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Rheology properties of coconut oil: temperature and shear rate - dependence of coconut oil shear stress

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ABSTRACT

Rheological properties of coconut oil were obtained at different temperatures. The coconut oil sample was subjected to viscometer measurements of dynamic viscosity at shear rate and temperature ranged from30 to 100rpm, and 22 to 34 degree Celsius, respectively. Results showed that coconut oil behaves as Newtonian fluid at that range of temperatures. Formulas of three and multi-constant were proposed to obtain more suitable prediction of temperature dependence of shear stress and dynamic viscosity of coconut oil. The best AAD% was calculated using our proposed formulas to be 0.0000%.

INTRODUCTION

Alternative equations of two constant, three constant and multi-constant forms were proposed by some researchers to describe the dependence of dynamic viscosity of liquids on temperature. Simple form of two-constant was proposed by De Guzman and Abramovic[1,2]. Three-constant forms were used and proposed in Vogel×s study, Andrade×s study, Noureddini×s study and in Abramovic×s study[2-5]. Multi-constant forms were proposed in several studies by Thorpe, Noureddini and Daubert[5-7]. A polynomial or exponential dependence between temperature and dynamic viscosity of vegetable oil were proposed in Stanciu×s study[8].

Equations to describe the effect of shear stress, shear rate and temperature on dynamic viscosity were proposed by some researchers. In addition, the flow behavior of liquids was explained (Newtonian or non-Newtonian). The shear rate and temperature dependencies of viscosity of alumina nanofluids were investigated experimentally by Zhou[9]. The dynamic viscosity and shear stress, as a function of shear rate of chitosan dissolved in weakly acid solutions were studied[10]. Newtonian or Non-Newtonian behaviors of different oil samples of vegetable oil were investigated by Akhtar[11]. Giap in his study has shown that few food grade vegetable oils behaved as pseudoplastic[12]. Ashrafi×s study showed the rheological properties of different samples of olive oils in a wide range of temperature[13]. The flow behavior of coconut fats was explained. The activation energy of coconut fats was also calculated by Tipvarakarnkoon[14]. The viscosities and specific heat capacities of twelve vegetable oils were experimentally determined as a function of temperature in Fasina×s study[15]. Santos in his study evaluated the temperature-dependent rheological behavior of un-used and used vegetable cooking oils[16]. The viscosity and shear stress of the three oil types were investigated as a function of the shear rate in a study by Hojjatoleslamy[17]. The variation of the dynamic viscosity with the shear stress for non-additive vegetable oils was studied by Stefanescu[18]. There are also several studies that proposed alternative equations to describe the dependence of dynamic viscosity of liquids on others parameters[19-21].

The objective of this work is to evaluate the rheological properties of coconut oil. The dependence of shear stress of coconut oil on shear rate will be studied. The dynamic viscosity and shear stress of coconut oil as a function of temperature will be measured. The relationship between the dynamic viscosity and shear stress of coconut oil with temperature will be found by fitting equations. In addition, the flow behavior of coconut oil will be determined whether Newtonian or non-Newtonian.

THEORY

Dynamic viscosity which is defined as the ratio of shear stress (force over cross section area) to the rate of deformation (the difference of velocity over a sheared distance), and it is presented as:

$$\eta = \frac{\tau}{\frac{\partial u}{\partial x}} \quad (1)$$

Where, η is the dynamic viscosity in Pascal-second (Pa.s); ô is shear stress (N/m^2); and, $\frac{\partial u}{\partial x} = \gamma$ is rate of deformation or velocity gradient or better known as shear rate (1/s). This relation will gives constant viscosity, if shear stress is proportionally changed with velocity gradient. Fluid that follows this behavior is termed as Newtonian fluid[23].

Power law model is usually used to evaluate the behavior of liquids, which is:

$$\tau = k\,\gamma^{n} \quad (2)$$

Where τ is shear stress (N/m^2), K is shear rate (1/s). K is the consistency coefficient (N/m^2.s^n) and n is the flow behavior index[24]. When the behavior of liquid is Newtonian then the flow index in Eq.(2) will be one. If the liquid have Non-Newtonian behavior then the value of flow index will deviated from one.

