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PERFORMANCE OF DIESEL ENGINE FUELLED WITH FOUR VEGETABLE OILS, PREHEATED AND AT ENGINE WORKING TEMPERATURE

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ABSTRACT: With the rise of restrictions imposed by law for gases emission, several technologies both for petrodiesel (PD) or diesel engines are been applied, such as the sulfur reduction and the injection electronic command, followed of gases recirculation and/or after-treatment. The utilization of biofuels is considered as an interesting option for pollutants reduction. In this study was evaluated the performance on short duration tests (minor period than the factory indication of the lubricant lifespan) of the Diesel engine fueled with four vegetable oils. With the aim to select the most interesting oils for future evaluations in long duration tests. The analyzed variables were fuel consumption, power relative loss and opacity, for oils of linseed, crambe, rapseed, jatropha , with 100 °C preheating and engine work temperature (60 °C) comparing those with the PD. It was verified that the vegetable oils, on average, present a lower consumption than the PD for the cases of working without load, however with load, they presented higher consumption. In addiction were observed that the oils show a higher relative power loss in relation of PD and provides lower emission of particulate matter. Crambe and canola presented the best performance among the evaluated oils.

KEYWORDS: consumption, brake power, opacity.

INTRODUCTION

Environmental pollution from fossil fuel sources has led to the development of research into the search for alternative fuels to petroleum products. Brazil with technology and market already developed for ethanol, gasoline substitute, looks for alternatives to complete substitution of petrodiesel (PD). One of the premises is not to suggest changes in the design of available diesel engines. At the moment vegetable oils and their derivatives are in focus because they present characteristics and properties similar to PD, being able to be applied pure or mixed to the petroleum derivative.

However, the quality parameters and the utilization procedures for unprocessed vegetable oils have not yet been defined. They draw attention because they are sources of lower obtaining cost and for not being classified as fuel by the legislation, which implies in facilities of handling, transport and storage. In spite of being favorable from the energetic and environmental point of view, the direct use of vegetable oils in diesel engines is problematic. Studies with several oils have shown that the application of these as fuel causes carbonization excess of the combustion chamber; contaminates and degrades the lubricant and causes accelerated wear of moving parts (HAZAR & AYDIN, 2010; DELALIBERA et al., 2012).

Some of these problems can be attributed to the occurrence of pyrolysis, polymerization, and other reactions that may occur during injection and combustion, impairing engine performance. High viscosity is the main reason, affecting the quality of the fuel atomization in the combustion chamber, but this can be mitigated by the fuel heating. Studies show that when heated to 145 °C, the soybean oil reaches the viscosity of the PD, besides increasing 3 points in the cetane number. The second reason for these problems may be related to the quality of the oil, which may be derived

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from genetics (fatty acids) and purification processes, which may favor resistance to thermal oxidation (RYAN III et al., 1984).

However, studies on motor fueled with pure vegetable oils and / or mixed with PD show reduced gas emission compared to PD (CAMPOLINA et al., 2011; BASINGER et al., 2010). Also, studies evaluating the emissions of engine gases fueled with preheated palm oil (85 °C) have found that to be advantageous, design adaptations (compression ratio, injection point and fuel demand) are required to improvement motor performance (PIMENTEL et al., 2002).

Tests carried out with PD and mixtures with castor oil biodiesel show that the opacity values decreased as the biodiesel content in the mixture increased, in which they decreased until mixtures of 75% of biodiesel in the PD. After this, the opacity values increased to the point of not differing from the PD (TABILE et al., 2009). For an engine with direct combustion system and electronic injection control, the opacity exceeded the emissions of PD when 50% ratio of degummed soybean oil in the PD was used; however, the opacity was lower for mixtures of 30 and 70% (CAMPOLINA et al., 2011).

In Brazil there is legislation (RESOLUTION/CONAMA No. 433, 2011) limiting the emission of polluting gases for engines of agricultural and road machinery in which is necessary to note that there is no technical-scientific criteria that justify such restriction values; due to that the aim of this study was to evaluate the technical behavior, the performance and emission of particulate matter of diesel engine when fueled with pure vegetable oil, preheated at 100 °C, at the injection pump inlet and at the engine working temperature (60 °C) in short duration tests (DELALIBERA, 2015), comparing them with PD, in order to select the most interesting oils for future long-term tests.

MATERIAL AND METHODS

1. Test Bench: The test bench was set up on a 4 kVA (3.2 kW@1.800rpm 60Hz) diesel generator (Table 1). As the engine was not new, it was necessary to check the valve settings, injection system (opening pressure of 13.21 MPa) and cylinder compression pressure (1.64 MPa). All verified and calibrated systems are as recommended by the manufacturer for an engine in good operating condition.

TABLE 1. Engine specifications according to manufacturer's manual.

