The Effect of Temperature and Biodiesel Fraction on the Viscosity of Biodiesel-Diesel Fuel Blends

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Abstract

This study aims determination of the effects of biodiesel fraction and temperature on the viscosities of blends of corn oil biodiesel with petro-diesel fuel. Corn oil biodiesel was produced by using sodium hydroxide (NaOH) as catalyst and methanol (CH_3OH) as alcohol. To produce the lowest viscosity corn oil biodiesel, many production parameters such as catalyst concentration, reaction temperature, reaction time and alcohol/oil molar ratio were optimized respectively at the first stage which is not consisted in this study. At the second stage concerned mainly with this study, the biodiesel produced by using predetermined optimum parameters was blended with petro-diesel fuel at the volume ratios of 5, 10, 15 and 20% and then each blend was studied to determine viscosity at different temperatures such as 10, 20, 30 and 40°C. One- and two- dimensional curve fit equations were derived by applying the least squares regression to experimental data. One-dimensional exponential equation ($\mu = \mu_0 + ae^{-b\phi}$) was found suitable to predict dynamic or kinematic viscosities of the blends with respect to temperature or biodiesel fraction. In this exponential equation, ϕ represents either biodiesel fraction in blend X or temperature T while μ_0, a and b are regression constants. Two-dimensional polynomial equation such as $\mu = \mu(T, X) = a + bT + cX + dT^2 + eTX + fX^2 + gT^3 + hT^2X + kTX^2$ was fitted to the dynamic or kinematic viscosity data to represent change of dynamic or kinematic viscosities of the blends versus temperature and biodiesel fraction in blend. For all the fitted equations, the calculated regression constants (μ_0, a and b) and regression coefficients (R^2) were given as tables.

Keywords: Alternative fuels, Corn oil biodiesel, Biodiesel-diesel fuel blends, Prediction viscosity models

Introduction

The depletion of fossil fuel reserves in the world has led to a growing and urgent interest in alternative energy sources, especially renewable ones will be more required soon [1]. For diesel engines, which will be used more widely in the near future due to their high thermal efficiency and superior fuel economy compared to gasoline engines [2], biodiesel is gaining more attention as a renewable alternative fuel. From a chemical point of view, biodiesel can be defined as mono-alkyl methyl or ethyl esters of long-chain-fatty acids derived from vegetable oils or animal fats via a reaction as transesterification. The reaction is achieved with mono-hydric alcohols like methanol and ethanol in the presence of an alkali catalyst [3]. Even though biodiesel cannot entirely replace petro-diesel fuel, it has many advantages such as: (1) Biodiesel is a renewable fuel, non-toxic, significantly reduces life-cycle net carbon dioxide emissions, and essentially free of sulfur and aromatic [1,4]. (2) Biodiesel comprises of about 10 to 11% oxygen by mass in the molecular structure. Therefore, it has higher cetane number, better ignition quality and produces less particulate matter, unburned or half-burned hydrocarbon, and carbon monoxide, in comparison with petro-diesel fuel [5]. (3) Biodiesel improves lubricity and reduces premature wearing of fuel pumps [3]. (4) Biodiesel can be completely miscible with petro-diesel fuel, allowing the blending of these two fuels in any proportion [6]. It can be used as neat or blended form in existing diesel engines without any significant modifications to the engines [3]. (5) The flash point temperature of biodiesel is higher than that of petro-diesel fuel. Although the flash point temperature does not directly affect the combustion, it makes biodiesel safer regarding the storage and transport [7]. Although these properties make it an ideal fuel for diesel engines, it has also some disadvantages such as lower heat of combustion and volatility, higher density, viscosity and cloud point temperature compared to petro-diesel fuel.

As the use of biodiesel becomes more widespread, it becomes important to know whether the basic properties of biodiesel-petro diesel fuel blends meets the related standard specifications for petro-diesel fuels. Additionally, researchers have shown a strong interest in modeling the combustion process in the engine in order to understand the fundamental characteristics of biodiesel combustion [4] and they use the basic properties as input data for engine combustion models or software. Also, because of the difficulty of determination of the basic properties of biodiesel-diesel fuel blends for infinite number of blending ratios by measurement, using blending or mixing equations to calculate these properties is very useful. Some studies include these equations are summarized as following.

In the study performed by Tat and Gerpen, the kinematic viscosities of soybean oil biodiesel and its blends (75, 50 and 20% by mass) with No. 1 and No. 2 diesel fuels were measured from the onset of crystallization to 100°C. Second-order polynomial equation was developed to calculate the kinematic viscosities of blends by using regression analysis. The correlation between fitted curve and the experimental data is very well and the lowest regression coefficient (R^2) was found as 0.9995 for all the fuel blends [8].

Alptekin and Canakci measured densities and kinematic viscosities of biodiesels derived from six different vegetable oils (sunflower, canola, soybean, cottonseed, corn oil and waste palm oil) and its blends with two different petro-diesel fuel (purchased from Shell Extra Diesel and Petrol Office firms). The blends (B2, B5, B10, B20, B50 and B75) were prepared by volume. Linear equation and a mixing equation originally proposed by Arrhenius were used to predict the densities and viscosities of the blends. For all blends, there was an excellent agreement between the measured and calculated densities and viscosities values [7].

Nita and Geacai reported that the changes of densities and viscosities of a corn oil, petro-diesel fuel and corn oil biodiesel at the temperature range of 20°C to 60°C with an increasing step of 5°C, and suggested empirical models to predict these fuel properties. According to results, it can be said that the estimation of the density using a linear correlation is very accurate in case of all fuels, and the estimation of the viscosity of fuels using a third-degree polynomial empirical equation has different accuracy [9].

