ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

PERFORMANCE ANALYSIS AND EMISSIONS PROFILE OF A DIESEL GENERATOR POWERED WITH ADDITIVATED BLENDS OF DIESEL, BIODIESEL AND ETHANOL

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Abstract. *Environmental concern with the use of fossil resources motivates several researches to find out substitutes to petroleum products, in particular for diesel oil. Biodiesel stands out for being renewable, nontoxic and easily degradable. The use of this fuel is suitable for Diesel engines with little or no physical modifications. Furthermore, biodiesel has some disadvantages such as higher viscosity, low volatility, and higher emissions of nitrogen oxides (NO_x) when compared to mineral diesel. This paper shows the results for the mechanical performance and emissions profile of a diesel engine operating with blends of diesel, biodiesel and ethanol. The tests occurred in a single cylinder diesel generator with mechanical indirect injection at 1800 rpm that powered a resistive electric panel. Four different fuels were tested: B5 (95% diesel, 5% biodiesel v/v), B50 (50% diesel, 50% biodiesel v/v), 92%B50+8%E (46% diesel, 46% biodiesel, 8% ethanol v/v). Finally, other composition was tested with the use of a cetane improver (DTBP: di-tert-butyl peroxide) in a ratio of 0.5% (91.54%B50+7.96%E+0.5%A). The compositions were prepared using the S-10 diesel oil and soybean biodiesel. The Tests occurred at low load conditions. Emissions profile, specific fuel consumption and energy analysis were evaluated. It was noticed a decreasing in energy efficiency, NO_x and CO emissions with increase in ethanol content and increasing of NO_x emissions with Biodiesel addition. The use of DTBP showed a slight increase in energy efficiency, but an increasing in NO_x and CO emissions was noticed. Considerations for future use of ethanol in diesel engines are presented.*

Keywords: *Diesel engines, ethanol, biodiesel, ternary blends.*

1. INTRODUCTION

Biodiesel has been widely proposed as a substitute for mineral diesel fuel. This fuel virtually does not generate residues of sulfur and has lower emissions of other pollutants due to the presence of the oxygen in its molecules (Qi, *et al.*, 2006; Lin, *et al.*, 2007). However, the use of biodiesel leads to a consistent increase in emissions of nitrogen oxides (NO_x) (Sandum *et al.*, 2005; Lapuerta *et al.*, 2008). Several solutions to this problem are generally used, such as exhaust gas recirculation (EGR) and the addition of oxygenated compounds such as ethyl and methyl alcohol or dimethyl ether (DME) (Yilmaz and Sanchez, 2012; Jie *et al.*, 2010; Yao *et al.*, 2007).

Yao *et al.* (2007) studied the effect of methanol injected into the intake air of a diesel engine. It was found reduction in NO_x and PM emissions with addition of methanol.

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. Montero and Stoytchevap (2011) comment that 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 ternary mixtures of diesel, biodiesel and ethanol can simultaneously reduce NO_x 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). Guarieiro *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. The blends were stable up to fractions lower than 10% of ethanol with purity of 99.5%.

Huang *et al.* (2009) studied the stability, emissions profile, energy efficiency and fuel consumption of diesel and ethanol blends aditioned with n-butanol. The results showed that the additive n-butanol improved the blend solubility. It was found an increase in fuel consumption, CO and THC emissions. The NO_x emissions were not conclusive.

This present work shows and discusses the results of emissions profile tests with binary and ternary blends of diesel, biodiesel and ethanol in a diesel engine. The aim is to reduce NO_x emissions, while increasing the percentage of renewable fuel in the combustible mixture.

2. MATERIALS AND METHODS

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

2.1. Instrumentation

The mass fuel flow was obtained by the gravimetric method using a digital scale. 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 through a gas analyzer that was able to evaluate the concentrations of CO_2 (%), CO and NO_x in ppm. A total of 25 measurements of gas emissions were done for each fuel. The main characteristics of the employed instruments are shown in Tab. 3.

Table 3. 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 (NO_x, CO and CO_2)	Gas Analyzer Tempest-100 (Telegan Gas Monitoring)	± 2%
Electric Power (W)	Digital Wattmeter AW-4700 (Icel)	± (3% + 5 dig.)
Fuel Consumption (diesel+biodiesel+ethanol)	Digital scale 9094 (Toledo)	± 2 g

ISSN 2176-5480

2.2. Fuels and Additive

The class S-10 diesel, ethyl alcohol 99.2% purity and soybean biodiesel blend used to make up the fuel compositions were kindly donated by Petrobahia (Petroleum Distributor of Bahia S.A.). Tab. 4 shows the main characteristics of the raw materials used for the fuel compositions.