Manufacturer/Model	YANMAR/B9C	Aspiration	Natural
Rotation range	1,050 to 2,300 rpm	Injection System	Mechanics
Number of cylinders	1	Combustion system	Antechamber
Compression pressure	1.47 a 1.86 MPa	Injection pressure	13.7 ± 0.49 MPa
Compression ratio	19.2:1	Lubrication	Forced by pump
Bore x Stroke	90 x 100 mm	Lubricant Pressure	0.049 a 0.49 MPa
Engine Capacity	636 cm^3	Lubricant Volume	1.5 to 2 L
Cycle	Diesel – 4 stroke	Cooling	Condensation water
Power rating	5.88 kW@1,800 rpm	Cooling volume	2.8 L

A manual three-way valve was adapted near the inlet of the engine's fuel power system which allows the fuel to be changed by directing the fueled inlet between two distinct reservoirs (petrodiesel and vegetable oil). Both fuels were supplied by gravity. A heating system was developed from a cylindrical electric resistance (diameter: 40 mm, length: 120 mm) of 450 W power, powered by 220 V. This involved an aluminum mass of 16 mm internal diameter, where a thermocouple type K sensor was inserted, which sends the temperature information to a CR-5.000® data acquisition system (Campbell Scientific), which stores and controls the temperature of the heater through a relay type device.

To measure the rotation of the crankshaft, a pass detection sensor was constructed from a Mel 32 transistor (similar to Til 78) and a class III laser pointer (output voltage <5,000MW), of green color. This was arranged on the coupling shaft of the motor to the generator, where 6 uniformly spaced bar were adapted which have the function of interrupting the laser beam, generating the signal for the acquisition system. For data reading it was used an e-Daq Lite® (HBM) datalogger with 200 Hz acquisition rate since it is possible to use a method that consists of timing the time elapsed between one pulse and another, allowing high frequencies of acquisition and resolution of more suitable scale for this variable.

To carry out evaluations under absorption condition of known power, a load bank was made of 9 halogen lamps (6 of 500 and 3 of 300 W), absorbing covers of 3.9 kW, corresponding to 66% of the nominal power of the engine. However, as the applied load exceeds around 20% of the generator nominal (3.2 kW), the load application periods did not exceed 10 continuous minutes, under the risk of damaging it by overheating.

2. Treatments: common petrodiesel S500B5 (PD) was used purchased at an urban fuel station and four vegetable oils (VO), were evaluated at two different temperatures (Table 2). The used oils were linseed (*Linum usitatissimum*), crambe (*Crambe abyssinica Hochst*), rapseed (*Brassica napus L.)* and jatropha (*Jatropha curcas L.*). All raw materials were produced in the experimental areas of IAPAR-PR and the VO was extracted by mechanical method through micro-presses expeller type, followed by simple filtration. For these, no physicochemical analyzes were performed.

TABLE 2. Treatments applied in the engine.

Treatment	Codification				
	Petrodiesel	Linseed	Crambe	Rapseed	Jatropha
Without preheating	PD	L60	CR60	C60	PM60
Preheated	-	L100	CR100	C100	PM100

The VO fuels were subjected to the temperature of 60 °C, which is the average temperature of the fuel inside the injection pump, after the engine has stabilized at the temperature of the cooling system (working temperature) and preheated at 100 °C. Temperatures were measured by a thermocouple inserted in the fuel access channel to the injection pump element. Temperatures higher than 100 °C in the injection pump were not applied; therefore, the engine presented operational failures when submitted to the load for linseed and jatropha oils. To obtain this temperature in the injection pump, the heating system worked with drive interval between 155 and 165 °C.

3. Test procedure: For variables stabilization, the engine was operated at a regime of 1,800 rpm load-free for a period of 40 minutes with the application of the treatment. Also, in the passage between treatments, this procedure was repeated with PD for the same period. This was standardized because it was the time required to stabilize the temperatures and pressures with the engine under free rotation (without power absorption in the generator).

4. Evaluated Variables:

4.1. Thermal behavior of the cooling and exhaustion system: Since the experiment lasted approximately 30 hours of motor operation (average 3.33 hours per test), and it was not performed in a controlled environment it was tried to identify the influence of ambient temperature in the variations of the working temperature of the cooling and exhaust gas systems. Thermocouple type K sensors were installed one in the exhaust gas tube, one meter from the cylinder head, and one for the cooling fluid in the engine block. The purpose of these was to evaluate the effect of the treatment on the thermal behavior of the engine. For the ambient temperature, it was used the internal sensor of the CR-5000 datalogger.