Benjumea et al. measured some basic properties (viscosity, density, heating value, cloud point, calculated cetane index and T10, T50 and T90 distillation temperature) of several palm oil biodiesel-diesel fuel blends. Arrhenius-type equation and Kay's mixing rules were used in order to predict kinematic viscosity and the other properties, respectively [6].

Joshi and Pegg carried out a study on the determination of flow properties of biodiesel-diesel fuel blends at low temperatures. In their study, the cloud point, pour point and dynamic viscosity of biodiesel derived from ethyl esters of fish oil, No. 2 diesel fuel, and their blends were measured from 298 K down to their respective pour points. Blends (B80, B60, B40 and B20) were prepared by volume. Arrhenius equations were used to predict the viscosities of the all fuels as a function of temperature. The calculated viscosities agreed well with measured values. An empirical equation for estimating the viscosities of these blends as a function of both temperature and biodiesel fraction was developed. It was specified that the dynamic viscosity of biodiesel and its blends increases as temperature decreases and shows Newtonian behavior down to the pour point temperature [3].

As seen from the some literature survey above, there is generally sufficient data available about determination of viscosities of biodiesel-diesel blends at certain temperatures. Hence the main objective of the present work is to measure viscosity of the corn oil biodiesel and its blends with Ultra Force Euro Diesel at different temperatures (10, 20, 30, 40°C), and derive new one- and two-dimensional equations to predict the viscosity by using the least square method. The biodiesel-diesel blends (B5, B10, B15 and B20) were prepared by volume. The names of blends are defined by the first letter of the name of the biodiesel B followed by the volume percent of the biodiesel in the blends as usual. For example, B5 signifies that, it is a blends of 5% volume corn oil biodiesel and 95% volume petro-diesel fuel. Also, B100 and D represent pure biodiesel and petro-diesel fuels, respectively.

Experimental Study

Biodiesel Production

In this study, commercially available refined corn oil was used in biodiesel production. It was not needed to perform a pretreatment to the oil because of being refined. Thus, methanol (CH_3OH) of 99.8% purity as alcohol and sodium hydroxide

(NaOH) of pure grade as catalyst were used in transesterification. The transesterification reaction was carried out in a 1 L flat-bottomed flask, equipped with a magnetic stirrer heater, thermometer and spiral reflux condenser. Haake Falling Ball Viscometer, Isolab pycnometer, top loading balance, Haake Water Bath and a stopwatch were used to measure dynamic viscosity and density. Many reaction parameters such as catalyst concentration, reaction temperature, reaction time and alcohol/oil molar ratio were optimized formerly to produce the lowest viscosity corn oil biodiesel, which were not mentioned in this study. These optimum reaction parameters were obtained as 0.90% catalyst concentration, 60°C reaction temperature, 60 minutes reaction time and 9:1 alcohol/oil molar ratio. Before starting the reaction, the catalyst was dissolved in methanol to make alcoholic solution of catalyst in a narrow-neck flask. In the flat bottomed flask, this alcoholic solution was added to the 200 g corn oil that was formerly warmed to about 80°C in a beaker. These reactants were mixed for 60 minutes at 50°C with stirring speed of 500 rpm by means of the magnetic stirrer heater. Transesterification reaction was carried out with the spiral reflux condenser for avoiding loss of alcohol. Also, reaction temperature was controlled by using thermometer to remain constant reaction temperature during the reaction. At the end of reaction, the resulting products mixture was transferred to a separating funnel. After a day, two phases occurred in the separating funnel. The upper phase consisted of methyl esters, and the lower one contained the glycerol, the excess methanol, the remaining catalyst together with soaps formed during the reaction and some entrained methyl esters and partial glycerides. After separation of the two layers by gravity, the upper layer (biodiesel) was washed with warm distilled water until the water became clear. Washed biodiesel was heated up to about 100°C to remove methyl alcohol and water residuals.

Density Measurement

Density can be defined as mass per unit volume. The densities of the produced biodiesel and its blends were measured in accordance with ISO 4787 standard by using Eq. (1) and making measurements by means of the top loading balance and Isolab pycnometer:

$$\rho_{\mathrm{biodiesel\ or\ blends}} = \frac{\mathrm{m_{total}} - \mathrm{m_{pycnometer}}}{\mathrm{m_{water}}} \rho_{\mathrm{water}} \tag{1}$$

where $\rho_{\mathrm{biodiesel\ or\ blends}}$ $(\mathrm{kg/m^3})$ is density of biodiesel or its blends at intended temperature (10, 20, 30, 40°C), $\mathrm{m_{total}}$ (g) is mass of the pycnometer filled with biodiesel or its blends, $\mathrm{m_{pycnometer}}$ (g) is mass of the empty pycnometer, $\mathrm{m_{water}}$ (g) is mass of water (empty pycnometer mass subtracted), ρ_{water} $(\mathrm{kg/m^3})$ is density of distilled water at intended temperature. $\mathrm{m_{pycnometer}}$ and $\mathrm{m_{water}}$ were experimentally determined as 42.74 g and 49.09 g, respectively. The measurements were conducted three times for each sample and the results were averaged. For example, by using Eq. (1) the density of B5 at 20 °C ($\rho_{\mathrm{B5,20°C}}$) was calculated as:

$$\mathrm{m_{total}} = 83.73\ \mathrm{g}$$

$$\mathrm{m_{pycnometer}} = 42.74\ \mathrm{g}$$

$$\mathrm{m_{water}} = 49.09\ \mathrm{g}$$

$$\rho_{\text{water},20°\text{C}} = 998.20 \text{ kg/m}^3$$

$$\rho_{\text{B5},20°\text{C}} = \frac{83.73 - 42.74}{49.09} 998.20 = 833.49 \text{ kg/m}^3$$

