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Measurement and Prediction of Density and Viscosity of Different Diesel-Vegetable Oil Binary Blends

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Abstract **– Vegetable oils can be considered as an alternative or emergency fuel for diesel engine. However, vegetable oils result in operational and durability problems for the long-term operation because of being much more viscous than diesel fuel. To eliminate this drawback, blending of vegetable oils with diesel fuel or alcohol is one of the most widely used techniques. In the existing literature, many studies are available on the measurement and prediction of density and viscosity of binary blends (especially biodiesel (BD)-diesel fuel (DF) blends), although, there is still the lack of comprehensive studies in which reliable density and viscosity data are presented, new regression models are proposed and compared with other regression models for waste cooking oil (WCO)-DF binary blends. Therefore, in the present study, (1) WCO was blended with DF on the volume basis of 2, 4, 6, 8, 10, 15 and 20 %, (2) the measurements of viscosities and densities of the binary blends were performed at various temperatures (278.15–343.15 K) in accordance with DIN 53015 and ISO 4787 standards, respectively, (3) the variations of viscosity and density values of binary blends vs. temperature were evaluated, (4) the new rational and exponential models as a function of temperature were fitted to the experimental data measured by the authors and Baroutian et al. (regarded as typically different data), and finally (5) the models were also compared to Yoon et al. and linear models, previously proposed by other authors, in order to investigate their reliability. According to results, (i) the best correlation was obtained by the rational model with the lowest maximum relative errors of 2.9679 % and 3.2725 % for the viscosity data measured by the authors (WCO-DF blends) and Baroutian et al. (palm oil (PO)-DF blends), and (ii) for the density data of WCO-DF and PO-DF binary blends, the best correlation was obtained using the exponential model giving the lowest maximum relative errors of 0.0470 % and 0.0581 %, respectively.**

Keywords **– Density; diesel fuel; exponential model; prediction; rational model; renewable energy; vegetable oil; viscosity**

1. INTRODUCTION

Due to the gradual depletion of world petroleum reserves, rapidly increasing their prices and growing concern about effects of exhaust emissions released from petroleum products on environmental and human health, alternative fuels have become an important need during the last decades [1]–[3]. In this sense, vegetable oils can be considered a promising renewable alternative fuel for diesel engines because of their several technical benefits such as: (1) higher flash point, lubricity and biodegradability [4]–[6], (2) non-toxicity, sulphur and aromatic contents [7], (3) ready availability [8], (4) renewability [8] and (5) liquid nature-portability [9]. Thus, many studies on using vegetable oils in diesel engines have been conducted by several researchers [10]–[12]. However, vegetable oils also have some

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shortcomings such as: (1) higher viscosity (about 10–20 times higher than DF) because of higher molecular weight and branched chemical structure, (2) poor cold flow properties, (3) lower volatility and (4) reactivity of unsaturated hydrocarbon chains [13]–[16]. These shortcomings mainly bring about operational and durability problems during direct or in-direct diesel engine tests for especially long-term operations [17]–[19]. Among these shortcomings, high viscosity causes poor fuel atomization resulting in larger droplet size, decreasing air-fuel mixing quality and incomplete combustion accompanied by decreasing engine performance and increasing exhaust emissions especially CO, HC and smoke [20]–[22]. Some techniques can be applied to vegetable oils to overcome the high viscosity problem such as: heating, blending with other fuels (diesel or alcohols), transesterification (i.e. converting to BD), thermal cracking, emulsification, etc. [23], [24]. Among these techniques, blending is one of the most practical techniques for reducing viscosity. In other words, in the existing literature, there are many studies on the measurement and prediction of densities or viscosities of BD-DF or BD-DF-alcohol blends by means of different regression models or approaches [21], [22], [25]–[30], nevertheless, few studies are available on the measurement and prediction of density and viscosity of WCO-DF blends using new regression correlation. Therefore, in order to eliminate the lack of such studies, in this study, (i) WCO was blended with DF at the volume ratios of 2, 4, 6, 8, 10, 15 and 20 %. The resulting binary blends were named to reflect their composition. For example, the name O2 indicates a blend consisting of 2 % WCO-98 % DF. Similar naming (O4, O6, O8, O10, O15 and O20) and fractions are also valid for the binary blends. (ii) The measurements of densities and viscosities of the WCO-DF binary blends were performed at various temperatures (278.15–343.15 K) according to the related standards. (iii) Effects of temperature on densities and viscosities of the binary blends were evaluated, and finally (iv) new regression correlations such as rational and exponential models for predicting the fuel properties were also proposed by comparing well-known models (Yoon et al. model and linear model) previously published in the existing literature.

