Determination of the Fire Resistance Characteristics of Transformer Insulating Oils Through Pool Fire Experiments

M. F. Bahari[1], S. Ab Ghani[1*], I. S. Chairul[1], N. H. Rahim[1], N. A. Muhamad[2]
[1]Electrical Asset Condition Monitoring Research Group (e-AMCM), Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2]Faculty of Engineering, Universiti Teknologi Brunei, Jalan Tungku Link Gadong, BE1410 Brunei Darussalam
[*]corresponding author's email: sharinag@utem.edu.my

Abstract – *Fire safety is crucial for oil-immersed power transformers due to the potential destruction of infrastructure, environmental damage, and risks to human health and safety caused by transformer fires and explosions. One of the essential elements of oil-immersed power transformers is the insulating oil, which is used for insulation and cooling purposes. However, the insulating oil can pose significant fire hazards, particularly mineral oil, which is highly flammable. Hence, it is crucial to perform fire resistance tests to determine the fire resistance characteristics of transformer insulating oils. This study investigates the fire resistance characteristics of O-class (mineral oil and fatty acid methyl ester) and K-class (natural and synthetic esters) transformer insulating oils through pool fire experiments simulating realistic fire scenarios. During the fire resistance test, ignition time and oil temperature were recorded. Subsequent Fourier transform infrared was used to analyse the chemical bonds of the transformer insulating oils. The Fourier transform infrared results revealed that mineral oil has strong aliphatic C-H stretching bands, characteristic of a straight hydrocarbon chain and with lower thermal and oxidation stability. On the other hand, the ester's oil has strong carbonyl C=O stretching peaks, characteristic of polar functional groups associated with increased oxidative stability. Results showed that mineral oil and fatty acid methyl ester ignited upon thermal exposure, while natural and synthetic esters did not ignite, even at temperatures exceeding 300 °C. These findings demonstrate that natural and synthetic esters exhibit superior fire resistance compared to mineral oil and fatty acid methyl esters.*

Keywords: *Fire resistance characteristics, Fire safety, Oil-immersed power transformer, Pool fire, Transformer insulating oil.*

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I. Introduction

Transformers insulating oils are essential elements of oil-immersed power transformers serving as both electrical insulators and cooling mediums. The primary role of transformer insulating oils is to insulate transformer components and dissipate the heat generated during transformer operation, thereby ensuring smooth operation and safety of in-service oil-immersed power transformers. For more than a century, mineral oils have been used as dielectric liquids in oil-immersed power transformers due to their superior dielectric properties, cooling capability, and affordability [1]-[3].

However, the power industry is searching for alternative transformer insulating oils that are fire-resistant and environmentally benign due to the flammability, non-renewability, and non-biodegradability of mineral oils [4],[5]. The use of mineral oils in oil-immersed power transformers poses a significant fire hazard, especially in the event of electrical faults or transformer oil leakages, which can result in fires and explosions, causing catastrophic destruction [3],[5],[6]. In addition, mineral oils are derived from refined crude petroleum, and they are hydrocarbon-based liquids that are susceptible to ignition when exposed to sufficient heat or spark, posing a risk of pool fires.

Transformer oil leakages, caused by faulty gaskets, cracked insulation, or loose covers, pose a serious threat to the environment due to the toxicity of mineral oils [3],[7],[8] and can culminate in fires and explosions if the leaking oil comes into direct contact with the high-voltage components inside the oil-immersed power transformer [7],[9]. Pool fires occur when the transformer insulating oil leaks onto the ground, forming a pool that is easily ignitable upon exposure to a heat source. Pool fires are difficult to extinguish and can spread to nearby equipment and facilities, presenting a serious safety hazard. Internal equipment failures or elevated operating temperatures can initiate fires within oil-immersed power transformers and can inflict significant damage to the transformer tank, adjacent equipment, and the entire substation, compromising the safe and reliable operation of the power grid [10],[11].

