PERFORMANCE, WEAR AND EMISSIONS EVALUATION FOR DIESEL ENGINES OPERATING WITH PURE BIODIESEL FROM PALM OIL (B100)

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Abstract. *. On a day it is a general agreement on the need to replace transportation fossil fuel for renewable one in order to reduce emission of greenhouse gases. Among available alternatives, there is ethanol, DME and biodiesel where the last one fits better to compression engine. Government and environment agencies wish spread the use of pure biodiesel to reduce carbon emissions, but engine manufacturers do not know how it impacts on engine performance and long term maintenance, therefore, on their guarantee. Furthermore, little information exists in the literature on compression engine performance running on pure biodiesel. This paper show performance and wear evaluation obtained from compression engine operating with pure biodiesel (B100) obtained from palm oil through transesterification with anhydrous ethyl alcohol. The tested engine was an indirect injection coupled to an electric generator, getset, (with injection pump VE type, 2.6 liters, compression rate of 22:1 and outcome power of 28 hp (20 kVA). The getset was instrumented with sensors for measuring species concentration in the exhaust gas, admission air and coolant temperature, fuel temperature and its mass flow rate as well as monitoring generator electric parameters. Figures present here came from the preliminary test with 100 operation hours divided into 50 hours running on diesel fuel and 50 hours running on pure biodiesel, both held on same load conditions (nominal load). After each 50 hours, the engine was open for visual inspection seeking signs of soot formation and residues, for dimensional cylinder, pistons, bearings and piston rings control as well as lubricant control. As far as the experiment has gone, no drawbacks was found as difficulty on cold or hot start, lubricant degradation, carbon accumulation on components exposed to combustion neither excessive wear beyond those expected for the operation time and load conditions. On the other hand, fuel stability composition has been an issue.*

Keywords: *Biodiesel fueling compression engines, palm oil from ethanol route, engine performance.*

1. INTRODUCTION

On a day is a general agreement on the need to replace transportation fossil fuel for renewable one in order to reduce emission of greenhouse effect. Among available alternatives, there is ethanol, DME and biodiesel where the last one fits better to compression engine. Government and environment agencies wish spread the use of pure biodiesel to reduce carbon emissions, but engine manufacturers do not know how it impacts on engine performance and long term maintenance, therefore on their guarantee. Furthermore, little information exists in the literature on compression engine performance running on pure biodiesel. In Brazil, many works in this direction have already been developed by research institutions and by private companies using various blended biodiesel derived from several seed oil as soybeans, castor and palm oil. However, the literature shows that these works aims on experiments with low percentage of biodiesel in diesel and, in this case, the vegetable oil acts only as an additive to the main fuel, the diesel.

A coordinated Program from Federal government involving research institutions and private companies named Pro-Biodiesel (Tests and trials to validate the use of B5 biodiesel blends in engines and vehicles) performed two sets of engine tests with biodiesel blend: one with a dynamometer coupled to the engine and another using blends in engines of a dedicated vehicle fleet, using biodiesel derived from soybean and castor oil, in proportions ranging from 2% to 100%. Test vehicles adopted mainly B5 (5% of biodiesel) and also B20 (20% of biodiesel) derived from soybean and castor. Dynamometers tests began with B20 (20% of biodiesel from soybean) with increments of 10% up to B100 and varying the load from 0 up to 100 %(0%, 25%, 50%, 100%). Dynamometer results showed that, for B5, a small increase up to 1% in power and 0.7% in torque and for B100, a 5% decrease in power and 8% decrease in torque were found when operating with B100, both under maximum load. Related with test vehicles, they were drove through 100.000 km and at the end no abnormal wear was found that could be associated with the use of biodiesel and was noted small amount of small carbon deposits in some components. Related with emissions always having diesel emission as reference, biodiesel operation had a reduction on CO concentration of 5% and 8%. HC concentration increased in the range of 5% and 7%. NO_X concentration also increased up to 4%. Specific fuel consumption raised as the biodiesel concentration grows, ranging from 1.6% up to 10%.

