

Thermal Performance of Nomex-910 and TUK Insulating Papers in Soya-based Natural Ester Oil

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Abstract: In this paper, evaluation of Nomex-910 and thermally upgraded Kraft (TUK) paper has been investigated in soya-based natural ester oil by performing accelerated thermal ageing. All the test samples have been prepared in standard oil/paper ratio in accordance with the IEEE Std. C57.154.2012 and are thermally stressed at 120°C, 150°C and 180°C as per modified ASTM D1934. Diagnostic measurements those including dielectric strength and tensile strength for insulating papers; UV/Vis spectroscopy, Dissipation factor, and Resistivity of oil have been reported as per ASTM standard test methods. The degree of concentration of conductive contaminants in Nomex system is slightly higher but are comparable. This is attributable to the high absorbance of Natural ester fluid. It is found, that dielectric strength and mechanical strength of Nomex paper is superior to that of the TUK paper. The deterioration rate of paper and the oil/paper insulation system has been verified with the natural ester-nomex insulation system and is found to be a possible alternative.

Keywords: Natural ester oil, Nomex paper, Spectroscopy, tensile strength.

1. Introduction

Power transformers play a preeminent role in the modern technical era and have the responsibility of reliable transmission and distribution of the electrical energy. The life of the transformer is highly attributable to the performance of the insulation system [1, 2]. The operating characteristics of solid and liquid insulations are greatly influenced by electrical and thermal stresses [3]. These stresses accelerate the ageing mechanism and consequently the service life of the insulating material gets reduced. The insulating materials become thermally unstable at elevated temperatures and lose many of their insulating properties. The rate of degradation of insulation depends on various factors such as moisture content, acid content, amount of oxygen and temperature [4]. Hydrolysis, Oxidation and Pyrolysis are the three main contributors to the degradation of insulating materials [5]. From the last several decades, numerous researchers have reported the performance of alternative insulating materials and their effect on transformer insulating materials with thermal and electrical stressing [6-15]. Cellulose based Kraft papers have been used as solid insulation in liquid filled power transformers from many decades [16]. Though the thermal class of the Kraft paper is low, it has been used by electrical utilities because of its low cost and reasonably good performance [17-18]. From the past few years, DuPont has introduced Nomex-910 electrical insulating papers which is comprised of both cellulose and aramid ingredients. It was developed to provide interlayer insulation and also used for conductor insulation in any transformer. It has a thermal class of 130°C in mineral oil and 140°C in ester oil [19]. Though Nomex insulating papers have higher thermal class than TUK paper, very less research work has been reported related to these materials [20].

TUK paper and mineral oil are the two solid and liquid insulations which have been used from many decades. At high temperatures, the cellulose paper exerts and loses many of its properties. Mineral oil filled transformers also requires additional fire safety measures and is not eco-friendly. Though, the combination works meticulously in spite of shortcomings in their electrical, thermal and mechanical properties, but there is still a need to find a better combination

Received: August 20th, 2019. Accepted: March 12nd, 2020

DOI: 10.15676/ijeel.2020.12.1.5

of solid and liquid insulations which should be environmental friendly and can enact proficiently than the existing insulations. Since performance of TUK and Nomex paper in natural ester oil is not disclosed yet, so in the present work two combinations i.e. TUK-ester and Nomex-ester have been considered for the present experimental investigation.

2. Experimental Investigation

A. Preparation of Samples

A large number of test samples have been prepared in the present experimental evaluation. Initially, all the conical flasks were rinsed with clean water and then dried out in air circulated oven by setting it to 100°C for 24 hours. This is done to remove all the moisture content which may be present in the flasks. Each flask was allowed to cool down to room temperature and then filled with natural ester oil. Oil filled flasks were again placed in the oven to ensure the complete removal of moisture content which may get added during the sample preparation. Dried TUK and Nomex papers were put separately in the oil filled flasks. Copper strip is also added to the flasks to simulate real operating conditions of the transformer. All the samples have been prepared in standard mass ratio in accordance with IEEE Std. C57.154.2012 [21]. Table 1 shows the specifications of the materials used in the experimental analysis.

Table 1. Details of materials used

Material	Specifications
Insulating Oil	Soya based Natural Ester Dielectric Fluid
Insulating Paper	Nomex-910 paper (3 mil) and Thermally Upgraded Kraft paper (3 mil)
Borosil Conical Flask	250 ml
Electric Oven	PID based temperature controlled oven, 500±2°C
Copper Strip	35 mm × 20 mm × 3 mm
Cork	Rubber

B. Thermal Ageing Procedure

According to IEEE Std. C57.100-2011 and IEC 60216-1:2013, only thermal stress is considered in the present experimental investigation work [22-23]. Accelerated thermal ageing has been performed on each prepared sample at 120°C, 150°C and 180°C for 48, 72 and 96 hours of ageing respectively. In order to obtain the considerable changes in the dielectric properties of the insulating materials, 24 hours of ageing duration is not considered. Initially, three samples of each Nomex and TUK paper in ester oil were taken and put inside the oven whose temperature was set at 120°C. After 48 hours of ageing, one sample of each paper was taken out from the oven and was allowed to cool down to room temperature. After that, both the samples were placed inside a dark room and handled in accordance with ASTM D923-15 [24]. Same procedure was followed after 72 and 96 hours of ageing. Now, there were three set of two samples obtained at 120°C after 48, 72 and 96 hours. Subsequently, diagnostic tests were performed on the obtained aged samples. Similar procedure was followed for obtaining aged samples at 150°C and 180°C.

