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PREDICTING SPECIFIC GRAVITY AND VISCOSITY OF BIODIESEL FUELS

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ABSTRACT

Biodiesel is a promising non-toxic and biodegradable alternative fuel in transport sector. Of all the biodiesel properties, specific gravity and viscosity are the most significant for the effects they have on the utilization of biodiesel fuels in unmodified engines. This paper presents models, which have been derived from experimental data, for predicting the specific gravity and dynamic viscosity of biodiesel at various temperatures and fractions. In addition a model has also been developed to predict the dynamic viscosity of the biodiesel from its specific gravity. In order to develop these models, the specific gravity and viscosity of rapeseed oil biodiesel, corn oil biodiesel and waste oil biodiesel blends (0B, 5B, 10B, 20B, 50B, 75B, and 100B) were tasted across a temperature range of 15.6^{o}C to 90^{o}C using EN ISO 3675:1998 and EN ISO 3104:1996 test procedures. Evaluation of the proposed models shows it has same order of accuracy as the other models published in literature.

Key words: Biodiesel, Density, Viscosity, Blend, Fuel supply system

1. INTRODUCTION

Biodiesel is an alternative fuel consisting of the alkyl monoesters of fatty acids derived from vegetable oil or animal's fats. An engine running on biodiesel shows inconsistency in performance and emission because of variation in physical and chemical properties associated with the use of different biodiesels. The physical and chemical property variations in biodiesels can be caused by feed stock, growing climate conditions, soil type, and production process [1]. Viscosity, specific gravity and heating value are the most important parameters for diesel engine performance and emission characterisation [2]. One of the major shortcomings of vegetable oils being used in diesel engines is their high viscosity. Higher viscosity causes poor fuel atomization during spray, increases the carbon deposition on fuel filter, demands more energy to the fuel pump and induces wear in the fuel pumps and injectors [3]. 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 affecting engine performance and exhaust emission [4, 5, 6].The density of the diesel fuel is also very important, since other crucial performance parameters of the engine such as cetane number and heating value are correlated against it [7]. In addition the density values help to measure the amount of fuel used in fuel supply system by volume method [2]. The variability of the density affects the power rate 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 being used, are mixing the diesel with biodiesel and/or pre-heating the biodiesel [8]. To modify the specific gravity and the viscosity of the biodiesel; simple, stable and reliable mathematical models are very important. These models can be used in fuel supply system characterisation, fuel spray behaviour studies and fuel combustion analysis. The effects of temperature, fraction of biodiesel, and the chemical structure on specific gravity and viscosity have been reported and empirical correlations also developed [2-10]. Riazi and Al-Otaibi [9] developed a model for estimation of viscosity of fuels at various temperatures from its refractive index (I). In this model the equation needs determination of molecular weight, specific gravity, boiling temperature and refractive index of compounds. Tat and Van Gerpen [10] modified Andrade equation to determine the viscosity of the biodiesel at different temperatures. In their equation there are three constants that vary with type of biodiesel, blends and temperature. Most of the available methods for the estimation of viscosity of are either too complicated or inconvenient to use, or they require some input parameters which are not readily available. Therefore, the objective of this paper is to develop 'simple and accurate' models for prediction of the specific gravity and dynamic viscosity of biodiesel at various temperatures and biodiesel fraction. In addition a model has also been developed to predict the dynamic viscosity of the biodiesel from its specific gravity.

2. MATERIALS AND METHODS

2.1 Materials

The biodiesels used in this study were corn oil biodiesel, rapeseed oil biodiesel and waste oil biodiesel) and purchased from No-Fossil Fuel Corporation, Huddersfield.

The corn oil biodiesel and rapeseed oil biodiesel were produced by transesterfication process from 'virgin' oil using methanol. The waste oil biodiesel was produced from local cooking oil waste. Normal diesel fuel was obtained from local fuel supplier. The biodiesel were blended with diesel fuel at 5%, 10%, 20%, 50%, 75% and 100% on volume base. For each biodiesel six samples were prepared and totally 19 samples were prepared for physical and chemical analysis.

