ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil
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VISCOSITY AND THERMAL CONDUCTIVITY OF SOYBEAN OIL-DIESEL BLENDS BETWEEN 293 AND 353 K

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Abstract. *Research on alternative fuels such as vegetable oils is attracting considerable attention due to pollutant emissions from conventional fuels, depletion of fossil fuel reserves, increase of petroleum costs and more severe emission protocols. This work reports on experimental data of dynamic viscosity and thermal conductivity of diesel fuel and soybean oil mixtures at different compositions for temperatures ranging from 293 to 353 K (20 to 80°C). The viscosity was measured with an oscillating piston viscometer and the thermal conductivity was determined via a hot-wire meter. An Arrhenius-type relationship and a mixing rule based on the classical relationship of Eyring were used to correlate the viscosity of the pure fluids and mixtures. The blend viscosity decreases with increasing diesel concentration and decreases with temperature. The thermal conductivity of the blends was observed to increase with temperature.*

Keywords: *soybean oil, diesel, blends, viscosity, thermal conductivity*

1. INTRODUCTION

Vegetable oils are being considered as fuel alternatives in diesel engines because of depleting resources of crude oil, its increasing price, and also global climate changes (Altin *et al.*, 2001). In Brazil there are several crops that can be used for producing vegetable oils to fuelling diesel engines. Hartmann *et al.* (2012) reported results of power, emissions and eficciency for soybean, sunflower and tung. However, problems associated with the high viscosity of vegetable oils, such as flow atomization and heavy particulate emissions (Franco and Nguyen, 2011), prevent their straight use in diesel engines. Possible solutions to these problems are transesterification with methanol, ethanol or butanol, which results in biodiesel fuels, or simply dilution with diesel fuel, giving rise to vegetable oil-diesel fuel blends (Schwab *et al.*, 1987).

Thermophysical properties of alternative fuels, such as viscosity, density and thermal conductivity, are essential input data for engine combustion models. However, the majority of the data in the literature is related to biodiesel and pure vegetable oils (Tat and van Gerpen, 1999; Rodenbush *et al.*, 1999; Kerschbaum and Rinke, 2004; Yuan *et al.*, 2005; Joshi and Pegg, 2007; Benjumea *et al.*, 2008; Brock *et al.*, 2008; Candeia *et al.*, 2009; de Lira *et al.*, 2010; Rámirez-Verduzco *et al.*, 2011; Ramírez-Verduzco *et al.*, 2012; Esteban *et al.*, 2012; Meng *et al.*, 2013; Joshi *et al.*, 2012; Silva *et al.*, 2012). Only a few number of studies deals with thermophysical properties of vegetable oil-diesel fuel blends (Tangsathitkulchai *et al.*, 2004; Wagner *et al.*, 2010; Franco and Nguyen, 2011). Most of these studies present viscosity and density data only, so there is a lack of studies dealing with thermal conductivity of vegetable oil and diesel fuel blends.

Wagner *et al.* (2010) experimentally determined the viscosity of unaltered waste soybean oil (WSO) blended with petroleum fuels. Three blend viscosity models (Arrhenius, Wright, and the ASTM D7152-05 standard) were evaluated for viscosity prediction over a temperature range of -10°C to 40°C. Results indicated that the Arrhenius method using volume fractions was the most accurate predictor of viscosity for binary blends made of WSO and diesel as well as multicomponent blends made from WSO, diesel, kerosene, and gasoline. Tangsathitkulchai *et al.* (2004) reported viscosity data for crude palm oil and coconut oil blended with diesel oil over the temperature range of 20°C to 80°C and for different mixture compositions. The reduction of viscosity with increasing liquid temperature followed an exponential relationship, with the two constants of the equation being a function of the volume percentage of the vegetable oil in the mixture. A single empirical equation was developed for predicting the viscosity of these fuel mixtures under varying temperatures and blend compositions. Franco and Nguyen (2011) presented dynamic viscosity and density of diesel fuel and vegetable oil mixtures at different compositions as a function of temperature (between 20°C and 80°C). The vegetable oils used were corn, canola, olive, peanut, soybean and sunflower. Viscosities of the pure oils and diesel were satisfactorily correlated with temperature by means of an Arrhenius-type relationship. The Arrhenius blending rule was found applicable to describing the composition dependence of viscosity of all vegetable oils-diesel blends at a fixed temperature. These relations were combined to develop a simple mixture viscosity model to predict the viscosity of the vegetable oil-diesel blends as functions of temperature and composition based on properties of the pure components.

