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Densities and Kinematic Viscosities in Biodiesel−Diesel Blends at Various Temperatures

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ABSTRACT: In recent years biodiesel fuel has been considered as an alternative fuel for diesel engines. This fuel is made by transesterification of vegetable oils (or animal fat) and alcohols in the presence of a catalyst. Density and viscosity are two important properties that are useful for selecting fuels. In this study the effects of temperature and volume fraction of biodiesel and diesel on the density and kinematic viscosity of blends were investigated. In the previous studies, some correlations have been presented for the prediction of these two properties, but the constants of these correlations differ depending on the type of biodiesel and diesel. In this study two general correlations were presented for estimating density and kinematic viscosity of the blends at several temperatures. These correlations depend on the temperature, volume fraction of biodiesel and diesel, and properties of pure biodiesel and diesel (pure density at 293.15 K and pure kinematic viscosity at 313.15 K). The predicted results showed high accuracy nevertheless to the generality of their constants.
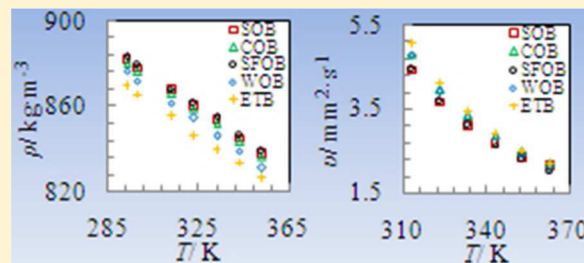
INTRODUCTION

Reducing sources of fossil fuels and their pollution has been the aim of extensive research performed on alternative energy sources, particularly renewable fuels. Biodiesel is an alternative renewable fuel for diesel fuel, which includes alkyl esters of fatty acids obtained from vegetable oils or animal fats by transesterification reaction.[1−3]

Biodiesel has many advantages, which have caused the consideration of this fuel in recent years. It is biodegradable, nontoxic, and renewable. In addition, biodiesel has a higher cetane number and flash point than diesel oil and effectively reduces the release of hydrocarbons and carbon monoxide and suspends particles from combustion. Biodiesel dissolves in diesel oil completely so it can be combined in any percent. Differences between biodiesel and diesel fuels exist (higher density and viscosity, higher cloud point and pour point (in some cases), and lower heat of combustion), but biodiesel can be used pure or mixed with diesel, without modification in diesel equipment directly.[4−6]

Viscosity and density are key parameters of fuel for diesel engines.[6] Higher viscous fuels demand more energy from the fuel pump and block the pump elements,[7] also tending to largely form droplets, leading to poor fuel atomization during spraying that affects engine performance and exhaust emission.[7,8] On the other hand density is an important property in that performance parameters such as the cetane number and heating value are correlated against it.[9] Furthermore, an increase in density can affect engine output power because the fuel injection systems measure the fuel by volume, so consequently a greater mass is injected.[10]

Several models have been proposed in the literature to predict biodiesel density and viscosity. Freitas et al.[11] evaluated the capability of four models that develops a method for predicting temperature dependence on viscosity of biodiesel based on fatty acid ester composition. The results for several biodiesel systems showed that the average deviation from the experimental data for Ceriani's[12] model was 8.07 %, for Krisnangkura's[13] model 7.25 %, for Yuan's[3] model 5.34 %, and for revised version of Yuan's model 4.65 % where their parameters were refitted by Pratas et al.[14,15] to the new data reported.

Density of Biodiesel. Tat and Van Gerpen[9] measured the specific gravities of soybean oil biodiesel and (75, 50, and 20) % blends with No. 1 and No. 2 diesel fuels from the onset of crystallization temperature to 373.15 K using the standard hydrometer method. The results indicated that biodiesel and its blends demonstrate linear temperature dependency behavior, and they developed eq 1:[9]

$$SG = a + bT \tag{1}$$

where SG is the specific gravity, T is the temperature in K, and a and b are constants that were found to depend on fuel.

In some works density was used instead of specific gravity in eq 1.[4,5,16−18] Nita et al.[19] prepared a mixture of rapeseed oil biodiesel−diesel blended at a volume fraction of 0.1 to 0.9 with steps of 0.1 and a measured density at 298.15 K. The experimental data are represented by Kay's mixing rule, eq 2, with an absolute average deviation of 0.014 %.[19]

$$\rho_m = v_1\rho_1 + v_2\rho_2 \tag{2}$$

where ρ_m is the density of mixture (kg·m^{-3}), ρ_1 and ρ_2 are densities of the components 1 and 2 (kg·m^{-3}), and ν_1 and ν_2

are volume fraction of the components 1 and 2. Also a and b are regression coefficients.