3. Results and Discussions

A. Dielectric Strength of paper

In designing an electrical apparatus, dielectric strength of the insulating paper serves as a great deciding factor in which it is to be used. This test determines the maximum voltage which can be applied across the thickness of the insulating paper before its failure. Mineral oil was used as a surrounding medium, which meets the specification of ASTM D3487 [25]. The quality of the surrounding medium has a noticeable effect on the test results. Any significant reduction in the BDV indicates the presence of moisture in the paper. This test was conducted in accordance

with ASTM D149-09 [26]. It is already known that the thermal class of Nomex paper in natural ester oil is more when compared with TUK paper.

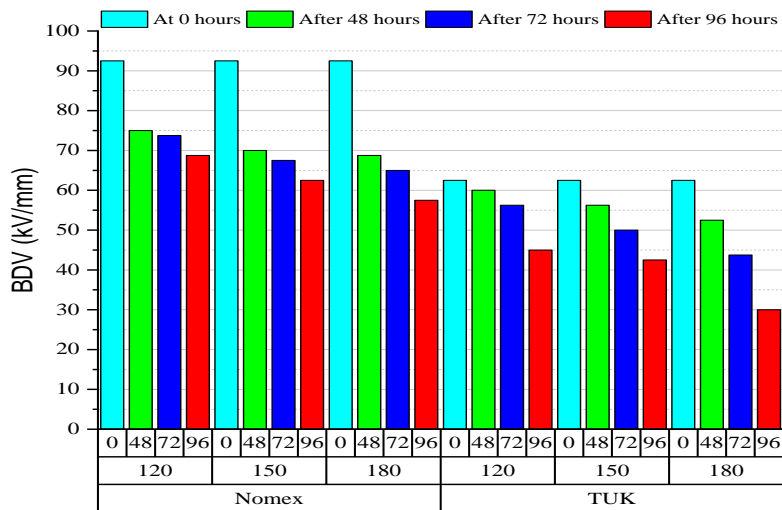


Figure 1. Variation in BDV of Nomex and TUK paper with accelerated thermal ageing.

It is observed from Figure 1 that the BDV of TUK paper sample falls down by more than 30% when the thermal stress ranges from 120°C to 150°C. At 180°C after 96 hours, the BDV value falls down by 52% from its virgin sample value. But in case of Nomex paper, the drops in BDV value are less and it is 37.83% at 180°C after 96 hours. Since Nomex paper is comprised of both cellulose and aramid ingredients, it exhibits better dielectric strength than TUK paper. It is found that, for same temperature and ageing duration, Nomex paper is more thermally stable and is less degraded than TUK paper. The transformer with Nomex paper can be overloaded for more time and consequently, the life of paper insulation is comparatively better than with TUK paper.

B. Tensile strength of paper

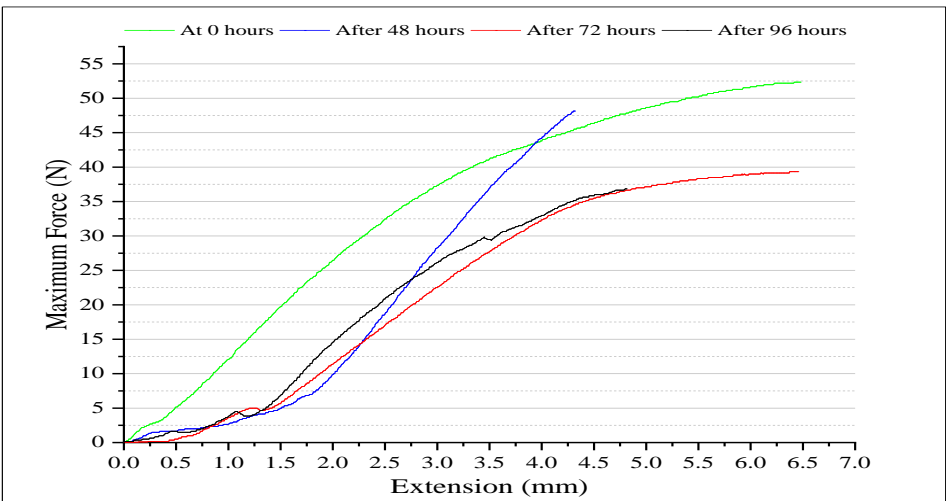


Figure 2. Tensile strength test result of Nomex paper at 120°C.

Tensile strength is indicative of serviceability of papers. During the wrapping of paper over the winding coils, the paper should be capable to bear the tensile force exerted on it. It determines the maximum amount of tensile stress that a material can take before failure. Degree of polymerization (DP) value and tensile strength of paper has a strong correlational with each other. With increase in ageing duration and stresses, the tensile strength of paper decreases. As the ageing of insulating paper is an irreversible process, the determination of tensile strength is very essential. Because a sudden short circuit in the winding conductors due to tearing and bursting of paper can cause catastrophic failure of the transformer. This test was conducted on Universal Testing Machine in accordance with ASTM D828-16 [27].