Transformer pool fires may be one of the main contributors to the number of electrical substation fire incidents worldwide. Large-scale fire plumes (i.e., the columns of hot gases, flames, and smoke rising above a fire), which are a consequence of transformer pool fires, raise concerns among the scientific community regarding the nature of pool fires [12]. Fuelled by high winds, the tilted fire plumes engulf adjacent equipment, buildings, and structures with soot, significantly expanding the area affected by the fire [12].

Since mineral oils pose a significant fire hazard, efforts are being made to substitute mineral oils with ester fluids. Both unused and in-service ester fluids are classified as K-class transformer insulating oils because of their exceptionally high fire points of above 350 °C [13]. Owing to their high fire points, ester fluids are preferred for on-site retrofilling of oil-immersed power transformers formerly insulated by mineral oils [13]. The development of ester fluids is a significant advancement in power system safety and risk management.

Unlike traditional mineral oils, ester fluids possess superior fire resistance characteristics and therefore, they are classified as K-class transformer insulating oils according to the IEC 61039-2008 standard [14]. From an insurance perspective, the use of ester fluids can be viewed as a proactive risk mitigation measure, potentially qualifying facilities for better coverage terms and rates.

Table I shows the comparison of the fire resistance parameters (flash point and fire point) between mineral oils, natural esters, and synthetic esters [15]-[20]. The flash point refers to the lowest temperature at which the transformer insulating oil vaporises to form an ignitable mixture in air, whereas the fire point refers to the temperature at which the vapours of the transformer insulating oil continue to burn after the oil is ignited even after the source of ignition is removed.

Owing to serious safety hazards posed by pool fires in oil-immersed power transformers, it is imperative to determine the fire resistance characteristics (ignition time, oil temperature, and occurrence of vaporisation) of different types of transformers insulating oils by means of pool fire experiments, which forms the motivation of this study. This study provides insight into the selection of the best transformer insulating oil that will minimise the risk of pool fires, which will be beneficial to the utilities.

TABLE I
COMPARISON OF THE FIRE RESISTANCE PARAMETERS BETWEEN DIFFERENT TYPES OF TRANSFORMER INSULATING OILS [15],[16],[17],[18],[19],[20]

Item	Mineral oils	Natural esters		Synthetic esters	Standard
Type	Refined crude oil-based distillate	Esterified palm oil	Refined vegetable oil	Chemical compounds derived from esterification between an alcohol and an organic acid	
Principal component	Mixture of hydrocarbons	Fatty acid methyl ester	Triglycerides	Pentaerythritol tetrastearate ester	
Flash point [°C]	≥ 135	≥ 135	≥ 250	≥ 250	IEC 60296, IEC 62770, IEC 61099
Fire point [°C]	—	≥ 175	≥ 300	≥ 300	
Fire class	O	O	K	K	IEC 61039

II. Methodology

A. Sample preparation

The methodology adopted in this study is presented in Fig. 1. The methodology begins with the selection of transformer insulating oils, followed by pre-processing of the oil samples, and concludes with the assessment of the results from fire resistance tests. Five commercially available transformer insulating oils were used in this study, namely, (1) Hyrax Hypertrans uninhibited mineral oil (Hyrax Oil Sdn. Bhd., Malaysia), (2) palm fatty acid ester (Lion Corporation, Japan), (3) FR3 natural ester dielectric fluid (Cargill Incorporated, United States of America), (4) Midel eN 1204 natural ester transformer fluid (MIDEL & MIVOLT Fluids Ltd., United Kingdom), and (5) Midel 7131 biodegradable synthetic transformer fluid (MIDEL & MIVOLT Fluids Ltd., United Kingdom). These transformer insulating oils are summarised according to type, as shown in Table II. All the transformer insulating oil samples were first pre-processed by 47-mm vacuum filtration assembly fitted with a nylon membrane with a pore size 0.22μm [21], followed by nitrogen bubbling for 2 min at a flow rate of ~1 L/min to get water content less than 30 ppm for mineral oil and less 200 ppm for ester oil [22].