Dynamic Viscosity Measurement

Viscosity is a measure of the resistance offered by a fluid to flow [10]. The dynamic viscosities of produced biodiesel or its blends were determined in accordance with DIN 53015 standard by using Eq. (2) and making measurements by means of the Haake Falling Ball Viscometer, Haake Water Bath and stopwatch:

$$\mu_{\text{biodiesel or blends}} = K_{\text{ball}}(\rho_{\text{ball}} - \rho_{\text{biodiesel or blends}})t \tag{2}$$

where $\mu_{\text{biodiesel or blends}}$ (cP) is dynamic viscosity of biodiesel or its blends at intended temperature (10, 20, 30, 40 °C), K_{ball} $(\text{mPa} \cdot \text{s} \cdot \text{cm}^3/\text{g/s})$ is constant coefficient of the viscometer ball, ρ_{ball} (g/cm^3) is density of the viscometer ball, and t (s) is falling time of the ball moving between two horizontal line marked on viscometer tube at limit velocity. K_{ball} and ρ_{ball} are $0.057 \text{ mPa} \cdot \text{s} \cdot \text{cm}^3/\text{g/s}$ and 2.2 g/cm^3, respectively. The measurements were done also three times for each sample and the results were averaged. For example, by using Eq. (2) the dynamic viscosity of B5 at 20 °C ($\mu_{\text{B5},20°\text{C}}$) was calculated as:

$$K_{\text{ball}} = 0.057 \text{ mPa} \cdot \text{s} \cdot \text{cm}^3/\text{g/s}$$

$$\rho_{\text{ball}} = 2.2 \text{ g/cm}^3$$

$$\rho_{\text{B5}} = 833.49 \text{ kg/m}^3$$

$$t = 37.05 \text{ s}$$

$$\mu_{\text{B5},20°\text{C}} = 0.057(2.2 - 0.83349)37.05 = 2.886 \text{ cP}$$

The kinematic viscosities of the produced biodiesel or its blends were determined by dividing dynamic viscosity to density at the same temperature, by using Eq. (3):

$$\nu_{\text{biodiesel}} = \frac{\mu_{\text{biodiesel}}}{\rho_{\text{biodiesel}}} \tag{3}$$

In Eq. (3), if $\mu_{\text{biodiesel}}$ and ρ_{biodisel} are in the unit of (cP) and (kg/L), respectively, then $\nu_{\text{biodiesel}}$ is obtained in unit (cSt). For example, the kinematic viscosity of B5 at 20 °C ($\nu_{\text{B5},20°\text{C}}$) was calculated as:

$$\nu_{\text{B5},20°\text{C}} = \frac{2.886}{0.83349} = 3.463 \text{ cSt}$$

The other properties of the fuels such as flash point (EN ISO 3679) and higher heating value (DIN 51900-2) were measured in Karadeniz Technical University Prof. Dr. Saadettin GUNER Fuel Research and Application Center. The properties, EN 14214 and ASTM D 6751 standard values are given in Table 1.

Uncertainty Analysis

The results obtained from experimental studies are generally calculated from measured physical quantities. These quantities have some uncertainties due to uncertainties of measuring tools and measurement systems. Therefore, uncertainty analysis should be applied for proving reliability of the calculated results. In this study, uncertainties of the measured and calculated physical quantities such as dynamic and kinematic viscosities and density values were determined by the method proposed by Kline and McClintock [11]. According to this method, if the result R is a given function of the independent variables $x_1, x_2, x_3, \dots, x_n$, and $w_1, w_2, w_3, \dots, w_n$ are the uncertainties of each independent variables, then the uncertainty of the result w_R is calculated by using the equation:

$$w_R = [(\frac{\partial R}{\partial x_1} \cdot w_1)^2 + (\frac{\partial R}{\partial x_2} \cdot w_2)^2 + (\frac{\partial R}{\partial x_3} \cdot w_3)^2 + \cdots + (\frac{\partial R}{\partial x_n} \cdot w_n)^2]^{1/2} \quad (4)$$

In this study, for example, by using the uncertainties of the top loading balance and stopwatch as 0.01 g, 0.01 s, respectively, the uncertainty of dynamic viscosity at 20 ℃ ($w_{\mu_{B5,20℃}}$) of B5 was calculated as:

$$\mu_{B5} = K_{ball}(\rho_{ball} - \rho_{B5})t$$

$$\mu_{B5} = \mu_{B5}(\rho_{B5}, t)$$

$$R \equiv \mu_{B5}$$

$$x_1 \equiv \rho_{B5} = 833.49\ kg/m^3$$

$$x_2 \equiv t = 37.05\ s$$

$$\frac{\partial \mu_{B5}}{\partial \rho_{B5}} = -K_{ball}t$$

$$\frac{\partial \mu_{B5}}{\partial t} = K_{ball}(\rho_{ball} - \rho_{B5})$$

$$w_{\mu_{B5,20℃}} = \left\{[-K_{ball} \cdot t \cdot w_{\rho_{B5,20℃}}]^2 + [K_{ball} \cdot (\rho_{ball} - \rho_{B5}) \cdot w_{t,20℃}]^2\right\}^{1/2} \quad (5)$$

