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EMISSIONS ANALYSIS OF A DIESEL ENGINE POWERED WITH DIESEL, BIODIESEL BLEND AND ETHANOL INJECTED TROUGH INTAKE AIR

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Abstract. *This work shows the emissions profile of a diesel engine operating with ethanol injected through the air intake pipe by electronic management system. The timing of injection was obtained by monitoring high pressure line of diesel injection. The system also has two thermal sensors able to measure the decreasing of the intake air temperature afforded by ethanol injection. The tests occurred in an electric generator at 1800 rpm. The ethanol injection was scheduled to occur 5º after top dead center (TDC). It was tested four fuel compositions, being adopted a binary mixture (D70B30) composed by 70% v/v diesel and 30% soybean biodiesel as the main fuel. The first of these compositions tested was the binary mixture without addition of ethanol, while the others showed increasing in the alcohol content. The results showed a consistent reduction of NOx by addition of ethanol, but with increased emissions of carbon monoxide (CO) and total unburned hydrocarbons (THC). The exhaust gases opacity was reduced to moderate ethanol amounts. The use of ethanol showed significant reduction in the intake air temperature, showing that ethanol can be an important tool for reducing NOx in the exhaust gases of diesel engines operating with higher levels of biodiesel.*

Keywords: *Emissions profile, ethanol, electronic injection.*

1. INTRODUCTION

Biodiesel has been widely proposed as a substitute for mineral diesel fuel, presenting good results in terms of flammability and lower environmental impacts of exhaust emissions in compression ignition engines. This fuel virtually does not generate residues of sulphur and has lower emissions of other pollutants due to the presence of the oxygen in its molecules (Sales, et al., 2006) (Lin, et al., 2007) (Hribernik et al., 2007). However, the use of biodiesel leads to a consistent increase in emissions of nitrogen oxides (NOx) (Sandum et al., 2005). This can be an obstacle to future growth in the biodiesel market and its application in engines (Zhu et al., 2011). Several solutions to this problem are generally used, such as exhaust gas recirculation (EGR) and the addition of oxygenated compounds such as ethyl alcohol or dimethyl ether (DME) (Yilmaz and Sanchez, 2012); (Jie et al., 2010).

The possibility of using oxygenated compounds, such as ethanol, motivates the study of these compounds in diesel engines, considering that this fuel can be produced from biomass on a large scale in countries with high agricultural potential, such as Brazil. As Montero and Stoytchevap (2011) comment, ethanol can increase the percentage of biofuel in the blend as well as improve the gas emissions profile when compared to mineral diesel.

The use of ethanol as a fuel for Diesel engines is justifiable but it requires some dedicated solutions. In general, ethanol injection in Diesel engines can be achieved by using ethanol-diesel blends or by the ethanol fumigation in the air intake.

The use of ternary mixtures of diesel, biodiesel and ethanol can simultaneously reduce NOx and particulate matter (PM) emissions (Lei et al., 2010). However this requires a limited amount of ethanol (up to 10% v/v) due to the miscibility problems of ethanol in diesel fuel, unless solubility additives are used (Lapuerta et al., 2007). Guariero et al. (2009) tested the stability of 18 binary and ternary blends of diesel, vegetable oils, biodiesel and ethanol for a minimum period of 90 days and found that the mixtures of ethanol with purity of 95% were not stable due to the polarity of the water molecule present in this compound. They also found that the blends were stable up to fractions lower than 10% of ethanol with purity of 99.5%.

The use of ethanol fumigation technique in the air intake of the engine requires few modifications in the engine. Lu et al. (2008) studied the effect of ethanol when injected into the air intake of the engine with various percentages of ethanol and several equivalence ratios of the overall fuel/air mixture. The results showed a substantial reduction in the NOx emissions when ethanol was used, but with an increase of the total unburned hydrocarbons (THC) and carbon monoxide (CO) emissions. Tsang et al. (2010) tested ethanol fumigation in a 4-cylinder direct injection diesel engine, observing the reduction in overall NOx, opacity and particulate matter mass, but with the increasing in the THC and NO2 emissions.