As one can see, experiments previously done did not focus on use of B100 neither paid attention on electricity generation. To cover such gap, Eletrobras sponsored a research on biodiesel production through transesterification of palm oil with ethyl alcohol as well as its energetic characterization and engine-generator set up (genset) performance under electric point of view doing long term run (500h). This article reports preliminary results (first 100 h) on evaluating performance, wear and emissions of a compression engine operating with B100 derived from palm oil through ethyl route.

2. MATERIALS AND METHODS

2.1. Fuels Characterization: biodiesel from palm oil and diesel.

The biodiesel used in this experiment was produced from palm oil through transesterification via ethylic route in the laboratory of the Chemical Engineering College at UFPa. Table 1 shows biodiesel and diesel fuels characterization data provided by the Biomass Characterization Laboratory at Mechanical Engineering College, UFPA. Additional information on the B100 and diesel can be obtained in NOGUEIRA (2008) and ROUSSET (2008).

Table 1. Physicochemical properties and Energy of B100 for palm oil and diesel.

PROPERTEY		B100 OF PALM OIL	DIESEL
Ultimate analysis	C [%]	78.93	85,80
	H [%]	13.45	13,50
	O [%]	3.00	0
	N [%]	3.25	0
	S [%]	1.37	1.30
Gross heating value [MJ/kg]		33.11	42.2
Net heating value [MJ/kg]		30.15	39.2
Density[kg/m^3] at 25° C		861.25	839.7
Water content [ppm]		56	------
Acidity index [mgNaOH/g]		0.45	------
Index soap [ppm]	at 60° C	456	-------
	at 80° C	4.864	
Flash point [ºC]		162	60
Viscosity (at 60° C) [cSt]		8.54	2.1

Source: Laboratory of Biomass characterization. EBMA – FEM/UFPA

The lower calorific value was calculated using the Eq. (1):

$$\mathrm{NHV_{fuel}} = \mathrm{GHV} - 9 \cdot \frac{\mathrm{m_H}}{\mathrm{m_{fuel}}} \cdot \mathrm{h_{lv}} \qquad (1)$$

where: GHV is the gross heating value provided by Tab. (1), m_H is the hydrogen mass contained in fuel, m_{fuel} is the fuel mass and h_{lv} is the water enthalpy of vaporization, which depends on water vapor pressure (adopt 1 atm).

Table 1 shows that biodiesel of palm oil has NHV smaller than diesel and that biodiesel density is bigger than the one of diesel. Using Eq. (2) is possible evaluate which one has more energy considering a constant volume (such as a drop size).

$$\frac{E_{diesel}}{E_{B100}} = \frac{NHV_{diesel} \times \rho_{diesel} \times V}{NHV_{B100} \times \rho_{B100} \times V} = \frac{39.2 \times 839.7}{30.15 \times 861.25} = 1{,}27$$

It means that, in volumetric basis, diesel fuel has 27% more energy than B100. In the compression engine, it means that at each injection, diesel will deliver 27% more energy than B100 therefore is expected that the engine running on diesel has specific fuel consumption (SFC) 27% smaller than the palm oil.

Another interesting point to observe on Tab. (1) is that palm oil biodiesel contains sulfur, at similar content as diesel and also contains moisture. Moisture reduces the NHV and sulfur causes SO_2 production, which drives to corrosive species.

B100 viscosity is four times bigger than diesel and despite the flash point is bigger, it is far low the temperatures inside the combustion chamber.

2.2 Experimental apparatus

The engine chosen to run B100 was an indirect injection compression engine, with VE type injection pump, 2.6 liter, compression ratio of 22:1, output power of 28 hp (20 kVA) manufactured by Hyundai. This engine works coupled an electric generator three-phase 20 kVA, 220V and 40A, forming a genset provided by Stemac, Fig. (1), monitored through a control panel equipped with a programmable logic controller. Figure 1 shows the generator of "Stemac" installed in research labs, fully instrumented, used in the development of research.

