Performance of Transformer Insulation Paper in the Presence of Multi Walled Carbon Nanotube (MWCNT) in Palm Oil Methyl Ester (POME)

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***Abstract*—The reliability of power transformers depends greatly on their insulation systems, which traditionally use Mineral Oil (MO) and Kraft paper. Due to environmental concerns with MO, Palm Oil Methyl Ester (POME) has emerged as a sustainable alternative, though it requires performance enhancement for high-voltage use. This study investigates the effect of adding 0.02 g/L Multi-Walled Carbon Nanotubes (MWCNTs) to POME on the mechanical and dielectric properties of Kraft paper, under both unaged and thermally aged conditions. Tensile strength (TS) was evaluated in both machine (MD) and cross directions (CD), while dielectric strength was assessed using AC Breakdown Voltage (ACBDV) tests per IEC standards. Tensile testing confirmed the anisotropic behavior of Kraft paper, with MWCNT addition improving strength by 13 % in the cross direction and showing only a 1.4 % decrease after aging. In the machine direction, strength remained high with minimal changes. All samples met IEC 60641-3-2 standards. AC breakdown voltage improved by 5.8 % in unaged and 3.0 % in aged MWCNT-treated samples, while aging effects were less severe compared to pure POME samples.**

Keywords*— *Kraft presspaper, POME, MWCNT, insulation, ACBDV, Tensile Strength

I. INTRODUCTION

Transformers play a crucial role in modern power systems, enabling the efficient transmission and distribution of electricity across long distances and varied voltage levels. They operate by stepping voltages up or down as needed, ensuring reliable power delivery to residential, commercial, and industrial sectors [1]. The performance and longevity of a transformer heavily depend on its insulation system, which comprises two main components: the insulating fluid and the solid insulation, typically Kraft presspaper. These components must function synergistically to provide sufficient dielectric strength, mechanical durability, and thermal stability throughout the transformer’s operational life [2].

Kraft paper is the most commonly used insulation material in power transformers, primarily composed of cellulose derived from softwood fibers processed through the Kraft pulping method. Cellulose-based insulation has been utilized for over a century due to its excellent dielectric properties, structural integrity, and compatibility with transformer oils. Cellulose, the fundamental component of Kraft paper and pressboard, is a natural polymer consisting of glucose units arranged in a specific linear configuration, as illustrated in Fig 1.

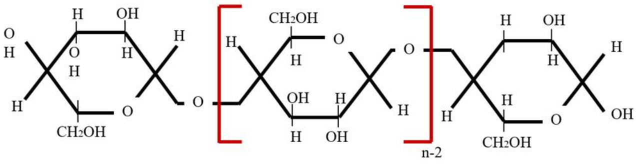

Fig. 1. Cellulose structure [3]

Transformer presspaper plays a dual role by serving both as an electrical insulator and a source of mechanical reinforcement within the transformer structure. Its overall performance is governed by a combination of physicochemical, mechanical, and electrical properties, all of which must comply with strict industry standards to ensure long-term operational reliability.

Mineral oil (MO) has been widely used as the insulating liquid due to its acceptable dielectric performance and long service history. However, environmental and sustainability concerns have prompted the power industry to search for eco-friendly alternatives to conventional mineral-based transformer oils. However, its low biodegradability, high flammability, and environmental impact have prompted a global shift toward more sustainable and eco-friendly alternatives. In response to these challenges, natural ester-based fluids derived from vegetable oils have emerged as promising replacements. Among them, Palm Oil Methyl Ester (POME) has shown considerable potential, particularly in tropical regions such as Malaysia, where palm oil is abundantly produced. POME is synthesized through the transesterification of refined, bleached, and deodorized palm olein (RBDPO), yielding fatty acid methyl esters (FAME) that possess favourable physicochemical properties, including lower viscosity, better oxidative stability, and high biodegradability [4].

Despite these advantages, further enhancement of POME's thermal and electrical properties is necessary to meet the performance demands of modern high-voltage transformers. One emerging solution is the incorporation of nanotechnology through the development of nanofluids. Nanofluids are engineered by dispersing nanoparticles into a base fluid, which can significantly improve heat transfer, dielectric strength, and chemical stability. MWCNTs have attracted particular interest for this purpose due to their exceptional electrical conductivity, high aspect ratio, and thermal stability. However, studies focusing on MWCNT integration in natural ester-based fluids such as POME are still limited and warrant deeper investigation.