The motor temperature data were correlated with the ambient temperature to verify if the changes occurred was influenced by the treatment or by the environment. For this the data were separated by work regime, two under free rotation (1,150 and 1,800 rpm) and one under load (3.9 kW @ 1,800 rpm), without considering the effect of the treatments. When there was a significant and positive correlation between the ambient temperature and the engine temperature, it was considered that the variations were environment dependent, and when there was no correlation, it was considered that there was treatment effect.

For the correlations, the Pearson coefficient was used for the data that presented normal distribution, and Sperman, for those that did not fit into normality. The tests of normality applied were D'Agostino, D'Agostino-Pearson, Lilliefors and Shapiro-Wilk. To consider normality, a non-significant result was required for at least three tests.

For the variables that did not present correlation was applied normality tests again. However, at this stage of analysis the treatment effect was considered in the data distribution, that is, the normality of the residues was verified obtaining for them the normality and homoscedasticity (Hartley and Cochran). In sequence, parametric variance analysis tests were applied followed by Scheffé's non-orthogonal contrasts test, in order to compare VO against PD.

4.2. Fuel consumption: This was evaluated under a regime of 1,150 (slow) and 1,800 rpm load-free, and under an absorption regime of 66% (3.9 kW@1,800 rmp) of rated power. The consumption was measured through the mass with a precision scale (0.01g), for a period of 5 minutes, with 5 repetitions for each treatment with this one obtains the specific consumption or per hour directly. This method was used because, as there are large variations in temperature in the reservoir injection system path, measurements by volume generate uncertainties and imprecision, and are considered not suitable for motor testing.

As these presented normality and homoscedasticity, parametric variance analysis (ANOVA) was performed blocking the effect of motor dependence, followed by multiple comparison tests by non-orthogonal contrasts of Scheffé.

4.3. Power loss: In order to estimate this variable, a method was developed that consists of an indirect measure, calculated through the area between the curve of rotation recovery when applied to the load (3.9 kW@1,800 rmp) and the free load rotation before its input, obtaining an index of loss of power and relative to the condition in which the motor is submitted. The lower the value of the obtained area, the lower the loss of power.

The 2 s interval immediately after the load input (total of 10 s) was used for the calculation, because it was the maximum response time to the acceleration return and stabilization of the rotation for this load condition, resulting in 400 readings for each repetition, obtained by the aforementioned presence sensor. Twenty repetitions of 10 s were performed for each treatment.

The Catman Easy-AP 3.3.5® program (HBM) was used to manipulate and integrate the data. The relative power loss indexes were submitted to normality and homoscedasticity tests and were presented in conditions for ANOVA application, followed by a comparison test by Scheffé's non-orthogonal contrasts.

4.4. Exhaust gas opacity: Emission of particulate matter (PM) was estimated using the indirect opacity method (NBR 13.037), using a TM-133® partial flow opacimeter and a TM-529® tachometer with interface by IGOR 2.1® (TECNOMOTOR) software. For this test, the exhaust gas outlet was modified by removing the muffler and directing it down so that the opacity measurements are the closest to the emissions in the exhaust window of the engine.

The opacity results ($k = m^{-1}$) were converted to mass estimates of PM per hour ($kMP = g\ h^{-1}$) and specific emission ($g\ kWh^{-1}$) by equations suggested by BRANCO et al. (2012) in which [eq. (1) estimates the concentration of soot or elemental carbon (*EC*) which constitutes the majority of the PM of the smoke (65 to 75%), and finally [eq. (2)]" estimates the emission of PM for the engine in a specific working condition. It was used 1,800 rpm, therefore, is the rotation of work required for this model of diesel generator.

$$EC(mgNm^{3}) = 147.509 * k(m^{-1}) \tag{1}$$

$$kMP(mgs^{-1}) = EC\frac{\frac{(mgNm^{-3})*Enginecapacity(L)}{1,000}*rpm}{2*60s} \tag{2}$$

Twenty repetitions were performed for each treatment and analysis of variance was applied, followed by Friedman's nonparametric multiple comparison test, since the data did not present normal distribution and the dependence of the motor between the treatments was considered, as already observed by CAMPOLINA et al. (2011). The analyzes were performed on Microsoft Excel 2010, SisVar 5.3 (FERREIRA, 2011) and BioEstat 5.3 (AYRES et al., 2012) programs.

RESULTS AND DISCUSSION

5.1. Thermal behavior of the cooling and exhaust system: There was no significant correlation between ambient temperature and maximum exhaust gas temperature at 1,800 rpm load-free and with the maximum exhaust gas temperature during the opacity tests (Table 3) been therefore considered independent (treatment effect exists). In the others, as there was a significant correlation, it was considered that the variations in these ones were dependent or caused by the environment and no sequential analysis was discussed.

TABLE 3. Correlation between the temperatures according to the operating regime.

