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ABSTRACT

Power transformers use mineral oil as an insulating liquid due to its outstanding dielectric properties. The poor biodegradability and toxicity of mineral oil have increased the interest in the use of a more environmentally friendly product such as ester-based oil. Generally, natural ester insulating oils (NEI) have a higher flash point and breakdown voltage compared to existing mineral oils. However, the higher price of NEI is the main obstacle to widely applied in power transformers. Therefore, alternative cheaper feedstock processing is required. This paper proposed waste cooking oil (WCO) as a potential alternative to the existing transformer insulating oil. The used of WCO promotes the optimal consumption of plant-based resources and more efficient waste management. Transesterification method is performed to remove the free fatty acids in the WCO and reduce the viscosity. The transesterification process is based on the chemical modification reaction between WCO, methyl alcohol (methanol) and sodium hydroxide (NaOH) catalyst lye that produces waste cooking oil methyl ester (WCOME). Chemical and electrical properties i.e. water content, acidity and breakdown voltage of the developed WCOME are compared with the existing WCO according to IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers (IEEE C57.147).

Keywords:
Acidity; Waste cooking oil methyl ester; Transesterification

1. Introduction

Mineral transformer oil is cheap and reliable insulants for industrial, power transmission and distribution transformers insulation system [1]. Due to its good dielectric properties, mineral oil has been used as heat transfer medium and insulating liquid in the power transformers for more than 100 years [2]. However, typical mineral oil has low fire points which can increase the risk of fire occurred once the transformer fails. In recent years, exploration of renewable sources has become

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very important. This is due to the rising in the market price of crude oil, the decline in uncontrolled oil price reserves, and the increase in environmental degradation [3]. On the other hand, natural ester-based liquids (NEI) have been studied for various applications [4-6]. For transformer application, NEI have a higher fire point, breakdown voltage, and excellent biodegradable characteristics besides enhancing fire safety and environmental sustainability [7]. Nonetheless, the high viscosity of the oil causes the liquidity becomes poor thus affect the transformer cooling efficiency [8]. The modification required on NEI to reduce its viscosity through chemical modification reaction. The chemical modification to be used is either esterification or transesterification reaction depending on the free fatty acid (FFA) present in the NEI oil. The percentage of FFA content is an important specification that affects the quality of palm oil in the storage, production and marketing stages [9]. This will enable NEI to be used in the distribution transformer [10]. An original NEI also has a higher total acid number (TAN) values which normally above than 0.3 mg KOH/g [11]. The most important obstacles of NEI is production costs mainly due to the cost of raw materials or chemicals such as vegetable oils, alcohols, and catalysts [12].

In this research, waste cooking oil (WCO) from palm-based is chosen since the price is cheaper compared to other natural ester oil. However, original WCO has a problem with its chemical and electrical properties such as low breakdown voltage, higher acidity and water content, which is not suitable to be used as an insulating oil [11]. The effect of higher acidity in WCO will increase hydrolytic stability and ageing duration process [13]. In addition, the acidity content is too high can lead to corrosion of metal parts such as transformer winding due to internal conduction that could cause explosion or fire outbreak in the transformer [14]. The chemical and electrical properties of WCO do not meet the minimum requirement as stated in the standards [15]. Therefore, WCO needs a process which can improve its chemical and electrical properties by using chemical modification reaction. Besides that, the aim of this research is to use NaOH as a catalyst to produce WCOME. In the meantime, the chemical and electrical properties of WCOME (NaOH) are compared with an existing WCO.

1.1 Waste Cooking Oil

The term “waste cooking oil” (WCO) is referred to the vegetable oil, which has been used for frying several times in food production. Waste cooking oil can be collected from the hotel, catering, camp, and restaurant. This collected wasted cooking oil has a variety of qualities and possesses different properties from neat vegetable oi. Besides that, statistic shows that the remaining waste oil which has been used and disposed of without treatment in Malaysia is about 50000 tonnes per year [16]. Utilization of waste cooking oils as feedstock for transformer oil has potential in solving the problem of disposal waste cooking oil.

1.2 Chemical Modification

During the frying process, the oil undergoes various physical and chemical transformations included the increase of viscosity and free fatty acids, and also colour [17]. The chemical modification such as transesterification process is usually implemented. The transesterification process will convert the free fatty acids of waste cooking oil in the present of methanol to methyl ester and modifies the properties of waste cooking oil to become suitable oil for transformers [18]. Percentage of free fatty acids in oil (FFA %) is a crucial element to be considered since it will affect the effectiveness of transesterification reaction and trigger some problems in the transformer. In the situation where the FFA is less than 5%, the transesterification process can perform immediately.

