Study of density and viscosity variation with temperature for fuels used for Diesel engine

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Abstract With the development of oil industry, diesel fuel resulted to be more appropriate as fuel for high-speed diesel engines, than vegetable oil, the first fuel used by Rudolf Diesel to test the diesel engine. Vegetable oils could represent an alternative to heavy fuel oil used in the low-speed marine diesel engines. Nowadays, diesel fuel is commercialized blended with up to 6% biodiesel. In the future, this percent is expected to increase. Taking into account these perspectives, it is necessary to know the behavior of the fuel components, when variations of temperature occur. Experimental densities and viscosities data for a vegetal oil, diesel fuel and biodiesel were reported here in the temperature range of 20^{o}C to 60^{o}C, and the accuracy of empirical models proposed to predict these properties at different temperatures was evaluated.

Keywords: Diesel oil, biodiesel, vegetable oil, density, viscosity

1. Introduction

At its first presentation at the World Exposition in Paris in 1900, the diesel engine patented by Rudolf Diesel was fuelled by vegetable oil. With the development of oil industry, diesel fuel resulted to be more appropriate as fuel for high-speed diesel engines, due to its improved properties.

Nowadays, since the environment pollution have attained alarming levels, and more and more frequently raises the question of how long the reserves of fossil fuels will last, biofuels are used in order to replace a part of the fossil fuels used in the transport sector. Diesel fuel is becoming to be commercialized blended with up to 6% biodiesel. This percent is expected to increase in the future, taking into account the benefits of biofuels: reduction of the environment pollution, reduction of the dependency on the imported fossil sources of energy. Vegetable oils could represent an alternative to heavy fuel oil used in the low-speed marine diesel engines.

Vegetable oils consist mainly of a mixture of triglycerides (esters of three fatty acids and glycerol) with small quantities of other components as mono- and di-glycerides, free fatty acids. Biodiesel obtained from vegetable oils or animal fats by transesterification reaction with a monoalcohol (usually methanol), consists mainly of a mixture of monoalkyl esters of fatty acids, with reduced quantities of monoalcohol, free glycerine, mono- and di-glycerides. Diesel fuel is a mixture of saturated linear and cyclic hydrocarbons with relatively reduced quantities of aromatics. Unless diesel fuel, vegetable oils and biodiesel contain oxygen in their molecules, resulting in an improved combustion of the fuel in the engine, with less carbon monoxide, hydrocarbons and particulate matters in the exhaust emissions.

The physicochemical properties of the fuels influence the behaviour and the performance of the vehicle engine. Density and viscosity are one of the most important characteristics of the liquids used as fuels in diesel engines. These properties influence the atomization and combustion processes that take place in the diesel engine, and the flow properties.

Density and viscosity of vegetable oils [1 – 6], diesel fuel [4-9] and biodiesel [9-20] were intensely investigated in the literature. Based on measured values for density and respectively viscosity of a large number of vegetable oils, diesel

ISSN-1223-7221

fuel, and biodiesel, predictive/correlation equations for the dependency of these properties on temperature were proposed in the literature [14, 19 -24]. The linear dependency of density on temperature is generally accepted for these fuels [19]:

$$d = aT + b \quad (1)$$

where d is the density, T – temperature, a and b are correlation parameters.

The dependency of viscosity of fuels like diesel fuel, biodiesel or vegetable oils, on the temperature was found to be satisfactorily described by an Arrhenius-type equation [3, 4, 10, 23]:

$$\eta = A \cdot \exp\left(\frac{B}{T}\right) \quad (2)$$

where η is the kinematic viscosity, T – temperature, A and B are correlation constants.

Equation (2) known as the Andrade correlation, is used in petroleum industry to predict the viscosity of liquid fuels. Some other equations derived from eq. (2) were used to correlate the viscosity of diesel fuel or biodiesel with temperature [14, 19, 23, 24].