The effect of temperature on dynamic viscosity of vegetable oil has been studied by several studies. These studies proposed two, three and multi-constant formula to describe this temperature dependence. Simple formulas of two-constant were proposed to describe the effect of temperature on dynamic viscosity. These are given by:

$$\eta = Ae^{\frac{B}{T}} \quad (3)$$

$$\eta = CT^{D} \quad (4)$$

Where η is the dynamic viscosity in cP, T is the temperature in K, A and B are constants. Eq.(1) is popularly known as the Andrade equation[1,4,25].

Three-constant formulas were used to represent the dynamic viscosity as a function of temperature, which are:

$$Ln\eta = A + \frac{B}{T} + \frac{C}{T^{2}} \quad (5)$$

$$Ln\eta = A + \frac{B}{T} + CT \quad (6)$$

Where η is the dynamic viscosity in Pa, s and T is the temperature in Kelvin. A, B, C and D are constants[2,26-29].

Polynomial formulas were also proposed to describe the variation of dynamic viscosity with temperature. These are represented in the following equations:

$$Ln\eta = A + \frac{B}{T} + CT + DT^{2} \quad (7)$$

$$\eta = A + BT + CT^{2} + DT^{3} \quad (8)$$

Where η is the dynamic viscosity in Pa, s in Eq.(8) and in cP in Eq.(7). T is the temperature in Kelvin. A, B, C and D are constants[30,8].

METHODOLOGY

Experimental apparatus

Two models of viscometer of different ranges were used to measure the viscosity of olive oils samples: A Brookfield Viscometer Model DV-I+ with accuracy $\pm$ 1% was used to measure the dynamic viscosity of coconut oil. YULA-15Z was operated at 100, 60, 50, 30 rpm.

Digital Prima Long Thermometer with accuracy 1% was used to measure the temperature. It has temperature range from –20°C up to +100°C. The temperature is controlled by using the Refrigerated and Heating CirculatorsF25-HD.

Statistical analysis

The dependence of dynamic viscosity and shear stress of coconut oil on temperature were analyzed by proposing some empirical relations. Microsoft Excel Program was used to make statistical analysis to our experimental data. The correlation constants for the best fit was estimated. Average absolute deviation (%AAD) of the data was calculated to select the best fit equation[22].

RESULTS, ANALYSIS AND DISCUSSION

The dependence of shear stress on shear rate

Power law model $\tau = k\,\gamma^{n}$ was used to fit our experimental data of shear stress of coconut oil as a function of shear rate. TABLE 1 shows the values of flow index (n) and the consistency coefficient (K). According to power law model, if the flow index (n) of a liquid is one, then it is Newtonian and if the value of flow index deviates from one then it shows the Non-Newtonian behavior. Coconut oil has flow index value close to one in the temperature ranged from 22 to 32 ÚC as shown in TABLE1. Our experimental data and our fitting curve using power law model of shear stress of coconut oil as a function of shear rate are plotted in Figure 1.

Giap and Akhtar obtained the flow index to be 0.9 at 25ÚC and 0.93 at 50ÚC, respectively. Giap and Akhtar obtained the behavior of coconut oil to be Non-Newtonian behavior-shear thinning (Pseudoplastic). Our calculated value of flow index is ranged from 1.17 to 1.3. This value is in disagreement with the previous values of Giap and Akhtar which indicates that coconut oil is a Non-Newtonian fluid-shear thickening (dilatent)[11,23].

TABLE 1 : Our values of flow index (n) and the consistency coefficient (K) using power law model

T (ºC)	K	n
22	0.05	1.17
24	0.04	1.19
26	0.04	1.22
28	0.03	1.25
30	0.03	1.27
32	0.03	1.30

The dependence of dynamic viscosity on temperature

Figure 2 shows the dynamic viscosity of coconut oil as a function of temperature. The measured experimental data of dynamic viscosity (η_{exp}) and the previously calculated values (η_{cal}) were compared.