However, if the FFA is more than 5%, the esterification process is essential to carry-out in order to reduce the FFA percentage in oil [19]. It is worth to mention that this study only focuses on WCO with FFA less than 5%, whereas the transesterification reaction via alkali catalyst is executed and examined. The percentage of FFA in the sample is approximately half of the acidity value as stated in the Eq. (1).

$$\%FFA \approx \frac{Acidity\ (mgKOH/g)}{2} \tag{1}$$

1.3 Transesterification Reaction

Transesterification reactions is a chemical process of reacting triglycerides with methyl alcohol using catalyst either alkali or acid, forming glycerol and fatty acid mehyl esters (FAME). Figure 1 shows the molecular representation of the transesterification reaction [20].

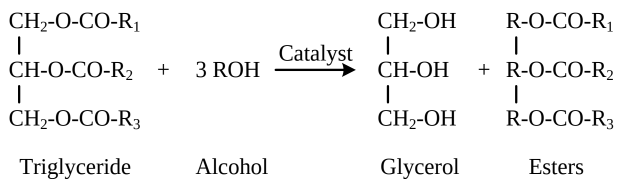

Fig. 1. Molecular of a transesterification reaction

When the transesterification reaction is incomplete, there will be either mono-, di- or tri-glyceride remaining in the chemical reaction mixture [21]. Transesterification reaction normally uses alcohols such as methanol, ethanol or butanol. Methanol is widely used in transesterification reaction since it is cheaper, easier to react, and also the shortest chain of alcohol [22]. In addition, there are different types of catalysts used in transesterification reaction such as enzyme catalyzed, acid-catalyzed, and alkaline catalysed [23].

Enzyme transesterification is an attractive method since it's can be performed under low temperature, do not form soaps, reduced environmental impact and energy requirement in chemical industrial processes [24]. However, enzyme transesterification has several disadvantages such as high-cost production, low reaction rate, longer reaction time, and higher catalyst cost [25]. Therefore, an alternative catalyst such as acid catalyzed has been introduced to encounter the drawback of enzyme transesterification. The commonly employed acids are sulphuric acid (H_2SO_4), sulfonic acid (SO_3H) and hydrochloric acid (HCl). The acid catalyst offers a higher yield, no soap formations, and low-cost catalysts. This provides advantages compared to enzyme catalyst in terms of yield and catalyst cost. Though, the main drawback of acid catalyzed are very slow reaction rate, higher cost of equipment, environmental effect, and higher temperature required [24].

Consequently, alkaline catalysts are potentially to overcome the limitation of the acid catalyst. Alkaline catalyst includes sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium methoxide ($NaOCH_3$), potassium methoxide ($KOCH_3$) and sodium ethoxide ($NaOCh_2CH_3$). NaOH and KOH catalysts are the most common catalysts used in the transesterification reaction process [26]. Its normally used because of the cheaper making process, economical catalyst cost in the market compared to other catalyst and ecologically [27]. Alkaline catalyst able to react at low temperature and atmospheric pressure, reacts faster, and can achieve a high conversion yield in a short time [28]. Besides that, the alkaline catalyst will react with FFA to form soap which is undesirable. When the presence of FFA content is higher than range, excessive soap formation can reduce the yield of fatty acid methyl ester (FAME) [29]. Alkaline catalyst is considered as the simplest method in producing methyl ester since it is easy to extract the esters respectively and does not form water during transesterification reaction [27].

In the previous study, Ignacio *et al.,* [30] has obtained the optimum molar ratio 6:1 for methanol to oil in producing methyl ester by using frying oil. Besides that, 94% of the yield can be produced at 50°*C* reaction temperature with one-hour time reaction by using 0.7% of sodium hydroxide (NaOH). Therefore, this paper investigated the potential of using NaOH alkaline catalyzed in producing transformer insulating oil (methyl ester based) from WCO.

2. Methodology

The summarized methodology is described in a flow chart as shown in Figure 2.

