

Prediction models for density and viscosity of biodiesel and their effects on fuel supply system in CI engines

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ABSTRACT

Biodiesel is a promising non-toxic and biodegradable alternative fuel used in the transport sector. Nevertheless, the higher viscosity and density of biodiesel poses some acute problems when it is used in unmodified engine. Taking this into consideration, this study has been focused towards two objectives. The first objective is to identify the effect of temperature on density and viscosity for a variety of biodiesels and also to develop a correlation between density and viscosity for these biodiesels. The second objective is to investigate and quantify the effects of density and viscosity of the biodiesels and their blends on various components of the engine fuel supply system such as fuel pump, fuel filters and fuel injector. To achieve first objective density and viscosity of rapeseed oil biodiesel, corn oil biodiesel and waste oil biodiesel blends (0B, 5B, 10B, 20B, 50B, 75B, and 100B) were tested at different temperatures using EN ISO 3675:1998 and EN ISO 3104:1996 standards. For both density and viscosity new correlations were developed and compared with published literature. A new correlation between biodiesel density and biodiesel viscosity was also developed. The second objective was achieved by using analytical models showing the effects of density and viscosity on the performance of fuel supply system. These effects were quantified over a wide range of engine operating conditions. It can be seen that the higher density and viscosity of biodiesel have a significant impact on the performance of fuel pumps and fuel filters as well as on air-fuel mixing behaviour of compression ignition (CI) engine.

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1. Introduction

Biodiesel is one of the renewable and environmentally friendly alternative biofuels that can be used in a diesel engine with little or no modification in the engine. The stringent emissions law, the depletion of fossil fuels and the interrelation of fossil fuels with politics have forced the world to find alternatives to fossil fuels [1,2]. Currently biodiesel is seen as a solution and almost every country is preparing a policy on production and use of biodiesel in its transport sector. In addition, the scientific research on production, storage, performance and emission of biodiesel has increased exponentially [3]. Biodiesel's characteristics strongly depend on various plant feed stock, growing climate conditions, soil type, plant health and plant maturity upon harvest. These parameters affect the physical and chemical properties, which also have direct relationship with performance and emission of the engine [4]. Among the biodiesel properties kinematics viscosity, density and

heating value are the most important parameters that affect the engine performance and the emission characteristics [5]. One of the major shortcomings of the biodiesels when used in a diesel engine is the detrimental effects caused by the high viscosity of fuel. Higher viscosity causes poor fuel atomization during spray, increases the carbon deposition on fuel filter, demands more energy from the fuel pump and wears the fuel pumps and injectors [2,6]. The higher viscosity causes mixture to burn lean in the engine as fuel moves slowly through the fuel filter and fuel lines. In addition, the higher viscosity of biodiesel fuel affects the start of injection, injection pressure and the fuel spray characteristics, which are the main parameters that affect engine performance and exhaust emission [7–9]. The density of the diesel fuel is also a very important parameter, since other crucial performance parameters of engine such as cetane number and heating value have been correlated against it [10]. In addition, the density values have also been used to measure the amount fuel in fuel system by volumetric method [5]. The variation of the density affects the power and the fuel spray characteristics during fuel injection and combustion in cylinder. To improve viscosity and density of the biodiesel the available techniques that are used are mixing the diesel with

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biodiesel and/or pre-heating the biodiesel [11]. The effect of mixing on density and viscosity variation of biodiesel with respect to temperature, percentage of blend, and the chemical structure (fatty acid, position and number of double bond) have been well reported. Different empirical correlations have been developed, which relate various performance parameters with density and viscosity of biodiesel [5–11]. The works of previous researchers on biodiesel density and viscosity have been summarized below.

1.1. Density of biodiesel

The specific gravity of biodiesel has been investigated by many researchers. Specific gravity is defined as a ratio of the density of a given solid or liquid substance to the density of water at a specific temperature and pressure, typically at 4 °C and 1 atm. Tat and Garpen [10] measured experimentally the specific gravity of 20%, 50%, 75%, and 100% soybean biodiesel as a function of temperature in the temperature range of crystallization temperature to 100 °C using the standard hydrometer method. The results indicate that the biodiesel and its blends demonstrate temperature dependent behaviour. They developed 1st degree linear-regression equation (1) shown below.

$$SG = a + bT \quad (1)$$

where SG is the specific gravity of blended biodiesel, T is the temperature in °C, and a and b are constants that depend on different percentages of biodiesel blends. Tat et al. [4] also reported similar linear equation for three different biodiesels namely, canola-oil biodiesel, soybean-oil biodiesel and fish-oil biodiesel. These equations were developed based on the data obtained from a capacitance type liquid level meter within temperature range of 20–300 °C. Clements (referenced in [10]) suggested that equation (2) can be used to determine the specific gravity of different biodiesel blends at a standard temperature. In this equation the specific gravity of the blend has been considered to be proportional to mass fractions of the constituents.

$$SG_{blend} = \sum SG_i M_i \quad (2)$$

where SG_{blend} is the specific gravity of the blend, SG_i is the specific gravity of the component i , and M_i is the mass fraction of the component i .

Alptekin and Canakci [5] carried out experimental tests on different biodiesels made of soybean oil, waste palm oil, sunflower oil, corn oil, canola oil, and cottonseed. They suggested a 1st degree empirical equation, which can relate the density of a biodiesel blend with the percentage of a biodiesel used as shown in equation (3).

$$D = Ax + B \quad (3)$$

where D is density (g/cm^3), A and B are constants, which vary with the type of the biodiesel and x is the biodiesel fraction. It can be clearly seen that there is no equation to the best of authors' knowledge that relates density of biodiesel blend, biodiesel fraction and temperature.

