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 along 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 its flow rate, eludd gas temperature at exit of combustion chamber, electric power produced and gas emitted composition (CO and* NO_x*,). Similar data was obtained for the genset operating with pure diesel oil for comparison. In order to quantify the inlet amount of energy the diesel oil and palm oil were submitted to 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* NO_x *concentration and small drop on exhaustion 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. Vegetable oils are important alternatives as substitute for petroleum fuels. Extensive reviews of vegetable oils and their use in internal combustion engines are available in recent literature, RAMADHAS (2004) and MISRA R.D (2010).

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 source, if any, comes from diesel generator sets (gensets). On the other hand, these village counties generally have large quantities of palms 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 availability of such oil gets smaller. Modify the engine generator set to consume pure vegetable oil promotes 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.

Yilmaz, N. and Morton, B. (2011) presents experimental results for two different diesel engines running on three different vegetable oils (peanut, sunflower and canola oils). The thermal efficiency, exhaust gas temperature and emissions composition were determined as a function of load at ambient and preheat conditions for vegetable oils. They found that vegetable oils pre-heating increases thermal efficiency. Vegetable oils also increases CO and NO emissions and reduce O2 and unburned HC concentration at exhaustion, as compared against pure diesel fuel operation. However, the difference was small and effect of preheating on O2 was not relevant. Unburned HC emissions reduction was the highest at no-load conditions.

In Brazil, FLEURY et al (2002) conducted tests of 400 hours in a motor MWM D229-6 direct injection burning palm oil in nature, the results showed 6% reduction on the output and increasing on exhaust gas temperature running on palm oil compared against pure diesel fuel. He also reported lube oil contamination and partial nozzles obstruction. Despite all these problems, the use of vegetable oils in diesel engines was satisfactory.

BELCHIOR et al (2005) conducted 350 hours tests on motor MWM D229 four-stroke direct injection of 70 kW. It was found that the amount of waste accumulation in the combustion chamber is inversely connected with palm oil injection temperature. He showed a small increase on fuel specific consumption for all load values, an increasing on CO concentration and reduction on NOx emission operating with palm oil as compared to pure diesel fuel operation.

COELHO (2005) demonstrated the feasibility of using palm oil in a field operation. A direct injection diesel engine MWM installed at Vila Cruzeiro, Soledad Moju County/Para, for a period of 2000 hours. The article shows that engine maintenance high costs were offset by the availability of local fuel at low cost. It concludes stating that the maintenance costs could be reduced if indirect injection engines were applied.

Previous experiments have shown that a reliable operation with direct injection engines is possible through vegetable oil pre-heating aiming to reduce its viscosity plus start and end vegetal oil operation with pure diesel use. Although the literature reports that vegetable oil perform better on indirect injection engines, no references were found this matter containing the performance of indirect injection engine operating on vegetable oil in nature.

The aim of this paper is to present results of the operation of an indirect injection diesel engine operating with palm oil and compare its performance data with those of a direct injection engine, both operating with palm oil at 100% of the rated load.

2. DESCRIPTION OF EXPERIMENTAL APPARATUS AND FUEL

The palm oil used during all tests was produced in Pará State and sent to the School of Chemical Engineering at UFPA, where it was neutralized and filtered and delivered to the School of Mechanical Engineering Engine Lab also at 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.1. Table 2 has Ultimate Analysis result also done for diesel and palm oil used at same lab. The lower calorific value, LHV, was calculated using the following equation:

$$LHV_{fuel} = GHV - 9 \cdot \frac{m_H}{m_{fuel}} \cdot h_{lv} \quad (1)$$

Where: GHV is the gross heating value obtained from Tab.1, mH is the hydrogen mass contained in fuel, mfuel is the fuel mass obtained from Tab.2 and hlv is the water enthalpy of vaporization, which depends on water vapor pressure (adopted 1 atm).

Table 1. Palm and diesel oil characterization. Diesel contains 5% of biodiesel.

