EVALUATING INDIRECT INJECTION DIESEL ENGINE PERFORMANCE FUELED WITH PALM OIL

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***Abstract**. Previous works has demonstrated the feasibility of palm oil application as fuel for compression engines as well as others vegetable oils. Such oils can be used without chemical transformations requiring only be filtered and neutralized, both simple processes, and they have high heating values similar to diesel oil. Problems already identified are related with its high viscosity at room temperature and requirement for larger residence time than diesel fuel to complete its combustion reaction. The first problem has been solved with oil pre-heating before high pressure injection pump inlet and there are available systems to perform this task. To the second problem (longer residence time) all proposed approach to solve it rely on keep high temperature in the combustion chamber and accelerate the chemical kinetics in such way that the engine available time for combustion is bigger than the fuel required residence time. It implies that the engine can operate with vegetable oils only at high loads, being replaced by diesel oils at medium and low loads. This problem has been report on all experiments using direct injection compressed engines. Indirect combustion engines have a pre-combustion chamber that is kept always at high temperature independent of the shaft load. Therefore it is supposed that such engines are able to operate with vegetable oils for their full range of operating load. This work tested an indirect injection engine assembled as part of a 20 kVA generator set, (genset) and the results compared with those of direct injection engine. Palm Oil was used as fuel and the genset received instrumentation to measure the fuel temperature and flow rate at engine inlet, elude gas temperature at exit of combustion chamber, electric power produced and gas emitted composition (CO and NOx,). Similar data was obtained for the genset operating with diesel oil for comparison. In order to quantify the inlet amount of energy the diesel oil and palm oil were submitted to test to quantify their high heating value and ultimate analysis. Results showed that indirect injection engine operating with palm oil have an increasing on specific consumption fuel as well as CO and NOx concentration and small drop on eluded gases temperature, compared with direct injection engine consuming palm oil for the same load percentage.*

Keywords: *palm oil as fuel, compression engine, indirect injection versus direct injection.*

1. INTRODUCTION

In the last three decades, research has been done successfully using biodiesel as fuel for compression engines. On the other hand, the modern use of pure vegetable oils directly in compression engines has a more recent history and is led by Germany.

The use of pure vegetable oils as fuel is problematic due its high flash point, low volatility and high viscosity, resulting in poor atomization and incomplete combustion. One solution to overcome these problems is the transesterification process (reaction of vegetable oil with alcohol to produce biodiesel). This is a fine chemical process that demands a sophisticated infrastructure hard to be found in most of Amazon region cities and villages. Furthermore, those towns are not connected to the national electricity transmission grid and their power, if any, comes from diesel generator sets (gensets). On the other hand, these towns generally have large quantities of trees capable of producing vegetable oils, many of them without commercial value that could be used as fuel in compression engines or converted into biodiesel. To convert this vegetable oil into biodiesel, it has to be sent to chemical plants usually located at bigger cities requiring transport logistic, difficult to be obtained as the amount of oil gets smaller. Modify the engine generator set to consume pure vegetable oil allows local fuel production that can be used to generate power and for transportation (mainly in boats and trucks), displacing fossil fuels and promoting the local economy.

A few projects have been developed in Brazil in the last decade related with use of pure vegetable oil in compression engines. FLEURY et al (2002) conducted tests of 400 hours in a motor MWM D229-6 direct injection burning palm oil. Results showed 6% reduction on output power running with palm oil related to diesel fuel as well as increasing on exhaust gases temperature. Major problems faced were lubricating oil contamination and nozzles partial obstruction. Despite these problems the use of vegetable oils in diesel engines was satisfactory.

BELCHIOR et al (2005) conducted 350 hours tests on 70 kW-MWM D229 engine, four-stroke, direct injection. It was found that the amount of residues accumulates inside the combustion chamber depends directly on the oil temperature at the injection pump inlet. Higher this temperature, less residues comes up in the combustion chamber. He reported a small increasing on the fuel specific consumption for all load values when operating with palm oil compared to diesel. He also found an increasing on CO emissions as well as NO_x reduction when operating with palm oil.

COELHO (2005) demonstrated the feasibility of using palm oil in a direct injection MWM diesel engine located at Vila Cruzeiro in the municipality of Soledad Moju/Pará, for a period of 2000 hours. The high cost of the engine service was offset by the local fuel availability at low cost. He reported that service cost could be reduced if they had used indirect injection engine.

