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Viscosity of Vegetable Oils and Biodiesel and Energy Generation

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***Abstract*—**The present work describes an experimental investigation concerning the determination of viscosity behavior with shear rate and temperature of edible oils: canola; sunflower; corn; soybean and the no edible oil: *Jatropha curcas*. Besides these, it was tested a blend of canola, corn and sunflower oils as well as sunflower and soybean biodiesel. Based on experiments, it was obtained shear stress and viscosity at different shear rates of each sample at 40ºC, as well as viscosity of each sample at various temperatures in the range of 24 to 85ºC. Furthermore, it was compared the curves obtained for the viscosity versus temperature with the curves obtained by modeling the viscosity dependency on temperature using the Vogel equation. Also a test in a stationary engine was performed in order to study the energy generation using blends of soybean oil and soybean biodiesel with diesel.

***Keywords*—**Biofuel, energy generation, vegetable oil, viscosity.

I. INTRODUCTION

ENERGY is a key element in sustaining modern society's way of life. The importance of its effects, which permeate all sectors of society, was evidenced by important political events (oil embargo in 1973, Iranian Revolution of 1979, Gulf War of 1991 and the invasion of Iraq in 2003), that definitely changed the human perception regarding the importance of energy.

Besides the importance of energy to the world that takes shape, there is the concern with the environmental preservation, which is structured both in efforts to optimize energy efficiency and investments in research, development and application of renewable resources and cleaner technologies. In this context, mention shall be done to the biofuels, particularly biodiesel, that is an ester of fatty acid obtained through some specific processes, among them transesterification is the more traditional (chemical reaction between vegetable oil or animal fat and alcohol - typically ethanol or methanol, in the presence of catalyst, producing biodiesel and glycerol). Researchers [1]-[4] have pointed out the importance of biofuels for energy generation.

Since the creation of the National Program for Production and Use of Biodiesel (PNPB) in Brazil, in December 2004 (as part of government efforts to strengthen family agriculture, especially in the North and Northeast regions), biodiesel has been added to diesel, on a mandatory basis, in the proportion of 2% (at the beginning of the program), 3% (in July 2008) and 5% (from January 2010 until today). Therefore, the importance of this biofuel is notable, since 42% of the demand for all petroleum products is represented by diesel, and as the biodiesel is blended with diesel, the dependence of diesel will be reduced. Furthermore, this importance is enhanced by the benefits derived from the social and environmental aspects.

The Brazilian government has made efforts to encourage diversification of oilseeds production, which have vital importance as feedstock for biodiesel. Unlike what happens with American alcohol, for example, biodiesel is a fuel that can help increase the supply of food, which knocks down one of the main criticisms of the Brazilian program: food security (once oilseeds are redirected to the energy agriculture). This is because the remaining protein of the production process (bran or pie) can be destined for animal feed market, thereby contributing to the production of meat and milk. However, the program may prove itself unsatisfactory (as in the case of the Northeast region) without the effective participation of social, union and government movements [5].

The study of the rheological behavior of vegetable oils is justified based on the arguments presented above. In this scenario, the viscosity is an important property of the fuel. It occurs, in the case of liquid fuels, by intermolecular cohesive forces, conferring resistance to fluid flow [6]. To study and to understand the rheological behavior of vegetable oils is the first step for further study of these same aspects in biodiesel and its blends (Bxx) with diesel.

Considering the recent increase in the type B diesel consumption in Brazil (5.2% in 2011 [7]) and also that the transportation sector is the main consumer of diesel in the country (representing the road segment by significant 64% of demand [7]) is valid and relevant to mention the influence of viscosity on automotive diesel engine operation, more precisely in the diesel fuel injection systems. It is useful to mention in advance that there is an optimum range in which the viscosity should lie. Too high values result in wear of the

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gear train, camshaft and tappets of the set of injection pumps due to the higher injection pressure; on the other hand, values below the optimum range may not provide adequate lubrication to the piston, cylinder and injectors (in case of hydrodynamic lubrication regime).

