

A STUDY ON BREAKDOWN PROPERTIES OF COCONUT OIL

Nguyen Van Dung*, Nguyen Hoai Trung

Department of Electrical Engineering, Cantho University,
Zone II, 3/2 Street, Ninh Kieu District, Can Tho city

*Email: vinaybharadwajt@gmail.com

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Abstract. This paper presents the results of AC electrical breakdown properties of coconut oil with and without Tertiary Butyl Hydroquinone (TBHQ) antioxidant. Ageing test of transformer oil was conducted according to the standard of IEC-61125 B at 120 °C for 72 h with the presence of copper as a catalyst. Experimental results showed that AC breakdown voltage of coconut oil was comparable to that of mineral oil. After ageing test, breakdown voltages of both coconut oil and mineral oil were decreased. The results also showed that breakdown voltage of aged coconut oil containing 0.5 wt% of TBHQ antioxidant (44.5 kV) was higher than those of aged coconut oil without TBHQ (40.8 kV) and aged mineral oil (24.6 kV). The breakdown voltage (V) of oils increased linearly with increasing the electrode gap (d), which was fitted by a line with a slope of E_{BD} . The E_{BD} of coconut oil (21.9 kV/mm) was higher than that of mineral oil (18.9 kV/mm). The presence of TBHQ (0.5 wt%) reduced the E_{BD} of coconut oil of about 13 %. However, after ageing test, coconut oil containing TBHQ (0.5 wt%) showed a higher E_{BD} in comparison with virgin coconut oil and mineral oil. TBHQ exhibited as an effective antioxidant for coconut oil under thermal oxidation conditions. Coconut oil had a lower lifetime index n than mineral oil (13.2 compared to 23.3).

Keywords: coconut oil, breakdown, ageing, transformers, additives.

Classification numbers: 2.3.1, 2.8.3.

1. INTRODUCTION

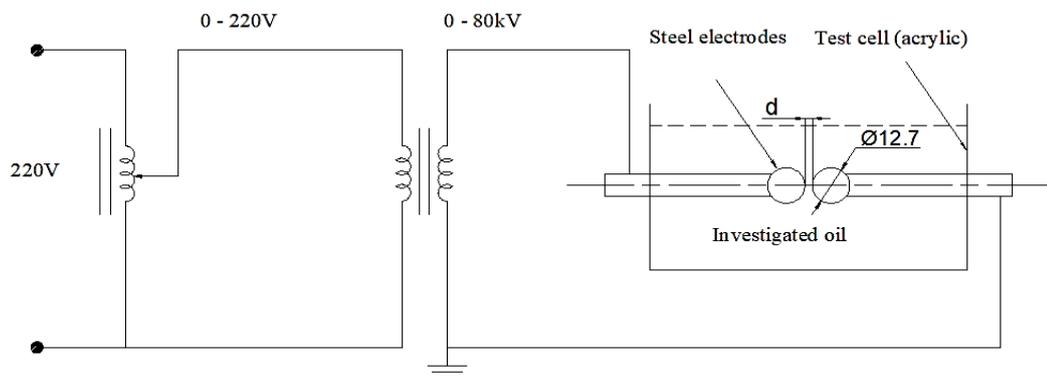
Vegetable oils have been studied for producing lubricants and biodiesel [1, 2]. In addition, many studies on vegetable oils for replacing mineral oil in transformers have been performed because of their high dielectric strength, high flash point and complete biodegradability [3-7]. However, disadvantages of vegetable oils are poor antioxidant, high viscosity and high pour point. Therefore, additives have been added to virgin vegetable oils. At present, Envirotemp[®] FR₃ based on soybean oil and BIOTEMP[®] produced from sunflower, safflower and soybean oils are commercialized. Viet Nam and other Asian countries have huge raw materials for producing vegetable oils. Oils extracted from rice bran, corn kernels and peanut kernels were investigated in a previous study [8]. However, these oils are unstable in oxidation and therefore need to be added with antioxidants. Hence, this study will examine coconut oil due to its high content of

saturated fatty acids which is expected to have high antioxidant capability. Recently, coconut oil has been studied for insulating purpose [9-12]. However, the influences of electrode gap, ageing and additives on breakdown characteristics of coconut oil have not yet been fully investigated. Therefore, these influences on the breakdown voltage of coconut oil have been investigated in this study. In addition, the $V-t$ characteristic of coconut oil was examined, and mineral oil was also studied for comparison purpose.

