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TECHNICAL PAPER

Energy analysis and exhaust emissions of a stationary engine fueled with diesel–biodiesel blends at variable loads

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Abstract Compression ignition engines are widely used for transportation and power generation around the world. Even though high efficiencies are obtained for these machines, their main energy source is a non-renewable fuel. In addition to that, greenhouse gases, nitrogen oxides, particulate matter and other non-desirable substances are emitted. Biodiesel is a fuel usually proposed for Diesel engines because it is non-toxic, renewable, can be produced from different oil seeds and does not require significant modifications in the engine. This work investigates the exhaust emissions and performance of a six-cylinder direct injection Diesel engine that drives a 60-kVA electric generator at 1800 rpm. The engine was fueled with five different blends (D95B5, D75B25, D50B50, D25B75, B100) of conventional diesel oil containing up to 10 ppm of sulfur (S10 class) and biodiesel at different loads. An in-house developed system for particulate matter (PM) evaluation was created. Gaseous emissions and energy flows were evaluated. A reduction of 45% in PM emissions was observed by increasing biodiesel content from B5 to B100 at the highest load tested (27 kW). CO and NOx emissions increased slightly when compared to the mixture commercialized in Brazilian market (5% biodiesel and 95% conventional diesel). No significant variation in energy efficiency was revealed by increasing the percentage of biodiesel in the blend.

Keywords Diesel engine · Biodiesel · Emissions · Energy analysis · Particulate matter evaluation

Abbreviations

List of symbols

$\dot{B}$	Exergy flow rate (kW)
c	Specific heat [kJ/(kg K)]
$\dot{E}$	Energy flow rate (kW)
$\dot{n}$	Molar flow rate (kmol/s)
$\overline{\text{LHV}}$	Low heating value (kJ/kmol)
$\dot{Q}$	Heat flow rate (kW)
R	Mixture constant [kJ/(kg K)]
W	Power (kW)

Subscripts

CV	Control volume
CW	Cooling water
EX	Exhaust gas
F	Fuel/formation
P	Products/pressure
R	Reactants
REF	Reference

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1 Introduction

Biodiesel is a fuel composed of esters from long-chain carboxylic acids, produced by transesterification of vegetable oil or animal fat using alcohol. It is biodegradable, nontoxic and can significantly reduce the emission rate of toxic (directly harmful to life) and greenhouse gases due to its closed carbon cycle [1]. One great advantage of using biodiesel is that it can be used as fuel in Diesel engines, pure or mixed with conventional diesel, with little or no design change [2]. According to Lapuerta et al. [3], the exhaust emissions of diesel engines operating with pure biodiesel and blends diesel/biodiesel have been reported in numerous studies.

Carbon monoxide (CO) is an intermediate product of combustion (incomplete combustion), which can cause nausea and headache at lower concentrations and even death at higher concentrations [4]. According to Xue et al. [5], most of the literature (86.4%) indicates a reduction in CO emissions by using biodiesel in comparison with conventional diesel. According to Roy et al. [6] reductions of 8% to 15% in CO emissions were found for an engine operating on rapeseed methyl ester blend (B20) when compared to pure diesel (B0) at different engine speeds. In the work of Raheman and Phadatare [7] a reduction of 73% in CO emissions was observed when the engine was operated using pure biodiesel instead of pure diesel. Haas et al. [8] reported a reduction of 48% in CO emissions by using soybean biodiesel. The presence of oxygen in its composition and the high cetane number of biodiesel are claimed to be the main reasons for these positive results. However, in tests developed by Tan et al. [9] and Muralidharan et al. [10] using jatropha biodiesel, increase in CO emissions was verified at low loads and decrease in CO emissions at high loads. Despite of it, Silitonga et al. [11] indicate that there are other papers claiming significant increases in CO emissions using different biodiesel concentration in the mixture with diesel. The high viscosity of the biodiesel may be the reason for the increase in CO emissions. High viscosity would cause poor spray distribution during injection generating incomplete combustion. Hence, it can be concluded that there is no clear trend for CO emissions regarding biodiesel-diesel blends since it strongly depends on injection pressure and fuel injection system. Besides that, fuel composition, viscosity and cetane number are also important making specific evaluations required.