System temperatures related to Room temperature		Correlation coefficient	Significance	Test
Free-flow cooling (1,150 +1,800 rpm)		0.512	$p<0.01$	Pearson
Cooling under load 3.9 kW@1,800 rpm		0.681	$p<0.01$	Spearman
Exhaust gases at 1,150 rpm	Minimum[1]	0.616	$p<0.01$	Pearson
	Medium[1]	0.687	$p<0.01$	Pearson
	Maximum[1]	0.537	$p<0.01$	Pearson
Exhaust gases at 1,800 rpm	Minimum	0.315	$p<0.05$	Pearson
	Medium	0.484	$p<0.01$	Pearson
	Maximum	**0.180**	***ns**	Spearman
Exhaust gas under Loading regime	Minimum	0.481	$p<0.01$	Spearman
	Medium	0.648	$p<0.01$	Spearman
	Maximum	0.711	$p<0.01$	Spearman
Exhaust gases during the Opacity test	Minimum	0.556	$p<0.01$	Pearson
	Medium	0.454	$p<0.05$	Pearson
	Maximum	**0.305**	**ns**	Spearman

*ns – Not significant; 1 – Average of the minimum, medium and maximum temperatures obtained by the acquisition system.

For the average of the maximum exhaust temperature obtained on the 1,800 rpm regime load-free, the ANOVA ($p < 0.05$) and the PD contrast test against the VO were significant ($p < 0.01$). We can state that on average, VO present higher exhaust gas temperature than PD (Table 4). This indicates that the vegetable oils presented greater thermal loss for this condition. HAZAR & AYDIN (2010) and SHEATA & RAZEK (2011) found similar results for the fuel canola oil and also the VO preheating (100 °C) also increased the exhaust gas temperature in comparison to the VO not heated. For this study, the last one was not observed. In contrast, BAYINDIR (2010) and ACHARYA et al. (2011) found that the VO presents lower exhaust gas temperature in relation to PD. ACHARYA et al. (2011) also commented that the rice bran oil preheated at 120 °C presents exhaust gases temperature similar to PD, as it was obtained in this test for the other studied cases, that is, the thermal loss on exhaustion gases would be the same. The tests were not significant for the gases maximum temperature during the opacity tests.

TABLE 4. Average temperatures according to the engine work speed for treatments.

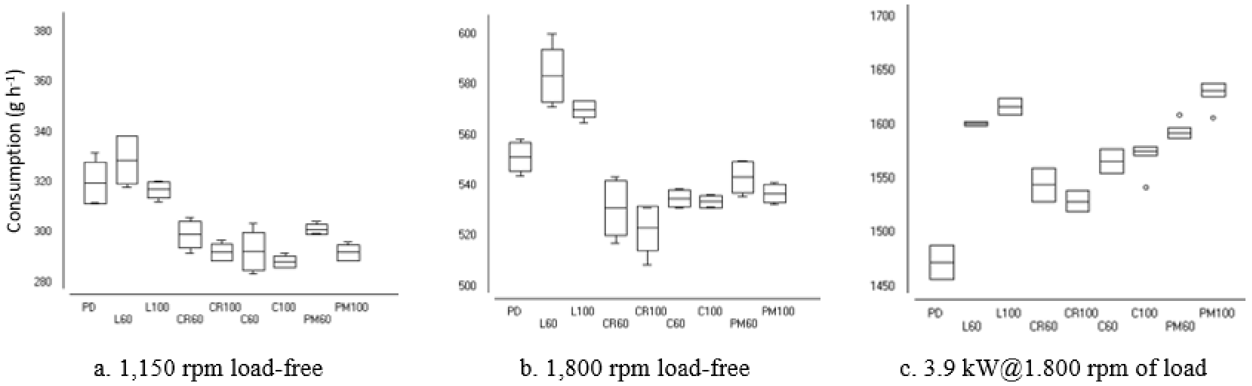
Engine Speed	Temperature (°C)		PD	L60	L100	CR60	CR100	C60	C100	PM60	PM100
1,150 rpm Load-free	Environment average		29.6	32.7	34.6	37.3	30.9	32.5	29.5	37.6	38.0
	Cooling average		84.3	86.1	87.5	84.8	85.9	85.0	85.3	87.5	87.5
	Exhaust gas	Minimum	57.0	66.9	61.2	65.6	57.5	59.9	56.2	63.0	62.5
		Medium	62.4	68.9	71.2	69.5	62.9	64.5	61.5	69.9	70.7
		Maximum	61.5	72.8	72.9	82.4	97.0	71.6	63.4	100.4	102.3
1,800 rpm Load-free	Environment average		29.6	32.7	34.6	37.4	30.9	32.5	29.5	37.6	38.0
	Cooling average		84.3	86.0	87.5	84.7	85.9	85.0	85.4	87.4	87.5
	Exhaust gas	Minimum	63.4	59.9	65.4	64.2	60.5	59.7	57.1	66.7	62.4
		Medium	65.2	74.8	74.4	70.2	66.9	65.8	63.1	72.2	71.2
		Maximum	**85.4**	**99.7**	**99.8**	**103.7**	**103.1**	**101.4**	**92.5**	**97.4**	**101.8**
3.9 kW@1,800 rpm of load	Environment average		31.5	33.4	37.4	36.3	36.7	34.9	37.9	41.0	39.5
	Cooling average		88.3	88.8	90.0	90.0	90.0	88.8	89.7	90.0	90.0
	Exhaust gas	Minimum	109.5	122.9	130.5	126.8	125.4	125.0	130.5	130.4	131.3
		Medium	125.6	128.0	138.1	133.4	133.1	131.1	136.8	139.3	139.8
		Maximum	134.4	132.2	144.8	139.1	138.2	135.6	142.1	145.8	145.8
Opacity test	Environment average		29.6	32.7	34.6	37.3	30.9	32.5	29.5	37.6	38.0
	Exhaust gas	Minimum	60.8	64.4	67.5	69.0	57.0	60.9	61.1	65.2	68.8
		Medium	71.2	67.3	89.9	85.4	72.9	82.6	86.4	91.4	89.8
		Maximum	**138.2**	**133.2**	**144.4**	**150.4**	**141.7**	**146.9**	**145.2**	**142.1**	**143.3**

