Temperature Effect on the Viscosities of Palm Oil and Coconut Oil Blended with Diesel Oil

C. Tangsathitkulchai[a],*, Y. Sittichaitaweekul[a], and M. Tangsathitkulchai[b]

School of [a]Chemical Engineering and [b]Chemistry, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand

ABSTRACT: One of the major difficulties in using crude vegetable oils as substitute fuels in diesel engines is their relatively high viscosities. Increasing the temperature of the crude vegetable oil, blending it with diesel oil, or the combination of both offers a simple and effective means of controlling and lowering the viscosities of vegetable oils. This work reports viscosity data, determined with a rotational bob-and-cup viscometer, for crude palm oil and coconut oil blended with diesel oil over the temperature range of 20–80°C and for different mixture compositions. All the test oil samples showed a time-independent Newtonian type of flow behavior. The reduction of viscosity with increasing liquid temperature followed an exponential relationship, with the two constants of the equation being a function of the volume percentage of the vegetable oil in the mixture. A single empirical equation was developed for predicting the viscosity of these fuel mixtures under varying temperatures and blend compositions.

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KEY WORDS: Coconut oil, diesel oil, palm oil, viscosity.

The instability of the price and supply of petroleum-based fuels has revived the search for alternative sources of energy. The use of vegetable oils in diesel engines, either in crude form or as their derived esters, has received increasing attention (1–5). Among the advantages of vegetable oils as alternative fuels are that they are nontoxic, they are safely stored and handled because of their high flash point, they are renewable energy sources, and they have net zero CO_2 emission and negligible SO_2 generation. In addition, vegetable oils could be used as supplementary fuels during periods of energy crisis and shortage. However, the direct use of neat vegetable oils in diesel engines without pretreatment or engine modification causes serious engine problems (6–8). Notably, the high viscosity of vegetable oil causes poor atomization, resulting in incomplete combustion of the fuel, formation of coke deposits around the injection nozzles, accumulation of gum materials inside the combustion chamber and cylinders, and contamination of lubricating oil from unburned residues.

The most obvious and simplest ways to lower the viscosity of vegetable oil are by increasing its temperature and/or by blending it with diesel oil in appropriate proportions. In Thailand, coconut oil and palm oil are the two most available vegetable oils that can be used as substitute fuels in internal-combustion engines. Approximately 5×10^4 and 8×10^5 metric tons per year of coconut oil and palm oil, respectively, are produced (9,10). Viscosity data on various blend compositions and over a temperature range are needed so that these vegetable oils can be used efficiently in diesel engines.

This work describes the measurement of the viscosities of coconut oil, palm oil, and their blends with diesel oil as a function of temperature and blend composition. Empirical equations for predicting the viscosities of the test oils also are presented.

EXPERIMENTAL PROCEDURES

The viscosities of crude palm oil (CPO), crude coconut oil, and blends of the two with automotive diesel oil were measured with a calibrated rotational bob-and-cup viscometer (Viscotester VT 550; Haake, Karlsruhe, Germany); the bob (inner cylinder) and cup (outer cylinder) are of a double-gap cylinder type, designated as an NV system by the manufacturer. The effect of temperature on the viscosity was studied over the 20–80°C range by circulating thermostated water through the jacket of the viscometer. Viscosities of some of the oil samples were also confirmed with a glass capillary viscometer (Cannon-Fenske, ASTM D 445) and a falling-ball viscometer (Haake). Chemical analysis of the vegetable oils was performed by hydrolysis and conversion of the FA to their FAME (11). Important fuel properties based on ASTM standards, including specific gravity (D 1298), flash point (D 93), heating value (D 240), viscosity (D 445), vapor pressure (D 323), and cetane index (D 976), were also determined (12).

