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Comparison of Polyol Ester and Mineral Oil under Thermal Aging

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Abstract—Insulating oil was historically dominated by mineral oil due to its cost-effectiveness and good properties. However, the limitations of mineral oil, particularly its availability and environmental concerns, present significant long-term operational risks. These factors motivate researchers and practitioners to seek alternative oils. Polyol esters, synthesized through specific chemical processes, demonstrate biodegradability and operational safety. This research evaluates the electrical, physical, and chemical properties of both oil types, focusing on parameters such as breakdown voltage, water content, acidity, viscosity, and density. Results indicate that polyol ester oils exhibit a more stable breakdown voltage and better moisture management due to higher water absorption capacity, and greater density stability and viscosity even after prolonged thermal aging. Despite a more pronounced increase in acidity, polyol ester oils appear to be a promising and sustainable alternative for long-term use in oil-filled electrical equipment such as transformers. This aligns with industry objectives for enhanced environmental sustainability and operational reliability.

Keywords: Transformer oil, Polyol ester, thermal aging, Elctrical, Chemical and Physical Properties.

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1. Introduction

Insulating oil is an important element in electrical equipment, especially transformers, which functions as electrical insulators and cooling media. The selection of proper Insulating oil is essential because it affects the efficiency, stability, and life of the electrical equipment. Traditionally, mineral oil has been widely used as Insulating oil because of its good properties and relatively low cost [1]. However, mineral oil has a significant environmental impact because it is difficult to decompose naturally and can pollute the soil and water when a leakage is occurred or when a disposal is not appropriate [2], [3].

In recent decades, research and development of alternative insulating oil has increased, one of which is polyol ester oil. Polyol ester based insulating oils are made through chemical processes that produce products that can be adjusted according to specific needs. This oil is known to have several advantages compared to mineral oil, including better thermal stability, biodegradability, and higher operational security [4]. The advantage of thermal stability in polyol ester oil means that this oil can maintain its quality longer even though it is used in high-temperature conditions. It is very important to ensure transformers and other electrical equipment can operate efficiently and safely for a long time. In addition, polyol ester oils are more environmentally friendly because they can be decomposed naturally, reducing the risk of environmental pollution in the event of leakage or if residual oil is removed [5], [6].

Although polyol esters have many advantages, their use in the electricity industry still faces

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several challenges. One of the main challenges is higher production costs compared to mineral oil [6]. In addition, polyol ester is known to have a higher viscosity and higher water affinity than mineral oil. Thus, further research is needed to fully understand the performance of polyol ester oils in various operational conditions and to ensure their use safely and efficiently [7]. Due to the lengthy lifespan of a power transformer and the gradual aging of its insulation system under normal conditions, aging tests typically use accelerated methods. The transformer's lifespan under regular working conditions is then estimated based on these tests [8], [9], [10].

This study aims to examine the characteristics and performance of polyol ester oils compared to mineral oil in thermal aging conditions. This works include investigation of electrical, physics, and chemical properties, evaluation of thermal performance, and analysis of strengths and weaknesses of polyol ester oils under thermal aging conditions. The results of this study are expected to provide a deeper insight into the potential of Polyol ester oil as an alternative Insulating oil that is more environmentally friendly and readily available. By conducting a comprehensive study, this research will not only increase knowledge about Insulating oil but also contribute to reducing the environmental impact of electricity industry activities and increasing energy efficiency in various oil-filled electrical apparatus.

2. Method

2.1 Sample Preparation

Samples used in this experiment consist of Polyol esters and mineral oil. Polyol esters are directly requested from their manufacturers, while mineral oil is obtained from the state electricity company of Indonesia (PLN). Both types of oil are used without initial treatment, or directly used as it is received from suppliers. Kraft paper and copper wire were added to the oils to simulate the real condition in the oil-filled transformer. Each oil containing paper-wrapped copper was put into the bottle before being exposed to thermal aging. The weight ratio between the oil, the kraft paper, and the copper wire was 800:8:7 grams.

2.2 Thermal Aging

In this experiment, thermal aging was conducted by heating the sample using an electric oven at temperatures of 120 °C for 14 and 28 days. Figure 1 shows the arrangement of samples inside the oven. Initially, the aging duration for both temperatures was set similarly for 28 days. After 14 days of aging, samples of each oil were taken out from the oven for electrical, chemical, and physical properties measurement. The two other samples were left inside the oven for another 14 days of thermal aging. Properties measurements were again measured after 28 days of aging.