All works previously described agreed that is possible to obtain reliable getset operation at full load operation if the pure vegetal oil is heated up to reduce its viscosity bring it near the diesel viscosity. To warm up the vegetable oil and remove it from the fuel system before engine shut down, the engine must have the start up and shut off cycles running on diesel fuels. All also agree that indirect injection engines should perform better than direct injection engines. Although this comments is very common in the literature (indirect better than direct for pure vegetable oil), there has no data comparing performance and emission of indirect against direct injection engines operating with pure vegetable oils.

This paper shows performance for an indirect injection getset engine running on palm oil at 100% of its nominal load and comparing these data with similar results coming from an direct injection getset engine operating at its nominal load, also operating with palm oil.

2. DESCRIPTION OF EXPERIMENTAL APPARATUS AND FUEL

The palm oil used during all tests was produced in Pará State and sent to the College of Chemical Engineering at UFPA, where it was neutralized and filtered and delivered to the Mechanical Engineering Engine Lab in UFPA. The oil energetic characterization was done at the Biomass Characterization Laboratory at FEM/UFPA. The result of such characterization, for palm oil and diesel oil used in the experiments, are shown in Tab. 2.1. Tab. 2.2 has Ultimate Analysis result also done for diesel and palm oil used. The lower calorific value was calculated using the equation:

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

Where: HHV is the gross heating value provided by Tab. 2.1, 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. Adopted Fuels, palm oil and diesel oil characterization. EBMA/FEM/UFPA 2010.

Property		Diesel	Palm Oil	Methods available for analysis
Gross heating value [kJ/kg]		42200	40700	ASTM D 240 ABNT NBR 8633
Net heating value [kJ/kg]		39200	38100	
Volatile content (% mass)		99.7	99.7	ABNT NBR 8112
Fixed carbon content (%mass)		0.3	0.25	ABNT NBR 14318 ASTM D 189, D 4530
Flash point [°C]		60	>344	ABNT NBR 7974 ASTM D93
Viscosity [cSt]	40° C	2.6	38.23	ABNT NBR 10441
	60°C	---	20.07	ABNT NBR 10441
	100°C	1.10	8.064	ASTM D445 e D1545
Density [kg/m^3] at 20°C		836.7	929.2	ABNT NBR 7148
Density [kg/m^3] at 85°C		---	858.4	ABNT NBR 7148

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

Table 2. Ultimate Analysis for diesel and palm oils. Oxygen obtained by difference.

Property	%C	%H	%N	%O	%S
Palm oil	75.54	12. 23	3. 61	8.62	0
Diesel	85.80	13.50	0	0	0.7

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

Table 2.1 shows that palm oil viscosity at 40°C is 16 times greater than diesel while the 100°C is 8 times higher. Viscosity decreasing with temperature can be seen in Figure 2.1. Gilles (2008) reports that the vegetable oil viscosity to be accepted into injection pump should be below 15 cSt. Figure 2.1 indicates that palm oil should have their temperature raised above 80°C. Fleury et al. (2002) as BELCHIOR et al. (2005) reported that palm oil inlet temperature should be between 80°C and 90°C to reduce deposit formation in the combustion chambers and nozzles.

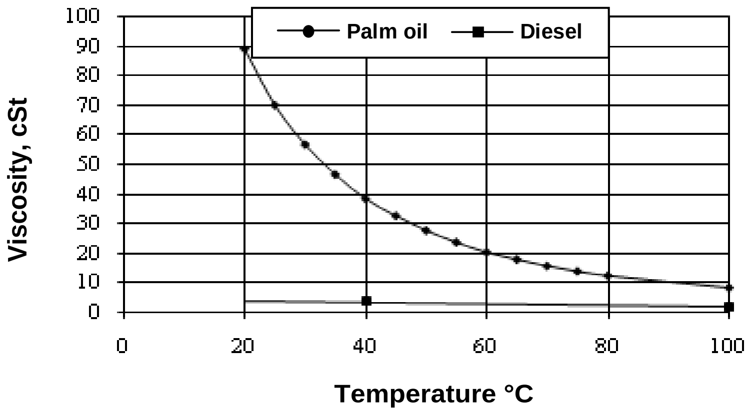

Figure 1. Viscosity x Temperature to palm oil and diesel. (Fleury et al., 2002)

Both above fuels were applied into the indirect injection and direct injection engines. The indirect injection engine was a Hyundai D4BBG1, 4 cylinders, 1800 rpm composing a generator of 25 kVA. The direct injection engine was a C40D64 Cummins, 4 cylinders composing a generator of 53 kVA. Experiments took place at 100% of engine rated load during 40 hours for each fuel. Diesel fuel results were adopted as reference for comparison against palm oil.