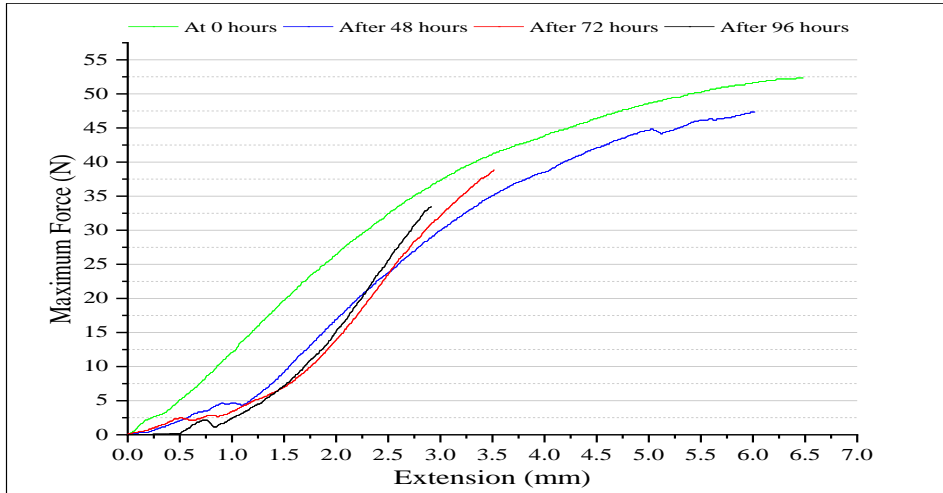


Figure 3. Tensile strength test result of Nomex paper at 150°C.

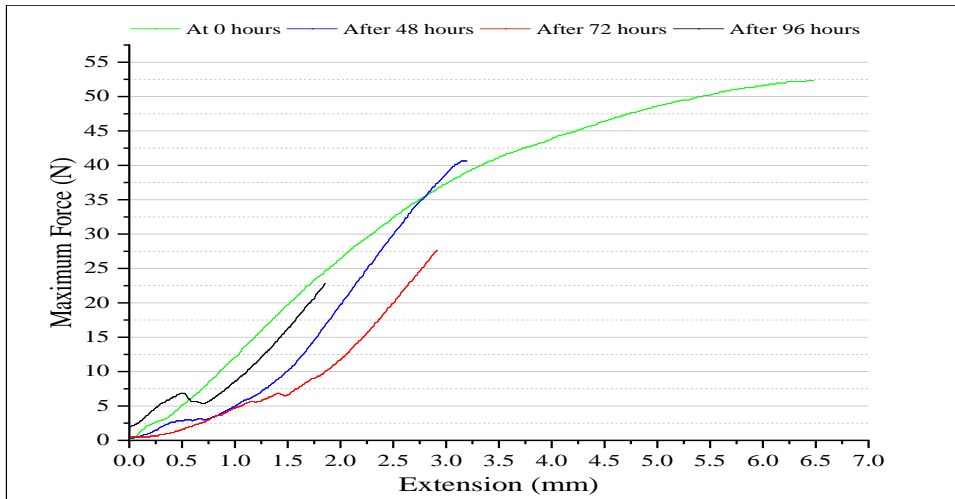


Figure 4. Tensile strength test result of Nomex paper at 180°C.

Figure 2-4 shows tensile strength test results of Nomex paper at different temperatures and ageing durations. It can be seen that, virgin paper sample takes maximum 52.35 N of tensile force before failure. As the paper sample ages, the value decreases and drops to 36.85 N after 96 hours of ageing at 120°C. The drops in tensile force are very high at 150°C and it reaches 22.85 N at 180°C after 96 hours.

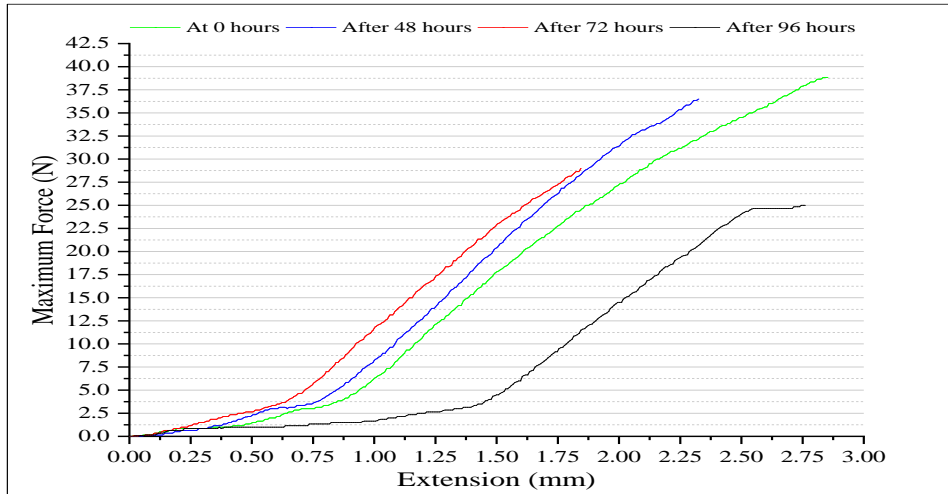


Figure 5. Tensile strength test result of TUK paper at 120°C.