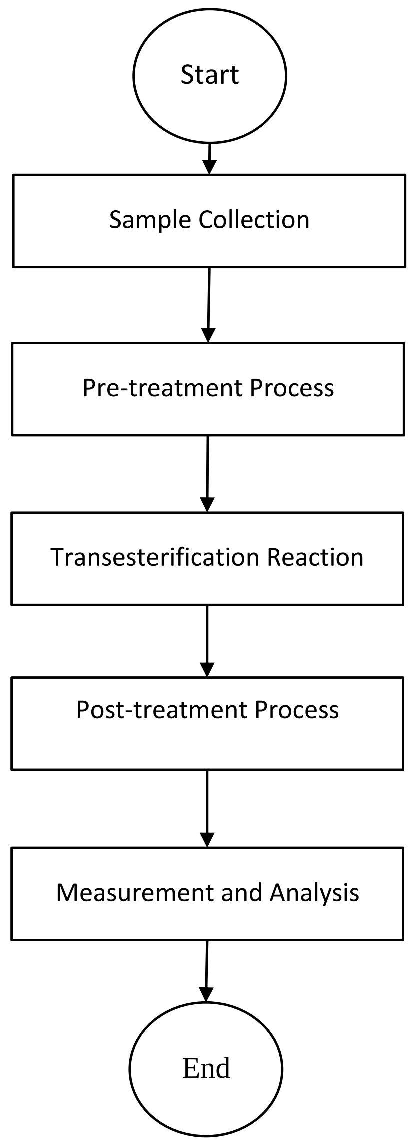

Fig. 2. Experimental process

2.1 Experimental Process

2.1.1 Stage 1: Sample collection

Waste cooking oil samples were collected from selected hotels and restaurants in Malaysia which used oil palm tree based as their cooking oil.

2.1.2 Stage 2: Pre-treatment process

Then, the collected WCO was heated gradually up to 120 °C for 10 minutes in order to reduce the water content. It is a vital process to minimize the water content in WCO before the transesterification can be executed. The heated WCO was left until its temperature drops to 50°C naturally, then the filtration process was performed to remove solid particles.

2.1.3 Stage 3: Transesterification reaction

After filtration, 1000ml of treated WCO was inserted into a 2000mL beaker and then stirred at 500 rpm. In the meantime, the oil was heated simultaneously until the temperature reached about 55 to 60°C. Within this process, 250ml of methyl alcohol (methanol) and 7.5g of catalyst lye (sodium hydroxide) were poured into the flask.

Next, dissolve the catalyst lye into the methanol and forming a meth oxide solution by using stirrer. It takes about 5 minutes for all of the lye to dissolve into the methanol. The temperature was controlled not exceed 60°C to prevent the methanol become evaporated. After continuously stirring, the solution was transferred to another 2000mL beaker, wrapped with aluminium foil and then stored in a thermos. The WCO and methyl alcohol are going to undergo a reaction called transesterification. After 48 hours of transesterification process, the oil was separated into two layers, known as FAME (top layer) and glycerol (bottom layer).

2.1.4 Stage 4: Post-treatment process

In this study, only the top layer (FAME) was considered for the next process. The methyl ester which located on the top layer of the beaker was transferred into another beaker and washed with 500mL of hot water (distilled water) to remove any unwanted glycerol. During the washing process, the oil was stirred at 500rpm for 5 minutes under controlled temperature at 120°C.

Next, the solution was transferred into separation funnel beaker for 15 minutes to remove the soap completely. This process was repeated 6 times to discard any unnecessary methanol and NaOH from methyl ester oil. The output product of this process is known as waste cooking oil methyl ester (WCOME). Afterward, this WCOME oil was heated for another 10 minutes at temperature above 120°C to vaporize the water content in it.

2.1.5 Stage 5: Measurement and analysis

Finally, the chemical and electrical properties of WCOME were then be assessed in accordance with the IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers (IEEE C57.147).

2.2 Chemical and Electrical Properties
2.2.1 Chemical properties (acidity and water content)

The acidity or Total Acid Number (TAN) is referred to the hydrolysis indicator or oxidation degree in which the mass of potassium hydroxide (KOH) in milligrams required to neutralize the acid in one gram of the sample. In this study, TAN was measured in accordance to ASTM D974 by using 848 Titrino Plus (Metrohm).

On the other hand, the water content in the oil was measured based on ASTM D1533 using 899 Karl Fischer coulometer (Metrohm). Karl-Fischer coulometer determines the content of water using chemical analysis by adding an iodine solution of known concentration as a reagent in carefully measured amounts [31].

