlN based nanofluids, focusing on (i) Characterization of particle size distribution and zeta potential analysis, (ii) Corona inception voltage studies under AC and DC voltages and PRPD analysis under harmonic voltages with different Total harmonic distortions (THD), (iii) Dielectric response spectroscopy studies, (iv) Flow electrification phenomenon of nanofluid (v) Fluorescence spectroscopy studies and (vi) Rheological properties of nanofluids.

**FIGURE 1. Sample preparation methodology.**

**II. EXPERIMENTAL STUDIES**

A. **SAMPLE PREPARATION**

Aluminium Nitride nanoparticle was procured with an average particle size of 20 nm from USA. Nanofluid is prepared by dispersing nanoparticles of different concentrations (0.0025%, 0.005%, 0.01% and 0.015%) in Synthetic ester fluid (MIDEL 7131) as demonstrated in figure 1. The nanofiller is mixed with ethanol by keeping mixture in ultrasonic bath for 20 min in order to achieve uniform dispersion. The solution is then centrifuged and washed for 2-3 times with ethanol and filtered. The collected nano powder is dried in oven at 110°C. Dried particle is then dispersed in the base fluid by magnetic stirring for 30 minutes. The mixture is then transferred into an Ultrasonicator (Sonic Vibra Cell sonicator) operating at a frequency of 20 kHz for a period of 3 hours. The prepared samples are finally stored in a desiccator.

**FIGURE 2. Flow electrification setup.**

B. **ELECTRICAL STUDIES**

Corona inception studies: High voltage is generated using Trek amplifier model 30/20A with an input from a function generator. The voltage is constantly increased in steps of 200 V/s. The test cell used for the present study is point plane configuration with a gap distance of 5 mm [25]. Needle and ground electrode is made up of stainless steel material with radius of curvature of needle electrode used is 50 ± 3 µm and a diameter of ground electrode 5 cm respectively.
UHF sensor: A non-directional broadband Ultra high frequency sensor is used to detect the PD activity. The sensor is placed at a distance of 20 cm from the needle in order to get a consistent measurement. UHF sensor output is analyzed and stored with a 4 channel Digital storage oscilloscope operated at 40 GS/s and with input impedance of 50 Ω. The spectrum analyzer used in the present study by operating it in zero span mode with the bandwidth resolution of 3 MHz.

Flow electrification: Streaming current is measured using spinning disc technique under laboratory conditions as shown in figure 2. A metallic disc of 40 mm diameter is sandwiched between cellulosic pressboards on either side. The current generation is measured using Keithley electrometer connected between the walls of fluid cell and the ground. System is enclosed within a Faraday cage to avoid noise interference in measurement.

Dielectric response spectroscopy: Dielectric parameters of the fluid is carried with the OMICRON-DIRANA with a three-electrode arrangement as per IEC 60247 standard. An external thermal controller is used and measurement is carried at 30°, 60° and 90°C [25].

C. RHEOLOGICAL STUDIES
Rheological characterization is carried using Anton Paar rheometer Modular Compact MCR 102 with cone plane geometry (CP 40) of 40 mm diameter. Cone is inclined at an angle 1° and gap distance of 0.08 mm is fixed between the measuring geometry. The temperature is controlled by P-PTD200/AIR Peltier controller and measurements were performed in the range of 30° to 90°C.

III. RESULTS AND DISCUSSION
A. CHARACTERIZATION OF NANOFLUIDS
1) PARTICLE SIZE ANALYSIS
The particle size distribution studies were carried out with the light scattering as a function of particle size with the principle of Laser diffraction (LD). Figure 3 shows the distribution of various concentrations of AlN nanoparticle dispersed in synthetic ester fluid. Number of particles is measured per 3 ml of the nanofluid solution. It is seen that the particle size increases and the number of particles decreases with the particles concentration. Liu et al studied the distribution of AlN nanoparticle based transformer oil for freshly prepared and observed nanofluid no sign of sedimentation even after 6 months [15]. It is observed that the mean particle size of 0.015% specimen is 740 nm which is 20 times higher than the lowest concentration (0.0025%). This indication probably signifies the act of coagulation or flocculation of nanoparticle which alters the particle size in the fluid. Du et al found the average size of TiO₂ less than 20 nm enhances the breakdown strength of the fluid up to 124% of the base fluid [26].