5.2. Fuel consumption: The VOs were lower than the PD (contrasts 1 and 5, Table 5) for the free-load regimes, but when loaded, the results were opposite (contrasts 9 and 10). Figure 1 shows that the L60 and L100 presented higher consumption than the other VOs for the free-load tests (contrasts 2, 6 and 11) and are equal to the MP60 and MP100 for under-load regimes. However, when L60 plus L100 treatments were compared with PD, they did not differ only in the work condition under speed of 1,150 rpm load- free (contrast 3, Table 5).

TABLE 5. Comparison of average group for fuel consumption, according to the working speed and significance of the contrasts analysis of variance.

Work Speed	Nº	Without preheating					Preheated				p valor
		PD	L60	CR60	C60	PM60	L100	CR100	C100	PM100	
1,150 rpm Load-free	1.	8	-1	-1	-1	-1	-1	-1	-1	-1	<0.01
	2.	0	3	-1	-1	-1	3	-1	-1	-1	<0.01
	3.	2	-1	0	0	0	-1	0	0	0	0.293
	4.	0	1	1	1	1	-1	-1	-1	-1	<0.01
1,800 rpm Load-free	5.	8	-1	-1	-1	-1	-1	-1	-1	-1	<0.05
	6.	0	3	-1	-1	-1	3	-1	-1	-1	<0.01
	7.	2	-1	0	0	0	-1	0	0	0	<0.01
	8.	0	1	1	1	1	-1	-1	-1	-1	<0.01
3.9 kW@1,800 rpm of Load	9.	8	-1	-1	-1	-1	-1	-1	-1	-1	<0.01
	10.	4	0	-1	-1	0	0	-1	-1	0	<0.01
	11.	0	1	-1	-1	1	1	-1	-1	1	<0.01
	12.	0	1	1	1	1	-1	-1	-1	-1	<0.01

Scheffé's comparison test for non-orthogonal contrasts



a. 1,150 rpm load-free b. 1,800 rpm load-free c. 3.9 kW@1.800 rpm of load

FIGURE 1. Box-Plot of averages and standard deviations for fuel consumption according to the regime.

There was a heating effect on VO consumption (contrasts 4, 8 and 12 of Table 5), because when preheated the fuel consumption was lower than those not heated for the free rotation regimes and, when under load, the preheating increased consumption (Figure 1b and 1c). According to RYAN III et al. (1984) and RYAN III & STAPPER (1987), preheating increases the number of VO cetane, which can result in lower consumption under free rotation, but the heating decreases the energy density of the VO favoring an increase in consumption for under load condition due to the increase in injection volume to compensate the power factor. HAZAR & AYDIN (2010) found for VO-powered motor, similar result for free-rotation test in which preheating (100 °C) reduced consumption by 9.64% over unheated. The authors commented that this is due to the reduction on viscosity due to heating (± 8 mm^2 s^{-1} at 100 °C for canola oil), favoring the atomization and combustion process. However, both VO treatments presented higher intakes than PD.

The results were similar to those found by DELALIBERA et al. (2010) for sunflower oil with and without preheating (90 °C). For the consumption results under load regime, corroborate with those presented by MARTINI et al. (2012), which observed a tendency on increase of the consumption with the increase of temperature on preheating of soybean oil in engine under regime of absorption at 70% of the nominal power. In addition, the authors commented that the preheating altered the fuel intake and return flows in the injection system, in which the hottest did not differ from the PD.