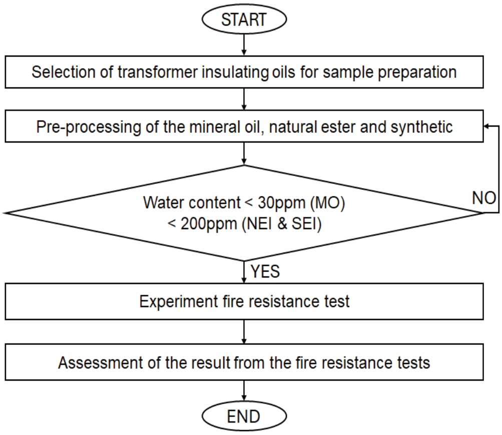

Fig 1. Flow chart of the methodology adopted in this study

TABLE II
LIST OF THE TRANSFORMER INSULATING OILS USED IN THIS STUDY

Type of transformer insulating oil	Brand name and manufacturer
Mineral oil	Hyrax Hypertrans (Hyrax Oil Sdn. Bhd., Malaysia)
Natural ester (fatty acid methyl ester)	Palm fatty acid ester (Lion Corporation, Japan)
Natural ester	FR3 (Cargill Incorporated, United States of America) Midel eN 1204 (MIDEL & MIVOLT Fluids Ltd., United Kingdom)
Synthetic ester	Midel 7131 (MIDEL & MIVOLT Fluids Ltd., United Kingdom)

B. *Experimental set-up*

The experimental setup is shown in Fig. 2(a) and (b). The fire resistance tests were conducted indoors to control the pool fire and eliminate wind interference, which could affect the results. The transformer insulating oil was ignited using a fire nozzle positioned at the centre of a metal tray (length × width × depth = 270 mm × 170 × mm × 50 mm). For the fire resistance test, 500 mL of transformer insulating oil was poured into the metal tray to a depth of 20 mm. The transformer insulating oil was directly heated using a liquefied petroleum gas nozzle with a maximum pressure of 400 kPa and mass flow rate of 1.0 kg/h to determine its fire resistance characteristics (ignition time (i.e., time from the start of the fire resistance test to the time when the transformer insulating oil ignites), oil temperature, colour change, and occurrence of vaporisation). The fire resistance tests were executed once all of the parametric settings were completed, ensuring a controlled and consistent environment for reliable data collection and analysis. During the fire resistance tests, an infrared camera model TG165, brand FLIR and a liquid thermometer model 31/162/0 brand Brannan were used to measure the surface and inner temperatures of the transformer insulating oil until the ignition temperature (i.e., the temperature at which the transformer insulating oil ignites) was reached. Fig. 2(c) shows a thermogram captured by the infrared camera, indicating the surface temperature of the transformer insulating oil at the selected point on the pool fire (325.3 °C).

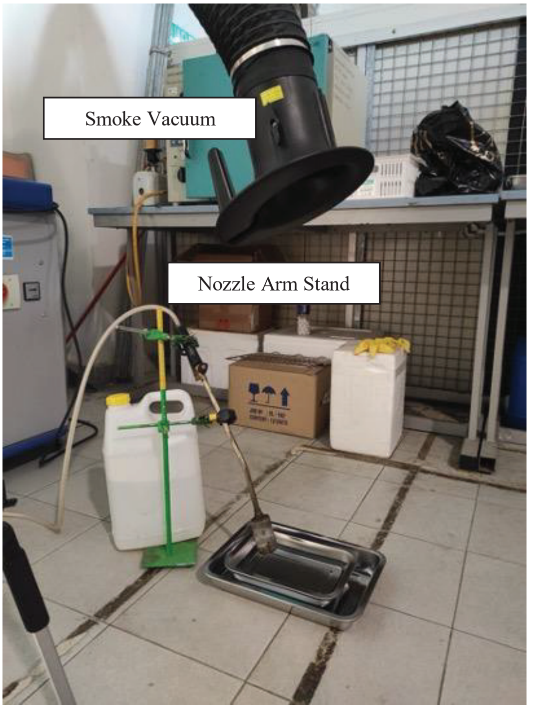

Fig. 2(a). Experimental set-up of the fire resistance test

Fig. 2(b). The surface of the transformer insulating oil was blasted by the fire nozzle

