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Comparative study on the accelerated thermal aging behavior between palm and rapeseed natural ester oils

N. L. M. Ridzuan, N. A. Bakar, S. A. Ghani, I. S. Chairul, N. H. A. Aziz
High Voltage Engineering Research Laboratory, Centre for Robotics and Industrial Automation, Faculty of Electrical Engineering, University Technical Malaysia Malacca, Malaysia

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ABSTRACT

The suitability of natural ester oils as an insulating medium in power transformers is discussed in this paper. Owing to environmental concerns, natural ester oils have great potential as mineral oil substitutes in power transformers. In this paper, the aging behaviors of palm and rapeseed natural ester oils were compared with that for mineral oil. The performance of these natural ester oils was assessed based on their properties (moisture content, acidity, and relative content of dissolved decay products) after accelerated thermal aging. The results showed that the palm oil has better performance compared to the rapeseed oil after accelerated thermal aging for 1500 h because of its lower acidity. This was further supported by the presence of sludge in the rapeseed oil after 1500 h of aging.

Corresponding Author:

Norazhar Abu Bakar,
High Voltage Engineering Research Laboratory,
Centre for Robotics and Industrial Automation,
Faculty of Electrical Engineering, University Technical Malaysia Malacca, Malaysia.
Email: norazhar@utem.edu.my

1. INTRODUCTION

Large oil-filled power equipment such as power transformers are essential in power systems. Hence, it is important to conduct regular monitoring and diagnosis of power transformers, which will affect the remnant life of the transformers [1-5]. Mineral insulating (MI) oils are typically used as the insulating and cooling medium in transformers [6-10]. However, there is a growing trend on the use of natural ester insulating (NEI) oils as MI oil substitutes because of their excellent biodegradability and environmental compatibility [7–9, 11–18]. By principle, the properties of insulating oils will degrade due to the combination of several factors such as electrical arcing, thermal aging, and oxidation [2, 3, 13, 19–23]. In general, transformer insulating oils have a critical temperature, which should not be exceeded to prevent electrical breakdowns. Beyond this temperature, the oil will degrade gradually and the insulating properties of the oil will eventually be lost due to thermal effects [3, 19, 24–26]. Hence, in this work, the performance of palm and rapeseed NEI oils was investigated based on laboratory thermal aging experiments at 130°C for 1500 h. The acidity level, moisture content, and relative content of desolved decay products (DDP) were measured for these oils and the results are presented in this paper.

2. METHODOLOGY

Three transformer insulating oils were chosen for this work: MI oil, palm oil, and rapeseed oil. MI oil was used as the basis for comparison with the NEI oils. The initial moisture content and acidity level were measured for each oil. A drying treatment process was performed if the oil did not fulfill the requirements in the ASTM D3487 [27] and ASTM D6871 [28] standards for the MI and NEI oils, respectively. Table 1 shows the initial properties of the oils prior to the accelerated thermal aging experiments.

Table 1. Initial properties of the MI oil, palm oil, and rapeseed oil

Property	MI oil	NEI oil	
		Palm oil	Rapeseed oil
Moisture content (ppm)	29.5	108.1	165.5
Acidity (mg KOH/g)	0.0288	0.0525	0.0575
DDP content	19.592	11.174	35.021

Five samples were prepared for each oil and laboratory accelerated thermal aging experiments were conducted based on the method proposed by Tenbohlen [29], as illustrated in Figure 1. The metal catalysts used to perform the accelerated aging were copper (Cu), zinc (Zn), aluminum (Al), and iron (Fe). The ratio of Kraft paper (KP) and pressboard (PB) to the oil by weight was 1:10 for each sample. The KP and PB were prepared according to the BS EN 60641 standard [30]. Next, the KP, PB, and metal catalysts were immersed in the oil for 24 h at room temperature (25℃ ± 5℃) without air-conditioned. Then, the aging test was conducted by placing all of the samples in a vacuum oven. The oven was set at a temperature of 130°C for 100, 250, 500, 1000, and 1500 h. For each aging period setting, the oil samples were taken out from the oven and left at room temperature for 24 h prior to measuring their properties. The moisture content, acidity, and DDP tests were conducted according to the ASTM D1533 [31], ASTM 664 [32], and ASTM D6802 [33] standards, respectively.