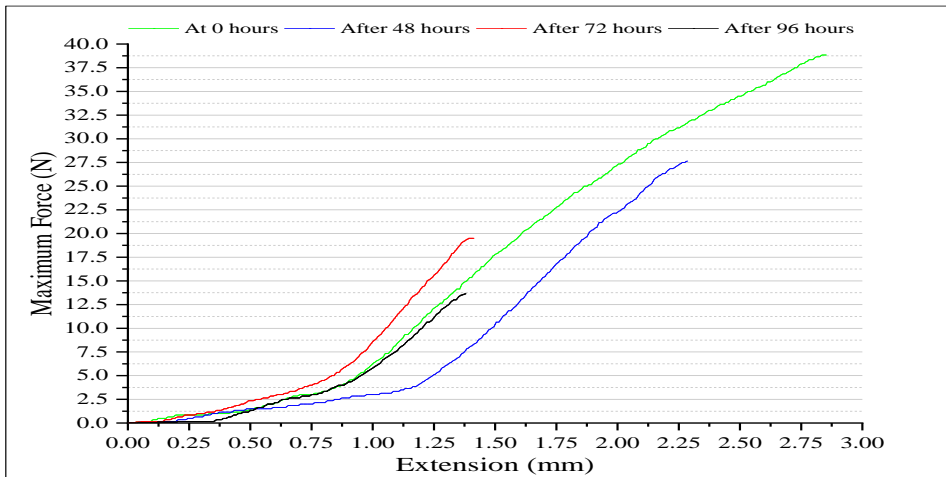


Figure 6. Tensile strength test result of TUK paper at 150°C.

Figure 5-7 shows tensile strength test results of TUK paper at different temperatures. The virgin TUK sample takes 38.85 N of tensile force before failure. The maximum tensile force falls down to 25 N after 96 hours of ageing at 120°C. The value drastically reduced to 6.65 N at 180°C. It is found that TUK paper starts breaking at very low value of tensile force at high temperatures. It is also found that the extension range in case of Nomex paper is high which indicates that the elongation of Nomex paper is comparatively more than that of TUK paper.

Figure 8 shows the variation in tensile strength of Nomex and TUK papers. At 120°C, the tensile strength of TUK paper sample falls down by 35.68%. This value further drop to 55.35% at 150°C and it is highest at 180°C. Tensile strength of TUK paper falls down drastically by 82.88% at 180°C. For Nomex paper, the tensile strength falls down by 29.59% and 36% at 120°C and 150°C respectively which is comparatively less than TUK paper. The value falls down by 56.33% at 180°C after 96 hours. It is found that Nomex paper has more tensile strength and can withstand high thermal stresses for long durations. Consequently, the DP value is also less

affected. Nomex paper is found to be more suitable for high temperature applications where high mechanical strength is desirable.

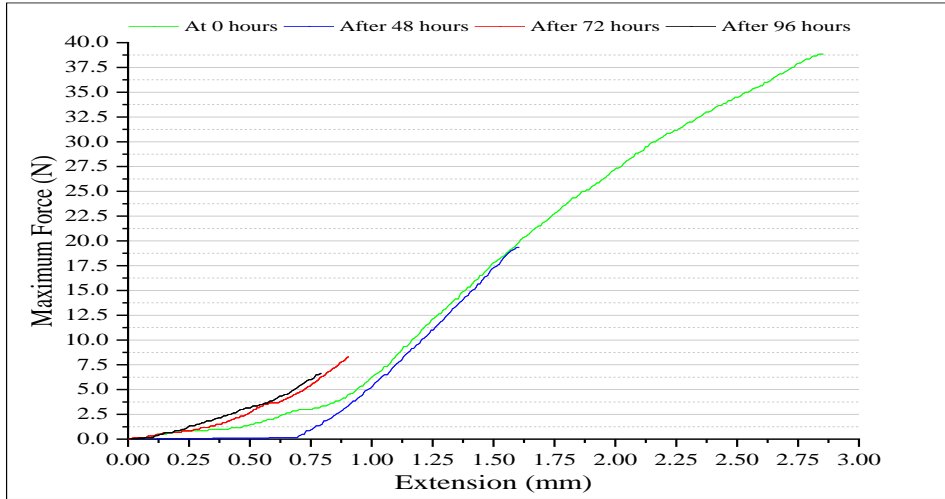


Figure 7. Tensile strength test result of TUK paper at 180°C.

