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Studying Physical Properties of Gas-To-Liquid Compared with Mineral Oil under Accelerated Thermal Aging

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Abstract — **Mineral oil (MO) has long been utilized in high-voltage power transformers, as a cooling and dielectric medium; because of it is availability as it is extracted from fossil oil. Recently, Gas-To-Liquid (GTL) has a significant increase in use due to its superior performance, its purity and chemical consistency over conventional mineral oils. This paper presents examination of the temperature effects on mineral (Diala S2) and gas to liquid (Diala S4) oil physical properties. Fresh oil and aged oil samples, of the two oil types, have been tested in this paper. Accelerated thermal aging test have been conducted in laboratory to simulate the heat stress experienced by transformers during operation. Three aged oil samples, of the two types of oil, have been prepared in laboratory (3, 6, and 10 days). Density and viscosity measurements were performed on these fresh and aged oil samples. The results concluded that during the initial years, chemical changes cause a minor drop in the density of the mineral oil. Conversely, GTL oil has superior qualities since it stays more stable over time. Over time, the density of both oils exhibits comparable stability, however GTL oil is favored over mineral oil due to its consistency and stability. Diala S4 and Diala S_2 oils have higher viscosity, suggesting superior cooling performance before aging. However, Diala S_2 dropped to 10.649 mm^2/s after three years, indicating its long-term consequences. Diala S4 oil had higher flow efficiency, enhancing transformer cooling and insulating performance within thermal aging. This is due to GTL oil, derived from natural gas, has higher resistance to chemical deterioration, allowing it to sustain its viscosity stability over extended periods. These results emphasize the importance of choosing oils, especially GTL oil type based on their apparent and physical stability over time.**

Keywords—**Transformer, mineral oil, GTL, Chemical test, Physical test.**

List of abbreviations

MO	*Mineral oil*
GTL	*Gas-To-Liquid oil*
DDF	*Dielectric Dissipation Factor*
DGA	*Dissolved Gas Analysis*
PL	*Photoluminescence*
UV-Vis	*Ultraviolet-Visible Absorption*
T	*Time Factor*

I. Introduction

The most essential component of the electrical power network is the power transformer. Transformers are susceptible to electrical, thermal, and chemical stressors during operation, which can cause catastrophic transformer failures and system outages by affecting transformer oil degradation [1]. In the transformer, oil serves as a cooling medium and an insulating liquid. Important information about the oil itself, the health of the transformer, and its operational state are all reflected in the oil condition. For more than a century, power transformers have utilized mineral oils (MO) because of their excellent dielectric performance and inexpensive cost. However, it may be contaminated with combustible gases and compounds, such sulfur and oxygen, which can degrade oil and solid materials that come into contact with it [2]. As a result, there have been significant efforts in recent years to either use different oil types with superior qualities or add additives to improve the properties of mineral oil. The transformer's service life will be extended as a result of the improved oil characteristics, which will be reflected in the oil condition and, subsequently, in the transformer oil assessment [1].

With the use of nanoparticles, oil-based nanofluids have been produced that have superior qualities to base oil. Nanofluids have the potential to improve the thermal characteristics of transformer oil [3, 4]. The thermal characteristics that are being studied are heat transfer coefficient and thermal conductivity. The percentage of carbon-based nanoparticles—which include carbon, carbon nanotubes, graphene, and graphene oxide—in the thermal properties of transformer oils was the largest among the different types of nanoparticles [5]. On the other hand, transformer oil's dielectric qualities might be improved by nanofluids. Partial discharge, breakdown strength, and dielectric dissipation factor (DDF) are some of these dielectric characteristics [6–10]. Although the effectiveness of adding nanoparticle additions to transformer oil has been demonstrated, long-term stability concerns still make it challenging to employ these additives in real transformers.

Alternatives to lubricating oil have been investigated, such as ester oils [11]. Natural ester has a considerable pressure drop but a medium temperature and a greater boiling point. Research on natural ester fibers has demonstrated that they have no discernible impact on the paper's deterioration or the fluid collapse device's failure rate [12, 13]. According to another study, the best way to address the shortcomings of the present isolated system is to use a combination of mineral oil and natural ester. Even still, ester oil's exorbitant cost has prevented widespread use despite its benefits.