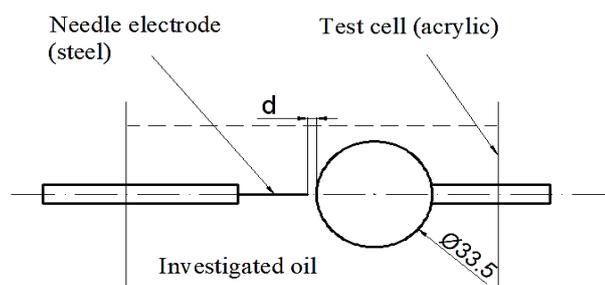
2. MATERIALS AND METHODS

2.1. Experimental Setup

Figure 1a shows the experimental setup for testing breakdown voltage and determining the relationship between the breakdown voltage and electrode gap. All experiments were performed with 50 Hz-AC voltage which can be adjusted from 0 to 80 kV by a transformer. The spherical electrode system, which is in compliance with the IEC-60156 standard, was used for the experiment.



a. Experimental setup



b. Needle-sphere electrode system

Figure 1. Experimental setup (a) and needle-sphere electrode system (b).

The breakdown voltage versus time to breakdown ($V-t$) was performed with the similar setup shown in Fig. 1a. However, in this test the spherical electrode system was replaced with the needle-sphere electrode system (Fig. 1b). The reason is that the time to breakdown of oil in

the spherical electrode system is more sensitive to the rate of voltage rise [13]. Therefore, it is difficult to evaluate the $V-t$ characteristic of oil in the spherical electrode system. Diameter of the needle electrode is 0.3 mm while the spherical electrode has a diameter of 33.5 mm.

2.2. Oil samples

Two kinds of oils were used for experiment. These are coconut oil and mineral oil named PLC supertrans. Virgin coconut oil was purchased from Vietcoco (Vietnam), and mineral oil was supplied from Petrolimex (Viet Nam). Fatty acid composition of refined coconut oil is shown in Table 1, and its physical, chemical and electrical properties are exhibited in Table 2. It is seen from Table 1 that saturated fatty acids reaches 91.4 % of total fatty acids. This feature is expected to form high oxidation stability of coconut oil. It is obtained from Table 2 that only the pour point of coconut oil does not meet a value specified by the ASTM-D6871. Other technical parameters of coconut oil without and with small content of TBHQ are close in values. Technical parameters of mineral oil were provided by the manufacturer. Before testing, oil samples were dried in vacuum oven (0.5 mbar) at 65 °C for 48 hours and then cooled down to ambient temperature within 24 hours under the same vacuum condition.

Table 1. Fatty acid composition of refined coconut oil.

No	Fatty acids	Structure	wt%
1	Caprylic acid	C8:0	8,0
2	Capric acid	C10:0	6,4
3	Lauric acid	C12:0	48,5
4	Myristic acid	C14:0	17,6
5	Palmitic acid	C16:0	8,4
6	Stearic acid	C18:0	2,5
7	Oleic acid	C18:1	6,5
8	Linoleic acid	C18:2	1,5

Table 2. Physical, chemical and electrical properties of refined coconut oil.