2. EXPERIMENTAL STUDY

2.1. Density and Viscosity Measurements

Density measurements of the WCO-DF binary blends were performed accordingly ISO 4787 standard by means of a pycnometer and top loading balance (±0.01 g). Dynamic viscosities of the blends were also determined according to DIN 53015 standard using Haake Falling Ball Viscometer, Haake Water Bath, a stopwatch (±0.01 s) and thermometer (±0.5 °C). The equations used to determine densities and viscosities were given as:

$$\rho_{\text{blends}} = \frac{m_{\text{total}} - m_{\text{pycnometer}}}{m_{\text{water}}} \rho_{\text{water}}, \quad (1)$$

$$\mu_{\text{blends}} = K_{\text{ball}}(\rho_{\text{ball}} - \rho_{\text{blends}})t, \quad (2)$$

where ρ, m, μ, K_{ball} and t are density, mass, dynamic viscosity, the coefficient of the viscometer ball and falling time of the ball moving between two horizontal lines marked on viscometer tube at limit velocity, respectively.

The density and viscosity measurements were carried out three times for each sample and the results were averaged. More details can be also found the authors' previous studies [31],

[32]. As is well known, kinematic viscosities were computed by dividing dynamic viscosity to density at the same temperature. Moreover, Annex Table 1 shows some important fuel properties (viscosity, density, flash point, cold filter plug point, average molecular mass, typical formula and higher heating value) of DF used to prepare the binary mixtures.

2.2. Uncertainty Analysis

In this study, the highest uncertainty of 0.4517 % was computed for all the targeted results (i.e. density and viscosity), using a method of Kline and McClintock [33], shows that the measurements are extremely reliable. In addition, an example calculation for uncertainty analysis was found in the authors' previous study [22].

3. RESULTS AND DISCUSSION

3.1. Change of Viscosity

The variations in kinematic viscosities of WCO-DF binary blends (O2, O4, O6, O8, O10, O15 and O20) measured by the authors versus temperature are illustrated in Fig. 1 where points and lines show the measurement points and calculated values. The viscosity data were correlated to temperature using rational model (Eq. (3)) previously suggested by the authors [21], [30] and Yoon et al. model (Eq. (4)) [34]. These models were formulated as:

$$\nu_{\text{blend}} = \frac{a+T}{b+c\cdot T}, \tag{3}$$

$$\nu_{\text{blend}} = a \cdot \exp\left(-\frac{T}{b}\right) + c, \tag{4}$$

where T is the temperature of binary blends in K or °C, and a, b and c are regression constants.

Viscosity values non-linearly decrease with increasing temperature. It can be seen that the rational and Vogel et al. models successfully represent the viscosity variation vs. temperature throughout all studied temperature in terms of qualitative behavior. In other words, the calculated values from the rational and Vogel et al. models are close to the measurements. Annex Table 2 lists kinematic viscosity data of the binary blends measured by the authors, percent relative errors between measured data and calculated values from Eq. (3) and Eq. (4), and regression constants and correlation coefficients (R) of these models. The maximum relative errors coming from Eq. (3) and Eq. (4) were computed as 2.9679 % and 5.2585 % with the minimum R values of 0.9994 and 0.9991, respectively. These results show that the rational model (Eq. (3)) developed to describe the variation in viscosity as a function of temperature shows an excellent agreement with the experimental kinematic viscosity data in terms of quantitative behavior.