Recently, hydrocarbon transformer oils, a novel procedure known as "gas-to-liquid (GTL) oil" has been developed. This technique produces hydrocarbon liquids, the majority of which are derived from natural gas and are composed of iso-paraffins. The Fischer-Tropsch process, a three-stage procedure, converts methane gas into a variety of liquid products, including base oils appropriate for transformer oil manufacturing. This oil offers excellent purity, good resistance to degradation, enhanced thermal properties, and steady performance. Because of its near total absence of sulfur and aromatics, transformer oil insulation is less negatively impacted by them. Furthermore, research conducted through experiments has demonstrated that sulfite corrosion significantly affects transformer insulating performance overall.

Gas-To-Liquid (GTL) oil was tested with three different types of oils, including non-naphthenic and naphthenic oils, in the study mentioned in [14]. The composition investigation revealed that GTL oil differed significantly from these oils, particularly in terms of alkane concentration. GTL has reduced density, greater flash points, and lower mass fraction characteristics (<0.0002%). Tests for lightning breakdown and thermal characteristics also revealed that GTL had higher thermal conductivity, larger thermal capacity, and increased resistance to pulse breakdown voltages.

In the study mentioned in [15], accelerated aging studies were carried out in the lab to examine and evaluate the impact of aging on the performance of GTL oil with a particular kind of mineral oil. The findings demonstrated that while GTL color changed more slowly than mineral oil, its aging effects were comparable to those of mineral oil in terms of moisture and acidity.

Additionally, GTL oil helps lower the total weight of transformers and other electrical equipment that are filled with oil because it is less damaging to the environment and does not corrode sulfur. The difficulty of creating bonding structures with water molecules causes water to diffuse more quickly during the gas-to-liquid conversion process, according to a study in [16].

Two insulating oils, Diala S_2 as mineral oil and Diala S_4 as GTL oil, were studied and their behaviors were given in [17]. Testing has been done on both fresh and aged oil samples to examine the qualities of the oil as it ages and its overall quality. In terms of electrical testing, the dielectric dissipation factor (DDF), resistivity, permittivity, and AC breakdown voltage of these three fresh and aged samples for the two oil kinds were measured. After the thermal heating test, dissolved gas analysis (DGA) is employed as a chemical test to measure the dissolved gases for the two oils. Additionally, optical spectroscopic measurements have been applied to the evaluation of insulating oil. Photoluminescence (PL) and ultraviolet-visible absorption (UV-Vis) examinations are two of the optical techniques that are used. The findings showed that after ten aging days, Diala S_4 breakdown voltage grew and improved. As Diala S_4 aged byproducts are lower than Diala S_2, its DDF was unaffected by aging and is superior to Diala S_2 relevant value. While Diala S_4 relative permittivity is somewhat decreasing, Diala S_2 relative permittivity is slightly increasing. When Diala S_4 ages, fewer by-products are created than when Diala S_2 ages. The carbon emissions of Diala S_4 are lower than those of Diala S_2. In Diala S4, the aged byproducts rise linearly with increasing aging durations, however in Diala S_2, they increase constant.

Accordingly, The study of gas-to-liquids (GTL) compared to mineral transformer oils is crucial in electrical engineering. It aims to improve performance and reduce transformer faults. Analyzing properties like viscosity and density contributes to developing efficient and sustainable energy solutions for grids. This research enhances transformers' performance under harsh conditions and opens new avenues for innovation in power transformer oil. As far as we are aware, there haven't been many research on the complete performance of gas-to-liquid (GTL) oil published in the literature. Consequently, there is much room for research on this subject, and in order to fill this vacuum in the literature, comprehensive experimental findings must be presented. Consequently, by examining the chemical and physical characteristics of two different types of oils—mineral oil and GTL oil—this research offers a continuation of study [17]. The emphasis was on using Diala S_4 ZX-I, the same type of oil used in study [17], as the GTL oil. To investigate how aging affects the qualities of oil, it is crucial to examine the aging sample. To investigate how aging affects the qualities of oil, it is crucial to examine the aging sample. By analyzing the transformer's condition and life, the experimental study that is being given is helpful in determining the transformer health index based on oil evaluation. This is the foundation for preventative maintenance. In order to assess the oil condition, it is crucial to examine the variations in electrical, chemical, and physical properties with in-service operations. The oil life is accelerated in this study to be equal to ten years of service, and at various accelerated stages of life, the impact of age on physical qualities, such as density and viscosity, is examined.

II. PREPARING SAMPLES OF ACCELERATED OLD OILS IN THE LABORATORY

The aging process of oil results in a gradual and irreversible alteration of the insulating oil's characteristics. Similar to what happens to transformer oil that is in use, it progressively loses its stability and oxidizes and degrades. Two well-known key elements that hasten transformer oil aging are oxygen and water. Oil and water contain dissolved oxygen, which is displayed on cellulose paper. Thus, two elements that quicken oil aging are temperature and electric fault. Temperature increases have the potential to cause moisture redistribution within the transformer's oil [18-20].