While advances in fluid performance are critical, it is equally important to evaluate the compatibility and impact of these nanofluids on solid insulation materials, especially Kraft presspaper. Kraft paper is known to degrade under thermal and electrical stress, leading to deterioration in tensile strength and dielectric behaviour. Thermal aging, in particular, accelerates cellulose breakdown, compromising the mechanical integrity and insulation reliability of the material. Assessing how nanofluid impregnation affects Kraft paper over time is essential for determining its suitability in real-world transformer conditions.

This study investigates the effect of MWCNT-enhanced POME on the mechanical and dielectric properties of Kraft insulation paper under both unaged and thermally aged conditions. Four sample groups were prepared: (A) Kraft paper with pure POME (unaged), (B) Kraft paper with POME-MWCNT nanofluid (unaged), (C) Kraft paper with pure POME (aged), and (D) Kraft paper with POME-MWCNT nanofluid (aged).

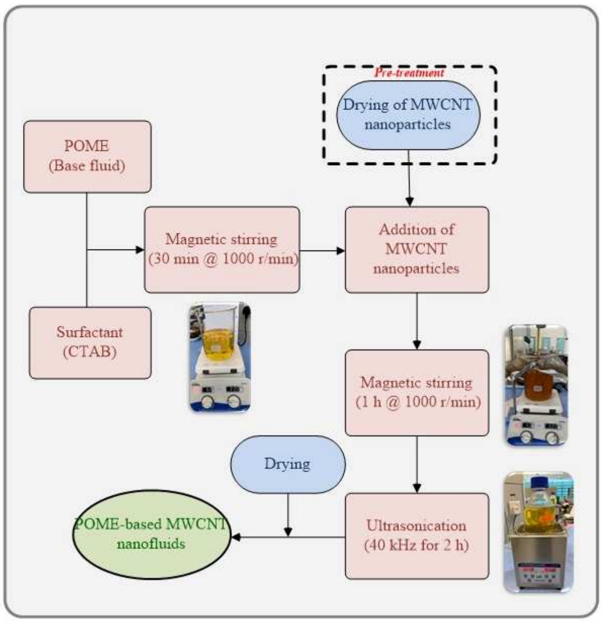

Fig. 2. Preparation of nanofluid Sample

Tensile strength (TS) tests were conducted in both machine direction (MD) and cross direction (CD) to assess anisotropic mechanical behaviour. In addition, Alternating Current Breakdown Voltage (ACBDV) tests were performed to evaluate dielectric strength. The results aim to determine the effectiveness of MWCNT nanofluids in enhancing the performance of natural ester-based transformer insulation systems, supporting the development of more sustainable and high-performance electrical equipment.

II. METHODOLOGY

A. *Preparation of Nanofluid Sample*

Fig 2 shows the overall process of preparation of nanofluid. This involved a 6:1 methanol-to-oil molar ratio with potassium hydroxide (KOH) as the catalyst. The reaction was conducted at 60°C for 60 minutes under continuous stirring, followed by a 24-hour separation period. The resulting mixture was then separated into layers, with crude glycerol removed and the FAME layer washed and purified. The final product, referred to as POME, was used as the base fluid for nanofluid preparation, following previously established methodologies [5].

Prior to use, POME was dried in a convection oven at 85°C for 24 hours to remove moisture, then allowed to cool to room temperature. One litre of the dried POME was used as the base fluid. To this, cetyltrimethylammonium bromide (CTAB) was added and magnetically stirred for 30 minutes to ensure uniform dispersion. The CTAB concentration was maintained at half the weight percentage of the nanoparticles, based on previous studies [6]. MWCNTs were then accurately weighed and added to achieve a concentration of 0.02 g/L. The mixture underwent ultrasonication at 50°C using a 40-kHz ultrasonic cleaner for four cycles of 30 minutes each, with 10-minute breaks between cycles to avoid overheating. This combined with magnetic stirring helped achieve a stable and homogenous nanofluid by minimizing nanoparticle agglomeration. The prepared nanofluid samples were subsequently dried at 85°C for 48 hours prior to their use in thermal aging experiments.

Table I presents the sample indicators for the four experimental conditions used to assess the influence of MWCNT nanoparticles and thermal aging on the properties of POME-based insulation fluids. Sample A consisted of pure POME with no aging treatment. Sample B involved POME with 0.02 g/L MWCNT, also without aging, to evaluate the immediate effects of nanoparticle inclusion. Samples C and D mirrored Samples A and B, respectively, but were subjected to thermal aging at 100°C for 50 hours to simulate long-term operational stress.