No	Parameter	Coconut oil	Coconut oil + TBHQ 0.5 wt%	ASTM-D6871
1	Viscosity at 40 °C (cSt)	25.9	27.2	≤ 50
2	Pour point (°C)	17.7	18	≤ -10
3	Flash point (°C)	296	301	≥ 275
4	Density at 20°C (g/ml)	0.919	0.921	≤ 0.96
5	Water content (mg/kg)	93	82	≤ 200
6	Breakdown voltage at 2 mm gap (kV)	40.3	36.5	≥ 35
7	Dissipation factor at 25 °C (%)	0.16	0.18	≤ 0.2
8	Corrosive sulfur	Not corrosive	Not corrosive	Not corrosive
9	Acid number (mg KOH/g)	0.01	0.01	≤ 0.06

2.3. Antioxidant

Tertiary Butyl Hydroquinone (TBHQ), provided by Sigma-Aldrich, was added into coconut oil with the concentration of 0.5 wt% for increasing the oxidation stability of coconut oil at high temperature. TBHQ is one of synthetic food grade antioxidants used for vegetable oils. TBHQ reacts with free radicals which result from the reaction of oxygen in air with unsaturated oil molecules. This prevents these radicals from taking up electrons from other unsaturated fatty acids, thus providing protection from auto-oxidation [14, 15].

2.4. Method and Procedure

2.4.1. Unaged oil

For breakdown voltage determination, the test was performed according to the IEC-60156 standard with the spherical gap of 2.5 mm. Experiment was repeated six times. Voltage applied to the electrode system was increased from 0 to until breakdown with the rate of 1 kV/s. A pause of 2 minutes was set in between two consecutive breakdowns. After each breakdown, oil inside the test cell was gently shaken to uniformly diffuse carbon particles.

In order to establish the relationship between the breakdown voltage and the electrode gap ($V-d$), the similar method to determine the breakdown voltage was used. However, the gap distance was changed in steps of 0.5 mm from 0.5 mm to 2.5 mm. The experiment was repeated six times at each value of the electrode gap. At each step, oil would be filtered to remove carbon particles before running the new test.

For $V-t$ test, the average breakdown voltage (V_{ave}) was first calculated from the value of six breakdown voltages. And then the voltage applying to the electrode system was increased in steps of 5 % from 70 % of V_{ave} to 100 % of V_{ave} . At each step, the breakdown time t was recorded.

All experiments were performed with virgin coconut oil and coconut oil with additive (TBHQ). However, $V-t$ characteristics were only determined with virgin oil.

2.4.2. Aged oil

The ageing process was carried out according to the standard of IEC-61125 B at 120 °C during 72 h with the presence of a cylindrical copper wire used as a catalyst. Oil samples were directly exposed to the air inside the oven in order to simulate the free breathing transformers and allow an oxidation process. Aged oil samples were tested to determine the breakdown voltage and establish the $V-d$ characteristics. All experiments were performed with virgin coconut oil, coconut oil containing antioxidant (TBHQ) and mineral oil.

3. RESULTS AND DISCUSSION

3.1. The breakdown voltage

The breakdown voltages (V_{BD}) of coconut oil, coconut oil with TBHQ (0.5 wt%) and mineral oil are exhibited in Table 3. It is seen that V_{BD} of unaged coconut oil is comparable to that of unaged mineral oil (51.3 ± 2.2 kV for coconut; 50.4 ± 2.6 kV for mineral oil). This indicates that coconut oil has high dielectric strength. It was recorded that TBHQ significantly affected V_{BD} of coconut oil. When adding TBHQ with concentration of 0.5 wt%, V_{BD} value of coconut oil is reduced about 5 % from 51.3 ± 2.2 kV to 47.8 ± 3.6 kV. However, the Figure 3 in

subsection 3.2 shows that V_{BD} of coconut oil containing TBHQ is still higher than the required value in ASTM-D6871 (which is ≥ 35 kV, at $d = 2$ mm). This is not in agreement with the reported results about rice oil, corn oil and peanut oil in our previous study [8]. The reason may be the difference in chemical composition between coconut oil and other vegetable oils (rice oil, corn oil and peanut oil). The standard deviation (STD) reaches the highest value for coconut oil with TBHQ ($\sigma = 3.6$ kV), and there is a minor difference in STD between coconut oil and mineral oil ($\sigma = 2.2$ kV for coconut oil; $\sigma = 2.6$ kV for mineral oil).