1.2. Viscosity of biodiesel

Viscosity is the property of a fluid by virtue of which it offers resistance to flow. The viscosity of a biodiesel is higher than the viscosity of fossil-diesel and some researchers have reported that the biodiesel viscosity can be up to 1.6 times that of diesel at 40 °C [11]. This ratio increases especially when the temperature is below 25 °C [11]. Blending of the biodiesel with diesel and pre-heating of

the biodiesel improves the viscous characteristics significantly [5,12,13]. The viscosity of biodiesel can be estimated from well known mixing laws such as the Grun–Nissan and Katti-Chaudhri laws, which were originally proposed by Arrhenius [14]. The laws are expressed in mathematical form as written in equation (4).

$$\ln(\eta_{max}) = x_1 \ln(\eta_1) + x_2 \ln(\eta_2) \quad (4)$$

where, η_{max} is the kinematic viscosity (mm^2/s) of the mixture, η_1 and η_2 are kinematic viscosities (mm^2/s) of components 1 and 2 and x_1 and x_2 are the mass or volume fractions of components 1 and 2. Alpetekin and Canakci [5] investigated the variation of the viscosity as a function of different percentages of blends of biodiesel. The test was done at 40 °C for a wide variety of biodiesels such as waste palm oil biodiesel, sunflower oil biodiesel, soybean oil biodiesel, corn oil biodiesel, cottonseed oil biodiesel and commercial diesel. They developed a second degree empirical equation (5) to calculate the viscosity of blended biodiesel taking the fraction of biodiesel in the mixture as the main parameter. It was found that the estimated values were close to the measured values.

$$\eta_{blend} = Ax^2 + Bx + C \quad (5)$$

where η is the kinematic viscosity (mm^2/s), A , B , C are coefficients and x is the biodiesel fraction. Most of the available methods for the estimation of biodiesel viscosity at different temperatures are fairly complicated and depend on a number of input parameters. These empirical correlations vary for each type of biodiesel depending on the Biodiesel source [15].

Riazi and Al-Otaibi [15] developed equation (6) for estimation of viscosity of liquid hydrocarbons and petroleum mixtures at various temperatures from their refractive index values (1). However, in this model the equation needs the values of molecular weight, specific gravity, boiling temperature and refractive index of compounds as input.

$$\frac{1}{\mu} = A + \frac{B}{I} \quad (6)$$

in the above equation μ is the dynamic viscosity (cp), A and B are constants specific to each component and I is the refractive index.

A modified equation was proposed by Tat and Van Gerpen [16] to determine the viscosity of the biodiesel at different temperatures. The equation is shown below.

$$\ln(\eta) = A + \frac{B}{T} + \frac{C}{T^2} \quad (7)$$

where A , B and C are constants, T is temperature in K, and η is the kinematic viscosity (mm^2/s).

In Tat and Van Gerpen's equation the constants A , B and C vary with the biodiesel type and the biodiesel fraction and this limits the general use of this equation. Pegg et al. [17] developed the equation (8) to calculate the dynamic viscosity of B100 as a function of temperature in the temperature range of 277–573 K.

$$\ln(\eta) = -2.4343 + \frac{216.66}{T} + \frac{293523}{T^2} \quad (8)$$

where η is the dynamic viscosity (mPa s), A and B are constants and T is the temperature (K). The comparison of predictions from empirical equation and the measured data showed an absolute error of 0.223 and correlation coefficient R^2 of 1.

By considering the carbon number, Krisnangkura et al. [18] proposed different equations [equation (9) and equation (10)] to determine viscosity of biodiesels with long and short carbon structure at different temperatures.

$$\ln(\eta_{C_{12}-C_{18}}) = -2.177 - 0.202z + \frac{403.66}{T} + \frac{109.772}{T}z \quad (9)$$

$$\ln(\eta_{C_6-C_{12}}) = -2.915 - 0.158z + \frac{492.12}{T} + \frac{103.35}{T}z \quad (10)$$

where $\eta_{C_6-C_{12}}$ and $\eta_{C_{12}-C_{18}}$ are the kinematic viscosities of biodiesels with number of carbon atoms varying from 6 to 12 and 12 to 18 respectively, in mm^2/s , T is the temperature in K, and z is carbon number.

In Krisnangkura's equations, number of the carbon atoms is required a-priori which limits the use of equation (9) and equation (10).

Most of the empirical correlations described above are dependent on some constants and vary with type of biodiesel and percentage of blends. It is very important to have a simple, stable and reliable estimation method of viscosity as a function of biodiesel fraction, temperature and density of biodiesel. These relations will be of immense use in engine intake, combustion, and exhaust modelling. Further the properties of biodiesels affect the dynamic flow phenomena in the fuel pump, fuel pipe, fuel filter and injector spray [19]. Based on the above requirements the objectives of this study have been formulated as: 1) to identify the effect of temperature and biodiesel fraction on density and viscosity of biodiesel blend as well as to develop a correlation for biodiesel fraction, temperature, density and viscosity of biodiesel and 2) to investigate and quantify the effect of density and viscosity of the biodiesel and its blends on the fuel supply system such as fuel pump, fuel filter, fuel injector and spray characteristics.

2. Materials and methods

2.1. Materials

In this study, commercially available three common types of biodiesels (corn oil biodiesel, rapeseed oil biodiesel, and waste oil biodiesel) obtained from a local company have been used for analysis. The corn oil biodiesel and rapeseed oil biodiesel were produced by transesterification process from 'virgin' oil using methanol and waste oil biodiesel was produced from local cooking oil waste. Normal diesel fuel was obtained from a local fuel supplier. The biodiesel were blended with diesel fuel at 5%, 10%, 20%, 50%, 75% and 100% on volume basis. For each biodiesel six samples were prepared. In total (including diesel) 19 samples were used for the density and viscosity measurements.

