Comparison of Insulating Properties between Natural Ester, Mineral Oil, and GTL Oil for Transformer Applications

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Abstract: The increasing demand for electrical energy has led to the widespread use of high-voltage transformers, commonly utilizing mineral oil as an insulating fluid due to its availability and low cost. However, concerns over environmental impact and safety have prompted the exploration of more eco-friendly alternatives, such as natural ester oil and GTL oil. This study compares the insulating performance of mineral oil, natural ester oil, and GTL oil at 100°C over periods of 168, 504, and 840 hours. Key findings include significant differences in the performance of the oils under aging conditions. At 100°C, natural ester oil maintained the highest breakdown voltage (43.16 kV), while mineral oil and GTL oil had lower values (24.36 kV and 23.68 kV, respectively). Mineral oil showed a notable decrease in resistivity, from 2.9 to 2.0, while natural ester oil remained more stable. In terms of tensile strength, natural ester oil exhibited a stronger performance (6.04 kN/m), compared to mineral oil (4.46 kN/m) and GTL oil (3.22 kN/m). These results highlight the superior insulating properties of natural ester oil and its potential for improving transformer performance and sustainability.

Keywords: Transformer, Mineral Oil, Natural Ester Oil, Gas-to-Liquid (GTL) Oil, Liquid Insulation.

1. Introduction

The growing demand for electrical energy, driven by industrial expansion and urbanization, underscores the vital role of high-voltage transformers in power distribution due to their ability to adjust voltage levels as needed. Liquid insulation is a key component of high-voltage transformers, and mineral oil is commonly used for both insulation and cooling purposes [1]. The widespread use of mineral oil is largely due to its availability, affordability, and effective electrical conductivity and cooling properties [2]. However, mineral oil presents several challenges, particularly in terms of its environmental impact and safety. As a petroleum-derived product, mineral oil is non-renewable and non-biodegradable [3]. Spills or leaks can lead to environmental contamination, affecting soil and water. Furthermore, mineral oil has a relatively low flash point, increasing the risk of fire [4,5]. As a result, there is a need to explore more environmentally friendly and safer alternatives. Ester oils, particularly canola oil, offer a promising solution. Canola oil, derived from rapeseed, is biodegradable and more environmentally friendly [6]. It also has a higher flash point than mineral oil [7,8], which lowers the risk of fire. Additionally, the thermal stability of rapeseed oil is relatively good, allowing it to withstand high temperatures in transformers.

In addition to ester oils, a new class of transformer oils known as gas-to-liquid (GTL) technology has been developed to produce purer transformer oils [9]. GTL oil is derived from natural gas through the Fischer-Tropsch process, which converts gas into liquid form [10]. GTL oil, with iso-paraffins as its primary component, contains fewer impurities than mineral oil and is believed to offer superior performance [11]. Another alternative is gas-to-liquid (GTL) oil, synthesized from natural gas into a liquid with a simpler molecular structure compared to conventional mineral oil. GTL oil has good dielectric strength and better heat dissipation properties than conventional mineral oil [12].

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Building on the previous study by A. D. Sorimuda Ritonga et al., which focused on a comparative analysis of liquid insulating materials for high-voltage transformers using ester oil derived from palm oil [14], this study differs in its objective to examine the insulating properties of natural ester oil derived from canola oil, in comparison to mineral oil and GTL oil, and assess its advantages as a transformer oil. The ultimate aim is to assist the energy industry in selecting a safer and cleaner insulating fluid, thus reducing the environmental and safety risks associated with mineral oil. This study will contribute to the development of more sustainable transformers and support the transition to cleaner energy.

2. Experimental Setup

A. Sample

The materials used in this research include mineral oil, natural ester oil, and GTL oil. Kraft paper is used as the insulating material, and copper serves as the conductor. In compliance with the IEEE C57.100-2011 standard, the oil volume is 391.2 mL, the weight of the insulating paper is 24 grams, and the copper conductor weighs 21 grams. Figure 1 presents the oil, paper, and copper samples used in this research.

(a) (b) (c)

Figure 1. Composition of Materials: (a) Oils, (b) Kraft Paper, (c) Copper

In this study, oil and paper samples were subjected to accelerated aging at temperatures of 100°C and 125°C for 5 weeks. The samples were placed in heat-resistant, sealed glass bottles and tested every two weeks. The aging schedule included T0 (initial samples), T1 (aged for 168 hours), T3 (aged for 504 hours), and T5 (aged for 840 hours).