As mentioned previously by RYAN III & STAPPER (1987), the heating of the VO, besides reducing the viscosity, favoring the processes of injection and atomization, also increases cetane number (CN), improving the fuel quality. However, heating changes the volume and density, resulting in lower energy content per volume and, as systems with mechanical injection control, volumetrically apply the fuel in the combustion chamber, heating may have resulted in negative engine performance. Similar effect was reported by HAZAR & AYDIN (2010), in which the preheating reduced the density on the canola oil by 5.18% in relation to the ambient temperature, reflecting in the increase of consumption, because the reduction of the density also reduces the energy contained in the same volume.

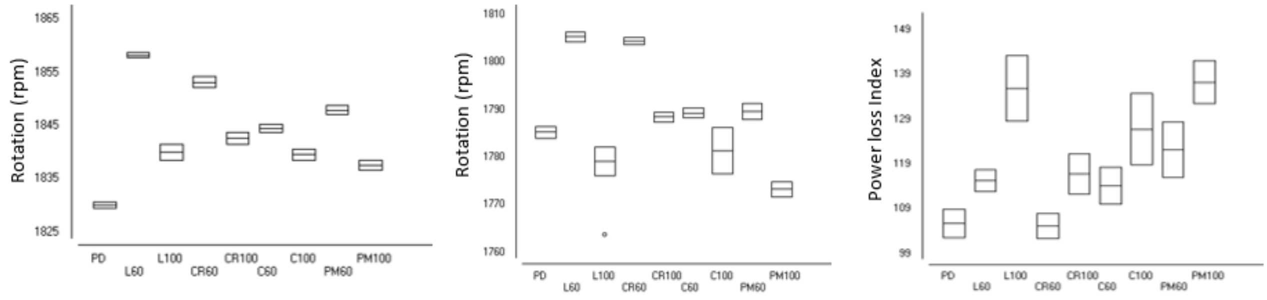
The fuel consumption under free rotation of the preheated VO presented lower variation when compared to the VO without preheating (Figure 1a and 1b and Table 6), indicating that the engine operation for them was more stable. This behavior can be explained by the influence of the variations of the environment on the fuel temperature, within the injection system, favored by the low consumption flow provided by this condition. It is also possible to observe (Table 6) that the relationships between the consumption under load regime divided by 1,800 rpm load-free, tend to be higher for VO than for PD.

TABLE 6. Average fuel consumption, coefficients of variation and consumption relations.

	1,150 rpm free-load		1,800 rpm free-load		3.9 kW@1,800 rpm of load			1.800 rpm Free-load
	Average (g h^{-1})	CV%	Average(gh^{-1})	CV%	Average (g h^{-1})	CV%	VO/PD*	
PD	319.85	2.58	551.28	1.03	1,472.45	1.07	-	2.70
L60	328.92	2.90	581.16	1.11	1,600.78	1.05	1.09	2.75
CR60	299.28	1.76	531.84	1.88	1,544.40	0.99	1.05	2.90
C60	292.25	2.57	534.84	0.61	1,566.99	0.70	1.06	2.93
PM60	301.06	0.68	543.43	1.13	1,596.75	0.59	1.08	2.94
L100	317.11	1.01	570.19	0.56	1,621.92	0.63	1.10	2.84
CR100	291.94	1.13	524.28	1.23	1,529.06	0.64	1.04	2.92
C100	288.29	0.78	533.62	0.48	1,569.02	0.98	1.07	2.94
PM100	291.94	1.11	536.88	0.64	1,625.73	0.86	1.10	3.03