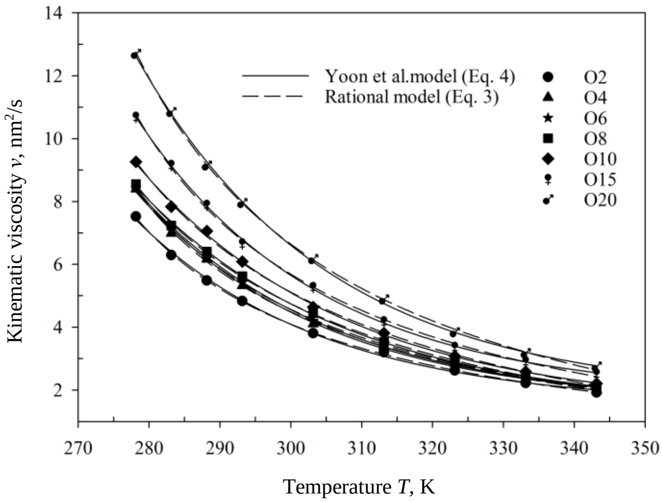

Fig. 1. Changes of kinematic viscosities of O2–O20 with respect to temperature.

The validity of the rational and Yoon et al. models for predicting viscosity was also investigated using data of PO-DF binary blends (PO5, PO10, PO15 and PO20) measured by Baroutian et al. [35] at various temperatures (20–90 °C), as shown in Fig. 2. Baroutian et al. [35] prepared their binary blends on volume basis. The viscosity variation of PO-DF binary blends with temperature shows also non-linear behavior. The relation between viscosity and temperature is found to be well expressed by the rational and Vogel et al. models for all studied temperatures. The dynamic viscosity data of PO-DF binary blends measured by Baroutian et al. [35], percent relative errors and regression parameters of models are given in Annex Table 3. The maximum relative errors between the measured and calculated values from Eq. (3) and Eq. (4) were obtained as 3.2725 % and 3.5801 % while the minimum R values were obtained as 0.9994 and 0.9992, respectively, showing that the rational model also better matches to the experimental data given by Baroutian et al. [35].

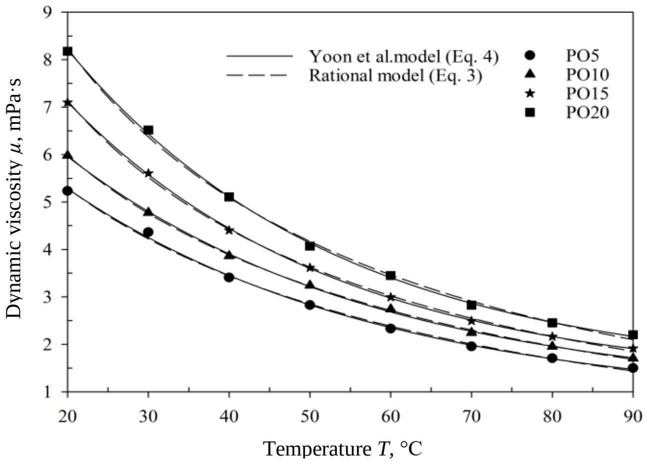

Fig. 2. Changes of dynamic viscosities of PO5–PO20 with respect to temperature.

In summary, according to the results mentioned above, the variation in viscosity with respect to temperature is found to be better represented by the rational model [21], [30] previously recommended by the authors in terms of qualitative and quantitative behaviors, and the model reliably can be used to predict viscosity of WCO-DF binary blends.

3.2. Change of Density

Fig. 3 shows the effects of temperature on changes of density of WCO-DF binary blends (O2, O4, O6, O8, O10, O15 and O20). The measured data illustrated points were correlated by means of the exponential model (Eq. (5)), previously derived by the authors [21], [29] for the various BD-DF blends, and well-known linear model (Eq. (6)) [36] such as:

$$\rho_{\text{blend}} = a \cdot e^{bT} + c \cdot e^{dT}, \tag{5}$$

$$\rho_{\text{blend}} = a + b \cdot T, \tag{6}$$

where T is temperature of blend in K or °C.