Table 3. The breakdown voltage of unaged coconut and mineral oils ($d = 2.5$ mm).

No	Types of oils	Unaged oils (kV)
1	Coconut oil	51.3 ± 2.2
2	Coconut oil + TBHQ 0.5 wt%	47.8 ± 3.6
3	Mineral oil	50.4 ± 2.6

Table 4 presents V_{BD} of aged oil samples. It was calculated that V_{BD} of aged coconut oil was approximately 1.7 times higher than that of aged mineral oil (40.8 ± 2.0 kV for aged coconut oil; 24.6 ± 3.9 kV for aged mineral oil). This result indicates that after ageing, coconut oil exhibits a higher breakdown voltage in comparison with mineral oil. The addition of TBHQ can increase V_{BD} of aged coconut oil about 9 % (44.5 ± 2.2 kV compared to 40.8 ± 2.0 kV). This is because TBHQ can decelerate the oxidation of coconut oil at high temperature. The similar phenomenon was observed with other vegetable oils [8, 9].

Table 4. The breakdown voltage of aged coconut and mineral oils ($d = 2.5$ mm).

No	Types of oils	Aged oils (kV)
1	Coconut oil	40.8 ± 2.0
2	Coconut oil + TBHQ 0.5 wt%	44.5 ± 2.2
3	Mineral oil	24.6 ± 3.9

The effect of oil conditions on V_{BD} of coconut oil and mineral oil is shown in Fig. 2, which was drawn from data exhibited in Tables 3 and 4. It can be seen that ageing significantly reduced V_{BD} of both coconut oil and mineral oil. However, the decrease in V_{BD} due to ageing is larger for mineral oil. For virgin coconut oil, ageing causes a reduction in V_{BD} by about 21 % from 51.3 ± 2.2 kV to 40.8 ± 2.02 kV. This result is not in line with previous findings [9]. The reason is suggested that in this study coconut oil was aged at 120 °C which was higher than ageing temperature (100 °C) used in the reference [9]. After ageing test, V_{BD} of mineral oil reduced about 51 % (from 50.4 ± 2.6 kV to 24.6 ± 3.9 kV). The reduction in V_{BD} of both oils is explained by the formation of organic acids when oils were aged at high temperature [4]. With the addition of TBHQ (0.5 wt%), ageing slightly decreased V_{BD} of coconut oil (from 47.8 ± 3.6 kV to 44.5 ± 2.2 kV). This shows the effectiveness of using TBHQ to improve V_{BD} of aged coconut oil.

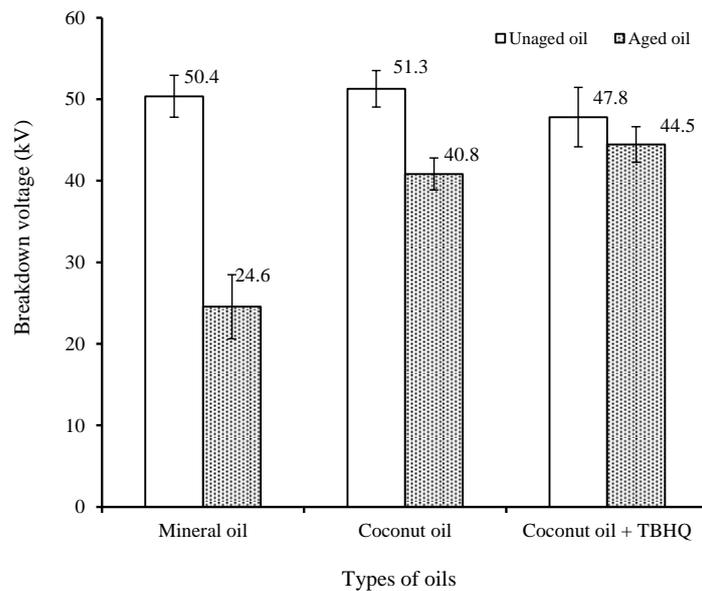


Figure 2. Breakdown voltages of oil samples ($d = 2.5$ mm).