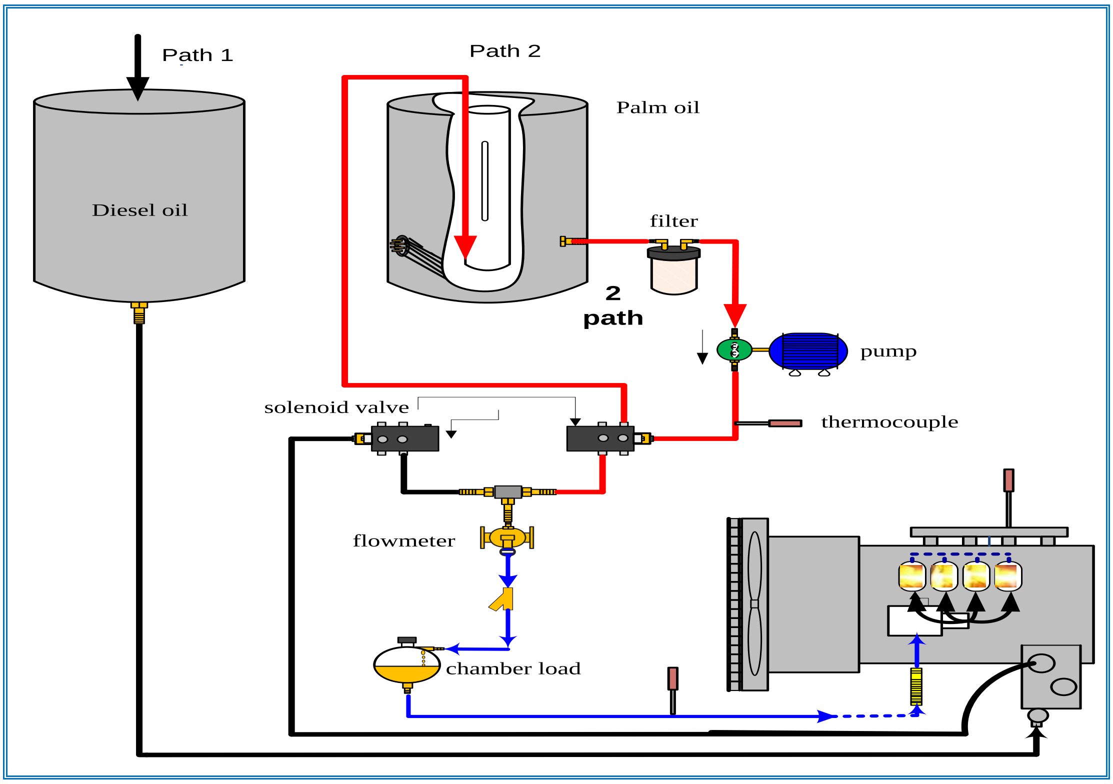

Figure 2. Experimental apparatus

Following Fig. 2.2, the system has two circuits with one reservoir each: one for diesel and another for palm oil. Before palm oil is accepted into the engine, it was heated to about 90°C in a stainless steel tank through an electrical resistance of 4500W. Such tank has an electrical mixer for uniform oil temperature. In order to warm up the palm oil circuit, pump circulates the oil through the filter solenoid valve and returns to tank. When the oil is the desired temperature, the diesel solenoid valve is closed and palm oil solenoid valve is open is open allowing the palm oil flow to the engine. Palm oil flows through the flow meter and reaches the loading chamber which has a small resistance that adjusts the oil temperature between 80°C and 90°C. The injection temperature is monitored by a thermocouple installed before the injector pump. The electricity produced is dissipated through a tubular resistance that can be adjusted to generate a load of 50%, 75% and 100% of rated genset power at 1800 rpm. The genset specific fuel consumption was obtained with the ratio between measured volumetric fuel flow rate with an OVALM III-39 Super Micro Flowmeter gear with an accuracy of ± 3% times the fuel density and the electrical power output obtained through the meter installed in the circuit resistance. The monitoring of temperatures was carried out with Type K thermocouples with an operating range superior limit of 1200°C. Three TC were installed: one before the injection pump to measure the fuel temperature; one after the circulation pump oil palm to measure the oil temperature coming from the tank; one still in the exhaust manifold tube in front of cylinder 3 gas exit to measure the temperature of exhaust gases. The electrical parameters were monitored by a SAGA 4500 analyzer of Lanis+Gyr with 1% accuracy. Acquisition software was developed by the research group to acquire and monitoring genset variables on real time. Exhaustion gas concentration was measured with a gas analyzer Tempest 100 by Confor Instruments at each 15 minutes providing measured information for O_2, CO, NO, SO_2, temperature and pressure. CO_2 information is provided based on the fuel chemical composition.