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/m3] at 20°C		836.7	929.2	ABNT NBR 7148
Density [kg/m3] 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 fraction 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 1 show that palm oil viscosity at 40°C is 16 times greater than diesel while the 100°C is 8 times higher. ROUSSET (2008) reports that the vegetable oil viscosity to be accepted into injection pump should be below 15 cSt. Therefore palm oil should have their temperature raised above 80°C to flow through the fuel system. 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.

Table 1 also provides interesting information related with the content of energy delivered to the combustion. Once mechanical injection pump deliver constant volume for a specific load, diesel NHV in volumetric basis is 32.7 GJ/m3 and palm one is 35.4 GJ/m3: 8.3% bigger than diesel.

2.1 Methodology

Both fuels (diesel and palm) were supplied for the same genset with indirect injection engine at different time (initially diesel as reference and then palm oil. The indirect injection engine was a Hyundai D4BBG1, naturally aspirated, 4 cylinders, 2607cm3 CC, 22.1 compression ratio, mechanical injection with nominal injection pressure of 11.770 – 12.750, running at constant speed of 1800 rpm, coupled to a electric generator of 20 kVA. The trials took place for 100% of generator rated load during 40 hours for both fuels. Diesel fuel results were adopted as reference.

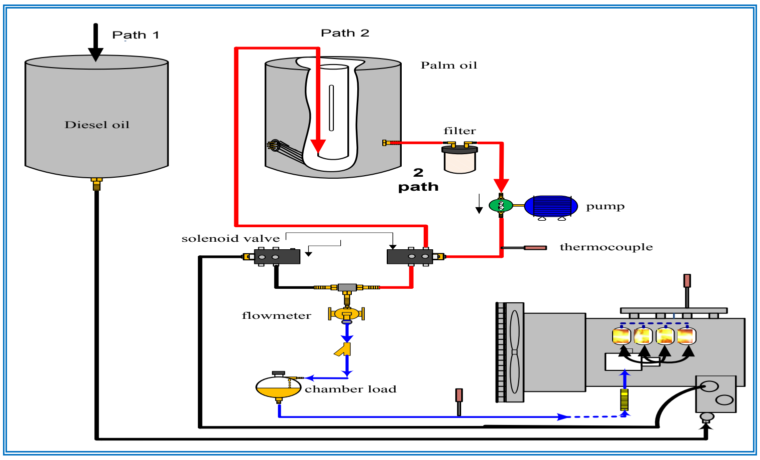

Figure 1. Experimental apparatus

Following Figure 1, engine is started up with diesel and simultaneously palm oil (PO) is heated to about 90°C in a stainless steel tank through an electrical resistance of 4500W. Such tank has an electric mixer for uniform oil temperature. Valve S2 is kept closed and electric pump flows the PO from and to the tank. After the vegetable oil achieves desired temperature, valve S1 is closed stopping diesel flow to the engine and S2 valve is open. Then, palm oil flows through the flowmeter and reaches the loading chamber, which has a small resistance that adjusts the temperature to be between 80°C and 90°C. The injection temperature is monitored by a thermocouple installed before the injection pump. The electricity produced is dissipated through a bank of tubular resistance that can be adjusted to 50%, 75% and 100% of rated genset (results here are only for 100% loadrpm). The genset fuel specific consumption was obtained measuring the fuel volumetric flow rate with OVALM III-39 Super Micro Flowmeter gear with an accuracy of ± 3%, and the electrical power was obtained through an analyzer SAGA 4500 of Lanis+Gyr with 1% accuracy installed in the resistance circuit. Temperature monitoring was carried out with type K thermocouples (operating range up to 1200°C) installed before the injection pump to measure the fuel temperature, after the PO circulation pump to measure the oil temperature at tank exit, at exhaust manifold tube in front of one cylinder exit to measure exhaust gases temperature. Acquisition software was locally developed for data acquiring and real time monitoring of the genset variables.

The exhaustion gas concentration was measured with the analyzer Tempest 100 for temperatures up to 800°C providing real-time information for O2, CO, CO2, NOx, NO, NO2 species and pressure.