The calculated values found by three-constant formula of Andrade's. Where A, B and C are constants for coconut oil (TABLE 2). Using Andrade's formula, the AAD% value was found by this work to be 95.95%. For instance, the calculated value of dynamic viscosity at 30°C was found to be 1.24cP[23]. Our measured experimental value of dynamic viscosity at 30°C (28.90cP) shows significant difference between our result and the literature

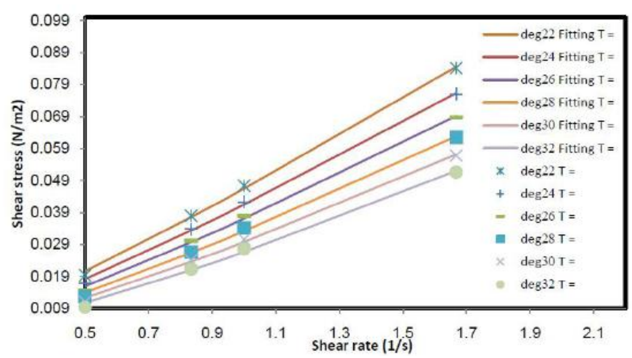

Figure 1: The shear stress of coconut oil as function of shear rate. The solid lines are representing power law model and the points are representing our experimental data

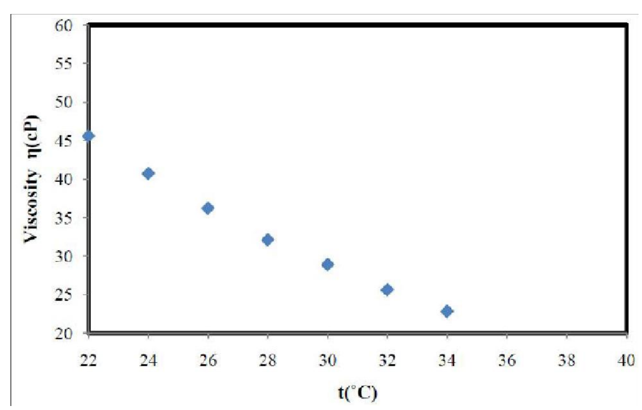

Figure 2: The measured values of the dynamic viscosity of coconut oil as a function of temperature

TABLE 2 : The constants given by Neelamegam using Andrade's formula

A	B	C	Temperature range (K)
-1.1211	11.0850	-0.0185	303 – 363

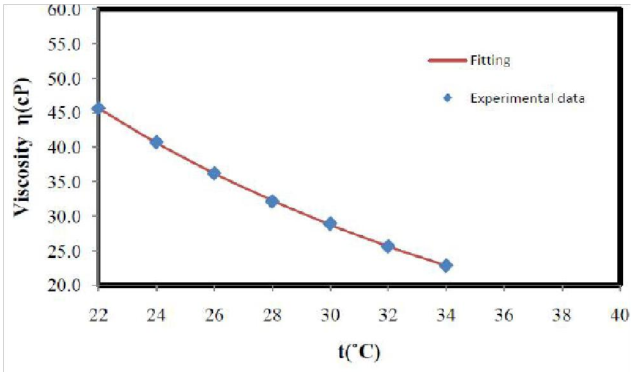

Figure 3: The dynamic viscosity ofcoconut oil as function of temperature. The solid lines are representing our modified Andrade's formula and the points are representing our experimental data

TABLE 3 :Our values of A, B and AAD% using the modified Andrade's formula of coiloconut

A	B (K)	C (K^2)	Temp. Range (K)	AAD%
13.86508	11.18442	- 0.05760	295 - 307	0.0015

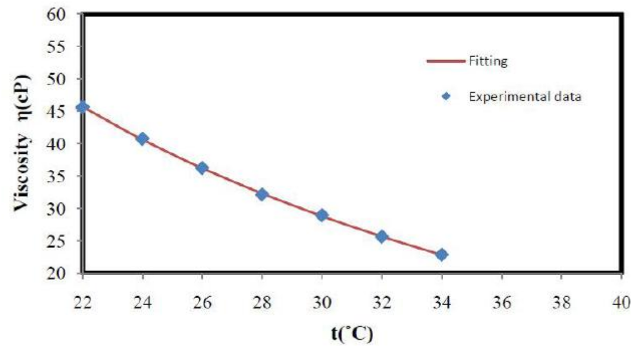

Figure 4: The dynamic viscosity ofcoconut oil as function of temperature. The solid lines are representing our proposed multi-constant formula and the points are representing our experimental data