This present work shows and discusses the results of emissions profile tests with ethanol fumigation in the air intake of a diesel engine by the use of a low pressure electronic injection system. The aim is to reduce NOx and particulate matter (PM) emissions, while increasing the percentage of renewable fuel in the combustible mixture. The timing of the ethanol injection was obtained by monitoring the diesel injection pressure, simplifying the adaptation of such a system in diesel engines with mechanical injection.

2. MATERIALS AND METHODS

2.1. Engine and Electric Generator

The tests were conducted in a three-phase generator manufactured by Kohlbach® powered by a single cylinder 4-stroke diesel engine, manufactured by Agrale® with indirect injection and maximum power of 10 HP. The engine and generator properties are described in Tab. (1) and (2). The tests occurred in conditions of same load for each fuel (1580 ± 10 W). The amount of main fuel supplied by the high pressure injector pump was regulated for each fuel to produce the same engine speed (1800 rpm).

Table 1. Engine Properties

Property	Engine
Maximum Power (kW)	7.6 (NBR-1585)
Speed (rpm)	1800-2500
Compression ratio	20:1
Number of Cylinders	1
Injection type	Indirect
Injection Pressure (MPa)	15
Sweep volume (cm^3)	567

Table 2. Generator Properties

Property	Generator
Maximum Power (kVA)	6.0
Nominal speed (rpm)	1800
Voltage	3~/ 220V/ 60Hz

2.2. Electronic Management System for Ethanol Injection

An electronic system was developed to allow ethanol injection in the intake manifold of an engine. Ethanol was injected in the intake stroke, thus it was necessary to make synchrony with the engine cycle. Synchrony detection was done by monitoring the injection pressure from the diesel injection line. The flowchart of the electronic control system is shown in Fig.1.

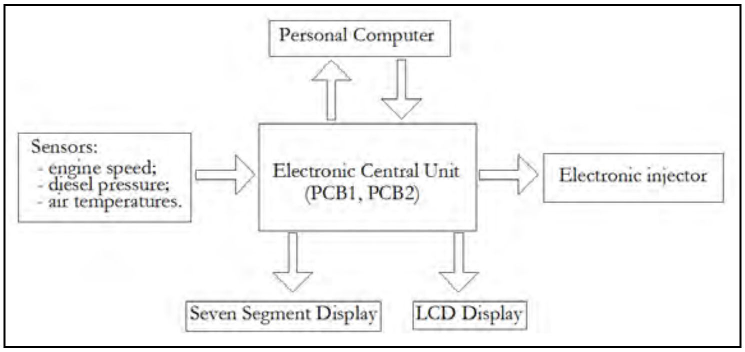

Figure 1. Lay-out of electronic management system.

The electronic central unit (ECU) has two printed circuit boards (PCBs), each one controlled by its respective microcontroller. PIC microcontrollers manufactured by Microchip® model 18F4520, with maximum frequency of 40 MHz, equipped with 4 counters/timers modules, 13 analogical inputs with 10-bit digital resolution, serial communication and two priority levels for external and internal interruptions were used. The first printed circuit board (PCB-1) is responsible for the engine speed measurement and displaying this value on a seven segments display, measurement of the inlet temperatures before and after the ethanol injection and the display of these temperatures on a alphanumeric LCD display, as well as the transmission of the measured data by the serial port to a PC.

The second printed circuit board (PCB-2) is responsible for determining the timing and duration of the ethanol injection. This is achieved by detecting the pressure pulse from the injection of diesel fuel, and doing the required calculations for achieving the pulse in initiation and duration.

The value of engine speed was discretized at regular intervals of 30 rpm and converted into an internal protocol for communication between two microcontrollers.

The temperature measurement was obtained using NTC thermistors. Through an amplification circuit, it was possible to measure temperatures with sensitivity up to 0.12 V/°C in the range of 15 to 30 °C.

There is communication with a PC via a serial port in order to allow the remote configuration of the injection settings. A digital word is sent by a microcomputer with the two most important parameters of the ethanol injection: the relative angle relating to the top dead center (TDC) at the beginning of the intake stroke and the injection duration measured in milliseconds. All circuits were properly packed in a plastic case. Front and back views of the apparatus are shown in Fig. 2.

(a) (b)

Figure 2. Front (a) and back (b) views of ECU case.