Ramírez-Verduzco et al.[20] studied the variation of density as a function of volume percent and temperature. They obtained data for six biodiesel−diesel blends at nine temperatures in the range of (293.15 to 373.15) K and proposed an empirical correlation, eq 3, to estimate the density. A value of 0.02 % for the absolute average deviation (AAD) was obtained for density.

$$\rho_m = \alpha V + \beta T + \delta \qquad (3)$$

where ρ_m is density (kg·m^{-3}), V is the volume percent of the biodiesel blends, and α, β, and δ are adjustable parameters that vary with the type of the biodiesel and diesel. AAD is defined by eq 4:

$$AAD = \frac{100}{n} \sum_{i=1}^{n} \frac{|calculated_i - experimental_i|}{experimental_i} \qquad (4)$$

where n is the number of data.

Viscosity of Biodiesel. Tate et al.[21] obtained the kinematic viscosity of biodiesel fuels (methyl esters of canola and soy and ethyl esters of fish oil) at a temperature range of (293.15 to 573.15) K by a modified form of the Andrade's equation proposed by Tat and Van Gerpen:[22]

$$\ln(v) = A + \frac{B}{T} + \frac{C}{T^2} \qquad (5)$$

where v is the kinematic viscosity, T is the temperature in K, and A, B, and C are constants. Results of the regressions using eq 5 indicated that the minimum R^2 is 0.951 for soy methyl esters.

Also Yuan et al.[23] used Vogel's equation for estimating the manner of kinematic viscosity by temperature:

$$\ln(v) = A + \frac{B}{T + C} \qquad (6)$$

where v is kinematic viscosity, T is temperature in K, and A, B, and C are constants.

Nita et al.[19] that their work was mentioned earlier comparing eqs 7 and 8 for predicting the viscosity of the mixture at 298.15 K. Equation 7 is the corrected relation of Grunberg−Nissan[24] with considering ideal behavior for the diesel−biodiesel combination.

$$\ln(v_m) = v_1 \ln(v_1) + v_2 \ln(v_2) \qquad (7)$$

$$v_m = (v_1 v_1^{1/3} + v_2 v_2^{1/3})^3 \qquad (8)$$

where v_m is the kinematic viscosity of the mixture, v_1 and v_2 are kinematic viscosities of components 1 and 2, and v_1 and v_2 are volume fractions of components 1 and 2. The results indicated that the accuracy of eq 7 (AAD = 2.27 %) is similar to the accuracy of eq 8 (AAD = 2.46 %).

In this study the density and viscosity of several biodiesel blends (soybean oil biodiesel (SOB), canola oil biodiesel (COB), sunflower oil biodiesel (SFOB), waste oil biodiesel (WOB), and edible tallow biodiesel (ETB)) with diesel are measured. Measurements were done at several volume fractions and temperatures. Then, according to the above-mentioned correlations, some new equations for density and kinematic viscosity are presented. These equations, unlike previous correlations in the literature, are independent of biodiesel type, so the density and kinematic viscosity of every type of

diesel−biodiesel blend in each temperature and volume fraction can be predicted using pure properties of diesel and biodiesel.

■ MATERIALS AND METHODS

Materials. Three different refined (virgin) vegetable oils (sunflower, canola, and soybean) were purchased from local stores (were obtained from supermarkets of Kermanshah), waste cooking oil was obtained from a local restaurant, and edible tallow was obtained from a local butcher shop. Available commercial diesel fuel was prepared from a local fuel supplier. The reagents used during synthesis and purification procedures were: methanol 99.9 % (chromatography grade, Merck), sulfuric acid 97 % (Merck), potassium hydroxide 85 % pellets (GR for analysis, Merck), n-hexane 95 % (extra pure, Merck), and methyl laurate (methyl dodecanoate) $\geq$ 99.7 % was supplied from Sigma as a standard for GC analysis, and some other chemicals were purchased from a local company.