In respect of NOx (nitrogen oxides), engines operating with biodiesel and its blends have presented increment in its emission rates [12]. This increase in NOx emissions can hinder the use of biodiesel. For Nabi et al. [13], the increase in NOx emissions is due to the presence of oxygen in the biodiesel molecule, which favors high pressure and temperature peaks in the combustion chamber, contributing to NOx formation from thermal route. In the work of Saravanan et al. [14] the influence of increasing flame temperature, oxygen content, ignition delay, and fuel density on NOx formation rate was investigated. This work confirms the contribution of these variables in the increase of NOx emissions by using biodiesel. In Raheman and Phadatare [7] it was shown that engines with mechanical injection systems have an advanced fuel injection time, due to the high bulk modulus (low compressibility) of biodiesel, which also contributes for increasing NOx emissions. Modern diesel engines with electronic control do not experience this effect. The increase in NOx emissions with different biodiesel concentrations is stressed in many papers. The magnitude of the increment varies according to the engine technology, though.

Particulate matter (PM) is a product of incomplete combustion and it is composed of an amorphous carbon core bonded to other organic materials. PM formation is influenced by several factors: fuel flow, flame pattern, the presence of some types of unburned hydrocarbon, pressure inside the combustion chamber and temperature inside the combustion chamber [15]. According to a statistical study, the addition of biodiesel in the conventional diesel generates significant reductions in PM emissions [16, 17]. Fattah [12] pointed out the positive effect that biodiesel causes on the PM emissions. This effect is attributed to the amount of oxygen present in the biodiesel composition, which results in a better combustion. In addition to the larger amount of oxygen, the smaller amount of aromatics and sulfur also contribute to reduction in PM emissions. However, other researchers reported increase in PM emissions by using biodiesel–diesel blends [18] and [19]. The high viscosity of biodiesel and the consequent poorer atomization during injection were indicated as causes for the increase in PM emissions in these works.

The specific fuel consumption (SFC) is the ratio of the mass of fuel consumed to the energy produced by an engine. The SFC is expected to increase about 14% when biodiesel is used in replacement of conventional diesel since the heating value of biodiesel is lower than the heating value of conventional diesel [3]. This increase in SFC depends on the type of engine and also on its condition of operation such as load and speed. Canakçi and Van Gerpen [20] compared the SFC of a 57 kW Diesel engine using conventional diesel and biodiesel and obtained an increase in the SFC of 2.5% in tests using B20 mixtures and an increase of 14% in tests using pure biodiesel (B100). However, from a thermodynamic point of view, the thermal efficiency is more appropriate than

SFC for evaluation of engine performance under different fuel compositions [3].

Canakçi and Hosoz [21] tested the thermal efficiency of a four-cylinder turbocharged diesel engine using biodiesel, conventional diesel, and biodiesel blends. It was observed that the biodiesel and the blends tested provided almost the same fuel conversion efficiency.

This work aims to evaluate the exhaust emissions and fuel conversion efficiency of a stationary Diesel engine, naturally aspired, with mechanically controlled direct injection, coupled to an electric generator using different diesel–biodiesel blends at different loads. A particulate matter measurement system was developed providing a simple method to determine the PM content.

2 Methodology

Equipment type and instrumentation characteristics as well as the methods used for measurements and analysis are described in this section.