2.3. Sensors and Calibration

2.3.1 Speed Engine Sensor

For the engine speed measurement an inductive sensor model LM-12-3004-PA manufactured by JNG sensors® was used. This sensor has a 12 VDC supply voltage. The sensor was mounted on the engine base in orthogonal position to the shaft, where two metallic plates diametrically opposed were fixed. This tachometer was calibrated in order to validate its reading. For this a digital portable photo-tachometer (TC-5035 model), manufactured by ICEL®, with digital resolution of 0.1 rpm was used. The maximum percentage error was by 0.33% occurring at 1500 rpm, making the use of correction factors in order to evaluate the speed engine during the ethanol injection unnecessary.

2.3.2 Diesel Injection Pressure Sensor

In order to monitor the diesel pressure in the injection line, a low-cost sensor 3PP6-12 model, Mobil line, manufactured by Ideal Sensors® was used. This sensor has a range of 0-30 MPa, with a voltage supply of 5.0 VDC and a proportional output to pressure in the range of 0.5 to 4.5 VDC. This sensor was calibrated in the static form, using nitrogen between 0 and 30MPa at regular intervals of 5 MPa. A Bourdon pressure gauge with an accuracy of 1% was used as the validation system. By adjusting the calibration line, it was possible to obtain the described relationship between the output voltage in Volts and the pressure in MPa, as described in eq. (1) with a correlation factor (R^2) of 0.9985.

$$Voltage(V) = 0.1324\ P(MPa) + 0.4818 \tag{1}$$

The input signal from the diesel pump pressure sensor of the engine presented a continuous voltage level of approximately 0.5 volts. Thus, the pressure pulses were conditioned by a specific circuit in order to become rectangular pulses and be interpreted by the microcontroller of the PCB-2. The input and output signals after being conditioned for the pressure pulses of the diesel oil pump are shown simultaneously in Figure 3.

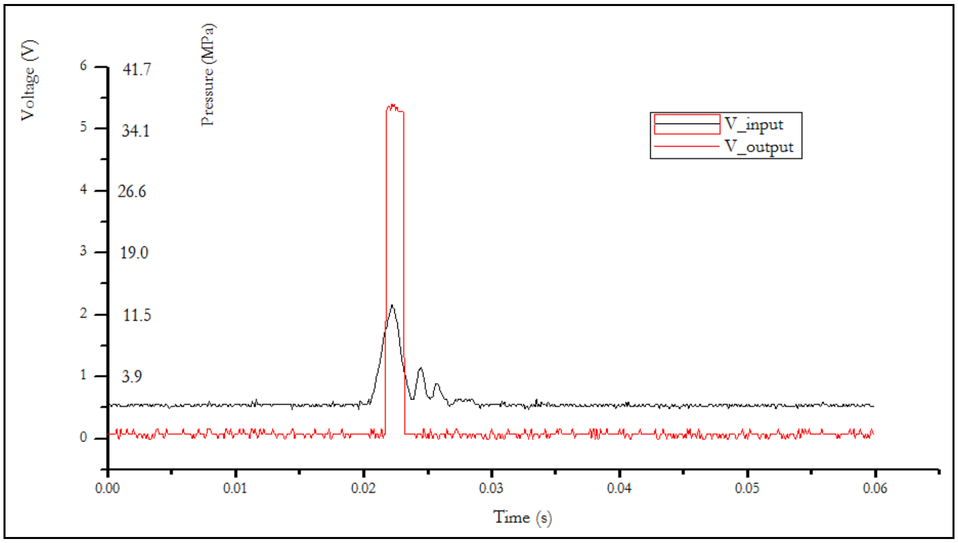

Figure 3. Comparation between input and output signals of diesel pressure sensor.

2.4. Air Intake Temperatures

For the measurement of the air intake temperatures, two NTC thermistors provided by Digikey model AL03006-1248-73-G1 with nominal resistance of 2.0 kOhms @ 25 °C were used. The sensors have glass encapsulation and cylindrical shape with a diameter of 1.6 mm and a length of 4.0 mm.

The calibration curve of the thermistors was obtained in the range of 5.0 °C to 80.0 °C in a thermostatic bath, as described by Ferreira and Pepe (2008). A digital thermometer model Penta Five, manufactured by Full Gauge with a resolution of 0.1 °C was used as a standard thermometer.