2.2. Density measurement

For measuring the density, standard procedures have been followed [20]. A glass hydrometer with specific gravity range of 0.7–1.0 with an accuracy of three decimal places was used in the measurement. To collect temperature-dependent data, a 100 ml graduated cylinder containing a biodiesel sample was placed in a temperature controlled bath. The water bath temperature could vary from room temperature to 95 °C. The test was repeated twice and the average value was taken. In addition to the hydrometer measurements, mass/volume method of density measurement was also used for comparison at 15.6 °C.

2.3. Viscosity measurement

The Standard Method [Petroleum products: Determination of kinematic viscosity and calculation of dynamic viscosity, the European standard EN ISO 3104:1996 [21] was used to measure the viscosity of the biodiesel samples. This method is commonly used

to measure the kinematic viscosity of liquid petroleum products. Since biodiesels also have almost similar properties as the fossil fuel this method has been considered appropriate for the measurement of viscosity of the biodiesel samples. The kinematic viscosity is determined by measuring the time taken for a known volume of fuel flowing under gravity to pass through a calibrated glass capillary viscometer tube. Cannon-Fenske Viscometer tube (size B) and Selecta viscosity bath were used for this purpose. The size B viscometer has approximate constants of 0.01 and kinematic viscosity range from 2 to 10 mm^2/s . The timing device with 0.01 s least count was used in present tests. The water bath temperature used has a temperature range from room temperature to 85 °C. The viscosity values below the room temperature were determined from the regression correlation from the data of this study and previous reports. For the experimental data to be acceptable the EN ISO 3104:1996 standards require the tests to be done two times and the first and second measurements should be within an accuracy of 0.02 mm^2/s . If the accuracy condition is satisfied the average of the two tests was taken. The tests were repeated two times and the average value was taken as representative value.

2.4. Mathematical models for the fuel supply system

To evaluate the effects of density and viscosity of different biodiesel blends on the fuel supply system (fuel pump, fuel pipe, fuel filter and fuel injector) several key fuel supply parameters such as, head loss, flow rate and Sauter mean diameter (SMD) were predicted using well-accepted mathematical models for different fuel blends under a wide range of engine operating conditions. The characteristics of the compression ignition (CI) engine used in this prediction model is summarised in Table 1. The model was used to determine the mass flow rate of fuel used to produce the required amount of power by the engine. The mass flow rate of fuel that needs to be injected for each cylinders and the power produced by the engine are calculated by the following equations:

$$m_i = 360N_R P / (NQ_v n \eta \theta) \quad (11)$$

$$P = NP_1 V_1 n \left[q - \frac{(\beta^\gamma - 1)}{(\gamma - 1)} \right] \quad (12)$$

$$\eta = 1 - \frac{1}{\gamma \alpha^{(\gamma-1)}} \frac{(\beta^\gamma - 1)}{(\beta - 1)} \quad (13)$$

$$q = \frac{Q_v}{ART_1} \quad (14)$$

Table 1
Engine characteristics.

Type of engine	Tturbocharged Diesel engine
Number of cylinders	4
Bore	103 mm
Stroke	132 mm
Inlet valve diameter	36.2 mm
Exhaust valve diameter	33.5 mm
Compressor inlet diameter	60 mm
Compressor outlet diameter	60 mm
Turbine inlet diameter	100 mm
Turbine outlet diameter	80 mm
Compression ratio	18.3:1
Injection system	Direct injection
Displacement	4.399 L
Cooling system	water
Recommended speed	850 rpm
Maximum power	74.2 kw @ 2200 rpm

where m_i is the fuel mass rate of injection for each cylinder (kg/s), P is the power developed, n is the number of cylinders, η is the thermal efficiency calculated by equation(13), Q_v is the calorific value of fuel(J/kg), ρ is the density of fuel(kg/m³), N_R is the rotational speed of engine(rev/s), N is the number of cycles calculated by $N = N_R/2$ for 4-stroke engine (cycles per sec), θ is the crank angle duration for injection(degrees), V_1 is the volume at start of the compression process per cycle (M³), α is the compression ratio, β is the cut-off ratio in the diesel cycle (1.5), γ is the air specific heat ratio, q is the heat supply factor, A is the stoichiometric air-fuel ratio, and, R is the gas constant of air (287 J/kg.K), and T_1 is the ambient temperature.

One of the other important fuel supply system components in the engine is a fuel filter. The main application of the fuel filter is to remove foreign matter of different sizes from the fuel as these could cause wear of the well polished materials. In addition, it filters any fraction of water left in the fuel to save the equipments from corrosion. The filter flow characteristics have been presented by Coulson and Richardsons [8] and modelled as described in equations (15–17). Equation (14) is the basic charctersitic equation for filtration. By assuming constant pressure difference (ΔP), equation (15) can be modified to equation (16). Further, Γ , ν and A are assumed constants and taking the fuel filter specific properties described in Table 2, equation (17) was developed. Equation (17) shows the inverse relationships between fuel flow rate and the viscosity of the fuel in the filter media.

$$\frac{dV}{dt} = \frac{A^2(-\Delta P)}{\Gamma \eta \nu V} \tag{15}$$

$$\frac{V^2}{2} = \frac{A^2(-\Delta P)t}{\Gamma \eta \nu} \tag{16}$$

$$Q = \frac{C}{\eta t} \tag{17}$$

in the above equations V (m³) is the volume of filtrate which passes through the filter in time t (s), A (m²) is the cross-sectional area of the filter cake, η (mm²/s) is the kinematic viscosity of the filtrate and ΔP (pa) is the applied pressure difference, Γ (m⁻²) is the filtration resistance constant, ν is the volume of cake deposited by unit volume of filtrate, and C is filtration property constant.