RESULTS AND DISCUSSION

Table 1 shows the chemical composition of the vegetable oils tested, analyzed as FAME and presented as weight percentages of the corresponding FA contents. CPO consists of about 50% saturated fat (palmitic acid) and 50% unsaturated fat (mainly oleic acid), whereas coconut oil contains about 90% saturated FA, of which 70% are lauric and myristic acids. Table 2 shows fuel properties of the two vegetable oils, compared with those of diesel oil, analyzed according to the ASTM standard method. In general, the fuel properties of palm oil and coconut oil are similar to those of diesel oil, except that the flash point and viscosity are much higher. At 40°C, the kinematic viscosities of CPO and coconut oil are greater than that of diesel oil by a factor of 12

*To whom correspondence should be addressed at School of Chemical Engineering, Institute of Engineering, Suranaree University of Technology, Muang District, Nakhon Ratchasima 30000, Thailand.
E-mail: chaiyot@ccs.sut.ac.th

TABLE 1
FA Compositions of Palm Oil and Coconut Oil (as wt%)

FA	C atom:double bond[a]	Crude palm oil	Crude coconut oil
Caprylic	8:0	0.3	6.4
Capric	10:0	—	5.4
Lauric	12:0	—	47.9
Myristic	14:0	1.1	19.7
Palmitic	16:0	45.8	9.7
Palmitoleic	16:1n-7	0.2	—
Stearic	18:0	3.9	2.7
Oleic	18:1n-9	39.0	6.6
Linoleic	18:2n-6	9.1	1.6
α-Linolenic	18:3n-3	0.3	—
Arachidic	20:0	0.3	—
% Saturated fat		51.4	91.8
% Unsaturated fat		48.6	8.2

[a]Number of carbon atoms in the FA, related to the position of the double bond (0–3) in the FA.

and 9, respectively. At 100°C, these factors diminish to 6.8 and 5.7, respectively.

Figure 1 shows a typical relationship between shear stress and the rate of shear for the test oils at various temperatures. Clearly, the two vegetable oils and diesel oil exhibit Newtonian flow behavior; i.e., the laminar viscosity, being the slope of the straight line, is independent of the rate at which the liquid is sheared. Also, the rheology of the oil samples was found to be time-dependent. That is, the shear stress was unchanged irrespective of the time of shearing action. Viscosities of some of the test oils were independently checked with a capillary viscometer and a falling-ball viscometer. The values determined by these three methods (rotational, capillary, and falling ball) differed by less than 5%.

Figure 2 shows the effect of temperature on the viscosities of palm oil and coconut oil blended with diesel oil at various volume percentages. It can be seen that viscosity decreases nonlinearly with increasing temperature. This behavior can be examined further by referring to Table 3, which shows the fractional decrease in viscosities for the oil mixtures over the 20–45°C range. For palm oil mixtures, 100% CPO shows the greatest reduction in viscosity, and this reduction diminishes as the volume percentage of palm oil decreases. For the same mixture composition, the fractional decrease in viscosity of the coconut oil mixtures is comparable to that of palm oil mixtures, except for crude (100%) coconut oil, which has a