The traditional relationship between resistance and temperature, shaped in a decay exponential function (WEBSTER, 1999) was used to find the adjusted curve of the thermistors as the temperature range studied on this paper is below 30 °C. Equations (2) and (3) were be obtained with a correlation factor (R^2) of 0.9993 in order to describe the relationship betwen the resistance (Ohm) and temperature (K) of thermistors 1 and 2, respectively.

$$R(Ohm) = 1999.e^{\left[\frac{3542.5.(T-298)}{(T.298)}\right]} \tag{2}$$

$$R(Ohm) = 1998.e^{\left[\frac{3549.0.(T-298)}{(T.298)}\right]} \tag{3}$$

2.5. Assembly Details

The assembly details of the test system are shown in Fig. 4, with the positioning of the pressure sensor in the diesel high pressure feed line of the injector pump, as well as the sensors used to measure the temperature reduction in the intake air.

An electric injection pump and a pressure regulator adjusted to 0.25 MPa were used for the ethanol injection system. A Bourdon gauge type measured the ethanol pressure during the tests.

An electronic injector manufactured by Honda®, KVB-T01 model, with a 12VDC supply voltage was used for the ethanol injection. This injector is standard on Honda motorcycles of 108 cm3. The electronic injector was installed in the intake pipe at a distant 100 mm away from the inlet of the engine, in a curved section in order to increase the turbulence and thus ensure a better air and ethyl alcohol mix.

Initially the system was tested in order to verify the injection delay. For this, a reflective-type optical sensor, a 45FSL-2LHE model, PNP type, manufactured by Allen Bradley, with a wavelength of 660 nm, a response time of 30 µs and supply voltage of 12VDC was used. This sensor was fixed to the engine housing. A reflective tape was attached to the flywheel of the engine so that when the engine was at top dead center, the tape was positioned in front of the optical sensor. These initial tests were conducted at 3 different speeds: 1700, 1750 and 1850 rpm, considering that the generator operates at a rated speed of 1800 rpm. The injection was programmed in order to occur exactly at the TDC. The maximum delay verified between the start of the injection and the top dead center was by 840 µs.

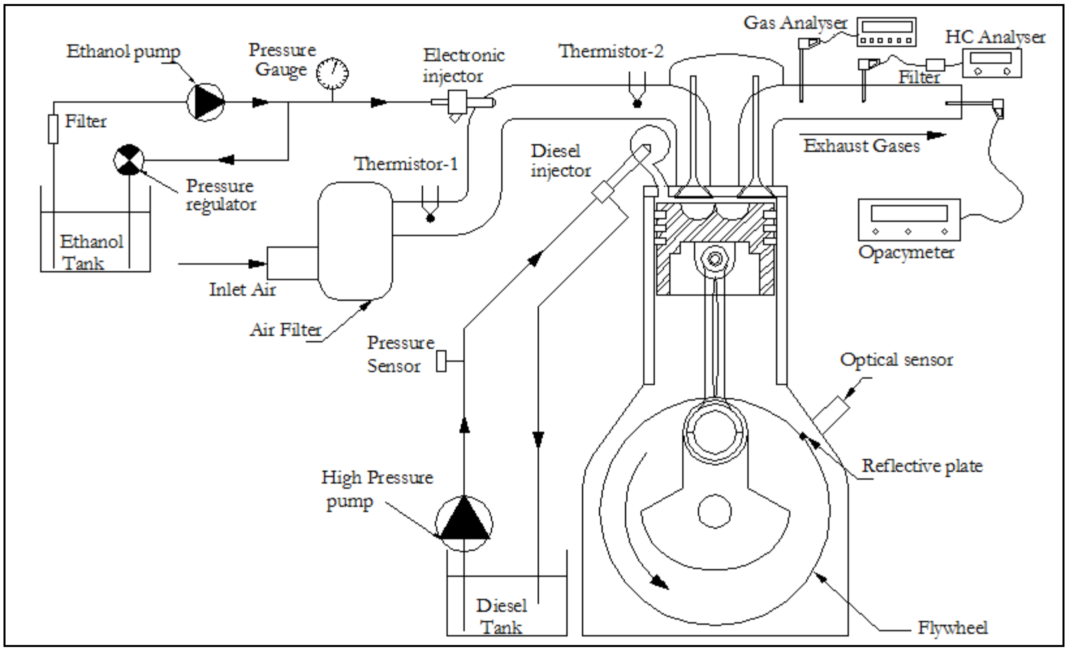

Figure 4. Details of system for double fuel injection.