It is necessary to know $w_{\rho_{B5,20℃}}$ for calculating $w_{\mu_{B5,20℃}}$. For this reasons, Eq. (4) should be reused for $w_{\rho_{B5,20℃}}$ as below:

$$\rho_{B5} = \frac{m_{total} - m_{pycnometer}}{m_{water}} \rho_{water}$$

$$\rho_{B5} = \rho_{B5}(m_{total}, m_{pycnometer})$$

$$R \equiv \rho_{B5}$$

$$x_1 \equiv m_{total} = 83.73\ g$$

$$x_2 \equiv m_{pycnometer} = 42.74\ g$$

$$\frac{\partial \rho_{B5}}{\partial m_{total}} = \frac{1}{m_{water}} \rho_{water}$$

$$\frac{\partial \rho_{B5}}{\partial m_{pycnometer}} = \frac{-1}{m_{water}} \rho_{water}$$

$$w_{\rho_{B5,20°C}} = [(\frac{1}{m_{water}} \rho_{water,20°C} w_{m_{total}})^2$$
$$+(-\frac{1}{m_{water}} \rho_{water,20°C} w_{m_{pycnometer}})^2]^{1/2}$$

$$w_{\rho_{B5,20°C}} = [(\frac{1}{49.09\ g} \cdot 998.20\ kg/m^3 \ \cdot 0.01g)^2$$
$$+\ (\frac{1}{49.09\ g} \cdot 998.20\ kg/m^3 \ \cdot 0.01g)^2]^{1/2} = 0.2876\ kg/m^3$$

If the value is used in Eq. (5), $w_{\mu_{B5,20°C}}$is calculated as:

$$w_{\mu_{B5,20°C}} = \left\{[-K_{ball} \cdot t \cdot w_{\rho_{B5,20°C}}]^2 + [K_{ball} \cdot (\rho_{ball} - \rho_{B5}) \cdot w_{t,20°C}]^2\right\}^{1/2}$$

$$w_{\mu_{B5,20°C}} = \{[-0.057\ mPa \cdot s \cdot cm^3/g/s \cdot 37.05\ s \cdot 0.2876 \cdot 10^{-3}\ g/cm^3)^2]$$
$$+[0.057\ mPa \cdot s \cdot cm^3/g/s \cdot (2.2\ g/cm^3 - 0.83349\ g/cm^3) \cdot$$
$$0.01\ s]^2\}^{1/2}$$

$$w_{\mu_{B5,20°C}} = 9.8772 \cdot 10^{-4}\ cP$$

Since the dynamic viscosity of the B5 was determined by using Eq. (1) as 2.886 cP, dimensionless uncertainty of dynamic viscosity becomes as:

$$w_{\mu_{B5,20°C}} = \frac{9.8772 \cdot 10^{-4}}{2.886} \cdot 100 = \%0.0342$$

For all values calculated using the same method, the highest and lowest uncertainties for dynamic and kinematic viscosity values were determined as 0.0201%-0.0408% and 0.0408%-0.0535%, respectively. According to these uncertainties, it can be said that the results have fairly high reliability.

Results and Discussion

Effect of Biodiesel Fraction on Viscosity

The changes of dynamic and kinematic viscosities of blends with respect to biodiesel fraction in the blend for different temperatures are shown in Fig. 1 and Fig. 2, respectively. It is clear from these figures that all the blends follow the same trend, i.e., viscosity of the blends increase exponentially with increasing biodiesel fraction in the blends for studied temperatures. In order to characterize the variation of the blends viscosities with respect to volumetric biodiesel fraction in the blends, it has been found suitable to fit exponential equations in the form:

$$\mu = \mu(X) = \mu_0 + ae^{-bX} \tag{6}$$

$$\nu = \nu(X) = \nu_0 + ae^{-bX} \tag{7}$$

where μ is dynamic viscosity (cP), ν is kinematic viscosity (cSt), μ_0, ν_0, a and b are regression coefficients and X is percent volumetric biodiesel fraction in the blend.

It can be seen in Fig. 1 and Fig. 2 that the changes of viscosities tend to be about linear with increasing in biodiesel fraction as temperature is decreasing. The minimum and maximum dynamic viscosity values are 2.233 cP of pure petro-diesel fuel at 40°C and 7.023 cP of pure biodiesel at 10°C, respectively. Similarly, the minimum and maximum kinematic viscosity values are 2.700 cSt of pure petro-diesel fuel at 40°C and 8.009 cSt of pure biodiesel at 10°C, respectively.

Table 2 shows the calculated by using Eq. (6) and measured dynamic viscosities of fuel blends, errors between them, and regression coefficients. The maximum absolute error ratio between the measured and calculated dynamic viscosity values is 3.738%. The regression coefficients (R^2) are between 0.9948 and 0.9991.

Similar quantities of Table 2 are given for kinematic viscosities in Table 3. In this case, the maximum absolute error ratio were obtained as 3.783% and the regression coefficients (R^2) were computed as between 0.9932 and 0.9989. According to regression analyze, it can be said that exponential regression properly fits the data and represents perfectly the both dynamic and kinematic viscosity-biodiesel fraction relationships.