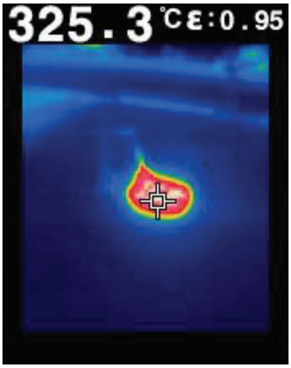

Fig. 2(c). Thermogram showing the surface temperature distribution of the transformer insulating oil captured by the infrared camera

III. Results and Discussion

A. *Fire resistance characteristics*

The fire resistance characteristics of the transformer insulating oils tested in this study are summarised in Table III. The results showed that there were significant differences in the fire resistance characteristics among the transformer insulating oils tested in this study. The mineral oil ignited after 99 s, and the surface and inner temperatures of the mineral oil were significantly lower than those of other transformer insulating oils, with a value of 135 and 124 °C, respectively. In addition, the mineral oil exhibited colour change and vaporisation after 60 s. In contrast, the FR3 and Midel eN 1204 natural esters did not ignite during the fire resistance tests. The surface and inner temperatures of these transformer insulating oils were significantly higher than those of mineral oil (297 and 288 °C (FR3), 295 and 287 °C (Midel eN 1204)), indicating superior fire resistance characteristics compared with mineral oil. However, the FR3 and Midel eN 1204 natural esters showed inconsistent results in terms of colour change and occurrence of vapourisation, where the FR3 natural ester displayed colour change and vapourisation after 1200 s, whereas the Midel eN 1204 natural ester displayed colour change without vapourisation.

Even though the palm fatty acid ester is a form of natural ester, this transformer insulating oil ignited after 422 s, and the surface and inner temperatures were determined to be 209 and 194 °C, respectively. The palm fatty acid ester exhibited colour change and vapourisation after 180 s. This indicates that the palm fatty acid ester had fire resistance characteristics midway those of mineral oil and natural esters. The results also showed that the Midel 7131 synthetic ester did not ignite during the fire resistance tests. Similar to the FR3 and Midel eN 1204 natural esters, the Midel 7131 synthetic ester exhibited high surface and inner temperatures (295 and 287 °C, respectively), colour change, and the absence of vapourisation.

Based on the results, it can be deduced that natural and synthetic esters (except for palm fatty acid ester) have superior fire resistance characteristics and higher temperature tolerance (i.e., the ability to withstand higher temperatures without being ignited), making them suitable for oil-immersed power transformers. Selecting a transformer insulating oil should be based on its fire resistance characteristics, as well as its intended application and potential hazards.

TABLE III
FIRE RESISTANCE CHARACTERISTICS OF THE TRANSFORMER INSULATING OILS TESTED IN THIS STUDY

Type of insulating oil		Mineral Oil	Natural ester (Triglycerides)		Natural ester (fatty acid methyl ester)	Synthetic ester
Brand name of the transformer insulating oil		A	B	C	D	E
Ignition time (s)		99	—	—	422	—
Oil temperature (°C)	Surface temperature	135	297	295	209	295
	Inner temperature	124	288	287	194	287
Color change		Yes	Yes	Yes	Yes	Yes
Vaporisation	Presence of vapour	Yes	Yes	No	Yes	No
	Start time (s)	60	1200	—	180	—

A: Hyrax Hypertrans, B: Cargill (FR3), C: Midel (eN 1204), D: Lion Corporation (PFAE), E: Midel (7131)

Note: The FR3, Midel eN 1204, and Midel 7131 transformer insulating oils did not ignite during the fire resistance tests, and therefore, the ignition times for these oils were not measured. The start time refers to the time when the transformer insulating oil starts to vaporise.