2.6. Fuels

The class S-500 diesel and soybean biodiesel blend used to make up D70B30 (70% petroleum diesel and 30% biodiesel) were kindly donated by Petrobahia (Petroleum Distributor of Bahia S.A.). The ethyl alcohol 99.3% purity was supplied by Química Moderna®. Table 3 shows the main characteristics of the raw materials used for the fuel compositions.

Table 3. Raw Material Properties for Fuels.

Property	Fossil Diesel	Soybean Biodiesel	Ethyl Alcohol
Weight molecular (kg.kmol^{-1})	136.3	291.77	30.1
Density at 20ºC	0.853	0.870	0.790
Latent heat of vaporization (kJ.kg^{-1})	270	200	840
Cetane number	48	56	6
Lower heating value (kJ.kg^{-1})	42820	36395	28300

Four different fuel compositions were tested. The tests started with a binary mixture of 70% v/v mineral diesel and 30% v/v biodiesel (D70B30) without any ethanol injection. After that, three compositions were tested with increasing ethanol content (D70B30-E5, D70B30-E9, D70B30-E15) added through the air intake pipe by controlling the injection time of the electronic injector.

The premixed ratio (PI), as described in Lu et al. (2008), for each fuel composition was determined by Eq. (4).

$$PI(\%) = \left(\frac{m_e LHV_e}{m_e LHV_e + m_{d\_b} LHV_{d\_b}} \right).100 \tag{4}$$

Where:
m_e is the is the mass of ethanol injected during each cycle in kg;
m_{d_b} is the is the mass of binary blend in each cycle in kg;
LHV_e is the ethanol lower heating value in kJ.kg^{-1};
LHV_{d_b} s the ethanol lower heating value of diesel and biodiesel blend in kJ.kg^{-1}.

Table 4 shows the ethanol premixed ratio for each fuel composition as well as the volumetric proportions of alcohol.

Table 4 – Energy and volumetric fractions of ethanol for each fuel.

Fuel	Ethanol premixed ratio (%)	Ethanol volumetric fraction (%)
D70B30	0.0	0.0
D70B30-E5	3.3	5.1
D70B30-E9	6.1	9.2
D70B30-E15	10.2	15.2

2.7. Instrumentation

The mass fuel flow normally introduced by the high pressure injection pump was obtained by the gravimetric method using a digital scale, while the ethanol flow was obtained by a volumetric meter with a resolution of 1ml. For each fuel, five cycles of consumption measurements were performed with a sampling time of 30 min. The generator power was obtained using a digital wattmeter with a sampling frequency of 3Hz.

The exhaust gases were determined by gas analysers. One of them could evaluate the concentrations of CO and NOx in ppm, while the others were able to measure the opacity and concentrations of unburned hydrocarbons (THC). For the latter, fine filters were placed in the collect line in order to retain particulate material from the discharge pipe of the engine. 25 measurements of gas emissions and exhaust gas opacity were done for each fuel. The main characteristics of the employed instruments are shown in Tab. 5.

Table 5. Properties of the Main Instruments

Property	Instrument model (manufacturer)	Measurement uncertainty
Air Temperature	Thermometer AN-3070 (Icel)	± (3%+0.2) ºC
Relative Humidity	Digital Thermohygrometer HT-208 (Icel)	± 3%
Exhaust Gas Analysis (NOx e CO)	Gas Analyser Tempest-100 (Telegan Gas Monitoring)	± 2%
Electric Power (W)	Digital Wattmeter AW-4700 (Icel)	± (3% + 5 dig.)
Fuel Consumption (diesel + biodiesel)	Digital scale 9094 (Toledo)	± 2 g
Exhaust Gas Analysis (THC)	Gas Analyser PC-Multigás (Napro)	± 3%
Opacity	Opacimeter NA-9000 (Napro)	± 3%

3. RESULTS

The average results for air intake temperature reduction, exhaust gas emissions profile and opacity are shown below. The ethanol injection was scheduled to start 5° after top dead center (TDC), thus respecting the delay for shutting down the exhaust valve of the engine. The measurement uncertainties presented below were evaluated for a reliability of 95%.