Biodiesel Production and Blend Preparation. In this study four different vegetable oils (sunflower, canola, soybean, and waste cooking oil) and edible tallow were used for biodiesel production. Since the acid numbers of the waste cooking oil and edible tallow were more than 1 mg KOH/g ((1.23 and 9.52) mg KOH/g, respectively), a pre-esterification stage carried out for these materials to achieve fatty acids content below 0.5 % (to achieve acid number below 1 mg KOH/g). Pre-esterification conditions were preformed with H_2SO_4 as a catalyst ($w = 0.005$; w is mass fraction), with a molar ratio of oil/methanol at 1:18 at 338.15 K for 5 h, as described by Encinar et al.[25] Therefore biodiesel was synthesized by transesterification of each of the five sample oils. The molar ratio of oil/methanol that used was 1:6, whereas the amount of potassium hydroxide as catalyst was 1 % of the oil's weight. The reaction was carried out at 333.15 K for 4 h under methanol reflux and stirring. Commercially available diesel fuel was prepared from a local fuel supplier. Biodiesels were blended with diesel fuel at (20, 40, 60, and 80) % on volume basis at ambient temperature.

Density Measurement. The hydrometer method described in ASTM Standard D1298 was used to measure the density of biodiesel fuels and their blends with diesel in ambient temperature and also $T=$ (298.15, 313.15, 323.15, 333.15, 343.15, and 353.15) K. Lin-Tech art. no. 600702-4 glass hydrometers with scale subdivision 0.5 kg·m^{-3} (uncertainty of the density measurements was $\pm$ 0.5 kg·m^{-3}) and a Lin-Tech art. LT/DB-55100/M density bath were used in the measurement (uncertainty of the temperature measurements was $\pm$ 0.01 K). The test was repeated three times for each sample, and the results were averaged.

Kinematic Viscosity Measurement. The kinematic viscosity measurement was carried out for each sample from (313.15 to 363.15) K in steps of 10 K according to ASTM Standard D445. Cannon-Fenske type glass capillary viscometers (size no. 75) and a Lin-Tech art (uncertainty of the viscosity measurements was $\pm$ 0.2 %) LT/VB-37000/M viscosity bath were used (uncertainty of the temperature measurements was $\pm$ 0.01 K). For the determination of kinematic viscosity, the efflux time that is the time for a known volume of liquid flowing under gravity to pass through the viscometer tube was multiplied by the viscometer constant. The viscometer constant is obtained from calibration by the manufacturer at (313.15 and 373.15) K so that it was linearly interpolated to other temperatures. This constant is equal to 0.008 mm^2·s^{-2} in

Table 1. Experimental Density and Kinematic Viscosity of Pure Biodiesels from Different Raw Materials and Diesel at Various Temperatures[a]

T/K	SOB	COB	SFOB	WOB	ETB	diesel
				$\rho_m/\text{kg·m}^{-3}$			
293.15	882.5	880.5	883.0	876.5	870.0	826.5
298.15	878.0	876.5	879.0	872.0	865.6	823.0
313.15	868.0	866.0	868.5	861.5	855.5	812.5
323.15	860.5	859.0	861.5	854.5	846.5	806.0
333.15	854.0	852.0	854.5	846.0	840.0	799.5
343.15	845.0	843.5	846.0	839.0	833.5	792.0
353.15	838.0	836.5	839.0	831.0	826.5	786.5
				$v_m/\text{mm}^2\text{·s}^{-1}$			
313.15	4.404	4.791	4.439	4.768	5.034	2.932
323.15	3.637	3.954	3.656	3.894	4.113	2.445
333.15	3.085	3.320	3.080	3.280	3.433	2.077
343.15	2.659	2.848	2.641	2.803	2.901	1.803
353.15	2.331	2.465	2.293	2.417	2.501	1.586
363.15	2.124	2.189	2.016	2.121	2.179	1.407

[a]The standard uncertainty u is $u(T) = 0.01$ K, and the combined expanded uncertainties U_c are $U_c(\rho_m) = 0.5$ kg·m^{-3} and $U_c(v_m) = 0.002$ mm^2·s^{-1} (level of confidence = 0.95).

313.15 K. Such as with density, the test was repeated three times for each sample, and the results were averaged.

■ RESULTS AND DISCUSSION

General Correlations for Density and Kinematic Viscosity. Table 1 shows the density of pure biodiesels and diesel at several temperatures. Also, Table 2 presents the density of different biodiesel–diesel blends by volume fractions of 0.8, 0.6, 0.4, and 0.2 at different temperatures. Ambient temperatures are shown below this table. As it can be seen, by reducing temperature and increasing the biodiesel volume fraction, the blend density increases.