B. *Colour change of the transformer insulating oils*

Fig. 3(a) to 3(e) shows the colour changes of the transformer insulating oils exposed to fire at ~300 °C. The colour of new insulating oil can change upon thermal exposure due to oil degradation and the formation of by-products. It can be observed from Fig. 2 that the colour of the fresh mineral oil was clear; however, the colour changed to light yellow after thermal exposure. The colours of the fresh FR3 natural ester and palm fatty acid ester were clear, and the colours darkened to a deep yellow or brown upon thermal exposure. The worst cases were observed for the Midel eN 1204 natural ester and Midel 7131 synthetic ester, where the colours of these oils changed to black after thermal exposure. The degree of colour change observed for the transformer insulating oils is influenced by the ignition time, oil temperature, and duration of thermal.

Fig. 3(a). Mineral oil colour changes before & after the fire resistance tests

Fig. 3(b). FR3 colour changes before & after the fire resistance tests

Fig. 3(c). Palm fatty acid ester colour changes before & after the fire resistance tests

Fig. 3(d). Midel 7131 colour changes before & after the fire resistance tests

Fig. 3(e). Midel eN 1204 colour changes before & after the fire resistance tests

C. Fourier transform infrared spectra of the transformer insulating oils

Fourier transform infrared (FTIR) spectroscopy is based on the absorption and transmission of infrared radiation by the sample under test over a range of wavenumbers (typically from 4000 cm^{-1} to 400 cm^{-1}). The infrared radiation results in vibrational motions of the molecules (stretching and bending modes) [23], creating a molecular fingerprint of the sample, where the absorption peaks correspond to the frequencies of vibrations between the bonds of the atoms constituting the sample. In simple terms, there is a close relationship between the FTIR spectrum and molecular structure of the sample. The primary functional groups in a transformer insulating oil are represented by the position of the absorption peak in the FTIR spectrum, and the intensity of the absorption peak is correlated with the number of functional groups [24]. Fig. 4(a) to Fig. 4(d) shows the FTIR spectra of the transformer insulating oils before and after the fire resistance test.

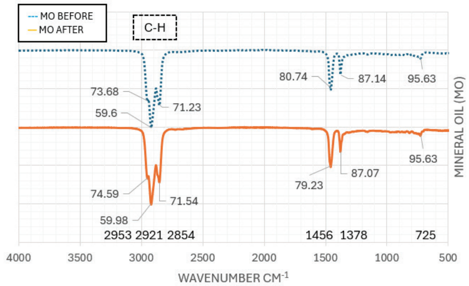

Fig. 4(a). FTIR spectra of the transformer insulating oils before and after the fire resistance test mineral oil (MO)

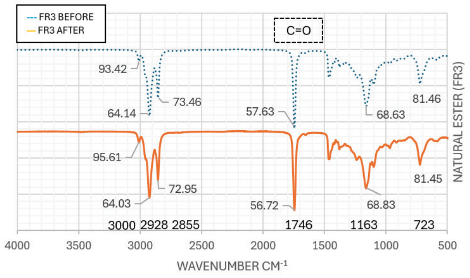

Fig. 4(b). FTIR spectra of the transformer insulating oils before and after the fire resistance test (FR3, natural ester)