Table 4. Raw Material Properties for Fuels.

Property	Fossil Diesel	Soybean Biodiesel	Ethyl Alcohol
Typical composition	$C_{9.84}H_{17.95}$	$C_{18.74}H_{34.43}O_2$	C_2H_6O
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
Stoichiometric ratio (kg air/kg of fuel)	14.6	12.5	9
Lower heating value (kJ kg^{-1})	42820	36395	28300

Four different fuel compositions were tested. The tests started with a commercial binary mixture of 95% v/v mineral diesel and 5% v/v biodiesel (B5). After that, two compositions were tested (B50, 92%B50+8%E)

The di-tert-butyl peroxide (DTPB), similarly to the 2-ethylhexylnitrate (2-EHN), is a known accelerator for spontaneous ignition and has been used as a cetane improver of diesel fuel in recent researches (Lee *et al.*, 2010). Tab. 5 shows the properties of (DTPB). The use of DTBP additive in a percentage of 5000 ppm (0.5%) can increase the cetane number of standard diesel fuel from 48 to 53.5 (EPA, 2004).

Table 5. Properties of DTBP (di-tert-butyl peroxide).

Property	**Value**
Composition	$C_8H_{18}O_2$
Flash Point (ºC)	6
Density (20ºC)	0.79
Autoignition Temperature (ºC)	165

In this study the additive di-tert-butyl peroxide, supplied by Merck®, was added in a ratio of 0.5% in volume in order to increase the cetane number of the ternary blend (92%B50+8%E) performing the fourth fuel composition (91.54%B50+7.96%E+0.5%A).

2.3. Energy Analysis

The tests took place within an ambient temperature of 30 ± 2 °C, while the relative humidity was constant at 55 ± 3 %. For each cycle, the engine was heated for 30 minutes. Lubricating oil was substituted for each fuel composition. The lubricating oil was Lubrax CI-4 (15W-40) manufactured by Petrobras®.

The combustion reaction is described in Eq. (1).

$$x\, C_{9.84}H_{17.95} + y\, C_{18.74}H_{34.43}O_2 + z\, C_2H_6O + a\,(O_2 + 3.76\, N_2) \rightarrow \\ b\, CO_2 + c\, CO + d\, H_2O + e\, O_2 + f\, NO_2 + g\, NO + h\, N_2 \tag{1}$$

The x, y and z coefficients are the fractions used in each fuel of the ternary mixture (x+y+z=1), while the other coefficients (a, b, c, d, e, f, g and h) were obtained using the measured data, and the mass balance of each element.

For the energy analysis some assumptions were made:

- The engine operates at steady state;
- The control volume includes the engine and the generator;

- The inclusion of additive does not modify the heating value of the fuel;
- The blends are ideal solutions;
- The kinetic and potential energy effects were not taken into account;
- The atmospheric air composition was assumed as 21% oxygen and 79% nitrogen on a molar basis;
- The unburned hydrocarbon concentrations, as well as SO_2, were not considered.

The specific fuel consumption (SFC), defined as the ratio between the total fuel consumed mass and the consumed energy, at a specific time and evaluated in g/kW.h, was obtained as in Eq. (2).

$$SFC = \frac{m_e + m_d + m_b}{\dot{W}_{vc}.\Delta t} \tag{2}$$

Where:
m_e is the is the mass of ethanol during each cycle in kg;
m_d is the is the mass of diesel in each cycle in kg;
m_b is the is the mass of biodiesel in each cycle in kg;
$\dot{W}_{vc}$ is the average of instantaneous power, measured in kW
Δt is the sampling time in hours.