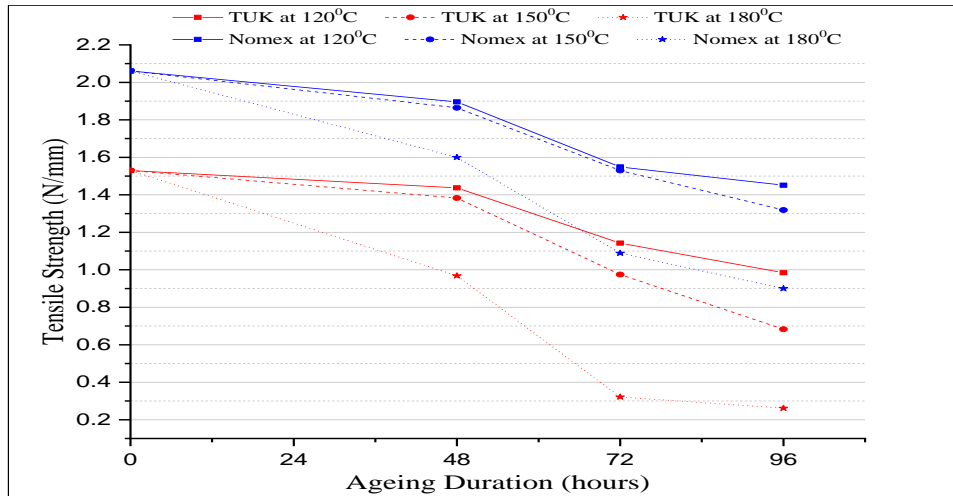


Figure 8. Variation in tensile strength of Nomex and TUK paper with accelerated thermal ageing.

C. UV/Vis Spectroscopy of oil

This test measures the amount of light absorbed by the oil sample due to the presence of dissolved decay products. The dissolved decay products in insulating oil contain variety of chemical compounds such as ketones, organic acids, peroxides and aldehydes. These compounds get partially adsorbed on the considerable surface of insulating paper which results in premature ageing of the power transformers. Therefore relative determination of by-product formation can be used as an important indicator of the insulating oil ageing. This test was conducted in accordance with ASTM D6802-02 [28] and sampling of oil was done with ASTM D923 [24].

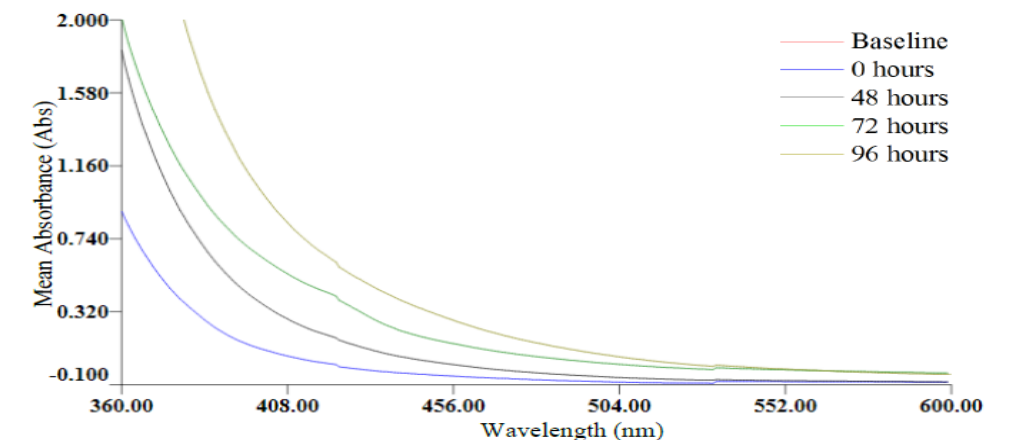


Figure 9. Variation in absorbance curve of Nomex oil sample with increase in ageing duration at 120°C.

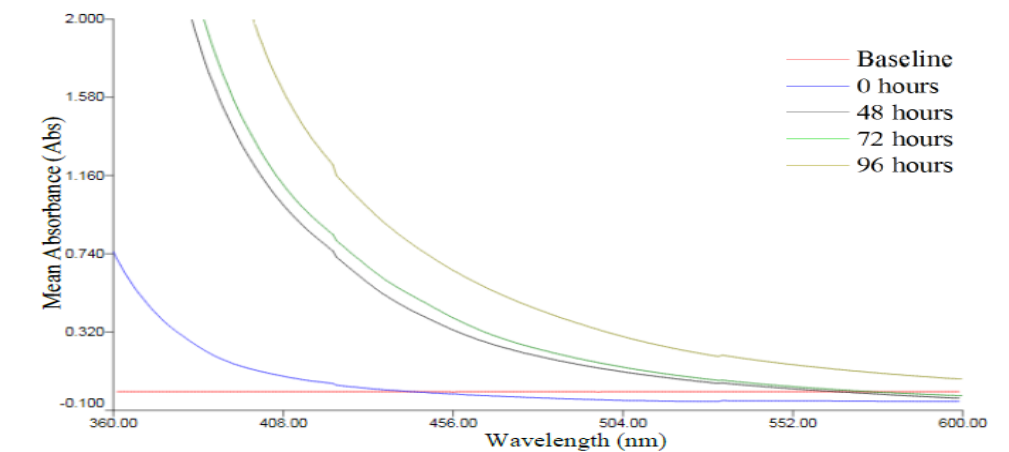


Figure 10. Variation in absorbance curve of Nomex oil sample with increase in ageing duration at 150°C.