Electricity generated through the genset was dissipated with a set of battery of resistances with total capacity of 53 kW, regulated to run with 15 kW/220V. Electrical parameters (current, frequency and voltage) were measured with a SAGA 4500, model 2382-4B manufactured by Landis+Gyr (accuracy ranging between 1% and 2%).

Fuel volumetric flow rate was measured with a flowmeter "flow-pet" Oval M III model LSF40, operating in the range from 0.3-6 L/h, precision of ±3% and maximum pressure of 0.49 MPa, connected to a digital display manufactured by TechMeter, which has a range of operation from 0-3 L/h, volume/pulse of 161 mL/pulse and output of 4-20 mA.

Figure1. Stemac 20 kVA genset

Exhaust gases composition was monitored with Tempest gas analyzer by Telegan monitoring CO emission in the range of 0-10,000 ppm, resolution of 1 ppm and accuracy of ± 0.01%(<0.1); NO_X in the range of 0-1000 ppm, resolution of 1 ppm and accuracy of ± 5 ppm (<100 ppm) and SO_2 in the range of 0-2000 ppm, resolution of 1 ppm and accuracy of ± 5 ppm (<100 ppm). Exhaust gas, intake air and coolant temperatures were measured with three thermocouples "K" type, with maximum reading of 1200ºC.

These above parameters, except concentration, were followed and recorded on line (software adopted was the DaqFactory by Azeotech) using a data collector model A202 manufactured by CONTEMP with 8 ports, input current from 0 to 20 mA, reading accuracy of ± 0.3% - 25º, reading in 170 ms/8 channels, communication port RS-485 and protocol modbus RTU. Microsoft Office Excel 2007 was used to treat the data collected, determining fuel specific consumption and plotting of graphs.

Engine cylinders wear were evaluated measuring their using dial gauge with precision of 0.01 mm and diameter comparator with range from 50 mm to 150 mm, manufactured by Mitutoyo.

The apparatus used in conducting the tests is described in the scheme of Fig. 2.

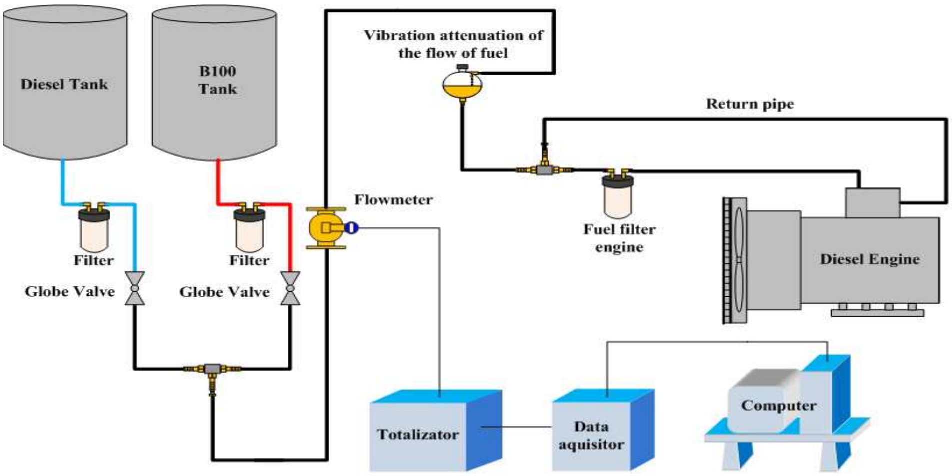

Figure 2. Test bench schema used in conducting the tests.

2.3 Experimental method

All tests were done using only B100 and data were acquired after the genset achieve steady state regime. Engine starts up without electric load and stays in idle condition up the coolant temperature be steady. Then the generator was switched on and electric load caused by the battery of resistance was gradually increased (50%, 75% e 100%) at intervals of five minutes. Once the genset was stable operating at 1800 rpm (60 Hz) at its maximum electrical output (14.3 kW) data acquisition began with electrical parameters (voltage, current, power and frequency), following by the fuel volumetric flow rate as well as intake air, exhaust gas and coolant temperatures. Exhaust gas sample was collected and its composition analyzed at every 15 minutes. Experiments were executed continually from 9:00 AM to 5:00 PM. After 50 hours of operation with diesel fuel under maximum load, the engine was disassembled for analysis and cleaning, assembled and run for another 50 hours with the B100 under the same loading conditions. After that, the engine was disassembled again and another evaluation was done, similar the previous one described. Comparison on diesel fuel and B100 was seek to relate solid carbon accumulation and wear conditions for cylinders, pistons, piston rings, bearings and engine crankcase.