In early 1980, with the reduction of sulfur content in diesel, it was noted a significant increase in the number of failures of rotary injection pumps (which are the main type of automotive diesel injection system, in which the fuel itself plays role of lubricant). It was believed, mistakenly, that the adjustment of the viscosity (and the use of additives) was the solution for the low lubricity, resultant by the sulfur reduction. However, there is evidence that the viscosity has no effect on lubricity, because the lubrication regime prevailing in the affected parts of the pump is the boundary layer regime, and not the hydrodynamic or elasto-hydrodynamic regime.

Actually, the viscosity influences the atomization of the fuel and, ultimately, the formation of deposits in the engine [8]. A widely used model of atomization is one in which the jet has a conical shape from the injector exit, and viscosity adjustment impacts the optimization of parameters related to the model, such as the reach of the spray, the diameters distribution of the spray and the breakup time of the drops of fuel [9]. High values of viscosity causes inefficient atomization of the fuel, so do not contribute to the formation of a good air-oil mixture (resulting in a poor combustion) [8]. On the other hand, Low values of viscosity causes an average droplet diameter too small, which decreases the reach of the particles within the chamber, and so part of the oil is not burned.

In this study, it was investigated the viscosity of edible oils: canola; sunflower; corn; soybean and the no edible oil: *Jatropha curcas*. Besides these, it was tested a blend of canola, corn and sunflower oils as well as sunflower and soybean biodiesel. Based on experiments, it was obtained shear stress and viscosity at different shear rates of each sample at 40ºC, as well as viscosity of each sample at various temperatures in the range of 24 to 85ºC. Furthermore, it was compared the curves obtained for the viscosity versus temperature with the curves obtained by modeling the viscosity dependency on temperature using the Vogel equation.

With the objective of verify the effect of using fuels with different viscosities, a test was conduced in a stationary engine using blends of soybean oil with diesel and blends of soybean biodiesel with diesel. In these energy generation tests, the values of specific fuel consumption (SFC) and emissions of CO for diesel, soybean biodiesel and mixtures of diesel-soybean oil and diesel-soybean biodiesel were determined.

II. MATERIAL AND METHODS

A. Materials

The vegetable oils (canola, sunflower, corn, soybean and blend) used in viscosity tests were purchased from the local market and used without further treatment. The *Jatropha curcas* oil was produced in the Fluminense Federal University at the Laboratory of Fluid Mechanics and environmental technology (LAMETA).

The fuel blends used in energy generation tests were prepared at the Thermo-sciences Laboratory of Mechanical Engineering Department at Fluminense Federal University (UFF).

It was used Oxx as the nomenclature to designate mixtures of soybean oil with diesel, being xx the percentage by volume of vegetable oil added to diesel. The following mixtures were used: O5; O10; O15 and O20, besides pure diesel (O0).

It was used Bxx as the nomenclature to designate mixtures of biodiesel with diesel, being xx the percentage by volume of biodiesel added to diesel. The following mixtures were used: B5; B10; B15; B20; B50 and B75, besides pure diesel (B0) and pure biodiesel (B100).

Diesel fuel used is from the Laboratory of Distributed Power Generation at Fluminense Federal University. This fuel is used as reference for the energy generation tests.

B. Experimental Procedure

For the viscosity tests it was used the Haake RS50 Rheometer with K20 thermostatic bath and DC5 head controller. In the RheoWin Job Manager software, it must be selected the most appropriated sensor (for each type of fluid) the working temperature and the type of analysis required. There are available the following test modes: controlled stress (CS); controlled strain (CR) and oscillation (OSC).

For this work, the DG 41 sensor was selected, and the analyses performed were the flow curve at the temperature of 40ºC and the temperature ramp from 24ºC to 85ºC. It was used 6.3 mL samples as indicated by the sensor manufacturer.

The energy generation tests were conducted in a stationary engine. The tests were made at constant speed of 3600 rpm and variable power.

For each fuel tested, a test was performed and a reply. Performance data and emissions were measured continuously during the test and the series of data were analyzed to obtain values representative of engine performance

The stationary engine used is formed by an engine, a generator and a control panel, with the possibility of producing electricity at 115V and 230V. The generator has a control system to regulate the motor rotation. The characteristics of the diesel engine are: 3600rpm; four-stroke; direct injection; one cylinder; air cooling system; 0.211L displacement volume; 2.0kW maximum output; 1.8kW nominal power; 2.5L fuel capacity and 47 kg weight.