B. Material and Electrical Characterization

The materials and methods used for the measurements in this study are based on established standards to ensure accuracy and reliability. The color scale of the oil was measured using the Livobond PFX 195, following the ASTM D1500 standard, which is used to determine the visual quality of the oil. For acidity, the Metrohm 702 SM Titrino was employed according to the IEC 60296 standard. Acidity plays a crucial role in determining the oil's effect on the insulation properties, as increased acidity can degrade the paper insulation in transformer windings [13]. The water content of the oil was measured using the Karl Fischer 875, in line with the ASTM D974 standard, which is essential for understanding the moisture level within the oil that could impact its dielectric properties.

The breakdown voltage (BDV), a critical test for evaluating the oil's ability to withstand electrical stress, was conducted using the Megger OTA 100 AF according to the IEC 60156 standard. This test involves applying an increasing voltage after a five-minute countdown and repeating the process five times to ensure consistency and accuracy [15]. The permittivity of the oil, which reflects its ability to store electrical energy in an electric field, was measured using a high-resistance meter in accordance with IEC 60246. Similarly, the dissipation factor (Tan Delta), which indicates the dielectric losses in the oil, was measured using an LCR meter based on the ASTM D924 standard.

Resistivity, which is an important factor in assessing the oil's insulating capabilities, was also measured using a high-resistance meter, following IEC 60246. High resistivity values indicate minimal contamination and better insulation performance. Finally, the tensile strength of the insulating paper was tested using the Dongguan Sinowon Universal Testing Machine, following the SNI ISO 1924-2:2016 standard. These measurements collectively provide a comprehensive evaluation of the insulating properties and stability of the oils tested in this study.

3. Results

A. Color Scale

Figure 2 presents the color scale results of transformer oils aged at 100°C. As observed, discoloration occurs progressively with the aging time, with oils showing greater changes in color at higher temperatures. At 100°C, the color scale values for the oils varied significantly, with natural ester oil showing the least discoloration (1.5) compared to GTL oil (2.2) and mineral oil (0.9). The degree of discoloration increases over time, suggesting a deterioration in the oil quality. The degradation of color at 100°C, though noticeable, is less severe than that observed at 125°C, where the oils exhibit even more pronounced discoloration. The accelerated aging process at 100°C results in the breakdown of the chemical structure of the oils, leading to the formation of peroxides and hydroperoxides, which are responsible for the yellowing and darkening of the oil. These chemical byproducts contribute significantly to the observed discoloration. In addition, the presence of contaminants like water and metal particles can exacerbate this process, promoting further oxidation and thermal degradation. Thus, oils at higher temperatures, especially 125°C, experience a more rapid degradation, underscoring the importance of managing aging conditions to maintain optimal oil performance in transformers.