2.4. Mathematical formulation

The equations presented below were used to process the information collected and produce concepts for the analysis and presentation of results of tests on the generator.

The mass flow of fuel was determined using the Eq. (2).

$$\dot{m}_{fuel} = Q_{fuel} \times \rho_{fuel,85ºC} \tag{2}$$

where Q_{fuel} is the volumetric flow of fuel measured by Flowpet and $\rho_{fuel,\ 85°C}$ is the fuel density at 85°C obtained from Table 2.1. Thermal power was quantified using the mass flow rate and LHV obtained from Tab. 2.1 through Eq. (3).

$$P_t = LHV_{fuel} \times \dot{m}_{fuel} \tag{3}$$

Specific fuel consumption, SFC, fuel mass flow was divided by the electrical power measured with SAGA 4500 analyzer.

$$SFC = \frac{\dot{m}_{fuel}}{P_{el}} \tag{4}$$

Equivalence ratio was evaluated using Eq. (5).

$$\Phi = \frac{\dot{m}_{fuel}/\dot{m}_{air}}{\left(\dot{m}_{fuel}/\dot{m}_{air}\right)_{st}} \tag{5}$$

m_{fuel}/m_{air} is the mass ratio between fuel and air flow rates. Equation denominator is the same ratio but at stoichiometric conditions. The mass of air was determined through measures of a manometer and a Pitot tube installed in the admission tube of air. The stoichiometric mass ratio between fuel and air was evaluated using information from ultimate analysis (Table 2.2)

3. RESULTS AND COMMENTS

3.1 Engines performance evaluation

Table 2 shows the operating conditions of the generator taken during testing for this paper.

Table 2. Operating conditions of the generator for the paper.

CONDITIONS OF OPERATION OF MOTOR AND GENERATOR	
Motor speed [rpm]	1800
Coolant temperature engine measured on the head [° C]	96 ± 2
Load regime applied to the engine [%]	100
Fuel	B100 of palm oil
Fuel/air ratio	0.050
Stoichiometric ratio (fuel/air)	0.068
Equivalence ratio [Φ]	0.749
Effective power at the generator output [kW]	14.3
Electric output frequency [Hz]	60

Results after 50 hours of operation on both fuels showed that the average specific fuel consumption of diesel was 297 g/kWh and the SFC for B100 was 330 g/kWh, meaning an increasing on B100 SFC of 10% therefore a decreasing in performance in the same percentage. Figure 3 shows a comparison between the SFC for the engine operating with B100 and diesel as function of time.

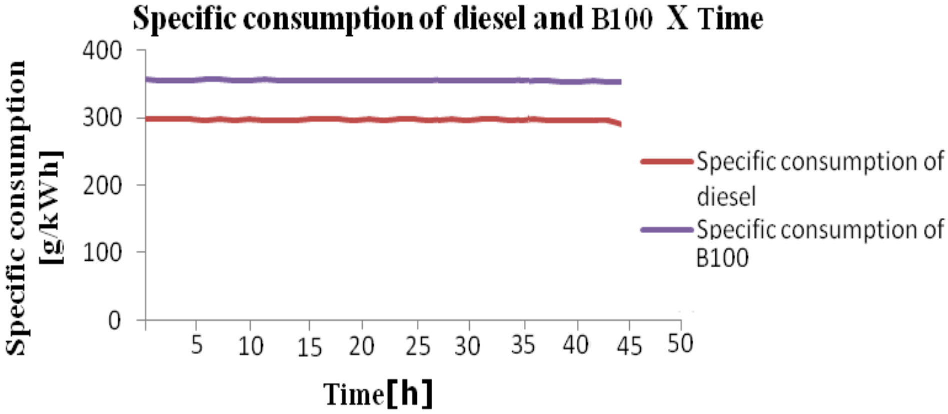

Figure 3. Specific fuel consumption as a function of time.

