Effect of the retro-filling process on kraft paper and gasket materials in transformers

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ABSTRACT

Mineral oil (MO) is the most widely used insulating liquid in oil-filled transformers. Numerous studies have investigated the use of alternative synthetic and ester-based insulating oils as replacements for MO. However, the effects of the retro-filling process on transformer materials remain insufficiently explored. This study examines the impact of retro-filling and thermal ageing on transformer kraft paper and gasket materials. Kraft paper strips, fluoroelastomer (FE) and nitrile butadiene rubber (NBR) gaskets, MO, synthetic oil (SO), and ester oil (EO) are used in the investigation. Initially, three sample bottles containing MO undergo thermal ageing for 200 hours at 130 °C. Subsequently, the retro-filling process is performed using MO, SO, and EO respectively. The samples are then subjected to an additional 200 hours of ageing at the same temperature. Results indicate that EO demonstrates superior performance in terms of shore hardness (+1.06%), while SO better preserves the tensile strength of kraft paper strips. These findings suggest that the retro-filling process can contribute to extending the service life of transformers.

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1. INTRODUCTION

Retro-filling is the process of replacing the existing insulating fluid in an operational transformer with new fluid. For instance, by changing the insulating oil that was previously used, such as mineral oil (MO). The transformer is effectively upgraded as a result. When retro-filling involves the use of an advanced fluid, such as synthetic oil (SO) or ester oil (EO), it provides further demonstrated advantages. The retro-filling method has become known as an acceptable way to address significant issues in transformer materials, such as ageing, decreased performance, and impact on the environment. Over time, the insulating and structural elements of transformers experience significant degradation due to exposure to electrical, thermal, and chemical stresses. These external factors compromise the electrical efficiency and mechanical integrity of transformers, resulting in elevated maintenance costs and potential failures [1]. Moreover, conventional insulating fluids, typically sourced from petroleum, represent hazards to the environment, such as low biodegradability and toxicity [2]. By replacing or enhancing the existing insulating fluid without requiring complete transformer replacement, the retro-filling process offers a sustainable and cost-effective approach to extending the transformer's lifespan while improving its operational performance. According to

Huang *et al.* [3], the FR3 natural ester insulating liquid was retro-filling in real time in a 220 kV 16 MVA power transformer in China. As for the retro-filled study, only a few reports on the property change of insulating paper retro-filled with biodegradable oil during the thermal aging process [4], [5]. The influences of retro-filling on the aging rate of insulating papers and related mechanisms have been hardly addressed. Hence, the study of a characteristic of insulating papers that immersed in retro-filled insulating fluid compared to MO is needed on providing feasible data for transformer oil insulation purposes.

This research aims to determine the impact of the retro-filling method on transformer materials. Dielectric strength and insulation resistance are essential metrics that reflect material performance and dependability in high-voltage settings [6]. Research emphasizes that retro-filling transformers with natural ester-based oils significantly enhance dielectric properties and environmental compatibility. For example, replacing aged MO with a 90% natural ester mixture increased dielectric strength by 43% while maintaining acceptable dissipation factors. These findings underscore the potential of retro-filling to improve the efficiency, reliability, and sustainability of transformer insulation systems [7]. Tensile strength and Shore A hardness offer insights into the mechanical durability of transformer components, which is crucial for structural integrity [8]. Chemical assessments, including acidity, are essential for evaluating the deterioration of insulating fluids, whereas ultraviolet-visible (UV-VIS) spectroscopy facilitates the monitoring of alterations in chemical stability and light absorption characteristics [9]. Together, these assessments offer an in-depth understanding of how retro-filling impacts the numerous properties of transformer materials.

The primary objective of this study is to determine the impact of the retro-filling procedure on the vital material qualities of transformers, with the goal of improving their durability, efficiency, and environmental sustainability. This research seeks to better understand the benefits and limitations of retro-filling in enhancing transformer performance through investigation of material's characteristics. These findings are likely to lead to the broader implementation of retro-filling in transformer maintenance and to the development of more sustainable and efficient energy systems [10].