The engine was modified in order to have a fuel consumption control by gravity, changing the original fuel tank by a remote tank, being possible to be placed on a balance

The electrical load was simulated on a load bank, where 150W power lamps are activated to modify the load. The measurement of instantaneous power, current frequency, voltage and electrical current are made using a measuring device manufactured by CCK CCK 4300 Automation Ltda (São Paulo, Brazil).

The reported values represent the average for four values of load (400W, 700W, 1000W and 1300W).

Emissions were measured using the gas analyzer built by Greenline 8000 Eurotron Instrument S.A. The equipment has measurement system of gas concentration by non-dispersive infrared (NDIR) and electrochemical method, in addition to measuring temperature, pressure and temperature of gases. The equipment has RS232 communication system for data acquisition and algorithms for calculating the efficiency indicators for different fuels. The resolution and the error limits of the equipment for CO measurements are: 1 ppm and ±10 ppm.

III. RESULTS AND DISCUSSION

Three types of characteristic curves were obtained for each viscosity test performed. Regarding the flow curve analyses at 40°C, it is possible to note for all the tested fluids the Newtonian behavior in which the shear rate (or velocity gradient) is proportional to the shear stress. Because of this, the graphical representation of a Newtonian fluid (shear stress x shear rate) is a line whose slope is equal to the constant of proportionality (in other words, the viscosity of the fluid).

The corresponding curves for each vegetable oil as well as the mixture of vegetable oils and biodiesel are represented in Fig. 1 to 8. Similar results have been reported in the literature for some vegetable oils. Therefore, as expected for a Newtonian behavior, the viscosity does not vary with increasing shear rate, and so it is called absolute or dynamic viscosity.