In this work viscosity and thermal conductivity of a soybean oil and their blends with a petroleum diesel fuel are studied as a function of temperature (from 293 K to 353 K) and composition (0%, 25%, 50%, 75% and 100% volume oil). The viscosity data was correlated using an Arrhenius-type relationship and a mixing rule based on the classical relationship of Eyring that allows the blend viscosity to be estimated from the properties and composition of the pure components.

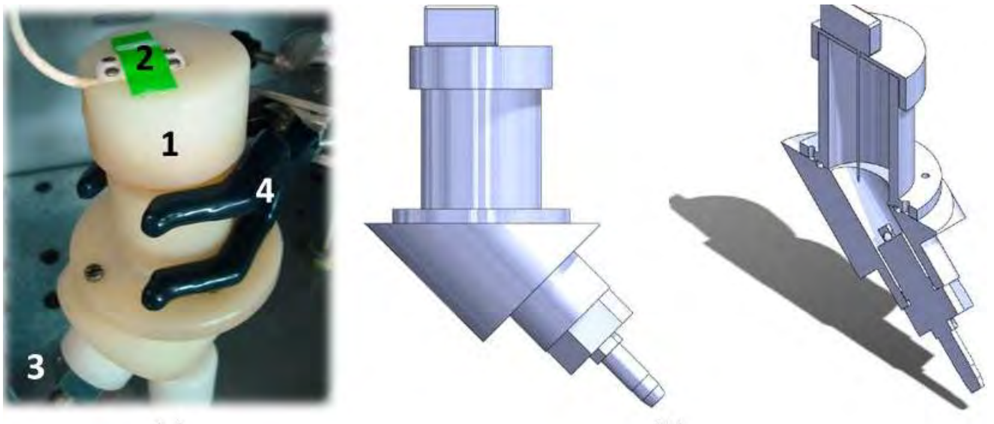
2. EXPERIMENTS

2.1 Materials

The soybean oil and automotive diesel used in this study were acquired in local market and used without any further treatment. The soybean oil was blended with automotive diesel fuel to make three mixture samples of 25%, 50% and 75% oil by volume. Blending was carried out at room temperature by adding a measured volume of the oil to diesel under continuous agitation. Thermal conductivity and dynamic viscosity measurements were performed at constant temperatures ranging from 293 to 353 K (20 to 80°C).

2.2 Viscosity and Thermal Conductivity

The experimental apparatus is schematically illustrated in Fig. 1a. The cell (1) is a cylindrical nylon piece (measurement cell) with an internal diameter of 32 mm and an internal volume of approximately 150 mL. The cell was designed to keep the soybean-diesel mixture tightly sealed and to allow easy and efficient positioning of the measuring instruments. Details of this cell can be observed in a cutaway view in Fig. 1b. The cell is instrumented for thermal conductivity (2) at the top and viscosity (3) at the bottom. An aluminum frame (4) fixes the cell inside an oven (not shown in Fig. 1) with a controlled temperature environment.



(a) (b)

Figure 1. Schematic description of the experimental apparatus.

