International Journal of Heat and Technology
Vol. 41, No. 1, February, 2023, pp. 63-71
Journal homepage: http://iieta.org/journals/ijht

Determination at Variable Temperatures and Analysis of the Physico-Thermal Properties of Palm Kernel and Castor Oil Methyl Esters as Dielectrics for Power Transformers

Kamhoua Achille[1*], Mengata Mengounou Ghislain[2], Monkam Louis[3], Moukengue Imano Adolphe[1]

[1] Laboratory of Technologies and Applied Sciences (LATS), University Douala, Douala 7236, Cameroon
[2] Dept. of Electrical Engineering and Industrial Computing, Laboratory of Technologies and Applied Sciences (LATS), University Douala, Douala 7236, Cameroon
[3] Dept. of Thermal Engineering and Energy, Laboratory of Technologies and Applied Sciences (LATS), University Douala, Douala 7236, Cameroon

Corresponding Author Email: kamhouaa@yahoo.fr

https://doi.org/10.18280/ijht.410107

Received: 24 August 2022
Accepted: 16 December 2022

Keywords:
thermal conductivity, relative density, methyl esters, specific heat, kinematic viscosity

ABSTRACT

Transformers have always used mineral oil as a liquid dielectric, and scientists have noted its harmful effects on human health and the environment. For more than two years, these vegetable oils have been positioned as real substitutes for mineral oils in view of their excellent physical, chemical and thermal properties. However, being oils sometimes intended for human consumption, such as sunflower oil, corn oil, olive oil, rapeseed oil, soya oil, rice bran oil, coconut oil, palm oil and many others, it is imperative to orientate the use of these oils towards the needs of the population. It is imperative to direct their use to natural non-edible esters in order to avoid a food shortage. Work is being done in this direction, but these are not yet fully determined in terms of their physico-thermal properties as in mineral and other edible oils. This work is a contribution to the determination and analysis of the physico-thermal properties of palm kernel and castor oil methyl esters (PKOME and COME) at variable temperatures. A comparison of the behavioural results with mineral oil (MO) widely used in processors shows a similar trend. Also, the values obtained by extrapolation at room temperature are compared to the values found in the literature concerning: relative density, we have a relative error of 3.47% for PKOME, 0.10% for COME, for kinematic viscosity we have a relative error of 8% for PKOME and 1.46% for COME. The second order polynomial correlations established from the measurements have a coefficient of determination close to 1. The values obtained from these correlations are in accordance with the expectations of ASTM D 1217 for relative density, ISO 3104 for kinematic viscosity, ASTM D 7896 for thermal conductivity and the adiabatic calorimetry method for specific heat.

1. INTRODUCTION

Oil in immersed transformers is essential for their operation. It ensures that the conductive parts are insulated from each other but also that the transformer is cooled optimally by transferring the heat generated from the hot spots to the outside environment. Mineral oils are the most common dielectric in the electrical industry in general and in transformers in particular. They account for 90-95% of the world's consumption, i.e., about 1,000,000 tonnes per year of specific heat [1]. The reasons for choosing mineral oils could be their low price, their excellent viscosity, and their dielectric and thermal properties, which are well known in the literature [2, 3]. Research into the causes of overheating in power transformers shows that the temperature of the hot spots can reach 180°C, thus highlighting the limitations of mineral oils in terms of fire safety, soil and water pollution, and their low biodegradability (30%) [4, 5]. In addition to these shortcomings, there is the spectre of an increasingly perceptible decline in global oil resources [6]. On the basis of these findings, the researchers investigated alternatives to mineral oils, including the use of synthetic oils and silicones. Synthetic oils are favoured over mineral oils because of their high degree of flame resistance (liquids with a minimum flash point above 300°C), but also for their thermal stability. Silicone oils are characterised by a very low pour point compared to mineral oils, good fire resistance (fire point above 330°C) but also good properties against ageing and oxidation [7, 8]. It is true that their use has improved the dielectric performance of power transformers, as shown by the studies conducted by Perrier et al. [9]. However, they still have to meet environmental and cost-competitive requirements because they are non-biodegradable, their use is eight times more expensive than mineral oils [10, 11]. In order to overcome the limitations of their uses, researchers have focused on natural esters or vegetable oils [12, 13]. Asea Brown Boveri (ABB) developed and patented in the USA in September 1999 BIOTEMP vegetable oil from grape seeds rich in oleic acid, Envitrotemp FR3 oil, produced from soya beans and patented in March 2000 [14, 15], RS50 oil developed from rapeseed oil [16, 17] by energy of France (EDF). Since then, the number of processors filled with natural esters has been increasing. Characterisation work on these oils includes determination of thermal conductivity from 20°C to 250°C; specific heat between 20 and 250°C; kinematic viscosity from -20°C to 100°C and relative density from -20°C to 100°C [18-21].

In the early 1980s, the use of natural esters as insulating and cooling fluids in power transformers was put on the agenda. Many prototypes were tested and patented. They are fully biodegradable and work well at high temperatures. They are now used in distribution transformers in some sensitive areas, opening up a new area of research into the physico-chemical characterization and analysis of the thermo-physical properties of natural food and commercial esters for application in transformers. Unfortunately, although previous investigations have already shown that vegetable oils are environmentally friendly and suitable for sensitive areas compared to mineral oils [12, 22, 23]. However, the fact remains that their use as a replacement fluid in submerged transformers leads to a dynamic expansion of plantations with loss of resources for biodiversity. (disturbance) of biodiversity [24, 25]. Studies by F. Danielsen et al show that the species richness of birds, lizards and mammals decreases in forests and is only 23% in oil palm plantations. Conversely, ants, bees and moths are higher in oil palm plantations than in forest sites [26]. Furthermore, the use of vegetable oils in industrial machinery can also create supply shortages for some countries, particularly those that rely heavily on imported vegetable oils, and food security problems in the face of ever-increasing global consumption [27, 28].