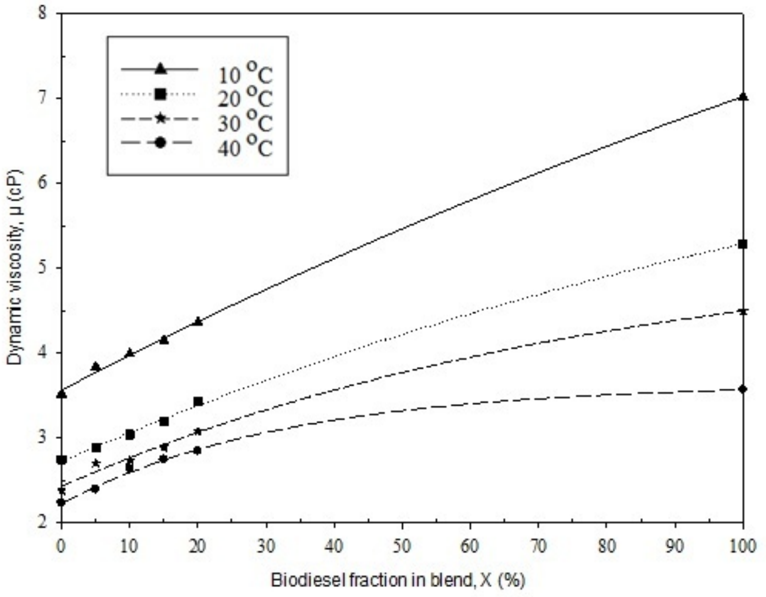

Fig. 1. Variation of dynamic viscosity with biodiesel fraction in blend

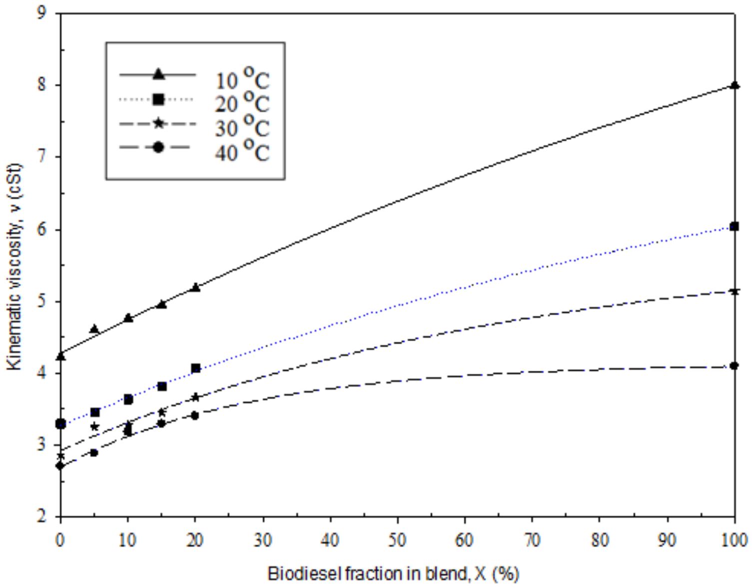

Fig. 2. Variation of kinematic viscosity with biodiesel fraction in blend

Effect of Temperature on Viscosity

Fig. 3 and Fig. 4 show the effects of temperature on dynamic and kinematic viscosities of biodiesel-diesel fuel blends. It is clear from these figures that all the blends viscosities follow the same trend: that of decreasing exponentially with increasing temperature. The experimental data, represented by different symbols for each blends in these figures, were correlated with an exponential equation by applying the least squares method:

$$\mu = \mu(T) = \mu_0 + ae^{-bT} \tag{8}$$

$$\nu = \nu(T) = \nu_0 + ae^{-bT} \tag{9}$$

where μ is dynamic viscosity (cP), ν is kinematic viscosity (cSt), μ_0, ν_0, a and b are regression coefficients, and T is temperature (°C).

The calculated by using Eq. (8) and measured dynamic viscosities of all fuel blends are shown in Table 4. The maximum absolute error ratio between the measured and calculated dynamic viscosities were computed as 4.089%, and regression coefficients (R^2) were obtained between 0.9832 and 1.0000. It can be clearly said that there is a good agreement between the measured and calculated values.

Table 5 also presents the experimentally measured kinematic viscosities, the calculated kinematic viscosities by Eq. (9), regression constants and coefficient (R^2) values and errors. As seen in the table, the maximum absolute error ratio is 4.084% and regression coefficients are obtained between 0.9829 and 0.9999. Thus, it can be said that Eq. (9) represents the experimental data in adequately accurate.