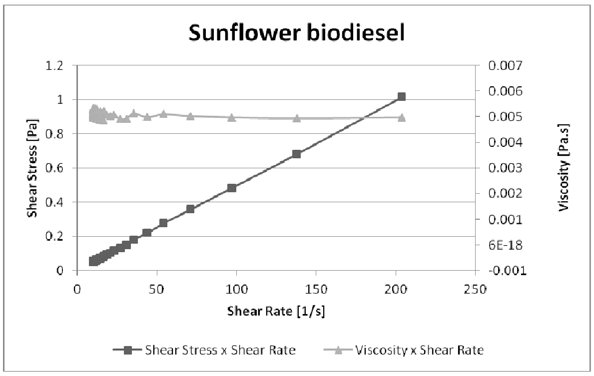

Fig. 1 Sunflower biodiesel flow curve at 40 ºC

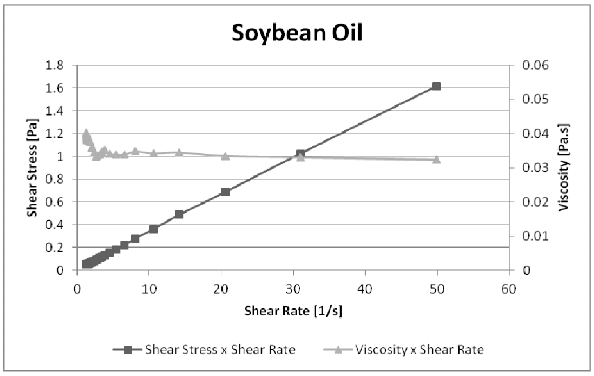

Fig. 2 Soybean oil flow curve at 40 ºC

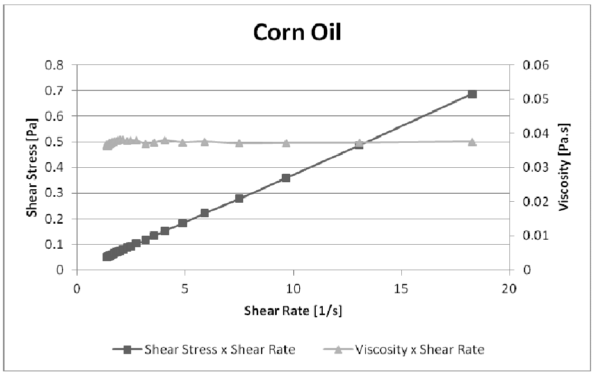

Fig. 3 Corn oil flow curve at 40 ºC

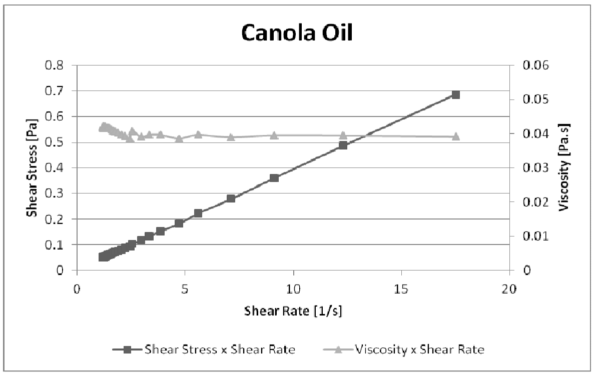

Fig. 4 Canola oil flow curve at 40 ºC

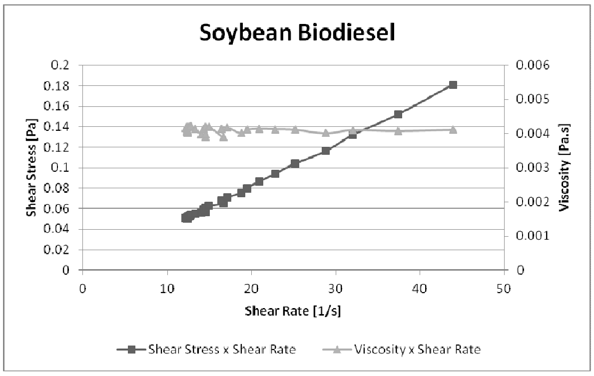

Fig. 5 Soybean biodiesel flow curve at 40 ºC

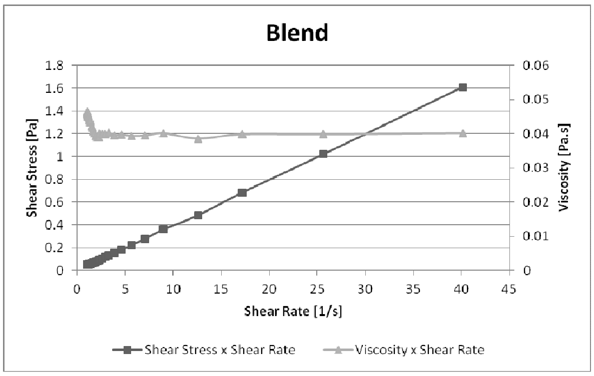

Fig. 6 Blend of vegetable oils flow curve at 40 ºC

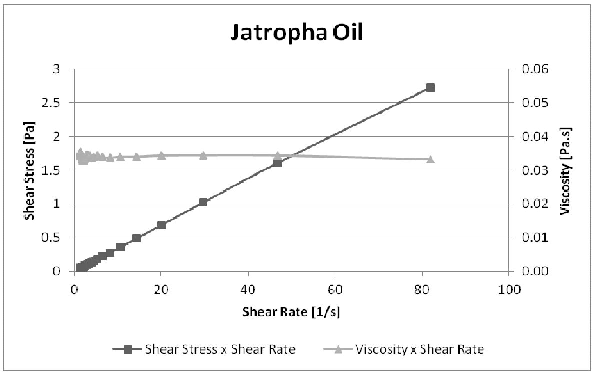

Fig. 7 *Jatropha curcas* oil flow curve at 40 ºC

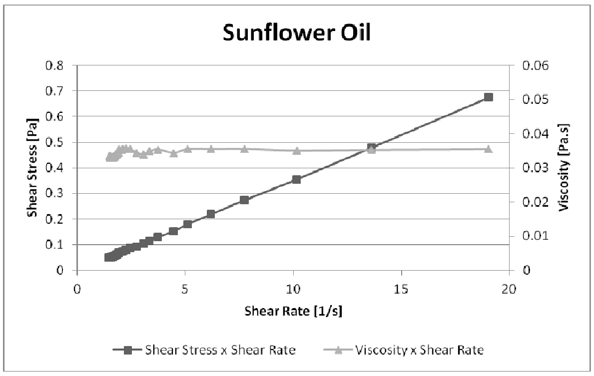

Fig. 8 Sunflower oil flow curve at 40 ºC

Regarding the analysis of viscosity behavior with temperature variation, it was considered the range of 24ºC to 85ºC. The importance of this analysis is to verify the viscosity behavior versus temperature variation, as in real cases we may expect an increase in temperature between the transfer pump (which transfers the fuel from the tank to the pump or injection unit) and the fuel injector (based on the importance of automotive fuel injection systems highlighted in the introduction of the work). Hence the design of the fuel injection system is impacted by the temperature variation, since liquids viscosity shows strong temperature dependence.

As expected, the viscosity of the samples decreases with an increase in temperature. This is because the liquid molecules have more energy at higher temperatures and in this case may oppose more intensely cohesive intermolecular forces. The result is that the energized molecules of the liquid can move more freely [6]. This behavior was also observed in other similar studies ([10]). Fig. 9 shows the measured values of viscosity as functions of temperature, as well as smooth curves connecting the plotted points fitted by Microsoft Excel.

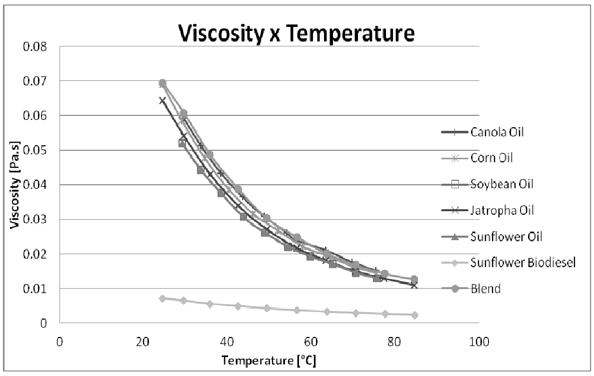

Fig. 9 Temperature ramp from 24 ºC to 85 ºC