To overcome the problems of using edible natural esters in submerged processors, it is essential to turn to natural esters with low food consumption rates. The literature presents palm kernel oil, whose worldwide consumption is only 4% in 2018 [29], castor oil which is inedible and toxic [30, 31], jatropha cursa oil [32] to name but a few. In the literature, we note an insufficiency of their thermo-physical characterization at variable temperatures. The values found in the literature are limited to room temperature, especially for palm kernel and castor oil methyl esters. One of the current solutions lies in the promotion of further research into the characterization of the physical properties of natural esters at varying temperatures, as discussed by Turgut et al. [33] in the determination of the thermal conductivity of sunflower and corn oils and by Hofmann et al. in the determination of the specific heat and thermal conductivity of natural esters from rapeseed, soybeans, sunflower palms [34]. In the last six years, several authors have worked on the characterization of the dielectric properties of palm kernel oil methyl esters (PKOME) and castor oil methyl esters (COME). The work of Mengounou et al. [35] focuses on the analysis of physico-chemical properties, including the density of palm kernel oil methyl esters at 20°C and the kinematic viscosity from 25°C to 70°C. Nkouetcha et al. [36] measure only the density at 20°C and the kinematic viscosity at 40°C of castor oil methyl esters. Ghislain et al. [37] propose an optimal blend between refined palm kernel oil and PKOME, having the best compromise between flash point and viscosity for use in power transformers.

This work contributes to the determination and analysis of thermo-physical properties at varying temperatures as a complement to the data on palm kernel and castor methyl esters as available for other mineral and synthetic oils. Approximation functions are established to cover the temperature ranges as specified in the standard, and a comparison is made with properties available in the literature. The parameters include relative density, thermal conductivity, specific heat, and kinematic viscosity.

2. MATERIALS AND METHODS

In sections 2.1 and 2.2, we present the common protocol for obtaining samples of palm kernel and castor oil methyl esters.

2.1 Palm kernel oil refining

Like most non-food vegetable oils, crude palm kernel oil and crude castor oil sold on the Cameroonian market are extracted in the traditional way and packaged in 1 litre bottles. Degumming and alkaline neutralisation constitute the refining process of crude palm kernel oil, as illustrated in Figure 1. The purpose of degumming is to remove substances from the crude oil that may become insoluble through hydration, such as gums and phospholipids. 400g of palm kernel oil is added to 48g of caustic soda solution. The mixture is slowly stirred for 40 minutes. Decanting allows the degummed oil to be recovered. The following neutralisation step reduces or eliminates impurities (free fatty acids). A solution of sodium hydroxide or caustic soda is prepared and added to the degummed palm kernel oil at room temperature and at a low stirring speed. The caustic soda reacts with the free fatty acids (FFA) present in the oil and forms a neutralisation paste. The neutralisation paste is then separated by centrifugation to recover the oil. The concentration of the NaOH solution increases with the phospholipid content of the natural esters to be refined. In order to avoid excessive oil loss, the concentration and percentage of NaOH in relation to the mass of oil must be chosen carefully [38, 39].

$$\underset{\text{Free fatty acids}}{\text{R-COOH}} + \underset{\text{caustic soda}}{\text{NaOH}} \rightarrow \underset{\text{sodium soap}}{\text{R} - \text{COO} - \text{Na}} + \underset{\text{water}}{\text{H}_2\text{O}} \qquad (1)$$

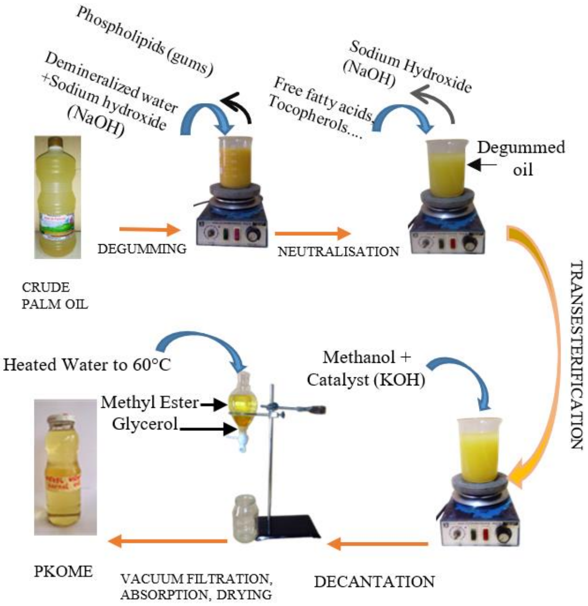


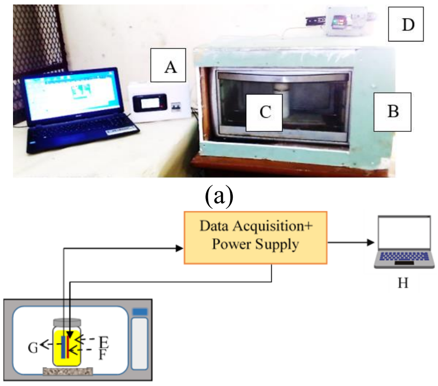
Figure 1. Palm kernel oil methyl ester refining and transesterification scenario

2.2 Transesterification process of palm kernel oil

The oil is transesterified in order to separate the natural esters from the glycerol and to reduce the viscosity. This is a process in which triglycerides are converted in the presence of an alcohol (methanol or ethanol) and a catalyst into ester and glycerol [40]. In the process described in Figure 1, crude palm kernel oil is mixed with methanol (CH_3OH) in the presence of potassium hydroxide (KOH), which increases its ability to dissipate the heat generated in the transformer. The process consists firstly of the formation of methoxide by adding to 6 grams of KOH 120 grams of methanol, followed by homogenisation under magnetic stirring at 60°C for 30 minutes. The formation of palm kernel oil methyl ester is carried out by mixing 300 g of natural palm kernel oil ester in the homogenised solution of KOH + CH_3OH for at least 120 minutes. The next step is decantation, where the mixture of esters + KOH + CH_3OH is introduced into a separating funnel and left to stand for at least half a day to ensure complete separation. At the end of this rest, glycerol is obtained, and the liquid above is less dense. Once the components are separated, the less dense part, which is the methyl ester, is extracted and then purified in a wash with water heated to 60°C to remove excess catalyst and unreacted methanol. The wash is repeated 7 to 10 times. The PKOMEs are finally dehumidified by absorption in a mixture of silica gel and activated clay. This is followed by vacuum filtration (filter porosity of 10 micrometers) of the bio-insulator to remove the residual activated clay and silica gel. Finally, the samples are dried at 80°C for 24 hours, then sealed in a bottle for storage [34, 38]. Figure 1 shows the refining and transesterification scenario for palm kernel oil methyl esters.