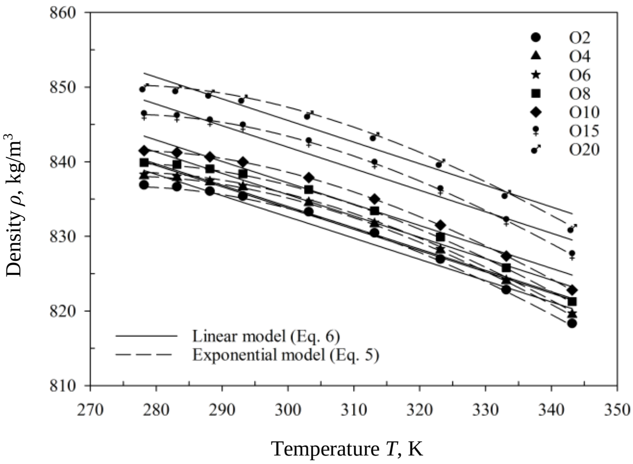

Fig. 3. Changes of densities of O2–O20 with respect to temperature.

Fig. 3 indicates that all blends have the same qualitative behavior. In other words, as temperature of blend increases density values quadratically decrease. The agreement between the measured data of the blends and the values obtained from the rational model can be seen to be perfect. Annex Table 4 shows density data for WCO-DF binary blends at various temperatures (278.15–343.15 K) measured by the authors, regression constants and correlation coefficients of models (Eq. (5) and Eq. (6)), and relative errors. The maximal differences between the measured data and the predicted densities from Eq. (5) and Eq. (6) are 0.0470 % and 0.2503 % with the minimal R values of 0.9999 and 0.9781, respectively. Fig. 3, and the relative errors and R values given in Annex Table 4 show that the qualitatively and quantitatively best agreement between the estimated and experimental values by the authors for all blends is captured by the exponential model, resulting in the lowest errors with meaningful variations, followed by the linear model.

In order to research reliability of the models, the density data of PO-DF binary blends (PO5, PO10, PO15, PO20 and PO30) measured at different temperatures (15, 30, 45, 60, 75 and 90 °C) by Baroutian et al. [35] were also fitted by means of the exponential and linear models, as shown in Fig. 4. The experimental data indicate that the binary blends show the similar temperature-dependent behavior. In other words, density values about linearly diminish with temperature. The rational and linear models accurately and fairly reflect the temperature-dependent behavior. Annex Table 5 lists the measured density values given by Baroutian et al. [35], regression parameters of Eq. (5) and Eq. (6) and percent relative errors. The maximum relative errors coming from the exponential and linear models were determined as 0.0581 % and 0.1021 %, while the minimum *R* values were computed as 0.9998 and 0.9995, respectively. According to these results, the exponential model is determined to be the better model to reflect the effect of temperature on densities of PO-DF binary blends measured by Baroutian et al. [35].

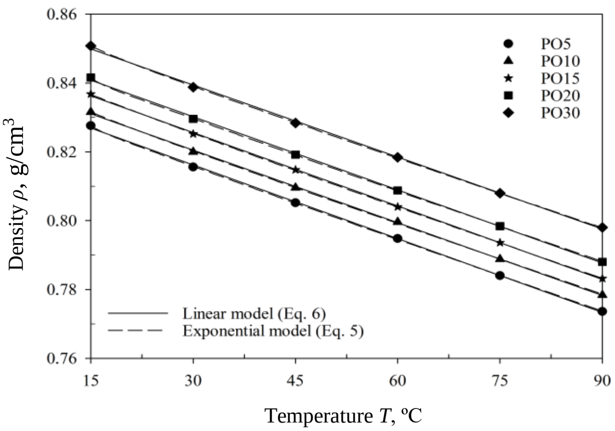

Fig. 4. Changes of densities of PO5–PO30 with respect to temperature.

Finally, Fig. 4 and regression results given in Annex Table 4 and Table 5 demonstrate that the density predictive capability of exponential model is found to be better for all temperatures, compared to the linear model previously suggested in the existing literature.