Table 3 shows a comparison between diesel fuel and B100 from palm oil (via ethylic route).

Table 3. Engine Performance analyzed using specific consumption in operations with diesel and B100

	diesel	palm oil biodiesel
Specific consumption(arithmetic average) [g/kWh]	297	330
Standard deviation [g/kWh]	1.39	0.84

Item 2.1 described that, in volumetric basis, diesel deliver 27% more energy to the engine at each fuel injection than palm oil B100 driving to an expected lower SFC for diesel compared with palm oil biodiesel 27% lower. Table 3 result shows that measured SFC for diesel only 10% smaller than palm oil biodiesel indicating a better combustion for palm oil biodiesel perhaps due to an easier evaporation or higher rate in chemical kinetics. This needs to be better analyzed.

3.2 Wear evaluation.

Visual inspection and dimensional control realized on internal components, feeding and lubrication systems showed no wear on moving metal components such as pistons, cylinders, piston rings and bearings that could be associated with the use of B100. However, operation with B100 showed a slight increasing in the wastes solid accumulation of solid at pistons head and valves and, the most inconvenient, fuel filter clogging. It was not noticed visually formation of lees in the lubricant neither in the oil pump, lubrication channels and crankcase.

Figure 4a shows residue buildup on the cylinder top near valves area after diesel operation and Fig. 4b after operation with diesel plus biodiesel. A small increasing on residue accumulation due B100 operation can be noticed.

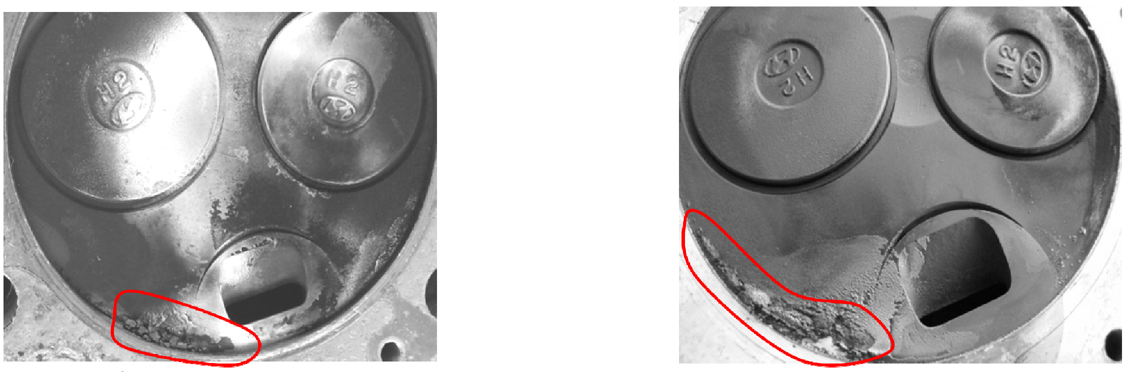

Figure 4. (a) left, residue on head when operating with diesel. (b) right, residue on head when operating with B100.

Table 4 shows the values for ovality, taper and clearance between piston rings measured at 2nd engine cylinder in comparison with expected wear presented after operation with diesel and B100.

Table 4. Data ovality and taper in the cylinder and clearance between piston rings.

	after diesel	after B100	Max allowed value
Ovality of the cylinder [mm]	0.01	0.01	0.046
Taper of the cylinder [mm]	0.02	0.02	0.091
Clearance between piston rings-1st ring compression [mm]	0.45	0.50	------
Clearance between piston rings-2nd ring compression [mm]	0.55	0.65	------

Visual analysis made at the fuel filters installed before the flow meter showed significant waste accumulation after B100 operation and not observed during diesel operation. The reason may be related to biodiesel structural instability that produces solid after some storage period. Further study to understanding the causes has been carried out by Chemistry group. The overcome this problem before a full explanation is obtained, biodiesel pre-heating will be adopted to assure that all solid are turned into liquid before flow to the inlet system. Figure 5a and Fig. 5b show the difference in fuel filter contamination after 50 hours operating with the diesel and with the B100, respectively.