Also, values of the kinematic viscosity of pure biodiesels and diesel at several temperatures and also the kinematic viscosity of biodiesel–diesel blends are presented in Tables 1 and 2, respectively. By reducing temperature and increasing the biodiesel volume fraction, the kinematic viscosity of blend is increased (Table 2).

Numerous correlations[3–5,9,11–21,23,24] for calculating the density and viscosity of pure biodiesels and blend of biodiesels and diesel in different temperature have been presented. Many of these correlations[3–5,9,11–18,21,23] are presented for estimating the density or viscosity of biodiesel at different temperature, and some of them[19–21] are used for calculating these properties (density and viscosity) for biodiesel–diesel blends at different temperatures. The constants of these correlations change according to the type of biodiesels and diesel.

In this study correlations for density and kinematic viscosity prediction are presented where their constants are independent of the type of biodiesels and diesel. These correlations have been obtained by combining previous correlations. Previous studies showed that the density of biodiesel–diesel blends depends on the pure density of eq 2. Also density has a linear function of temperature of eq 1. With respect to these two facts and knowing that the density of pure components is always measured at 293.15 K, an equation for estimating biodiesel–diesel blend density is presented as below:

$$\rho_m = v_1\rho_{1,293.15} + v_2\rho_{2,293.15} + a + bT \tag{9}$$

where ρ_m, $\rho_{1,293.15}$, and $\rho_{2,293.15}$ are the mixture density and density of components 1 and 2 at 293.15 K in kg·m^3, v_1 and v_2

are volume fractions of components 1 and 2, T is temperature in K, and a and b are correlation constants. These constants are independent of biodiesel and diesel type; hence for calculating a mixture density just the density of pure biodiesel and diesel at 293.15 K are needed. By paying attention to the trend of biodiesel–diesel blend viscosity versus volume fraction of biodiesel, it can be deduced that the kinematic viscosity of mixture similar to the kinematic viscosity of pure components is expressed as eqs 7 and 8. Also, the change of kinematic viscosity with temperature can be described well by eqs 5 and 6. The viscosity of pure components is always measured at 313.15 K, so proposed equations for kinematic viscosity are presented as below:

$$v_m = v_{1,313.15}^{v_1} v_{2,313.15}^{v_2} \exp(c + d/T + e/T^2) \tag{10}$$

$$v_m = (v_1 v_{1,313.15}^{1/3} + v_2 v_{2,313.15}^{1/3})^3 \exp(f + g/T + h/T^2) \tag{11}$$

$$v_m = v_{1,313.15}^{v_1} v_{2,313.15}^{v_2} \exp(i + j/T + k) \tag{12}$$

$$v_m = (v_1 v_{1,313.15}^{1/3} + v_2 v_{2,313.15}^{1/3})^3 \exp(l + m/T + n) \tag{13}$$

where v_m, $v_{1,313.15}$, and $v_{2,313.15}$ are the mixture kinematic viscosity and the viscosity of components 1 and 2 at 313.15 K, respectively, in mm^2·s^{-1}, v_1 and v_2 are volume fractions of components 1 and 2, T is temperature in K, and c to n are equation constants. Also these constants are independent of biodiesel and diesel type, so for calculating the mixture kinematic viscosity, the pure kinematic viscosity of biodiesel and diesel at 313.15 K should be known.

Constants a to n in eqs 9 to 13 are obtained by fitting these equations with literature data[2,16,17,20] (data in Table 3), and the following correlations were found (some of these data are in mass fraction, converted to volume fraction):

$$\rho_m = v_1\rho_{1,293.15} + v_2\rho_{2,293.15} + 217.17 - 0.74T \tag{14}$$

$$v_m = v_{1,313.15}^{v_1} v_{2,313.15}^{v_2} \exp(-0.7076 - 1583.9914/T + 564416.7837/T^2) \tag{15}$$