2. MATERIALS AND METHODS

In this work, the insulating oils employed were MO, SO, and EO. Kraft paper strips and pressboards were used for the solid insulations. The gasket materials chosen for this work were Viton® fluoroelastomer (FE) and nitrile butadiene rubber (NBR) sheets. This study used four different metal catalysts: copper, aluminium, iron, and zinc. To eliminate any water content in oil, the nitrogen bubbling treatment, which used nitrogen gas, was applied. A detailed explanation regarding the accelerated thermal ageing procedure and the measurements of the insulating oil sample properties, including moisture content, acidity, AC breakdown voltage, and relative content of dissolved decay products (relative DDP) are elaborated in this section. Physical testing measurements which is tensile strength and Shore A hardness test for kraft paper strips and gaskets, also presented in this section.

2.1. Samples of solid insulation and insulating oil preparation

For this experiment, three bottles of samples were prepared. Each sample consisted of insulating oil (MO, SO, and EO), kraft paper strips, pressboards, metal catalysts, and gasket materials (FE and NBR). Table 1 shows all the sample details used for this experimental work.

Table 1. The accelerated thermal ageing test materials

Sample no.	Insulating oil	Solid insulations	Metal catalysts	Gasket materials
1	MO	Kraft paper strips and pressboards	Copper, aluminium, iron, and zinc	FE and NBR
2	SO	Kraft paper strips and pressboards	Copper, aluminium, iron, and zinc	FE and NBR
3	EO	Kraft paper strips and pressboards	Copper, aluminium, iron, and zinc	FE and NBR

There were approximately 500 mL of insulating oil in each sample. Prior to undergoing nitrogen bubbling treatment, the insulating oils underwent filtration to assure that their moisture content was within the acceptable ranges (≤35 mg/kg (MO) and ≤200 mg/kg (EO and SO)) [11]. The standard of ASTM D3487 [12], ASTM D6871 [13], and IEC 61099 [14] is used for MO, EO, and SO respectively. The minimum requirement of AC breakdown voltage with a gap distance of 1 mm between the electrodes is 20 kV for both MO and EO. The minimum requirement of AC breakdown voltage with a gap distance of 2.5 mm gap between electrodes for SO is 45 kV. The transformer oils' acidity was measured to ensure that it was ≤0.03 mg KOH/g (MO and SO) and ≤0.06 mg KOH/g (EO). The FE and NBR gasket materials had measurements of 8.5 cm×25 cm×0.3 cm. To verify that the solid insulations were 1:10 of the insulating oil mass, the pressboards (dimensions: 6 cm×2.5 cm×0.22 cm) and kraft paper strips (dimensions: 28 cm× 2 cm×0.075 cm) were weighed. According to the BS EN 60641 standard, the kraft paper strips, pressboards, and metal catalysts were dried at 105 °C for 12 hours in a forced air ventilation oven once weighed [15]. The drying procedure is vital to ensure that the kraft paper strips' weight is 0.05 wt.% less than their starting weight. The catalysts made of copper, aluminium, iron, and zinc had fixed weights of 1.25, 0.25, 1.25, and 0.25 g, respectively. For sample preparation, bottles consisting kraft paper strips, pressboards, metal catalysts, and gasket materials were immersed in respective insulating oil for a whole day at room temperature prior to the accelerated thermal ageing process.

The retro-filling and thermally ageing process involves the following steps: i) three sample bottles containing MO are placed in a laboratory oven; ii) accelerated thermal ageing is conducted for 200 hours at 130 °C [16]; iii) after 200 hours, the bottles are removed from the oven; iv) once cooled, the aged MO is drained from the bottles; v) the bottles are then refilled with MO, EO, and SO, respectively; and vi) a second round of accelerated thermal ageing is carried out for an additional 200 hours at 130 °C following the retro-filling process.

