ANALYSIS OF PERFORMANCE, EXHAUST GAS EMISSIONS AND WEAR OF A FOUR-STROKE SIX-CYLINDERS DI DIESEL ENGINE COUPLED TO A DC MOTORING DYNAMOMETER, OPERATING WITH DIESEL AND PALM OIL BIODIESEL BLENDS.

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Abstract. *This study aims to examine exhaust gas emissions, engine performance and wear of four-stroke six-cylinders stationary engine coupled to a dynamometer, operating with diesel and blend of palm oil biodiesel. The following parameters have been monitored: torque, specific fuel consumption, lubricating oil, nozzles, combustion chamber, opacity, and exhaust gases. After 148 hours of operation, the lubricating oil is still able to remain in use; internal inspection of the engine showed no abnormality neither in the combustion chambers nor its components. The engine presented a slight loss of power operating with blend palm oil biodiesel compared to diesel oil. At low temperatures (range 12,5 °C), palm oil biodiesel crystallize, causing obstruction in the fuel filters. Levels of exhaust gases emissions from palm oil biodiesel mixture were similar to diesel oil.*

Keywords*: palm oil biodiesel, exhaust gas emission, engine performance*

1. Introduction

In Brazil, the electrical energy used in isolated communities is based on electric generators powered by diesel fuel. However, the transport of this fuel to remote locations is difficult and complicated which increases the product price. The replacement of diesel by biodiesel derived from oilseeds existing in the region itself is an efficient alternative to solve this problem of logistics. Furthermore, the use of biofuel contributes to keep people in their places of origin, strengthen the local economy by creating jobs; and to reduce emissions of pollutants from the use of diesel fuel.

According to the National Agency of Petroleum, Natural Gas and Biofuels (ANP), biodiesel is a fuel comprised of alkyl esters of fatty acids of long chain, derived from vegetable oils or animal fats, whose specifications are contained in the Technical Regulation of ANP resolution Nº 7, 19 March 2008. The mixture of biodiesel and petroleum diesel fuel, defined as biodiesel blends, is designated as (BX) where X is the percentage of biodiesel, for example (Rand, 2003; Sorensen et al., 2008).

Biodiesel has many advantages over petroleum fossil fuel. It is renewable; can be produced from an enormous variety of oilseeds as a source of raw material; the obtaining and burning does not contribute to the increase of CO2 in the atmosphere; it has a high flash point, excellent lubricity. Beyond this it helps to generate jobs in the primary sector and prevents the exodus of workers in the field. (Tickell, J. et al., 2000). However, biodiesel has some disadvantages, compared to convectional diesel fuel: higher viscosity; lower energy content; higher nitrogen oxide (NOx) emissions; slight reduce in performance; decrease in torque, power and fuel efficiency (Gibilisco, 2006).

Silvio et al. (2002), conducted studies in a naturally aspirated MWM 229 direct injection four-stroke 70 kW diesel-generator fuelled with 100% palm oil heated at 100 °C. Tests showed that increasing the temperature palm oil presented lower viscosity, better combustion and less deposits. It was also observed that the performance and endurance of the diesel generator increases compared to operation in ambient conditions.

Rakopoulos et al. (2006) conducted tests in a four stroke, direct injection, diesel engine in order to analyse exhaust gas emission. The engine was fuelled with diesel fuel, cottonseed oil, soybean oil, sunflower oil, corn oil, olive kernel, rapeseed oil methyl ester and palm oil methyl ester. Comparing diesel fuel with biodiesel blends tests results shows that the smoke density was significantly reduced, NOx emissions were slightly reduced; CO emissions were reduced; and the unburned hydrocarbons (HC) emissions showed no definite trend.

Soni et. al. (2008) investigated the performance and emission evaluation of automotive diesel engine operating with B0, B10, B20, B30, B50 and B100. The result shows that higher content of palm oil biodiesel reduce the emission of CO, HC, PM, and CO2 and the addition of biodiesel could increase the power and torque. Tests show that NOx decreased when the content of palm biodiesel increases.

Ahmet et al. (2008) studied biodiesel from used frying palm oil and its blends with diesel fuel in a four-cylinder, naturally aspirated indirect injection (IDI) diesel engine. The engine performance, injection, and combustion characteristics were investigated over a range of engine speeds at full load, using petroleum-based diesel fuel (PBDF), biodiesel, and its blends. Results show that when the engine was fueled with biodiesel and its blends, the brake specific fuel consumption increased slightly relative to PBDF due to its fuel properties and combustion characteristics. Compared to PBDF biodiesel and its blends also showed a slight drop in the engine power with increased peak cylinder pressure and reduced ignition delay.