The effect of viscosity on fuel flow through pump was investigated by calculating the head loss that occurs in the pumping network. The head loss that occurs in pipes is dependent on the flow velocity, pipe length and diameter, and a friction factor based on the roughness of the pipe and the Reynolds number of the flow. In the simulation model the frictional head loss in section and head pipe was calculated by:

$$h_f = 2.4384 \left(\frac{R}{\rho u^2} \right) \left(\frac{L}{d_i} \right) \left(\frac{u^2}{2g} \right) \tag{18}$$

Where h_f (m) is friction head loss, $R/\rho u^2$ the dimension-less friction factor calculated by the equation $(R/\rho u^2) = (0.0396/N_{Re}^{0.25})$ for the

turbulent flow, N_{Re} is Reynolds number, L/d_i is the equivalent length to pipe diameter ratio, u is the velocity head (m/s) and g is the gravitational acceleration (m/s²).

The other important process that affects the performance of the engine system is the fuel-air mixing process in the engine cylinder. The penetration length, spray angle and Sauter mean diameter (SMD) are the major parameters to quantify the efficiency of mixing process. Since the viscosity and density of the fuel have less effect on the penetration length and the spray angle, the present work is focused only on the effect of biodiesel blending on the SMD. The SMD is the diameter of the model droplet whose volume to surface area ratio is equal to the ratio of the sum of all droplet volumes (V) in the spray to the sum of all droplet surface areas (A). There are different models to correlate the fuel properties and the injector characteristics with SMD. In this simulation the model developed by Hiroyasu and Arai has been used [22]:

$$\frac{SMD}{D} = 0.38Re^{0.25}We_1^{-0.32} \left(\frac{\mu_l}{\mu_g} \right)^{0.37} \left(\frac{\rho_l}{\rho_g} \right)^{-0.47} \tag{19}$$

where We_l is the Weber number given by $We_l = (u^2 D \rho_l) / \sigma$, Re is the Reynolds number given by $Re = (u D \rho_l) / \mu_l$, u (m/s) is the velocity of jet, ρ_l (kg/m³) is the density of the liquid, μ_l (N.s/m²) is the dynamic viscosity of the liquid, D (m) is the nozzle hole diameter, ρ_g is the density of the gas, and μ_g is the dynamic viscosity of the gas (N s/m²), and σ is the surface tension at the liquid–gas interface(N/m).

3. Result and discussion

3.1. Effect of biodiesel fraction and temperature on density

Density can be defined as the ratio of the mass of an object divided by its volume. The density of the biodiesel was measured for various temperatures and biodiesel blends. Table 3 shows the density variation of corn oil biodiesel, rapeseed oil biodiesel and waste oil biodiesel blends. Three of the biodiesels blends have close density values and with minimum value of 853 kg/m³ at 0% biodiesel fraction and maximum value of 880 kg/m³ at 100% biodiesel fractrion. The density of the blend is increasing with increase in the biodiesel volume fraction. Since three of the biodiesels and their blends have very close density values, a common first degree regression equation was developed by taking the average slope and the interception point. The correlation is described by the equation (20).

$$\rho_{blend} = 0.2523x + 854.33 \tag{20}$$

where ρ_{blend} is the density of diesel and biodiesel blends and x is the volume fraction of biodiesel at 15.6 °C.As shown in Table 3, density values corresponding to volume/mass method, hydrometer method, mixing equation (2) and regression analysis equation(20) developed in this study were compared with each other and errors were calculated. The hydrometer and mass/volume methods, hydrometer method and mixing equation and the hydrometer method and regression correlation have showed maximum absolute error of 0.60%, 0.50%, and 0.29% respectively. The regression correlation and the experimental values have R^2 of 0.9945. This indicates that if the density of pure diesel and pure biodiesel are known, equation (2) or equation (20) can be used to determine the density of biodiesel blend at given blend percentage fraction with confidence. Fig. 1 shows the effect of temperature on density of 100% biodiesel measured in the present study and the estimated density by Tat and Gerpen correlation [10].

Table 2
Fuel filter specification.

Filter size	33 cm × 20.32 cm
Thickness:	0.45 mm
Maximum pore size	30–120 μm
Particle removal efficiency	>97%
Particle size in diesel:	> 15 μm
particle size range in filter	3–10 μm

Table 3
Density of biodiesel blend by experimental methods, mixing equation and correlation equation at 15.6 °C.

Type of Biodiesel	Fraction of Biodiesel (%)	Density, by mass/volume	Density using hydrometer	Density using mixing equation (2)	Density using correlation equation (11)	Absolute percentage error between		
						Mass/volume and hydrometer methods	Mixing equation (2) and hydrometer methods	Correlation equation (11) and hydrometer methods
Corn Oil biodiesel	0	853.36	855.00	853.36	854.43	0.1919	0.0000	0.1252
	5	856.39	860.00	854.68	855.70	0.3049	0.3164	0.0799
	10	857.94	860.00	855.99	856.97	0.2406	0.2268	0.1121
	20	859.10	860.00	858.62	859.52	0.0112	0.1719	0.0491
	50	866.61	865.00	866.50	867.15	0.1856	0.0120	0.0625
	75	874.10	875.00	873.08	873.51	0.1025	0.1177	0.0680
Rapeseed oil biodiesel	100	879.65	885.00	879.65	879.87	0.6087	0.0000	0.0255
	5	854.96	855.00	854.68	855.70	0.4608	0.5008	0.0870
	10	859.04	860.00	855.99	856.97	0.1115	0.3552	0.2407
	20	856.97	860.00	858.62	859.52	0.3536	0.1924	0.2973
	50	865.09	865.00	866.50	867.15	0.0102	0.1637	0.2384
	75	871.77	870.00	873.08	873.51	0.2028	0.1499	0.1998
Waste oil biodiesel	100	879.35	880.00	879.65	879.87	0.0739	0.0337	0.0591
	5	857.48	860.00	854.68	855.70	0.2944	0.3265	0.2069
	10	857.58	855.00	855.99	856.97	0.3008	0.1854	0.0707
	20	860.25	850.00	858.62	859.52	1.1911	0.1892	0.0846
	50	866.68	860.00	866.50	867.15	0.7710	0.0205	0.0540
	75	875.32	875.00	873.08	873.51	0.0366	0.2565	0.2068
	100	879.55	880.00	879.65	879.87	0.0512	0.0109	0.0364