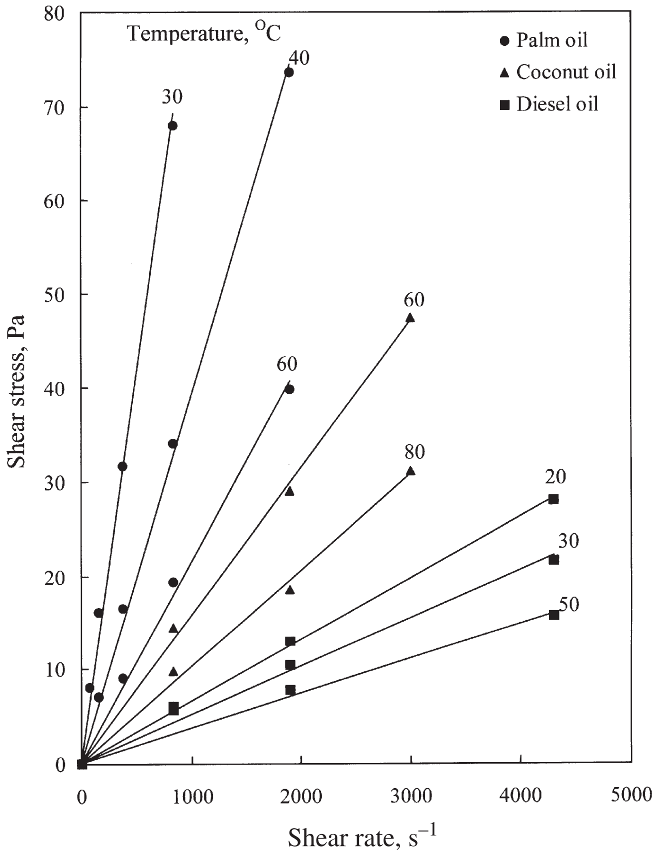

FIG. 1. Rheological curves of crude palm oil, coconut oil, and diesel oil at various temperatures.

fractional decrease in viscosity about 35% less than the crude palm oil. The difference could be attributed to the fact that at temperatures below 45°C, part of the CPO exists as solid fat particles that disperse in the liquid oil phase. An increase in temperature from 20–45°C not only decreases the viscosity of the clear liquid phase but also helps to dissolve the fat particles, thus further lowering the viscosity of the oil suspension by decreasing the amount of suspended fat particles, which increase the viscosity of a mixture. This is in contrast with the crude coconut oil, which is present as a clear liquid over the same temperature range.

Two types of empirical equations are often used to describe the relation between viscosity (μ) and temperature (*T*) (13,14):

TABLE 2
Some Fuel Properties of Palm Oil, Coconut Oil, and Diesel Oil Measured According to ASTM standards

Fuel property	ASTM	Palm oil	Coconut oil	Diesel oil
Density (15.5°C), g/cm^3	D 1298	0.908	0.915	0.832
Flash point, °C	D 93	260	200	70
Gross heating value, kJ/kg	D 240	37,600	40,500	45,000
Kinematic viscosity	D 445			
At 40°C, mm^2/s		36.0	27.4	3.01
At 100°C, mm^2/s		8.14	6.91	1.20
Reid vapor pressure (37.8°C), bar	D 323	0.03	0.027	0.065
Cetane index	D 976	42	35	53