Figure 1. Samples were thermally aged in the electric oven

2.3 Testing

The electrical, physical, and chemical properties of polyol ester and mineral oil samples were tested, and the effect of aging on the properties was evaluated. IEC provides a set standard of test methods and their limit values for a synthetic ester [11], as depicted in Table 1. Although the standard is intended for unused synthetic esters, IEC 61099 can also be used as a reference for evaluating the condition of in-service polyol ester by comparing them to the fresh oil specifications. In the current investigation, the tested properties are breakdown voltage, acidity, water content, viscosity, and density.

Table 1. Test methods and their limit for synthetic ester, according to the IEC 61099

Properties	Test Method	Limits
Breakdown voltage	IEC 60156	Min. 45 kV
Resistivity at 90 ºC	IEC 60247	Min. 2 GΩ.m
Dissipation factor	IEC 60247	Max. 0.03
Viscosity, at 40 ºC	ISO 3104	Max. 35 cSt
Density, at 40 ºC	ISO 3675	Max. 1000 mg/cm^3
Pour point	ISO 3016	Max. -45 ºC
Flash point	ISO 2719	Min. 250 ºC
Fire point	ISO 2592	Min. 300 ºC
Water content	IEC 60814	Max. 200 ppm
Soluble acidity	IEC 62021	Max. 0.03 mg KOH/g

3. Result and Discussion

3.1 Breakdown Voltage

Breakdown voltage is a fundamental property that indicates the capacity of insulation material to withstand an electric stress before experiencing failure. Figure 2 presents the breakdown voltage of polyol esters and mineral oil, before and after thermal aging. The data elucidates how the breakdown voltage of polyol ester oil and mineral oil varies with increased thermal aging duration.

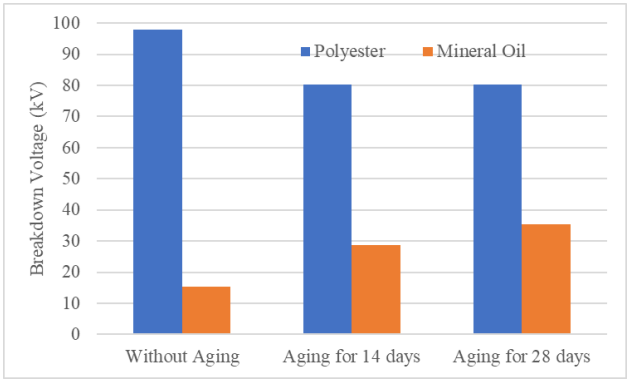


Figure 2. The breakdown voltage of polyol ester and mineral oils before and after thermal aging.

Without aging, a clear difference in the breakdown voltage of polyol ester and mineral oil was evident. Polyol ester demonstrated superior resistance to electrical breakdown compared to mineral oil. This implies that under normal operating conditions, polyol ester is better equipped to handle high voltages without experiencing electrical failure.

Under thermal aging, behavior of both oils show an intriguing shift. Mineral oil, which initially exhibited poor insulating properties, showed a significant improvement in its ability to withstand electrical stress. This enhancement could be attributed to the evaporation of certain volatile components within the oil that were detrimental to its insulation. In contrast, polyol ester experienced

a slight decline in its insulating capacity due to initial degradation caused by thermal aging. However, the breakdown voltage of Polyol esters remains higher than that of mineral oils during the aging period. This behavior is also observed in [12].

As the aging process continued, mineral oil maintained its improved insulating performance trend but it never reached the level achieved by polyol ester. Polyol ester, on the other hand, demonstrated remarkable stability, retaining a high level of insulation even after prolonged exposure to thermal aging. This consistency highlights its suitability for applications requiring a long application as insulation in electrical apparatus.

3.2 Water Content

Understanding how the water content of Insulating oil changes with time is very important because an increase in water content or humidity can reduce the oil insulation's capability. Figure 3 shows the water content of polyol esters and mineral oil for different thermal aging durations: 0, 14, and 28 days.

In the initial conditions, there are significant differences between the two oils. Mineral oil has a relatively low water content at 33.54 ppm. On the other hand, polyol esters have a much higher water content at 570.33 ppm. Interestingly, despite having a high initial water content, polyol esters have a much higher breakdown voltage (Figure 2). This phenomenon will be discussed further in the discussion section (3.6).