2) ZETA POTENTIAL ANALYSIS
Zeta potential is the measure of electrochemical equilibrium at the fluid particle interface. Measurements is carried using Horiba SZ-100 nanoparticle. Higher the magnitude of zeta potential, higher is the stability of nanofluid irrespective of the polarity. The stability significance on colloidal solution depends on the balance existing between the electrical double layer and the Van der Waals force acting in between. Figure 4 demonstrates the zeta potential measurement with various concentrations of AlN in base fluid at ambient temperatures of 25°, 45° and 60°C. Zeta potential magnitude more than ±30 mV is desired as electrostatically stable suspension. The pH of solution holds important parameter in zeta potential, AlN being acidic in nature reduces the pH of the nanofluid and increases the positive charges on the surface of the particle. This could be the reason for the zeta potential increment with the AlN filler inclusion. Factors that affect zeta potential are pH value, temperature of the medium and ionic strength.

Zeta potential magnitude tends to increase up to certain concentration above which reduction is observed which could
be due to the act of agglomeration of particles suppressing the electrical double layer (EDL) in the fluid. Due to thermal excitation at higher temperatures, the ionic strength of the material alters in the solution reducing the overall stability of the nanofluids. Similar results is observed with decrement in zeta potential magnitude with increasing temperatures at low ionic strength of the solution [27]. Nanofluid specimens with 0.006% and 0.0075% were prepared and their stability is measured. Specimen with 0.006% concentrations shows similar characteristics as 0.005% at ambient temperature 30°C while at higher temperatures of 45° and 60°C there is a reduction observed. While 0.0075% concentrations drastically reduces in magnitude irrespective of the applied temperature. 0.005% concentration shows relatively better stability irrespective of the measuring temperature.

### B. ELECTRICAL PROPERTIES OF NANOFLUIDS

#### 1) CORONA INCEPTION VOLTAGE STUDIES

Corona inception voltage measurement were carried out using point plane configuration (non-uniform electric field) by adopting UHF technique. Figure 5a shows typical UHF signal obtained due to corona discharge and its corresponding fast Fourier transform (FFT) analysis is shown in Figure 5b. The dominant frequency of UHF signal lies at 0.9 GHz.

Figure 6 shows the variation in corona inception voltage in nanofluids with different concentrations of AlN, under AC and DC voltages. 20 measurements were obtained for every experiment and deviation in voltage is obtained. It is observed that CIV is lower under AC voltage followed with +DC and −DC voltages. The cause for reduced CIV could be due to space charge free zone formed by the alternating positive and negative cycles causing constant electric field to initiate at much lower voltage than DC voltages, where the influence of deposited charges alters the local electric field. An increment is observed with inclusion of filler up to a certain concentration (0.005%) above which there is a reduction in the inception voltage. The cause for enhancement is due to uniform dispersion of nano filler reducing the local electric field enhancement at the needle tip. The result correlates well with the zeta potential analysis. Corona inception voltage with the maximum enhancement of 28% is achieved by dispersing 0.005% concentration AlN nanoparticle in the synthetic ester fluid. Hwang et al indicates the relaxation time constant of charges trapped by nanoparticles is lower than time constant of the streamer propagation [28]. The trapping tendency of nanoparticle converts fast moving electrons slower leading to suppressed streamer propagation and improves the discharge resistance with the nanofluids. Particle size of nanoparticle plays a major role in distortion of local electric field and exists as discrete phase usually causing reduction in dielectric breakdown strength [29].