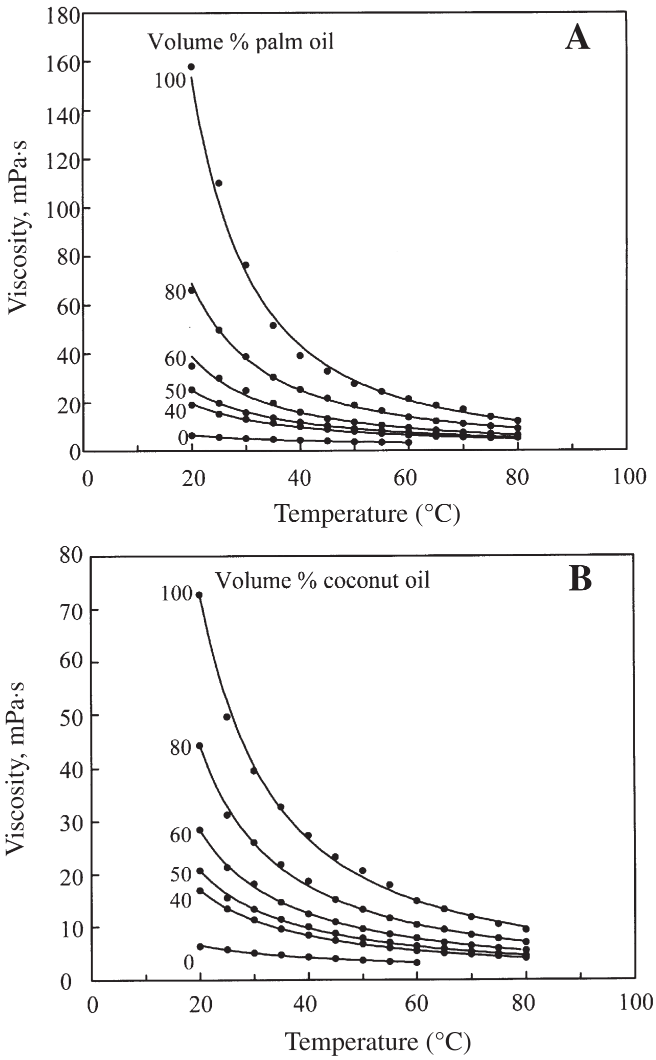

FIG. 2. Effects of temperature and composition on the viscosity of vegetable oil/diesel mixtures: (A) palm oil, (B) coconut oil.

$$\ln \mu = A + \frac{B}{T} \quad [1]$$

and

$$\ln \mu = A + \frac{B}{T + C} \quad [2]$$

where A, B, and C are constants of the equations. However, the viscosity data of vegetable oil–diesel mixtures obtained in this work were best fitted by a simple exponential equation:

$$\mu = aT^b \quad [3]$$

where μ is in mPa·s and T is in °C. Figure 3 shows plots of viscosity vs. temperature for palm oil and coconut oil blends on a log–log scale according to Equation 3. The values of constants a and b as determined by linear regression analysis are given in Table 4 for palm oil/diesel and coconut oil/diesel mixtures, respectively.

In Figure 3 the viscosity curves converge to a common point, designated here as a coordinate (μ^*, T^*). By applying

TABLE 3
Fractional Decrease in Viscosities of Vegetable Oil/Diesel Mixtures over the 20–45°C Temperature Range

Palm oil/diesel oil		Coconut oil/diesel oil	
Palm oil (vol%)	Fractional decrease in viscosity	Coconut oil (vol%)	Fractional decrease in viscosity
100	4.8	100	3.1
80	3.1	80	3.0
60	2.6	60	2.6
50	2.4	50	2.5
40	2.1	40	2.3