Table 2. Experimental Density and Kinematic Viscosity of Biodiesel (1) + Diesel (2) Blends with Biodiesels from Different Raw Materials at Various Volume Fractions of Biodiesel and at Various Temperatures[a]

biodiesel	v_1	ambient temperature	T/K = 298.15	T/K = 313.15	T/K = 323.15	T/K = 333.15	T/K = 343.15	T/K = 353.15
					ρ_m/kg·m^{-3}			
SOB	0.8	874.0[b]	867.0	857.0	850.0	841.0	834.5	828.0
	0.6	861.0[c]	857.0	844.5	838.0	831.0	824.5	817.5
	0.4	847.0[d]	844.0	833.5	827.0	820.0	813.0	806.5
	0.2	836.0[e]	834.0	823.5	817.0	810.0	803.5	797.0
COB	0.8	871.0[f]	866.0	855.5	846.5	839.5	833.0	826.5
	0.6	860.0[g]	856.0	843.5	837.0	830.0	823.5	816.5
	0.4	847.5[h]	844.0	834.0	827.0	820.0	813.5	807.0
	0.2	836.0[i]	833.5	823.5	816.5	810.0	803.5	796.5
SFOB	0.8	872.0[d]	867.0	857.0	850.0	841.5	834.5	828.0
	0.6	863.0[j]	857.0	845.0	838.0	831.5	825.0	818.0
	0.4	847.0[k]	844.5	834.0	827.0	820.5	813.5	807.0
	0.2	837.0[l]	834.0	824.0	817.0	810.5	803.5	797.0
WOB	0.8	869.0[m]	862.5	852.0	843.5	836.5	829.5	823.0
	0.6		853.5	841.5	834.5	827.5	821.0	814.0
	0.4	846.5[n]	842.5	832.0	825.5	818.5	812.0	805.5
	0.2	836.0[d]	833.0	823.0	816.0	809.5	802.5	796.0
ETB	0.8	863.5[j]	857.5	845.5	838.5	832.0	825.0	818.0
	0.6	853.5[h]	848.0	838.0	831.0	824.0	817.5	810.5
	0.4	843.0[o]	840.0	830.0	823.0	816.5	809.5	803.0
	0.2	834.5[P]	832.0	822.0	815.0	808.5	801.5	795.0

biodiesel	v_1	ambient temperature	T/K = 313.15	T/K = 323.15	T/K = 333.15	T/K = 343.15	T/K = 353.15	T/K = 363.15
					v_m/mm^2·s^{-1}			
SOB	0.8		3.952	3.294	2.787	2.402	2.103	1.913
	0.6		3.658	3.060	2.568	2.203	1.930	1.720
	0.4		3.374	2.814	2.389	2.061	1.826	1.610
	0.2		3.085	2.566	2.227	1.911	1.701	1.519
COB	0.8		4.313	3.569	2.975	2.546	2.208	1.945
	0.6		3.840	3.199	2.691	2.389	2.002	1.761
	0.4		3.502	2.918	2.469	2.138	1.870	1.654
	0.2		3.160	2.636	2.227	1.920	1.677	1.506
SFOB	0.8		4.045	3.358	2.846	2.435	2.122	1.866
	0.6		3.641	3.004	2.548	2.216	1.910	1.687
	0.4		3.356	2.787	2.364	2.042	1.781	1.575
	0.2		3.013	2.511	2.125	1.834	1.606	1.424
WOB	0.8		4.333	3.560	2.981	2.559	2.217	1.951
	0.6		3.835	3.168	2.672	2.297	2.008	1.757
	0.4		3.473	2.884	2.434	2.118	1.840	1.612
	0.2		3.176	2.639	2.238	1.945	1.693	1.544
ETB	0.8		4.516	3.721	3.092	2.631	2.276	2.009
	0.6		4.042	3.337	2.786	2.375	2.075	1.813
	0.4		3.590	2.957	2.495	2.135	1.861	1.643
	0.2		3.186	2.643	2.233	1.926	1.686	1.477

[a]Standard uncertainties u are $u(v_1)$ = 0.1 and $u(T)$ = 0.01 K, and the combined expanded uncertainties U_c are $U_c(\rho_m)$ = 0.5 kg·m^{-3} and $U_c(v_m)$ = 0.002 mm^2·s^{-1} (level of confidence = 0.95). [b]Ambient temperature = 288.35 K. [c]292.35 K. [d]293.35 K. [e]294.75 K. [f]290.95 K. [g]291.95 K. [h]292.75 K. [i]293.95 K. [j]290.55 K. [k]293.55 K. [l]292.95 K. [m]288.75 K. [n]292.45 K. [o]293.75 K. [P]294.15 K.

$$v_m = (v_1 v_{1,313.15}^{1/3} + v_2 v_{2,313.15}^{1/3})^3$$
$$\exp(-0.7408 - 1569.8723/T + 562771.4152/T^2) \tag{16}$$

$$v_m = v_{1,313.15}^{v_1} v_{2,313.15}^{v_2} \exp(-3.4423 + 579.6112$$
$$/T - 144.3929) \tag{17}$$

$$v_m = (v_1 v_{1,313.15}^{1/3} + v_2 v_{2,313.15}^{1/3})^3$$
$$\exp(-3.4595 + 582.7057/T - 144.0976) \tag{18}$$

Using these equations the density and kinematic viscosity of biodiesel−diesel blends at different temperatures could be determined.