2.1 Engine and electric generator

The tests were conducted in a six-cylinder, 4-stroke, naturally aspirated Diesel engine, model D225-6 manufactured by MWM Brasil® with direct injection and maximum power of 130 hp (96.94 kW), shown in Fig. 1. The engine load was controlled by a three-phase generator, model ATE-60 (60 kVA) manufactured by Negrini®. The engine and generator specifications are described in Tables 1 and 2. The tests were conducted at fixed speed (1800 ± 5 rpm) and at three different loads: 9, 18, 27 kW, which correspond to 14, 27 and 41% of maximum load at this speed, respectively. An in-line high-pressure pump supplies diesel fuel to mechanical injectors, which opens at a pressure of 21 MPa. An automatic servomotor regulates the amount of fuel that is supplied to the combustion chamber in order to keep the engine speed constant at different loads.

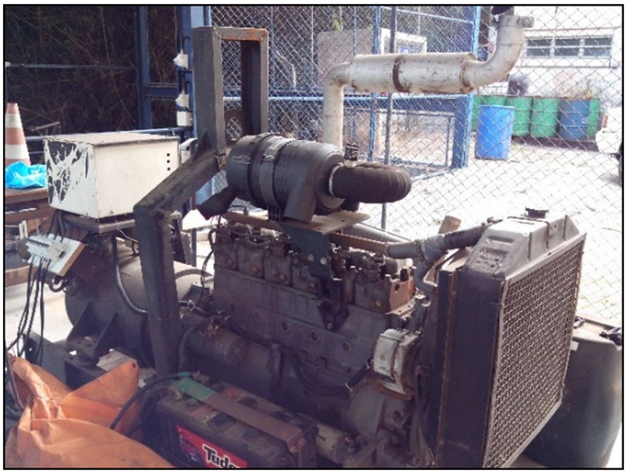

Fig. 1 Six-cylinder, four-stroke, MWM diesel engine

Table 1 Engine specifications

Property	Engine
Maximum power (kW)	95.61 kW at 2400 rpm
Speed (rpm)	1800–3500
Compression ratio	17:1
Number of cylinders	6
Injection type	Direct
Injection pressure (MPa)	20
Engine displacement (cm^3)	5658

2.2 Assembly details

The assembly details of the test system are shown in Fig. 2. Electric resistances were used to dissipate the power generated in a tank full of water. A recirculating water pump connected to a cooling tower was used to keep the water temperature constant in the tank. Tests were carried out in five cycles of 30 min for each load and blend assessed. The measurements were performed at 1800 rpm and at three different loads (9, 18, and 27 kW). Cleaning of fuel injection system and replacement of lubricating oil, fuel and air filters were performed prior each blend test.

2.3 Instrumentation

An orifice plate flowmeter model S25 manufactured by Eletta® was used for measurement of cooling water flow rate. The fuel consumption was determined by gravimetric method using a digital scale. The initial mass of fuel on the balance was 15 kg. The mass of fuel was registered every 5 min for 30 min. The power generated was measured using a digital wattmeter with a sampling frequency of 3 Hz. The exhaust gas composition was determined by a gas analyzer capable of evaluating the concentration of CO, CO_2, and NOx in ppm (v/v). Cooling water temperature and exhaust gas temperature were measured using a digital thermometer. The tests took place at a temperature of 29 ± 3 °C and relative humidity of 58 ± 4%. The main characteristics of the instruments used are shown in Table 3.

Although the Brazilian standard ABNT-NBR14489 recommends the use of a CVS (constant volume sampler) dilution tunnel for particulate matter assessment, an in-house developed device was used as in Menezes and Cataluña [22]. The developed device directly collects a gas fraction from the exhaust pipe using a vacuum pump. Ball valves were used to control the operation of the sample line. Since the gas temperature in the exhaust pipe is high, an aluminum filter holder was used to support the 0.7-μm fiberglass filter (Milipore®) elements. The developed device is composed of a double-stage vacuum pump with maximum flow rate of 8.5 m^3/h manufactured by Suryha® to keep the flow constant (set to 12 LPM) through the PM filter and a flowmeter with range of 0–15 L per minute (LPM) manufactured by RWR®. Flexible resistances were used along the sample line and filter surface to heat the gas. An electronic controller, model INV1713J, manufactured by Inova®, was used to keep the gas temperature at 115 °C avoiding water and hydrocarbons condensation on the filter surface. The in-house developed device is also connected to a nitrogen purge to allow the cleaning of the sample line before each measurement. Figure 3 shows the flowchart of the developed device.