Ahmet et al. (2009) studied the performance and combustion characteristics of direct injection (DI) diesel engine fueled with methyl ester of waste frying palm oil methyl ester and canola oil, operating at constant speed (1500 rpm) under full load. The results indicated that, compared with petroleum diesel, biomass fuels decreased engine performance and changed the characteristics of combustion. It was also observed that both types of biodiesel caused reductions in carbon monoxide (CO), unburned hydrocarbons (HC) and opacity of smoke emissions, but they caused an increase in nitrogen oxides (NOx).

P. Benjumea et al. (2009) applied a combustion diagnosis model including exergy analysis to a turbocharged (TC) automotive diesel engine fuelled with neat palm oil biodiesel (B100) and diesel fuel (B0) at two altitudes above sea level: 500 and 2400 m. Result shows that as altitude increased, biodiesel fuelling led to shorter combustion duration, and higher in-cylinder pressures and fuel–air equivalence ratios. Brake thermal efficiency decreased with altitude for both fuels, but in a greater extent for B0. For all fuels and altitudes, exergy destruction rose sharply when combustion started. At both altitudes, the cumulative exergy destruction was higher for B100 due to its earlier and faster combustion process.

Teixeira et al. (2009) analyzed the physical properties influence of commercial diesel, palm oil methyl ester obtained by transesterification/esterification process, and its blends with commercial diesel in the performance and in the exhaust gas emissions of a single cylinder diesel engine. Tests show an increasing in NOx emissions when engine was fuelled with biodiesel and its blends and the specific consumption of biodiesel and its blends increased about 4% compared to commercial diesel.

Dutra et al. (2009) studied the performance and exhaust gas emissions of a single cylinder diesel engine operating with commercial diesel, palm oil methyl esters obtained by transesterification and esterification processes. Tests showed that NOx emissions from biodiesel and its blends are higher when compared to commercial diesel; biodiesel fuels have higher cetane number and shorter ignition delay periods than commercial diesel; CO_2 emissions were higher when the engine operated with biodiesel compared with commercial diesel.

The objective of the present study is to analyze the performance, exhaust gas emissions and wear of a four-stroke six-cylinders DI diesel engine coupled to a DC motoring dynamometer, operating with diesel and palm oil biodiesel blends, fueled with commercial diesel fuel, palm oil biodiesel blend (B20) obtained by transesterification process.

2. MATERIAL AND METHOD

2.1 Diesel Fuel

Diesel oil is a fossil fuel, named in honor of the German engineer Rudolf Diesel, who in 1892 invented the diesel engine. This fuel is produced from the fractional distillation of crude oil, resulting in a mixture of carbon chains mainly composed of hydrocarbons. It also has in its composition, in small amounts, oxygen, nitrogen and sulfur (Gibilisco, 2006).

The diesel fuel used in this work was purchased at a gas station in the city of Belém do Pará, whose characteristics are in accordance with Resolution Nº. 2 of the National Energy Policy Council (CNPE), published in March 2008, which established in 3% the percentage of biodiesel blend with diesel.

2.2. Production process and specifications for palm oil biodiesel

2.2.1 Palm Oil

Palm oil comes from the palm (*Elaeis guineensis*), a tree originated in Africa, which is suitable for tropical regions, with hot and humid climate and high precipitation. Brought from Africa by slaves, the palm was first planted in the Northeast of Brazil, and latter cultivated in others state. The country is now the third largest producer in Latin America and the state of Pará, in the Amazon region, accounts for 85% of domestic palm oil production.

The idea of using vegetable oil as fuel is old, dating from the time the diesel engine was invented. However, as approximately 20% of a vegetable oil molecule is made up of glycerin, its viscosity is high. To use vegetable oil as fuel in conventional diesel engines is necessary to reduce its viscosity to values similar to diesel oil. Transesterification is a method widely used to reduce the viscosity of vegetable oils. It consists of a reversible reaction to convert triacyglycerol lipids by alcohols to alkyl esters without first isolating the free fatty acids.

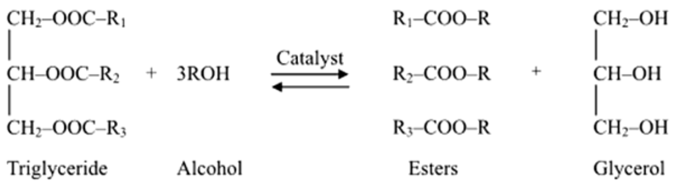

Figure 1 – Transesterification reaction with alcohol (Dermibas, 2008).

A catalyst is usually used to improve the reaction rate and yield and excess alcohol is used to shift the equilibrium to the product side. During this process the glycerin is removed from the vegetable oil, reducing its viscosity (Dermibas, 2008). Figure 2 show a schematic representation of the transesterification reaction.