Due to the non-linear loading on transformer the sinusoidal wave shape is distorted containing different harmonic content and THD% which causes additional stress on
TABLE 1. Units corona inception and applied harmonic voltages.

| Specimens | $3f$ | $5f$ | $7f$ | $3f+ 4\%$ THD | $7f+ 4\%$ THD | $3f+ 40\%$ THD | $7f+ 40\%$ THD |
|-----------|------|------|------|--------------|--------------|--------------|--------------|
| SEO       | 8.634| 8.551| 8.125| 8.326        | 7.952        | 7.353        | 7.103        |
| 0.0025%   | 9.611| 9.543| 9.561| 9.509        | 8.762        | 7.975        | 7.456        |
| 0.005%    | 10.489| 10.248| 10.219| 10.336       | 9.321        | 8.668        | 8.211        |
| 0.01%     | 10.499| 10.332| 10.314| 10.241       | 9.701        | 9.044        | 8.964        |
| 0.015%    | 10.113| 10.022| 10.017| 9.819        | 9.135        | 8.408        | 8.037        |

Table 1 shows the variation in corona inception voltage on application of harmonic voltage profiles of nanofluids. It is noticed that a drastic decrement in CIV is observed under the impact of higher frequency harmonics. This reduction can be supported with the $dV/dt$ variation in applied voltage which is relatively higher than the fundamental sinusoidal input ($f = 50$ Hz). AlN based nanofluids shows better performance with such distortion in comparison to the base fluid (SEO). The variation in CIV with different concentrations of nanofluid did not show any significant variation under harmonic AC voltages.

Figure 7 shows phase at which discharge occurs, under harmonic AC voltages with different THD’s. It is observed that discharges occurs when the $dV/dt$ variation is high. Number of discharges with the applied frequency at different THD’s is shown in the Table 2. It is clear that the number of discharges reduces which hinders the PD activity by the fillers in the fluid.

2) DIELECTRIC RESPONSE SPECTROSCOPY

Dielectric response spectroscopy gives the dielectric constant ($\varepsilon_r$) and dielectric loss tangent (tan $\delta$). Figure 8 shows tan $\delta$ of AlN nanofluids in the frequency ranges of 0.1 to 1000 Hz at ambient temperatures of 30°, 60° and 90° C. The bound charges are formed over nanoparticle surface under the influence of external field known as surface charge due to the effect of polarization [31]. It is observed that tan $\delta$ tends to reduce with the supply frequency due to the randomness of dipole orientation inability at higher frequencies. The relaxation time constant of free charges for the nanofluids can be expressed as

$$\zeta = \frac{2\varepsilon_1 + \varepsilon_2}{2\sigma_1 + \sigma_2}$$  \hspace{1cm} (1)

where $\sigma_1$ and $\sigma_2$ are the conductivities of the fluid and filler, $\varepsilon_1$ and $\varepsilon_2$ are the permittivity of the fluid and the nanoparticle.

Turning or dipole polarization is mainly influenced by the temperature and applied field and obtained after $10^{-10}$ s to $10^{-2}$ s which is relatively slower than ionic polarization faster.
in $10^{-15}$ s to $10^{-12}$ s [32]. The loss factor of nanofluid is considerably higher due to the requirement of additional energy to orient dipoles to the direction of applied electric field. Also, $\tan \delta$ increase with temperature which is due to the thermal excitation and higher relaxation losses. The conduction ion attracts charge from the applied voltage at the electrical double layer leading to the orientation polarization mechanism.