Equation 3 to this point, one obtains

$$\mu^* = a(T^*)^b \quad [4]$$

Eliminating the constant a from Equations 3 and 4 gives

$$\frac{\mu}{\mu^*} = \left(\frac{T}{T^*}\right)^b \quad [5]$$

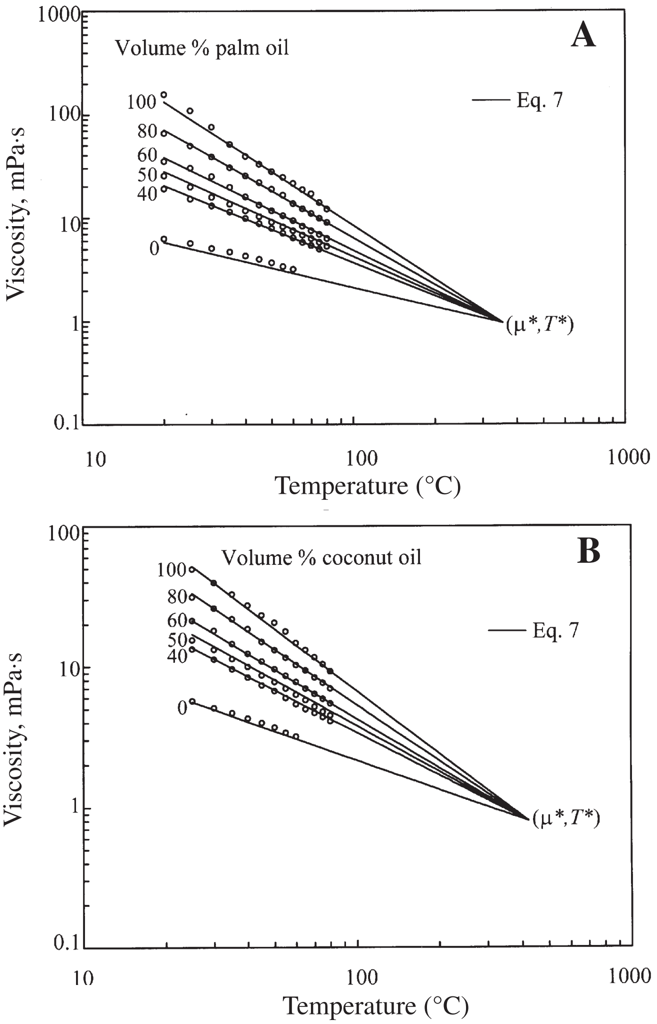

FIG. 3. Linear correlation between viscosity and temperature on a log–log scale: (A) palm oil/diesel mixtures, (B) coconut oil/diesel mixtures.

TABLE 4
Values of Constants in the Viscosity Correlation (Eq. 3) for Vegetable Oil/Diesel Mixtures

	Constant *a*		Constant *b*		Regression coefficient	
Vegetable oil (vol%)	Palm oil	Coconut oil	Palm oil	Coconut oil	Palm oil	Coconut oil
0	41.9	41.9	–0.62	–0.62	0.992	0.992
40	406	368	–1.01	–1.03	0.997	0.998
50	713	536	–1.12	–1.09	0.999	0.997
60	1,933	987	–1.30	–1.18	0.994	0.999
80	5,325	2,306	–1.45	–1.32	0.998	0.997
100	35,863	5,539	–1.82	–1.45	0.995	0.994

TABLE 5
Values of Constants in the Viscosity Equation: $(\mu/\mu^*) = (T/T^*)^{a'V+b'}$

Vegetable oil	μ* (m Pa·s)	*T** (°C)	*a′*	*b′*	SSQR[a]	SE of estimate (%)
Palm oil	0.97	354	–0.011	–0.62	0.0631	3.1
Coconut oil	0.80	422	–0.008	–0.69	0.1054	4.4

[a]Sum of square of relative error.

where b is a function of the vegetable oil composition, as shown in Table 4, which can be represented by a linear expression

$$b = a'V + b' \quad [6]$$

where a' and b' are constants and V is the volume percentage of vegetable oil in the oil mixtures. Combining Equations 5 and 6 gives the final proposed correlation for predicting the viscosities of vegetable oil/diesel mixtures:

$$\frac{\mu}{\mu^*} = \left(\frac{T}{T^*}\right)^{a'V+b'} \quad [7]$$

A total of 73 and 69 data points for palm oil and coconut oil mixtures, respectively, were fitted to the final form of Equation 7, using nonlinear regression analysis based on the minimization of the sum of square of relative error (SSQR), defined as: $\Sigma[(\mu_{i,\text{meas}} - \mu_{i,\text{pred}})/\mu_{i,\text{meas}}]^2$. Figure 3 shows the fitting results. Table 5 shows the values of equation constants derived from such curve fitting, with μ*, *T**, and *V* having the units of mPa·s, °C, and volume percentage of vegetable oil, respectively. The overall SE of estimates were determined to be 3.1 and 4.4% for the palm oil and coconut oil blends, respectively, using the formula: $S = [\text{SSQR}/(n-2)]^{1/2}$, where n is the number of data points. The comparison between the measured and predicted viscosities of the oil mixtures is given in Figure 4. The random distribution of the points about the 45° line indicates the justification of the developed correlation, with 97% of the data being within ±10% of the predicted value.