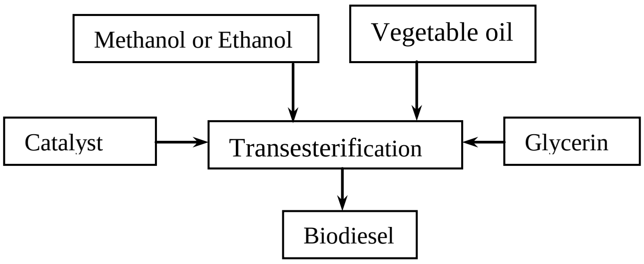

Figure 2 - Schematic representation of the transesterification reaction (Speight, 2008).

The biodiesel utilized in this work was manufactured in a plant for producing biodiesel deployed by the Department of Chemistry of the Military Institute of Engineering (IME) and installed at the Pará Federal University (UFPA). Biodiesel from palm oil was obtained from the transesterification reaction of palm, using ethanol as reagent and sodium hydroxide as catalyst.

2.2.1 Palm Oil Biodiesel (B20)

In this work were used two types of fuel: diesel, specified in Section 2.1, and (B20), which is the mixture of palm oil biodiesel, specified in section 2.2.1, with diesel fuel specified in section 2.1.

2.3 Engine and Instrumentation

2.3.1 Engine and Dynamometer

The tests Were Performed at the Laboratory of Engines of Brazilian Army Technological Center (CTEx), in order to analyze the performance and emissions of exhaust gases from a diesel engine coupled to a dynamometer bench, whose specifications are shown in tab. 1 and tab. 2, respectively.

Table 1. Diesel Engine Specifications

ENGINE	**Mercedez Benz**
Model	OM447LA
Type	Water-cooled, 4 stroke
Dimension (L × W × H)	940 × 1315 × 1080 (mm)
Number of cylinders	6
Compression ratio	16,5:1
Bore × Stroke	128 × 155 mm
Valves per cylinder	2
Injection system	Direct injection
Rated Power NBR ISO 1585	266 kW at 1500 rpm 302 kW at 1800 rpm

In order to allow the measurement of parameters relating to operation, the diesel engine and dynamometer were instrumented with the following sensors: PT100 temperature sensors in the range of 0 to 200 °C, for monitoring the temperature of engine coolant, water brake dynamometer, the intake air, ambient air, the engine lubricating oil and fuel; PT100 temperature sensor in the range 0 to 800 ° C, for monitoring the temperature of engine exhaust; pressure sensor in the range 0 to10 bar for monitoring the fuel injection pump inlet; Pressure sensor in the range 0 to 20 bar for monitoring the lubricating oil and engine intake air.

Table 2. Dinamometer Specification

DINAMOMETER	**Shenk**
Model	DS 630 1-E
Type	hydraulic
Capacity	630 kW at 55000 rpm
Operation	Automatic

2.3.2 Opacimeter

The standard NR NIE-DIMEL-080, approved in April 2008, defines partial flow opacimeter as an instrument used to measure the opacity of smoke generated by a compression ignition engine, capturing part of the smoke produced by the exhaust pipe, The technical characteristics of equipment used in this work to evaluate engine exhaust gases emissions (opacimeter NA-9000) are specified in tab 3.

Table 3. Opacimeter Specifications

OPACIMETER	**NAPRO**
Model	NA-9000
Opacity	0 - 100%
Absorption Coefficient (K)	0 to 9.99 $m^{(-1)}$
Accuracy	± 2% relative
Resolution	0.1%
Ambient operating temperature	5 - 40 ° C
Ambient operating humidity	0 - 95%

In addition to measuring the opacity, opacimeter NA-9000 also controls the measurement process and runs its own diagnostic system for automatic calibration.

2.3.3 Flow Meter

The amount of fuel consumed by the engine during testing was constantly monitored by DF-210 Flow meter. This equipment measure and display instantaneous and total fuel flows. The unit is used in combination with a positive displacement flow detector. The technical characteristics of flow meter and flow detector equipment are reported in tab. 4.

Table 4. Flow Meter Specification

FLOW METER	**Ono Sokki**
Model	DF-210A
Detector Model:	FP-213
Measurement range:	0,06 to 60 l/h
Accuracy:	± 0,5%
Dimension (HxWxD) (mm) :	201x30x160 mm

2.4.4 Gas Analyzer

The gas analyzer MODAL 2010-AO from NAPRO, whose technical characteristics are reported in table 5, measures the concentration CO, CO_2 and O_2 in volume percentage (v%) and the concentration of HC and NOx in parts per million (ppm). The equipment uses a non-dispersive infrared system for determining the concentration of CO, CO_2 and HC, and performs the measurement of O_2 and NOx by electro-chemical cells. Furthermore, it is capable to measure the angular speed and the temperature of engine lubricating oil.

