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Electrical Breakdown Strength Characteristics of Palm kernel oil Ester-based Dielectric Fluids

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Abstract- **Natural ester fluids have been synthesized from crude palm kernel oil for consideration as an alternative to mineral oil based insulating fluid. Chemical modification of the oil enhanced the physico-chemical properties of the fluid. This paper presents the statistical analysis of the AC electrical breakdown strength of the synthesized esters in comparison with the crude palm kernel oil sample. The breakdown test was carried out in accordance with ASTM 1816 test method using a bespoke test cell designed for small sample volume. The estimated characteristic breakdown strength of the esters, defined as the 63.2% cumulative failure probability, is significantly higher than the BS148 mineral oil. The slopes, indicating the shape parameters, are similar. The results suggest that, at least in this regard, the synthesized esters may serve as an alternative to mineral oil as a transformer fluid.**

I. INTRODUCTION

Dielectric fluids are used in transformers to improve the dielectric strength of insulating paper and protect the live and grounded part of transformers from failure. Conventional mineral insulating oil is often used for this purpose. But environmental concern over oil spillage from transformers following insulation failure and uncertainty concerning petroleum products availability have shifted attention towards research in the development of sustainable dielectric fluid for electrical insulation. Chemical modification of seed-based oil was found to influence physico-chemical properties of the oil [1]. Earlier work has shown that side branching in hydrocarbon compounds influences the conduction mechanism due to high mobility of charges present [2]. This work reports on the statistical analysis of breakdown field of various alkyl esters of palm kernel oil.

Measurements of breakdown field vary for each specimen of a sample as the weakest link which is the most probable breakdown spot, is randomly distributed. The breakdown field measurements of insulating materials can be regarded as a random variable and the likely electrical breakdown field of an insulating material can be estimated from the distribution of the breakdown field data using statistical techniques [3]. The breakdown field of insulating materials is sometimes expressed as the mean value of measured breakdown field of a number of samples. The breakdown strength test of electrical insulation materials can be carried out under progressive stress conditions where the breakdown voltage is measured for a number of test specimens. A number of statistical analytical tools are available for the analysis of statistical data, but the Weibull distribution is the most commonly used distribution function for statistical analysis of breakdown field data. It was reported that the Weibull distribution has wide applicability and is a type of extreme value distribution in which the system fails when the weakest link fails [4]. The cumulative probability of failure for the two-parameter Weibull distribution is given by

$$F(v) = 1 - exp\left\{-\left(\frac{v}{\alpha}\right)^{\beta}\right\} \qquad 1$$

where $F(v)$ is the cumulative probability of breakdown at voltage, v, α, the characteristic breakdown voltage is the value of v, at which the cumulative probability of failure is $(1 - \exp\{-1\}) = 0.632$, and β, is the shape parameter, which is a measure of the range of failure voltages within the distribution [3]. The behaviour of insulating fluids following synthesis can be evaluated from estimation of the characteristic breakdown strength, the shape parameter, and the confidence bounds of the distribution describing an insulating fluid. Martin *et al* reported that Weibull distribution function is appropriate for the calculation of withstand voltage of ester-based transformer oils [5].

II. EXPERIMENTAL

A. Sample Preparation

An alkyl ester (PKOAE1) was synthesized from laboratory purified palm kernel oil by transesterification. Epoxy alkyl ester (PKOAE2) was then synthesized by epoxidation of PKOAE1 with an *insitu* peracetic acid [6]. Branched alkyl esters (PKOAE3 and PKOAE4) were then prepared using an

Table1: Sample Description

Sample	Description
PPKO	Purified palm kernel oil
PKOAE1	Palm kernel oil methyl ester
PKOAE2	Palm kernel oil epoxy methyl ester
PKOAE3	Palm kernel oil methyl ester with C-3 carbon side chain
PKOAE4	Palm kernel oil methyl ester with C-4 carbon side chain
BS148	Mineral Insulating Oil

acid-catalyzed ring-opening reaction of PKOAE2 and acid anhydrides in the presence of nitrogen. Sample descriptions are summarized in Table 1. The samples were dried by degassing at reduced pressure in a vacuum oven at temperature of 85˚C for 2 hours. A sample of BS148 mineral insulating oil and purified palm kernel oil was also dried by degassing in a vacuum oven at a temperature of 85˚C for 2 hours.