2.3 Determination of thermal conductivity

The experimental setup based on the ASTM D7896 transient hot wire (THW) method in Figure 2 is used to determine the thermal conductivity of samples. It consists of a stainless steel cylinder 4 cm in diameter and 8 cm high, designed to contain the test substance, into which a polymer (Kapton) heating wire with a linear power of 5 $W.m^{-1}$is inserted. A platinum PT 100 temperature probe is attached to this heat source with a polymer adhesive tape resistant to heat up to 250°C. up to 250°C. The whole assembly is placed in a fully insulated electric oven with adjustable temperature. The temperature and time data acquisition device consists of an Arduino UNO board and a MAX 6675 amplifier module.



(a)

(b)

Figure 2. (a) Experimental set-up (b) Schematic diagram

where, A-Data Acquisition; B-Thermal Room; C-Cylindrical Tank; D-PID Temperature Controller; E-Bio-insulator Liquid; F-Polymide Heaters; G-Platinum PT100; H-Personal Computer.

The measurement time is controlled by a relay that opens the resistor supply circuit after 4 seconds, set in the program run by the module. The data is recorded every second. This relatively short time was achieved during the calibration of our system by reproducing the thermal conductivity of known distilled water. In the literature, the hot wire method indicates that measurements should be made at short times. This requirement limits the effects of natural convection flow resulting from temperature-dependent density variations on the thermal conductivity measurement. This is the case in the work of Turgut et al. [33, 41].

To determine the thermal conductivity of the medium in which the hot wire is immersed, the slope of the variation of the temperature of the hot wire as a function of the logarithm of time and the linear power of the wire are used. This method is developed in the work of Fontes et al. [42] and reproduced here in Eqns. (2) and (3).

$$P = \frac{T(t) - T(0)}{Ln(t)} \tag{2}$$

$$P = \frac{Q}{4\pi\lambda} \Leftrightarrow \lambda = \frac{Q}{4\pi P} \tag{3}$$

Q: Linear power of the heating wire [W/m]; P: Value of the slope of the trend curve generated in EXCEL; t: Time [ms], ΔT :Variation temperature of heating wire [°C]; λ: Conductivité Thermique [W/m°C].

The calibration of our device is carried out by measuring the thermal conductivity of water at 40°C. This is obtained by using the slope P of the trend curve plotted in EXCEL and shown in Figure 3. The value of the coefficient of determination R^2 shows the validity of the approximation function. Using the Eq. (3), we obtain the thermal conductivity λ.

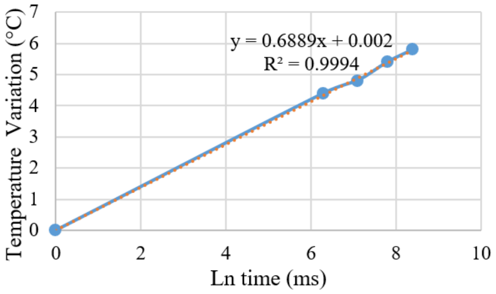


Figure 3. Line of variation of the hot wire temperature as a function of Ln(t)

Applying Eq. (3), we obtain the thermal conductivity of water.

$$\lambda = \frac{5}{4\pi \times 0.6889} = 0.577 \tag{4}$$

The calculated thermal conductivity is 0.577 W/m°C and that of the literature is 0.61 W/m°C with a measurement error of less than 3%.

This is because the medium in which the hot wire is immersed has an influence on its temperature variation: if the liquid is a good thermal conductor, the wire will heat up less than if it is not.

2.4 Determination of the specific heat

The heat of mass reflects the ability of a body to absorb heat and heat up. For mineral insulating liquids, standard values for the specific heat of natural esters are established [37, 39]. The experimental set-up for the determination of the specific heat is shown in Figure 4 and is based on the adiabatic calorimetry method using an adiabatic calorimeter. A mass of liquid corresponding to a volume of about 120 ml at temperature T (°C) is introduced into the calorimeter equipped with a heating resistor, a stirrer and a PT 100 temperature sensor. The heater is then switched on and off for 25 minutes with stirring every 5 minutes to homogenise the temperature of the liquid in the calorimeter as described in the calorimeter technical file. By recording the temperature variation of the system (oil + calorimeter) and the heating time via our microcontroller, we obtain the affine line y of Eq. (4).

$$y = kx + b \tag{5}$$

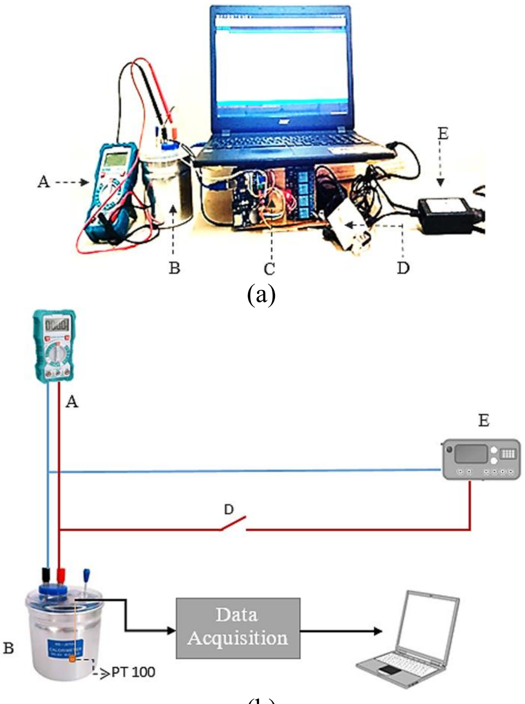
The directing coefficient k results from modelling with Excel the graph of the variation of the internal energy temperature $\Delta U_{Oil+Cal}$ of the system as a function of the heating time.

$$\Delta U_{Oil+cal} = k\Delta\theta \tag{6}$$

$$\Delta U_{Oil+cal} = (m_{Oil}C_{Oil} + m_{cal}C_{Al}).\Delta\theta \tag{7}$$

C_{Oil}: Specific heat of the oil [J.kg^{-1}. °C^{-1}]; m_{cal}l: Mass of the calorimeter [kg]; C_{cal} : Specific heat of the calorimeter [J.kg^{-1}. °C^{-1}]; m_{Oil}: Mass of the oil [kg]; k: Heat transfer to the system [J.kg^{-1}. °C^{-1}]; Cp: Specific heat [J.kg^{-1}. °C^{-1}]. The figure below is the experimental setup and the schematic diagram for measuring specific heat using an adiabatic calorimeter.