Accuracy of Equations. In this study equations for the density and kinematic viscosity of biodiesel−diesel blends are presented by using experimental data of previous studies.[2,16,17,20] For determining density, the pure density of components at 293.15 K should be known. In Table 1 values of biodiesel density (SOB, COB, SFOB, WOB, and ETB) and pure diesel at 293.15 K are shown. By using these values and eq 14, the densities of different mixtures can be calculated.

Table 3. Density and Kinematic Viscosity of Different Biodiesel (1) + Diesel (2) Blends Obtained from Literature

system	NDP[a] of density	NDP of kinematic viscosity
biodiesel (1) + ULSD (2)[20]	72	72
commercial biodiesel (1) + low sulfur petrodiesel (2)[2]		99
colza biodiesel (1) + coconut biodiesel (2)[17]	55	55
soybean biodiesel (1) + coconut biodiesel (2)[17]	45	45
cotton seed biodiesel (1) + babassu biodiesel (2)[16]	45	45
soybean biodiesel (1) + babassu biodiesel (2)[16]	45	45
total	262	361

[a]NDP: number of data points.

The percent error (percent error = (|calculated value − experimental value|)/(experimental value)·100) of densities calculated by eq 14 for experimental data is presented in Figure 1. According to Figure 1 minimum and maximum percent
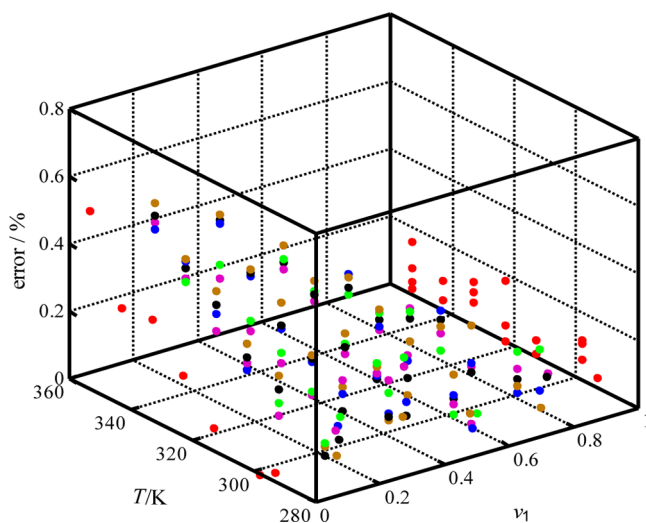
Figure 1. Percent error between the experimental and the calculated density by empirical eq 14 at different temperatures (T/K) and volume fractions of biodiesel (v_1). Red ●, pure biodiesels and diesel; purple ●, SOB (1) + diesel (2); blue ●, COB (1) + diesel (2); green ●, SFOB (1) + diesel (2); black ●, WOB (1) + diesel (2); brown ●, ETB (1) + diesel (2).

errors for estimating of density are 0.00 % and 0.53 %, respectively. Furthermore in Table 4 the absolute average deviations of pure biodiesel and diesel and biodiesel−diesel blends are presented. As it can be observed, the absolute average deviation of total data is 0.12 %. Also minimum and maximum absolute average deviations for pure components and blend of ETB + diesel are 0.08 % and 0.15 %, respectively.

Also for calculating viscosity of biodiesel−diesel blends at different temperatures, the viscosity of pure component at 313.15 K should be known. In Table 1 the pure viscosities of biodiesels (SOB, COB, SFOB, WOB, and ETB) and pure diesel at 313.15 K are presented. Using these data and eqs 15 to 18, kinematic viscosities of biodiesel−diesel blends can be determined. Figure 2a−d shows the percent error of eqs 15 to 18 to calculate pure biodiesels, diesel, and biodiesel−diesel blend kinematic viscosity in comparison with experimental data.