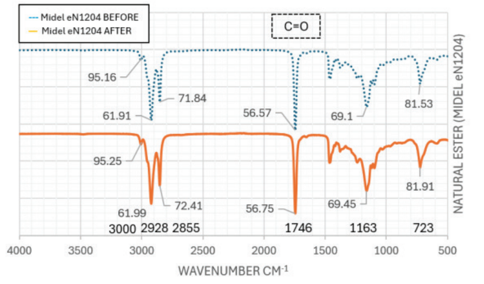

Fig. 4(c). FTIR spectra of the transformer insulating oils before and after the fire resistance test (Midel eN 1204, natural ester)

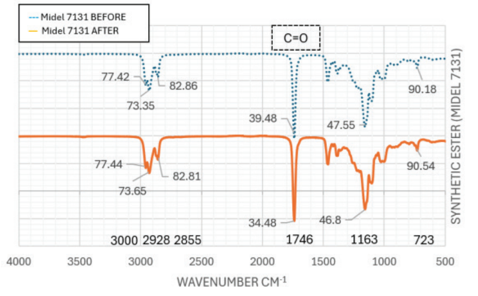

Fig. 4(d). FTIR spectra of the transformer insulating oils before and after the fire resistance test (Midel 7131, synthetic ester)

As shown in Fig. 4(a), the intensities of the absorption peaks for the mineral oil slightly decreased by less than 1% compared with those for the mineral oil before fire resistance tests. The absorption peaks at 2921, 2854, and 1456 cm^{-1} are associated with C–H stretching and bending vibrations of the molecules in the mineral oil [25], [26]. The differences in the transmittance values before and after the fire resistance tests were also marginal (less than 1%) for the FR3, Midel eN 1204, and Midel 7131 transformer insulating oils as shown in Fig. 4(b), 4(c) and 4(d). These transformer insulating oils also exhibited absorption peaks ascribed to C=O stretching vibrations within a wavenumber range of 1700–1800 cm^{-1}, indicating the presence of ester groups, which is common in such oils [27]. Overall, the intensities of the absorption peaks only showed slight differences before and after the fire resistance tests, indicating that the mineral oil, natural esters, and synthetic esters remained stable after the fire resistance tests.

IV. Conclusion

This study investigated the fire resistance characteristics of Hyrax Hypertrans mineral oil, FR3 natural ester, Midel eN 1204 natural ester, palm fatty acid ester (natural ester), and Midel 7131 synthetic ester through pool fire experiments. The mineral oil was found to ignite quickly and produced vapour at a relatively low temperature, suggesting that the oil is highly flammable and poses a serious safety hazard upon exposure to a heat source (fire).

In contrast, the natural and synthetic esters (except for the palm fatty acid ester) did not ignite and generally did not produce visible vapour, indicating that these oils have better fire resistance characteristics than mineral oil and palm fatty acid ester. Even though the palm fatty acid ester ignited during the fire resistance test, the ignition time of this oil was longer than that of mineral oil. The FTIR spectra revealed that the intensities of the absorption peaks of the transformer insulating oils were not significantly altered by the fire resistance tests.

The differences in the absorption peaks between the mineral oil, FR3 natural ester, Midel eN 1204 natural ester, and Midel 7131 synthetic ester were attributed to stretching vibrations, reflecting the differences in the molecular structures of these oils. Based on the results, it is crucial to select a K-class transformer insulating oil with exceptional fire resistance characteristics to minimise fire hazards and ensure long-term operational reliability of oil-immersed power transformers.

These findings have important implications for the design and maintenance of the transformers, particularly in areas with high fire risk and strict safety regulations. In this context, insulating oils based on esters are better than mineral oil in enhancing operational safety and reducing fire hazards. To extend these results, future research should focus on investigating the long-term performance of ester oil under thermal, electrical and moisture ageing conditions.

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Conflict of Interest

The authors declare no conflict of interest in the publication process of the research article.

Author Contributions

Author 1: Data and video collection, analysis, writing – original draft preparation; Author 2: Supervision, draft review and editing, material preparation; Author 3: Resources, material preparation, validation; Author 4: Critical review, proofreading; Author 5: Visualisation & finalized.

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