Density and viscosity influence fuel atomization and the combustion process. These physical parameters are used to calculate indexes that provide a basis for comparison between fuels for diesel engines, like cetane index and ignition index. Cetane index (CN) is used to evaluate the combustion quality (ignition delay) of a fuel like light distillate diesel oils or biodiesels, used for high-speed diesel engines. Calculated ignition index (CII) is used to evaluate ignition quality of fuels like heavy fuel oils or vegetable oils used for low-speed diesel engines.

The aim of this paper is to report experimental densities and viscosities of fuels or potential fuels for diesel engines like vegetable oil, diesel oil and biodiesel, in the range of 20°C – 60°C, and to evaluate the accuracy of empirical equations used to evaluate density and respectively viscosity variation with temperature.

2. Experimental

Commercially available vegetable oil (corn oil), diesel oil and biodiesel were used in this study. **Table 1** reports some of the fuels properties. Analysis methods used to characterize these fuels were SR EN ISO 2719:2003 for flash point, SREN 14104:2003 for acidity index, SR EN ISO 12937:2003 for water content, SR EN ISO 3675:2003 for density. The refractive index was determined using a thermostated Abbe refractometer.

Table 1. Properties of vegetable oil, diesel oil and biodiesel

Property	Vegetable oil	Diesel oil	Biodiesel
Flash point, °C	277	68	130
Acidity index, mgKOH/g	0.17*	-	0.27
Water content, mg/kg	493	105	250
Density at 15°C, kg/m^3	922	843	883
Refractive index at 25°C	1.4706	1.4674	1.4540

*Free acidity express as % oleic acid.

The density and viscosity were simultaneously measured using an Anton Paar device, SVM 3000 type. The density measurement is based on the "U" vibrating tube method, while the viscosity is measured with a rotational viscometer. The uncertainty in density determination was ± 0.00005g/cm^3, and ±0.70% for the viscosity respectively. The temperature of the samples was controlled with an accuracy of ± 0.02°C.

The measurements were conducted in the temperature range of 20°C to 60°C, with an increasing step of 5 degrees. All measurements at each temperature were repeated three times and the results were averaged.

The accuracy of empirical equations used to correlate density and respectively viscosity with temperature was evaluated using the corresponding values of absolute error (AE) calculated with the equation:

$$AE = P_{\exp} - P_{calc} \quad (3)$$

where AE is the absolute error, P_{exp} is the measured value of the property, and P_{calc} is the calculated value of the property.

3. Results and Discussions

Experimental results of density measurements for the investigated fuels in the temperature range of 20°C to 60°C are shown in **Fig.1.**

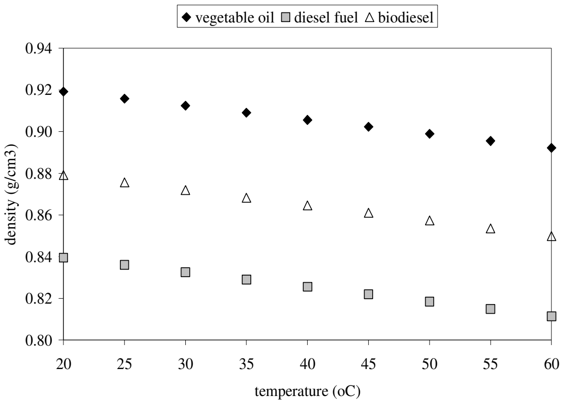

Fig.1. Density of vegetable oil, diesel oil and biodiesel as function of temperature

From Fig. 1 it can be observed a linear change in density with the increase of temperature for vegetable oil, diesel fuel and biodiesel, the density of these fuels decreasing with a similar rate.

At the same temperature, the vegetal oil has the greater density and the diesel oil, the smaller one. There is a difference of 0.04 g/cm^3 between the density of diesel fuel compared to biodiesel, and of biodiesel compared to vegetable oil respectively.