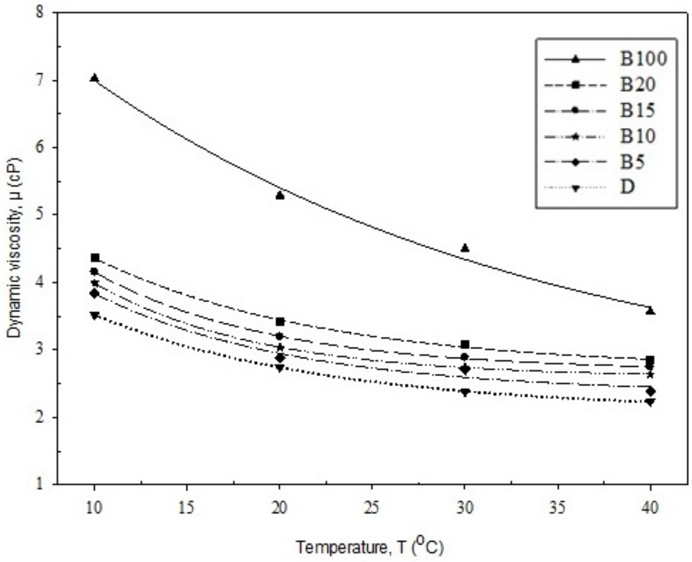

Fig. 3. Variation of dynamic viscosity with temperature

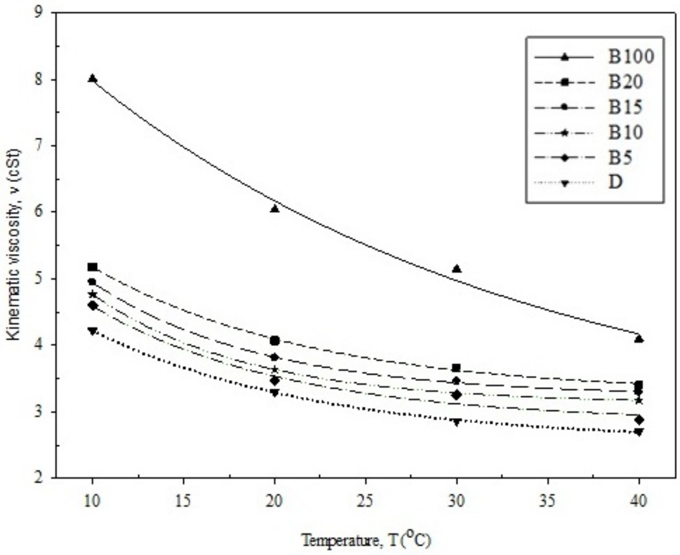

Fig. 4. Variation of kinematic viscosity with temperature

A Model for the Viscosities as a Function of Temperature and Biodiesel Fraction

In this study, also two-dimensional surface curve fit equations were derived for dynamic and kinematic viscosities. In these equations, second order dependence to biodiesel fraction and third order dependence to the temperature of viscosities were found appropriate, as given in Eqs. (10) and (11):

$$\mu = \mu(T, X) = a + bT + cX + dT^2 + eTX + fX^2 + gT^3 + hT^2X + kTX^2 \quad (10)$$

$$\nu = \nu(T, X) = a + bT + cX + dT^2 + eTX + fX^2 + gT^3 + hT^2X + kTX^2 \quad (11)$$

In these equations, μ is dynamic viscosity (cP), ν is kinematic viscosity (cSt), a, b, c, d, e, …, k are regression coefficients, T is temperature (°C) and X is biodiesel fraction in blend.

The values of the regression constants and coefficients (R^2) for dynamic and kinematic viscosities calculated with Eq. (10) and Eq. (11) are given in Table 6 and 7, respectively. As seen in these tables, the maximum absolute error ratios between the measured and calculated dynamic and kinematic viscosities are 3.438%, 3.448%, and the regression coefficients (R^2) are 0.9956, 0.9954, respectively. Therefore, it can be said that the measured and predicted values are in good agreement.

Fig. 5 and 6 show contour plots of dynamic and kinematic viscosities of biodiesel-diesel fuel blends obtained from Eqs. (10) and (11) as a function of temperature and biodiesel fraction, respectively. These plots can be used to make quick estimates of viscosities for a given blending ratio at a specific temperature.

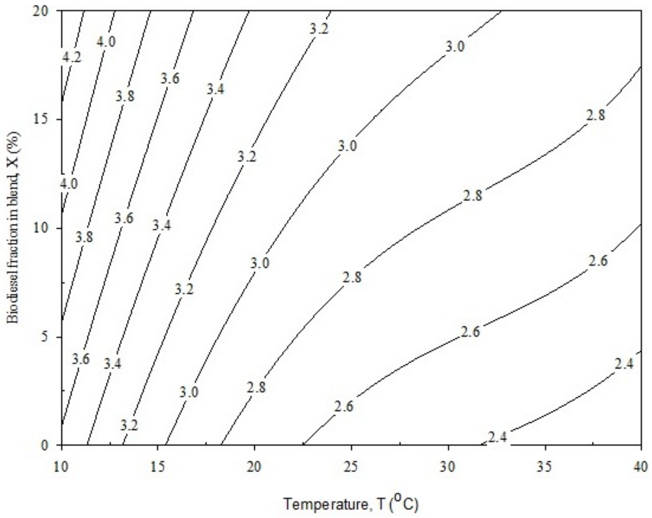

Fig. 5. Variation of dynamic viscosity with biodiesel fraction in blend and temperature

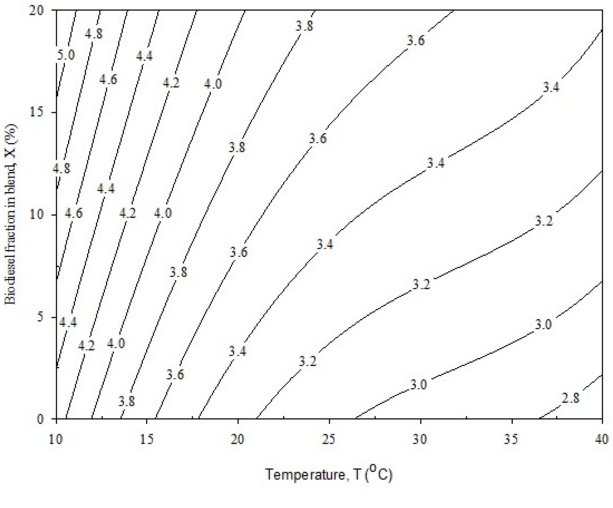

Fig. 6. Variation of kinematic viscosity with biodiesel fraction in blend and temperature

Conclusion

In this study, the effects of biodiesel fraction and temperature on the viscosities of blends of corn oil biodiesel with petro-diesel fuel were investigated experimentally. One- and two-dimensional regression models were proposed to predict viscosities of the blends for various blending ratios and at different temperatures. The following conclusions can be drawn from this study:

- The exponential equations are quite suitable to represent viscosity-biodiesel fraction or viscosity-temperature variations.
- The two-dimensional surface equations show fair degree of accuracy with regression coefficient (R^2) of 0.9956 and 0.9954 for representing change of dynamic and kinematic viscosities with biodiesel fraction and temperature at the same time, respectively.

