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Feasibility Study on the use of Magnesium Silicate for Reclaiming Synthetic Ester Insulating Liquid

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SUMMARY

Mineral insulating oil is used in transformers for insulation and cooling purposes. Due to the rise in environmental concerns and depleting of mineral oil sources, the search for alternative insulating liquids for liquid-filled transformers has been an interesting topic of research for many years. After extensive research, ester-based dielectric liquids have been accepted as potential alternatives to mineral insulating oils. Biodegradability, extended service life, and higher water saturation limits are key aspects for comprehensive consideration of these new liquids. However, viscosity, oxidation stability, application in cold regions, and availability of sufficient monitoring knowledge are challenges for the application of esters. To date, the research reports indicate that the ester fluids show an excellent thermal, physicochemical, and comparable dielectric properties to that of the mineral oil. It is important to understand the maintenance and reclamation avenues to ensure the safe service life of a transformer using these new biodegradable liquids. Reclamation, also known as regeneration, of transformer oil re-establishes its performance and characteristics close to its original conditions by several mechanical, chemical, or physical means. It is learned from the literature that adsorbent-based reclamation is accepted to be more productive in treating insulating liquids. Reclamation of mineral oils for transformers is a well-studied subject, in where commercial units are available for electrical utilities. In these units, the adsorbent of choice is Fuller's earth. However, at this time, there is not much information on procedures for reclamation of esters fluids.

The present article provides preliminary results of a study on the reclamation of a typical synthetic ester fluid by using magnesium silicate-based adsorbents. The experimental results include mineral insulating oil for a baseline reference. Both liquids are subjected to accelerated aging under open beaker conditions. The aged liquids are then regenerated using a pressure percolation method with two magnesium silicate-based adsorbents. Properties of the liquids before and after reclamation are compared to understand the efficiency of the adsorbents. The analysis performed include acidity, interfacial tension, water content, and dielectric breakdown voltage.

Water content and breakdown voltage results were not satisfactory after reclamation since the obtained values after reclamation were worse than the aged values. The reasons behind these results are explained in the article but mostly due to adsorbent conditioning and pre-treatment of the reclaimed oils. On the other hand, acidity, and interfacial tension show improvements after reclamation because the adsorbents were efficient on removing degradation products generated during aging. From the initial results, it is understood that the selected adsorbents have some potential for the reclamation of synthetic esters. However, there is a need to investigate other reclamation procedures such as other methods of filtration, number of extractions or passes, cost of the adsorbents, ratio of adsorbent to oils, conditioning of the oils after reclamation to explore the feasibility of using these adsorbents.

KEYWORDS

Power transformer, insulating liquids, synthetic esters, reclamation, regeneration, reconditioning, adsorbents.

INTRODUCTION

Power transformers are one of the most crucial assets of the power system network. Any incipient failure or unplanned outage of transformers may result in service interruptions and affect the reliability of power grids. The insulation system of a transformer, which consists of oil and paper, largely influences its useful service life [1]. Mineral oil (MO) has been used as transformer insulating liquid and coolant for many decades. Its dielectric and physicochemical properties made MO a widely used transformer insulating liquid. However, the rise in environmental concerns made the transformer industry look for alternatives to MO.

Since the 1970s, ester dielectric liquids (synthetic and natural) have been extensively researched for their use as alternatives to MO in transformers [1, 2]. However, various challenges including condition monitoring, workability, reclamation, and reconditioning are still investigated. The present work is a attempt made to address the challenges concerning the reclamation of ester fluids.

The aging of the power transformer largely confines to the degradation of its solid-liquid insulation system. Mineral insulating oils and ester dielectric liquids are different in their chemical composition. Therefore, the mechanisms and the nature of decay products that are produced during degradation are different.