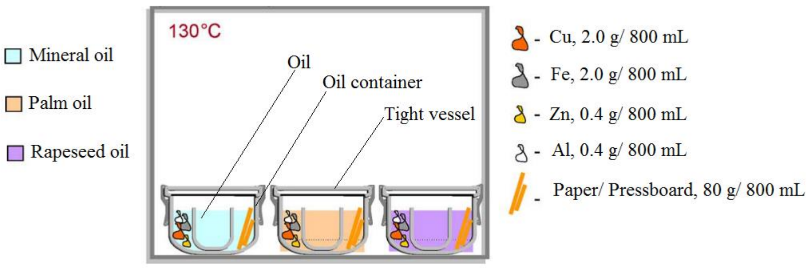


Figure 1. Accelerated thermal aging test setup [29]

3. RESULTS AND DISCUSSION

3.1. Moisture content

The electrical characteristics of an insulating liquid can be severely degraded by excessive moisture content. A high moisture content indicates that the insulating liquid is not suitable for some electrical applications due to degradation of its properties [31]. For this reason, moisture content measurements were performed on the oil samples using a coulometer (Model: 899, Metrohm AG, Switzerland).

Figure 2 shows the moisture content of aged MI and NEI oils investigated in this work. It can be observed that the NEI oils have significantly higher moisture content than the MI oil for different periods of aging. This is indeed expected because NEI oils have greater affinity towards moisture compared to MI oils [26, 34]. There are no obvious trends observed for the moisture content of NEI oils, as shown in Figure 2. The change in the moisture content of the MI oil is most significant after 250 h of aging, with a percentage difference of 59.52%. Likewise, the change in the moisture content of the palm oil is highest after 250 h of aging, with a percentage difference of 142.73%. The palm oil has the highest moisture content (289.1 ppm) after 500 h of aging.

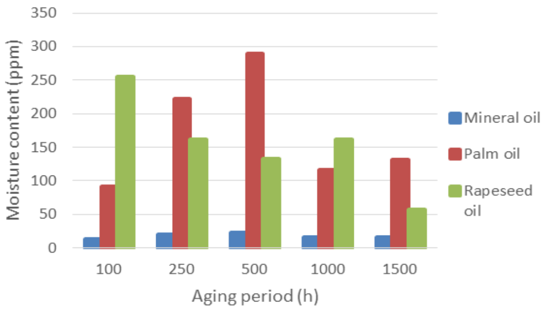


Figure 2. Moisture content of the MI, palm, and rapeseed oil samples for different periods of aging

3.2. Acidity

New and used insulating liquids may contain acidic constituents such as additives or degradation products formed in in-service transformers such as oxidation products [32]. Hence, acidity tests were performed to determine the acidity of the oil samples for different periods of aging using a compact titrator (Model: 848 Titrino Plus, Metrohm AG, Switzerland).

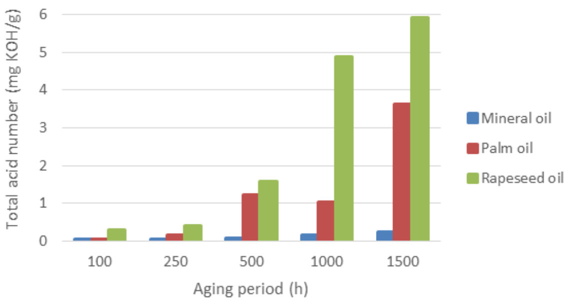


Figure 3. Acidity of the MI, palm, and rapeseed oil samples for different periods of aging

The acidity level is indicated by the total acid number (TAN), which is measured by the automatic potentiometer titration system. The TAN indicates the total amount of dissolved acids. Figure 3 shows the measured TAN values of the oil samples. In general, the acidity level increases after each oil undergoes the accelerated thermal aging process. The TAN of the MI oil, palm oil, and rapeseed oil increase by a factor of 9, 69, and 103, respectively, relative to their initial values after 1500 h of aging. The oxidation process and hydrolytic reactions with additional materials break down the fatty acid chains, which increases the TAN values of the oil samples.