value. It was found that the literature values didn't fit our experimental data. As a result, Andrade's formula was not the best fit for our experimental data of dynamic viscosity of coconut oil. Accordingly, Andrade's formula was modified in order to obtain a suitable description of our experimental data of dynamic viscosity as a function of temperature. The constants of Andrade's formula were determined using the modification form. Our experimental values ($ç_{exp}$) and calculated values ($ç_{cal}$), using the modified form of Andrade's formula of dynamic viscosities at different temperatures were compared. The AAD% is calculated by using the modified form of Andrade's formula to be0.0015%. The calculated dynamic viscosity using the modified form of Andrade's formula at 30°C was found to be 28.74cP, which indicates that Andrade's modified formula fits our experimental data. This result indicates that the modified form of Andrade's formula fits our experimental data. TABLE 3 gives the values of the constants of the modified form of Andrade's formula. These values are in disagreement with Neelamegam's values (TABLE 2)[26]. Our experimental data and our fitting curves using our modified Andrade's formula of dynamic viscosity of coconut oil as a function of temperature are shown in Figure 3.

This work proposed multi-constant formula to obtain proper prediction of temperature dependence of dynamic viscosity of coconut oil. The η_{exp} and η_{cal} were used to propose the formulas that fit our experimental data. The proper prediction is selected by using AAD% value.

Our proposed formula of multi-constant is found to be which fits our experimental data of dynamic viscosity. Our calculated values of A, B, C, D, E and AAD% of the data, are tabulated in TABLE 4. Figure 4 shows our experimental data and our fitting curves using our proposed multi-constant formula of dynamic viscosity of coconut oil as a function of temperature.

This work obtained the dynamic viscosity of coconut oil to be 28.90cP at 30°C. Neelamegam measured the dynamic viscosity of coconut oil to be 28.77cP at 30°C[26]. Our value of dynamic viscosity of coconut oil at 30°Cis in good agreement with Neelamegam's value.

The dependence of shear stress on temperature

TABLE 4 : Our values of A, B, C, D, E and AAD% using our proposed multi-constants formula

A (cP)	B (cP.°C)	C (cP)	D ($cP/°C^E$)	E	Temp Range (°C)	AAD%
75.88200	829.02260	-21.97239	7.96680	-4.17787	22 - 34	0.0000

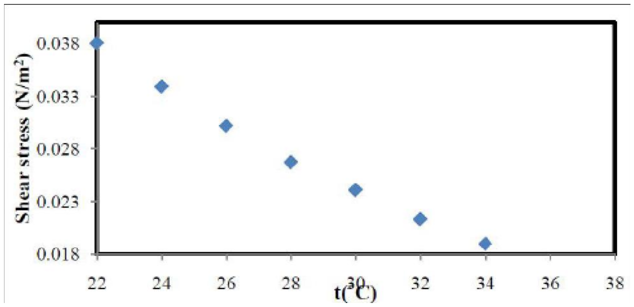

Figure 5: The measured values of shear stress of coconut oil as a function of temperature at 50 rpm

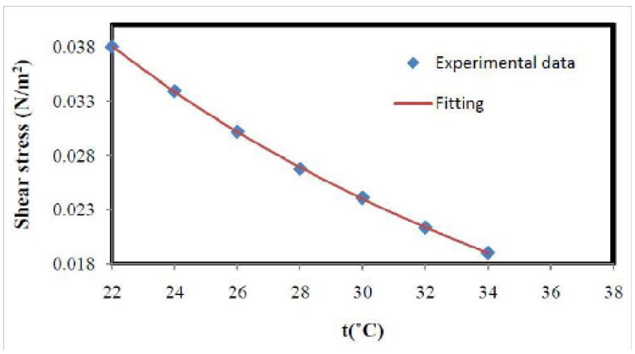

Figure 7: The shear stress of coconut oil as a function of temperature. The solid lines are representing Eq. 10 of three-constant formula and the points are representing our experimental data