Reclamation of transformer oil re-establishes performance close to original conditions by several physical, chemical, or adsorbent means [3]. Fuller's earth has been widely established and accepted for the reclamation of mineral insulating oils. For the acceptable limits of reclaimed mineral oil, IEEE Std C57.106-2015 englobes the expected parameters for the oil to be considered for re-use in electrical equipment. Unfortunately, there is not yet a standard that has studied what are the acceptable values for a reclaimed ester fluid.

The reclamation of natural ester-based insulating liquids has been reported in [4]. Authors reported that reclamation of natural esters is merely not possible for aged liquid with kinematic viscosity of 35% above its original value. None of the adsorbents used in their study were effective in improving the viscosity. The possibility of using Fuller's earth to reclaim synthetic esters is reported in [5, 6]. In these studies, it has been reported that the application of Fuller's earth for the reclamation of esters remains unfavourable because of its ineffectiveness in retaining the oxidation products that are formed during the thermal degradation of ester fluids. IEEE Std. C57.147-2018 mentions that magnesium silicate-based adsorbent may be effective for the reclamation of natural ester fluids.

This article provides preliminary results of a study on the reclamation of a synthetic ester fluid. Mineral insulating oil has been considered for reference purposes. The aged liquids are regenerated with two magnesium-based adsorbents under pressure percolation. The changes in a few liquid parameters following the reclamation process with both the adsorbents are reported in this paper.

EXPERIMENTAL

A typical synthetic ester and mineral oil are used for the present work as liquid insulating materials. To simulate a power transformer insulation system, kraft paper is also considered during the aging experiments, ratio of 1:20 (paper: oil). For thermal aging, an open beaker aging method based on modified ASTM D1934 – 20 is used. The thermal aging of the samples is performed in a conventional oven at 150 °C for 8 weeks to degrade the insulating materials to a greater extent. After aging, a uniform cooling period of 24 hours is allowed for all the beakers before testing.

As per IEEE Std. C57.637, both gravity-percolation and pressure-percolation methods are widely accepted for the transformer oil treatment process [7]. For this study, pressure percolation has been explored due to the less consumption of time. Also, two different magnesium silicate-based adsorbents (AD1 and AD2) are chosen for the reclamation process at a laboratory scale setup. The adsorbent pod is half-filled with the adsorbent, which is preheated at 60°C, and the preheated insulating liquids pass through the adsorbent pod with the help of vacuum pressure. The recovered liquid (filtrate/final liquid) samples are characterized, and the results are compared to the aged and unaged liquid properties to assess the efficiency of the reclamation.

RESULTS AND DISCUSSION

As highlighted in the above paragraphs, the physicochemical characterizations, including acidity, interfacial tension (IFT), water content, and AC breakdown voltage, are performed on the aged liquids before and after reclamation. It is to be understood that the reclamation is performed only for one cycle (single pass). The details of the changes in the liquid properties following the treatment are explained in the following sections.

Acidity

Total acid number (TAN) or neutralization number is a widely accepted aging marker for transformer insulating liquids [8]. The oxidation of these liquids during the thermal degradations generates by-products which results in an increase in the acid number value of the insulating liquid [9]. The TAN is a measure of the total amount of KOH solution that is required to neutralize the acids present in the insulating liquid. The acidity values of MO and SE before and after reclamation with two adsorbents, AD1 and AD2, are represented in Fig. 1. The non-aged samples are also taken into consideration as a reference. The results shown are the average of three measurements.

From the obtained values, after aging, the acidity of the SE is higher than the acidity of MO. This can be explained by the hygroscopic nature of the ester fluids, which let them actively participate in hydrogen bonding as hydrogen acceptors. This results in the higher water saturation limits in ester fluids when compared to MO, which further contributes to the formation of long-chain fatty acids and thus increases the acidity values. It is known that the concentration of long-chain fatty acids in ester fluids is weak and non-detrimental to the insulation degradation [10]. On the other hand, the low molecular weight (LMW) or short chain fatty acids that are also formed due to the oxidation of insulating liquids contribute to the accelerated degradation of the insulation paper. Nevertheless, the TAN does not provide an exact concentration of the low molecular weight acids in the insulating oils, which are detrimental to the transformer insulation system. It is important to understand the concentration of LMW acids in insulating liquids, not studied in this article, to interpret the liquid's degradation rate effectively [11].