2.2 Specific Gravity Measurement

In this study the density was measured using hydrometer using the European test procedure, EN ISO 3675:1998 [11]. The glass hydrometer with specific gravity range of 0.7 to 1.0 within accuracy of three decimal places was used in the measurement. To collect temperature-dependent data, a 100ml graduated cylinder containing the biodiesel sample was placed in temperature controlled bath. The water bath temperature can vary from 15 to 95^{o}C. The test was repeated twice and the average value was taken.

2.3 Viscosity Measurement

The European test procedure standard [12], EN 3104:1996, was used to measure the kinematic viscosity of the 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 applied for the investigation of viscosity of the biodiesel. 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 2 to 10mm^2/s. The timing device with 0.01 seconds discrimination was used during the experimentation. The water bath temperature can vary from room temperature to 85^{o}C. The viscosity values below the room temperature were determined from the regression correlation of this study and previous reports.

3. RESULT AND DISCUSSION

3.1 Predicting Specific Gravity of Biodiesel Fuels

Specific gravity is the ratio of the density of the substance to that of water at 15.6^{o}C. Figure 1 shows the variation of specific gravity of corn oil biodiesel, rapeseed oil biodiesel and waste oil biodiesel with the biodiesel fraction blend. Three of the biodiesel blends have closely matching specific gravity values with a minimum value of 0.853 at 0% biodiesel fraction and maximum value of 0.880 at 100% biodiesel fraction. It was observed that the specific gravity of a blend increases with increase in the value of biodiesel volume fraction. Since three of the biodiesels and its blends have very close specific gravity values a common first degree regression equation was developed taking the average slope and interception point. The regression equation is described by equation (1).

$$SG_{blend} = 2.33x10^{-3} X + 0.855 \quad (1)$$

Where SG_{blend} is specific gravity of diesel and biodiesel blends and X is volume fraction of biodiesel at 15.6^{o}C. Clements (referenced in [13]) suggested using equation (2) to determine the specific gravity of different blends at a standard temperature. In this equation the specific gravity has been shown to be proportional to mass fraction 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 component *i*, and M_i is the mass fraction of component *i.*
To test the accuracy of the proposed equation against the equation proposed in literature a comparative analysis was carried out by using the values obtained from the hydrometer method, equation (1) and mixing equation (2). A comparison of the hydrometer method and equation 2 has shown maximum absolute error of 0.50% whereas a comparison of the hydrometer method and equation 1 has shown maximum absolute error of 0.29%. The correlation coefficient (R^2) for this data was 0.9945. This indicates that if the specific gravity of pure diesel and pure biodiesel are known, equation (1) or equation (2) can be used with confidence to determine the specific gravity of biodiesel blend at given blend percentage fraction.

After developing a correlation for specific gravity at a given temperature further work was carried out to establish effect of temperature on density. Figure 2 shows the effect of temperature on specific gravity of 100% biodiesel. For comparison the estimated specific gravity by Tat and Gerpen [7] correlation has also been included. The temperature was varied from 290K to 360K for 100% corn oil biodiesel, rapeseed and waste oil biodiesel and diesel. Three of the biodiesel have very closely matching specific gravity values at a given temperature. It was further seen that the specific gravity of the biodiesel decreases with the increase in temperature. To generate the regression correlation the average specific gravity of the biodiesel at given temperature was taken and a linear-regression equation (3) was developed. The measured average biodiesel specific gravity and regression line have maximum absolute error of 0.26% and R^2 of 0.992. Similarly the specific gravity of diesel in relation with temperature was developed and described in equation (4). The diesel density values based on empirical equation and the measured density value have maximum absolute error of 0.15% and R^2 of 0.9962.