4. CONCLUSIONS

In the present study, the variations in viscosity and density values of WCO-DF binary blends versus temperature were determined. Viscosity and density measurements were performed according to DIN 53015 and ISO 4787 standards, respectively. The rational and exponential models were fitted to the viscosity and density data of WCO-DF binary blends measured by the authors and PO-DF binary blends measured by Baroutian et al. [35]. Moreover, the predictive capabilities of the models were compared to Yoon et al. model [34] and linear model [36] recommended by the other authors. The following conclusions can be drawn from this study:

– The rational model is determined to be the better predictor than Yoon et al. model [34]. The lowest maximum relative errors arising from the rational model were determined as 2.9679 % and 3.2725 % for the WCO-DF and PO-DF binary blends, compared to

Yoon et al. model [34] (5.2585 % and 3.5801 %), respectively;

- The exponential model fits the density data of WCO-DF and PO-DF binary blends so better that it produces the lowest maximum relative errors of 0.0470 % and 0.0581 %, compared to the linear model (0.2503 % and 0.1021 %), respectively;
- Shortly, the characteristics of qualitative and quantitative changes of measured density or viscosity data with respect to temperature are more similar to the mathematical structure or change characteristic of the rational and exponential models, compared to the other models (Yoon et al. model and linear model) previously suggested in the literature. Therefore, the rational and exponential models have the lowest maximum errors and the highest *R* values, mentioned above.

ANNEX

TABLE 1. SOME IMPORTANT FUEL PROPERTIES OF DIESEL FUEL

Property	Unit	Measurement standards	DF
Viscosity at 40 °C[a]	mm^2/s	DIN 53015	2.700
Density at 15 °C[a]	kg/m^3	ISO 4787	832.62
Flash Point[b]	°C	EN ISO 3679	63
CFPP[b]	°C	EN 116	–6.0
Average molecular mass	g/mol	–	169.883[c]
Typical formula	–	–	$C_{12.31}H_{21.975}$[d]
HHV[b]	kJ/kg	DIN 51900-2	45950

[a]Measured in Internal Combustion Engines Lab. at Karadeniz Technical University; [b]Measured in Prof. Dr. Saadettin GÜNER Fuel Research and Application Center at Karadeniz Technical University; [c]Calculated from typical formula; [d]Calculated from HHV and Mendeleev's formula.

TABLE 2. KINEMATIC VISCOSITY DATA OF DIESEL-WASTE COOKING OIL BINARY BLENDS MEASURED BY THE AUTHORS, RELATIVE ERRORS BETWEEN MEASURED AND CALCULATED VISCOSITIES FROM EQ. (3) AND EQ. (4), AND REGRESSION PARAMETERS FOR DIFFERENT TEMPERATURES

Temp. *T*, K	Measured *v*, mm^2/s						
	Oil Volume Fraction *X*, %						
	2	4	6	8	10	15	20
278.15	7.522	8.394	8.437	8.553	9.262	10.693	12.689
283.15	6.289	6.990	7.142	7.234	7.833	9.163	10.838
288.15	5.482	6.168	6.184	6.403	7.058	7.893	9.1360
293.15	4.830	5.320	5.422	5.618	6.087	6.665	7.9440
303.15	3.804	4.101	4.199	4.443	4.639	5.277	6.1570
313.15	3.198	3.395	3.453	3.531	3.810	4.185	4.8720
323.15	2.620	2.848	2.864	2.929	3.074	3.373	3.8310
333.15	2.221	2.361	2.375	2.398	2.584	2.913	3.1680
343.15	1.920	1.989	2.036	2.096	2.204	2.522	2.7410

TABLE 2 (CONTINUED)

Oil Volume Fraction *X*, %	Eq.	Regression constants a	b	c	*R*
2	Eq. (3)	–6.042e^{2}	3.485e^{2}	–1.409	0.9998
4		–5.305e^{2}	2.405e^{2}	–9.731e^{-1}	0.9997
6		–5.132e^{2}	2.123e^{2}	–8.634e^{-1}	0.9999
8		–4.712e^{2}	1.488e^{2}	–6.163e^{-1}	0.9998
10		–4.577e^{2}	1.269e^{2}	–5.259e^{-1}	0.9994
15		–4.913e^{2}	1.569e^{2}	–6.351e^{-1}	0.9995
20		–4.501e^{2}	1.026e^{2}	–4.174e^{-1}	0.9998
2	Eq. (4)	2.161e^{5}	26.48	1.493	0.9991
4		2.648e^{5}	26.31	1.520	0.9992
6		2.027e^{5}	27.03	1.489	0.9996
8		8.404e^{4}	29.68	1.315	0.9996
10		9.945e^{4}	29.44	1.365	0.9995
15		3.922e^{5}	26.00	1.825	0.9998
20		3.361e^{5}	26.89	1.805	0.9997