4.1. Air Intake Temperatures

The measured values for the air intake temperatures at the upstream and downstream points of the injection for each fuel tested are shown in Tab. 6.

Table 6. Results for Air Intake Temperatures.

Fuel	Upstream temperature (ºC)	Downstream temperature (ºC)
D70B30	29.5 ± 0.2	29.5 ± 0.2
D70B30-E5	29.5 ± 0.3	19.2 ± 0.3
D70B30-E9	30.8 ± 0.2	15.0 ± 0.2
D70B30-E15	30.7 ± 0.2	14.2 ± 0.2

As can be observed, the use of ethanol results in a significant reduction in the air intake temperature caused by the high latent heat of vaporization of this fuel, as shown in Table 3.

4.2. Exhaust Gas Emissions

The results for nitrogen oxides (NOx) and carbon monoxide (CO) emissions are shown in Fig. 5. Oxygen in the fuel can increase the NOx emissions in Diesel engines. However, as can be seen, the addition of ethanol caused a significant reduction in NOx emissions due to poorer combustion caused by ethanol introduction. Since this fuel has a low cetane number, ethanol can cause delay in the peak pressure resulting in a decreasing of temperature in the combustion chamber. Additionally, the high latent heat of vaporization of ethanol caused high temperature reduction in the air intake pipe of the engine, thereby reducing the NOx emissions.

Carbon monoxide is a toxic and odorless gas. It is generally formed when the engine operates in an environment rich in an equivalence ratio of fuel/air. The carbon monoxide emissions show a consistent increase with the addition of ethanol in the fuel composition due to weak ignitability of ethanol.

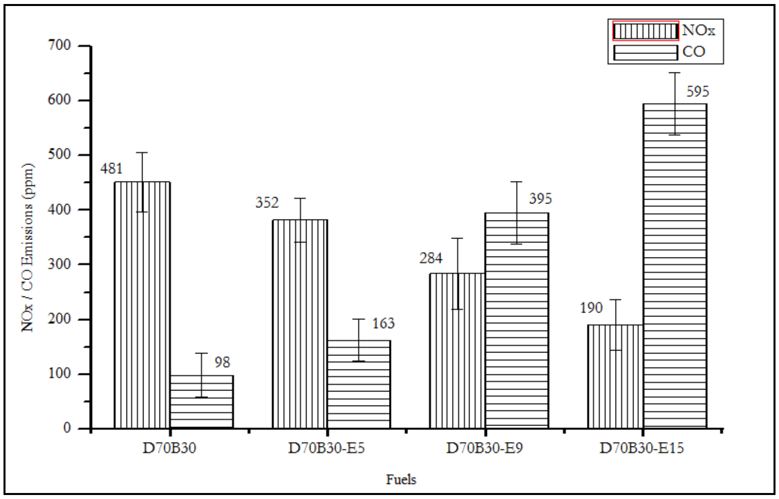

Figure 5. CO and NOx emissions for each fuel.

In general, unburned hydrocarbons can be formed in diesel engines by incomplete combustion, rich combustion operation or deposits of hydrocarbon on the walls of the combustion chamber. The results for the total unburned hydrocarbons (THC) emissions are shown in Fig. 6, where an increase in THC emissions with the addition of ethanol can be noticed. By having a weak ignitability due to its low cetane number, as well as a lower temperature in the combustion chamber, the ethanol introduction in pre-mixture can produce rich zones where the flame is not able to burn it, favouring the formation of total unburned hydrocarbons.

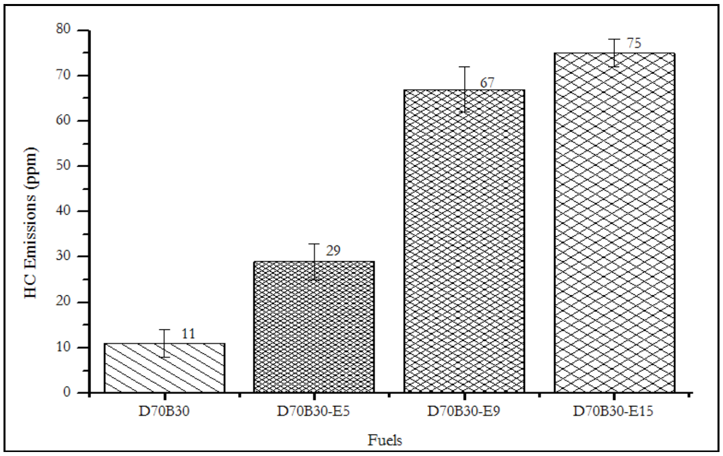

Figure 6. Results for THC emissions.