2.2.2 Electrical properties (breakdown voltage)

Breakdown voltage (BdV) of oil sample was measured based on ASTM D1816 by using OTS60PB Portable Oil Tester (Megger). Two 36mm mushroom electrodes with a gap of 1.0 mm were used to measure BdV of WCOME.

3. Results and Discussion

Table 1
Chemical and electrical properties of WCO and WCOME (NaOH) samples

Property	Unit	Specification for Natural Ester Fluids [32]	WCO	WCOME (NaOH)
Acidity	(mg KOH/g)	≤ 0.06	2.7972	0.2578
Water content	(mg/kg)	≤ 200	1036.5	75.12
Breakdown voltage	(kV)	≥ 20	7	33.4

The appearance of developed insulating oil from WCO to WCOME is shown in Figure 3. It was observed that the colour of WCO was changed from darker to a light brown after transesterification reaction. During transesterification reaction, the glycerine was removed from the oil chain and separated between it and methyl ester as shown in Figure 3(b).

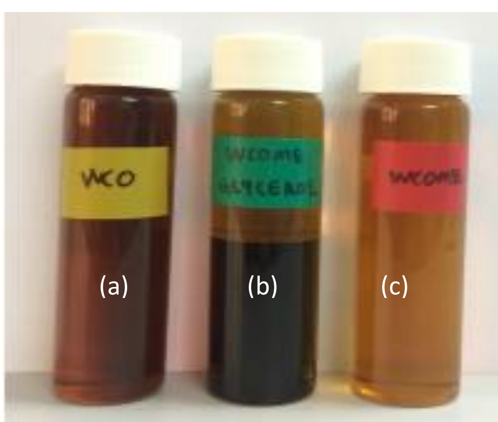

Fig. 3. (a) WCO, (b) Raw WCOME, (c) WCOME

In the meantime, the acidity of WCO has been reduced from 2.7972 mg KOH/g to up to 0.2578 mg KOH/g (WCOME) after transesterification process which is corresponding to 90.78% as shown in Figure 4. However, for WCOME is still higher than the prescribed limit for new ester-based insulating oil (less than or acidity equal to 0.06 mgKOH/g).

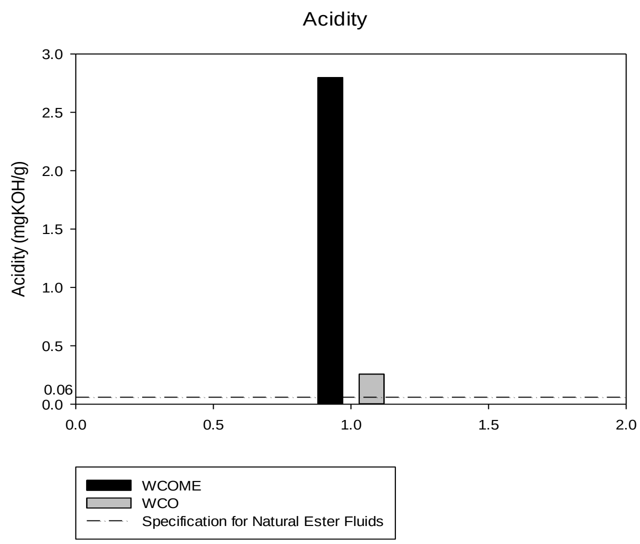

Fig. 4. Acidity of WCO and WCOME

Meanwhile, the water content of WCO has been improved significantly after go through the transesterification process. WCO water content has been reduced by 92% from its initial value, 1,036ppm to 75ppm (WCOME) as shown in Figure 5. It also means that the water content of WCOME meets the limit for ester-based insulating oil (200 ppm) as stated in the standard.