Table 3 shows the permittivity and $\tan \delta$ of nanofluids at applied frequency of 50 Hz. Inclusion of nanoparticles increases the relative capacitance of the fluid by the charging capability of fillers under applied electric field. Nanofluid with 0.005% showed a relatively lower $\tan \delta$ at ambient temperature due to its excellent stability and the interfacial polarization acting between the filler and fluid is minimum. Nanoparticles forms a potential well distribution by induced surface charges on the interface of nanoparticle and oil matrix having the tendency to influence the charge carriers [32]. Specimen with concentration of 0.0025% and higher concentrations (0.01% and 0.015%) did not show any significant variation at ambient temperature (30°C) due to their relative lower stability in the solution. The trapping and detrapping mechanism exhibited by nanoparticle tends to increases $\tan \delta$ of the material where the impact of interfacial polarization is predominant on the nanofluid stability. Dielectric constant or relative permittivity is the ratio of real component of capacitance with fluid in test cell to the capacitance of bare test cell. The permittivity $\varepsilon'$ measurement of nanofluids did not show significant variation with the nanoparticle concentration in oil matrix.

3) FLOW ELECTRIFICATION

Streaming current generated at the oil pressboard interface is shown in the figure 9 under controlled disc rotational speed (100- 600 rpm) at different temperatures. It is observed that the streaming current increases with the rotation speed of the disc which is responsible by the frictional force exerted between the oil and the pressboard medium. Also, it is noticed that the current increases abruptly above the shear rate of 300 rpm. Nanofluids show relatively higher magnitude of current to the base fluid (SEO) which could be due to the charging tendency of nanoparticles. Similar results were observed with the dispersion of TiO$_2$ in natural ester fluid [33]. The unsaturated fatty acid in ester fluid reacts with NH$_2$ molecule on the surface of the nanoparticle forms covalent bond [15]. In addition, the temperature further increases the current due to the reduction in viscosity of the fluid and increased mobility of charge carriers due to thermal excitation of ions.

At ambient temperature of 30°C, streaming current is lower with Synthetic ester oil (SEO) and increases with the addition of filler concentration. While at higher temperatures of 60°C and 90°C specimen with 0.0025% and 0.005% concentration of AlN showed a relatively lower magnitude of current. AlN nanoparticle having higher thermal conductivity, traps the thermal energy and reduces the mobility of ions. The increment in magnitude with higher concentration could be due to the act of agglomeration and higher charge mobility.

4) FLUORESCENCE SPECTROSCOPY

Fluorescence spectroscopy is based on the presence of fluoropores in fluid which is responsible for the absorption of light.
of radiation into the light emission of specific wavelength. Figure 10 shows the variation in the intensity and emission wavelength of synthetic ester based nanofluids measured using square cuvette. The naturally available fatty acid content in ester based fluid is the principle source of fluorescence emission. The emitted fluorescence undergoes reflection back and forth in the oil medium before reaching the detector. The detector causing light reabsorption is known as the inner filter effect. It is observed that fluorescence intensity increases with the inclusion of filler due to the relatively large presence of fluorophores in the fluid. In addition, the intensity also depends on the pH value of the solution. The excitation and emission maximum span lies in the range of 250-350 nm and no significant shift is observed in its wavelength, with the addition of nano filler.

C. RHEOLOGICAL PROPERTIES OF NANOFLUIDS

Rheological characterization is carried to study on the deformation and flow matter under loading and environmental conditions. The variation in flow attributes for nanofluids could be due to the concentration, particle size, structure and surface aspects of the filler dispersed. Mineral oil and ester oil exhibit Newtonian behaviour [34] i.e., viscosity is independent of applied shear rates. for a Newtonian behaviour fluid shear stress exerted on the fluid is given as

$$\tau = \mu \gamma$$  \hspace{1cm} (2)

where $\gamma$ is the shear rate and $\mu$ is the coefficient of viscosity. Yield stress is the minimum applied stress above which structure of fluid deforms to flow condition. Due to the viscous behavior of the fluid no yield stress exists for the synthetic ester and its nanofluids. Power law equation derives the no yield stress as

$$\tau = k \gamma^n$$  \hspace{1cm} (3)

where $k$ is called the consistency coefficient and $n$ is the power law index. The parameters governing the rheological aspects obtained by using the cone plane geometry (as shown in Figure 11).