2.2. Characteristics measurements of insulating oils, kraft paper strips, and gasket materials

The water content of insulating oil can be tested using the Karl Fischer titration method using Metrohm 899 coulometer. All the value of insulating oil passed within the standard given based on ASTM D1533 [17] both MO and SO, while IEC 61099 for EO. The acidity of the insulating oil samples was measured according to the ASTM D664 standard [18] using Metrohm 848 Titrino plus compact titrator. The AC breakdown voltage of the insulating oil samples was determined using Megger OTS60PB portable oil tester in accordance with the ASTM D1816 standard [19]. Using an UV–VIS spectrophotometer (Model: UV-1800, Shimadzu Corporation, Japan), the relative DDP of the thermally aged insulating oil samples was determined [20], [21]. A kraft paper strip was placed between the upper and lower clamps of a tabletop EI-1007E computerized servo-controlled universal testing machine to determine the tensile strength of the strips. Then, in compliance with the BS 4415-1 standard, the upper clamp was raised until the kraft paper strip ruptured, and the tensile force needed to do so was simultaneously measured and recorded [22]. The Shore A hardness durometer was used to assess the gasket materials' hardness under ASTM D2240-15 [23].

3. RESULTS AND DISCUSSION

The AC breakdown voltage, water content, and acidity of oil samples (MO, SO, and EO) were measured following their filtering and nitrogen bubbling treatment. After that, the dried kraft paper strips, pressboards, FE and NBR gasket materials, and metal catalysts were immersed in the treated MO to produce three bottles of Sample 1 (Table 1). All bottles underwent 200 hours of accelerated thermal ageing at 130 °C. After 200 hours, the bottles were left to cool down. Then, the MO inside all bottles was flushed out, and transferred to amber bottles as part of the retro-filling procedure. Next, new treated MO, EO, and SO were added into each former bottles producing Sample 1, Sample 2, and Sample 3 respectively (Table 1). After the retro-filling procedure, all samples were aged for additional 200 hours at 130 °C. This section discusses the impact of retro-filled and thermal ageing on the properties of transformer's material.

3.1. Properties of the treated insulating oils

The AC breakdown voltage, water content, relative DDP, and acidity of the treated insulating oils (Table 2) prior to the accelerated thermal ageing were found to correspond to the acceptable limits according to ASTM D3487 (MO), IEC 61099 (SO), and ASTM D6871 (EO) standards. AC breakdown voltage ≥20 kV for an electrode gap of 1 mm (MO and EO), AC breakdown voltage ≥45 kV for an electrode gap of 2.5 mm (SO), water content ≤35 mg/kg (MO) and ≤200 mg/kg (EO and SO), acidity ≤0.03 mg KOH/g (MO) and ≤0.06 mg KOH/g (EO and SO).

Table 2. Properties of the treated insulating oil samples

Property	Unit	MO	SO	EO
AC breakdown voltage	kV	36.8	52.4	31.1
Water content	mg/kg	23.4	78.4	58.8
Relative DDP	—	0	0	0
Acidity	mg KOH/g	0.025	0.022	0.060

3.2. Impact of retro-filling and thermal ageing on the relative DDP and acidity of insulating oils

Table 3 presents the percentage changes on relative DDP and acidity of the retro-filled and thermally aged (RFTA) of MO, SO, and EO.

Table 3. Percentage changes in relative DDP, and acidity of the RFTA oils

Insulating oil sample	Relative DDP	Percentage changes in relative DDP (%)	Acidity (mg KOH/g)	*Percentage changes in acidity (%)
RFTA-MO	176.6	+176.6	0.8760	+3404
RFTA-SO	73.15	+73.15	0.1466	+566.4
RFTA-EO	63.74	+63.74	0.5581	+830.2

* Percentage changes in relative DDP and acidity were established regarding the relative DDP and acidity of the MO, SO, and EO after retro-filling and thermal ageing. The positive symbol signifies an increase, while the negative symbol signifies a decrease.

Relative DDP is the region below the absorbance curve that measure using a UV-VIS spectrophotometer. Due to thermal ageing, an insulating oil that has darkened in colour has more decay products (i.e., impurities and suspended particles) [24]. New insulating oils have a relative DDP of 0 for MO, SO, and EO since they are predominantly clear and pale yellow. After the RFTA process, the insulating oil samples' relative DDP increased to 176.6 (MO), 73.15 (SO), and 63.74 (EO).