3.3. Relative content of dissolved decay products

The relative content of DDP of the oil samples was determined using an ultraviolet-visible (UV-VIS) spectrophotometer (Model: UV-1800, Shimadzu Corporation, Japan). New oils are almost transparent to the monochromatic beam of light in the visible spectrum and the absorbance curve will shift towards longer wavelengths as the relative content of DDP increases. The DDPs in insulating oils are composed of various compounds such as peroxides, aldehydes, ketones, and organic acids. Each of these compounds are partially adsorbed on the large surface of the insulating paper, which leads to premature aging of power transformers. Hence, the presence of by-products in the insulating oil can be used as an indicator of the aging of the oil [33].

a. MI oil

Figure 4 shows the variation of the UV-VIS absorbance with wavelength for the MI oil samples aged under different periods of aging. It can be observed that the increase in absorbance is slow for the first 500 h of aging. The absorbance peak occurs at 391 nm after 1000 h of aging whereas the absorbance peak occurs at 435 nm after 1500 h of aging. It is evident that the absorbance decreases at a higher wavelength with an increase in the relative content of DDP of the MI oil.

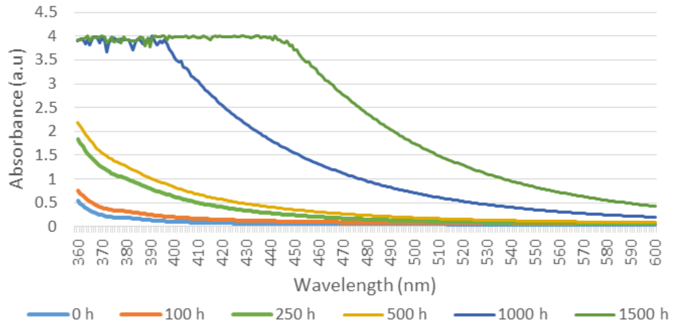


Figure 4. Variation of the UV-VIS absorbance with respect to wavelength for the MI oil

b. MI oil

The same trend can be observed for the palm oil, as shown in Figure 5. However, the increase in absorbance is slower for the first 500 h for the palm oil compared to that for MI oil. In addition, the absorbance peak occurs at a longer wavelength for the palm oil compared to that for the MI oil.

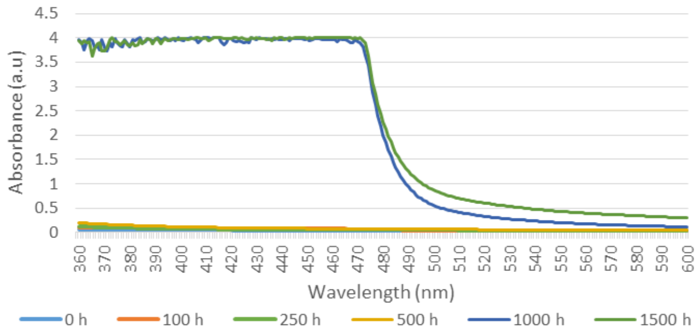


Figure 5. Variation of the UV-VIS absorbance with respect to wavelength for the palm oil

c. Rapeseed oil

In contrast, the rapeseed oil shows a different trend compared with the MI oil and palm oil, as shown in Figure 6. The increase in absorbance is quite fast for the rapeseed oil where the absorbance peak occurs just after 250 h of aging. The wavelength at which peak absorbance occurs increases with an increase in the aging period. It can also be observed that there is a shift in the wavelength at which the absorbance peak occurs from 430 nm (1000 h of aging) to 390 nm (1500 h of aging).

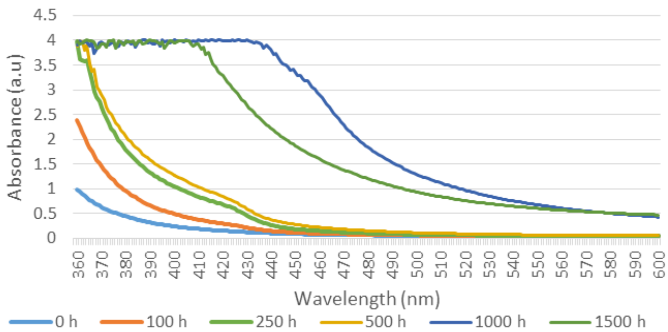


Figure 6. Variation of the UV-VIS absorbance with respect to wavelength for the rapeseed oil

Figure 7 shows the relative content of DDPs for the MI, palm, and rapeseed oil samples determined from the area under the UV-VIS absorbance-wavelength curves shown in Figures 4-6. The initial relative content of DDP is 19.59 for the MI oil (0 h of aging) and the value increases significantly after 1000 h of aging (369.06). The relative content of DDP continuously increases to 580.73 after 1500 h of aging.