Our experimental data of shear stress of coconut oil as a function of temperature at 50rpm is plotted in Figure 5. Three and multi-constant formulas were proposed in this study to describe the effect of temperature on the shear stress of coconut oil. The τ_{exp} and τ_{cal} were used to propose the formulas that fit our experimental data. The proper prediction is selected by using AAD% values. Our three and multi-constant formulas were used to fit our experimental values of the shear stress of coconut oil, which are:

$$\ln \tau = A - \frac{B}{C + T} \quad \textbf{(9)}$$

$$\tau = \frac{A + B t^{C}}{D} \quad \textbf{(10)}$$

$$Log\, \tau = A + \frac{B}{(C + T)^{D}} \quad \textbf{(11)}$$

Where τ is shear stress (N/m^2), T is the temperature in Kelvin, t is the temperature in degrees Celsius. TABLE 5 shows our calculated values of A, B, C, D, AAD%.AAD% values of three and

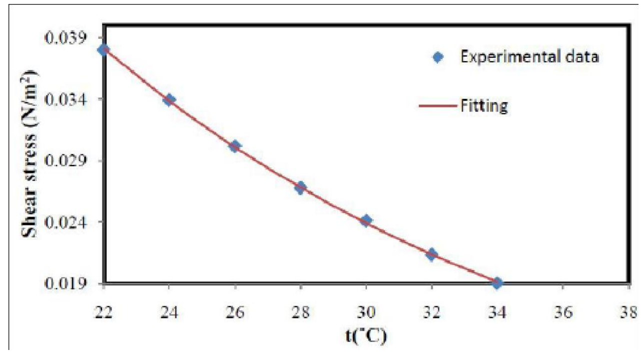

Figure 6: The shear stress of coconut oil as a function of temperature. The solid lines are representing Eq. 9 of three-constant formula and the points are representing our experimental data

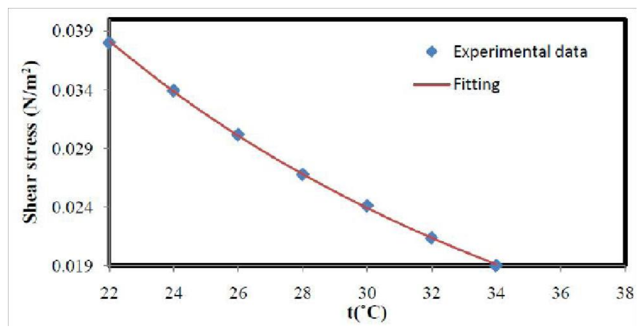

Figure 8: The shear stress of coconut oil as a function of temperature. The solid lines are representing Eq. 11 our proposed multi-constant formula and the points are representing our experimental data

multi-constant formulas are tabulated in TABLE 5 to be 0.0003%using (Eq.9) 0.0007% using (Eq. 10) and 0.0019%using (Eq.11). Accordingly, our proposed three and multi-constant formulas are suitable to describe the dependence of shear stress of coconut oil as a function of temperature. Our experimental data and our fitting curves using our proposed three and multi-constant formulas of shear stress of coconut oil as function of temperature are plotted in Figure 6, 7 and 8.

CONCLUSIONS

The behavior of coconut oil was investigated by this work at the temperature range from 22 to 32°C to be Non-Newtonian-shear thickening (dilatent). A comparison was made by this work between the measured experimental data of dynamic viscosity and the previously calculated values. The calculated values are found by using the three-constant formula

TABLE 5 : Our values of A, B, C, D and AAD% using our proposed three and multi-constants formula

The formula	A	B	C	D	Temp Range	AAD%
Eq. 9	-20.94655	-5215.61905 K	0.005852 K		295 - 307K	0.0003
Eq. 10	-2.79965 N/m^2	31.01058	-0.58512($(N/m^2)/°C^C$)	60	22 - 34°C	0.0007
Eq. 11	-20.93759	$72.1671K^D$	0.08440K	72.25299	295 - 307K	0.0019

of $\mathrm{Ln}\eta = A + \frac{B}{T} + CT$ Andrade's. A, B and C are constants for coconut oil[26]. It was found that the literature values[26] didn't fit our experimental data. Accordingly, a modification was introduced to Andrade's formula in order to obtain a suitable description of our experimental data of dynamic viscosity as a function of temperature. The results indicate that Andrade's modified formula fits our experimental data. Another formula of multi - constant form ($\eta = A + \frac{B}{t} + C\mathrm{Ln}(t) + Dt^E$) is proposed to obtain another suitable prediction of temperature dependence of dynamic viscosity of coconut oil. The constants of our proposed formula were estimated to give the best fit.

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