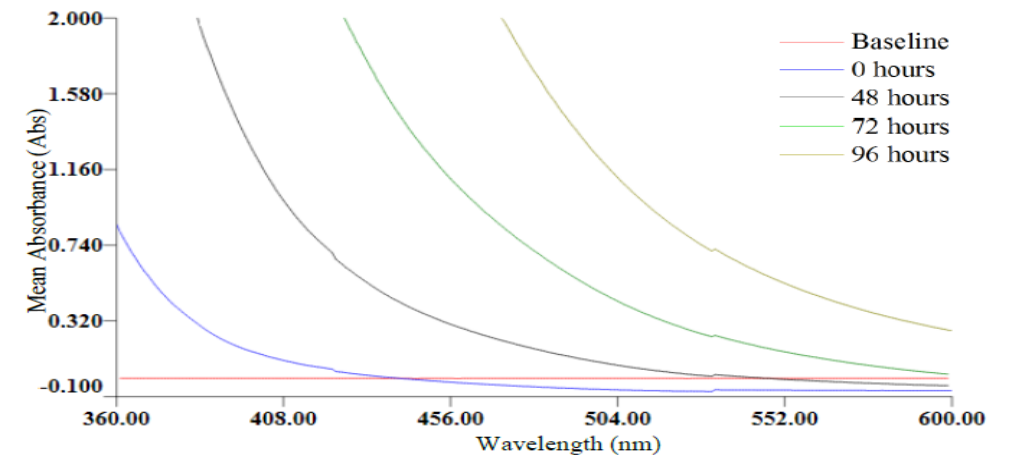


Figure 11. Variation in absorbance curve of Nomex oil sample with increase in ageing duration at 180°C.

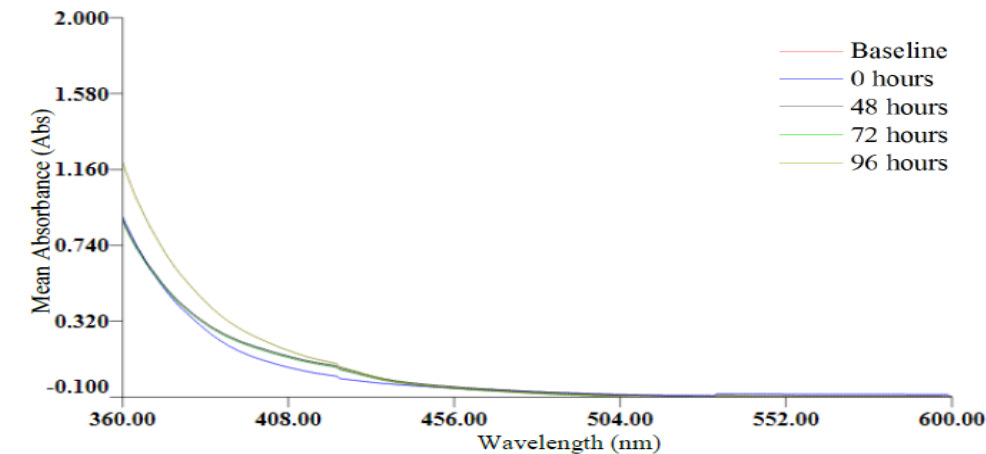


Figure 12. Variation in absorbance curve of TUK oil sample with increase in ageing duration at 120°C.

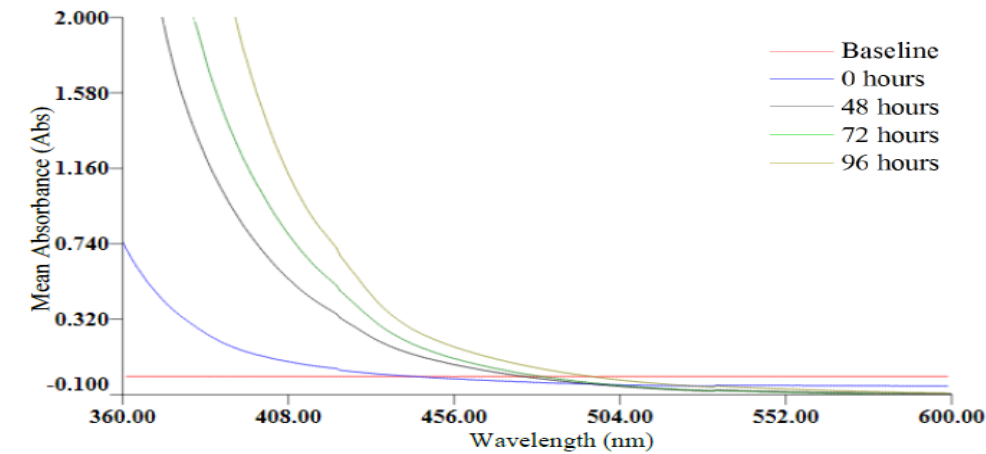


Figure 13. Variation in absorbance curve of TUK oil sample with increase in ageing duration at 150°C.