B. *Breakdown Strength*

An AC voltage was applied using a 50kV step-up transformer for the breakdown test. During each experiment, the applied voltage was increased manually from zero at a rate of approximately 0.4 kV/s until breakdown occurred. A transformer control unit (TCU) monitored the cell current and interrupted the supply voltage to the step-up transformer when breakdown occurred in the sample test cell (fig. 1). The cell was designed to take small sample volumes (≈5ml) with a sphere electrode gap of 1 mm. In comparison, the volume required using the IEC 156:1995 standard designed cell is 350 ml to 600 ml. For each of the ester samples, ten breakdown measurements were carried out at 20 ˚C, while five breakdowns were carried out on BS148 and PPKO samples at 20˚C and 30˚C respectively.

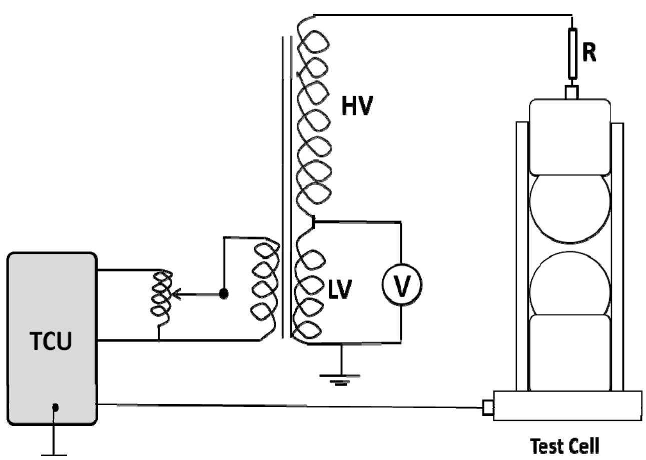

Fig. 1: Schematic of electric breakdown test setup and bespoke breakdown test cell.

III. RESULTS AND DISCUSSION

Table 2 shows the analysis of the breakdown test results for PPKO, PKOAE1, PKOAE2, PKOAE3, PKOAE4 and BS148 samples using Normal (Guassian) statistics. The mean breakdown voltage of BS148, which was evaluated to be 26.4 kV, with a standard deviation of 1.8 kV is comparable with the recommended breakdown voltage of Insulating oil in Electric equipment with voltage rating of 345 kV and above [7]. Also shown in Table 2, are the results obtained from purified palm kernel oil and the processed esters. The mean breakdown voltages for purified oil was 40.6 kV and this value increased to 42.6 kV following epoxidation and esterification. The standard deviations of the breakdown voltage measured for the esters and the mineral oil samples are similar, indicating low dispersion in the breakdown voltage data. The mean breakdown strength of palm kernel oil samples was compared with the minimum mean breakdown voltage recommended in the literature for natural ester (as-received) insulation fluid measured using standard test methods ASTM D1816. A natural ester based dielectric fluid is recommended to have a minimum mean breakdown voltage of 35 kV (1 mm gap) for voltage class of 345 kV and above [8]. However, in this study the mean breakdown voltage for the synthesized alkyl ester has a breakdown voltage that exceeds this limit by a significant amount.

Table 2: Normal Distribution parameters of the Breakdown Test

Samples	No. of Breakdowns	Mean BDV (kV)	Standard Deviation (kV)
PPKO	5	40.6	1.79
PKOAE1	5	42.2	1.41
PKOAE2	5	42.6	0.98
PKOAE3	5	42.4	2.60
PKOAE4	5	42.1	1.41
BS148	5	26.4	1.83

Table 3 shows that Weibull parameters of the AC breakdown field data of the oil samples. The characteristic breakdown strength of the samples denoted as α, and the shape parameter, β, are tabulated with their respective 95% confidence intervals. The correlation coefficients of the breakdown data when fitted to the Weibull function, equation 1, are much greater than the critical correlation coefficient of $R^2 = 0.918$ for 10 breakdowns [3]. This demonstrates a strong linear relationship between the two parameters. The statistical data shows a slight improvement in the characteristic breakdown strength of the alkyl ester samples when compared to PPKO. This shows that alkyl ester derivatives of purified palm kernel oil have improved breakdown strengths. The characteristic electric field strength of the palm kernel oil ester derivatives is