Cp: Specific heat [J/kg°C]. The figure below is the experimental setup and the schematic diagram for measuring specific heat using an adiabatic calorimeter.



(a)

(b)

Figure 4. (a) Experimental set-up (b) schematic diagram

where, A-Voltmeter; B-Adiabatic Calorimeter; C-Data Acquisition; D-Light Switch; E-DC Power Supply.

The adiabatic calorimeter is supplied with 5V and draws a current of 2.1A for all experiments, assuming that the electrical work received by the resistor is entirely transformed into thermal energy and adsorbed by the system. Figure 5 shows the evolution of the internal energy change $\Delta U_{Oil+Cal}$ captured by the system as a function of the temperature change ΔT at each time t. The 10 GBN mineral oil is the calibration oil for the device at 20°C.

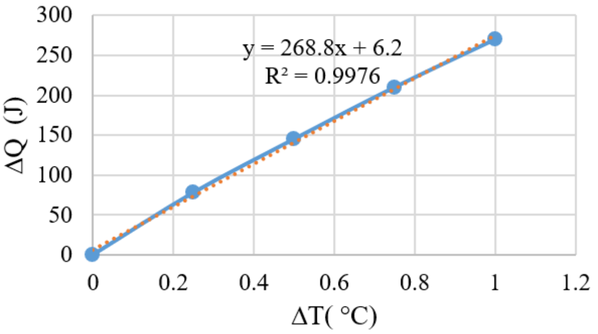


Figure 5. Line of heat variation as a function of (ΔT)

$$\Delta U = IUt \tag{8}$$

$$C_{oil} = \frac{268.8 - 0.068 \times 897}{0.120} = 1732 \tag{9}$$

The calculated specific heat is 1732 J.kg^{-1}. °C^{-1} with a relative measurement error of less than 6%.

2.5 Determination de la kinematic viscosity

The choice of an oil also depends on its kinematic viscosity. This is the characteristic power of liquids to resist the movement of one part of the fluid relative to the other. The viscosity of the oil influences the flowability of the medium one could also say the heat transfer and thus the ability to cool electrical equipment. The ISO 3104 standard recommends less than 12 mm^2/s at 40°C for insulating oils in transformers [43]. To determine the viscosity of our samples, we used a capillary viscometer. The kinematic viscosity Eq. (10) is determined from the flow time of the insulating liquid between the viscometer marks, where k is the constancy of the viscometer, t is the flow time of the oil between the two marks, and c is the kinematic energy correction.

$$\eta = k(t - c) \tag{10}$$

2.6 Determination of the relative density

The density of the oil characterises the mass of the oil over its volume. It is an intrinsic characteristic of oil. This density varies with temperature. Indeed, increasing the temperature of oil expands its volume, which will change the value of the density. The relative density is the ratio between body density ρ_c and the reference body density ρ_{cr} under specific conditions, Eq. (11).

$$d = \frac{\rho_c}{\rho_{cr}} \tag{11}$$

The density of our samples is measured using a 0.01g digital analytical balance, a 25 ml pycnometer and a temperature-controlled container. The density is expressed by the Eq. (12) where m is the mass and V the volume and ρ is the density.

$$\rho = \frac{m}{V} \quad (12)$$

2.7 Uncertainties and measurement errors

The measuring instruments used are all calibrated. The tests are carried out at variable temperatures. For all our measurements, the tests are repeated 3 times per sample at all temperatures to ensure the repeatability of the results. In addition, for all physical-thermal quantities, we determine the standard deviation of the measurements of each sample at each temperature and a relative error of measurement from the maximum deviation.

3. DISCUSSION AND RESULTS

3.1 Relative density

The results of the density measurements for PKOME, COME and MO Oil are given in Table 1, and their evolution is presented in Figure 6.

Table 1. Experimental results for the relative density (d) of PKOME, COME and MO

T (°C)	20	40	60	80	100	σ [min-max]	Error
D PKOME	0.883	0.868	0.860	0.856	0.850	[0.0085-0.009]	2.1%
D COME	0.917	0.936	0.933	0.927	0.916	[0.007-0.011]	1.7%
D MO [44]	0.859	0.850	0.840	0825	0.810	/	/
D PKOME [3, 4]	0.864	/	/	/	/		3.47%
D COME [4]	0.956	/	/	/	/		0.10%

The evolution of relative density of PKOME, COME and MO with temperature for KPOME, COME, and MO oils is shown in Figure 6.

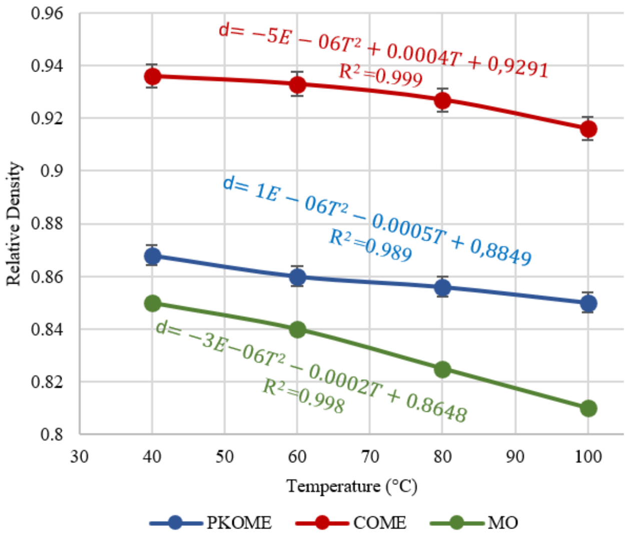


Figure 6. Experimental density results of PKOME, COME and MO

Table 1 shows the values of the average at different temperatures. The values at 20°C are those obtained by correlation from the empirical functions of their evolution with temperatures between 40°C and 100°C. A comparison at 20°C of the extrapolated values with literature data shows a low relative error for the different oil samples. For PKOME, we have a relative error of 2.1%. For COME we have a relative error of 4%. This result shows that castor methyl ester is denser than NL oil and PKOME respectively. These errors show that the difference between the values estimated from the established approximation functions are negligible and we can thus determine the densities at different temperatures below 100°C. Figure 6 shows that the density of the samples decreases with increasing temperature from 40°C to 100°C. Furthermore, the values obtained at 20°C (0.883 and 0.917) are in line with the recommendations of ASTM D 1217 which place the relative densities of natural esters between [0.87 to 0.92] [45, 46].