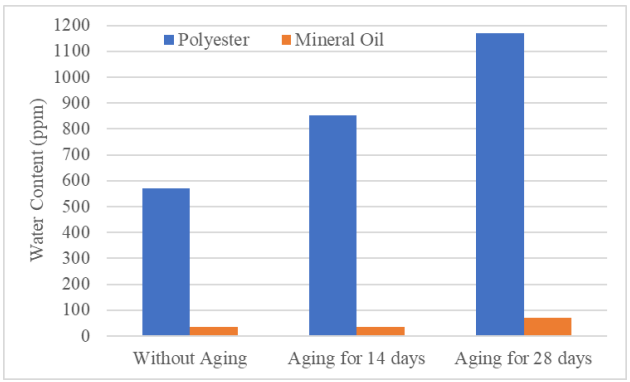


Figure 3 Water content of polyol ester and mineral oils before and after thermal aging.

Exposure of mineral oil and polyol ester to thermal aging for 14 days induced a different in their water absorption characteristics. Mineral oil exhibited a modest increase in water content, which is agree with literature [13], indicative of its relative hydrophobicity. Conversely, polyol ester demonstrated a pronounced affinity for water, as indicated by a significant increase in its moisture content. This heightened hydrophilicity of polyol ester had a slight detrimental impact on its dielectric properties, as reflected in a slight decline in breakdown voltage (Figure 2). However, this water affinity is beneficial for combined oil-paper insulations, as will be further elaborated in the discussion section.

During the 28-days aging period water content of mineral oil and polyol ester showed a distinct trend. Mineral oil demonstrated a gradual increase in water content, which is in line with findings reported in [13]. The rate of increase was significantly slower than that observed for polyol ester. Conversely, polyol ester exhibited a substantial and sustained rise in water content, escalating from 570.33 ppm at initial condition to 1171.23 ppm after 28 days of aging. This pronounced hydrophilicity can contribute to improved moisture management; the potential for deaccelerated hydrolysis and subsequently preventing an early degradation of cellulose insulation. Interestingly, polyol ester can still maintain its superior dielectric performance, as evidenced by a higher breakdown voltage (Figure 2), confirming the results reported in [6].

3.3 Acid Number

Acidity is an important parameter for assessing the condition and age of Insulating oil because the increase in acidity can indicate oil degradation, which in turn will affect oil performance as isolation. Figure 4 presents the acid number (measured in mg KOH/Gram) of two Insulating oils - mineral oil and polyol esters - for different thermal aging durations: 0 days, 14 days, and 28 days.

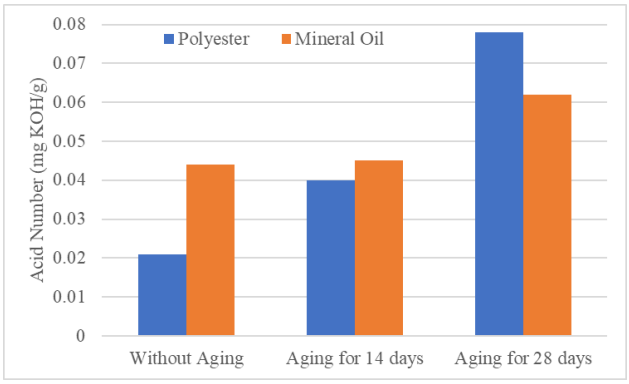


Figure 4. Acid number of polyol ester and mineral oils before and after thermal aging.

At first, the acidity levels of the two oils were noticeably different. Mineral oil had an initial acidity of 0.044 mg KOH/gram, while polyol esters had a lower initial acidity of 0.021 mg KOH/gram. This indicate that polyol ester has a better potential chemical stability in the absence of aging.

After 14 days of thermal aging, changes in acidity were observed. Mineral oil showed a slight increase in acidity to 0.045 mg KOH/gram, demonstrating its relative chemical stability over the 14 days. In contrast, polyol esters exhibited a significant rise in acidity to 0.040 mg KOH/gram, almost matching the acidity of mineral oil. Despite this notable increase, polyol esters still had a lower acidity than mineral oil. After 28 days of aging, the acidity of both oils continued to rise. Mineral oil's acidity increased to 0.062 mg KOH/gram, which well-agree with research findings in [14], indicating a slow degradation process and moderate stability under prolonged thermal stress. Conversely, polyol esters showed a more remarkable rise in acidity, reaching 0.078 mg KOH/gram after 28 days.

3.4 Viscosity

Viscosity is an important property that affects the flow characteristics and thermal performance of insulating oil. Low viscosity indicates good cooling performance. Figure 5 shows the kinematic viscosity (measured in cSt.) of polyol esters and mineral oils for different thermal aging durations: 0 days, 14 days, and 28 days.