Table 5. Gas Analyser MODAL 2010-AO Specification

TYPE	RESOLUTION	ACCURACY	GRADE
HC	1 ppm	12 ppm or 5% of the reading(1)	0 - 2000 ppm
CO_2	0,01%	0,06% or 5% of the reading(1)	0 - 20 %
CO	0,1%	0,5% or 5% of the reading(1)	0 - 15 %
O_2	0,01%	0,1% or 5% of the reading (1)	0 - 25 %
NOx	1 ppm	32 ppm in the range from de 0 to 1000 ppm 60 ppm in the range from 1001 to 2000 ppm 120 ppm in the range from 2001 to 5000 ppm	0 - 5000 ppm

(1): the greatest value

2.5 Test Procedure

2.5.1 Local of the Experiments

The experiments were performed at sea level, with average ambient temperatures close to 300 K, relative humidity of 70% and atmospheric pressure of 762 mm/Hg. Laboratory of Engines is divided into two sections: control section and equipment section. In the control section is located the engine ignition system and two computers: one designed to monitoring and receiving data from the dynamometer and other designed to receiving data from opacimeter and gas analyzer. The equipment section contains the dynamometer, the water tank, the air compressor, the opacimeter, the flow meter and other instruments showed schematically in figure 3.

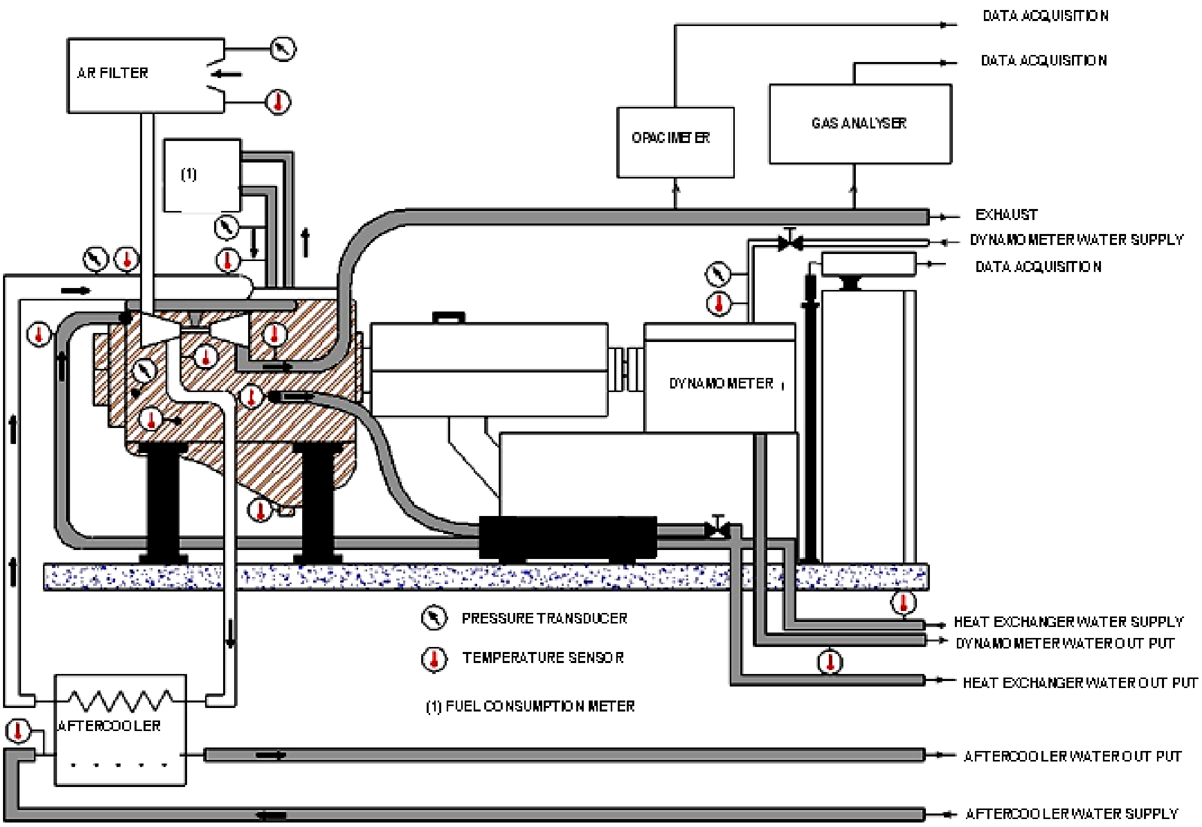

Figure 3. A schematic representation of the mechanism utilized for carry out the tests with diesel and biodiesel blends

2.5.2 Performance Testing

To maintain the regularity of the results, before beginning the tests, the engine ran at idle, for fifteen minutes, to stabilize the temperatures of the engine cooling water and the temperatures of lubricating oil.