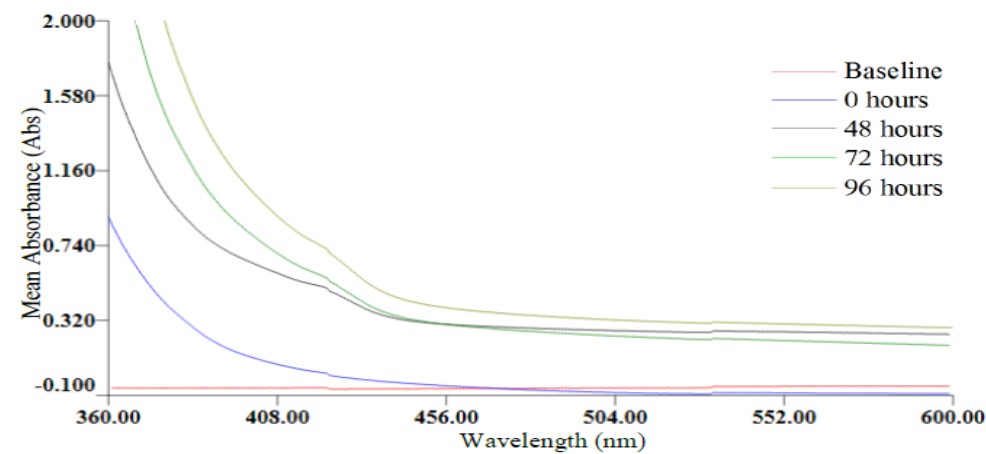


Figure 14. Variation in absorbance curve of TUK oil sample with increase in ageing duration at 180°C.

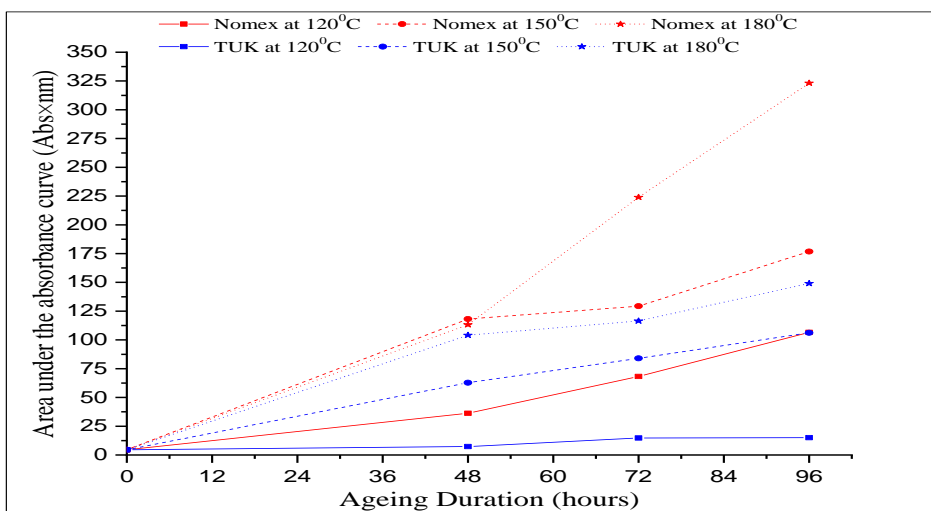


Figure 15. Variation in area under the absorbance curve of Nomex and TUK oil samples with accelerated thermal ageing.

Figure 9-14 shows the test results of UV/Vis Spectroscopy of Nomex and TUK oil samples at different temperatures and ageing durations. It can be seen that the absorbance curve shift upwards at lower wavelengths with increase in ageing duration and temperature. More shifts indicate presence of more dissolved decay contents in oil. The area under the absorbance curve has a strong relationship with the amount of dissolved decay content in oil.

From figure 15, it is found that UV spectra of TUK oil samples occupied less area under the absorbance curve than that of Nomex samples. Significant variations in absorbance curve were observed at temperature above 150°C. At high temperatures, the Nomex impregnated oil sample struggles in its purpose and shows less oxidation stability than that of TUK sample. Though the thermal class of Nomex paper in natural ester oil is more when compared with TUK paper in natural ester oil, but Nomex paper is giving more dissolved decay products in ester oil and this may also affect the cooling performance of the oil. The absorption coefficient of Nomex test samples is found to be more than TUK test samples. This indicates that the sludge formation due to oxidation and acid formation due to thermal stress is more in Nomex test samples. This dissolved decay products also affects the dissipation factor and resistivity of the insulating oil.

D. Dissipation factor of oil

Dissipation factor of an insulating material serves as a great influencing factor when the material is exposed to high thermal stresses. It is indicative of the dielectric losses in insulating oil when used in an alternating field. It is also indicative of the changes in the quality of the insulating material resulting from degradation of insulation in service. Presence of small amount of moisture in oil can greatly influence the value of dissipation factor.

A good insulating oil has dissipation factor below 0.005. This test was conducted in accordance with ASTM D924-15 [29]. Figure 16 shows variation in dissipation factor of Nomex and TUK oil samples at different temperatures for 96 hours of ageing. Dissipation factor for virgin oil sample is found to be 0.00625 and it increases with increase in temperature and ageing duration. It is found from the test results that the Nomex impregnated oil sample has very high dissipation factor which indicates high dielectric losses in oil and therefore the amount of energy dissipated as heat is also more. In case of TUK impregnated oil sample, the variation in dissipation factor is very less which indicates that the quality of TUK oil sample is good and it is not degraded much by accelerated thermal ageing.