Always on PO tests, the engine was started up and run on diesel fuel for about 15 minutes and then switches from diesel to oil palm and switch back to diesel in the final minutes to clean all the entire feeding line from PO and prevent waste accumulation. The test with pure diesel fuel took 40 hours in order to obtain a reference database and then another period of 40 hours with palm oil, all at 100% of rated load for both fuels.

Data from direct injection engine was carried out by MORAES (2010), in LABEM / FEM / UFPA using genset of 52 kVA with engine Cummins model C40D64, simple aspired, 4 cylinders , 3920 cm3 CC, 18,5:1 compression ratio mechanical injection with nominal injection pressure of 172 kPa, running at constant speed of 1800 rpm, also at 100% of rated load for diesel and palm oil.

3- MATHEMATIC FORMULATION

Following are the equations used to converted collected data and convert them into parameters that allow understand and quantify gensets performance.

The fuel mass flow rate was determined using the equation 3.1

$$\dot{m}_{fuel} = Q_{fuel} \times \rho_{fuel,85°C} \quad (3.1)$$

Where: Qfuel is the fuel volumetric flow rate measured with the Flowpet. $\rho_{fuel,85°C}$ is the fuel density at 85°C in case of palm oil (Table 1). Knowing the fuel mass flowrate and its low heating value, the inlet fuel power available is evaluated using Eq. 3.2.

$$P_t = LHV_{fuel} \times \dot{m}_{fuel} \quad (3.2)$$

Where: LHVfuel is the lower heating value of fuel obtained by Eq. 2.1. To evaluate the specific fuel consumption (SfC) the fuel mass flowrate was divided by the electrical power measured from the generator with the SAGA 4500.

$$SfC = \dot{m}_{fuel}/P_{el} \quad (3.4)$$

Equivalence ratio was evaluated using Eq. 3.5.

$$\Phi = \frac{m_f/m_{air}}{m_f/m_{air}|st} \quad (3.5)$$

mf/mair is the adopted fuel- air mass ratio divided by the same ratio at stoichiometric conditions. Air mass flowrate was determined through measures of a manometer and a Pitot tube installed in the admission tube of air.

The air mass flowrate was avaluated using Eq. 3.6.

$$\dot{m}_{air} = \rho_{air} \cdot A_{tube} \cdot v_{air\ mesure} \quad (3.6)$$

Where A_{tube} is tube area and $v_{air\ mesure}$ is intake air velocity measured com hot wire anemometer.

The stoichiometric fuel-air mass ratio mass was determined with the information from ultimate analysis in Tab. 2.

4. RESULTS

Table 3 presents 40 hours average results with engines running on steady for both engines and fuels operating with 100% of each nominal load capacity. IIE results were obtained in this work and all DIE data were extracted from MORAES 2010, also averaged after 40 operation hours. The analysis is done comparing the results from indirect injection engine with direct injection engine for 40 hours of operation, eight hours daily and 100% load generator using the same fuel (diesel and palm oil).

Table 3. Average values for the two engines after 40 hours of continue operation running on 100% load.

Injection Engine	Fuel	Specific fuel consumption (L/kW-h)	Cylinder Exhaust Gas Temp. (ºC)	CO (ppm)	NO_x (ppm)	Equivalence ratio(fuel/air)	Generator Load (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

The figures below depict in a single graph tests with diesel and palm oil for each engine and their respective variables over time. Data in these figures came from the most stable hour of operation for both engines and fuels.

Figure 2 shows results for SfC. It was expected that the direct injection engine has a smaller specific consumption since their power was three times bigger. Changing from diesel to palm raised SfC 13.9% with IIE while it raised only 6.3% with the DIE. From specific fuel consumption standpoint, direct injection engine showed better performance because the palm oil impact on increasing the SfC was higher in the indirect injection than the direct injection. MORAES 2010 states that is possible to reduce vegetable oil SfC anticipating fuel injection point and / or decreasing the fuel droplet size increasing fuel injection pressure.