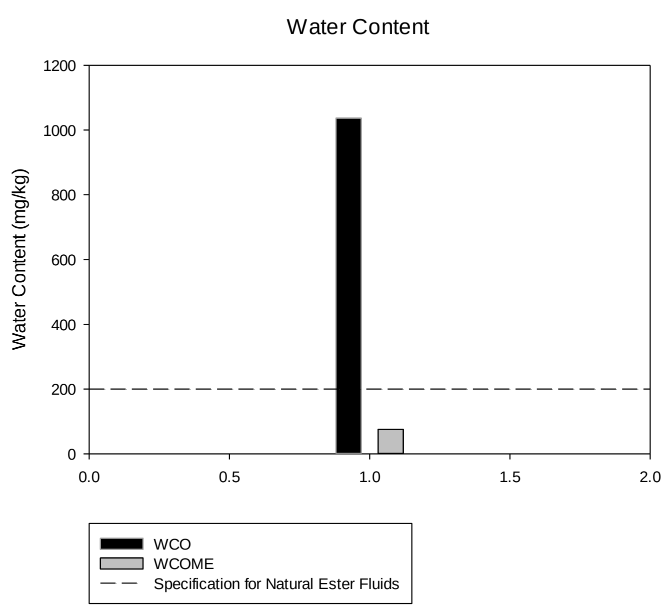

Fig. 5. Water content of WCO and WCOME

For electrical properties, it was observed that the WCO BdV has been boosted from 7kV to 33kV after transesterification process as stated in Table 1. In accordance with the standard, the BdV for transformer oil should be more than 20kV, hence indicates that WCOME electrical properties offer a better BdV. Table 1 summarizes the results obtained for chemical and electrical properties of WCO and WCOME.

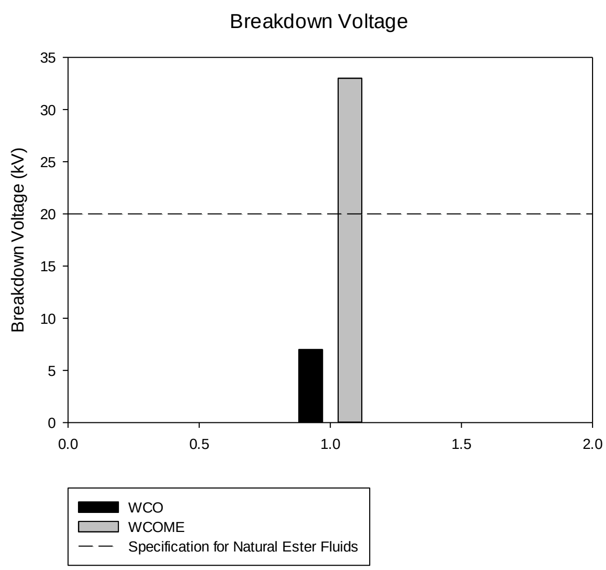

Fig. 6. Breakdown voltage of WCO and WCOME

Based on the result tabulated in Table 1, water content and BdV of WCOME are satisfied with the specification for natural ester fluids as stated in the standard. However, it was observed that the acidity obtained for WCOME is higher than the maximum acidity allowable for transformer insulating oil. Therefore, another treatment process is required before the oil can be used as a transformer insulating oil. Reclamation techniques may have the possibility to reduce the acidity in WCOME. Nevertheless, other suggestions of treatment in reducing the acidity is neutralization technique will be performed [33]. Further investigation on this matter will be covered in our future work.

Although the water content in WCOME has been enhanced and meet the requirement of transformer insulating oil, however it can be further improved by introducing another treatment such as nitrogen to reduce the water content in it. Another way to reduce the water content is by using a vacuum oven to dry the sample by using both heat and vacuum before assessing their water content. Further reduction of water content in WCOME will offer a better quality of transformer insulating oil. It is noticed that the water content in insulating oil will increase when exposes to the low temperatures and ambient air.

Hence will accelerate the deterioration of insulating paper, and also give a negative impact on the breakdown voltage of the transformer insulating. This is because the breakdown voltage remains higher when the percentage of moisture saturation is below 20% but then decreases significantly as relative when moisture saturation increases [35].

4. Conclusions

The aim of the presented work is to produce WCOME transformer insulating oil based on a reaction of catalytic transesterification between WCO, methanol (CH_3OH) and homogenous alkali catalyst using sodium hydroxide (NaOH). This reaction is expected will influence the chemical and electrical properties (water content, acidity and breakdown voltage) of WCO. Based on the experimental results, the chemical and electrical properties of the final product from this process, which known as WCOME has been improved and almost fulfil the requirement as a transformer insulating oil. The water content of the oil sample has been reduced by 92% from its initial, while the BdV has been boosted nearly 5 times from its original value. Although the acidity of the WCOME has been reduced by 90% but then it still not meets the requirement for a new transformer insulating oil. Therefore, though the experimental results show that there is a potential to introduce an alternative transformer insulating oil from WCO, however further treatment process is required before it can be applied in the transformer.

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