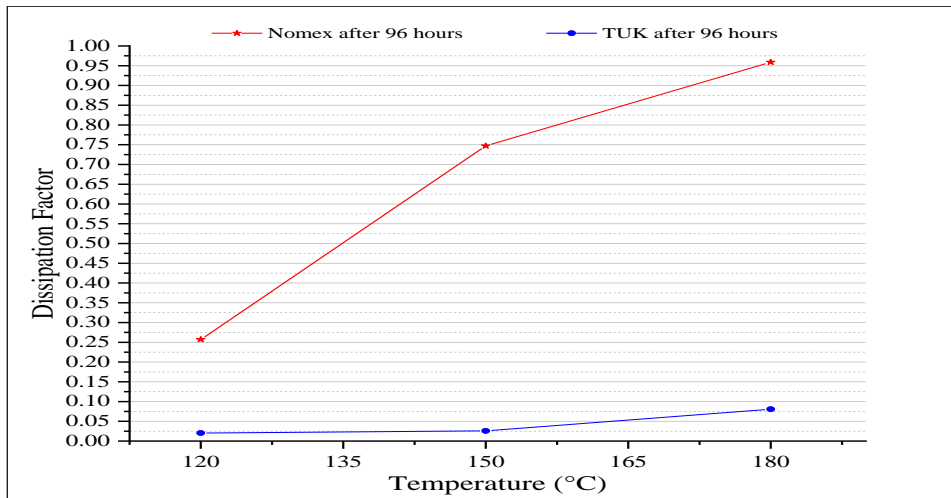


Figure 16. Variation in dissipation factor of Nomex and TUK oil sample with accelerated thermal ageing.

E. Resistivity of oil

Resistivity of the material is also correlated with dissipation value, and measures the electrical insulating properties of the insulating material. High value of resistivity is desirable in order to have low content of free ions and indicates low amount of conductive contaminants. This test was conducted in accordance with ASTM D1169-11 [30].

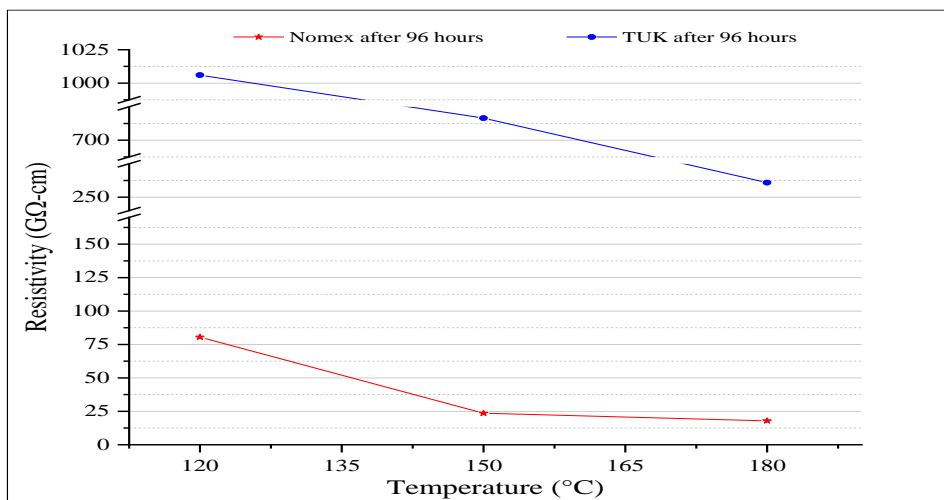


Figure 17 Variation in resistivity of Nomex and TUK oil sample with accelerated thermal ageing.

Figure 17 shows the variation in resistivity value of Nomex and TUK impregnated oil samples at different temperatures. Resistivity decreases as the insulating material ages. For virgin oil sample, the resistivity is found to be 4.769 TΩ-cm. It is found that the Nomex paper in natural ester oil produces more amount of free ions as well as the concentration of conductive contaminants than that of TUK paper. Therefore, Nomex impregnated oil sample degrades at much faster rate when it is exposed to high temperatures for longer durations.

4. Conclusion

It is found that, the BDV and tensile Strength of Nomex insulation paper is much higher than that of thermally upgraded cellulose insulation paper. But TUK paper in natural ester oil has less dissolved decay contents, low dissipation factor and high resistivity value. TUK is cellulose based, and is evident that the dielectric and mechanical strength of the TUK paper will significantly be affected or degraded at high temperatures. In TUK-Ester oil combination, the oil samples shows much better results for UV/Vis Spectroscopy, dissipation factor and resistivity test. However, rate of degradation of TUK paper is higher in natural ester fluid. Alternatively, in Nomex-Ester oil combination, deterioration of oil is higher whose properties may be regained by dehydration and other conditioning processes. Hence it is inferred that, Nomex paper in natural ester oil performs better than TUK-Ester combination and is an effective alternative for high voltage oil-paper insulation systems.

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