$$\delta = \delta_0 + r \tan \alpha$$  \hspace{1cm} (4)

where $\delta_0$ is the gap distance between the apex of the cone to the peltier plate, $r$ is the radius of the cone and $\alpha$ is the angle of inclination of cone. The shear rate $\gamma$ is the progressive shearing deformation applied to the fluid is given by the ratio of angular plate velocity ($u = \omega \times r$) to gap distance

$$\gamma = \frac{\omega \cdot r}{\delta_0 + r \tan \alpha}$$  \hspace{1cm} (5)
1) EFFECT OF SHEAR RATE ON SHEAR STRESS

Figure 12 shows the variation in shear stress of synthetic ester based nanofluids at different temperatures with respect to the shear rate (1 - 1000 s\(^{-1}\)). A linear relationship is guiding the shear stress on the applied shear rate of the fluid indicating Newtonian behaviour of the fluids. This increment is due to the alteration of frictional force acting on the fluid with shear rates. Shear stress is dependent on the viscosity of the fluid, which causes a reduction at higher temperatures. At lower temperature (30\(^{\circ}\)C), nanofluids exhibit a higher slope with the concentration of the filler inclusion. Since nanoparticle offers flow resistance to the fluid. While at higher temperatures this effect is found diminishing and show no significant variation due to the alteration in thermal energy by the AlN nanoparticles. The shear stress and the streaming current generation correlates well. Muto et al derives a charge distribution model by assuming Debye proving the proportional relation between streaming current and shear force [35].

2) IMPACT OF TEMPERATURE DEPENDANCE ON VISCOSITY

Viscosity of the fluid is a thermo physical property which determines the resistance to shear and its flow state where higher viscous signifies more resistance to fluid flow. The fluid transfers thermal energy due to convection mechanism which accelerates on applied higher flow rates (shear rate). Also, heat transfer of the fluid depends on density, thermal conductivity, specific heat capability and by the velocity of the fluid. In general, reduction in viscosity with increase in temperature have high impact on heat transfer capability especially at the interface [36]. The change in viscosity with the impact of temperature is measured at a constant shear rate of 100 s\(^{-1}\) as shown in figure 13a. The viscosity of the nanofluids are influenced by size, type and volume fraction of nano particles and their temperature. The concentration of the nano particle have a direct correlation with the viscosity of the nanofluids due to its molecular interactions between the nanoparticle and the base fluid. The lower variation in concentration was considered for better stability where viscosity did not exhibit any remarkable change with the addition of nanoparticles and are equivalent to SEO specimen. Similar results were observed with viscosity with addition of hexagonal Boron nitride (h-BN) up to 0.05 wt% to mineral oil and observed no alteration in viscosity for entire temperatures range tested [37]. Ehsan et al., have showed considerable variation in viscosity with increase in weight percentage, which is of larger quantity [38]. In the present study, further increase in quantity of nano filler to the base liquid showed reduction in stability and hence the study was restricted up to 0.015%. Jin et al study on silica dispersed in mineral oil did not shows considerable variation with loading of nanoparticles [39]. Mohammed et al notice the percentage difference of less than 0.5% with the inclusion of Fe\(_3\)O\(_4\), TiO\(_2\) and Al\(_2\)O\(_3\) [40]. In addition, a slight reduction in decay rate of viscosity is observed with the increment of AlN concentrations. The temperature dependence on viscosity governs the exponential decaying curves following Arrhenius equation.