TABLE 2 (CONTINUED)

Eq.	Relative Errors, %[a]						
	Oil Volume Fraction *X*, %						
	2	4	6	8	10	15	20
Eq. (3)	0.1547	0.3468	0.0169	0.2335	0.0339	0.9140	0.3800
	1.1715	1.0076	0.1217	1.1280	1.2511	0.9255	1.1720
	0.2591	1.5220	0.2642	0.6902	2.4990	1.4023	0.2986
	0.2305	0.3342	0.5417	0.5509	0.8602	1.5382	0.0190
	0.6384	1.7294	1.1814	0.5464	2.4250	0.0678	0.2827
	1.8531	0.3202	0.2386	1.2815	0.4077	1.3985	0.0028
	0.4237	1.5574	0.5239	0.3752	1.6860	2.1432	2.6477
	0.9356	0.1204	0.6223	1.8550	0.2135	0.7177	1.2596
	0.7150	0.8283	0.5408	2.5378	2.9664	2.7544	2.9679
Eq. (4)	1.3699	1.0611	0.7696	1.0034	0.6034	0.0828	0.5237
	1.7539	2.0118	0.9474	1.7186	1.8939	0.3136	0.4702
	1.3334	0.1368	0.9632	0.2870	1.5601	0.4747	1.3899
	0.5414	0.6874	0.3434	0.2082	0.1831	2.0331	0.6737
	0.1485	1.0354	0.4675	1.0686	1.7275	1.2339	1.3427
	3.9005	2.3878	2.2726	0.4709	1.4920	1.3023	2.5366
	1.6706	3.5569	2.5332	1.4931	0.2806	0.6339	0.0858
	0.6540	0.0922	0.5762	1.5892	0.3224	0.6764	1.1382
	4.2700	5.2585	3.6576	0.9269	1.0436	1.1976	1.0419

[a]Relative error = $|v_{est} - v_{exp}|/v_{exp}$

TABLE 3. DYNAMIC VISCOSITY DATA OF DIESEL-PALM OIL BINARY BLENDS MEASURED BY [30], RELATIVE ERRORS BETWEEN MEASURED AND CALCULATED VISCOSITIES FROM EQ. (3) AND EQ. (4), AND REGRESSION PARAMETERS FOR DIFFERENT TEMPERATURES

Temp. T, °C	Measured μ, mPa·s — Oil Volume Fraction X, % 5	10	15	20
20	5.23237	5.97925	7.09959	8.17842
30	4.3610	4.77593	5.60581	6.51867
40	3.40664	3.86307	4.40249	5.10788
50	2.82573	3.24066	3.61411	4.07054
60	2.32780	2.74274	2.9917	3.44813
70	1.95436	2.24481	2.49378	2.82573
80	1.70539	1.95436	2.16183	2.45228
90	1.49793	1.70539	1.91286	2.20332

TABLE 3 (CONTINUED)

Oil Volume Fraction X, %	Eq.	Regression Constants a	b	c	R
5	Eq. (3)	$-2.074e^{2}$	$-2.218e^{1}$	$-6.625e^{-1}$	0.9996
10		$-2.313e^{2}$	$-2.137e^{1}$	$-6.969e^{-1}$	0.9998
15		$-2.419e^{2}$	$-1.655e^{1}$	$-7.280e^{-1}$	0.9996
20		$-2.302e^{2}$	$-1.369e^{1}$	$-5.909e^{-1}$	0.9994
5	Eq. (4)	7.628	39.00	0.7139	0.9992
10		8.524	38.43	0.8945	0.9997
15		10.77	33.58	1.1700	0.9999
20		12.53	33.56	1.3090	0.9997

TABLE 3 (CONTINUED)

Eq.	Relative Errors, % — Oil Volume Fraction X, % 5	10	15	20
Eq. (3)	1.0881	0.0875	0.4671	0.7597
	3.2725	0.3031	1.5367	2.2447
	0.9436	0.5568	0.4169	0.2396
	0.7186	0.4796	0.2785	2.3923
	2.2470	1.1525	0.9489	0.4397
	2.5517	2.4256	2.1056	2.9795