As a result, various stresses are applied to the in-service transformer, which will have an impact on the electrical, chemical, and physical properties of the oil. Analyzing these impacts of oil aging and degradation aids in transformer oil condition evaluation. To investigate these characteristics of the Diala S_2 and Diala S_4 oils, aged oil samples with varying aging times have been prepared. In order to replicate the real transformer condition, the two tested oil samples (Diala S_2 as a MO and Diala S_4 as a GTL) are prepared for accelerated aging in the lab and are submerged in paper [20-23]. Fig. 1 depicts the stages and procedures of the oil sample preparation. Before thermal aging, all oil samples of the two oil types (Diala S_2 and Diala S_4) are firstly prepared by placing them in a vacuum oven for 24 hours. This allows the transformer oil to be circulated through a heated vacuum-extraction unit, eliminating any absorbed water and maintaining the oil samples' low moisture content. Then, using a heating oven, three samples of each type of oil were exposed to accelerated aging at 120 °C under semi-sealed conditions for varying lengths of time (3, 6, and 10 days).

The half-life rule [23], which stipulates that the aging rate of transformer oil doubles with every 7 °C rise in operating temperature, was followed in performing the accelerated aging test. The standard operating temperature for transformer oil is 60 °C. One day of accelerated aging is therefore equal to about 380 days of natural aging of the oil in a field transformer when the accelerated aging test is carried out in an oven at 120 °C. Equations (1) and (2) state that aging the old transformer oil by one day, or about 380 days, is equal to subjecting the oil sample to a 24-hour oven at 120 °C [23].

$$\text{Accelerated Aging Factor} = \frac{120℃-60℃}{7℃} = 8.57 \quad (1)$$

$$\text{Time Factor (T)} = 2^{8.57} = 380 \quad (2)$$

PROCEDURES AND EXPERIMENTAL SETUP

The experimental approach and methods for determining the viscosity and density are described in this section.

Density Measurement

Determining the electrical characteristics of an oil is dependent on its density, as insufficiently dense oils can cause insulation concerns. Density testing exposes the chemical and physical properties of the oil, such as viscosity and thermal conductivity, which affect the transformer's performance. Any variation in density could be a sign that the oil contains undesirable or contaminating substances. A hydrometer and a container are used to gather the liquid for density testing in accordance with ASTM D1298. Samples of the two types of oils are gathered in a sterile container at several accelerated life stages. According to the specification, the temperature of both types of oils is verified to be 16 °C. The samples are placed in the device, and the density on the surface of the liquid is measured. According to the specification, the acceptable limit is from 0.862 to 0.895 [24].

Viscosity Measurments

Testing for viscosity can be used to ascertain the oil's flowability, which helps assess the transformer's performance. Knowing how heat is transported throughout the transformer through this test helps to improve the cooling system. Any variation in viscosity could be a sign of declining oil quality, necessitating repairs or replacements. The phrases "dynamic viscosity" and "kinematic viscosity" are used to characterize fluid properties. Measuring a fluid's dynamic viscosity—that is, its resistance to flow under shear forces—will reveal how the fluid behaves when subjected to forces, such as oils. Kinematic viscosity is the ratio of dynamic viscosity to the density of the fluid and expresses how easily the fluid flows under the influence of gravity. Therefore, each of them affects the behavior of fluids under different conditions. ASTM D445 standard is used to measure the dynamic viscosity of fluids. In this research, the Capillary device located in the chemical laboratories of the Ministry of Electricity was used. The test temperature was taken into account to be 40 degrees Celsius. Acceptable Limits From 9 to 12 were taken into account according to the specification [25, 26].

RESULTS AND DICUSSION

Table I and Figure 2 show the density measurements of mineral oil and GTL (Gas-to-Liquid) oil over a period of time ranging from 0 to 10 days in the oven, equivalent to 0 to 10 years in service. The density of mineral oil showed that the measurement after 10 days became 0.8633 while the fresh was 0.8643, and after 3 days it was 0.8636 while the density measurement of the samples after 6 days of accelerated age reached 0.8631 g/cm³. Thus, the density decreases slightly