The validity of the proposed equation was further checked by comparing the viscosity values of coconut oil and palm oil from the works of Noureddini *et al.* (14) and Bari *et al.* (5), respectively, with those predicted by Equation 7. Table 6 shows the results. In general, the viscosity values at various temperatures agree reasonably well, but Equation 7 tends to overestimate the results somewhat for most of the temperatures. It is believed that Equation 7 can be used to estimate the viscosity of oil mixtures for temperatures greater than 80°C, as long as there are no changes in the chemical structures and compositions of the vegetable oil due to the effect of overheating. Equation 7 can be used to determine the temperature required for heating a given composition of a vegetable oil/diesel mixture to yield the desired viscosity. For example, to lower the viscosity of CPO to that of diesel oil (4.3 mPa·s at 40°C), it would be necessary to heat palm oil to about 148°C. If this temperature is too high, a blend of 30 vol% palm oil may be used, reducing the required temperature to 74°C. For the purpose of using crude vegetable oil as a substitute diesel engine fuel, the judicious use of both heating and blending techniques can provide an effective means for controlling the proper viscosity.

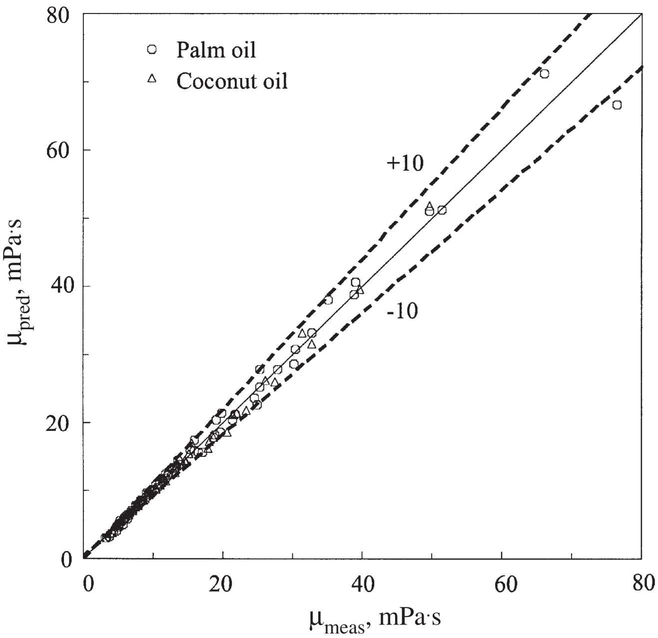

FIG. 4. Comparison of measured and predicted viscosities of vegetable oil/diesel mixtures.

TABLE 6
Validity of the Proposed Viscosity Equation

Temperature (°C)	Viscosity, mPa·s			
	Coconut oil		Palm oil	
	Noureddini *et al.* (14)	Equation 7	Bari *et al.* (5)	Equation 7
30	—	—	56.0	66.0
37.8	28.0	29.1	—	—
40	—	—	38.0	40.3
48.9	19.8	19.8	—	—
50	—	—	27.1	27.5
60	13.3	14.2	20.1	20.1
70	—	—	14.5	15.4
80	—	—	11.5	12.3
82.2	7.6	9.1	—	—
90	—	—	8.6	10.2
95	—	—	7.1	9.3
100	5.2	6.8	—	—
110	4.4	5.9	—	—

To ensure the possible smooth running of the engine, however, important fuel properties such as heating value, vapor pressure, flash point, density, and cetane number must also be ascertained.

Recently, de Almeida *et al.* (15), who ran a direct injection four-stroke 70 kW diesel generator with 100% palm oil, reported that by increasing the palm oil admission temperature to 100°C, it was possible to operate the engine up to 300 h with acceptable combustion performance and fewer problems with deposit formation. Based on this maximum admission temperature of 100°C, the maximum allowable viscosity of crude palm oil as predicted by Equation 7 is 8.5 mPa·s. Alternatively, without preheating and by assuming that the fuel temperature is at 40°C, the maximal blend level that gives the acceptable viscosity of 8.5 mPa·s can be estimated from Equation 7 to be 34 vol% of palm oil in the mixture.

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