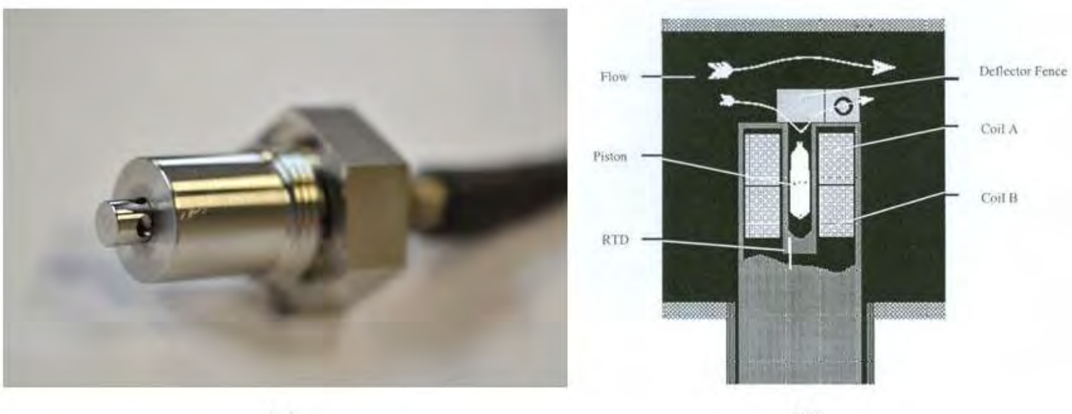
The thermal conductivity meter (2) is a Decagon KD2 Pro model, as shown in Fig. 2a. The operating principle of this device is based on the transient hot-wire method, in which the thermal conductivity (k) values are obtained by solving the transient heat conduction equation in cylindrical coordinates in a homogeneous medium. With this technique, a heat pulse is applied to a needle (sensor in Fig. 2b), and the temperature response with time is monitored at the heated needle both during and after the heat pulse. The nature of the temperature response depends on the thermal conductivity of the material. Natural convection arising from the transient heating of the fluid adjacent to the needle must be avoided (Cobos, 2010).

The viscosity meter (3) is shown in Fig. 3a. This piston-style viscometer, shown in a cutaway view in Fig. 3b, contains two magnetic coils inside a stainless steel body. A low mass stainless steel piston inside the measurement chamber is magnetically forced back and forth in the fluid. The time required for the piston to move a fixed distance is then very accurately related to the viscosity of the fluid in the chamber. Temperature is measured continuosly with the use of a resistance temperature detector (RTD) mounted at the base of the viscometer measurement chamber (Cambridge, 2009).

The experimental procedure to determine the thermal conductivity and dynamic viscosity as a function of temperature and volumetric composition is described as follows. Initially, the cell (1) shown in Fig. 1 is cleaned to remove waxes

(a) (b)

Figure 2. Thermal conductivity meter (Decagon, 2010).



(a) (b)

Figure 3. Cutaway view of viscosity meter sensor tip (Cambridge, 2009).

and moisture and the conductivity meter (2) and the viscometer (3) are positioned at the top and at the bottom of the cell, respectively. The cell is completely filled with the liquid whose properties are to be determined. Then, the oven is turned on and the desired temperature is set. A proportional-integral-derivative (PID) controller is responsible for controling the temperature. When the desired temperature is achieved and stabilized, which is characterized by constant readings ($\pm 0.1^\circ$C) during half an hour, three thermal conductivity measurements are carried out and an average value is calculated. After this, the viscosity is measured, with an average value calculated from ten measurement points.

The uncertainty of the thermal conductivity measurement was ± 0.02 W/(m·K) (68% confidence level). The uncertainty of the viscosity measurement was ± 0.1 cP (68% confidence level).

3. RESULTS

During all thermal conductivity tests care was taken to ensure that convective heat exchange was negligible. The fluid sample and the vertically mounted sensor were kept still during the measurements and all potential sources of vibration were eliminated. To verify the absence of free convection in the liquid sample, preliminary thermal conductivity measurements of pure soybean oil and diesel fuel were performed in a glass beaker for visual inspection of the fluid.