Table 3: Weibull Parameters of the Breakdown test

Samples	*N*	*Characteristic value, α* (kV/mm)	*95% Conf. Bound for α (kV/mm)*	*Shape parameter, β*	*95% Conf. Bound for β*	*Correlation Coefficient*
PPKO	5	41	39.92 – 42.73	23.05	13.13 – 55.31	0.981
PKOAE1	10	43	41.96 – 43.60	28.85	19.25 – 48.32	0.983
PKOAE2	10	43	42.18 – 43.59	33.84	22.58 – 56.68	0.947
PKOAE3	10	43	41.48 – 45.25	12.76	8.51 – 21.37	0.937
PKOAE4	10	43	41.51 – 44.82	14.49	9.67 – 24.27	0.948
BS148	5	27	25.83 – 28.59	15.49	8.82 – 37.17	0.941

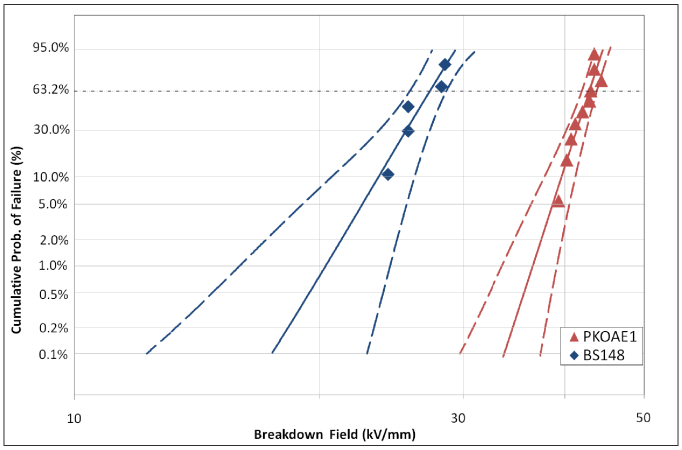

Figure 1: Weibull plot of PKOAE1 and Mineral oil

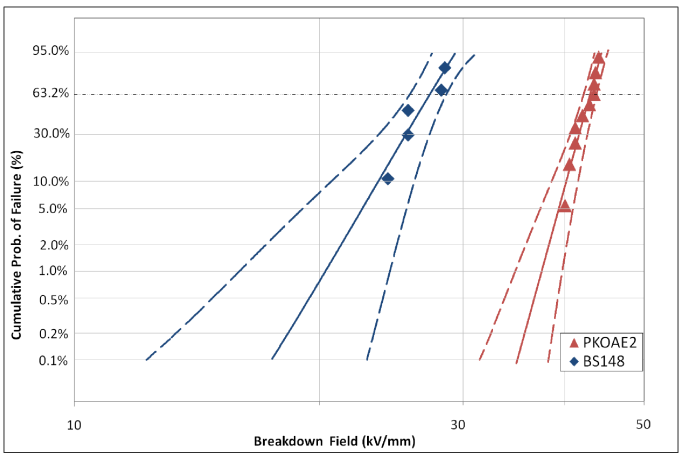

Figure 2: Weibull plot of PKOAE2 and Mineral oil

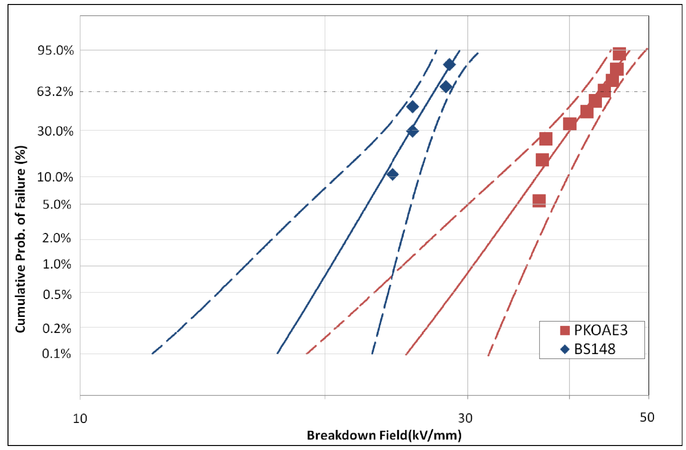

Figure 3: Weibull plot of PKOAE3 and Mineral oil

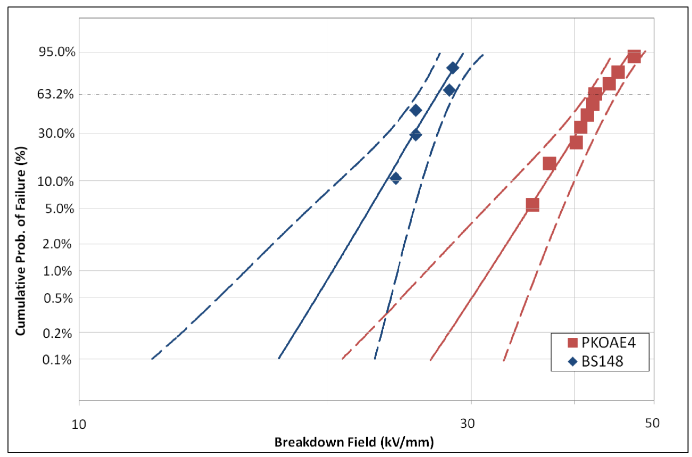

Figure 4: Weibull plot of PKOAE4 and Mineral oil

about 37% better than BS148 mineral insulating oil.

The high values for the fitted shape parameter, β, of palm kernel oil ester derivatives demonstrates that the ester derivative have a narrow distribution of breakdown field. Figures 1 through 4 show plots of the Weibull distributions obtained from the breakdown measurements for the different oil types at the different stages of preparation. The Weibull distribution of the synthesized esters was compared to that of mineral oil (BS148). Over the full range of failure probability, the breakdown strength of the esters is significantly greater than the mineral oil. The results demonstrated that no significant difference in the Weibull distribution following epoxidation. However, the shape parameter of PKOAE1 and PKOAE2 demonstrates that the breakdown values tend to cluster around a modal value with low variability, while that of the branched alkyl esters are more dispersed. High β values for PKOAE1 and PKOAE2 suggest low dispersion in the breakdown data of the samples. A decrease in the β values for PKOAE3 and PKOAE4 suggest that impurities introduced during the processing may have lead to high dispersion of the their breakdown data. But the β values are similar to the β value of BS148.

IV. CONCLUSION