The analysis of performance and exhaust gas emissions were performed using the instruments specified in section 2.3 and illustrated in figure 3. After being executed the preliminary measures described in section 2.4.2, the tests follow the script described below:

i) The load and angular velocity applied to the engine were set by computer 1 through the software called Logs DinMon, acquired from Logs Sistemas Eletrônicos Ltda. Thus, the data of torque and power were obtained and stored on the same computer.

ii) The specific consumption was measured by the Flowmeter DF-210A.

iii) The opacity of the exhaust gas was measured by Opacimeter Napro NA-9000. The data were sent to be processed and stored by the computer 2.

iv) The emissions of CO, CO_2, HC, O_2 and NOx produced by the engine were captured by the Gas Analyzer NAPRO MODAL 2010-AO. Data for each type of emission were sent to be processed and stored by the computer 2.

v) The above procedure was performed with two types of fuel: commercial diesel and palm oil biodiesel (B20). In tests the engine was operated with an angular velocity of 1800rpm; and, for each fuel, the engine was subjected to three types of load: 70%, 100% and 110% of full load.

2.5.3 Lubricating oil

The behavior of lubricating oil during the tests were analyzed by Chevron of Brazil Ltda. Collections were made on samples of 100 ml of lubricating oil every 50 hours of use, listing the following data: number of hours worked; powers achieved, average temperatures, maximum temperatures, and the level of oil in the crankcase.

2.5.4 Organic Elements Engine Analysis

The technical team of MTU of Brazil Ltda was responsible for conducting the analysis of organic elements in the engine used in this work. Despite the internal inspection of the engine and injector nozzles have been predicted to occur every 250 hours of operation, it was advanced to 148 hours due to logistical problems on the supply of biodiesel.

3. RESULTS AND DISCUSSION

The graphics showed in section 3 correspond to tests results performed with the CI engine Mercedez Benz OM447LA, fueled with commercial diesel and palm oil biodiesel (B20), whose characteristics were described section 2.1 and 2.2, respectively. The experiment was conducted with the engine operating at three different loads, as mentioned in section 2.5.4.

3.1 Specific Fuel Consumption

Figure 4 shows that when the engine was fuelled with B20 the specific fuel consumption increases 5%, compared with diesel fuel. This was observed throughout the test in which the engine was subjected to loads of 70, 100 and 110% of full load.

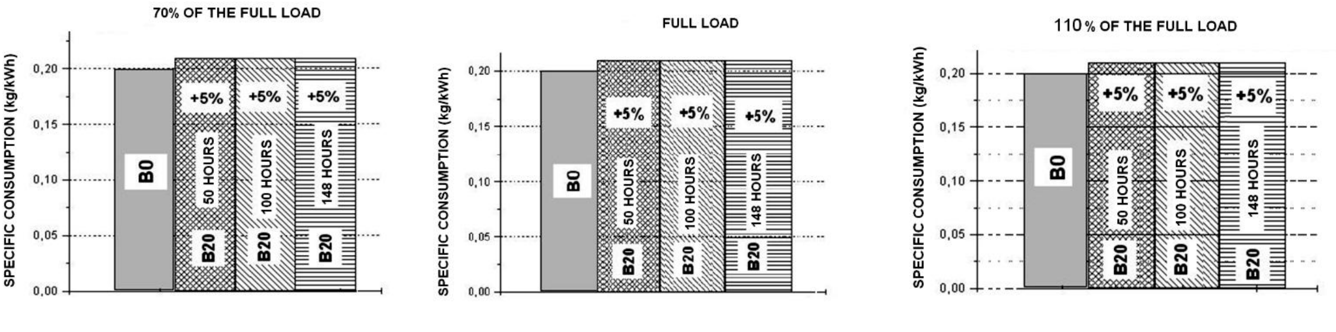

Figure 4. Specific Fuel Consumption with the engine operating at 70%, 100% and 110% full load at 1800 rpm.

3.2 CO_2 Emissions

Figure 5 shows that CO_2 emissions from engine operating with B20 were slightly higher than diesel fuel.