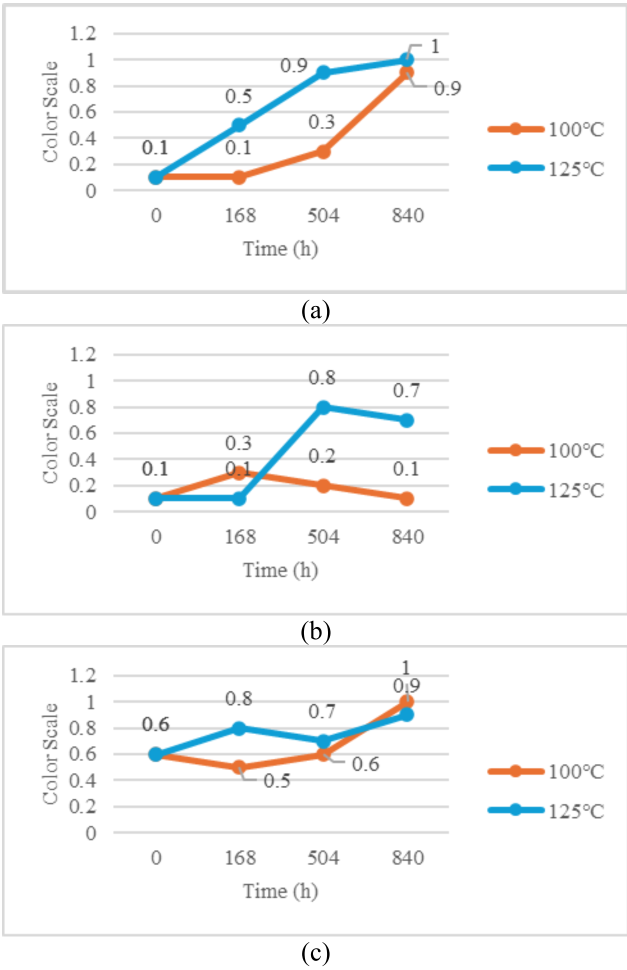
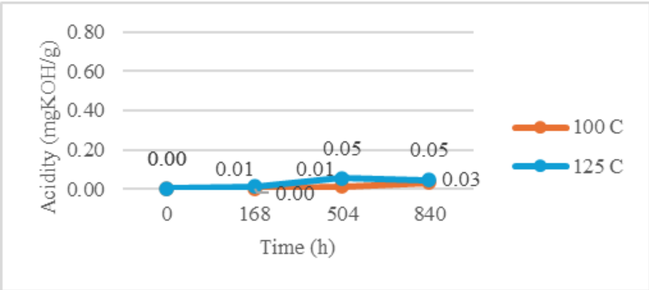


Figure 2. Color scale of (a) mineral oil, (b) GTL oil, (c) natural ester oil test results.

B. Acidity

Figure 3 shows the acidity levels of transformer oils aged at 100°C. The results indicate noticeable differences in the acidity trends for mineral oil, natural ester oil, and GTL oil over time. At 100°C, the acidity of mineral oil increased from 0.325 to 0.7, reflecting a significant rise as aging progressed. This increase is likely due to the accumulation of acidic byproducts from the oxidation reactions that occur in the oil, which become more pronounced with extended aging. Similarly, natural ester oil exhibited an increase in acidity, though less dramatic, rising from 0.033 to 0.1. This moderate increase suggests that while natural ester oil is more resistant to degradation than mineral oil, oxidation still plays a role in its aging process. In contrast, GTL oil exhibited minimal acidity increase, from 0.044 to 0.041, suggesting better stability at this temperature compared to the other oils. The relatively stable acidity in GTL oil may be attributed to its higher purity and resistance to the formation of acidic degradation products. The presence of impurities and contaminants, which can lead to the formation of basic compounds or acid precipitation, further complicates the aging process and affects the acidity levels. These findings highlight the importance of managing oil purity and aging conditions to minimize acidity buildup, which can negatively affect the oil's insulating properties and overall performance in transformers.



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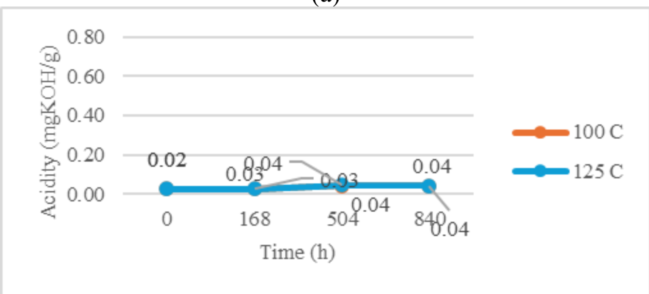

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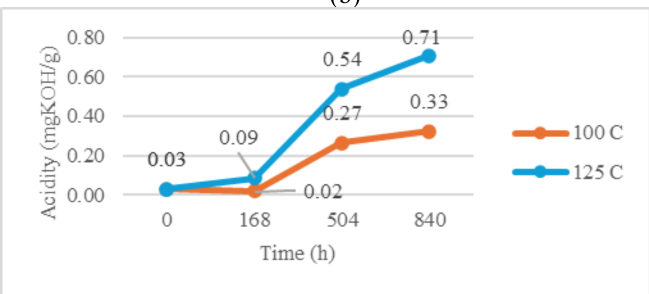

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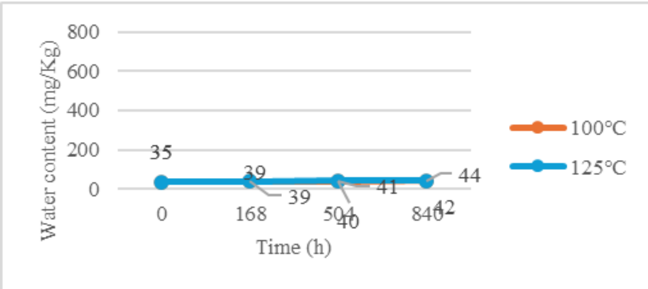
Figure 3. The acidity of (a) mineral oil, (b) GTL oil, (c) natural ester oil test results.