This work investigates the electrical breakdown strengths and distributions of dielectric fluids developed from alkyl esters of palm kernel oil. The molecular structure of the esters was modified to improve its low temperature performance. A comparison of the breakdown behaviour of the esters and mineral oil was carried out. The mean AC breakdown field of the ester was significantly higher than that of mineral oil sample. The side branched carbon chain did not appear to have any effect on the breakdown field. With the reported low viscosity and high oxidative stability of the esters [2,6], the high breakdown field of the synthesized esters makes it viable alternative insulating fluid.

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REFERENCES

[1] B, R. Moser, B. K. Sharma, K. M. Doll, S. Z. Erhan, 2007, Diester from Oleic Acid: Synthesis, Low Temperature Properties, and oxidation Stability, J. Amer. Oil Chem. Soc. 84, 675-680. *J. Am. Oil Chem. Soc.* Vol. 84, pp. 675-680.

[2] A.A. Abdelmalik, A.P. Abbott, J.C. Fothergill, S. Dodd & R.C. Harris, Effect of Side Chains on the Dielectric Properties of Alkyl Esters Derived from Palm Kernel Oil, 17th *International Conference on Dielectric Liquid*, Trondheim, Norway, 2011.

[3] IEEE Std 930-2004, *IEEE Guide for the Statistical Analysis of Electrical Insulation Breakdown Data*, IEEE, 2005.

[4] L.A. Dissado, J.C. Fothergill, *Electrical Degradation and Breakdown in Polymers*, IEE, 1992.

[5] D. Martin and Z.D. Wang, Statistical Analysis of the AC Breakdown Voltages of Ester Based Transformer Oils, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 15, No. 4, Pp. 1044-1050, 2008.

[6] A.A. Abdelmalik, A.P. Abbott, J.C. Fothergill, S. Dodd & R.C. Harris, "Synthesis of a Base-Stock for Electrical Insulating Fluid based on Palm Kernel Oil", *Industrial Crops and Products*, 33, 532–536, 2011.

[7] IEEE Std C57.147-2008, *IEEE Guide for Acceptance and Maintenance of Natrural Ester Fluids in Transformers*, IEEE.

[8] C.T. Dervos, C.D. Paraskevas, P. Skafidas, P. Vassiliou, 2005, Dielectric Characterization of Power Oils as a Diagnostic life Prediction Method, *IEEE Insulation Magazine*, Vol. 21, No. 1.