Under normal condition, polyol esters exhibit a higher kinematic viscosity of approximately 1.656 cSt compared to that of mineral oil at about 1.277 cSt. This is an indicative that polyol esters have a reater resistance to flow and lower fluidity. It is well-known that a common drawback of ester oils, both synthetic and natural, is their high viscosity.

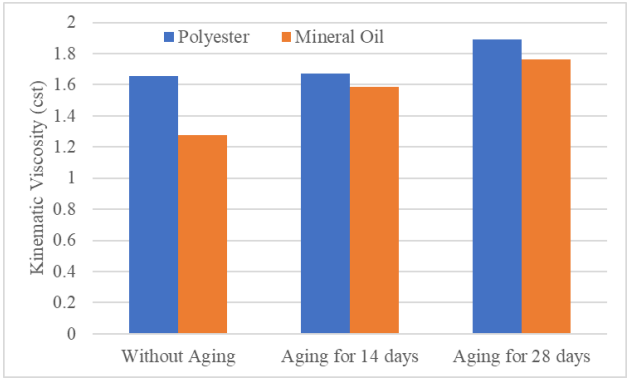


Figure 5. Kinematic viscosity of polyol ester and mineral oils before and after thermal aging.

After 14 days of thermal aging, the kinematic viscosity of both oils increases. This behavior was also noted in [15] [16]. Mineral oil's viscosity rises significantly to 1,587 cSt, indicating that thermal aging affects its molecular structure, leading to higher viscosity. Polyol esters also experience an increase in viscosity, reaching 1,674 cSt after 14 days. This slight increase suggests that the viscosity of polyol esters is relatively stable compared to mineral oil. After 28 days, the viscosity of both oils continues to rise. Mineral oil's viscosity further increases to 1,764 cSt, while polyol esters show a smaller increase to 1,890 cSt. Although mineral oil's viscosity increases more, it remains lower than that of polyol esters. This ongoing rise indicates changes in the chemical composition and molecular interactions of both oils, which is attributed to polymerization due to the oxidation [17].

3.5 Density

Relative density is an important property that can affect the performance and efficiency of insulating oil in various electrical equipment. Figure 6 shows the density (measured in gram/cm³) of mineral oil and polyol esters for different thermal aging durations: 0 days, 14 days, and 28 days.

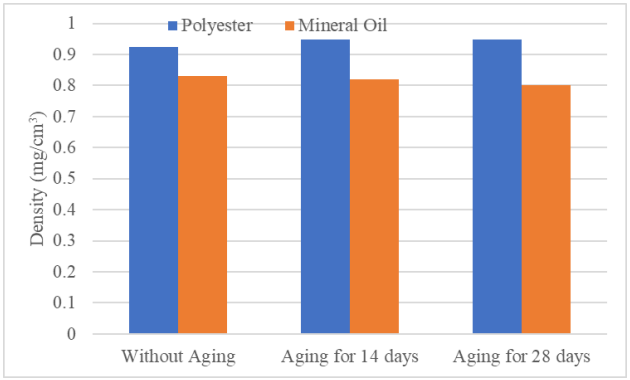


Figure 6. Density of polyol ester and mineral oils before and after thermal aging.

Mineral oil has an initial density of 0.83 g/cm³, which is lower than that of polyol esters, which is approximately 0.923 g/cm³. This indicates that polyol esters are denser and more compact under normal conditions, which also means that their molecules are more tightly packed compared to those in mineral oil.

After thermal aging for 14 days, the density of both oils change in different ways. Mineral oil's density slightly decreases to 0.82 g/cm³, likely due to thermal expansion or the degradation of heavier molecules into lighter ones. In contrast, polyol esters' density increases to 0.948 g/cm³, possibly due to the formation of more complex molecular compounds or less thermal expansion compared to mineral oil. After 28 days, these trends continue: the density of mineral oil further decreases to 0.80 g/cm³, while polyol esters' density slightly decreases to 0.947 g/cm³. Throughout the aging process, polyol

esters consistently maintain a higher density than mineral oil.

3.6 Discussion

This section discusses two important phenomena that occur during the thermal aging process: the oxidation reactions in both oils and the considerably greater increase in water content in polyol esters compared to mineral oil.