For determination of heat exchanged between the engine and the ambient, the First Law of Thermodynamics was applied to the engine in a steady state, as shown in Eq. (3) (Moran and Shapiro, 2009).

$$\dot{Q}_{VC} = \dot{n}_c\left(\bar{h}_p - \bar{h}_R\right) + \dot{W}_{VC} \tag{3}$$

Where:
$\dot{Q}_{VC}$ is the heat flow crossing the control surface (losses) in kW;
$\dot{n}_c$ is the fuel molar flow in kmol/s;
$\bar{h}_p$ is the molar combustion enthalpy in combustion gases in kJ/kmol;
$\bar{h}_R$ is the reactants combustion enthalpy in kJ/kmol;

The energy in the exhaust gas was determined by Eq. (4):

$$\dot{Q}_d = \dot{n}_c(\overline{PCI}) - \dot{W}_{VC} - \left|\dot{Q}_{VC}\right| \tag{4}$$

Where:
$\dot{Q}_d$ is the energy lost by the exhaust gas from the control surface in kW;
$\overline{PCI}$ is the molar lower heating value of fuel in kJ/kmol.

The generator energy efficiency (ε) defined as the ratio of useful energy produced by the generator and the contained energy in the consumed fuel was determined according to Eq. (5).

$$\varepsilon\,(\%) = \left(\frac{\dot{W}_{vc}.\Delta t}{m_e LHV_e + m_d LHV_d + m_b LHV_b}\right)\cdot 100 \tag{5}$$

Where:
LHV_e is the ethanol lower heating value in $kJ.kg^{-1}$;
LHV_d is the lower heating value of diesel fuel in $kJ.kg^{-1}$;
LHV_b is the lower heating value of biodiesel fuel in $kJ.kg^{-1}$;
Δt is the sampling time in h.

3. RESULTS

3.1. NO_x/CO Emissions

ISSN 2176-5480

The results for NO_x and CO emissions are shown in Fig. 1. These results are the variations in emissions for each fuel when compared to B5 blend, measured in ppm (v/v). NO_x emissions are mostly related to the maximum temperatures obtained within the combustion chamber during combustion, but oxygen in the fuel may also increase the NO_x emissions in Diesel engines. It is possible to sse in Fig. 1 that the highest NO_x emissions occurred with the use of the biodiesel, probably due to the higher amount of oxygen present in this fuel. The addition of ethanol caused a reduction in NO_x emissions. The addition of a fuel with a very low cetane number is expected to significantly increase ignition delay, so producing the peak pressure at a later stage, resulting in a decreasing of combustion chamber pressure and temperature as discussed by Park *et al*. (2011) who observed that increasing of ethanol content in diesel oil increases the ignition delay. Additionally the high latent heat of vaporization of ethanol can induce temperature reduction in the combustion chamber, as described by Zhu *et al.* (2011) who tested the effect of ethanol in biodiesel blends.

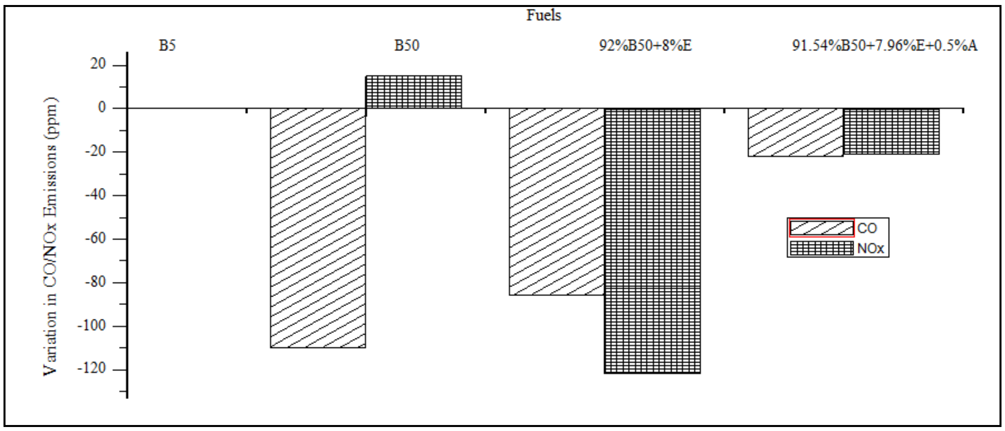

Figure 1. Variation in CO and NO_x emissions for each fuel related to D95B5 blend (ppm).

According to other authors (Randazzo and Sodré, 2011) since the small low heating value of ethanol in comparison with diesel oil, higher fuel amounts are required to produce the same power from the engine, thus intensifying fuel vaporization and reducing the temperatures attained in the combustion chamber, thereby reducing the NO_x emissions.