Table 4. Density Data and Absolute Average Deviation between the Experimental and the Calculated Density by Empirical eq 14 for Pure Components and Different Biodiesel (1) + Diesel (2) Blends, Respectively, Obtained in This Work over the Temperature Range (288.35 to 353.15) K along with the NDP[a]

system	NDP	T/K	$\rho_m/\text{kg·m}^{-3}$	AAD (%) of eq 14
pure biodiesels and diesel	42	293.15−353.15	786.5−883.0	0.08
SOB (1) + diesel (2)	28	288.35−353.15	797.0−874.0	0.12
COB (1) + diesel (2)	28	290.95−353.15	796.5−871.0	0.13
SFOB (1) + diesel (2)	28	290.55−353.15	797.0−872.0	0.13
WOB (1) + diesel (2)	27	288.75−353.15	796.0−869.0	0.13
ETB (1) + diesel (2)	28	290.55−353.15	795.0−863.5	0.15
total	181	288.35−353.15	786.5−883.0	0.12

[a]The standard uncertainty u is $u(T) = 0.01$ K, and the combined expanded uncertainty U_c is $U_c(\rho_m) = 0.5$ kg·m^{-3} (level of confidence = 0.95).

Maximum percent errors for eqs 15 to 18 are 5.86 %, 6.49 %, 6.15 %, and 7.27 %, respectively. In Table 5 absolute average deviations for pure component and biodiesel−diesel blends are presented. As shown, total absolute average deviations for eqs 15 to 18 are 1.30 %, 1.45 %, 1.31 %, and 1.47 %, respectively. According to the obtained results for estimating kinematic viscosity, the accuracy of eq 15 is higher than the other equations. Also results show that eq 7 is more suitable than eq 8 for mixtures.