Even though the trends are similar for the MI and palm oils, the rate of increase in DDP is different between both oils. The palm oil has a higher rate of increase in DDP compared to the MI oil for the first 1000 h of aging. After 1000 h of aging, the rate of increase in DDP of the palm oil is lower than that of the MI oil, with a difference of 5.76%.

A different trend is observed for the rapeseed oil, as shown in Figure 7. The relative content of DDP increases significantly for the first 1000 h of aging. However, the relative content of DDP then decreases from 535.07 to 436.51 after an additional 500 h of aging. This is due to the presence of sludge in the sample after 1500 h of aging, as shown in Figures 8(c) and 9. It is believed that the increase in acidity is the main factor that leads to the formation of sludge [35], which will reduce the dielectric strength of the oil. The presence of sludge can also reduce heat transfer if it is deposited on the insulating paper or inside radiator pipes [36].

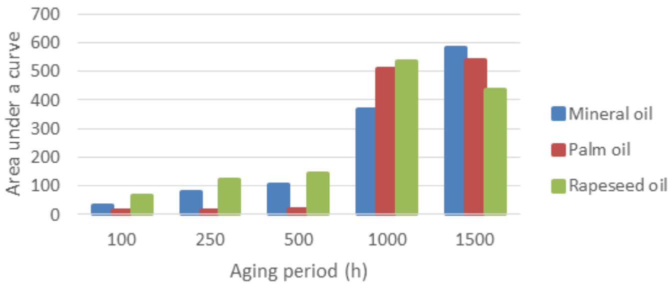
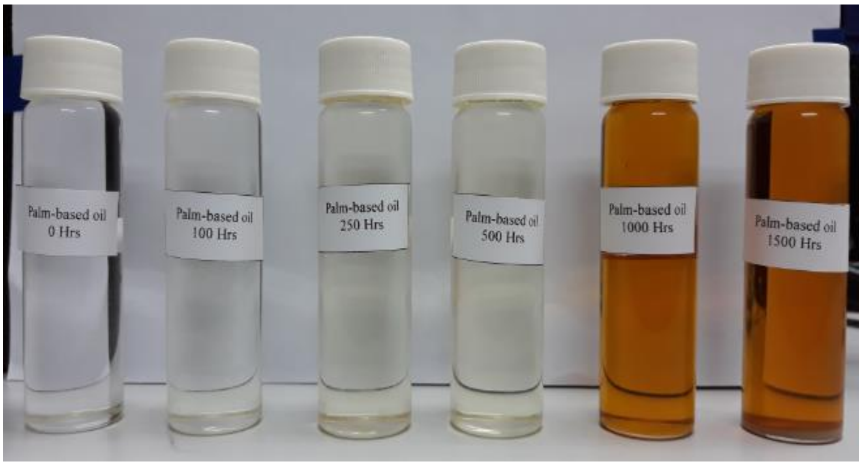


Figure 7. Relative content of DDPs of the MI, palm, and rapeseed oil samples determined from the area under the UV-VIS absorbance-wavelength curves within a wavelength of 360–600 nm