C. *Water Content*

Figure 4 shows the water content of transformer oils aged at 100°C, revealing distinct trends across the three oil types. Natural ester oil exhibits the highest water content, increasing from 389.27 ppm to 751.80 ppm as aging progresses. This significant rise reflects the hygroscopic nature of ester-based oils, which readily absorb moisture from the surrounding environment and from the degradation products during aging. Mineral oil, in contrast, shows a smaller increase in water content, ranging from 43.6 ppm to 47.49 ppm over the same period. This comparatively lower rise indicates that mineral oil is less prone to moisture absorption than natural ester oil, although water content still increases due to the aging process and potential contamination. GTL oil demonstrates the least variation in water content, increasing slightly from 34.20 ppm to 31.78 ppm. This stability suggests better resistance to moisture absorption, likely due to its higher purity and refined chemical composition, which minimize the interaction with water.Overall, the results underscore the importance of monitoring water content in transformer oils, as excessive moisture can degrade the dielectric properties and accelerate the aging process of both the oil and associated insulating materials. Natural ester oil's higher water content highlights its susceptibility to moisture-related issues, whereas GTL oil's stability presents a notable advantage in maintaining performance under prolonged aging conditions.



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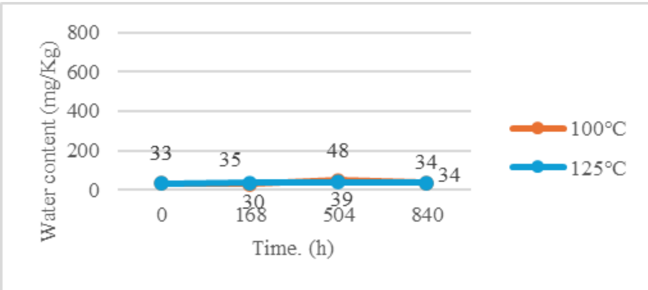

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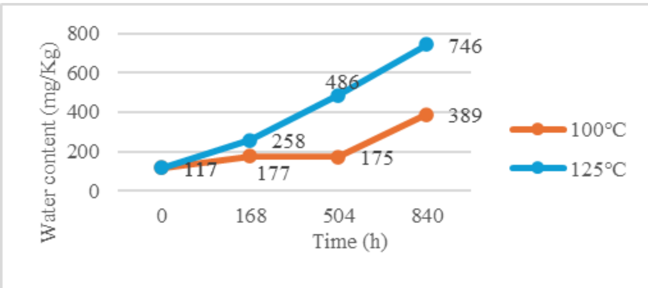

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Figure 4. Water Content of (a) mineral oil, (b) GTL oil, (c) natural ester oil test results

D. Breakdown Voltage (BDV)

Figure 5 shows the breakdown voltage (BDV) results for transformer oils aged at 100°C. Among the three oil types, natural ester oil consistently exhibits the highest BDV values, ranging from 43.16 kV to 57.7 kV over the aging period. This superior performance can be attributed to its excellent insulating properties and chemical resilience, which help maintain strong dielectric strength even under aging conditions. Mineral oil shows moderate stability in BDV, with values between 23.68 kV and 28.4 kV at 100°C. While its performance remains relatively stable during the aging process, its dielectric strength is significantly lower than that of natural ester oil, indicating its limited capacity to withstand high-voltage stresses under prolonged use. GTL oil, on the other hand, displays values ranging from 24.72 kV to 27.4 kV. Although slightly higher than mineral oil in some instances, GTL oil shows a gradual decline in BDV with aging, reflecting a loss of insulation properties over time. This degradation may be influenced by oxidative processes and the accumulation of impurities during the aging process. The findings highlight the superior insulating performance of natural ester oil compared to mineral and GTL oils at 100°C. Its higher BDV values suggest that natural ester oil is better equipped to handle high-voltage stresses, making it a more reliable and eco-friendlier alternative for transformer applications. However, the moderate stability of mineral oil and the initial strength of GTL oil indicate that these oils can still serve as viable options under specific operational conditions.