The temperature was varied from 290 K to 360 K for 100% corn oil biodiesel, rapeseed and waste oil biodiesel. Three of the biodiesel have very close density values at a given temperature and the density of the biodiesel decreases with the increase in temperature. To generate the regression correlation the average density of the biodiesel at given temperature was taken and a linear-regression equation (21) was developed. The measured average biodiesel density and regression line have maximum absolute error of 0.25% and R^2 of 0.9930. Similarly the density of diesel as a function temperature was experimentally determined and is described in equation (22). The diesel density empirical equation and the measured density values have maximum absolute error of 0.15% and R^2 of 0.9962.

$$\rho_{biod} = -0.69T + 1075 \tag{21}$$

$$\rho_{diesel} = -0.657T + 1051 \tag{22}$$

where ρ_{biod} is the density of biodiesel is, ρ_{diesel} is the density of diesel and T is the temperature.

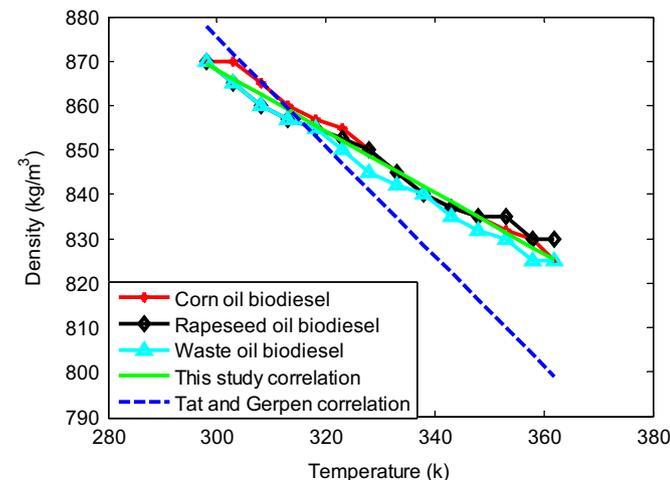


Fig. 1. Biodiesel density Variation with temperature.

These regression equations were compared with Tat and Gerpen linear-regression equation (1) and it was noticed that there is a relatively higher absolute error of about 3.5%. This difference may be because of the different biodiesels used in this study and that used by Tat and Gerpen [11]. In Fig. 1 it can further be seen that in between 320 and 330 K the density of the biodiesel is similar to the normal diesel density (850 kg/m³ to 860 kg/m³). This implies that if there is a system to pre-heat the biodiesel in the temperature range of 320–330 K, the density of Biodiesel could be matched to the density of pure diesel. In the present study equation (23) has been developed to estimate the density of various biodiesel blends at a given temperature. For this purpose mixing equation (2) developed by Clements [10] and the regression equations (21) and (22) of this study have been used. Equation (23) can be used to determine the density of a binary blend of biodiesel and diesel at given temperature and blending fraction.

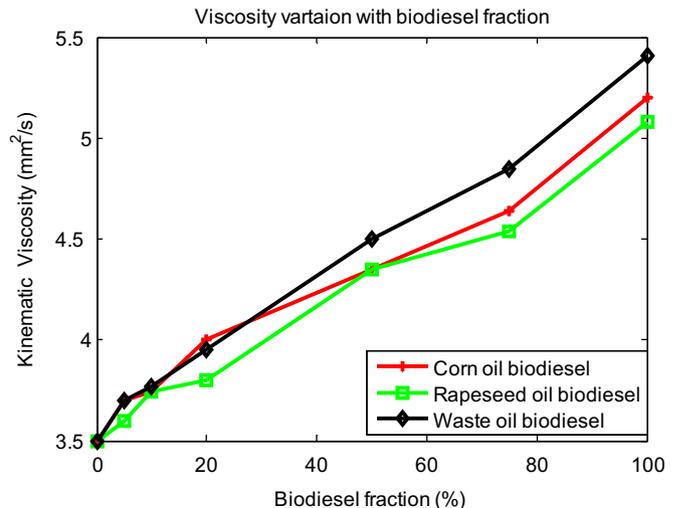


Fig. 2. Kinematic viscosity variations with biodiesel blend percentage.

Table 4
kinematic viscosity of biodiesel and its blends at 40 °C.

Biodiesel	Blend (%)	Measured	A	B	C	R ²	Calculated kinematic viscosity		Absolute error between measured and	
							Regression correlation	Grun–Nissan	Regression correlation	Grun–Nissan
Corn oil biodiesel	0	3.50	8 × 10 ⁻⁶	0.0147	3.593	0.984	3.5930	3.5000	0.0930	0.0000
	5	3.80					3.6667	3.5590	0.1333	0.2410
	10	3.74					3.7408	3.6190	0.0008	0.1210
	20	3.72					3.8902	3.7421	0.1702	0.0221
	50	4.35					4.3480	4.1370	0.0020	0.2130
	75	4.54					4.7405	4.4978	0.2005	0.0422
Rapeseed biodiesel	100	4.89	7 × 10 ⁻⁶	0.0143	3.537	0.987	5.1430	4.8900	0.2530	0.0000
	0	3.50					3.5366	3.5000	0.0366	0.0000
	5	3.76					3.6083	3.5793	0.1517	0.1807
	10	3.90					3.6803	3.6605	0.2197	0.2395
	20	4.08					3.8254	3.8283	0.2546	0.2517
	50	4.47					4.2691	4.3795	0.2009	0.0905
Waste oil biodiesel	75	4.62	5 × 10 ⁻⁵	0.0129	3.597	0.992	4.6485	4.8989	0.0285	0.2789
	100	5.48					5.0366	5.4800	0.4434	0.0000
	0	3.50					3.5970	3.5000	0.0970	0.0000
	5	3.87					3.6628	3.5703	0.2073	0.2997
	10	3.77					3.7310	3.6420	0.0390	0.1280
	20	3.95					3.8750	3.7898	0.0750	0.1602
	50	4.30	4.3670	4.2702	0.0670	0.0298				
	75	4.85	4.8458	4.7168	0.0042	0.1332				
	100	5.21	5.3870	5.2100	0.1770	0.0000				

$$\rho_{mix} = (-0.033T + 24.4)X - 0.657T + 1051 \quad (23)$$

where ρ_{mix} is density of the binary (kg/m³), X is volume fraction of the biodiesel and T is the temperature (K).