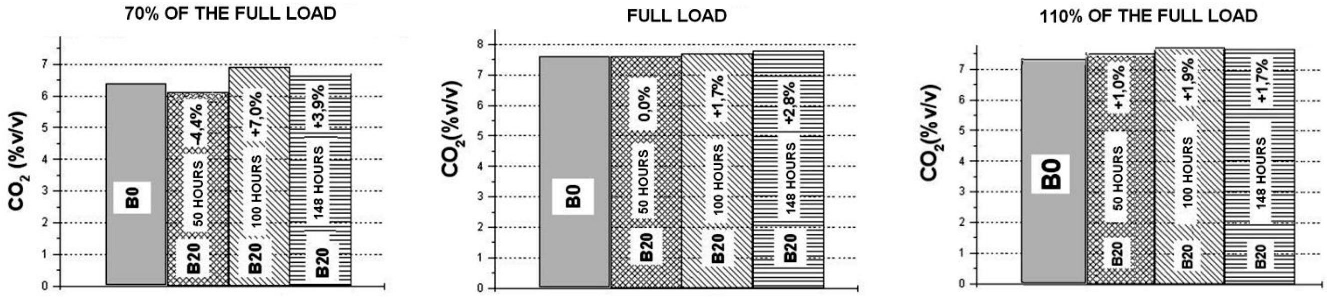

Figure 5. CO_2 Emissions with the engine operating at 70%, 100% and 110% full load at 1800 rpm.

3.3 NOx Emissions

Results showed that NOx emissions were slightly smaller when engine operated with B20 at 70 and 100% of the full load. However when the engine operated at 110% of full load, NOx emissions were considerable smaller than diesel fuel, as can be seen in figure 6.

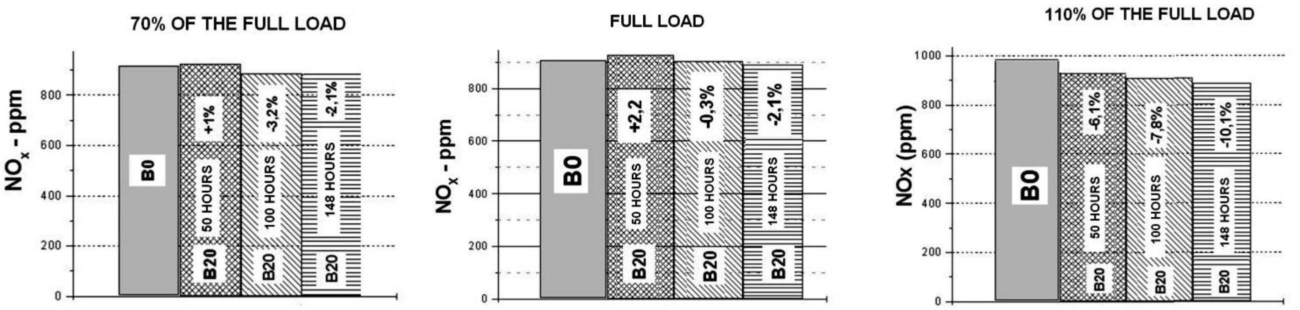

Figure 6. NOx Emissions with the engine operating at 70%, 100% and 110% full load at 1800 rpm.

3.4 Opacity

Opacity is the amount of soot present in the exhaust gas emission. It is calculated from the reduction of light transmission through the exhaust gas emission (Kemp 2006). Figure 6 shows that the opacity from the B20 is smaller compared with the opacity from diesel fuel in all testes, except for the firsts 50 hours when the engine was operating ith 110% of full load.

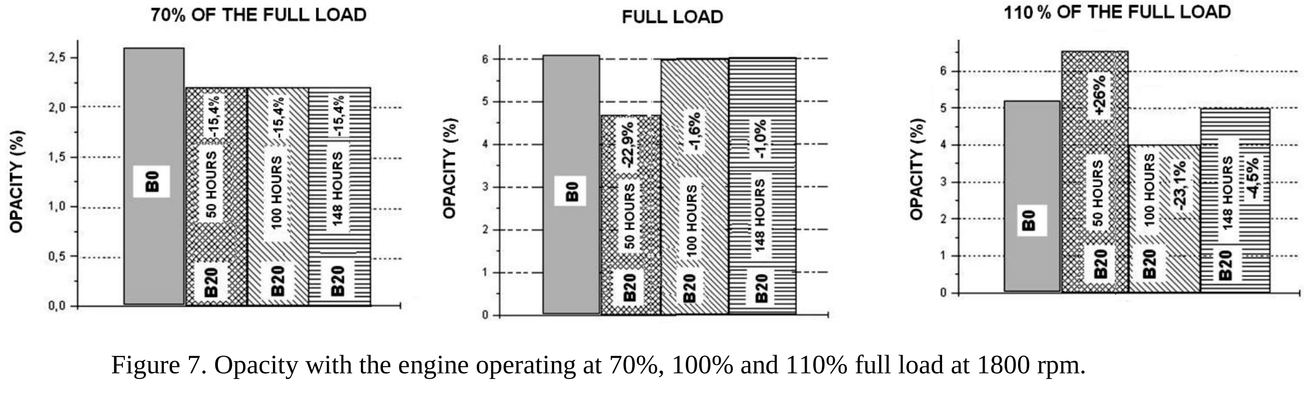

Figure 7. Opacity with the engine operating at 70%, 100% and 110% full load at 1800 rpm.