After being collected, the PM amount was evaluated by gravimetric method. All the filters were placed on a silica gel dryer for 24 h at a temperature of 25 °C and relative humidity of 65% before being weighed on a digital scale with a resolution of 0.001 mg, model MX-5, manufactured by Toledo®.

Table 2 Generator specifications

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

2.4 Fuels and blends

The diesel class S10, which contains at most 10 ppm of sulfur, and biodiesel composed of a mixture of soybean

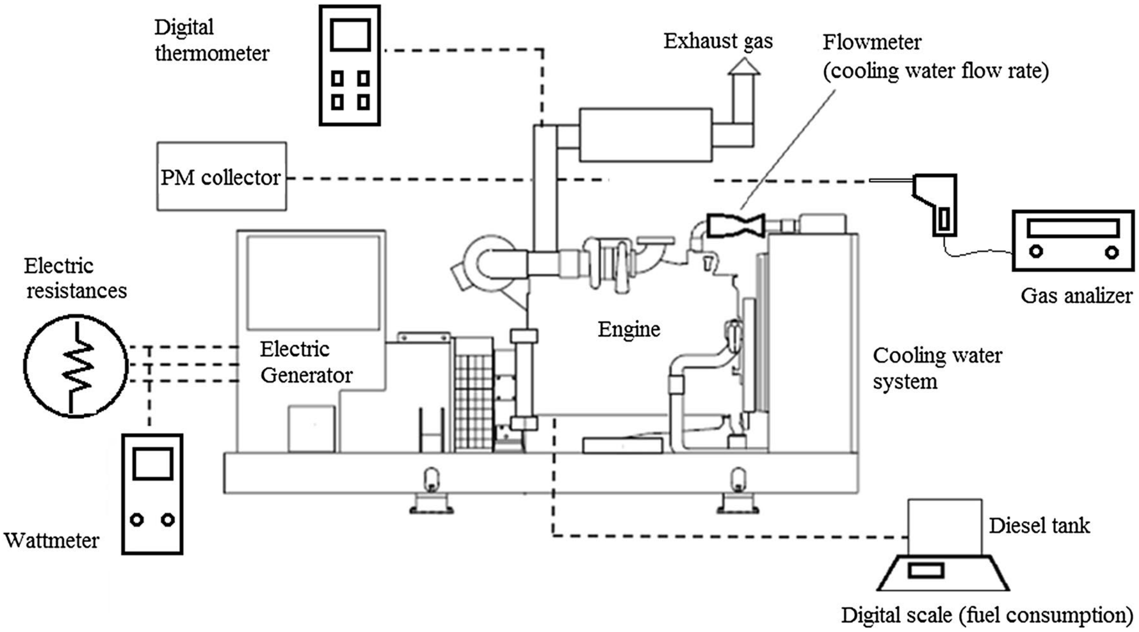

Fig. 2 Details of engine-generator assembly

Table 3 Specifications of main instruments

Property	Instrument model (manufacturer)	Measurement uncertainty
Ambient temperature	Thermometer AN-3070 (Icel)	± (3% + 0.2) °C
Relative humidity	Digital thermohygrometer HT-208 (Icel)	±3%
Exhaust gas analysis (CO_2, NOx and CO)	Gas analyzer tempest-100 (telegan gas monitoring)	±2%
Electric power (W)	Digital wattmeter AW-4700 (Icel)	± (3% + 5 dig.)
Fuel mass consumption	Digital scale 9094 (Toledo)	±2 g
Exhaust gas and cooling water temperatures	Digital thermometer/type K thermocouple MT-525 (Minipa)	± (3% + 0.2) °C
Water cooling flow rate	Flowmeter S25 (Elleta)	±3%