The density as obtained from experiments results on rapeseed oil biodiesel were compared with estimated value of biodiesel density using equation (23) and a maximum percentage error of 0.54% was observed. This implies that equation (23) can be used with confidence to estimate the density of the biodiesel blend at any temperature and biodiesel fraction.

3.2. Effect of biodiesel fraction and temperature on viscosity

Various studies were conducted to estimate viscosity of corn oil biodiesel, rapeseed oil biodiesel, and waste oil biodiesel blends at various temperatures. The effect of the biodiesel blends' fraction and temperature on the kinematic viscosity of biodiesel was

investigated and corresponding models were developed. The models were compared with the models published in the literature. Fig. 2 shows the kinematic viscosity of corn oil biodiesel, rapeseed oil biodiesel, and waste oil biodiesel blends at different biodiesel volume fractions as obtained in the present study.

The biodiesel kinematic viscosity increases with increasing biodiesel blend fraction for all the blends. The rapeseed biodiesel have higher kinematic viscosity as compared to corn oil biodiesel and waste oil biodiesel blends. The experimental data were correlated by an empirical second degree correlation described as equation (24). The coefficients A , B , and C used in equation 24 are described in Table 4. This equation can be used to estimate the viscosity of biodiesel at a given biodiesel fraction.

$$\eta_{corr} = Ax^2 + Bx + C \quad (24)$$

where η_{corr} is the kinematics viscosity (mm²/s), A , B , C are coefficients of the second degree equation and x is biodiesel fraction.

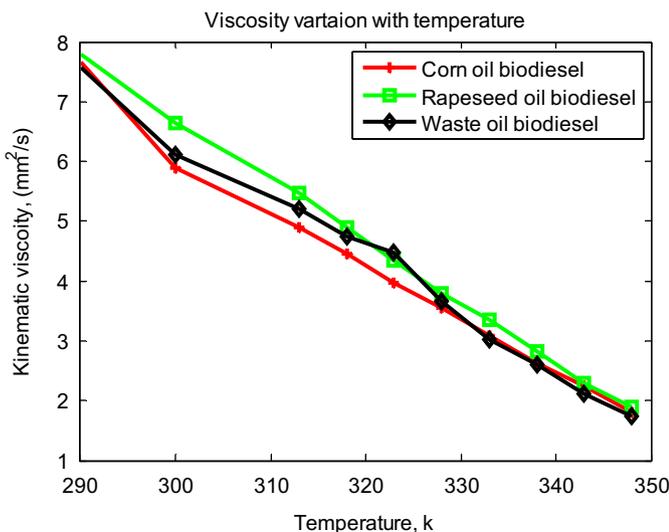


Fig. 3. Biodiesel kinematic viscosity variations with temperature.

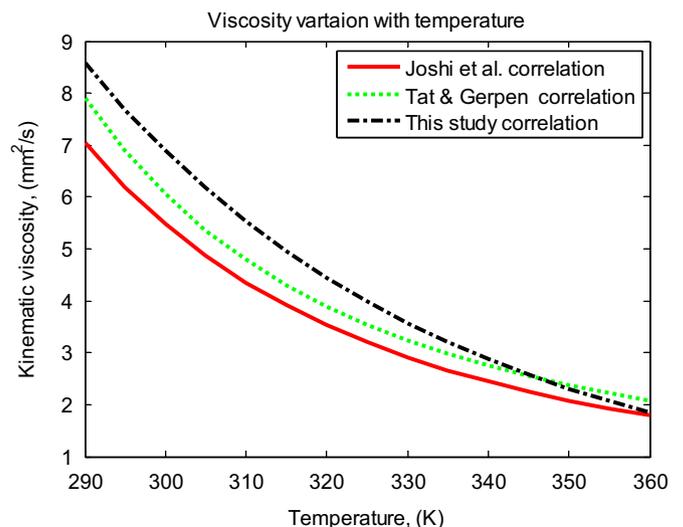


Fig. 4. Viscosity of biodiesel with temperature range of 290 K–360 K.

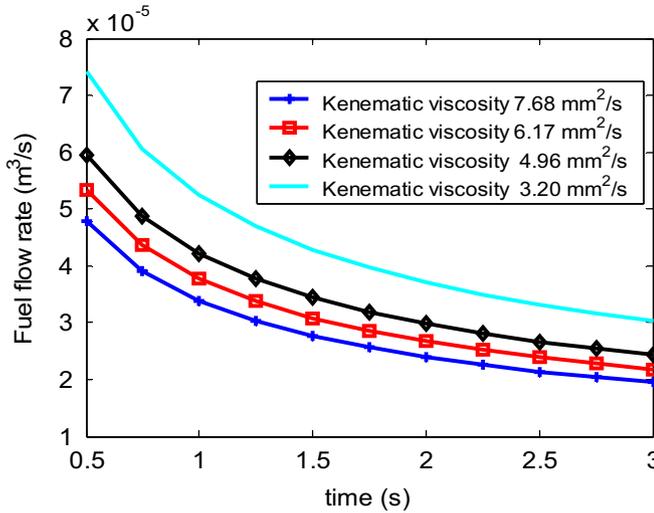


Fig. 5. Fuel flow rate through fuel filter for fuels with different kinematic viscosity values.