TABLE I. SAMPLE INDICATOR

Sample	Sample Description
A	POME (without aging)
B	POME + 0.02 g/L MWCNT (without aging)
C	POME (with aging 50- hours)
D	POME + 0.02 g/L MWCNT (with aging 50- h)

B. *Aging Procedure*

Kraft insulation papers were cut into 50 × 50 mm sheets and pre-dried in an oven for 24 hours to remove any residual moisture. The dried papers were then immersed in either the dried POME or the prepared nanofluid, followed by an impregnation process conducted at 90 °C for 24 hours in a vacuum oven to ensure thorough absorption of the fluid into the paper. After impregnation, the samples were subjected to thermal aging at 100 °C for 50 hours, a duration selected as part of a pilot study to simulate long-term operational stress. Throughout the process, the oil-to-paper weight ratio was consistently maintained at 20:1, in accordance with previous studies [3, 7, 8].

C. Experimental Procedure

Tensile strength tests were conducted using a Shimadzu Autograph AGS-X Series universal testing machine. Presspaper samples were prepared according to the IEC 60641-2 standard, with each strip measuring 15 mm in width and 100 mm in length [9]. For each type of presspaper, a total of twenty samples were tested. To assess the mechanical anisotropy of the insulation paper, tensile tests were performed in both the MD and the CD, with ten specimens designated for each orientation.

The alternating current breakdown voltage (ACBDV) test of Kraft presspaper was carried out in accordance with the standards IEC 60243 [10]. The test was performed in an oil medium, using 600 ml of dried nanofluid as the insulating medium. Two equal electrodes with 25 ± 1 mm with their edges rounded to a radius of 3 ± 0.2 mm made from stainless steel were used. The applied voltage had a frequency of 50 Hz and was increased at a rate of 2 kV/s until the breakdown. For each condition, then breakdown measurements were recorded to determine ACBDV.

Results are analysed using Weibull analysis, which is widely applied to interpret breakdown behavior in terms of failure probability, making it easier to compare the performance and failure risks of different sample conditions [11]. The scale parameter represents the characteristic breakdown voltage at which 63.2 % of the samples are expected to fail, while the shape parameter describes the data distribution and indicates the variability or consistency of breakdown events. This dual-parameter approach provides a comprehensive understanding of the breakdown characteristics for each sample condition.

III. RESULTS AND DISCUSSION

A. Tensile Strength (TS)

The TS of the Kraft insulation paper was evaluated in both the CD and MD to assess the anisotropic mechanical behaviour of the material under different experimental conditions. The results are presented in Fig 3 and 4, respectively.

Fig 3 illustrates the TS values in the CD orientation. All samples exceed the IEC 60641-3-2 standard minimum value of 35 MPa [12], indicating compliance with baseline mechanical performance requirements. Sample A (POME, unaged) recorded a TS of 49.24 MPa, while the addition of MWCNTs in Sample B (0.02 g/L MWCNT, unaged) significantly improved the strength to 55.68 MPa, a 13 % increase. This enhancement is attributed to the reinforcing effect of MWCNTs, which promote better fiber interaction.

After thermal aging at 100 °C for 50 hours, the TS of Sample C (POME, aged) decreased slightly to 46.78 MPa, indicating the onset of thermal degradation. However, Sample D (MWCNT nanofluid, aged) showing only a 1.4 % decrease compared to the unaged Sample B, suggesting that the presence of MWCNTs effectively mitigated mechanical degradation during aging.

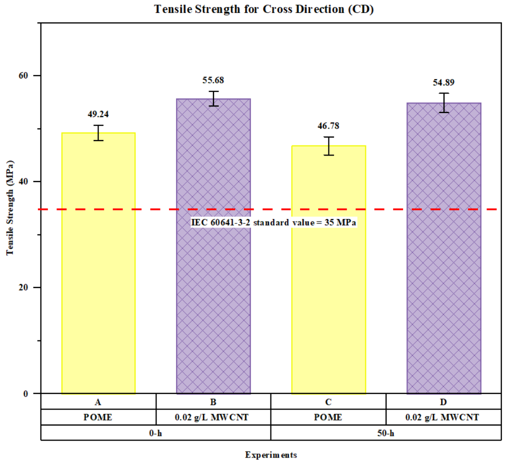

Fig. 3. Tensile strength analysis for Cross Direction

As shown in Fig 4, all MD samples recorded substantially higher TS values than their CD counterparts, confirming the anisotropic nature of Kraft paper. This is due to the predominant alignment of cellulose fibers in the machine direction during manufacturing [13, 14]. The MD of paper is parallel to the direction of travel during the manufacture of the paper; CD is perpendicular to MD.