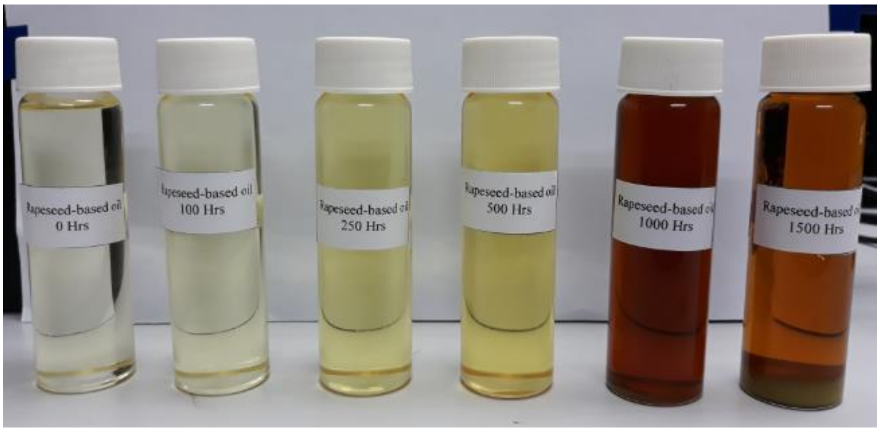
3.4. Oil colour

Oil colour is an important characteristic and it can indicate the degree of degradation of the oil. Figure 8 shows the photographs of the MI, palm, and rapeseed oil samples aged at 130°C for different periods of aging. It can be seen that the new oil samples are highly translucent. The colour of the oils becomes darker with an increase in the aging period and therefore, the oil colour change can be used as an indicator of the degradation rate of the oil due to aging. It is evident that the rate of discolouration is significantly higher for the MI oil compared with the NEI oils during the thermal aging process. Table 2 shows percentage increase in the properties of the MI, palm, and rapeseed oils subjected to accelerate thermal aging is compared.

(a)



(b)



(c)

Figure 8. Colour of the, (a) MI oil, (b) palm oil, (c) rapeseed oil samples from 0 h to 1500 h of aging (from left to right)

Figure 9. Formation of sludge in the rapeseed oil after 1500 h of aging

Table 2. Percentage increase in the properties of the MI, palm, and rapeseed oil samples after aging relative to their initial values

Property	Percentage increase (%)						Type of oil with the highest percentage increase
	MI oil	Aging period (h)	Palm oil	Aging period (h)	Rapeseed oil	Aging period (h)	
Moisture content (ppm)	0.00	0	167.44	500	54.26	100	Palm oil
Acidity (mg KOH/g)	757.64	1500	6789.71	1500	10200.70	1500	Rapeseed oil
Relative content of DDP	2864.10	1500	4735.48	1500	1146.43*	1500	Rapeseed oil*
Conclusion							Rapeseed oil

* Sample has visible sludge.

4. CONCLUSION

The percentage increase in the properties of the MI, palm, and rapeseed oils subjected to accelerate thermal aging is compared, as shown in Table 2. The percentage increase in the moisture content, acidity, and relative content of DDP of the oils after aging was determined relative to their initial values. The aging periods chosen for this comparison are the periods when the properties are maximum. In general, the oil with the highest percentage increase in moisture content, acidity, and relative content of DDP content is undesirable. Based on the results, the rapeseed oil is unfavorable compared to the palm oil because it has the highest percentage increase of acidity along with the presence of sludge after 1500 h of aging. The formation of sludge can hinder the circulation of the transformer oil, resulting in ineffective cooling.

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BIOGRAPHIES OF AUTHORS

Nur Lidiya Muhammad Ridzuan. She received the BEng. (Hons) degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka (UTeM) and currently doing the master's in Electrical Engineering also at UTeM. Her research interests are in electrical insulation, power equipments and insulation condition monitoring.

Norazhar Abu Bakar. He received the BEng. (Hons) in Electronics and Electrical from Leeds University, UK, MSc. (Eng.) in Control Systems from Sheffield University, UK and PhD in Electrical and Computer Engineering from Curtin University. Currently, he served as lecturer at University Teknikal Malaysia Melaka (UTeM), Malaysia. His research interests are in transformer condition monitoring and advanced control systems.

Sharin Ab Ghani. He received the BEng. (Hons) degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka (UTeM) in 2008 and the MEng. Degree in Electrical Engineering from Universiti Tenaga Nasional, Malaysia in 2012. He served as a lecturer at Universiti Teknikal Malaysia Melaka (UTeM). Currently, he is a PhD student at Universiti Teknologi Malaysia. His research interests are in electrical insulation, power equipments & insulation condition monitoring, and renewable energy.

Imran Sutan Chairul He received the Bachelor of Electrical Engineering (Industrial Power) from Universiti Teknikal Malaysia Melaka (UTeM) in 2008. In 2012, he received the Master of Electrical Engineering from Universiti Tenaga Nasional. Currently, he is a lecturer at Universiti Teknikal Malaysia Melaka (UTeM). His research interests include liquid and gas insulation as well as condition monitoring of power transformer.

Nur Hakimah Ab Aziz. She received the BEng. (Hons) in Electrical Engineering from Universiti Teknologi Malaysia (UTM), MEng in Electrical Power Engineering from University of South Australia (UniSA), Australia and PhD in Electrical Engineering from University of Strathclyde Glasgow. Currently, she served as lecturer at University Teknikal Malaysia Melaka (UTeM), Malaysia. Her research interests include condition monitoring, diagnostics and prognostics and dielectric ageing.