Viscosity data obtained for the vegetable oil, diesel oil and biodiesel as function of temperature is presented in **Fig. 2.**

It can be seen that the points representing experimental viscosity of vegetable oil stand apart. Diesel fuel and biodiesel have similar viscosities, while the viscosity of vegetable oil is clearly greater. The difference in viscosity between vegetable oil on one hand, and diesel fuel and biodiesel on the other hand, is reducing with the increase of temperature. It can be observed from Fig.2 that the dependency of viscosity on temperature is more marked in the case of vegetable oil compared to diesel fuel and biodiesel. There were similar variations in the viscosity of diesel fuel and biodiesel with temperature.

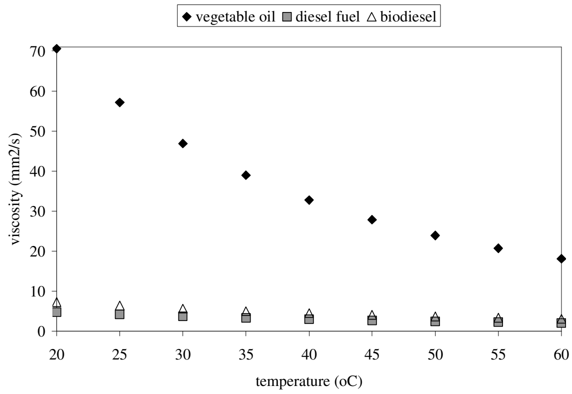

Fig.2. Viscosity versus temperature for vegetable oil, diesel fuel and biodiesel

Density experimental data obtained for the three investigated fuels were correlated by a linear equation (eq.1), and the correlation parameters were calculated using the least square regression analysis. The value of the correlation coefficients for the investigated fuels is reported in Table 2.

Table 2. Correlation parameters for density calculation

Fuel	Correlation parameters (eq.1)		Correlation coefficient (R^2)
	a	b	
Vegetable oil	-0.0007	0.9387	1
Diesel fuel	-0.0007	0.8939	1
Biodiesel	-0.0007	0.8536	1

Figure 3 presents the distribution of absolute error for vegetable oil, diesel fuel, and biodiesel density correlation, using eq.(1). As can be seen from **Fig.3**, the density of different fuels used for diesel engine can be estimated with a good accuracy using the same empirical equation. The estimation of the density using a linear correlation is very accurate in the case of diesel fuel and slightly underestimated in the case of biodiesel and respectively slightly overestimated in the case of vegetable oil. The difference between experimental and calculated density is slowly increasing with the increase of temperature.

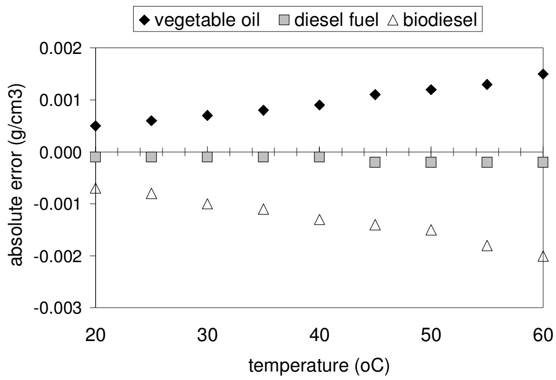

Fig.3. Absolute error distribution for vegetable oil, diesel fuel and biodiesel density correlations

The maximum absolute error occurs at the upper limit of the investigated range of temperature and is 0.0020 g/cm^3 in the case of biodiesel, 0.0015 g/cm^3 in the case of vegetable oil and 0.0002 g/cm^3 in the case of diesel fuel.

A greater accuracy in correlating the viscosity of the fuels investigated with temperature than eq.(2) offers, was obtained with a third-degree polynomial equation:

$$\eta = eT^3 + fT^2 + gT + h \qquad (4)$$

where e, f, g, and h are correlation parameters.

The value of the correlation coefficients for viscosity calculation with eq. (4) for the investigated fuels and the corresponding correlation coefficients (R^2) are reported in **Table 3**.