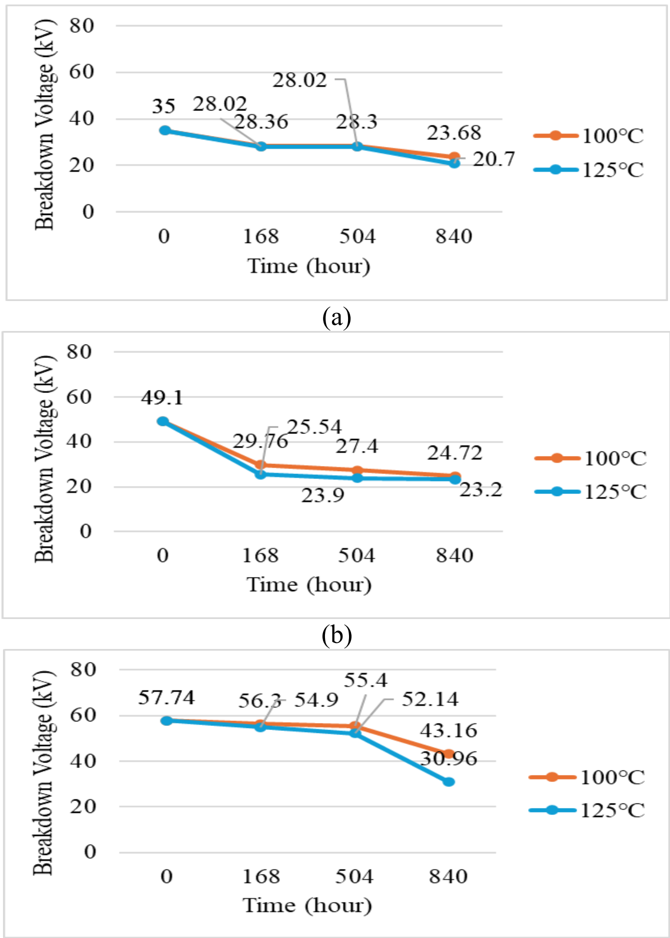

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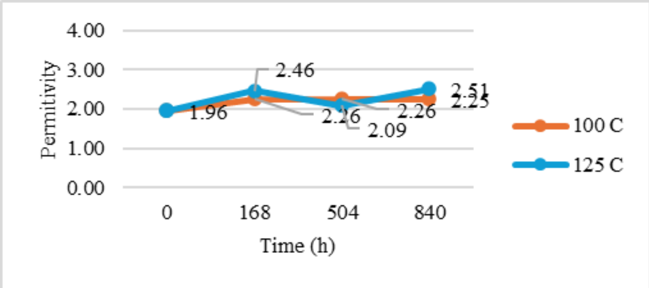
Figure 5. BDV of (a) mineral oil, (b) GTL oil, (c) natural ester oil test results.

E. Permittivity

Figure 6 shows that the permittivity of the three oil samples varies with time and temperature. Temperature and aging time significantly influence transformer oil permittivity, with mineral oils showing an increase at higher temperatures but a decrease over time. In contrast, natural ester oils maintain relatively stable permittivity, although slight fluctuations are observed. The increase in permittivity at 100°C, driven by the accumulation of water , is followed by a decrease at 125°C, possibly due to chemical structure changes. GTL oil shows an initial decrease in permittivity, followed by an increase at higher temperatures. Overall, elevated temperatures accelerate chemical reactions that impact permittivity, and long-term effects depend on the degradation and quality changes of the oil.