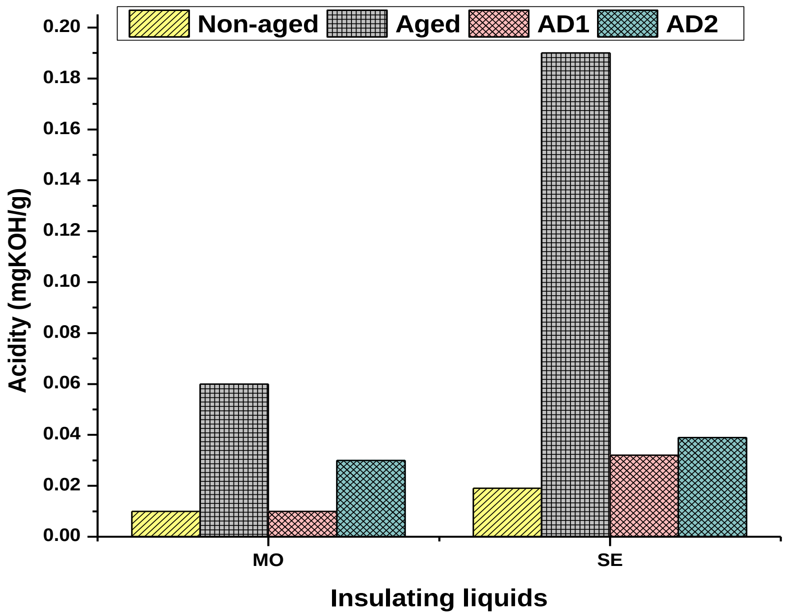

Fig. 1: Acidity of MO and SE before and after reclamation.

The regenerated samples (both MO and SE) show improvement within a single pass. The obtained values are close to the values of non-aged samples, which are in line with the established literature and within the acceptable limits for mineral oil [12, 13]. The improvement in acid number after reclamation shows the potential of the adsorbents in reducing the oxidation products from the liquids.

Nevertheless, it has been observed that the liquids treated with AD1 show relatively better improvement in both liquids.

Interfacial tension (IFT)

Interfacial tension is a routinely used characterization method, which indicates the soluble polar contaminants concentration and degradation products in insulating liquids [10, 14]. The IFT measurements are performed on MO and SE before and after reclamation with both the adsorbents AD1 and AD2. The non-aged samples are also taken into consideration as a reference. The graphical representation of the obtained IFT values of the liquids is shown in Fig. 2. The values are the average of three measurements.

From Fig. 2, it is observed that the IFT values of aged MO and SE are similar, and the very low IFT values describe that the liquids are highly degraded. The IFT values have increased after reclamation, and this trend is similar in both liquids. This suggests that these adsorbents are capable of removing or reducing the polar contaminants from the liquids.