3.2 Kinematic viscosity

The evolution of kinematic viscosity with temperature for KPOME, COME, and MO oils is shown in Figure 7.

Table 2 shows the average values of the kinematic viscosity at different temperatures. The interior of the transformer is subject to a heating effect. The comparison of these values with literature data at 40°C gives us a relative error for the different oil samples. For PKOME, we have a relative error of 8%. For COME we have a relative error of 1.43%. Figure 7 shows that the kinematic viscosity decreases from 20°C to 100°C. For PKOME, it is from 5.54 to 2.72 for an average of 0.81. For COME, this decrease is from 16.47 to 8.8, with an average of 1.67. and for MO, from 9.95 to 3.54, with an average of 2.17. The values of the kinematic viscosity at 40°C and 100°C of palm kernel and castor methyl esters are in accordance with those recommended in the literature for natural esters [4, 47].

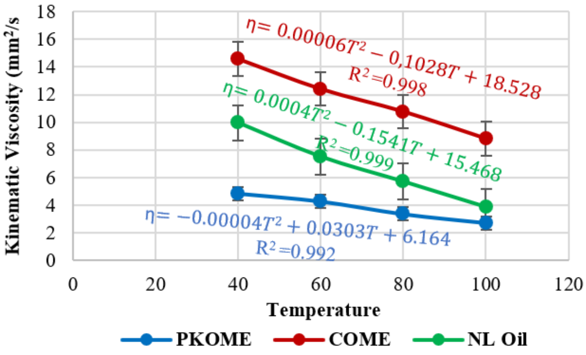


Figure 7. Experimental result for the viscosity of PKOME, COME, and MO

The results of the kinematic viscosity measurements for PKOME, COME, and MO are given in Table 2 and their evolution is presented in Figure 8.

3.3 Thermal conductivity

The results of the thermal conductivity measurements for PKOME, COME, and MO oil are given in Table 3.

Table 2. Kinematic viscosity heat experimental results for PKOME, COME, and MO

T (°C)	20	40	60	80	100	σ [min-max]	Error
η PKOME	5.54	4.85	4.28	3.36	2.72	[0.72-0.75]	3.2%
η COME	16.47	14.61	12.42	10.77	8.8	[0.07-0.76]	1.8%
η MO [44]	12.54	9.95	7.65	5.7	3.86	/	/
PKOME [3]	/	4.46±0.11	/	/	/		8%
COME [40]		14.4	/	/	/		1.46%
COME [4]	/	4.46	/	/	/		8%

Table 3. Thermal conductivity experimental results for PKOME, COME, and, MO

T (°C)	25	40	60	80	100	σ [min- max]	Error
λ PKOME	0.182	0.175	0.166	0.158	0.150	[0.010-0.012]	2.14%
λ COME	0.173	0.166	0.157	0.151	0.144	[0.010-0.011]	1.41%
λ MO [48]	0.133	0.130	0.128	0.126	0.120	/	/

Table 4. Experimental result of the specific heat of PKOME, COME and MO

T (°C)	25	40	60	80	100	σ [min- max]	Error
C_P PKOME	1500.06	1850	2140	2335	2541	[5.1-5.28]	5.8%
C_P COME	1523.23	1883	2182	2373	2565	[5.1-5.34]	6.12%
C_P MO [44]	1820	1930	2000	2150	2195	/	/

The evolution of thermal conductivity with temperature for KPOME, COME, and MO oils is shown in Figure 8.

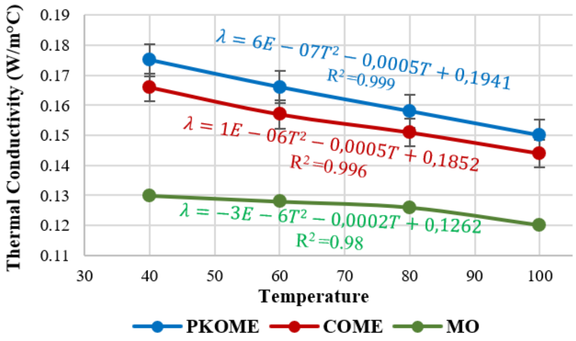


Figure 8. Experimental results on the thermal conductivity of PKOME, COME, and MO oils

Table 3 shows the average values of the thermal conductivity measured in the temperature range from 40°C to 100°C. The thermal conductivity of PKOME at 40°C is 0.175 W.m^{-1}°C^{-1} and 0.150 W.m^{-1}°C^{-1} at 100°C, for a decrease with temperature, on average 0.0086. For COME, the thermal conductivity is 0.166 W.m^{-1}°C^{-1} at 40°C and W.m^{-1}°C^{-1} at 100°C, for a decrease with temperature of on average 0.007. For MO, it is 0.130 W.m^{-1}°C^{-1} at 40°C and 0.120 W.m^{-1}°C^{-1} at 100°C, for a temperature decrease of 0.0033 on average. It can also be seen that for all temperatures, the thermal conductivity values of PKOME and COME are higher than those of MO. However, the comparative analysis in Figure 8 shows that the thermal conductivity decreases with temperature for all samples. The thermal conductivity of PKOME is better than that of COME and mineral oil; but also, the values of bio-insulating liquids and mineral oil in this study are in accordance with the data prescribed in the literature [48, 49].

3.4 Specific heat

The results of the average values of the specific heat measurements for PKOME, COME, and MO oils are presented in Table 4.

The evolution curves of specific heat with temperature for PKOME, COME, and MO are presented in Figure 9.