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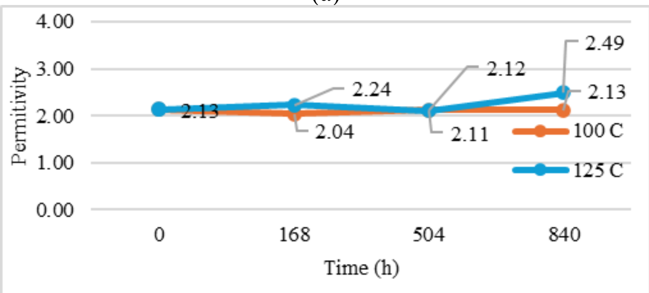

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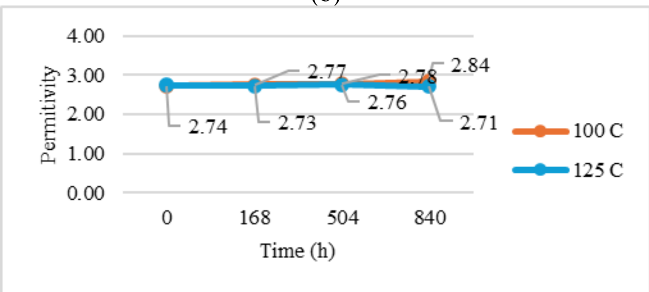

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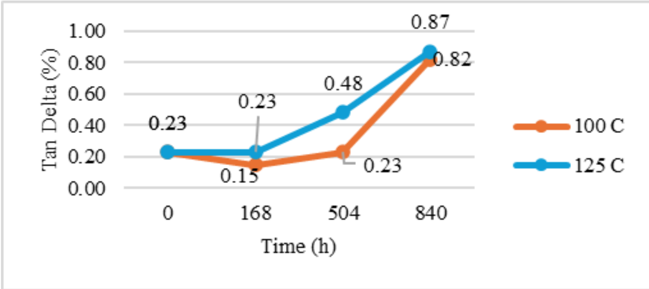
Figure 6. The permittivity of (a) mineral oil, (b) GTL oil, (c) natural ester oil test results.

F. Dissipation factor (Tan δ)

Figure 7 shows At 100°C, the dissipation factor (Tan δ) varies significantly among transformer oils, reflecting differences in their stability and degradation under thermal stress. Mineral oil exhibits pronounced fluctuations, starting at 0.82 and rising sharply to 2.70 after prolonged aging, indicating substantial degradation due to contamination and thermal effects. In contrast, natural ester oil maintains exceptional stability, with a consistent Tan δ of 0.22 throughout the aging process, showcasing its resistance to thermal and oxidative degradation. GTL oil shows moderate initial values, with a Tan δ of 0.387, followed by improvement to 0.243 at later stages, possibly due to the breakdown of contaminants and stabilization of its properties. These variations underscore the superior performance of natural ester oil in maintaining dielectric integrity compared to mineral and GTL oils.



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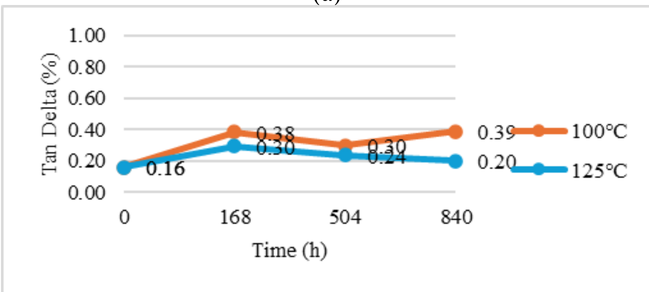

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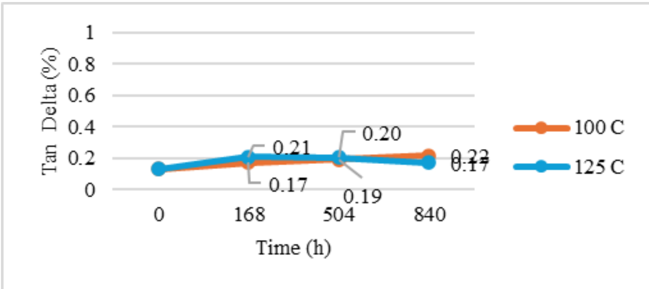

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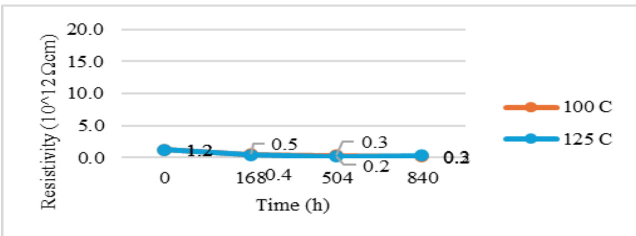
Figure 7. Tan Delta of (a) mineral oil, (b) GTL oil, (c) natural ester oil test results.