4.3. Opacity

The opacity of the exhaust gases of diesel engines is mainly caused by the formation of particulate material composed of solid carbon soot generated in rich mixture zones inside the cylinder during combustion reaction.

The opacity measured by the coefficient of light absorption is shown in Fig. 7. With the increased ethanol content, it is possible to note a slight reduction in the opacity until moderate concentrations of ethanol, which does not occur for high levels of alcohol. The use of ethanol can lead to oxygen-rich areas during the combustion process within the cylinder, thereby reducing the formation of particulate material In general and also verified by Tsang et al. (2010), the opacity reduction with the use of ethanol is less noticeable under low load conditions, such as those in the present test.

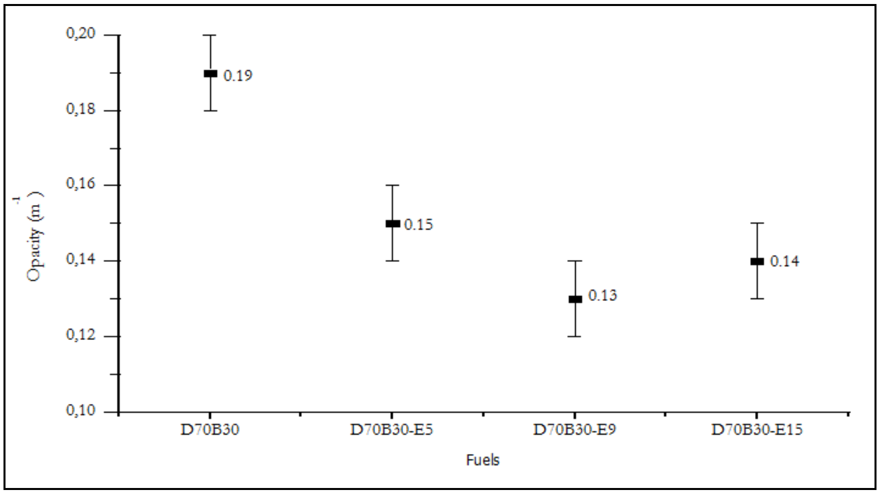

Figure 7- Opacity of Exhaust Gases.

4. CONCLUSIONS

The use of ethanol can be a valuable alternative to reduce NOx emissions when using biodiesel as fuel in compression ignition engines. Furthermore, by reducing diesel fuel consumption in these engines ethanol can help to reduce the consumption of fossil fuel resources.

This paper presented a description of a system which introduces ethanol through the air intake pipe of the engine avoiding the inconvenient separation of phases when using the ternary blends of diesel, ethanol and biodiesel. Furthermore, the fumigation technique enables the use of alcohol with a higher water content which would not be possible in case of using blends because water promotes phase separation in such mixtures.

The electronic injection system described in this paper can be implemented with minimal changes in engine construction, considering that the detection of the synchrony of the oil pressure pulse prevents the implementation of a specific sensor on the engine camshaft.

The results for the emissions profile of a stationary engine using as main fuel, a binary blend of diesel and biodiesel with high levels of biodiesel in the blend (D70B30) and increasing ethanol content being injected into the air intake pipe were presented.

The results for the air temperature measurements at the upstream and downstream points of injection showed air cooling with ethanol injection up to 17.0 ºC. The high latent heat of the ethanol vaporization accounts for this significant reduction which can change the combustion characteristics significantly.

The CO and THC emissions increased with ethanol content. However, NOx emissions fell consistently coupled with a slight reduction in opacity, thus breaking the traditional inverse relationship between NOx and particulate matter emissions (PM).

The results indicate the need for further research into new low cost additives that reduce ignition delay of the fuel composition in order to compensate for the low cetane number of ethanol.

The use of ethanol injected into the air intake can be a valuable method in the future for controlling NOx emissions in diesel engines when using blends with high levels of biodiesel, favouring the preservation of natural resources by reducing the consumption of mineral diesel oil.

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