Comparing sunflower oil with sunflower biodiesel and soybean oil with soybean biodiesel, it is observed that the viscosity of the biodiesel is smaller than that of the oil *in natura* that originated it (with the transesterification and transformation of fatty acid esters, a significant reduction of viscosity occurs) as already observed in other studies. This fact is one of the reasons why the oils *in natura* are unsuitable for use as fuel, although some authors support the use of vegetable oils *in natura* to replace diesel, highlighting the advantages related to the fuel atomization of the oils, through the development of heating systems, temperature control and fuel injection control systems (basically composed of injection pump and fuel injectors).

The study of the viscosity dependency on temperature can be refined by obtaining equations giving the viscosity as a function of temperature for each type of oil. Among the most commonly used viscosity-temperature equations, the most accurate is the Vogel equation [11], which is given by

$$\eta = ae^{b/(T-c)} \tag{1}$$

where η represents viscosity, *T* is the absolute temperature (measured in Kelvin), and *a*, *b*, *c* are constants which we may choose as to better fit the resulting curve to available data. Generally, at least three viscosity measurements at different temperatures are needed in order to determine the three constants. There are two main methods used to choose *a*, *b* and *c*. The first consists of computing their values by solving a system of 3 equations obtained by substitution of the values of three viscosity measures into the general Vogel equation. In case we have access to more data, we can use least squares regression to find the curve which best fits the whole dataset. The first method is preferable if we aim to minimize the error at the boundary of the temperature range, even in case a larger dataset is available; since we wanted the better general representation, we employed the latter method.

For each set of temperature-viscosity values (t_i, η_i), we want to find values for the Vogel constants *a*, *b* and *c* that minimize the sum of $(\eta_i - \eta(t_i))^2$, where $\eta(t_i)$ is computed using the Vogel equation. We found such values for each type of oil using Microsoft Excel Solver. Table I presents the values of *a*, *b* and *c* obtained for each oil sample. Fig. 10 shows how the curves we obtained from the Vogel equation compare with the viscosity values we measured.