3.4 Effective Power

Figure 8 shows that, compared with diesel, the engine loses power when operating with B20. This was observed throughout the test, and when the engine was subjected to a load of 110% of full load, the power loss appears more pronounced. This fact is related to the calorific value of fuels. The higher the calorific value of fuel, the greater the ability to generate power.

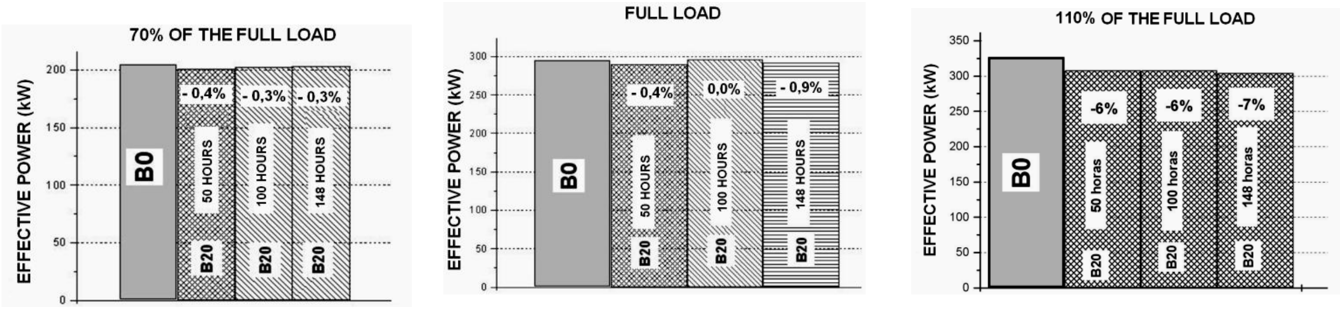

Figure 8. Effective power with the engine operating at 70%, 100% and 110% full load at 1800 rpm.

4. CONCLUSION

In this work, it was observed that the specific consumption of B20 and was slightly higher than commercial diesel. This result is in agreement with Lapuerta et al. (2008), who also find that when the engine is operating with biodiesel, an increase on specific consumption is expected, compared to diesel fuel. This result can be easily understood considering the definition of specific fuel consumption as the fuel mass flow rate per unit of power produced (Johnston, 1992). Therefore specific consumption is directly related to the heat value of a fuel. The higher the heat values of fuel, the lower the specific consumption.

Biodiesel has oxygen in its molecule thus it requires a smaller amount of oxygen in the combustion compared to fossil fuel. Therefore, it is natural a higher e presence of O_2 and a lower presence of CO_2 in the exhaust gases emission when operating with biodiesel. Specifically in this work, CO_2 emissions from B20 were higher compared with diesel fuel. Probably, the combustion of B20 is not taking place properly, but this fact could only be proved if we had the emissions data from O_2 emissions.

The formation of NOx is related to nitrogen (N_2) and oxygen (O_2) in air of air-fuel mixture at the time of combustion, or the nitrogen (N_2) present in the composition of the fuel itself. As biodiesel used in this study has low levels of (N_2) in its composition, the majority of NOx emissions from B20 is associated with the first case.

According to HI-FEI (2005), the formation of NOx associated with nitrogen in the air of air-fuel mixture is proportional to four factors: concentration of nitrogen $[N_2]$; exposure time of fuel to the maximum temperature that occurs inside the cylinder in the time of combustion (t); oxygen concentration $[O_2]$; and the temperature inside the cylinder at the time of combustion (T). The factors are related by the following equation $[NO]\sim[N_2].\ t.[O_2]^{1/2}.\exp^{(-1/T)}$. Contrary to most results in the literature (Lapuerta, 2008) tests conducted in this study show that emissions of NOx from B20 were lower when compared to diesel. This may be related to any of the foregoing factors. It is necessary to further study on this subject to support more precise conclusions.

Diesel fuel has higher opacity in the exhaust gas emission compared to B20. This occurs partly because the higher concentration of oxygen in biodiesel aids the soot oxidation process and partly because biodiesel has longer carbon chains and absence of aromatics and sulfur.

The technical team of MTU of Brazil Ltda inspected the inside of the engine using borescopes, they checked the combustion chambers and their components. The engine nozzles were also observed by test performed on the bench. Internal inspection of the engine showed no abnormality in the combustion chambers neither their components. The nozzles also showed no irregularity.

The company Chevron of Brazil Ltda presented the report of sample analysis of lubricating oil on the 148 hours of operation with B20. According to specialists from the Chevron of Brazil Ltda, oil lubricant was still able to remain in use.