$$SG_{biod} = -6.9x10^{-4}T + 1.075 \tag{3}$$

$$SG_{diesel} = -6.57x10^{-4}T + 1.051 \tag{4}$$

Where SG_{biod} is density of biodiesel, SG_{diesel} is density of diesel and *T* is temperature (K).The regression equation was compared with Tat and Gerpen equation and it was noticed that the maximum absolute error was about 3.5%. This difference may be due to the nature of the biodiesel used in Tat and Garpen study. In this study the biodiesels used have different sources and production processes. In figure 2 it can be seen that in between 320-330K the specific gravity of the biodiesel is similar to the normal diesel density (0.850 to 0.860). This implies if there is a system to pre-heat the biodiesel in temperature-range of 320-330K, the drawback of biodiesel in relation to density could be minimized. In the present study a new equation (5) has been developed using mixing equation (2) and the regression equations (equation 3 and 4) to estimate the specific gravity of biodiesel. Equation (5) can be used to determine the specific gravity of the binary blend of biodiesel and diesel at given temperature and blending fraction.

$$SG_{mix} = (3.3E - 5T + 0.0244)X - 6.57E - 4T + 1.051 \tag{5}$$

Where SG_{mix} is density of the binary (kg/m^3), *X* is volume fraction of the biodiesel and *T* is the temperature (K). The specific gravity as obtained from the experimental results of rapeseed oil biodiesel were compared with estimated value of biodiesel specific gravity using equation (5) and shows maximum error of 0.0054. This implies that equation (5) can be used to estimate the density of the biodiesel blend at any temperature and biodiesel fraction.

3.2 Predicting Dynamic Viscosity of Biodiesel Fuels

Viscosity is the resistance to flow in fluid system. Table 1 provides the data on the dynamic viscosity of corn oil biodiesel, rapeseed oil biodiesel, and waste oil biodiesel blends at different biodiesel volume fraction. The biodiesels' kinematic viscosity increase with increasing biodiesel blend fraction for all the blends. The experimental data were correlated as function of biodiesel fraction by empirical second degree equation described as equation (6) and a similar correlation was reported by Apetekin and Cankci[2]. The coefficients of equation (6) values are described in table 1 for the three biodiesels. This equation can be used to estimate the viscosity of biodiesel at a given biodiesel fraction.

$$\mu_{corr} = Ax^2 + Bx + C \tag{6}$$

Where μ_{corr} is the dynamic viscosity (Pa.s), *A, B, C* are coefficients of the second degree equation and *X* is biodiesel fraction. A more well known mixing law available in literature is, the Grun-Nissan and Katti-chaudhri law, originally proposed by Arrhenis [14]. The law is written as equation (7).

$$\ln(\nu_{\max}) = x_1 \ln(\nu_1) + x_2 \ln(\nu_2) \tag{7}$$

Where, ν_{mix} is the kinematic viscosity (mm^2/s) of the mixture, ν_1 and ν_2 are kinematic viscosities (mm^2/s) of components 1 and 2 and x_1 and x_2 are the volume fractions of components of 1 and 2. In this study the kinematic viscosity was changed to dynamic viscosity. Table 1 also presents the measured viscosity values, the calculated viscosity values by equations (6 and 7), the correlation regression equation (6) coefficients, R^2 values, and the absolute error between the measured and calculated viscosity of different biodiesel.

Table 1 **Dynamic viscosity of biodiesel and its blends at 40°C.**

Type of Biodiesel	Blend (%)	Measured dynamic viscosity 10^{-3} Pa.s	A	B	C	R^2	Calculated dynamic viscosity by:		Absolute error between measured and	
							Regression correlation, (10^{-3} Pa.s)	Grun-Nissan (10^{-3} Pa.s)	Regression correlation	Grun-Nissan
Corn oil Biodiesel	0	2.9868	$8x10^{-9}$	$1x10^{-5}$	0.0031	0.9891	3.0661	2.9868	0.0794	0.0000
	5	3.2581					3.1401	3.0479	0.1180	0.2102
	10	3.2087					3.2094	3.1049	0.0007	0.1038
	20	3.1996					3.3421	3.2148	0.1425	0.0153
	50	3.7697					3.7680	3.5852	0.0017	0.1846
	75	3.9684					4.1437	3.9315	0.1753	0.0369
	100	4.3015					4.5240	4.3015	0.2226	0.0000
Rapeseed biodiesel	0	2.9868	$5x10^{-8}$	$1x10^{-5}$	0.0031	0.9874	3.0180	2.9868	0.0312	0.0000
	5	3.2297					3.0849	3.0602	0.1448	0.1695
	10	3.3503					3.1615	3.1445	0.1887	0.2057
	20	3.4964					3.2783	3.2808	0.2182	0.2157
	50	3.8669					3.6931	3.7887	0.1738	0.0783
	75	4.0276					4.0524	4.2707	0.0248	0.2432
	100	4.8188					4.4289	4.8188	0.3899	0.0000
Waste oil biodiesel	0	2.9868	$2x10^{-8}$	$1x10^{-5}$	0.0031	0.9921	3.0695	2.9868	0.0828	0.0000
	5	3.3184					3.1407	3.0615	0.1777	0.2570
	10	3.2331					3.1996	3.1233	0.0334	0.1097
	20	3.3980					3.3335	3.2602	0.0645	0.1378
	50	3.7267					3.7848	3.7009	0.0581	0.0258
	75	4.2453					4.2416	4.1287	0.0037	0.1166
	100	4.5825					4.7381	4.5825	0.1557	0.0000