Carbon monoxide is generally formed when the engine operates in a rich environment of fuel/air mixture. The carbon monoxide emissions in Fig. 1 show a consistent decrease with the addition of biodiesel, since this fuel has oxygen in its molecules. The addition of ethanol shows a slight increase in CO emissions, probably due to the fact that the ethanol addition decreases the overall biodiesel content in the fuel mixture. The reduction in cetane number with ethanol introduction can increase the CO emissions.

DTBP does not have nitrogen in its composition such as others cetane improvers (2-EHN) but, the induced reduction of the ignition delay of the combustion will increase the combustion pressure and temperature. This may be the reason why the use of the additive led to a very slight increase in NO_x emissions when compared to ternary blend with ethanol (92%B50+8%E). The use of DTBP caused an increasing in CO emissions. Other authors found different results (Nandi and Jacobs, 1995).

3.2. CO_2 Emissions

Figure 2 shows the results for CO_2 emissions. These results are the variations in emissions for each fuel when compared to B5 blend, measured in % (v/v). There is no appreciable variation in CO_2 emissions with increasing ethanol and biodiesel content. The gas analyzer uncertainly (0.2%CO_2) can make impossible to measure the variation in CO_2 emissions with ethanol introduction. Since ethanol is a renewable fuel, this CO_2 amount can be reused in the photosynthesis process of the plants, thus the use of ethanol in Diesel engines can be an important strategy to control global warming.

ISSN 2176-5480

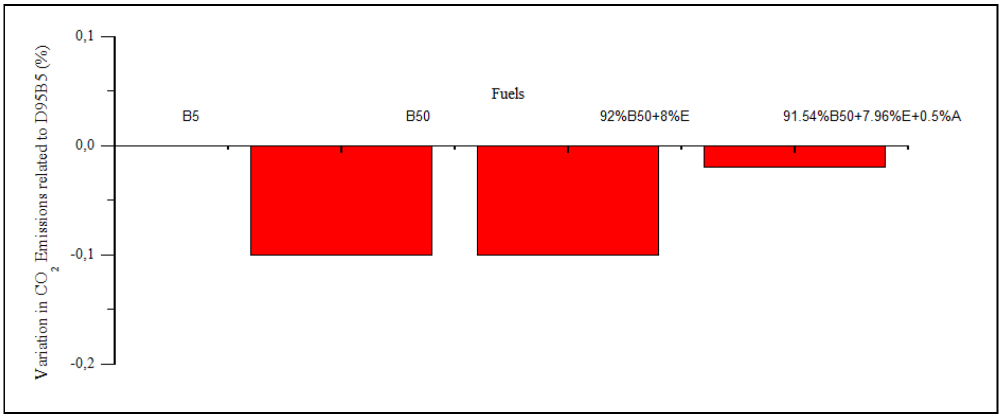

Figure 2. Variation in CO_2 emissions related to B5 (%).

3.3. Energy Analysis

Figure 3 shows the total specific fuel consumption for the four fuel compositions. As shown in Fig. 3, a consistent increase in the total specific fuel consumption with biodiesel and ethanol content can be seen. Biodiesel and Ethanol has low calorific values, thus to maintain the same output power, the total fuel consumption tends to be higher than the binary blend B5. The use of the additive leads to a very slight reduction in the total fuel consumption, since it can increase the combustion performance.

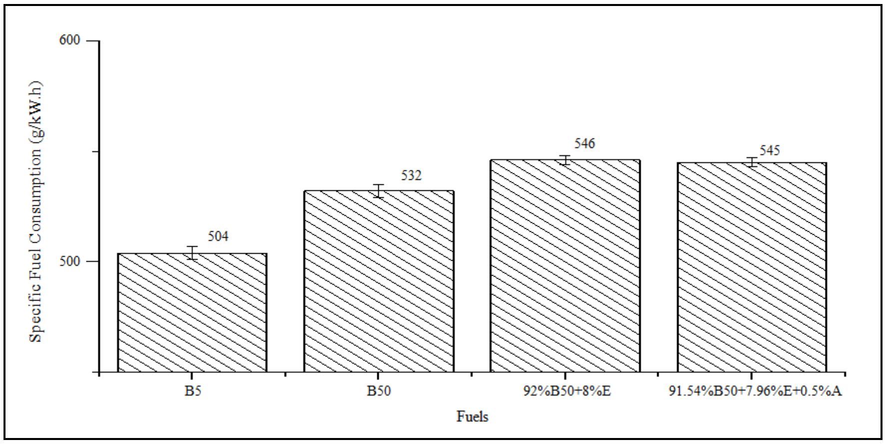

Figure 3. Results for total specific fuel consumption.