TABLE I
VALUES FOR THE VOGEL CONSTANTS

Oil	Vogel constants		
	a	*b*	*c*
Canola	0.000117781	1024.21043	138.2571147
Corn	0.000173021	866.1068617	153.3320406
Soybean	0.000213098	763.6312654	163.6917445
Jatropha	7.59865E-05	1137.107536	129.3428974
Sunflower	5.11282E-05	1381.206756	104.4928648
Biodiesel Sunflower	3.98741E-05	1191.128796	68.7321597
Biodiesel Soybean	5.905E-05	942.287211	94.146183
Blend	1.57442E-06	3235.628026	4.30956185

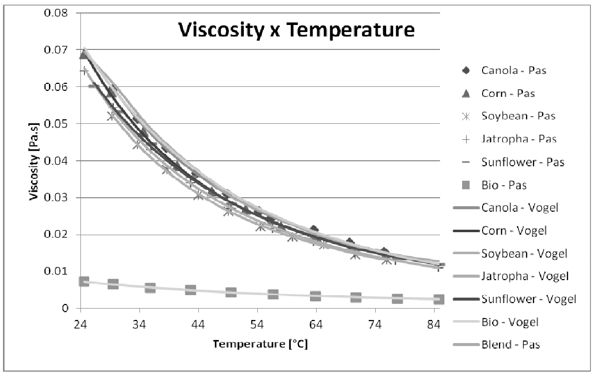

Fig. 10 Viscosity x temperature using Vogel equation

In the energy generation tests, Fig. 11 shows the behavior of SFC for diesel-soybean oil mixtures and diesel-soybean biodiesel blends. The specific fuel consumption is lower for mixtures of 5% soybean oil than that for diesel. For this percentage, the oil has an oxygenating effect which improves engine performance, with an average of 1.9% decrease from the SFC. For larger percentages of mixture, the SFC increases, indicating a drop in engine performance. This is a consequence of lower heating value of soybean oil and of the increasing of the difficulties to burn fuel in the combustion chamber, requiring more fuel. For mixtures of 20% soybean oil, the increase in SFC is 4.5%. In the case of diesel-soybean biodiesel blends, a slight decrease in the SFC can be observed for smaller proportions of the mixture (5% to 10% soybean biodiesel). This decrease is due to the oxygenating capacity of biodiesel. For larger values of the mixture (15% to 100% soybean biodiesel), the SFC increases. This increase in SFC is due to the lower heating value of biodiesel, requiring more fuel. As the mixing ratio increases, the specific fuel consumption increases. The SFC hits an increase of 14% for the use of pure biodiesel compared to diesel.

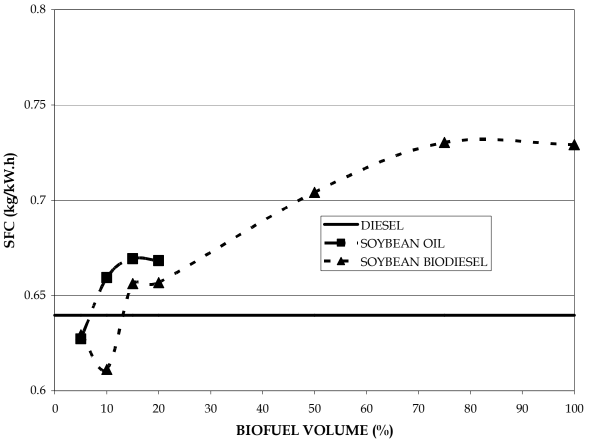

Fig. 11 Mean values of SFC for soybean biodiesel and soybean oil blended in diesel

Fig. 12 shows the mean values of CO for soybean oil and soybean biodiesel blended in diesel. It may be noted that in proportions of up to 5% of soybean oil, the mixtures have an advantage in relation to diesel. For higher proportions, the CO emission increases to a level of 405 ppm for the mixture with 20% of soybean oil, 18% higher than the levels achieved by diesel emissions. The increase in the amount of CO shows a less efficient combustion. In the case of diesel-soybean biodiesel blends, it can be observed that the emission of CO for mixtures was lower than for diesel. The CO emission decreases by increasing the proportion of soybean biodiesel in the blend. In the case of pure biodiesel, the reduction in CO emission was 21% compared with diesel.