3.2. The V - d characteristics

Figure 3 shows the V - d characteristic of mineral oil, coconut oil with and without TBHQ before and after ageing test. The V_{BD} linearly increases with electrode gap. The high values of the coefficient R^2 ($R^2 > 0.98$) shown in Table 5 indicate that linear regression model is well fitted to the breakdown data in the range of investigated gap distance, the slope of a fitted V - d line can be denoted as E_{BD} (in kV/mm).

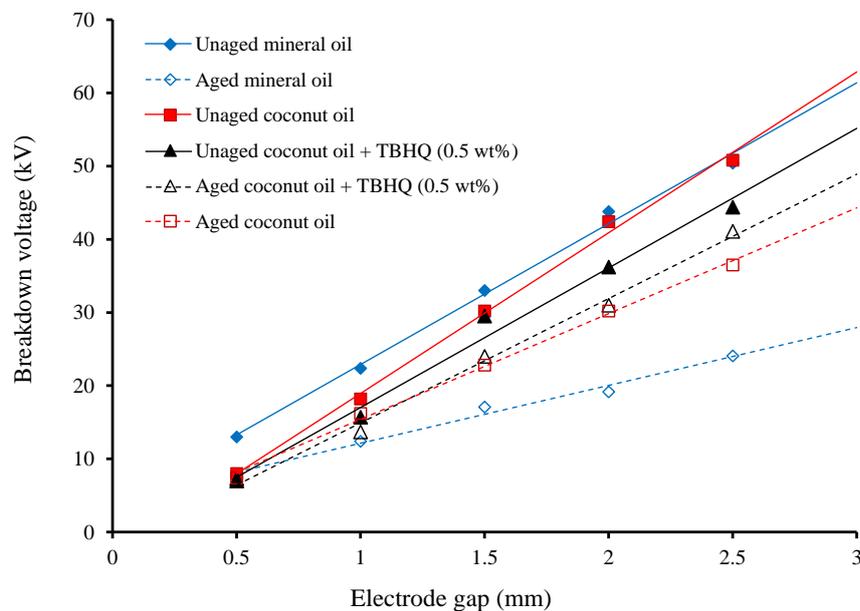


Figure 3. V - d plots of oil samples.

After ageing test, the breakdown voltages of investigated oils and E_{BD} of the oils were found to be reduced significantly. It can be also seen that E_{BD} of virgin coconut oil is higher than that of mineral oil for both unaged and aged conditions. For unaged oil case, V_{BD} of coconut oil is comparable to that of mineral oil as the gap distance exceeds 2.0 mm. Below this value of gap distance, coconut oil shows a lower value of V_{BD} compared to mineral oil. The addition of TBHQ (0.5 wt%) results in lower value of V_{BD} of coconut oil. The E_{BD} of coconut oil is slightly higher compared to mineral oil (21.9 kV/mm for coconut oil; 18.9 kV/mm for mineral oil). However, the presence of TBHQ (0.5 wt%) reduced the E_{BD} of coconut oil about 15% from 21.9 kV/mm to 18.7 kV/mm. For aged oil case, V_{BD} of coconut oil is higher than that of mineral oil within the range of electrode gap investigated. The E_{BD} of coconut oil is approximately 1.8 times higher compared to mineral oil (8.2 kV/mm for mineral oil; 14.6 kV/mm for coconut oil). The increase of E_{BD} of aged coconut oil with the presence of TBHQ confirms the antioxidant effect of TBHQ on coconut oil under thermal oxidation condition.

Table 5. Mathematical functions of V - d characteristics of oils.