■ CONCLUSION

In this study the density and kinematic viscosity of biodiesel−diesel blends are investigated. For this aim five biodiesels (SOB, COB, SFOB, WOB, and ETB) are compounded with diesel in volume fractions of 0.8, 0.6, 0.4, and 0.2. Then density and kinematic viscosity of mixtures are measured at several temperatures. Results showed that, by reducing temperature and increasing the volume fraction of biodiesel, density and kinematic viscosity are increased. According to this trend and the results of previous studies, new equations are obtained for estimating density and kinematic viscosity of the blends. The difference of these correlations with the previous ones is that constants of these equations are independent of the used biodiesel and diesel type. For estimating the density of biodiesel−diesel blends just the densities of pure diesel and biodiesel at 293.15 K are needed; also for estimating kinematic viscosity just having a kinematic viscosity of pure diesel and biodiesel id sufficient. The presented equations in this study have a high accuracy. The maximum percent error for eq 14 is 0.53 %, and the absolute average deviation for calculating density is 0.12 %. Among four equations that are presented for estimating kinematic viscosity, eq 15 has the highest accuracy, and the maximum percent error and absolute average deviation for calculating kinematic viscosity by this equation are 5.86 % and 1.30 %, respectively.
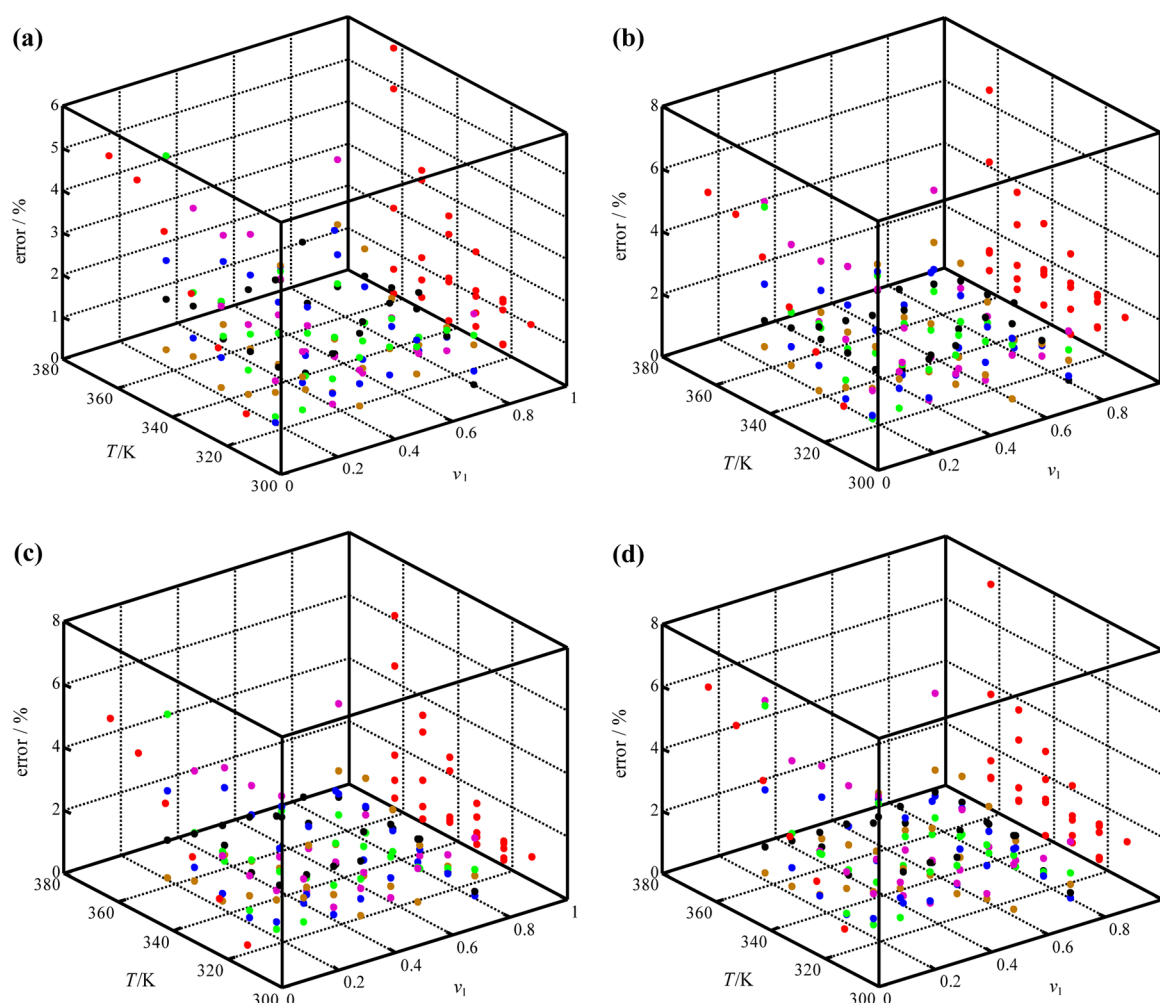
Figure 2. Percent error between the experimental and the calculated kinematic viscosity by (a) empirical eq 15, (b) empirical eq 16, (c) empirical eq 17, and (d) empirical eq 18 at different temperatures (T/K) and volume fractions of biodiesel (v_1). Red ●, pure biodiesels and diesel; purple ●, SOB (1) + diesel (2); blue ●, COB (1) + diesel (2); green ●, SFOB (1) + diesel (2); black ●, WOB (1) + diesel (2); brown ●, ETB (1) + diesel (2).

Table 5. Kinematic Viscosity Data and Absolute Average Deviation between the Experimental and the Calculated Viscosity by Empirical eqs 15 to 18 for Pure Components and Different Biodiesel (1) + Diesel (2) Blends, Respectively, Obtained in This Work over the Temperature Range (313.15 to 353.15) K along with the NDP[a]

			v_m	AAD (%)			
system	NDP	T/K	$mm^2 \cdot s^{-1}$	eq 15	eq 16	eq 17	eq 18
pure biodiesels and diesel	36	313.15–363.15	1.407–5.034	1.78	2.14	1.64	1.98
SOB (1) + diesel (2)	24	313.15–363.15	1.519–3.952	1.52	1.57	1.58	1.67
COB (1) + diesel (2)	24	313.15–363.15	1.506–4.313	1.07	1.09	1.08	1.14
SFOB (1) + diesel (2)	24	313.15–363.15	1.424–4.045	1.43	1.47	1.55	1.57
WOB (1) + diesel (2)	24	313.15–363.15	1.544–4.333	1.04	1.15	1.03	1.15
ETB (1) + diesel (2)	24	313.15–363.15	1.477–4.516	0.71	0.91	0.8	1.05
total	156	313.15–363.15	1.407–5.034	1.30	1.45	1.31	1.47

[a]The standard uncertainty u is $u(T)$ = 0.01 K, and the combined expanded uncertainty U_c is $U_c(v_m)$ = 0.002 $mm^2 \cdot s^{-1}$ (level of confidence = 0.95).

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Notes

The authors declare no competing financial interest.

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