All tests on palm oil started its genset operation on diesel oil for about 15 minutes and then switch the solenoid valves from diesel to oil palm. The shut off operation ran again on diesel fuel for 10 final minutes aiming to clear the entire fuel line injection system from palm oil to prevent waste accumulation.

Tests were performed in an indirect injection engine for a period of 40 hours with diesel in order to obtain a database and then for a period of 40 hours with palm oil all with 100% of rated load of the generator for both fuels. The tests in the direct injection engine were carried out by MORAES (2010) at LABEM/FEM/UFPA using 100% of rated load of the generator for the diesel and palm oil.

3- MATHEMATIC 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. (3.1).

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

where Q_{fuel} is the volumetric flow of fuel measured by Flowpet and $\mathbf{r}_{fuel,\ 85°C}$ is the fuel density at 85°C obtained from Table 2.1. Thermal power was quantified using the mass flowrate 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)

4. ANALYSIS OF RESULTS

Table 3 shows the average obtained values during the experiments as well as the equivalence ratio calculated. The analysis was done comparing the results from indirect injection engine with direct injection engine after 40 hours operation at 100% load generator using the same fuel (diesel and palm oil).

Following Tab. (3) are figures, starting with Fig. (3), showing results on time chosen to be analyzed because demonstrates to be as steady as possible during the two engines operation. Such figures depict in a single graph results for diesel and palm oils as well as for direct and indirect injections.

Table 3. Means values for the two engines

Injection Engine	Fuel	Specific fuel consumption (L/kW-h)	Cylinder Eluded Gas Temperature (ºC)	CO (ppm)	NOx (ppm)	Equivalence ratio(fuel/air)	Load power (kW)
Indirect	Diesel	0.36	290	591	820	0.74	14.86
	Palm oil	0.41	263	616	1000		14.76
Direct	Diesel	0.32	510	491	1292	0.76	35.83
	Palm oil	0.34	527	409	1224		36.17

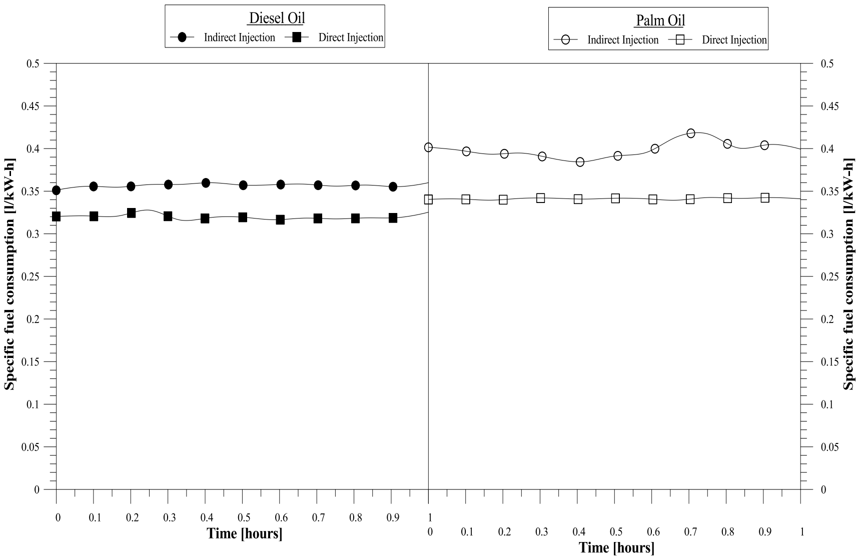

Figure 3. Specific fuel consumption 100% nominal load.