If we consider that the lubricating oil does not show any type of contamination; the combustion chamber and nozzles suffered no unusual wear during engine operation, the power loss does not affect significantly engine performance, and the amount of polluting elements existing in the exhaust gases emissions are smaller or are close compared to diesel, we can conclude that the B20 fuel has characteristics similar to this fuel, which enables you to replace it. However, it noted that 148 hours of operation is not sufficient to validate any assertion. For a more striking conclusion is necessary to have a longer period of observation.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

C.A. Silvio, R. Carlos, V.G. Marious, S.R. Leonardodos and F. Guilherme, Performance of a diesel generator fueled with palm oil. Journal of Fuels 81 (2002), pp. 2097–2102.

C.D. Rakopoulos, K.A. Antonopoulos, D.C. Rakopoulos, D.T. Hountalas and E.G. Giakoumis, Comparative performance and emissions study of a direct injection diesel engine using blends of diesel fuel with vegetable oils or biodiesels of various origins, Energy Conversion and Management 47 (18–19) (2006), pp. 3272–3287.

Demirbaş, Ayhan, 2008, “Biodiesel: a realistic fuel alternative for diesel engines” Ed. Springer, 208 p.

Dutra, L. M., Teixeira, C. V., Colaço, M. J., Alves, L. S. B., Caldeira, A. B., 2009, “Performance and Emission Comparative Analysis of an Engine Operating with Palm Oil Methyl and Ethyl Esters and Their Blends with Diesel” 20th International Congress of Mechanical Engineering; Gramado, RS, Brazil.

Gibilisco, Stan, 2006, “Alternative Energy Demystified”, Ed. McGraw-Hill Professional, 322 p.

IH-FEI, Paul Liu., 2005, “Energy, technology, and the environment”. Ed. ASME.

Johnston, R. M., 1992, “ Elements of applied thermodynamics”. Ed. Naval Institute, 574 p.

Kemp W. H., 2006, “Biodiesel: basics and beyond: a comprehensive guide to production and use for the home and farm”. Ed. Aztext, 588 p.

Lapuerta, M., Armas, O., Fernandez, J. R., 2008, “Effect of Biodiesel Fuels on Diesel Engine Emissions”. Progress in Energy and Combustion Science. v. 34. p. 198-223.

N.O. Ahmet, C. Mustafa, T. Ali and S. Cenk, Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters, Fuel 88 (2009), pp. 629–636.

N.O. Ahmet, M. Canakci and C. Sayin, Effects of biodiesel from used frying palm oil on the exhaust emissions of an indirect injection (IDI) diesel engine, Energy Fuels 22 (2008), pp. 2796–2804.

P. Benjumea, J. Agudelo and A. Agudelo, Effect of altitude and palm oil biodiesel fuelling on the performance and combustion characteristics of a HSDI diesel engine, Fuel 88 (2009), pp. 725–731.

S.S. Wirawan, A.H. Tambunan, M. Djamin, and H. Nabetani. “The Effect of Palm Biodiesel Fuel on the Performance and Emission of the Automotive Diesel Engine”. Agricultural Engineering International: the CIGR Ejournal. Manuscript EE 07 005. Vol. X. April, 2008.

Rand, Salvatore J., 2003, “Significance of tests for petroleum products”, Ed. ASTM International, 258 p.

Silva, R. J., Nebra, S. A. and Rossi, L. F. S., 1993, “Emission and Control of Pollutants in Cement Industry”, Third International Conference on Waste Management in the Chemical and Petrochemical Industries; Salvador, BA, Brazil, CETREL S.A., IAWQ, Vol. I, pp. 363-370.

Sorensen, B., Breeze, P., Suppes, Galen J., Storvick T., Da Rosa, Aldo V., Gupta, Harsh K., Doble, M., Yang, Shang-Tian, Kalogirou, S., Sukanta R., Maegaard, P., Pistoia Gianfranco, 2008, “Renewable Energy Focus Handbook”, Ed. Acadeic Press, 519 p.

Speight, J. G., 2008, “Synthetic fuels handbook: properties, process, and performance”, Ed. McGraw-Hill Professional, 421p.

Stevens, Christian V., Verhé, Roland, 2004, “Renewable Bioresources: Scope and Modification for Non-Food Applications” Ed. John Wiley and Sons, 310 p.

Teixeira, C. V., Colaço, M. J., Alves, L. S. B., Caldeira, A. B., Leiroz, A. J., 2009, “Analysis of Performance and Emissions of an Engine Operating with Palm Oil Methyl Ester and its Blends with Diesel”, 20th International Congress of Mechanical Engineering; Gramado, RS, Brazil.

Tickell, J.; Tickell, K.; 2000 “From the fryer to the fuel tank: the complete guide to using vegetable oil as an alternative fuel” Ed. Biodiesel America, 162 p.

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