Figure 4 presents the thermal conductivity data for pure components and blends as a function of temperature and composition. For pure soybean oil, thermal conductivity presents a little decrease with temperature up to approximately 325 K, then starts to increase. For pure diesel, thermal conductivity increases with temperature. For temperatures up to 335 K, pure soybean oil has the highest conductivity in comparison to pure diesel. However, for temperatures higher than 335 K, it seems to present an inversion of this behaviour. Thermal conductivity of the diesel fuel is more sensitive to temperature than the soybean oil. At a fixed blend, conductivity increases with temperature similarly to that of pure diesel. For temperatures up to 335 K, the blend conductivity decreases with increasing diesel concentration. For values higher than 335 K, blend conductivity seems to be indifferent to composition and temperature.

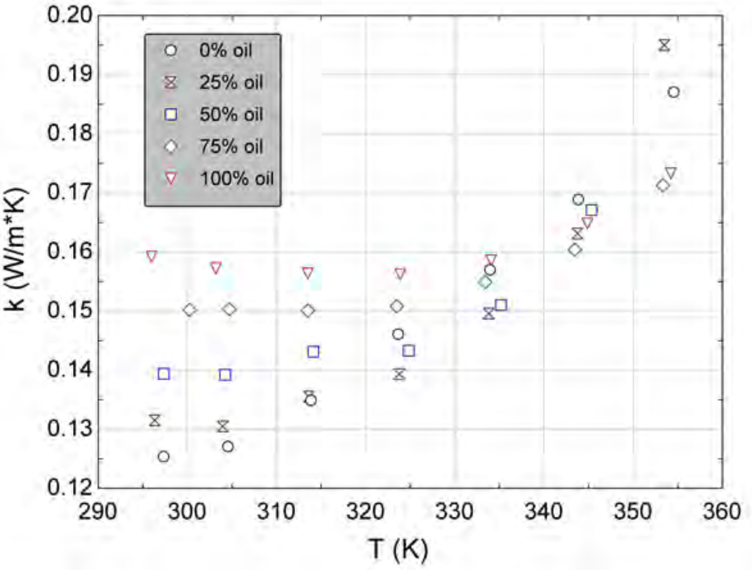


Figure 4. Thermal conductivity data for soybean oil-diesel blends.

Figure 5 shows viscosity data obtained for the pure soybean oil (100% oil) and diesel fuel (0% oil) as a function of temperature. At a given temperature, soybean oil has the highest viscosity, as expected. Compared to the diesel, the soybean oil is approximately 10-11 times more viscous when the temperature is decreased from 340 K to 295 K. Viscosity data obatained for the soybean oil blended with the diesel fuel as a function of composition and temperature is also presented in Fig. 5. For the blends, viscosity decreases with temperature similarly to that of the pure soybean oil and the diesel. As expected, the blend viscosity decreases with increasing diesel concentration. An Arrhenius type relationship was used to correlate the viscosity with temperature,

$$\mu = A \exp\left(\frac{E}{RT}\right) \tag{1}$$

where μ is dynamic viscosity, T is absolute temperature, A is a constant, E is the activation energy and R is the universal gas constant. Parameters A and E were determined by least-squares regression and can be visualized in Table 1.

Although the Arrhenius relationship (Eq. (1)) is satisfactory for correlating blend viscosity as a function of temperature, a more universal approach was used for the soybean oil-diesel blends. Extending the classical relationship for viscosity of a pure liquid due to Eyring (Glasstone *et al.*, 1941) to these blends,

$$\ln \mu = \phi \ln \mu_O + (1 - \phi) \ln \mu_D \tag{2}$$

where ϕ is the oil volume fraction and the subscripts O and D stands for pure soybean oil and diesel, respectively. This relation has been used for predicting transport properties of ideal liquid mixtures based on properties of individual components (Polling *et al.*, 2000). AAD (average absolute deviation) using Eq. (2) can be visualized in Table 1. This result is reasonable for these soybean oil-diesel blends, once the components have similar chemical structures and form miscible solutions at all proportions within the temperature range investigated (Franco and Nguyen, 2011).