Figure 13b shows the Arrhenius plot for various synthetic ester based nanofluids with the assistance of the viscosity variation over the temperature. The slope of the Arrhenius plot depicts the activation energy. Activation energy is the energy required to reduce the viscosity by dissociate the molecules of the oil which is reduces the conduction of charge mobility [41]. Table 4 shows the activation energy for specimens with different concentrations of AlN, higher the activation energy better the cooling properties of the fluid. It is observed that the activation energy increases with the concentration of filler.
3) FREQUENCY SWEEP CHARACTERISTICS OF NANOFLUIDS

Figure 14 shows the frequency sweep measurement of synthetic ester based AlN nanofluids with the angular frequency range of 1 to 100 rad/s at different temperatures. A constant percentage of deformation of 1% strain amplitude is chosen within the linear viscoelastic region (LVER) from the amplitude sweep. The possible structural change with the inclusion of nanoparticle is identified. The value of loss modulus $G''$ is always found dominant over the storage modulus $G'$ indicating the nanofluids are governed by the viscous behavior than the elastic nature throughout the frequency sweep. The value of $G'$ and $G''$ increases with the applied angular frequency attributing to the fractural aggregates which tends to overlap under applied shear condition [42]. Similar behavior is exhibited by AlN nanofluids as base fluid showing higher $G''$ than $G'$. Also, the impact on $G'$ and $G''$ shows an increment with higher temperatures. The magnitude difference between the viscous properties with elastic property is very high showing pure viscous behavior of the fluids. The storage modulus ($G'$) reduces with the increasing concentrations of filler due to the incapability of elastic behavior at higher loading conditions and molecular bonding tends to break. The $G'$ for SEO is $4 \times 10^{-3}$ which is comparatively higher than the 0.015% concentration of nanofluid having $2 \times 10^{-3}$. This reduction in storage modulus is addressed by the higher elastic behaviour exhibited by the SEO specimen. At higher temperatures of 60° and 90°C the storage modulus of SEO is relatively similar due to its insignificant resistance to molecular thermal excitation in the fluid which offers low deformation on elastic behaviour. On the other hand, specimen with 0.015% concentration shows a lower $G'$ at 30° and 60°C and observed to increase drastically at 90°C depicting the agglomerated nanoparticle in oil matrix, at higher temperature, with larger particle size stimulates the phase separation in the fluid’s nature. The loss modulus ($G''$) of SEO and nanofluid (0.015%) was lying in the same range for the ambient temperature whereas at higher temperature (60°C and 90°C), the nanofluid exhibited a lower $G''$ compared to SEO. This confirms that increased concentration of AlN on SEO alters the flow pattern associated with the nanofluids at higher temperatures. This could probably be due to the property exhibited by nanoparticle forming clusters or particles agglomeration tending to reduce the viscous nature of the specimen with the inclusion of nanoparticles.
**References**

[1] P. Rozga, A. Beroual, P. Przybylek, M. Jaroszewski, and K. Strzelecki, “A review on synthetic ester liquids for transformer applications,” *Energies*, vol. 13, no. 23, p. 6429, Dec. 2020.

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

[3] D. Amin, R. Walvekar, M. Khalid, M. Vaka, N. M. Mubarak, and T. C. S. M. Gupta, “Recent progress and challenges in transformer oil nanofluid development: A review on thermal and electrical properties,” *IEEE Access*, vol. 7, pp. 151422–151438, 2019.

[4] A. Nasiri, M. Shariati-Niasar, A. Rashidi, A. Amrollahi, and R. Khodafarin, “Effect of dispersion method on thermal conductivity and stability of nanofluid,” *Experim. Thermal Fluid Sci.*, vol. 35, no. 4, pp. 717–723, May 2011.

[5] J. Li, Z. Zhang, P. Zou, S. Grzybowski, and M. Zahn, “Preparation of a vegetable oil-based nanofluid and investigation of its breakdown and dielectric properties,” *IEEE Elect. Insul. Mag.*, vol. 28, no. 5, pp. 43–50, Sep. 2012.

[6] K. Swati, K. S. Yadav, R. Sarathi, R. Vinu, and M. G. Danikas, “Understanding corona discharge activity in titania nanoparticles dispersed in transformer oil under AC and DC voltages,” *IEEE Trans. Dielectrics Electr. Insul.*, vol. 24, no. 4, pp. 2325–2336, 2017.