Table 4 also presents the experimentally measured viscosity, the calculated viscosity by equation (4), the regression correlation (24) and R^2 values, and the absolute error between the measured and calculated viscosities of the three biodiesel blends.

The kinematic viscosity of the biodiesel as obtained in the present study varies in the range of 3.55–5.48 mm^2/s . The measured and regression correlation have maximum absolute error of 0.299 and the maximum of R^2 value of 0.984. Both Grun–Nissan correlation (equation (4)) and the empirical correlation proposed in this study have reasonable accuracy in estimating kinematic viscosity of the biodiesels. However, the regression coefficient variation with the type of biodiesel limits the use of correlation equation (24). Fig. 3 shows the kinematic viscosity of 100% corn oil, rapeseed biodiesel and waste oil biodiesel variation within temperature range of 295 K–360 K. It can be seen that the kinematic viscosity of the biodiesel decreases with the increase in temperature.

The empirical correlation for the dynamic viscosity as a function of temperature is described by equation (25) which has been developed based on the experimental results and the developed equation has R^2 value of 0.9999. Joshi et al. [6] and Tat & Gerpen [12]

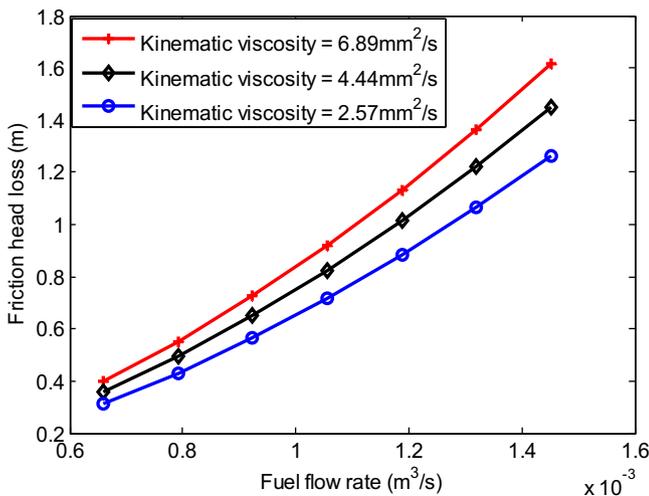


Fig. 6. Flow rate- friction head loss characteristics of fuel pump at different viscosity.

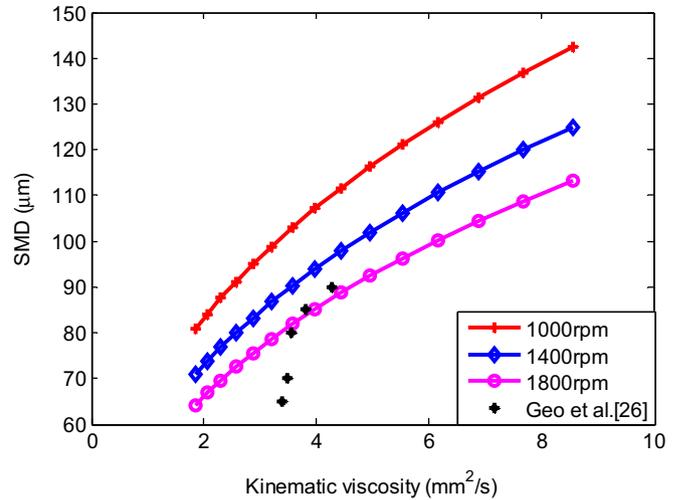


Fig. 7. Sauter mean diameter variation with kinematic viscosity of biodiesel using Hiroyasu and Arai Model [22].

have modified the Arrhens equation for prediction of biodiesel viscosity at different temperatures. The viscosity values obtained from Joshi et al. and Tat & Gerpen dynamic viscosity correlations and the regression correlation developed in this study are shown in Fig. 4. All of the curves follow similar trend. The empirical correlation of the kinematic viscosity and temperature is described by equation (25) for the experimental results obtained in the present study.

$$\ln(\eta) = -0.0219T + 9.12 \quad (25)$$

where T is the temperature in K, and η_{corr} is the kinematic viscosity in mm^2/s .

Further, the density and kinematic viscosity of biodiesel were correlated and an equation was developed relating viscosity as function of density as shown below in equation (26). This equation could be used to estimate kinematic viscosity of the biodiesel for the known density of biodiesel. The values from predicting model and the experimental values have a maximum absolute error of 0.37.

$$\ln(\eta) = 0.0357\rho - 29.02 \quad (26)$$

where T is the temperature in K, and η is the kinematic viscosity in mm^2/s of the fuel biodiesel at a given temperature and ρ is the density of the biodiesel at a given temperature.

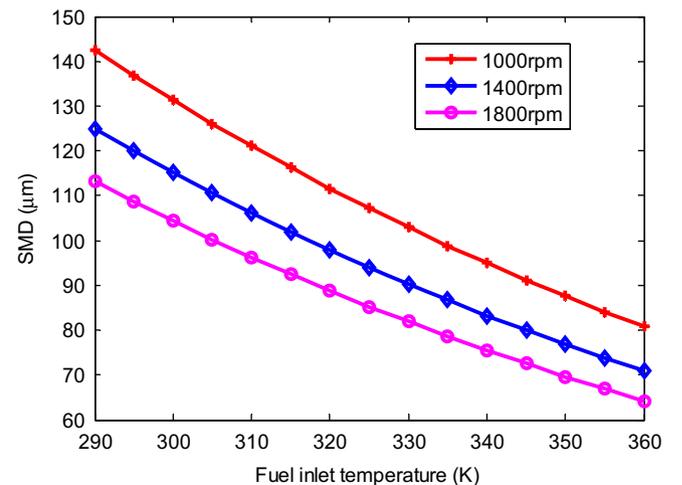


Fig. 8. Sauter mean diameters for temperature range of 290 K–395 K using Hiroyasu and Arai Model [22].