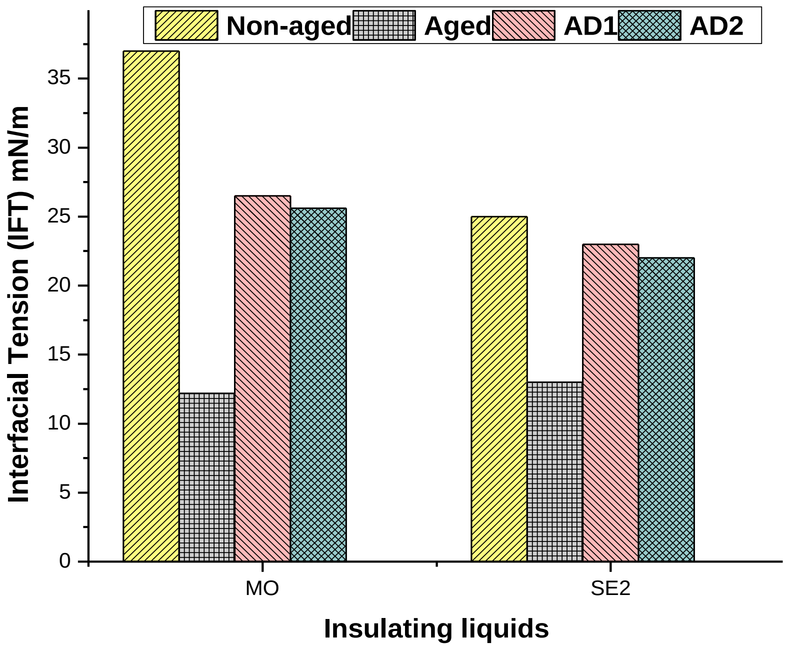

Fig. 2: IFT of MO and SE before and after reclamation.

However, IFT values of MO are not within the acceptable limits of unused liquids mentioned in [13] for a single pass, which is 30 mN/m. Simultaneously, the ester fluids showed promising improvement in IFT values after reclamation with AD1 and AD2 by achieving values close to their original condition. AD1 is more efficient in removing the soluble polar contaminants and oxidation products from the ester fluids when compared to AD2.

Water content

It is established that the insulating liquids absorb additional water content with an increase in temperature and liquid degradation [15]. This increase in water content is one of the main causes that lead to the deterioration of the insulation system. Therefore, it is necessary to monitor the water content in the liquid insulating medium periodically. Even though the reconditioning techniques (dehydration and degassing) are recommended to reduce the moisture, the adsorbent treatment ought to reduce the moisture while also removing the oxidation products. The water content measurements of aged samples and regenerated samples of MO and SE have been performed using the Karl Fischer titration method. The graphical representation of the obtained values is shown in Fig. 3. These values are the average of the three measurements and the non-aged samples are taken as reference.

It is noticed that the increase in water content in both MO and SE after thermal aging of 8 weeks appears reasonable as per the aging studies of insulating liquids. After eight weeks of aging, the SE has reached 6% of its saturation limit while, MO has reached 24% of its saturation. Therefore, the interpretation of water content in MO and SE are different, which is to be clearly understood by comparing their relative water contents [11].