[7] 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. Dielectrics Electr. Insul.*, vol. 21, no. 3, pp. 1100–1108, Jun. 2014.

[8] D. Xiang, L. Shen, and H. Wang, “Investigation on the thermal conductivity of mineral oil-based alumina/aluminum nitride nanofluids,” *Materials*, vol. 12, no. 4, p. 4217, Dec. 2019.

[9] R. H. Müller, *Zetapotential and Partikelladung in der Laborpraxis*, 1st ed. Stuttgart, Germany: Wissenschaftliche Verlagsgesellschaft, 1996.

[10] H. Yu, L. Li, T. Kido, G. Xi, G. Xu, and F. Guo, “Thermal and insulating properties of epoxy/aluminum nitride composites used for thermal interface material,” *J. Appl. Polymer Sci.*, vol. 124, no. 1, pp. 669–677, Apr. 2012.

[11] E.-S. Lee, S.-M. Lee, D. J. Shanefield, and W. R. Cannon, “Enhanced thermal conductivity of polymer matrix composite via high solids loading of aluminum nitride in epoxy resin,” *J. Amer. Ceram. Soc.*, vol. 91, no. 4, pp. 1169–1174, Apr. 2008.

[12] J. Zheng, S. He, J. Wang, W. Fang, Y. Xue, L. Xie, and J. Lin, “Performance of silicone rubber composites filled with aluminum nitride and alumina trihydrate,” *Materials*, vol. 13, no. 11, p. 2489, May 2020.

[13] 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,” *Current Appl. Phys.*, vol. 8, no. 6, pp. 710–712, 2008.

[14] D. Liu, Y. Zhou, Y. Yang, L. Zhang, and F. Jin, “Characterization of high performance AlN nanoparticle-based transformer oil nanofluids,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 5, pp. 2757–2767, Oct. 2016.

[15] R. Bartnikas, “Partial discharges. Their mechanism, detection and measurement,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 5, pp. 763–808, Oct. 2002.

[16] S. Marklous, S. Tenbohlen, and K. Feser, “Detection and location of partial discharges in power transformers using acoustic and electromagnetic signals,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 6, pp. 1576–1583, Dec. 2008.

[17] H. Chai, B. T. Phung, and S. Mitchell, “Application of UHF sensors in power system equipment for partial discharge detection: A review,” *Sensors*, vol. 19, no. 5, p. 1029, Feb. 2019.

[18] M. El-Adawy, T. Paillat, Y. Bertrand, O. Moreau, and G. Touchard, “Physicochemical analysis at the interface between conductive solid and dielectric liquid for flow electrification phenomenon,” *IEEE Trans. Ind. Appl.*, vol. 46, no. 4, pp. 1593–1600, Jul. 2010.

[19] J. Miao, M. Dong, M. Ren, X. Wu, L. Shen, and H. Wang, “Effect of nanoparticle polarization on relative permittivity of transformer oil-based nanofluids,” *J. Appl. Phys.*, vol. 113, no. 20, May 2013, no. 204103.

[20] I. Kedzia, “Investigation of transformer oil electrification in a spinning disk system,” *IEEE Trans. Electr. Insul.*, vol. 24, no. 1, pp. 59–65, Feb. 1989.

[21] K. Aoop, R. Sadr, M. Al-Jubouri, and M. Amani, “Rheology of mineral oil-SiO2 nanofluids at high pressure and high temperatures,” *Int. J. Thermal Sci.*, vol. 77, pp. 108–115, Mar. 2014.

[22] P. J. Meyer, S. A. Adio, M. Sharifi, and P. N. Nwosu, “The viscosity of nanofluids: A review of the theoretical, empirical, and numerical models,” *Heat Transfer Eng.*, vol. 37, pp. 387–421, Mar. 2016.