3.6.1 Oxidation

A continuous increase in water content (Figure 2) and acidity (Figure 3) in both oils during the thermal ageing is indicative of the occurrence of oxidation. The rise in water content and acidity in hydrocarbon-based oils due to oxidation is explained by Equations (1) through (11) [18].

Oxidation reactions in Insulating oil are initiated when hydrogen radicals escape from hydrocarbon compounds in the oil, as represented by Equation 1.

$$RH \rightarrow R^* + H^* \quad (1)$$

Oxidation occurs due to the unavoidable presence of oxygen in the oil. R* radical resulting from Equation (1) that meets oxygen will form peroxide radical ROO* based on Equation (2).

$$R^* + O_2 \rightarrow ROO^* \quad (2)$$

Radical hydrogen (H*) which meets radical peroxide ROO* will react to form hydroperoxide rooh based on equation (3). Further reactions can cause water formation based on equation 4 - 6.

$$ROO^* + H^* \rightarrow ROOH \quad (3)$$
$$ROOH \rightarrow RO^* + OH^* \quad (4)$$
$$RO^* + RH \rightarrow ROH + R^* \quad (5)$$
$$OH^* + RH \rightarrow H_2O + R^* \quad (6)$$

Two peroxide radicals ROO* can react with each other, followed by further reactions, which will lead to the formation of carboxylic acids in oil, as depicted by equations 7 - 11.

$$2ROO^* \rightarrow ROH + O_2 + RCOH \quad (7)$$
$$RCOH + O_2 \rightarrow RCOOOH \quad (8)$$
$$RCOOOH \rightarrow RCOO^* + OH^* \quad (9)$$
$$RCOO^* \rightarrow R^* + CO_2 \quad (10)$$
$$RCOO^* + RH \rightarrow R^* + RCOOH \quad (11)$$

The formation of water and acids due to the oxidation are confirmed by Equations (6) and (11), respectively.

The higher water content in the polyol ester is likely causing its breakdown voltage to decrease. It is well known that an increase in water, exceeding 30% for new oil and 10% for contaminated oil, will significantly weaken the oil's ability to withstand electrical breakdown [19]. The amount of water an oil can hold depends on its saturation limit, as shown in equation (12) [20], [21]. Mineral oil can hold about 60 ppm of water at room temperature, while polyol esters can hold about 2700 ppm before reaching saturation.

$$w_{rel} = \frac{w_{act}}{w_{sat}} \quad (12)$$

Where:

w_{rel} = Relative water content (%)

w_{act} = Actual water content (ppm)
w_{sat} = Saturated water content

3.6.2 Water Content Increase

It is evident from Figure 2 that both mineral and polyol ester oils exhibit increased water content when subjected to thermal aging. As described in equation (6), oxidation produces water in both oil types, but polyol esters demonstrate a more significant water absorption rate. This behaviour is attributed to the polar nature of polyol esters in contrast to the nonpolar mineral oil [22]. The polarity of polyol esters enables them to readily attract water molecules from the paper insulation immersed in them. This attraction is facilitated by the formation of hydrogen bonds between the partially positively charged hydrogen atom from a water molecule and the oxygen atom of the ester molecule [6], [22].

The transfer of water vapor from paper insulation to polyol ester oil is beneficial, as it creates a drying effect, a property that is not exhibited by mineral oil. Paper insulation immersed in polyol esters demonstrates enhanced resistance to degradation induced by water vapor compared to that in mineral oil. This characteristic contributes to an extended service life expectancy for paper insulation immersed in polyol ester [6]. Consequently, transformers employing polyol esters possess a longer operational lifespan relative to those utilizing mineral oil.

4. Conclusion

The performance of polyol esters compared to traditional mineral oils under thermal aging conditions, focusing on their electrical, physical, and chemical properties, have been studied. It is found that polyol ester oils outperform traditional mineral oils in terms of breakdown voltage and thermal stability. Polyol esters exhibit a more stable breakdown voltage even after thermal aging, better moisture management due to higher water absorption, and greater density stability. Although they show a more significant increase in acidity, which is an indication of a greater susceptibility to oxidation for longer periods of thermal aging, their overall performance makes them a more sustainable choice. Despite their higher initial costs, the stable viscosity, biodegradability, and improved operational efficiency of polyol esters make them a promising alternative for long-term use in oil-filled electrical equipment like transformers. It should be noted that this study was carried out without applying any pretreatment to the two types of oils. Incorporating such pretreatment in future studies may offer a more comprehensive understanding of the comparative thermal aging characteristics of the oils.

Acknowledgment

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