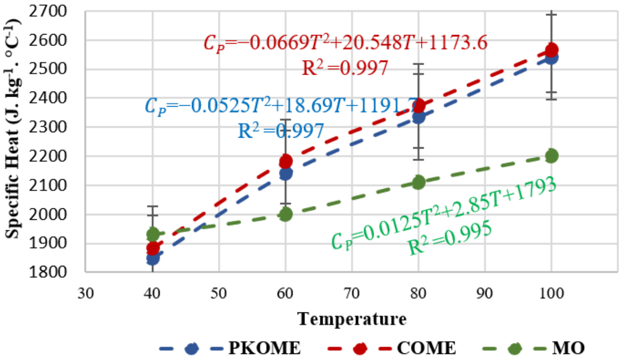


Figure 9. Specific heat evolution curves for PKOME, COME and MO

Table 4 shows the values of the average thermal conductivity measured in the temperature range from 40°C to 100°C. The information in this table shows that the specific heat of PKOME at 40°C is 1850 J/kg°C and 2541 J/kg°C at 100°Cfor an increase with temperature, on average 230. For COME, it is 1883 J/kg°C at 40°C and 2565 J/kg°C at 100°C for an increase with temperature, on average, 227. For MO, it is 1930 J/kg°C at 40°C and 2195 J/kg°C at 100°C for an increase with temperature, on average, 88.33. The values of PKOME and COME at 25°C obtained by extrapolation from the empirical models are in accordance with those of the literature which recommends a minimum and maximum specific heat value between 1500 and 2380 J/kg°C [48]. However, the analysis of Figure 9 shows that the specific heat increases with temperature. This increase in specific heat with temperature could be due to the chemical composition of natural esters rich in oleic acid [50, 51]. The values obtained at each temperature are close to each other.

3.5 Summary of results

In the Table 5, we summarise our results and compare them with those from the literature.

Table 5. Contributions to the physico-thermal properties of PKOME and COME

Physico-thermal properties			Limit values	Previous work		
Titles	Expressions	Tests Methods	[4, 39]	[35]	[36]	Current work
Density Relative	PKOME: $d=-1E-06T^2-0.0005T+0.8849; R^2=0.989$	ASTM D1217	[0.87 - 0.92] at 20°C	0.864	/	0.883±0.021
	COME: $d==-5E-06T^2-0.0004T+0.9291; R^2=0.999$			/	0.956	0.921±0.04
Kinematic Viscosity $(mm^2.s^{-1})$	PKOME: $\eta=-4E-05T^2-0.0304T+6.1685; R^2=0.992$	ISO 3104	[2,3 - 9,8] 14.4 at 40°C	4.46±0.11	4.46	4.85±0.08
	COME: $\eta=0.0001T^2-0.1147T+18.933; R^2=0.998$			/	18	14.61±0.0146
Specific Heat $(J.kg^{-1}°C^{-1})$	PKOME: $C_P=-0.0525T^2+18.69T+1191.7; R^2=0.997$	Adiabatic calorimetry	[1500 - 2300] at 25°C	/	/	1506.3
	COME: $C_P=-0.0669T^2+20.548T+1173.6; R^2=0.997$					1523.2375
Thermal Conductivity $(W.m^{-1}°C^{-1})$	PKOME: $\lambda=6E-07T^2-0.0005T+0.1941; R^2=0.999$	ASTM D7896	[0.16 - 0.17] at 25°C	/	/	0.182
	COME: $\lambda=1E-06T^2-0.0005T+0.1854; R^2=0.997$					0.173

4. CONCLUSION

The only physico-thermal properties known so far of palm kernel and castor methyl esters are viscosity and density at room temperature. This work provides additional information on these properties as well as the thermal conductivity and specific heat of these two esters. These parameters are determined at four temperature steps, and approximation functions are established. A comparative analysis is made with the properties of mineral oils with regard to the overall behaviour, on the one hand, and with existing values at room temperature from the literature after extrapolation. The trends are identical to those of the mineral oils and the relative errors are acceptable, notably 2.1% and 4% for the relative density at 20°C of PKOME and COME, respectively. For the kinematic viscosity at 40°C, they are 8% and 1.46%, respectively, for PKOME and COME. The analysis shows that the use of liquid bio-insulators in processors can be oriented towards these natural esters that are not or hardly edible. The results collected thus offer the possibility to consider a complete heat transfer study within the immersed transformer.

ACKNOWLEDGEMENTS

The authors wish to express their sincere thanks to all members of the Power Systems Research Team for their valuable and constructive suggestions during the planning and development of this research work. Special thanks go to Dr Tchamdjio Nkouetcha and Nguedap Richard Daris of the University of Douala's School of Pure and Applied Sciences.

REFERENCES

[1] Kassi, K.S., Fofana, I., Volat, C., Farinas, M.I., Meghnefi, F. (2015). Impact du Vieillissement des Huiles Minérales des transformateurs de puissance sur leur capacité de refroidissement. XIIème Colloque Interuniversitaire Franco-Québécois sur la Thermique des Systèmes Sherbrooke, Québec, Canada.

[2] Rouse, T.O. (1998). Mineral insulating oil in transformers. IEEE Electrical Insulation Magazine, 14(3): 6-16. https://doi.org/10.1109/57.675572

[3] Dombek, G., Gielniak, J. (2018). Fire safety and electrical properties of mixtures of synthetic ester/mineral oil and synthetic ester/natural ester. IEEE Transactions on Dielectrics and Electrical Insulation, 25(5): 1846-1852. https://doi.org/10.1109/TDEI.2018.007223

[4] Rao, U.M., Fofana, I., Jaya, T., Rodriguez-Celis, E.M., Jalbert, J., Picher, P. (2019). Alternative dielectric fluids for transformer insulation system: Progress, challenges, and future prospects. IEEE Access, 7: 184552-184571. https://doi.org/10.1109/ACCESS.2019.2960020

[5] Salama, M.M., Mansour, D.E.A., Daghrah, M., Abdelkasoud, S.M., Abbas, A.A. (2020). Thermal performance of transformers filled with environmentally friendly oils under various loading conditions. International Journal of Electrical Power & Energy Systems, 118: 105743. https://doi.org/10.1016/j.ijepes.2019.105743

[6] Shafiee, S., Topal, E. (2009). When will fossil fuel reserves be diminished?. Energy policy, 37(1): 181-189. https://doi.org/10.1016/j.enpol.2008.08.016

[7] Kuwahara, H., Tsuruta, K., Munemurs, H., Ishii, T., Shiomi, H. (1976). Partial discharge characteristics of silicone liquids. IEEE Transactions on Electrical Insulation, EI-11(3): 86-91. https://doi.org/10.1109/TEI.1976.297904

[8] Gockenbach, E., Borsi, H. (2008). Natural and synthetic ester liquids as alternative to mineral oil for power transformers. In 2008 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Quebec, QC, Canada, pp. 521-524. https://doi.org/10.1109/CEIDP.2008.4772928

[9] Perrier, C., Beroual, A.J.I.E.I.M. (2009). Experimental investigations on insulating liquids for power transformers: Mineral, ester, and silicone oils. IEEE Electrical Insulation Magazine, 25(6): 6-13. https://doi.org/10.1109/MEI.2009.5313705