As for acidity, MO (0.025 mg KOH/g), SO (0.022 mg KOH/g), and EO (0.060 mg KOH/g) had the lowest acidity at first. The insulating oil samples' acidity elevated to 0.8760 mg KOH/g (MO), 0.1466 mg KOH/g (SO), and 0.5581 mg KOH/g (EO) during the RFTA process. The insulating oil samples showed a percentage increased in acidity of +3404% (MO), +566.4% (SO), and +830.20% (EO). The occurrence of hydrolysis and pyrolysis processes during the RFTA process of MO, resulted in the formation of long-chain or medium-chain fatty acids, contributes to the significant rise in acidity of the MO.

3.3. Impact of retro-filling and thermal ageing on the tensile strength of kraft paper strips

Table 4 shows the percentage degradation on the tensile strength of the kraft paper strips immersed in MO, SO, and EO after the RFTA process. Tensile strength is a material's ability to withstand tensile forces without breaking or deforming. It measures the maximum stress or loads a material can endure before it fails in tension. It is an essential mechanical property used to evaluate a material's suitability for applications involving structural integrity and load-bearing capabilities.

Table 4. Percentage degradation in tensile strength of the RFTA kraft paper strips

Insulating oil sample	Kraft paper strips	Tensile strength (MPa)	*Percentage degradation in tensile strength (%)
—	KP (O)	91.00	—
RFTA-MO	KP (MO)	56.62	−37.78
RFTA-SO	KP (SO)	58.73	−35.46
RFTA-EO	KP (EO)	53.31	−41.41

KP (O): original kraft paper strip, KP (MO): Kraft paper strip immersed in MO, KP (SO): kraft paper strip immersed in synthetic oil, KP (EO): kraft paper strip immersed ester oil.
*Tensile strength degradation was determined as a percentage of the original kraft paper strip's tensile strength. A negative sign indicates a decrease, whereas a positive sign represents an increase.

Based on Table 4, kraft paper strips immersed in three different types of insulating oil have a decreasing value after 200 hours of the RFTA process. Among the results, tensile strength of KP(EO) has decreased by 41.41% due to its inherent chemical structure and properties. Due to certain chemical substances in MO that strengthen kraft paper, the degradation of KP(MO) is 37.78%. As for KP(SO), it is observed that the degradation is 35.46%. In this experimental study, KP(SO) shows good strength of tensile compared to other samples. EO, notable for their pronounced polarity and hygroscopic nature, are increasingly favoured for use in power transformers. These properties facilitate efficient moisture uptake from the transformer insulation architecture, thus enhancing the rate of moisture expulsion from the kraft paper insulation. Nevertheless, the continued thermal stress during operation leads the absorbed moisture to initiate ester hydrolysis, yielding low-molecular-weight acids and alcohols. These degradation products, in turn, catalyse structural weakening of the cellulose matrix by reducing the cellulose's degree of polymerization and, consequently, the tensile strength of the kraft paper insulation. In contrary, synthetic ester formulations provide markedly greater hydrolytic stability, yielding fewer and less aggressive by-products [25].

3.4. Effect of retro-filling and thermal ageing on the Shore A hardness of the gasket materials

Figures 1 and 2 present the Shore A hardness of the gasket materials (NBR and FE) subjected to immersion in MO, SO, and EO with RFTA process. It can be seen that the NBR is more fragile than the FE rubber sheet. The initial measurement of a Shore A hardness of the NBR and FE were 79.00 and 82.30, respectively. From the results, when the NBR was immersed in MO, SO, and EO and subjected with RFTA process, the NBR degraded 94.7%, 85.9%, and 96%, respectively. NBR is made from a copolymer of butadiene and acrylonitrile, while FE are made primarily of fluorinated carbon-based monomers. The chemical structure of FE imparts exceptional resistance to a wide range of chemicals, including aggressive solvents and fuels. In contrast, NBR has good resistance to many oils and fuels but may not perform as well against certain chemicals, particularly those containing aromatic compounds or strong acids. Additionally, FE exhibit superior high-temperature performance compared to NBR. Thus, FE can withstand elevated temperatures without significantly degrading their mechanical properties, making them suitable for extreme heat or thermal cycling applications. On the other hand, NBR has a lower upper-temperature limit and may experience reduced performance or become more brittle when exposed to high temperatures over an extended period.