The dynamic viscosity of the biodiesel varies in the range of $2.96x10^{-3}$ to $4.81x10^{-3}$Pa.s. The maximum absolute error between the measured and calculated dynamic viscosity (by Grun-Nissan equation (7)) is 0.257. The measured and regression correlation have maximum absolute error of 0.389 and the minimum R^2 value of 0.987. Both Grun-Nissan and the empirical correlation proposed in this study have reasonable accuracy to estimate the dynamic viscosity of the biodiesels. However the regression coefficient variation with type of the biodiesel creates difficulty of using the correlation equation (6). Figure 3 shows the dynamic viscosity of 100% corn oil, rapeseed oil and waste oil biodiesel variation with temperature range of 295K to 360K. It can be seen that the dynamic viscosity of the biodiesel decrease with the increase of the temperatures. The empirical correlation for the dynamic viscosity and temperature is described by equation (8) which has been developed based on the experimental results. The correlation has R^2 value of 0.9999 and is similar to Joshi *et al*. correlation [15]. Joshi *et al*. [15] and Tat & Gerpen [13] have modified the Arrhens equation for predication of biodiesel dynamic viscosity at different temperature. 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 figure 4. All of the correlations curves follow the same trend. This correlation developed in this study has maximum absolute error of 0.65 whereas Joshi *et al*. and Tat & Gerpen have an error of 0.45.

$$\mu_{corr} = -0.0285\ln(T) + 0.1659 \tag{8}$$

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

Further analysing the experimentally measured specific gravity and dynamic viscosity of biodiesel an equation was developed relating viscosity as function of specific gravity as shown below in equation (9). This equation could be used to estimate dynamic viscosity of the biodiesel for known specific gravity of biodiesel. This will save the skilled manpower, chemicals and test facilities to be expensed for experimental analyses of viscosity.

$$\ln(\mu) = 35.7SG - 36.1 \tag{9}$$

Where μ is dynamic viscosity and SG is specific gravity of the biodiesel at given temperature. Furthermore, Grun-Nissan equation (7) has been further modified and a new euation has been developed [equation (10)] by combining equation 3, 4 and 9 to determine the viscosity of the blend at given temperature and biodiesel fraction. The modified mixing equation has maximum absolute error of 0.50.

$$\ln(\mu_{mix}) = (-0.0012T + 0.8456)X - 0.0234T + 1.363 \tag{10}$$

Where μ_{mix} dynamic viscosity of the biodiesel X is volume fraction of the biodiesel and T is the temperature (k). Equation (10) can be used to determine the dynamic gravity of the binary blend of biodiesel and diesel at given temperature and blending fraction.

4. CONCLUSION

In this study models have been developed for predicting the specific gravity and dynamic viscosity of biodiesel at various temperatures and fractions using experimental data. The experiments have been conducted according to EN ISO 3675:1998 and EN ISO 3104:1996 test procedures. From the study the following conclusion can be drawn:

1. The specific gravity and 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 within a temperature range of 15.6°C to 90°C. It is noticed that specific gravity and viscosity of the biodiesels increase with increase in the biodiesel fraction. It is also seen that the specific gravity and viscosity of each blend decreases with increase of the temperature.