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Tables

Table 1. Some fuel specifications of commercial petro-diesel fuel, produced biodiesel and its blends, and corresponding standard values for biodiesel

Fuel Properties	Units	Corn Oil Biodiesel	Petro-Diesel Fuel	B5	B10
Kinematic viscosity at 40°C	cSt	4.095	2.700	2.882	3.174
Density at 15°C	kg/m^3	877.13	833.33	834.96	837.61
Flash Point Temperature	°C	169	63	68	69
Higher Heating Value	kJ/kg	39930	45950	45368	44984

Table 1 (Continued)

Fuel Properties	Units	B15	B20	EN 14214	ASTM D 6751
Kinematic viscosity at 40°C	cSt	3.291	3.400	3.50-5.00	1.90-6.00
Density at 15°C	kg/m^3	839.44	842.09	860-900	*
Flash Point Temperature	°C	70	72	101≤	130≤
Higher Heating Value	kJ/kg	44643	44399	*	*

Table 2. For different temperatures, measured and calculated dynamic viscosities of corn oil biodiesel, petro-diesel fuel and biodiesel-diesel fuel blends using Eq. (6), error ratio between measured and calculated dynamic viscosities, and regression constants (μ_0, a, b) and coefficients (R^2)

Temp. T (°C)	Measured dynamic viscosity, μ (cP)						μ_0	a	b	R^2
	Biodiesel fraction in blend, X (%)									
10	3.514	3.838	3.989	4.150	4.360	7.023	14.0393	-10.4765	0.0040	0.9990
20	2.743	2.886	3.040	3.193	3.423	5.287	7.9546	-5.2334	0.0067	0.9991
30	2.376	2.702	2.736	2.889	3.074	4.496	5.3475	-2.9207	0.0123	0.9948
40	2.233	2.388	2.638	2.741	2.841	3.564	3.6325	-1.4050	0.0300	0.9964

Table 2 (Continued)

Calculated dynamic viscosity, μ (cP)	Absolute error ratio (%)
Biodiesel fraction in blend, X (%)	Biodiesel fraction in blend, X (%)

0	5	10	15	20	100	0	5	10	15	20	100
3.562	3.770	3.973	4.172	4.368	7.016	1.388	1.766	0.386	0.551	0.190	0.089
2.721	2.893	3.060	3.221	3.377	5.276	0.794	0.263	0.667	0.895	1.329	0.196
2.426	2.601	2.764	2.918	3.063	4.493	2.138	3.738	1.052	1.035	0.335	0.048
2.227	2.423	2.591	2.736	2.861	3.562	0.246	1.474	1.755	0.160	0.718	0.042

Table 3. For different temperatures, measured and calculated kinematic viscosities of corn oil biodiesel, petro-diesel fuel and biodiesel-diesel fuel blends using Eq. (7), error ratio between measured and calculated kinematic viscosities, and regression constants (ν_0, a, b) and coefficients (R^2)

Temp. T (°C)	Measured kinematic viscosity, ν (cSt)						ν_0	a	b	R^2
	Biodiesel fraction in blend, X (%)									
	0	5	10	15	20	100				
10	4.218	4.598	4.764	4.945	5.179	8.009	13.2377	-8.9602	0.0054	0.9987
20	3.298	3.463	3.636	3.811	4.072	6.038	8.1759	-4.9035	0.0083	0.9989
30	2.863	3.251	3.281	3.456	3.666	5.147	5.8257	-2.9006	0.0145	0.9932
40	2.700	2.882	3.174	3.291	3.400	4.095	4.1356	-1.4441	0.0354	0.9955

Table 3 (Continued)

Calculated kinematic viscosity, ν (cSt)						Absolute error ratio (%)					
Biodiesel fraction in blend, X (%)						Biodiesel fraction in blend, X (%)					
0	5	10	15	20	100	0	5	10	15	20	100
4.277	4.516	4.748	4.974	5.194	8.016	1.410	1.779	0.325	0.600	0.305	0.089
3.272	3.471	3.663	3.846	4.022	6.037	0.776	0.280	0.742	0.928	1.218	0.005
2.925	3.128	3.316	3.492	3.655	5.145	2.169	3.783	1.085	1.044	0.291	0.033
2.691	2.925	3.122	3.286	3.424	4.093	0.314	1.519	1.638	0.139	0.711	0.031

Table 4. For different biodiesel fractions, measured and calculated dynamic viscosities of corn oil biodiesel, petro-diesel fuel and biodiesel-diesel fuel blends using Eq. (8), error ratio between measured and calculated dynamic viscosities, and regression constants (μ_0, a, b) and coefficients (R^2)

Biodiesel fraction in blend, X (%)	Measured dynamic viscosity, μ (cP)				μ_0	a	b	R^2
	Temperature, T (°C)							
	10	20	30	40				
0 (Pure Diesel)	3.514	2.743	2.376	2.233	2.0970	3.1420	0.0795	0.9998
5	3.838	2.886	2.702	2.388	2.3546	3.6769	0.0914	0.9832
10	3.989	3.040	2.736	2.638	2.5921	4.3553	0.1137	1.0000
15	4.150	3.193	2.889	2.741	2.6888	4.1488	0.1045	0.9995
20	4.360	3.423	3.074	2.841	2.7173	3.7008	0.0814	0.9985
100 (Pure Biodiesel)	7.023	5.287	4.496	3.564	2.1895	7.1773	0.0402	0.9933

Table 4 (Continued)

Calculated dynamic viscosity μ (cP)				Absolute error ratio (%)			
Temperature, T (°C)				Temperature, T (°C)			
10	20	30	40	10	20	30	40
3.515	2.737	2.386	2.227	0.054	0.193	0.433	0.237
3.828	2.945	2.591	2.449	0.242	2.065	4.089	2.579
3.989	3.040	2.735	2.638	0.005	0.006	0.003	0.007
4.147	3.202	2.869	2.752	0.050	0.281	0.681	0.412
4.357	3.443	3.039	2.859	0.066	0.607	1.132	0.665
6.991	5.401	4.338	3.627	0.455	2.167	3.507	1.767