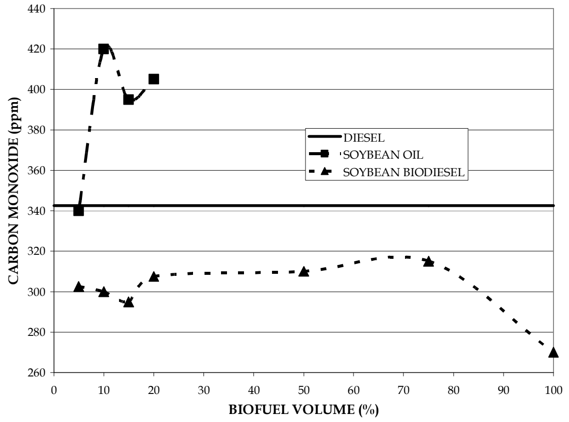

Fig. 12 Mean values of CO for soybean biodiesel and soybean oil blended in diesel

IV. CONCLUSION

The importance of energy and the development of

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alternative energy sources and clean technologies are presented as key themes in the current global context. The study of the rheological behavior of vegetable oils - raw materials for the production of biodiesel - is fundamental to the complete understanding of biodiesel and its blends with diesel. On the other hand, the use of pure vegetable oils as fuel is only possible if the cost of auxiliary systems (for heating and viscosity control) is feasible from the cost point of view.

Viscosity plays an important role in the atomization of the fuel when injected into the combustion chamber. However, it will exert influence on the fuel injection system only when the hydrodynamic lubrication regime is characterized as the predominant regime (for the case of systems where the fuel itself is responsible for lubrication).

In this work, it was evaluated the viscosity behavior of various vegetable oils, a mixture of vegetable oils, and also biodiesel. All fluids tested showed the Newtonian behavior, where the shear rate is directly proportional to the shear stress. In this case, the viscosity is constant with the shear rate, which was also observed in other similar studies.

The temperature has influence on viscosity. The increase of the temperature results in the decrease of the viscosity, as expected. It can be noted that the viscosity of biodiesel is considerably lower than the vegetable oil that originated it (in the case of biodiesel from soybean and sunflower).

Considering the range from 25ºC to 60ºC (approximately) it can be noted a pronounced variation in viscosity for vegetable oils and the mixture of vegetable oils; already, in the range of 60ºC to 85ºC, for the same fluids mentioned, the variation is less pronounced. However, in the case of biodiesel, the viscosity shows modest variation with temperature compared to the other fluids tested (for the entire temperature range).

With respect to energy generation, soybean oil and soybean biodiesel can be added to diesel fuel to be burned in combustion engines. These compounds have an oxidative capacity that is useful to improve engine performance, but this ability only gives you an edge when the mix ratio is 5% for vegetable oil and 10% for biodiesel. The gains made in reducing the SFC using the oxygenating additives affect about 2% in the case of 5% soybean oil blended with diesel and about 4.5% for 10% soybean biodiesel blended with diesel. Using a larger proportion of mixture generates increases in SFC by 9% on average when pure biodiesel is used, and 3% with mixture of 20% soybean oil are used.

The addition of soybean oil in diesel reduces emissions of CO only for mixtures of up to 5% soybean oil. In the case of biodiesel addition in diesel, CO emissions decrease with the mixture reaching a 21% reduction, when pure soybean biodiesel (B100) is used.

Soybean oil can be successfully applied in CI engine blending with diesel up to 20% of soybean oil. Soybean oil can also be converted in biodiesel and applied in CI engines neat or blended with diesel in any proportion. Concerning the exhaust emissions its better use soybean biodiesel or blends of soybean biodesel with diesel instead of blends of soybeans oil with diesel. The use of vegetable oils blended with diesel is limited because of their higher viscosity.

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