2. Empirical equations to predict the specific gravity of biodiesel and its blends as function of biodiesel fraction and temperature has been developed. The empirical equation and the measured data are closely matched with a maximum error of 0.0054.

3. Empirical equations to predict the dynamic viscosity of biodiesel and its blends from specific gravity of biodiesel have been developed.

4. The Grun-Nissan viscosity equation has been further modified to predict the dynamic viscosity of biodiesel from the biodiesel fraction and temperature values. All the empirical equations show fair degree of accuracy.

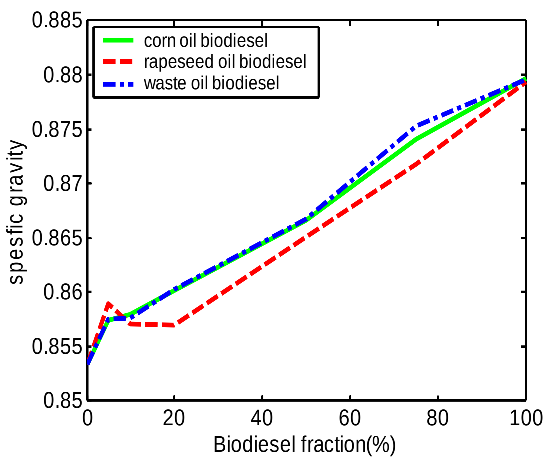

Figure 1 Measured specific gravity of corn oil, rapeseed and waste oil biodiesel as function of biodiesel fraction

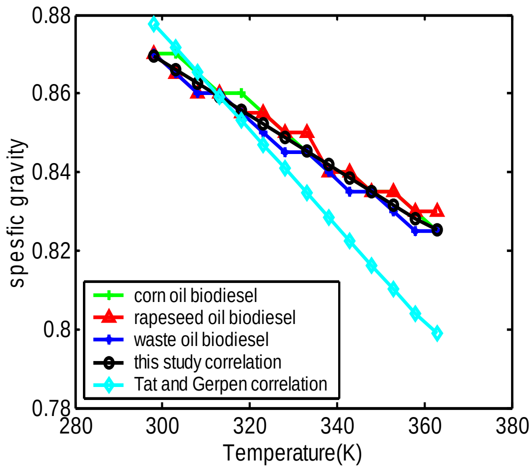

Figure 2 Measured and predicted specific gravity of biodiesel in the temperature range of 290K to 360K

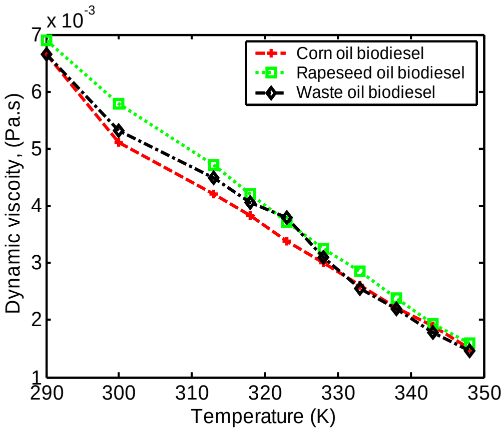

Figure 3 Measured dynamic viscosity Corn oil, rapeseed and waste oil biodiesel as function of temperature

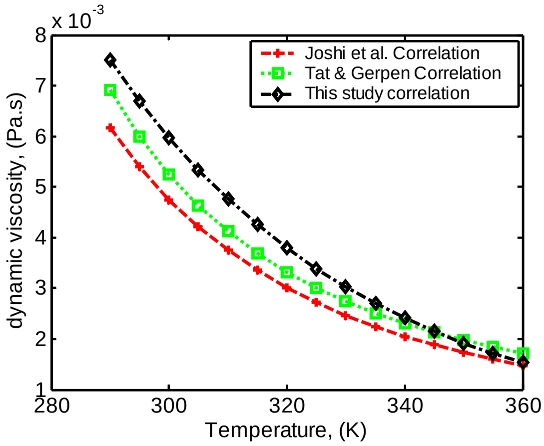

Figure 4 Predicted dynamic viscosity of biodiesel with temperature range of 290K to 360K

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