[10] Danikas, M., Sarathi, R. (2020). Alternative fluids–with a particular emphasis on vegetable oils–as replacements of transformer oil: A concise review. Engineering, Technology & Applied Science Research, 10(6): 6570-6577. https://doi.org/10.48084/etasr.3943

[11] Pahlavanpour, B., Wilson, G., Heywood, R. (1999). Environmentally friendly insulating oil. In IEEE Seminar on Engineering and the Environment-How It Affects You, London. https://doi.org/10.1049/ic:19990550

[12] Rafiq, M., Lv, Y.Z., Zhou, Y., Ma, K.B., Wang, W., Li, C.R., Wang, Q. (2015). Use of vegetable oils as transformer oils–a review. Renewable and Sustainable Energy Reviews, 52: 308-324. https://doi.org/10.1016/j.rser.2015.07.032

[13] Bashi, S.M., Abdullahi, U.U., Yunus, R., Nordin, A. (2006). Use of natural vegetable oils as alternative dielectric transformer coolants. Journal-The Institution of Engineers, 67(2): 4-9.

[14] Oommen, T.V. (2002). Vegetable oils for liquid-filled transformers. IEEE Electrical Insulation Magazine, 18(1): 6-11. https://doi.org/10.1109/57.981322

[15] Evangelista Jr, J.M., Coelho, F.E.B., Carvalho, J.A., Araújo, E.M., Miranda, T.L., Salum, A. (2017). Development of a new bio-based insulating fluid from Jatropha curcas oil for power transformers. Advances in Chemical Engineering and Science, 7(2): 235. https://doi.org/10.4236/aces.2017.72018

[16] Fernández, I., Ortiz, A., Delgado, F., Renedo, C., Perez, S. (2013). Comparative evaluation of alternative fluids for power transformers. Electric Power Systems Research, 98: 58-69. https://doi.org/10.1016/j.epsr.2013.01.007

[17] Duy, C.T., Lesaint, O., Denat, A., Bonifaci, N., Bertrand, Y. (2008). Streamer propagation and breakdown in rapeseed oil at high voltage. In 2008 IEEE International Conference on Dielectric Liquids, Chasseneuil, France, pp. 1-4. https://doi.org/10.1109/ICDL.2008.4622525

[18] Scatiggio, F., Pepe, F., Sacco, S., Serafino, C. (2019). Increased loadability of transformers immersed in natural ester. In 2019 IEEE 20th International Conference on Dielectric Liquids (ICDL), Roma, Italy, pp. 1-4. https://doi.org/10.1109/ICDL.2019.8796759

[19] Ahmed, M.R., Islm, M.S., Karmaker, A.K. (2021). Experimental investigation of electrical and thermal properties of vegetable oils for used in transformer. In 2021 International Conference on Automation, Control and Mechatronics for Industry 4.0 (ACMI), Rajshahi, Bangladesh, pp. 1-4. https://doi.org/10.1109/ACMI53878.2021.9528278

[20] Hamid, M.H.A., Ishak, M.T., Suhaimi, N.S., Adnan, J., Hashim, N.I., Ariffin, M., Katim, N.I.A., Abd Rahman, R. (2022). Electrical properties of palm oil and rice bran oil under AC stress for transformer application. Alexandria Engineering Journal, 61(11): 9095-9105. https://doi.org/10.1016/j.aej.2022.02.049

[21] Wajanasoonthon, K., Suksri, A. (2021). Electrical breakdown voltage of palm oil and nano graphene filler in nanofluids application on transformer insulating oil. In Key Engineering Materials, 902: 59-63. https://doi.org/10.4028/www.scientific.net/KEM.902.59

[22] Chairul, I.S., Bakar, N.A., Othman, M.N., Ab Ghani, S., Khiar, M.S.A., Talib, M.A. (2021). Potential of used cooking oil as dielectric liquid for oil-immersed power transformers. IEEE Transactions on Dielectrics and Electrical Insulation, 28(4): 1400-1407. https://doi.org/10.1109/TDEI.2021.009536

[23] Subburaj, S.K., Rengaraj, M., Mariappan, R. (2020). Evaluating critical characteristics of vegetable oil as a biodegradable insulating oil for transformer. International Journal of Emerging Electric Power Systems, 21(5): 128. https://doi.org/10.1515/ijeeps-2020-0128

[24] Omont, H. (2010). Contributions de la production d'huile de palme au développement durable. Problématique générale, controverses. Agronomie - Environnement, 17(6): 362-367. https://doi.org/10.1051/ocl.2010.0342

[25] Fitzherbert, E.B., Struebig, M.J., Morel, A., Danielsen, F., Brühl, C.A., Donald, P.F., Phalan, B. (2008). How will oil palm expansion affect biodiversity?. Trends in ecology & evolution, 23(10): 538-545. https://doi.org/10.1016/j.tree.2008.06.012

[26] Danielsen, F., Beukema, H., Burgess, N.D., Parish, F., BrÜhl, C.A., Donald, P.F., Fitzherbert, E.B. (2009). Biofuel plantations on forested lands: Double jeopardy for biodiversity and climate. Conservation Biology, 23(2): 348-358. https://doi.org/10.1111/j.1523-1739.2008.01096.x

[27] Pompili, M., Calcara, L., Sturchio, A., Catanzaro, F. (2016, October). Natural esters distribution transformers: A solution for environmental and fire risk prevention. In 2016 AEIT International Annual Conference (AEIT), Capri, Italy, pp. 1-5. https://doi.org/10.23919/AEIT.2016.7892754

[28] Santeramo, F.G., Searle, S. (2019). Linking soy oil demand from the US Renewable Fuel Standard to palm oil expansion through an analysis on vegetable oil price elasticities. Energy Policy, 127: 19-23. https://doi.org/10.1016/j.enpol.2018.11.054

[29] Olatounde, J. (2020) Les facteurs déterminants du marché mondial des huiles végétales. Bioclips.