According to Fig. 3, there was an increasing on the SFC of 13.9% running on palm oil relative to diesel with indirect injection engine and an increasing of 6.3% for the direct injection. Under SFC point of view, DI had a better performance than II. It was expected that DI engine has a somewhat smaller SFC since its power is twice bigger than then II, see Tab. (3). However, the impact of palm oil in increasing the specific consumption of the engines was higher in the indirect injection than the direct injection. MORAES (2010) states that the specific fuel consumption of vegetable oil can be improved anticipating the fuel injection point and/or decreasing the droplet size of fuel injected into the chamber.

Figure 4 shows a decreasing of 11.5% on the exhaust gas temperature for palm oil in II engine and DI had only a decreasing of 3.35%. It is true that indirect injection engines have maximum temperature inside the combustion chamber greater than the direct injection engine, therefore, it has exhaust temperature lower for the II engine and higher for DI engine. These high temperatures in the combustion chamber II engine speed up the fuel vaporization and chemical reaction.

Comparing eluded gas temperatures for diesel and palm oil, the first always have higher temperature, despite be DI or ID. Higher eluded gas temperature for DI engine indicates its combustion started early than II, reinforcing the proposal that the anticipation of the injection point can bring gains in engines consuming pure vegetable oil.

Figure 5 shows no significant changes in levels of CO, although Tab. 2 informs that diesel has more carbon than palm oil. It indicates that diesel combustion of was more efficient possibly consequence of having more time to achieve complete combustion once it started early. Again, it suggests that a reduction in droplet size as well as advance in the fuel injection point can bring efficiency gains to the vegetable oil.

Having in mind that palm oil contains more nitrogen in its composition than diesel (see Tab. 2), Fig. (6) compares the NO_x emissions for both fuels and both engines. NO_x emission from the DI running on palm oil decreased 5.2% compared with diesel fuel. On the other hand, II had an increasing on NO_x concentration of 23.3% running on palm oil over the diesel fuel. It indicates that, in the case of DI, palm oil combustion reduces the maximum temperature due its delay on combustion start caused by increasing on its vaporization time, reducing the conversion of N_2 from air into NO_x balancing the nitrogen brought in by palm oil. In the case of II, the pre-combustion chamber keeps the inside gases at higher temperature longer than the DI case promoting NOx production, being the nitrogen origin coming from the fuel and air.

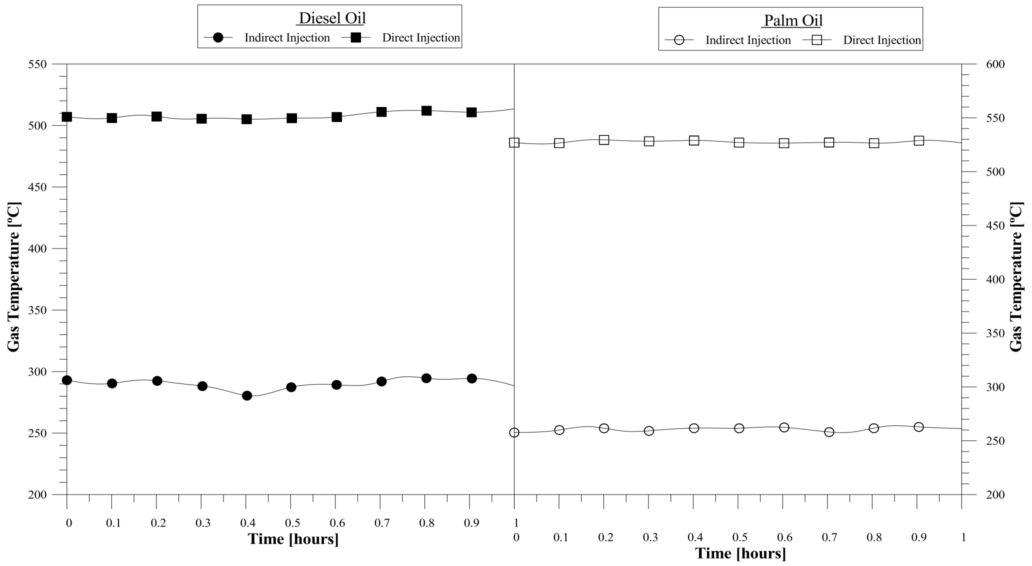

Figure 4. Cylinder eluded gas temperature. 100% load.