Figure 5. (a) left, fuel filter after 50h of diesel operation. (b) right, fuel filter after 50h of B100 operation.

3.3 Emissions evaluation.

Two species were monitored for diesel fuel and B100 palm oil: carbon monoxide (CO) and nitrogen oxides (NO_X). Figure 6 shows lower CO emission for biodiesel than diesel. It is worth remember that the presence of CO in the exhaust gases indicate a waste of fuel energy, since it reflects incomplete combustion. The low levels of CO perceived in the B100 exhaustion indicates a better combustion justifying the efficiency gain described at the end of item 3.1. CO concentration operating with B100 is 25% less than operating with diesel.

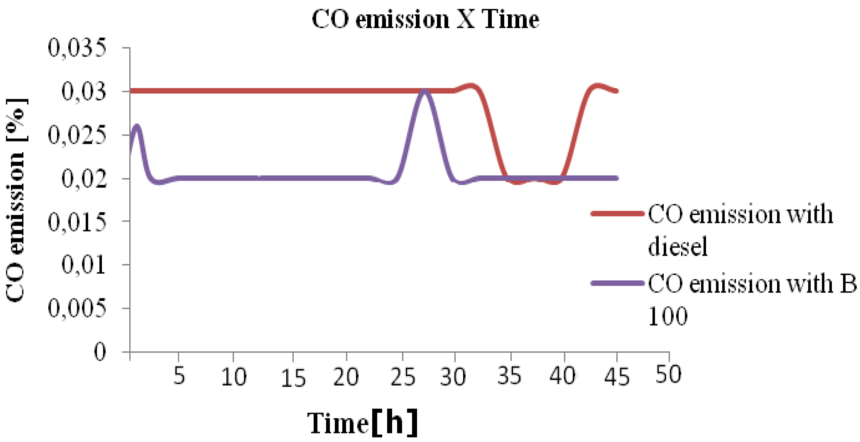

Figure 6. Carbon monoxide emissions as a function of time.

Figure 7 shows NO_x emission for diesel and B100. Remembering that B100 has nitrogen in its composition and diesel does not have, it is supposed to expect more NO_x coming from B100. Figure 7 shows just the opposite. B100 produced less NO_x concentration than diesel, approximately 10% less (See Tab. 5). NO_x production depends on nitrogen availability, maximum gas temperature and the time that the gases stay above the trigger temperature. Therefore Fig 7 indicates that diesel produces higher temperatures than B100 and keeps such temperature higher longer than B100.

Figure 8 shows exhaustion gas temperature for both fuels as function of operation time. There, exhaustion gases from biodiesel achieved higher temperature than diesel (app. 3.5%). Exists for engine exhaust temperature an inverse relationship between the maximum temperature inside the combustion chamber and the temperature measured at the exhaust manifold. Therefore B100 had a maximum temperature within the combustion chamber less than the diesel (what justifies the reduction of NO_x emission). A possible cause for this phenomenon may be associated with B100 larger ignition delayed compared with diesel.

Table 5 shows the arithmetic average for emissions and exhaust gas temperature after diesel and B100 in 50 hour test.