Table 5. For different biodiesel fractions, measured and calculated kinematic viscosities of corn oil biodiesel, petro-diesel fuel and biodiesel-diesel fuel blends using Eq. (9), error ratio between measured and calculated kinematic viscosities, and regression constants (ν_0, a, b) and coefficients (R^2)

Biodiesel fraction in blend, X (%)	Measured kinematic viscosity ν (cSt)				ν_0	a	b	R^2
	Temperature, T (°C)							
	10	20	30	40				
0 (Pure Diesel)	4.218	3.298	2.863	2.700	2.5450	3.7630	0.0810	0.9998
5	4.598	3.462	3.251	2.882	2.8520	4.4266	0.0937	0.9829
10	4.764	3.636	3.281	3.174	3.1230	5.2583	0.1164	0.9999
15	4.945	3.811	3.456	3.291	3.2341	4.9808	0.1069	0.9996
20	5.179	4.072	3.666	3.400	3.2649	4.3955	0.0834	0.9986
100 (Pure Biodiesel)	8.009	6.038	5.147	4.095	2.5735	8.1089	0.0406	0.9932

Table 5 (Continued)

Calculated kinematic viscosity ν (cSt)				Absolute error ratio (%)			
Temperature, T (°C)				Temperature, T (°C)			
10	20	30	40	10	20	30	40
4.219	3.289	2.876	2.692	0.023	0.251	0.464	0.281
4.586	3.531	3.118	2.956	0.145	2.007	4.084	2.578
4.764	3.635	3.283	3.173	0.016	0.011	0.064	0.031
4.944	3.821	3.435	3.303	0.014	0.270	0.587	0.373
5.173	4.094	3.625	3.421	0.098	0.540	1.118	0.626
7.976	6.173	4.972	4.171	0.405	2.245	3.394	1.875

Table 6. For different biodiesel fractions and temperatures, measured and calculated dynamic viscosities of biodiesel-diesel fuel blends using Eq. (10), error ratio between measured and calculated dynamic viscosities, and regression constants (a, b, c, d, … , k) and coefficient (R^2)

Temperature T (°C)	Biodiesel fraction in blend X (%)	Measured dynamic viscosity μ (cP)	Calculated dynamic viscosity μ (cP)
10	0 (Pure Diesel)	3.514	3.563
	5	3.838	3.773
	10	3.989	3.976
	15	4.150	4.172
	20	4.360	4.362
20	0	2.743	2.704
	5	2.886	2.893
	10	3.040	3.069
	15	3.193	3.232
	20	3.423	3.382
30	0	2.376	2.423
	5	2.702	2.609
	10	2.736	2.774
	15	2.889	2.920
	20	3.074	3.046
40	0	2.233	2.225
	5	2.388	2.422
	10	2.638	2.593
	15	2.741	2.738
	20	2.841	2.856

Table 6 (Continued)

Absolute error ratio (%)	Coefficients	Regression coefficient
1.420	$a = 5.5000$ $b = -2.6400\text{x}10^{-1}$ $c = 4.9310\text{x}10^{-2}$ $d = 7.8680\text{x}10^{-3}$ $e = -8.2640\text{x}10^{-4}$ $f = -8.5710\text{x}10^{-6}$ $g = -8.2870\text{x}10^{-5}$ $h = 1.6150\text{x}10^{-5}$ $k = -1.2940\text{x}10^{-5}$	$r^2 = 0.9956$
1.672		
0.308		
0.549		
0.045		
1.414		
0.270		
0.983		
1.243		
1.194		
2.007		
3.438		
1.410		
1.080		
0.907		
0.353		
1.440		
1.690		
0.105		

0.545		

Table 7. For different biodiesel fractions and temperatures, measured and calculated kinematic viscosities of biodiesel-diesel fuel blends using Eq. (11), error ratio between measured and calculated kinematic viscosities, and regression constants (a, b, c, d, … , k) and coefficient (R^2)

Temperature T (°C)	Biodiesel fraction in blend X (%)	Measured kinematic viscosity ν (cSt)	Calculated kinematic viscosity ν (cSt)
10	0 (Pure Diesel)	4.218	4.279
	5	4.598	4.520
	10	4.764	4.751
	15	4.945	4.972
	20	5.179	5.182
20	0	3.298	3.252
	5	3.462	3.472
	10	3.636	3.674
	15	3.811	3.858
	20	4.072	4.023
30	0	2.863	2.922
	5	3.251	3.138
	10	3.281	3.329
	15	3.456	3.495
	20	3.666	3.634
40	0	2.700	2.693
	5	2.882	2.925
	10	3.174	3.123
	15	3.291	3.289
	20	3.400	3.420

Table 7 (Continued)

Absolute error ratio (%)	Coefficients	Regression coefficient
1.446	$a = 6.5950$ $b = -3.1590x10^{-1}$ $c = 5.6600x10^{-2}$ $d = 9.4200x10^{-3}$	$r^2 = 0.9954$
1.685		
0.260		
0.552		
0.069		
1.370		
0.306		
1.056		
1.235		
1.183		
2.067		

3.448	$e = -9.1080\text{x}10^{-4}$ $f = -5.4290\text{x}10^{-5}$ $g = -9.9030\text{x}10^{-5}$ $h = 1.8500\text{x}10^{-5}$ $k = -1.5370\text{x}10^{-5}$	
1.490		
1.131		
0.856		
0.255		
1.499		
1.578		
0.057		
0.611		