Sample A (POME, unaged) had a tensile strength of 95.87 MPa. When MWCNT was added, Sample B (0.02 g/L MWCNT, unaged) slightly increased to 96.55 MPa, showing less than 1 % improvement. This small difference suggests that adding MWCNT has only a minor effect in the MD, likely because the fibers are already strongly aligned in this direction.

After 50 hours of thermal aging at 100 °C, the tensile strength of Sample C (POME, aged) dropped to 91.34 MPa, which is a 4.7 % decrease compared to Sample A. On the other hand, Sample D (MWCNT, aged) maintained a high tensile strength of 94.94 MPa, only 1.7 % lower than the unaged Sample B. This reduction is attributed to the thermal degradation of cellulose fibers, which causes chain scission and weakens the hydrogen bonding between fibers.

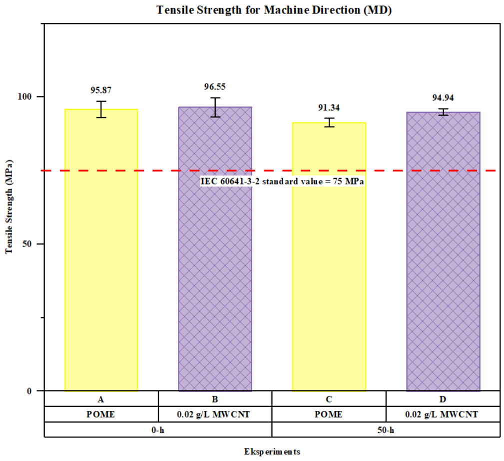

Fig. 4. Tensile strength analysis for Machine Direction

Notably, all samples in MD exceeded the IEC minimum requirement of 75 MPa, ensuring mechanical robustness suitable for transformer insulation applications.

B. AC Breakdown (ACBDV)

Fig.5 and Table II present the Weibull probability analysis of ACBDV for Kraft paper samples impregnated with POME and POME-based nanofluids containing 0.02 g/L MWCNT, both before and after thermal aging.

A comparison between Sample A (POME, unaged) and Sample B (POME + 0.02 g/L MWCNT, unaged) shows that the characteristic breakdown voltage (α) increased from 48.66 kV/mm to 51.48 kV/mm, reflecting a 5.8 % improvement. This indicates that the incorporation of MWCNTs effectively enhances the dielectric strength of Kraft paper in its unaged state. Under aged conditions, Sample D (POME + MWCNT, aged) also outperformed Sample C (POME, aged), with α increasing from 47.52 kV/mm to 48.96 kV/mm, equivalent to a 3.0 % enhancement. This demonstrates that MWCNTs not only improve initial insulation performance but also contribute to maintaining dielectric strength after thermal aging.

In contrast, comparing Sample A and Sample C (both using pure POME) reveals a 2.3 % decrease in breakdown voltage due to aging, highlighting the expected degradation effect under thermal stress. Lastly, the comparison between Sample B and Sample D, both containing MWCNTs, shows a 4.9 % reduction in breakdown strength after aging. Although a performance drop is observed, it is notably less severe than that seen in the POME-only samples, confirming that MWCNTs help mitigate aging-related dielectric deterioration and enhance the long-term reliability of the insulation system.

In this study, three key probability distribution percentiles were identified from the Weibull fitting, as presented in Table II. The ACBDV values at low failure probabilities (1% and 10%) indicate the voltage limits for safe and continuous operation, thereby reflecting the reliability of the Kraft insulating paper. Conversely, the 50% probability corresponds to the average ACBDV value.

TABLE II. SHAPE, SCALE, AND AC BREAKDOWN VOLTAGE OF WEIBULL PROBABILITY

Sample	Shape Parameter, β	Scale Parameter, α	V 1 % (kV/mm)	V 50 % (kV/mm)	V 90 % (kV/mm)
A	6.99	48.66	24.98	48.43	54.65
B	26.09	51.48	43.06	51.40	52.98
C	8.23	47.52	27.22	47.24	52.63
D	18.66	48.96	38.26	48.71	51.14