Eq.	Relative Errors, %			
	Oil Volume Fraction *X*, %			
	5	10	15	20
	0.6327	0.3821	0.1340	0.4710
	3.1931	1.4699	3.2413	3.1448
Eq. (4)	0.9405	0.3214	0.1017	0.4293
	3.5801	0.4925	0.4997	1.2931
	1.2448	1.0796	0.9107	0.1135
	0.1661	0.7892	0.3977	1.5416
	1.0274	2.1632	0.5928	1.2355
	1.3776	1.2801	0.6247	1.4002
	0.6308	0.1652	0.1193	0.4890
	1.6767	0.5061	0.2383	1.6674

TABLE 4. DENSITY DATA OF DIESEL-WASTE COOKING OIL BINARY BLENDS MEASURED BY THE AUTHORS, RELATIVE ERRORS BETWEEN MEASURED AND CALCULATED VISCOSITIES FROM EQ. (5) AND EQ. (6), AND REGRESSION PARAMETERS FOR DIFFERENT TEMPERATURES

Temp. *T*, K	Measured ρ, kg/m^3						
	Oil Volume Fraction *X*, %						
	2	4	6	8	10	15	20
278.15	836.90	838.10	838.30	839.90	841.50	846.29	849.89
283.15	836.65	837.85	838.05	839.64	841.24	846.04	849.64
288.15	836.06	837.26	837.46	839.06	840.65	845.45	849.04
293.15	835.39	836.59	836.79	838.38	839.98	844.77	848.36
303.15	833.30	834.49	834.69	836.28	837.88	842.65	846.24
313.15	830.45	831.64	831.84	833.43	835.02	839.78	843.35
323.15	826.94	828.12	828.32	829.90	831.48	836.22	839.78
333.15	822.84	824.02	824.21	825.79	827.36	832.07	835.61
343.15	818.32	819.49	819.69	821.25	822.81	827.50	831.02

TABLE 4 (CONTINUED)

Oil Volume Fraction *X*, %	Eq.	Regression Constants				*R*
		a	b	c	d	
2	Eq. (5)	1246	–1.091e^{-3}	–2162	–1.171e^{-2}	0.9999
4		1245	–1.086e^{-3}	–2182	–1.178e^{-2}	1.0000
6		1241	–1.078e^{-3}	–2216	–1.190e^{-2}	1.0000
8		1256	–1.099e^{-3}	–2135	–1.157e^{-2}	1.0000
10		1262	–1.105e^{-3}	–2127	–1.151e^{-2}	1.0000
15		1256	–1.084e^{-3}	–2222	–1.183e^{-2}	1.0000

Oil Volume Fraction *X*, %	Eq.	Regression Constants				*R*
		a	b	c	d	
20		1268	$-1.094e^{-3}$	–2192	$-1.168e^{-2}$	1.0000
2	Eq. (6)	$9.182e^{2}$	$-2.851e^{-1}$	–	–	0.9781
4	Eq. (6)	$9.195e^{2}$	$-2.855e^{-1}$	–	–	0.9784
6	Eq. (6)	$9.197e^{2}$	$-2.856e^{-1}$	–	–	0.9783
8	Eq. (6)	$9.214e^{2}$	$-2.862e^{-1}$	–	–	0.9784
10	Eq. (6)	$9.232e^{2}$	$-2.867e^{-1}$	–	–	0.9787
15	Eq. (6)	$9.285e^{2}$	$-2.883e^{-1}$	–	–	0.9782
20	Eq. (6)	$9.324e^{2}$	$-2.896e^{-1}$	–	–	0.9784

TABLE 4 (CONTINUED)