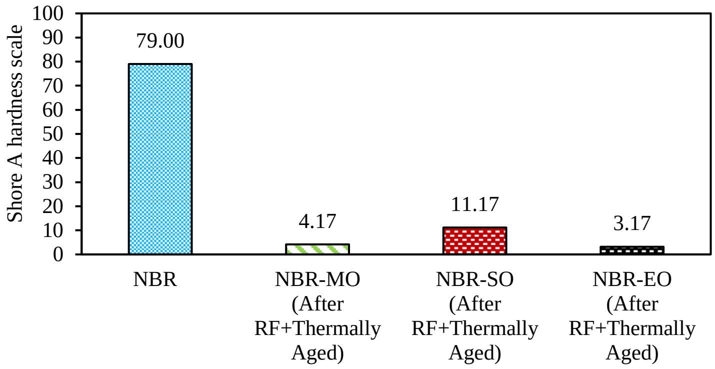

Figure 1. Shore A hardness of the NBR gasket materials

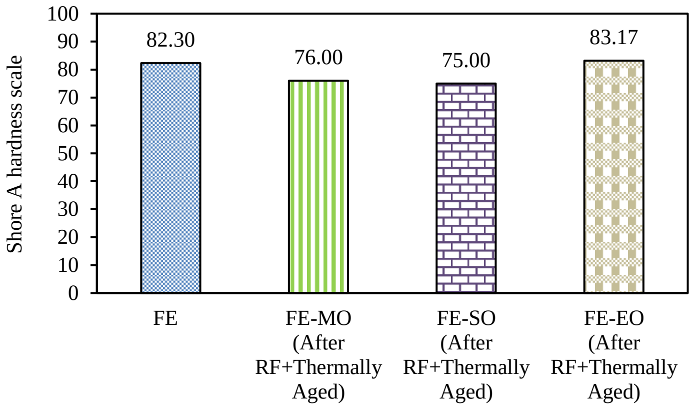

Figure 2. Shore A hardness of the FE gasket materials

Figure 2 demonstrate that FE-EO for Shore A hardness reading increases by 1.06%, unlike in other insulating oils. After the RFTA process, the Shore A hardness of FE-MO and FE-SO is degraded 7.65% and 8.87%, respectively. The unique chemical structure of the FE contributes to its hardness and resistance to deformation. Therefore, when tested using the Shore A hardness method in ester oil, FE-EO will likely maintain their hardness and integrity, resulting in good Shore A hardness readings. This indicates their superior chemical resistance and ability to withstand the effects of ester oil without significantly changing their mechanical properties. The esters' polarity accelerates the migration of plasticizers from the NBR, causing the material to swell, soften, and exhibit higher permeability, which ultimately leads to a breakdown of the mechanical seal. This failure jeopardizes the hermetic enclosure of the transformer, permitting moisture ingress that can accelerate the degradation of the solid insulation system. By contrast, FE gaskets show a pronounced resistance to ester fluids, presenting negligible swelling and preserving their sealing capacity even when exposed to elevated temperatures for extended periods.

4. CONCLUSION

In this study, a retro-filling and thermal ageing process was carried out for 200 hours at 130 °C using MO, SO, and EO, following an initial phase of accelerated thermal ageing with MO. After retro-filling and subsequent ageing, key parameters were evaluated, including the relative DDP and acidity of the insulating oils, the tensile strength of kraft paper strips, and the Shore A hardness of FE and NBR gasket materials. The experimental findings indicate that EO enhances the Shore A hardness of FE gaskets by 1.06%, while SO demonstrates superior performance in preserving the tensile strength of kraft paper strips.

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AUTHOR CONTRIBUTIONS STATEMENT

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Imran Sutan Chairul	✓	✓	✓		✓	✓		✓	✓		✓	✓		
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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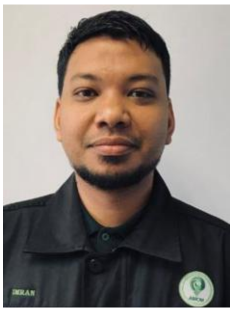

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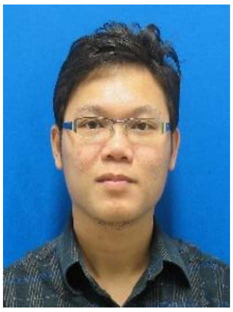

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