*Vegetable oil on petrodiesel

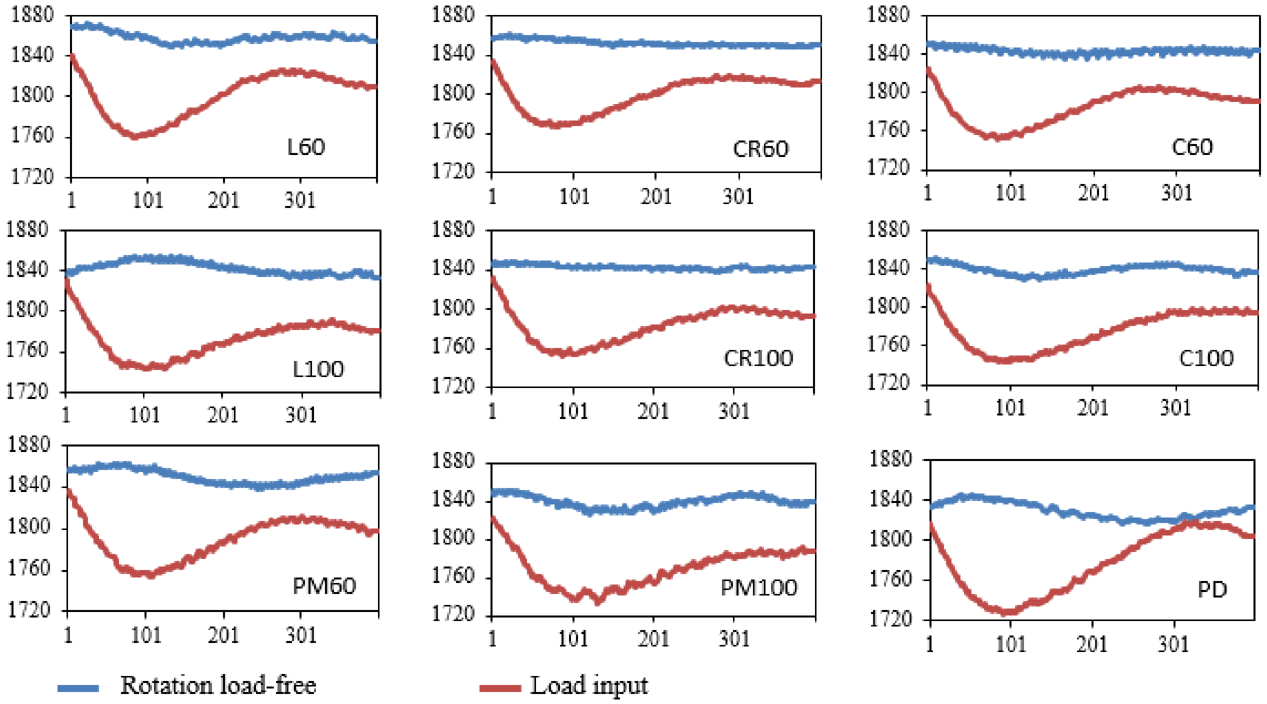
5.3. Loss of power: On Figure 2a and 2b it is possible to observe that the treatments with VO without preheating, present statistically superior average of rotation. It should be noted that the throttle handle always remained in the same position for all treatments. This behavior may have been caused by the energy density of each treatment, resulting in different potencies, due to the theoretically constant volume of injection and also joint effects provided by the injector pump advance system, which could not be measured or determined.



a. Rotation load-free b. Rotation under load c. Power loss

FIGURE 2. Box-plot of averages and standard deviations from rotation (a, b) and power loss index (c).

Figure 3 shows that the initial rotation drop for the PD is higher than for the VO, but at the end of the recovery, the rotation stabilizes near the regime under free rotation. This is probably due to the higher energy density of the PD, requiring less fuel under the condition of free rotation, resulting in a larger initial drop, due to the pump advance response time, but returning near the initial condition. Analyzes show that VOs generally present greater power loss compared to PD (Figure 2c) as shown by contrast 13 (Table 7) and the averages presented in Table 8.



Abscissa Axis - number of readings per second (200 Hz)
Vertical Axis - Engine working speed (rpm)

FIGURE 3. Average rotation curves to free regime and load input in the 2 s time.

VO preheating also had a negative effect on power loss (contrast 14, Table 7), with higher rates. HAZAR & AYDIN (2010) found similar effect because preheating increases the volume and reduces the energy density of the fuel, which injection system can not compensate for high power demands.

TABLE 7. Contrasts for comparing the relative power loss index.

	Nº	Without preheating					Preheated				Σ	p value
		PD	L60	CR60	C60	PM60	L100	CR100	C100	PM100		
Relative power loss index	13.	8	-1	-1	-1	-1	-1	-1	-1	-1	0	<0.01
	14.	0	1	1	1	1	-1	-1	-1	-1	0	<0.01
	15.	4	-1	-1	-1	-1	0	0	0	0	0	<0.01

Scheffé's comparison test for non-orthogonal contrasts

Contrast 15 (Table 7) shows that treatments without preheating present greater power loss compared to PD. It is also possible to observe that only the CR60 treatment showed no difference in PD (Figure 3 and Table 8), a fact that may be related to its high calorific value and cetane number (40,482 and 44.6 kj kg^{-1} respectively, KNOTHE et al., 2006) in relation to the other VO .

TABLE 8. Average power loss, coefficient of variation and relationship vegetable oil petrodiesel.