Eq.	Relative Errors, %						
	Oil Volume Fraction *X*, %						
	2	4	6	8	10	15	20
Eq. (5)	0.0315	0.0087	0.0330	0.0199	0.0012	0.0040	0.0406
	0.0340	0.0114	0.0308	0.0206	0.0026	0.0017	0.0376
	0.0248	0.0024	0.0401	0.0122	0.0064	0.0104	0.0470
	0.0332	0.0110	0.0318	0.0188	0.0022	0.0026	0.0386
	0.0348	0.0120	0.0311	0.0186	0.0035	0.0020	0.0365
	0.0349	0.0128	0.0307	0.0182	0.0038	0.0007	0.0358
	0.0341	0.0115	0.0323	0.0150	0.0015	0.0028	0.0370
	0.0310	0.0090	0.0364	0.0111	0.0014	0.0065	0.0405
	0.0372	0.0147	0.0301	0.0157	0.0047	0.0004	0.0338
Eq. (6)	0.2389	0.2372	0.2338	0.2254	0.2323	0.2386	0.2304
	0.0985	0.0968	0.0934	0.0860	0.0928	0.0979	0.0894
	0.0014	0.0032	0.0066	0.0153	0.0074	0.0028	0.0104
	0.0918	0.0938	0.0972	0.1049	0.0983	0.0929	0.1009
	0.1834	0.1845	0.1881	0.1963	0.1901	0.1837	0.1929
	0.1841	0.1857	0.1894	0.1984	0.1916	0.1859	0.1943
	0.1052	0.1062	0.1101	0.1188	0.1115	0.1057	0.1148
	0.0461	0.0444	0.0415	0.0318	0.0394	0.0460	0.0371
	0.2503	0.2490	0.2448	0.2363	0.2442	0.2501	0.2411

TABLE 5. DENSITY DATA OF DIESEL-PALM OIL BINARY BLENDS MEASURED BY BAROUTIAN ET AL. [30], RELATIVE ERRORS BETWEEN MEASURED AND CALCULATED VISCOSITIES FROM EQ. (5) AND EQ. (6), AND REGRESSION PARAMETERS FOR DIFFERENT TEMPERATURES

Temp. T, °C	Measured ρ, kg/m^3				
	Oil Volume Fraction X, %				
	5	10	15	20	30
15	0.8276	0.8316	0.8368	0.8416	0.8508
30	0.8156	0.8200	0.8252	0.8296	0.8388
45	0.8052	0.8096	0.8148	0.8192	0.8284
60	0.7948	0.7996	0.8040	0.8088	0.8184
75	0.7840	0.7888	0.7936	0.7984	0.8080
90	0.7736	0.7784	0.7832	0.7880	0.7980

TABLE 5 (CONTINUED)

Oil Volume Fraction X, %	Eq.	Regression Constants				R
		a	b	c	d	
5	Eq. (5)	5.375	–0.5787	0.8377	$-8.825e^{-4}$	0.9998
10		$5.044e^{-3}$	–0.1375	0.8418	$-8.669e^{-4}$	0.9999
15		$2.418e^{-3}$	$-9.213e^{-2}$	0.8471	$-8.714e^{-4}$	0.9999
20		45.43	–0.7067	0.8513	$-8.572e^{-4}$	1.0000
30		$1.782e–^{2}$	–0.1799	0.8603	$-8.371e^{-4}$	0.9999
5	Eq. (6)	$8.377e^{-1}$	$-7.147e^{-4}$	–	–	0.9998
10		$8.416e^{-1}$	$-7.040e^{-4}$	–	–	0.9998
15		$8.470e^{-1}$	$-7.116e^{-4}$	–	–	0.9998
20		$8.515e^{-1}$	$-7.086e^{-4}$	–	–	0.9997
30		$8.604e^{-1}$	$-6.979e^{-4}$	–	–	0.9995

TABLE 5 (CONTINUED)

Eq.	Relative Errors, %				
	Oil Volume Fraction X, %				
	5	10	15	20	30
Eq. (5)	0.0004	0.0041	0.0111	0.0053	0.0042
	0.0261	0.0331	0.0236	0.0105	0.0292
	0.0143	0.0004	0.0290	0.0138	0.0122
	0.0380	0.0581	0.0053	0.0219	0.0296
	0.0064	0.0012	0.0113	0.0135	0.0063
	0.0180	0.0281	0.0005	0.0119	0.0166
Eq. (6)	0.0750	0.0673	0.0566	0.0866	0.1021
	0.0808	0.0585	0.0548	0.0774	0.0790
	0.0420	0.0395	0.0218	0.0504	0.0718
	0.0023	0.0300	0.0378	0.0227	0.0154
	0.0124	0.0000	0.0038	0.0056	0.0071
	0.0288	0.0206	0.0312	0.0348	0.0515

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