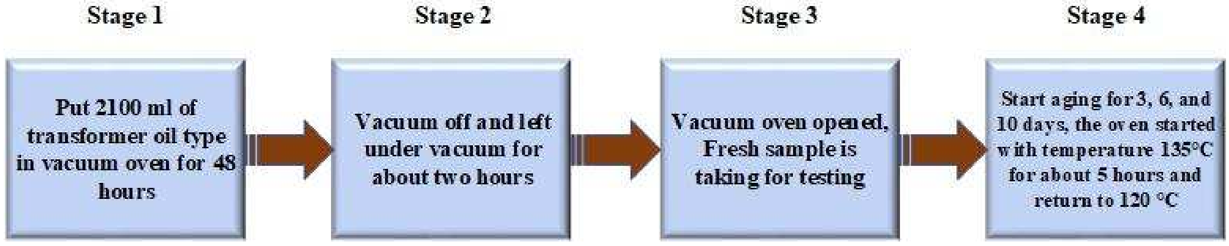

Fig. 1. Oil sample preparation steps/stages

during the first years, but remains relatively stable thereafter. This slight decrease can be attributed to chemical changes that may occur over time, such as the loss of light components or a change in composition. As for the GTL oil type, the fresh sample, and the samples after 3, 6, and 10 days of accelerated age reached 0.7945, 0.7939, 0.7938, and 0.7932 g/cm³ respectively. Thus, the density remains more stable, indicating that GTL oil retains its properties better over time. This result confirms that both oils show relative stability in density over time, indicating that the chemical changes that occur do not significantly affect the density after a long period. While GTL oil is preferred in terms of stability and consistency compared to mineral oil.

TABLE I. DENSITY COMPARISON BETWEEN DIALA S_2 ZX-A AND DIALA S_4 ZX-I

Samples	Density (g/cm³)	
	Mineral oil (Diala S_2)	**GTL oil (Diala S_4)**
Fresh	0.8643	0.7945
3 years	0.8636	0.7939
6 years	0.8631	0.7938
10 years	0.8633	0.7932

Fig. 2. Density of Diala S_2 Zx-A and Diala S_4 Zx-I Oils during aging.

Table II and Figure 3 show the kinematic viscosity measurements of mineral oil and GTL oil over a period of 0 to 10 days of accelerated aging. For GTL oil, the viscosity was 11.698, 11.664, 11.659, and 11.696 mm²/s for fresh samples and samples after 3, 6, and 10 days of accelerated aging, respectively as showing in Table II and Figure 3. Diala S_2 oil has a higher viscosity, which suggests superior cooling performance, according to the data. Three years later, it dropped to 10.649 mm²/s. It grew somewhat to 10.732 mm²/s after six years, although Diala S_4 stayed at 11.659 mm²/s. It rose to 10.883 mm²/s after ten years, demonstrating the long-term consequences of aging. Diala S_4 is appropriate for applications needing continuous performance because, in spite of its higher viscosity, it exhibits stronger stability over time. While, dynamic viscosity reached 9.2944, 9.26, 9.27, and 9.2775 mPa s, respectively. As for the mineral oil, the viscosity was 9.4603, 9.1968, 9.2624 and 9.395 mPa s over a period of 0 to 10 days of accelerated age as showing in Table III and Figure 4. The findings demonstrate that GTL oil has a higher flow efficiency, which enhances transformer cooling and insulating performance. The impact of age on viscosity becomes noticeable over time. After three years, the Dynamic viscosity of GTL oil stayed at 9.26 mPa.s., whereas that of Diala S_2 oil dropped to 9.1968 mPa.s. After six years, GTL oil was nearly constant at 9.27 mPa.s., whereas Diala S_2 oil grew somewhat to 9.2624 mPa.s. The viscosity of Diala S_2 oil returned to 9.395 mPa.s after ten years, however GTL oil stayed at 9.2775 mPa.s. A number of variables, including temperature, moisture content, and chemical interactions, can account for these findings. Natural gas-derived GTL oil has higher resistance to chemical deterioration, enabling it to sustain its viscosity stability over extended periods of time.

This indicates that GTL oil has proven its quality well over time, demonstrating its stability. Thus, the viscosity test results confirmed that GTL oil retains its properties better than mineral fuel oil over time. The developments in the chemical and dynamic viscosity of oils cause greater changes, which may affect their long-term performance. These results affect the importance of choosing oils based on their apparent and physical stability.