G. Resistivity

Figure 8 shows that resistivity decreases significantly in all three oil types during aging. Mineral oil experiences a decrease of 1.01 at both 100°C and 125°C after 840 hours, indicating deterioration due to the accumulation of contaminants, which leads to increased dielectric losses and reduced permittivity. Natural ester oils, maintaining a resistivity around 16.60 at 100°C, show fluctuations at higher temperatures, reflecting better aging resistance. In contrast, GTL oil, starting at 13.29, exhibits a sharp drop and fluctuation, signaling instability in oil quality.



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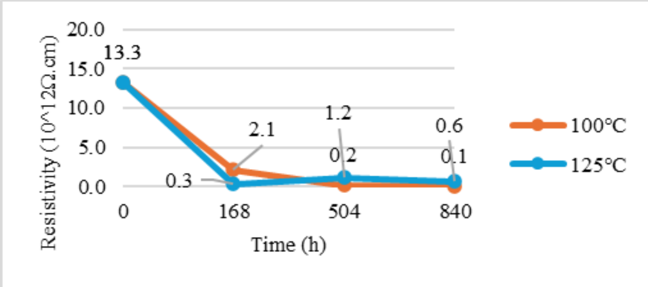

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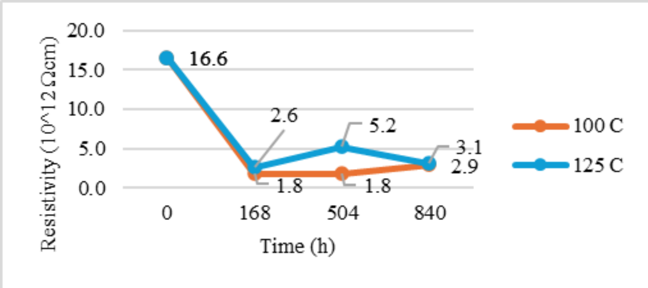

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Figure 8. Resistivity of (a) mineral oil, (b) GTL oil, (c) natural ester oil test results.

H. Tensile Strength (TS)

The tensile strength of transformer paper exhibits a marked decline with increasing aging time, driven primarily by thermal degradation. Under standard conditions, the initial tensile strength is measured at 8.24 kN/m. Aging at 100°C reveals distinct performance trends among the tested insulating oils. Mineral oil shows a consistent reduction in tensile strength, declining from 6.30 kN/m at T1 to 4.47 kN/m at T3, with a slight stabilization at 4.46 kN/m at T5. This pattern highlights the susceptibility of mineral oil to oxidative and thermal degradation during prolonged exposure to elevated temperatures.

Natural ester oil demonstrates superior performance, maintaining higher tensile strength throughout the aging process. The tensile strength increases marginally from 6.08 kN/m at T1 to 6.42 kN/m at T3, before decreasing slightly to 6.04 kN/m at T5. These results suggest that natural ester oil provides enhanced thermal protection, likely due to its inherent chemical stability and better insulating properties.

In contrast, GTL oil shows a more pronounced decrease in tensile strength over time. Starting at 5.50 kN/m at T1, the strength declines to 4.24 kN/m at T3 and further reduces to 3.22 kN/m at T5. This significant reduction indicates the limited ability of GTL oil to mitigate thermal degradation compared to natural ester oil, although it performs better than mineral oil in the initial stages of aging.

The findings underscore the critical influence of insulating oil type on the mechanical durability of transformer paper under thermal stress. While natural ester oil emerges as the most effective option for maintaining tensile strength, the rapid deterioration observed with mineral and GTL oils highlights the urgent need for advanced, thermally stable insulating fluids in transformer applications.