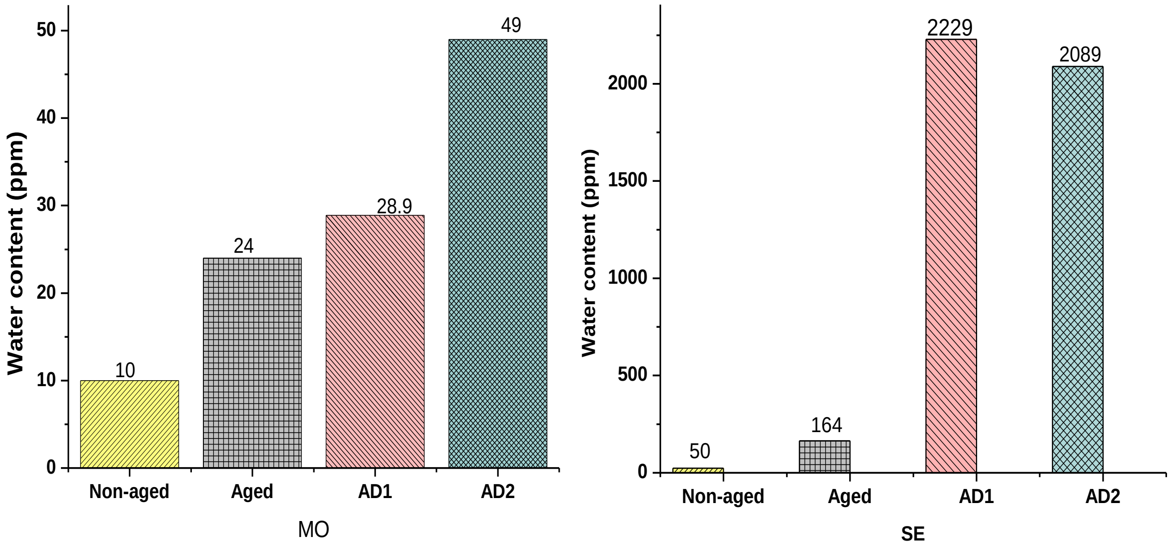

Fig. 3: Water content in MO and SE before and after reclamation.

It is also observed that there is an extreme increase in the water content of SE liquid after regenerating with AD1 and AD2, which is almost 80% of the liquid's water saturation limit [16]. After several trial tests, it is recognized that the desired adsorbents are not efficient in removing the moisture from both MO and SE. Also, these adsorbents release some amount of moisture when preheated at 60°C. The higher water content values of SE after reclamation are due to the migration of moisture from the adsorbents to the liquids. The ability of esters to hold more moisture also played a role in increasing the moisture in oil. Since the reclamation of transformer liquids is always performed in conjunction with reconditioning in industrial practices; the drying process certainly should reduce the moisture in the treated liquids.

Dielectric breakdown voltage

The dielectric breakdown voltage is an important parameter to be considered to decide on any regenerated transformer liquid. The breakdown voltage (BDV) of the liquids should always be within the acceptable limits as per the existing standards, only available for mineral oil. The breakdown measurements have been performed with a 2.5 mm electrode gap as per ASTM D1816, and the results are the average of the obtained values after the five measurements. The BDV values of MO and SE before and after the reclamation with two adsorbents are tabulated in Table 2. It is to be mentioned that the regenerated samples have not been reconditioned (dehydrated/degassing) or filtered prior to the BDV testing.

Table 2: BDV values of MO and SE before and after reclamation.

Dielectric breakdown (kV)	MO	SE1
Non-aged	62	65
Aged (8 weeks at 150°C)	48	45
Regenerated with AD1	13	12
Regenerated with AD2	11	15

The BDV values of MO and SE after aging are almost similar and are in line with those reported in the literature [17]. The BDV of MO and SE are not meeting the minimum acceptable limit, which is 25 kV for MO (regenerated), and 30 kV for SE (new fluid). The lower BDV values in SE may be attributed to the higher water content (see Fig. 3). It is to be mentioned that due to the applied pressure, fine adsorbent particles are carried along with the insulating liquid during the reclamation process. These microparticles also act as local conduct particles that may lead to an early breakdown of the liquid. When the regenerated liquids were subjected to AC voltage, hissing noise and minor sparks are witnessed at a very low voltage (around 5 kV), ultimately leading to lower BDV values. The choice of adsorbent particle size is dependent on the type of percolation used to reclaim the liquid. For MO, the percolation towers use fine clays whereas powdered clays are used in the reclamation by contact process. Therefore, from the observations, it may be suggested that other reclamation methods using similar adsorbents may be suitable to treat synthetic ester fluids.

CONCLUSION

Experimental analysis has been performed at a laboratory scale to study the feasibility of using magnesium silicate-based adsorbents for reclamation of synthetic ester insulating liquid. From the results, it is understood that the adsorbents AD1 and AD2 are effective in improving the acid number and IFT while removing the oxidation products and contaminants from MO and SE. The dielectric strength for both MO and SE decreases significantly after reclamation. Water content also increased after reclamation.

Recommendations for future work include the study of other percolation methods, including finding magnesium silicate-based adsorbents in a suitable particle size to be used in reclamation by pressure percolation. Other parameters to explore consist of the study of other adsorbents, adsorbent-liquid ratios, and the number of passes to be performed to achieve acceptable operational conditions for SE liquids.

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