TABLE II. KINEMATIC VISCOSITY COMPARISON BETWEEN DIALA S_2 ZX-A AND DIALA S_4 ZX-I OILS DURING ACCELERATED AGING

	Kinematic Viscosity (mm²/s)	
	Mineral oil (Diala S_2)	**GTL oil (Diala S_4)**
Fresh Sample	**10.946**	11.698
3 years Sample	10.649	11.664
6 years Sample	10.732	11.659
10 years Sample	10.883	11.696

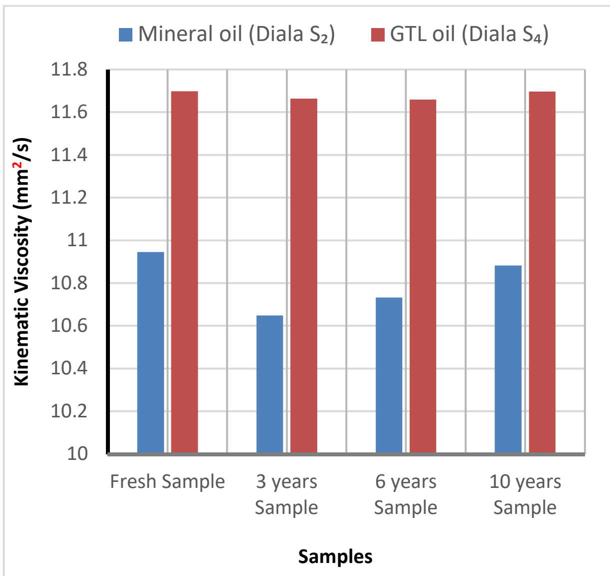

Fig. 3. Kinematic Viscosity of Diala S_2 Zx-A and Diala S_4 Zx-I Oils during aging.

TABLE III. DYNAMIC VISCOSITY COMPARISON BETWEEN DIALA S_2 ZX-A AND DIALA S_4 ZX-I OILS DURING ACCELERATED AGING

	Dynamic Viscosity (mm^2/s)	
	Mineral oil (Diala S_2)	**GTL oil (Diala S_4)**
Fresh Sample	9.4603	9.2944
3 years Sample	9.1968	9.26
6 years Sample	9.2624	9.27
10 years Sample	9.395	9.2775

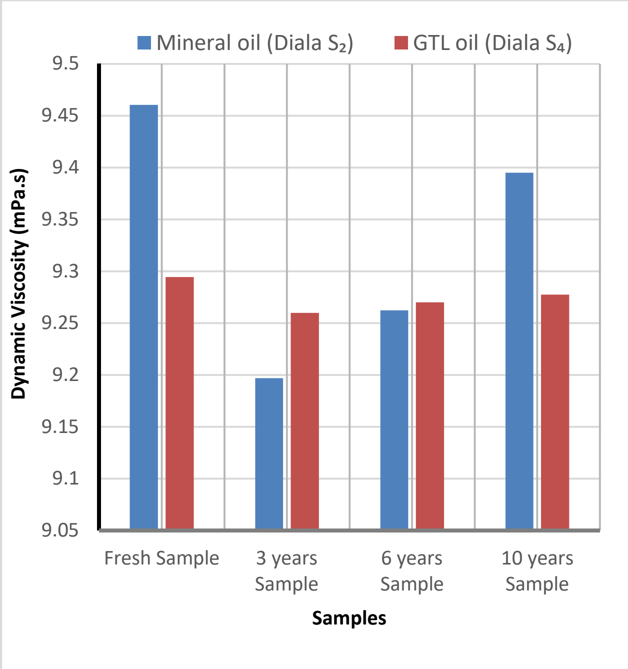

Fig. 4. Dynamic Viscosity of Diala S_2 Zx-A and Diala S_4 Zx-I Oils during aging.

CONCLUSION

In electrical engineering, comparing gas-to-liquids (GTL) to mineral oils is essential. It seeks to decrease transformer defects and enhance performance. By examining characteristics like density and viscosity in addition to other properties, grid energy solutions may be made more sustainable and effective. This study brings up new possibilities for power transformer oil improvement and improves the performance of transformers in challenging environments. Building on previous research that indicated GTL (Diala S_4) oil has lower dielectric losses than mineral oil (Diala S_2), this paper aims to evaluate the effect of aging on the oil physical properties; density and viscosity of both mineral oil (Diala S_2) and GTL oil (Diala S_4). The focus was on how these properties change over time, which helps in understanding the stability of oils and their suitability for transformers. The two types of oils were accelerated in age using an electric furnace. The study found that the density decreased slightly over the course of age, indicating minor chemical changes. Despite the changes, the density remained within an acceptable range. GTL oil showed better stability, with minor changes over the years, indicating that it retained its physical properties well. The viscosity results indicated that GTL oil retains its density and viscosity better than mineral oil over time. This stability makes it a preferred choice compared to mineral oil.

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