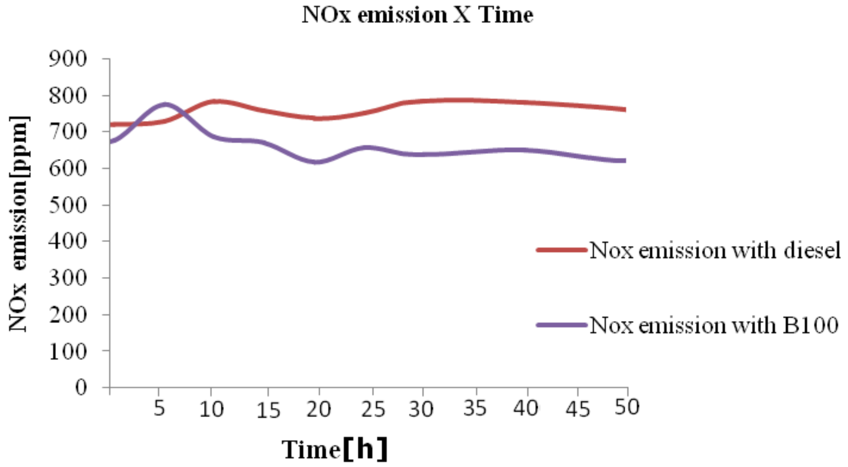

Figure 7. Nitrogen oxides emissions as a function of time.

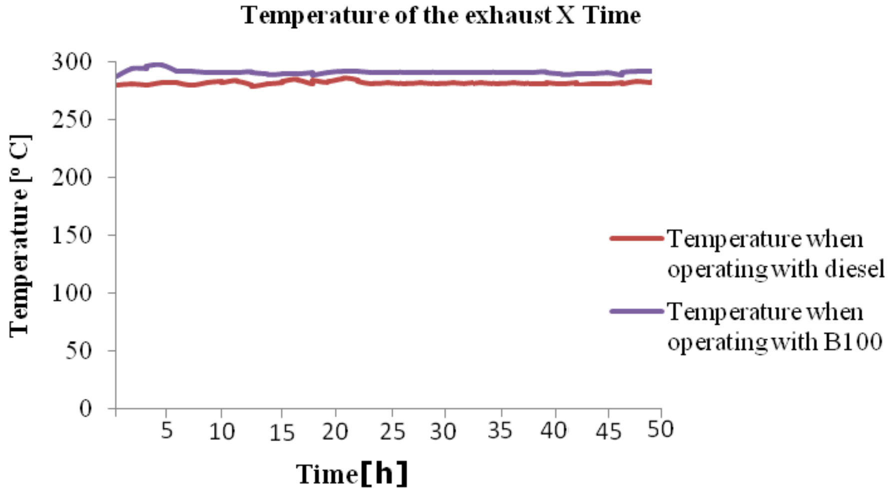

Figure 8. Temperature of gases exhaust as a function of time

Table 5. Temperature of exhaust gases and emissions after operation with diesel and B100

	OPERATION WITH DIESEL	OPERATION WITH B100
TEMPERATURE OF THE EXHAUST [^{O}C]	282	292
STANDARD DEVIATION [^{O}C]	1.47	2.34
Carbon Monoxide- CO [%]	0.028	0.021
Nitrogen oxides - NO_X [ppm]	749	671

4.0 CONCLUSIONS

From the functional point of view, the engine behaved very well in operations with B100 in comparison with diesel operation. B100 did not have trouble on cold and hot starts or even failure during operation. As for the results of performance assessments, wear and emissions, was noted a 10% increase in specific fuel consumption of engine in the operation with B100 compared to diesel operation, considered a positive result, since the energy contained in the B100 is 27% lower than in the diesel, which demonstrates that the B100 has easy vaporization and good rate on chemical kinetics.

In the evaluation of internal engine components, as crankshaft, cylinders, piston rings and bearings, was not observed significant increase in wear that could be attributed to the use of B100. However, it was noticed a slight increase in solid waste on the cylinder top. Fuel filter presented the most concern problem which the accumulation of fatty material after 50 hours of operation with B100. Such problem was attributed to the B100 thermal instability.

The emissions analysis showed B100 with 25% reduction in CO and 11% reduction of NO_x, compared with the levels shown during diesel operation, which shows a better performance for biodiesel from palm oil in the combustion reactions.

Despite this preliminary result is optimistic, it has pointed out some concern that must be verified their evolution during the remaining 500 hours of operation that the Eletrobras project requires.

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