Table 6 shows the energy flows entering and leaving the engine for the four tested fuels.

Table 6. Results for Energy Analysis.

Energy Flow (kW)	Fuels			
	B5	B50	92%B50+8%E	91.54%B50+7.96%E+0.5%A
Input Energy	9.38	9.35	9.39	9.37
Electric Power	1.58	1.58	1.58	1.58
Losses	5.78	5.62	5.78	5.78
Exhaust Gas Heat	2.02	2.08	2.03	2.01

ISSN 2176-5480

The input energy values are similar for all fuels. The low heating value in B50, 92%B50+8%E and 91.54%B50+7.96%E+0.5%A blends is compensated by the surplus mass given by the high fuel consumption of blends with ethanol and high biodiesel amount. The biodiesel shows the highest amount in exhaust gas heat, since this fuel can increase the exhaust gas temperature. There is a noticeable amount of energy in exhaust gas and losses in the engine/generator surface for all fuels. Further studies for heat recover of these energy fractions are justifiable.

The results for energy efficiency of the engine for each fuel tested are shown in Fig. 4. The efficiency calculation refers to overall efficiency of the engine-generator set, thus taking into account the losses of the mechanical transmission added to those caused by the Joule effect in the generator and electrical power cables.

The B50 mixture presented increased energy efficiency due to the higher cetane number of the two materials with a higher numeric value of this property. Oxygen in biodiesel molecule can increase the energy efficiency. It´s possible to note a slight reduction in energy efficiency with increasing ethanol content in the fuel composition. This occurs because of the low cetane number of ethanol, as shown in Tab. 4. This reduction was not significant, when taking into account the fact that ethanol has a low calorific value and a cetane number which is much lower than that of diesel and/or biodiesel. The oxygen in the ethanol molecule can improve the combustion process. The reduction in specific fuel consumption with addition of DTBP caused a very small increase in engine energy efficiency, although the measurement uncertainty makes reliable conclusions impossible.

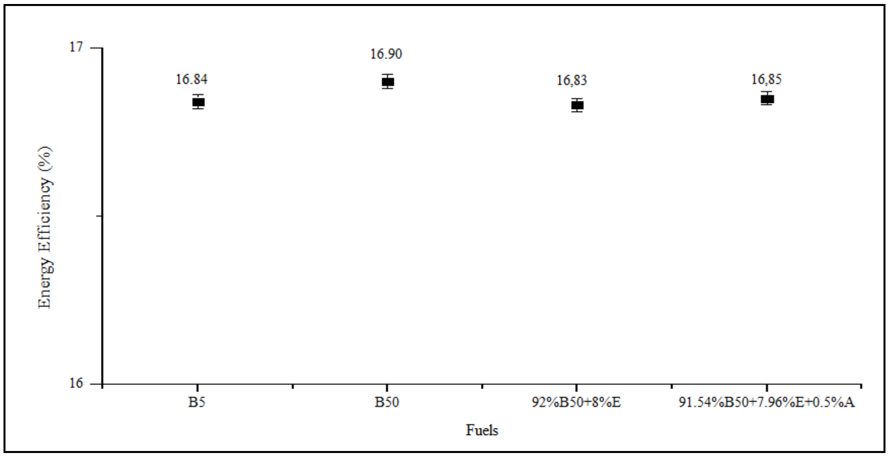

Figure 4. Energy Effciency for each fuel.

4. CONCLUSIONS

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

The results for an engine emissions profile operating with diesel-biodiesel-ethanol blends were presented. The results for energy efficiency shown that biodiesel caused an improving in the engine efficiency, since this fuel has higher cetane number and oxygen content than mineral diesel.

The NO_x emissions reduced consistently coupled with addition of ethanol. The ethanol high latent heat of vaporization can justify this reduction, since a reduction in the combustion chamber temperature can change the combustion characteristics. The blends with ethanol showed low CO emissions, since this fuel is an oxygenated fuel.

The DTBP additive caused increasing in CO and NO_x emissions and a very small increasing in energy efficiency. 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 can be a valuable method in the future for controlling NO_x emissions in diesel engines when using blends with high levels of biodiesel, favoring the preservation of natural resources by reducing the consumption of mineral diesel oil.

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