	Without preheating (60 °C)				Preheated at 100 °C				
	PD	L60	CR60	C60	PM60	L100	CR100	C100	PM100
Average	106.17	115.66	105.53	114.55	122.72	136.38	117.29	127.19	137.74
CV%	3.04	2.09	2.65	3.64	5.03	5.34	3.83	6.25	3.51
VO/PD	-	1.09	0.99	1.08	1.16	1.28	1.10	1.20	1.30

5.4. Opacity of the exhaust gases: Opacity evaluations show that, except for L60, the VO emitted less particulate matter (PM) than the PD (Table 9). It was still found a difference between the C100, PM60 and C60 that presented lower opacity than CR60, CR100, L60 and L100. According to KITTELSON & KRAFT (2014) and STOREY et al. (2015), these are intrinsically related to the physical-chemical properties of each oil, as is the case of PD, that PM emission is related to the amount of sulfur and, for the engine, the characteristics of the of injection system type, combustion system, the thermal efficiency of the assembly and the condition of engine wear which may favor the passage of lubricant into the combustion chamber. No effect of heating was observed on opacity.

TABLE 9. Opacity data, multiple comparison test and estimated particulate material emissions to the work speed of 1,800 rpm.

Treatment	Opacity – k (m^{-1})		Estimated particulate material			
	Medium	Average	Medium* ($g\ h^{-1}$)	Average* ($g\ h^{-1}$)	Medium* ($g\ kWh^{-1}$)	Average* ($g\ kWh^{-1}$)
C100	**9.47**	9.11	47.98	46.15	8.15	7.84 a
PM60	**9.61**	9.55	48.68	48.38	8.27	8.22 a
C60	**9.61**	9.56	48.68	48.43	8.27	8.23 a
PM100	**9.76**	9.68	49.44	49.04	8.40	8.33 a b
CR60	**10.09**	9,96	51.12	50.46	8.69	8.58 b c
CR100	**9.94**	9,99	50.36	50.61	8.56	8.60 b c
L100	**10.09**	10.03	51,12	50.81	8.69	8.64 b c
L60	**10.09**	10.90	51.12	55.22	8,69	9.38 c d
PD	**16.05**	15.81	81.31	80.09	13.82	13.61 d

Averages followed by the same letter in the column did not differ among the Friedman test ($p < 0.05$)
* Estimated values using the BRANCO et al. (2012) transformations for speed of 1,800 rpm

According to RYAN III et al. (1984) and PETERSON et al. (1983) the oils with a high concentration of fatty acids with levels of unsaturation 2 and 3, as in the case of linseed oil which presents more than 50% of linolenic fatty acid (18: 3) in its composition (POPA et al., 2012), tend to result in lower performance compared to less unsaturated composition oils. These fatty acids with a high degree of unsaturation can undergo pre-combustion, causing incomplete combustion, forming carbonization, emitting more smoke, lower thermal efficiency, resulting in higher consumption and lower power.

HAZAR & AYDIN (2010) evaluating a diesel engine fueled with a 50% mixture of canola oil in the PD, preheated (100 °C), observed reduction of 26.3% in PM emission compared to PD. AGARWAL et al. (2010) also, in a motor with a direct combustion system found an effect of the pre-heating of the VO on PM emission being for the pre-heated emitted less than the unheated ones, and both were smaller than the PD.

Considering that this type of engine is still produced, and the emission limits of PM stipulated by the legislation (CONAMA nº 433/2011) for the lower powers (19 to 37 kW, 0.6 g kWh^{-1}) which exceed from 3.2 to 6.3 times the studied engine power, PM emission was 23 and 14 times higher for the PD and VO respectively. Since emissions laws are increasingly strict, emissions may limit the use of engines with a simpler constructive arrangement leading to an increase in the cost of acquisition, especially in the case of agriculture which is a production system considered pollutant mitigator.

It was also observed that the measurements of the opacimeter did not represent the reality of the emissions due to their measurement principle (they are extremely influenced by the characteristics of the sampling probe in conjunction with variables such as the exhaust pipe diameter and internal obstacles, altitude and temperature, relative humidity and atmospheric air quality) and the necessary methodology and, therefore, it is concluded that this is not suitable for using in scientific research.

CONCLUSIONS

The treatments with vegetal oil did not influence in a significant way the work temperature of the motor in comparison with petrodiesel.

There was an effect of the engine working speed on fuel consumption, in which, when under free rotation the vegetable oils presented lower average consumption than for petrodiesel, and when under load was observed the reverse. The preheating also had an effect on the consumption among vegetable oils, in which the consumption was lower under a free-rotation regime and, when under load, the consumption was higher for preheated oils than those without pre-heating.

Vegetable oils have a greater loss of potency than petrodiesel, and preheated oils have a greater loss of potency than non-preheated oils.

Vegetable oils have a lower overall opacity than petrodiesel, and there was no effect of the preheating of the fuel oil on the emission of particulate matter.

The crambe oil, following the canola oil presented the best results.

The preheating of the fuel was less interesting than the non-preheated ones in relation to the technical behavior of the engine. However, the literature shows that in long-term tests (DELALIBERA, 2015), preheating presents positive results regarding to the engine life.

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