Table 3. Correlation parameters for viscosity calculation

Fuel	Correlation parameters (eq.5)				R^2 *
	e	f	g	h	
Vegeta-ble oil	$-5x10^{-4}$	0.0946	-6.0350	157.670	0.9999
Diesel fuel	$-1x10^{-4}$	0.0029	-0.2195	8.159	1.0000
Biodiesel	$-2x10^{-4}$	0.0045	-0.3440	12.562	1.0000

*Correlation coefficient

The distribution of absolute error for vegetable oil, diesel fuel and biodiesel viscosity calculation using eq. (4) is presented in fig.(4). The estimation of the viscosity of fuels used for diesel engine using a parabolic empirical equation has different accuracy, depending on the type of the fuel and on the temperature.

The accuracy of viscosity prediction is relatively good for a relatively low range of temperature variation, near the ambient temperature. The estimation of the viscosity using a parabolic correlation has a good accuracy in the case of diesel fuel and biodiesel. The absolute error of diesel fuel and biodiesel viscosity prediction is slightly increasing with the increase of temperature.

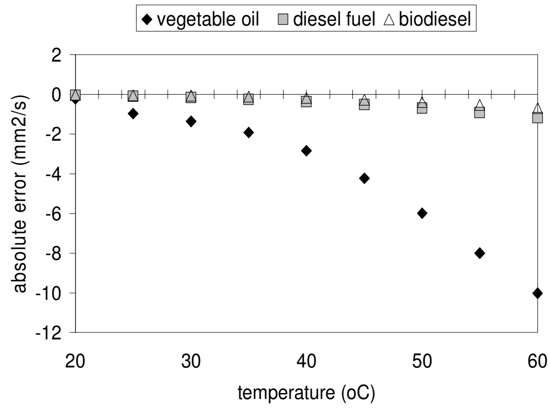

Fig.4. Absolute error distribution for vegetable oil, diesel fuel and biodiesel viscosity correlations

The accuracy of vegetable oil viscosity estimation using eq.(4) is relatively good for ambient temperature, but the error is rapidly increasing with temperature increasing. The absolute error of viscosity predicted using eq.(4) at 60°C is -0.6926 mm^2/s in the case of biodiesel, -1.1804 mm^2/s in the case of diesel fuel and -10.0190 mm^2/s in the case of vegetable oil.

On the best of our knowledge, this evaluation of some important properties (density and viscosity) dependency on temperature for fuels used for diesel engine, using the same predictive equations, was not presented in the literature. The experimental data presented in this study are in accordance with data presented in the literature [14, 19, 23-26]. Other empirical equations for viscosity estimation with improved accuracy at different temperatures could be proposed in the future.

4. Conclusions

Experimental densities and viscosities data for a vegetal oil, diesel fuel and biodiesel were reported and the accuracy of empirical models proposed to predict these properties was evaluated.

From this study the following conclusions can be drawn:

- both density and viscosity decrease from vegetable oil to biodiesel and diesel fuel, and both density and viscosity of the three fuels decrease with the increase of temperature;
- for the same temperature, the vegetal oil has the greater density and the diesel oil, the smaller one;
- the dependency of the density on the temperature is of the same nature for the three investigated fuels, being of linear nature;
- the estimation of the density using a linear correlation is very accurate in the case of diesel fuel and slightly underestimated in the case of biodiesel and respectively slightly overestimated in the case of vegetable oil;
- for the same temperature, diesel fuel and biodiesel have similar viscosities, while the viscosity of vegetable oil is clearly greater;
- there were similar variations in the viscosity of diesel fuel and biodiesel;
- the dependency of viscosity on temperature is more marked in the case of vegetable oil compared to diesel fuel and biodiesel
- the estimation of the viscosity of fuels used for diesel engine using a third-degree polynomial empirical equation has different accuracy, depending on the type of fuel and on the temperature;
- the estimation of the viscosity using a parabolic correlation has a good accuracy in the case of diesel fuel and biodiesel.
- the absolute error in diesel fuel and biodiesel viscosity prediction is slightly increasing with the increase of temperature;
- the accuracy of vegetable oil viscosity estimation using a third-degree polynomial equation is relatively good for ambient temperature, but is rapidly increasing with the temperature increase.

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