Furthermore an attempt has been made to develop a correlation to predict viscosity of a biodiesel blend at a given temperature. For this a new equation (27) has been developed by combining equation (21), (22) and (26) to determine the viscosity of the blend at given temperature and biodiesel fraction. The modified mixing equation has a maximum absolute error of 0.50.

$$\ln(\eta_{mix}) = (-0.0012T + 0.8456)x - 0.0234T + 8.64 \quad (27)$$

where η_{mix} is the viscosity of the biodiesel, x is the volume fraction of the biodiesel and T is the temperature (K).

The kinematic viscosity prediction models of the biodiesel described by equations (25), (26) and (27) are used to determine numerically the kinematic viscosity at various temperatures, density and biodiesel fraction values. These models can be used in design and investigation of fuel supply systems (fuel pump, fuel filter, fuel pipe, and injectors) as well as in predicting air-fuel mixing phenomena and combustion characteristics.

3.3. Effect of density and viscosity on the fuel filter, pump pressure and air-fuel mixture

This section describes the effects of the biodiesel viscosity and density on the fuel filter; fuel pump and injection spray characteristics in the engine cylinder. The simulation results obtained from the model have been explained below. Fig. 5 illustrates the variation of the fuel flow rate through the fuel filter as function of time for different values of kinematic viscosity representing various biodiesel blends. It can be seen that the fuel flow rate decreases with time in the fuel filter media. This can be explained on the simple fact that at the starting of filtration the voidage are active and the filtration rate is higher [8]. After a while the active voidage of the filter reduces and the filtration rate becomes constant. Fig. 5 also shows the effect of viscosity on the fuel flow rate through the fuel filter. It can be seen that when the fuel viscosity increases the fuel flow rate decreases. This can be attributed to higher flow resistance encountered by highly viscous fluid.

The fuel filter rate has direct effect on the fuel flow rate in the injector and hence the power produced by the engine. The higher viscosity means lower flow rate of fuel and lower engine power by the engine.

Fig. 6 shows the fuel pump head loss versus the fuel flow rate of biodiesel and diesel fuel for different viscosity values. It can be seen that at a constant head, fuel with higher viscosity yields lower fuel flow rate than fuel with lower viscosity. A similar trend has been reported by Bannikov et al. [23].

Fig. 7 shows the relationship between the kinematic viscosity and Sauter mean diameter (SMD) of fuel for different engine speeds. The SMD value of the fuel in combustion cylinder is determined by using a well-accepted model of Hiroyasu and Arai [22]. It can be seen that when the engine speed increases the SMD of the fuel in the cylinder decreases. The same trend has been reported by Hiroyasu [24]. It is also seen that when the kinematic viscosity of the biodiesel increases, the SMD also increases proportionally. This can be explained by the fact that when the kinematic viscosity and surface tension of the fuel increase, the cohesion and the surface viscosity between fuel molecules increase [25]. As a result, the SMD of the fuel increases in the cylinder chamber. The increase in the SMD means reduced surface area of the fuel droplet. As a result the tendency of evaporation of fuel decreases and this might decrease the performance of the engine and increase the emissions. Geo et al. [26] compared the SMD corresponding to diesel, B5, B10, B20 and B100 of Jatropha oils blends. Their results show that the SMD gradually increases with increasing blend ratio of the biodiesel and they concluded the

kinematic viscosity to be the major factor for this. The effect of kinematic viscosity of the biodiesel on the SMD has been reported by Geo et al. and has been shown on Fig. 7. The reported values show the similar trend when compared with the data predicted in this study.

The same trend has been also reported by Park et al. [27] for SMD variation for 20% ethanol blend biodiesel (BDE20) and 100% biodiesel. Since BDE20 has lower kinematic viscosity than 100B, the former has lower SMD. Fig. 8 illustrate the SMD of the biodiesel fuel verses injected fuel temperature for different engine speeds. It can be seen that the SMD of the biodiesel decreases with increase in the injected fuel temperature. This is because when the temperature increases, the inter-molecular forces decrease. As a result the SMD decreases in the engine cylinder. This facilitates the evaporation of the fuel and combustion rate in the engine cylinder.

4. Conclusion

In this study models have been developed for predicting the density and kinematic viscosity of biodiesel blends at various temperatures and volume fractions. The experiments have been conducted according to EN ISO 3675:1998 and EN ISO 3104:1996 test procedures. From the study the following conclusions can be drawn:

1. The density and kinematic viscosity of the rapeseed oil biodiesel, corn oil biodiesel and waste oil biodiesel blends (0B, 5B, 10B, 20B, 50B, 75B, and 100B) have been measured in the temperature range of 15.6 °C–90 °C. It has been noticed that the specific gravity and the viscosity of the biodiesel blends increase with increase of the biodiesel fraction. It is also seen that the density and viscosity of each blend decreases with increase in the temperature.
2. Empirical equations to predict the density and the viscosity of the biodiesel and its blends as function of temperature have been developed. The empirical equations and the measured data are closely matched with R^2 of 0.993 for the density model and 0.999 for the kinematic viscosity model.
3. Empirical equations to predict the kinematic viscosity of the biodiesel and its blends from the density values of biodiesel fuels have been developed. The values from predicting models and the experimental values match closely.
4. The Grun–Nissan viscosity equation has been further modified to predict the kinematic viscosity of biodiesel blends from the biodiesel fraction and operating temperature values. The empirical models show fair degree of accuracy with a maximum absolute error of 0.50.
5. Viscosity of the biodiesel affects the performance of the fuel supply system including fuel pump, fuel filters and air-fuel mixing behaviour. The available experimental data show reasonable agreement with predicted trends.

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