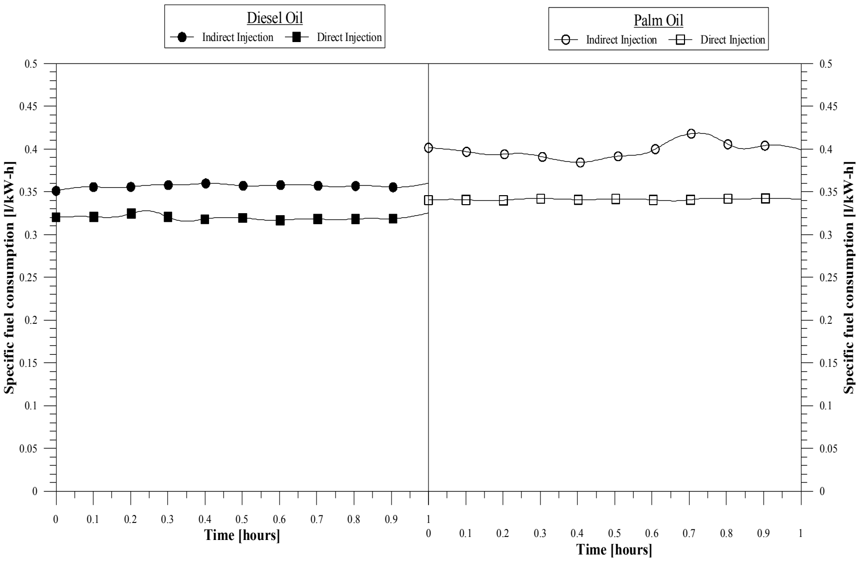

Figure 2. Specific fuel consumption 100% nominal load.

Figure 3 shows exhaust gas temperature. The fuel change from diesel to palm had opposite consequence in the engines. Exhaust gas temperature at cylinder exit decreased 10.3% for IIE and increased 3.3% for DIE.

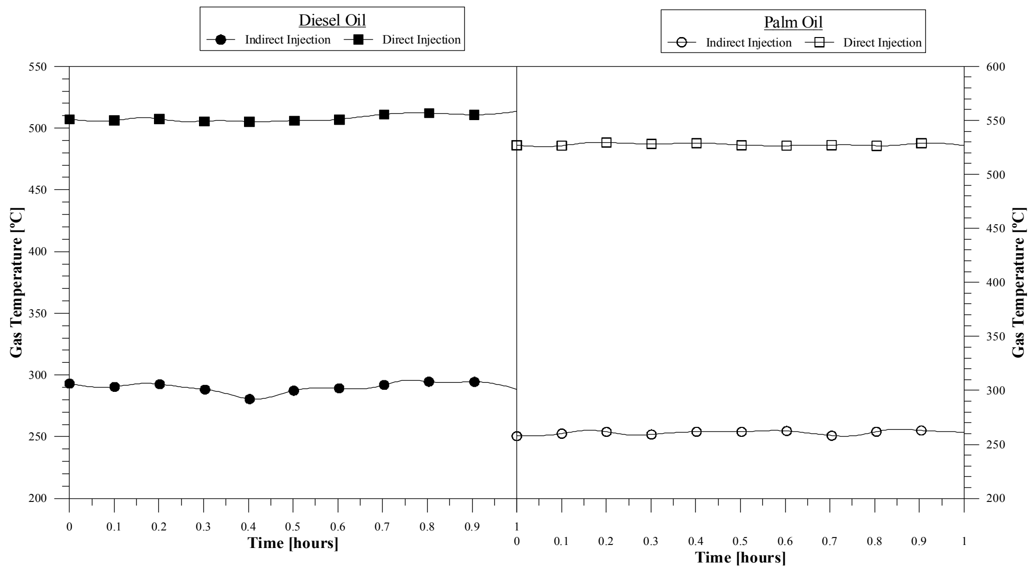

Figure 3. Exhaust Gas temperature.

Figure 4 shows CO concentration results. Such concentration indicates how long the combustion process went toward its completion: lower its concentration, closer to completion. CO concentration increased with fuel change from diesel to palm of 4.2% for IIE and decreased of 16.7% for DIE. It is important to have in mind that ultimate analysis inform that diesel has 10.3% more carbon than palm what leads to an expectation that all carbon species have less concentration for palm than for diesel.