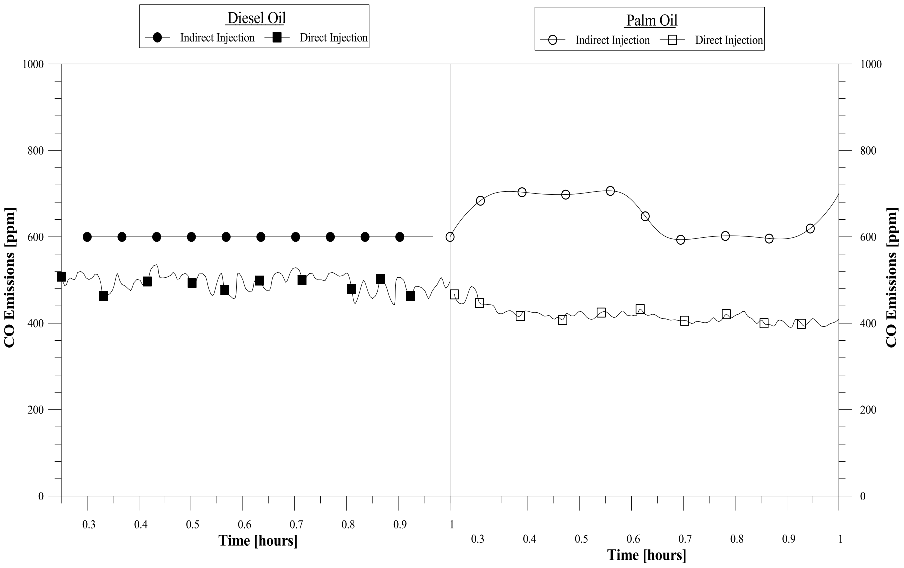

Figure 5. CO Emissions.

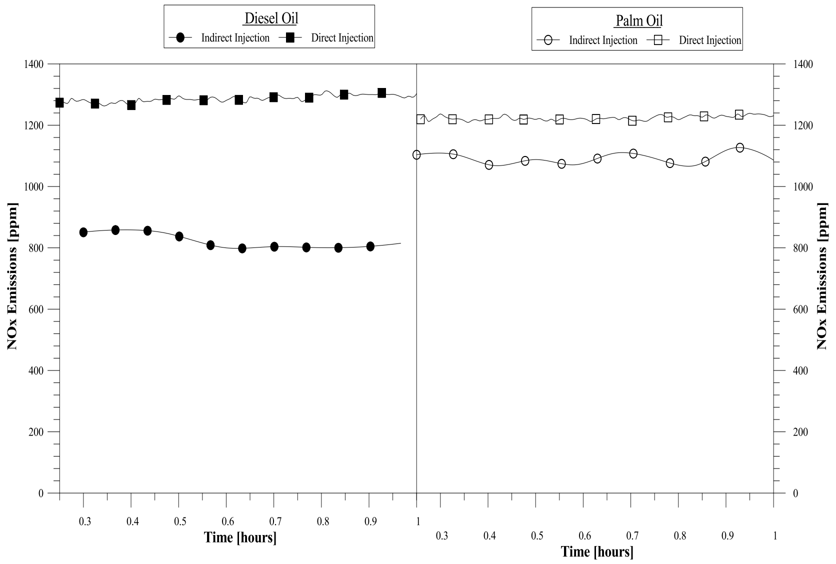

Figure 6. NO_x Emissions

5. CONCLUSIONS

Results presented in this paper comparing the use of palm oil in direct and indirect injection compression engines operating at full nominal capacity show no advantage on the II over the DI as proposed in the literature. The specific fuel consumption for II increased more than for DI, NO_x emission was bigger and CO emission was equivalent despite there is potential to improve palm oil performance advancing the fuel injection point related to diesel oil and reducing the droplet size with the increasing on the injection pressure.

Therefore, as stated by Moraes (2010), direct engine operation with palm oil is limited to a very high partial load (85% of nominal load). Indirect injection engines should be brought to partial loads and verified if they can operate at lower partial load than direct engines, what seems feasible once II keeps high gases temperature in its pre-combustion chamber what can make possible vegetable oil vaporize at very lower partial load. Experiment should be to verify how low the partial load may go with II engines without compromising its operation and compare this limit with the limited presented by Moraes (2010).

6. ACKNOWLEDGEMENTS

The CAPES and ELETROBRAS

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