[30] Ghazza, A., Madiq, B., Aitlhaj, L., Kriet, M. (2020). Toxicité cornéenne de l´ huile de ricin: à propos d´ un cas et revue de la littérature. PAMJ-Clinical Medicine, 2(8): 20820. https://doi.org/10.11604/pamj-cm.2020.2.8.20820

[31] Dumeignil, F. (2012). Propriétés et utilisation de l'huile de ricin. Oléagineux, Corps gras, Lipides, 19(1): 10-15. https://doi.org/10.1051/ocl.2012.0427

[32] Ciappina, A.L., Ferreira, F.A., Pereira, I.R., Sousa, T.R., Matos, F.S., Melo-Reis, P.R., Almeida, L.M. (2017). Toxicity of Jatropha curcas L. latex in Allium cepa test. Bioscience Journal, 33(5): 1295-1304. https://doi.org/10.14393/BJ-v33n5a2017-33835

[33] Turgut, A., Tavman, I., Tavman, S. (2009). Measurement of thermal conductivity of edible oils using transient hot wire method. International Journal of Food Properties, 12(4): 741-747. https://doi.org/10.1080/10942910802023242

[34] Hoffmann, J.F., Vaitilingom, G., Henry, J.F., Chirtoc, M., Olives, R., Goetz, V., Py, X. (2018). Temperature dependence of thermophysical and rheological properties of seven vegetable oils in view of their use as heat transfer fluids in concentrated solar plants. Solar Energy Materials and Solar Cells, 178: 129-138. https://doi.org/10.1016/j.solmat.2017.12.037

[35] Mengounou, G.M., Imano, A.M., Vardamides, J.C. (2016). Analyse des proprietes physico-chimiques de l'huile de palmistes transesterifiee. Sciences, technologies et développement, Edition spéciale, pp. 210-212. https://doi.org/10.1109/TDEI.2021.009536

[36] Nkouetcha, E.T. (2019). Elaboration and performance analysis of a bio-based insulating liquid from castor oil for power transformers. Open Access Library Journal, 6(5): 1. https://doi.org/10.4236/oalib.1105404

[37] Ghislain, M.M., Gerard, O.B., Emeric, T.N., Adolphe, M.I. (2022). Improvement of environmental characteristics of natural monoesters for use as insulating liquid in power transformers. Environmental Technology & Innovation, 27: 102784. https://doi.org/10.1016/j.eti.2022.102784

[38] Lecuna, R., Delgado, F., Ortiz, A., Castro, P.B., Fernandez, I., Renedo, C.J. (2015). Thermal-fluid

characterization of alternative liquids of power transformers: A numerical approach. IEEE Transactions on Dielectrics and Electrical Insulation, 22(5): 2522-2529. https://doi.org/10.1109/TDEI.2015.004793

[39] Bertrand, Y., Hoang, L.C. (2004). Vegetable oils as substitute for mineral insulating oils in medium-voltage equipments. CIGRE.

[40] Bertrand, Y., Lauzevis, P. (2013). Development of a low viscosity insulating liquid based on natural esters for distribution transformers. In 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013), Stockholm, Sweden, https://doi.org/10.1049/cp.2013.0701

[41] Codreanu, C., Codreanu, N.I., Obreja, V.V.N. (2007). Experimental set-up for the measurement of the thermal conductivity of liquids. Romanian Journal of Information Science and Technology, 10(3): 215-231.

[42] Fontes, D.H., Ribatski, G., Bandarra Filho, E.P. (2015). Experimental evaluation of thermal conductivity, viscosity and breakdown voltage AC of nanofluids of carbon nanotubes and diamond in transformer oil. Diamond and Related Materials, 58: 115-121. https://doi.org/10.1016/j.diamond.2015.07.007

[43] Tlhabologo, B.A., Samikannu, R., Mosalaosi, M. (2021). Alternative liquid dielectrics in power transformer insulation: A review. Indonesian Journal of Electrical Engineering and Computer Science, 23(3): 1761-1777. http://doi.org/10.11591/ijeecs.v23.i3.pp1761-1777

[44] Kurzweil, P., Schell, C., Haller, R., Trnka, P., Hornak, J. (2021). Environmental impact and aging properties of natural and synthetic transformer oils under electrical stress conditions. Advanced Sustainable Systems, 5(8): 2100079. https://doi.org/10.1002/adsu.202100079

[45] IEC, I. (2013). 62770 Fluids for electrotechnical applications-Unused natural esters for transformers and similar electrical equipment. Geneve.

[46] International Electrotechnical Commission. (2012). Fluids for electrotechnical applications-Unused mineral insulating oils for transformers and switchgear. Int. Stand, 4: 43.

[47] Rafiq, M., Lv, Y.Z., Zhou, Y., Ma, K.B., Wang, W., Li, C.R., Wang, Q. (2015). Use of vegetable oils as transformer oils–a review. Renewable and Sustainable Energy Reviews, 52: 308-324. https://doi.org/10.1016/j.rser.2015.07.032

[48] ombek, G., Nadolny, Z., Przybyłek, P. (2016). The role of the type of insulating liquid in the transformer temperature distribution. Computer Applications in Electrical Engineering, 14: 148-157. https://doi.org/10.21008/j.1508-4248.2016.0013

[49] Rafiq, M., Shafique, M., Azam, A., Ateeq, M., Khan, I. A., Hussain, A. (2020). Sustainable, renewable and environmental-friendly insulation systems for high voltages applications. Molecules, 25(17): 3901. https://doi.org/10.3390/molecules25173901

[50] Santos, J.C.O., Santos, M.G.O., Dantas, J.P., Conceição, M.M., Athaide-Filho, P.F., Souza, A.G. (2005). Comparative study of specific heat capacities of some vegetable oils obtained by DSC and microwave oven. Journal of thermal analysis and calorimetry, 79(2): 283-287. https://doi.org/10.1007/S10973-005-0050-X

[51] Contreras-Gallegos, E., Domínguez-Pacheco, F.A., Hernández-Aguilar, C., Salazar-Montoya, J.A., Ramos-Ramírez, E.G., Cruz-Orea, A. (2017). Specific heat of vegetable oils as a function of temperature obtained by adiabatic scanning calorimetry. Journal of Thermal Analysis and Calorimetry, 128(1): 523-531. https://doi.org/10.1007/s10973-016-5864-1

NOMENCLATURE

Greek symbols

η	Kinematic viscosity, $mm^2.s^{-1}$
C_P	specific heat, J. kg^{-1}. K^{-1}
d	Relative density
λ	thermal conductivity, W.m^{-1}. $°C^{-1}$

Subscripts

Ln(t)	logarithm of time
A	Ampere
DC	Direct Current
ms	millisecond