Figure 5 compares NOx emissions for both fuels and engines. Its concentration increased for IIE of 22.0% changing from diesel to palm. On the other hand, DIE behavior was just the opposite: decreased 5%. Looking into Tab. 2 (Ultimate analysis), palm has more nitrogen what leads to the expectation that changing from diesel to palm increases the concentration of nitrogen content species.

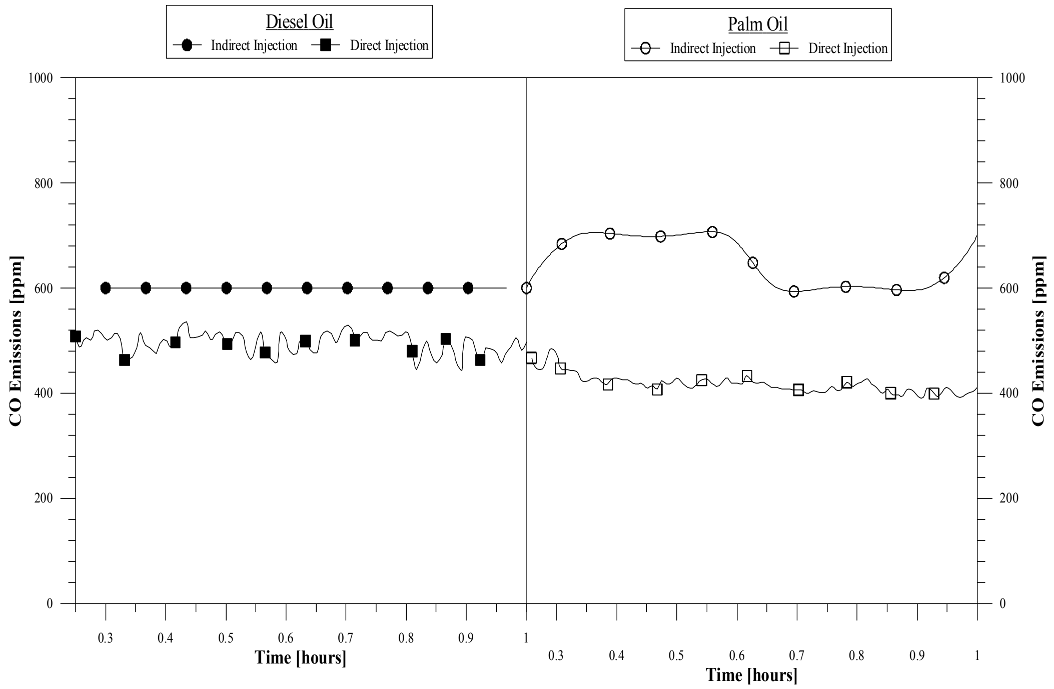

Figure 4. CO mol fraction in both engine exhaust gases.