Grunberg and Nissan (1949) introduced a fitting parameter (C_{OD}) to Eq. (2) to consider the non-idealities,

$$\ln \mu = \phi \ln \mu_O + (1 - \phi) \ln \mu_D + \phi(1 - \phi)C_{OD} \tag{3}$$

where C_{OD} is regressed to experimental data. The viscosity data correlation using Eq. (3) can be visualized in Fig. 5 and the obtained AAD regressing the experimental viscosity data (C_{OD}=0.2995) can be observed in Table 1. An improvement in the results is observed.

4. CONCLUSIONS

Experimental data of dynamic viscosity and thermal conductivity of soybean oil-diesel fuel blends at different compositions for temperatures ranging from 293 to 353 K was reported. The main conclusions arising from this study are as follows.

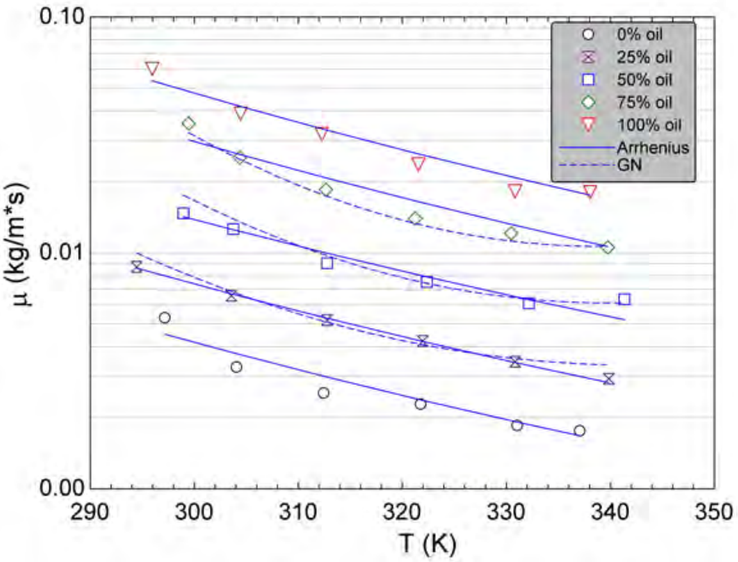


Figure 5. Dynamic viscosity data for soybean oil-diesel blends.

Table 1. Model parameters and statistical quantities.

Blend	A (10^{-6}kg/m s)	E (kJ/kmol)	AAD$_{Arr.}$$^{(1)}$ (%)	AAD$_{ideal}$$^{(1)}$ (%)	AAD$_{GN}$$^{(1)}$ (%)
0% oil	1.036	20.708	9.81	-	-
25% oil	1.989	21.863	1.59	7.08	6.71
50% oil	4.288	20.156	6.76	8.45	8.01
75% oil	4.631	20.502	9.92	9.54	4.77
100% oil	6.902	22.042	8.58	-	-

$^{(1)}$ average absolute deviation ($AAD = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{(\mu_{cal}-\mu_{exp})}{(\mu_{exp})}\right|$)

- The thermal conductivity of the blends was observed to increase with temperature for a fixed composition. However the thermal conductivity of pure soybean oil exibited a smooth convex behaviour with temperature. At a fixed temperature, thermal conductivity increases as the composition of oil increases up to 335 K. After this point, the influence of composition on the thermal conductivity seems to be less significant;

- Compared to the diesel fuel, the soybean oil is approximately 10-11 times more viscous in the range of temperature evaluated. As expected, the blend viscosity decreases with increasing diesel concentration and decreases with temperature similarly to pure soybean oil and the diesel. An Arrhenius type relationship correlated well the viscosity, but a more universal approach based on the classical Eyring theory also presented good results, indicating the validity of the ideal solution viscosity hypothesis as first approximation.

- The viscosity correlation can be used to identify desirable ranges of composition and temperature for efficient atomization and burning in diesel engines.

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