Table 1. Tensile strength test results

No	Type of Oil	Time	Temp (°C)	TS (kN/m)
1	Initial Condition (T0)		25	8.24
2	Mineral	T1	100	6.30
3	Mineral	T3	100	4.47
4	Mineral	T5	100	4.46
5	Mineral	T1	125	3.44
6	Mineral	T3	125	*
7	Mineral	T5	125	*
8	Natural Ester	T1	100	6.08
9	Natural Ester	T3	100	6.42
10	Natural Ester	T5	100	6.04
11	Natural Ester	T1	125	5.01
12	Natural Ester	T3	125	3.26
13	Natural Ester	T5	125	*
14	GTL	T1	100	5.50
15	GTL	T3	100	4.24
16	GTL	T5	100	3.22
17	GTL	T1	125	3.14
18	GTL	T3	125	*
19	GTL	T5	125	*

The value * indicates that the sample could not be tested.

4. Analysis and Discussion

This section provides an analysis of the test results obtained during the testing of dielectric properties, durability, and changes in physical characteristics of mineral oils, GTL oils, and natural ester oils.

A. Color Scale

The findings reveal that the extent of discoloration varies significantly across oil types and aging conditions. The severe discoloration observed at higher temperatures, particularly in mineral and GTL oils, aligns with known oxidation processes. The more stable color properties of natural ester oil suggest its superior resistance to oxidative degradation, corroborating studies emphasizing the thermal stability of natural ester-based insulating fluids.

B. Acidity

The acidity results demonstrate that mineral and natural ester oils experience marked increases with temperature and aging, which is consistent with their tendency for oxidative degradation. Interestingly, the initial decrease in acidity observed in GTL oil at higher temperatures may be due to base compound formation, a phenomenon occasionally noted in synthetic oils. This behavior suggests that GTL oil could offer unique advantages in specific thermal scenarios, although further validation is required.

C. Water Content

The rising water content across all oil types highlights their hygroscopic nature under high-temperature aging. The relatively lower water absorption in GTL oil under prolonged conditions confirms its comparative moisture resistance, a finding that aligns with its synthetic formulation. Natural ester oil, while absorbing more moisture, demonstrates improved dielectric performance, indicating its potential for applications demanding higher environmental sustainability.

D. Breakdown Voltage (BDV)

Natural ester oil consistently outperforms in BDV tests, reinforcing its superior insulating properties. The degradation of BDV in mineral and GTL oils at elevated temperatures underscores the necessity of regular oil maintenance in transformers operating under extreme conditions. These results are consistent with literature findings highlighting the enhanced dielectric stability of natural esters.

E. Permittivity

Permittivity trends reveal significant differences in chemical stability across oil types. The relatively stable permittivity of natural ester oil suggests robustness against chemical alterations during aging. The observed fluctuations in GTL oil and the decline in mineral oil suggest potential limitations in their long-term reliability as insulating fluids.

F. Dissipation Factor (Tan δ)

The Tan δ measurements further substantiate the superior dielectric stability of natural ester oil, with its gradual increase reflecting controlled degradation. Conversely, the significant fluctuations in mineral and GTL oils indicate susceptibility to contaminants and degradation products, echoing findings from similar experimental setups.

G. Resistivity

The significant decline in resistivity for mineral and GTL oils during aging, especially under higher temperatures, reflects increased contamination and degradation. The relative stability of natural ester oil suggests its ability to resist conductive impurity accumulation, corroborating its enhanced aging characteristics reported in the literature.

H. Tensile Strength

The progressive decline in tensile strength of insulating papers immersed in all oil types underlines the combined thermal and oxidative stress they endure. Natural ester oil's better performance at lower temperatures indicates its potential for preserving mechanical integrity, although its limitations at higher temperatures warrant further improvement.

5. Conclusion

The investigation into the dielectric properties, durability, and physical characteristic changes of mineral oil, GTL oil, and natural ester oil under varying aging and temperature conditions highlights significant differences in their performance. Natural ester oil demonstrated superior stability across multiple parameters, including breakdown voltage, permittivity, resistivity, and tan delta, making it the most reliable option for high-temperature applications and long-term insulation performance. Although GTL oil showed moderate stability and lower moisture absorption at specific conditions, its performance diminished significantly at elevated temperatures. Mineral oil, despite being widely used, exhibited the fastest decline in quality due to its susceptibility to oxidation and degradation under thermal stress. These findings underscore the potential advantages of natural ester oil in transformer applications, especially where high thermal and dielectric stability is required. Future research could focus on enhancing the thermal resilience and cost-efficiency of natural ester oils, exploring alternative formulations, and studying their environmental and operational impacts to further optimize their use in the energy sector.

6. Acknowledgment

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