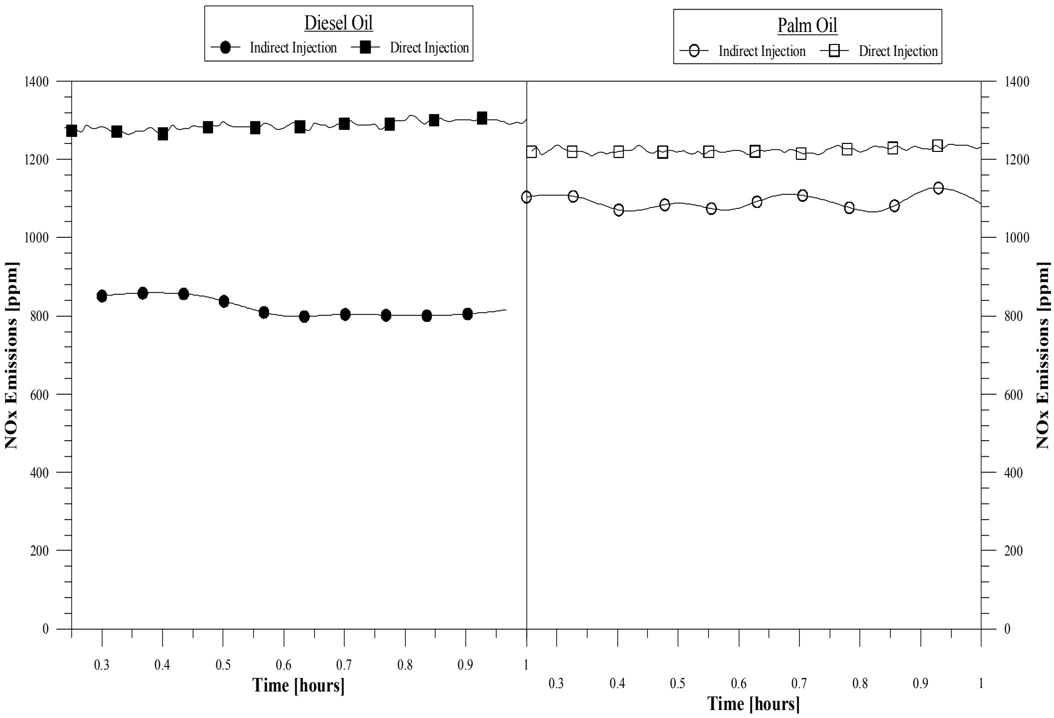

Figure 5. NO_x mol fraction in both engine exhaust gases.

It is important to have in mind that fuels were switched without change in most of the operation parameters (fuel injection point, compression ratio, injection pressure, etc.). The only one change was the fuel inlet temperature which was 55°C higher than the diesel one. It is inferred from CO concentration result s that palm´s combustion duration (time between injection kinetics hold) is longer than diesel in the IIE engine and faster for DIE. The amount of CO informs how close the combustion is from completion (smaller, closer). Once the mean combustion temperature must be the same (same output power in both cases), longer combustion period leads to higher NOx concentration and higher CO concentration at end drives to lower gas temperature (energy not released): evidence for both facts was saw in above results.

Changing fuels (from diesel to palm) in DIE makes the combustion duration shorter once the CO concentration is smaller, gas exit temperature higher and less NOx. A possible explanation for this finding, changing from diesel to palm slow down the combustion speed for IIE and hurry up for DIE is the combustion pre-chamber. Pre-chamber holds a rich fuel combustion delaying the fuel reaction with oxygen once most of the oxygen is in the main chamber. If the fuel is not able to leave the pre-chamber (such as liquid condensing) the engine will stop. As IIE SfC increases when fuel is changed from diesel to palm, it can be understood as consequence of higher palm viscosity which creates difficulty for palm flow through the communication holes between pre and main chamber. Possibly, changing from diesel to palm requires bigger holes.

As DIE do not have pre-chamber, changing from diesel to palm does not impact as significantly as IIE on the engine performance (SfC is basically the same) and results behaves as expected, i.e., as palm has less carbon than diesel, its CO concentration is smaller, the exhaustion gas temperature is higher and NOx concentration is smaller, probably consequence of a smaller mean temperature after a longer combustion duration.

All above hypothesis can be confirmed installing a pressure gauge on the top of one cylinder and monitoring the pressure variation with shaft angle with after fuel switch.

5. CONCLUSIONS

This paper presents comparison on indirection injection engine performance running with diesel and then switched to palm oil, at 100% of its nominal load and without changing on operation parameters except inlet injection pump temperature which was raised into 55°C on palm application. Such engine behavior was compared with direct injection engine behavior under similar fuel change done by Moraes 2010.

Obtained results suggest that the IIE pre-chamber as well as higher palm viscosity slow down the combustion speed making longer the combustion duration, time between the fuel injection start and gas temperature gradient approach zero, when fuel is changed from diesel to palm. It was inferred from the fact that changing from diesel do palm, CO and NOx concentration increases, exhaust gas temperature decreases and the SfC raises. DIE behaves just the opposite. Changing from diesel to palm reduces CO and NOx concentration increase exhaust gas temperature, keeping SfC almost the same.

If the above conclusion is true, what can be verified through pressure x crank angle plot for the same engine with different fuels, IIE performance improvement can be achieved starting early the injection (constraint by the end of the compression stroke) as well as increasing the hole diameter between pre and main chamber.

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