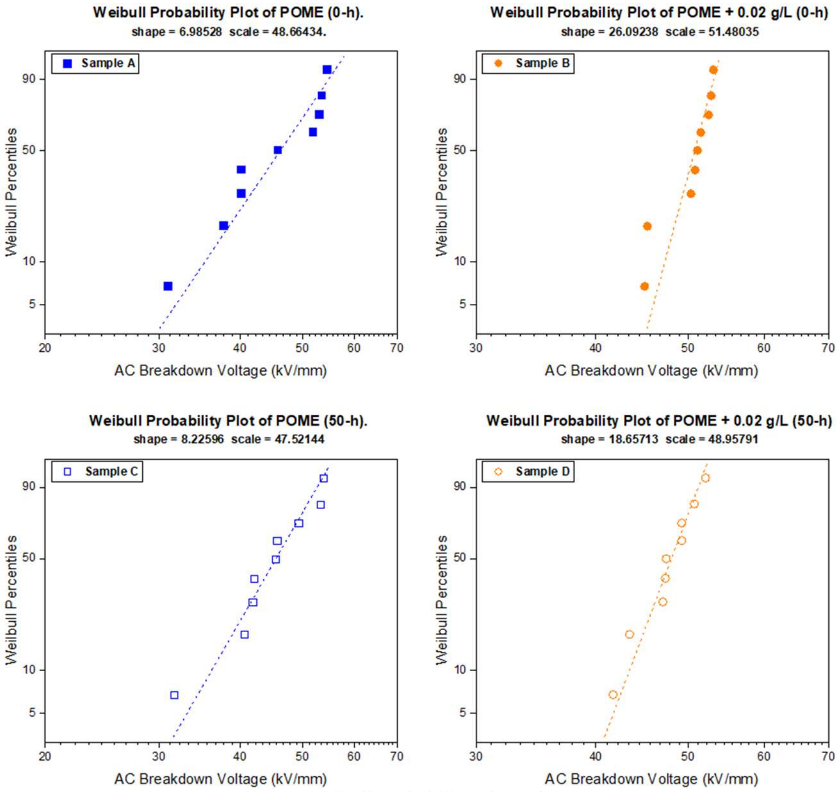

Fig. 5. Weibull probability plots of ACBDV

IV. CONCLUSION

This study evaluated the mechanical and dielectric performance of Kraft insulation paper impregnated with POME and POME-based nanofluids containing MWCNTs, under both unaged and thermally aged conditions. Mechanical behavior was assessed through TS in both MD and CD, while dielectric strength was evaluated using ACBDV supported by Weibull statistical analysis.

The TS test results confirmed the anisotropic nature of Kraft paper, with MD values significantly higher than CD due to the directional alignment of cellulose fibers during manufacturing. In the CD orientation, MWCNT incorporation led to a notable 13 % increase in TS (from 49.24 MPa in Sample A to 55.68 MPa in Sample B), and only a slight reduction of 1.4 % after aging (Sample D vs Sample B), indicating strong reinforcement and thermal resistance. In the MD orientation, TS improvement from MWCNTs was minimal (less than 1 %), but samples still maintained high mechanical integrity. Even after aging, the reduction in TS was lower in MWCNT-treated samples (1.7 %) compared to those using pure POME (4.7 %). All samples in both directions exceeded IEC 60641-3-2 minimum requirements, demonstrating mechanical suitability for transformer insulation.

In terms of dielectric performance, the inclusion of MWCNTs led to a 5.8 % increase in characteristic breakdown voltage (α) in unaged samples and a 3.0 % increase in aged samples, compared to POME-only conditions. Aging resulted in a 2.3 % reduction in α for pure POME samples (Sample A to C), whereas MWCNT-treated samples experienced only a 4.9 % decline (Sample B to D), confirming the stabilizing effect of MWCNTs under thermal stress. Weibull shape parameters (β) also indicated more consistent and reliable breakdown behavior in nanofluid-treated samples.

In conclusion, the results clearly demonstrate that MWCNT-reinforced POME nanofluids significantly improve both the mechanical and dielectric performance of Kraft insulation paper. The improvements are especially evident under thermally aged conditions, where MWCNTs help maintain strength and insulation reliability. These findings support the potential application of MWCNT-based natural ester nanofluids as an environmentally friendly and high-performance alternative to conventional transformer insulation systems. Future research may focus on long-term aging behavior, nanoparticle optimization, and compatibility with other insulation components for industrial application.

While this study has demonstrated the benefits of incorporating MWCNTs into POME-based insulation systems, several areas remain open for further investigation. Future work should focus on optimizing nanoparticle concentration and dispersion techniques to achieve maximum performance. Additionally, chemical characterization techniques such as FTIR, SEM, and TGA should be applied to assess microstructural changes, thermal stability, and fiber-nanoparticle interactions. These investigations will contribute to a more comprehensive understanding of nanofluid-insulated systems and support the development of reliable, sustainable transformer insulation materials.

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