No	Types of oils	Unaged oils		Aged oils	
		Mathematical functions	R^2	Mathematical functions	R^2
1	Coconut oil	$V = 21.96d - 3.02$	0.997	$V = 14.44d + 0.96$	0.997
2	Coconut oil + TBHQ 0.5 wt%	$V = 19.06d - 2.03$	0.987	$V = 16.98d - 2.05$	0.995
3	Mineral oil	$V = 19.24d + 3.65$	0.995	$V = 7.91d + 4.23$	0.987

3.3. The V - t characteristics

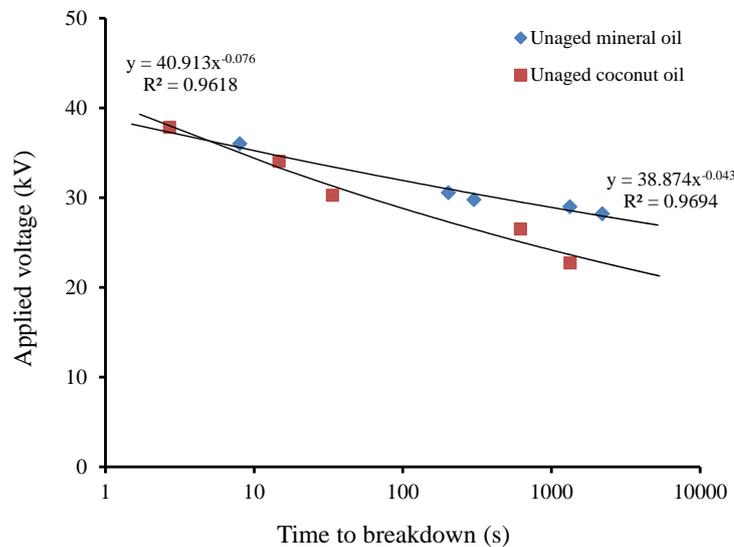


Figure 4. V - t plots of oil samples ($d = 2.5$ mm).

Figure 4 shows the relationship between applied voltage (V_{APP}) and time to breakdown (t). It is seen that the time to breakdown significantly reduces when raising the applied voltage. The $V_{APP} - t$ plots vary with the power law as seen in equation (1). This equation can be used to estimate the sensitivity of oil to overvoltage and calculate the working voltage for insulation

with a lifetime of 30 years [16]. $V_{APP} - t$ of coconut oil is steeper than that of mineral oil. Although, the coefficient A of coconut oil is about 1.05 times higher than that of mineral oil (40.91 compared to 38.88), the lifetime index n of coconut oil is only 56.5% of mineral oil ($1/0.076=13.2$ compared to $1/0.043=23.3$). This indicates that at the same applied voltage, the time to breakdown is lower for coconut oil. Therefore, coconut oil can withstand overvoltage for a short time and suffer a lower value of operating voltage for a long time compared to mineral oil.

$$V_{APP} = A.t^{-1/n} \quad (1)$$

4. CONCLUSIONS

The physical, chemical and electrical parameters of coconut oil were measured with and without the TBHQ antioxidant (0.5 wt%). It was obtained that these parameters have met the ASTM-D6871 standard except for the pour point. The breakdown characteristics of coconut oil were studied. Experimental results showed that at the electrode gap of 2.5 mm, the breakdown voltage of unaged coconut oil was as high as that of unaged mineral oil (51.3 ± 2.2 for coconut oil; 50.4 ± 2.6 for mineral oil). After ageing, the breakdown voltage of both coconut oil and mineral oil has decreased significantly. The breakdown voltage has decreased about 21 % for coconut oil and 51 % for mineral oil. However, the effect of ageing on coconut oil can be reduced by adding the antioxidant TBHQ at a concentration of 0.5 wt%. The breakdown voltage has increased linearly with increasing the electrode gap. For unaged oil case, the breakdown voltage of coconut oil is similar to mineral oil over the entire investigated electrode gap. However, aged coconut oil has a higher breakdown voltage than aged mineral oil. As the electrode gap increases, the breakdown voltage increases with the slope of 14.6 kV/mm for aged coconut oil and 8.2 kV/mm for aged mineral oil. In addition, the $V_{APP}-t$ characteristics of investigated oils changed according to the inverse power law, and the lifetime index n of coconut oil is significantly lower than that of mineral oil (13.2 compared to 23.3).

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