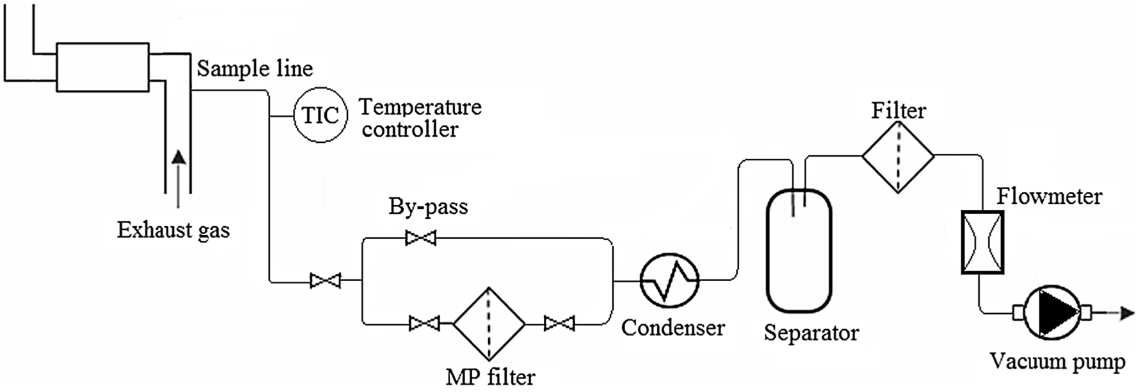

Fig. 3 Flowchart of the particulate matter collector

Table 4 Properties of the basic fuels used to prepare the tested blends

Property	Conventional diesel	Biodiesel
Average formula	$C_{9.84}H_{17.95}$	$C_{18.74}H_{34.43}O_2$
Molecular weight (kg kmol^{-1})	136.3	291.8
Relative density at 20 °C	0.853	0.870
Heat of vaporization (kJ kg^{-1})	270	200
Cetane number (ASTM-D613 CFR)	48	57
Viscosity at 40 °C (cSt)	2.90	4.95
Isentropic Bulk Modulus at 1 atm/40 °C (MPa)*	1400	1600

* Tat and Van Gerpen [23] for methyl soy ester—Fig. 17, page no. 14

Table 5 Volumetric composition and energy content of tested blends

Fuel	Conventional diesel (%)	Biodiesel (%)	LHV (MJ/kg)
D95B5	95	5	43.15
D75B25	75	25	41.95
D50B50	50	50	40.63
D25B75	25	75	38.83
B100	0	100	37.50

biodiesel (17% v/v) and yellow grease biodiesel (83% v/v) were used to produce the blends. Both, S10 diesel and biodiesel were donated by Petrobahia®. Table 4 shows the main characteristics of the fuels used for production of the blends. All the tests were carried out with the same batch of blends.

Five different blends were tested. The tests started with a binary mixture of 95% v/v of conventional diesel and 5% v/v of biodiesel (D95B5), which is a fuel commercially supplied in the Brazilian market. Table 5 describes the volumetric composition and energy content of the blends tested.

2.5 Energy analysis

Prior the tests of each blend, the engine was heated up for 25 min and the lubricating oil was replaced. The lubricating oil used was Lubrax CI-4 (15W-40) manufactured by Petrobras®. The combustion reaction is described in Eq. (1).

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

It was considered that the combustion products contain some CO. The x and y coefficients are the molar ratios of the diesel and biodiesel in one mole of blend ($x + y = 1$), 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. To perform energy analysis, the following assumptions were made:

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

- 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;
- Since the air stream is very close to the standard reference state (25 °C) its energy was ignored;
- SO_2 and HC (hydrocarbons) emissions were not considered.

The energy flows crossing the engine control volume are presented in Fig. 4.

The energy balance for the evaluated control volume can be expressed by Eq. (2), in which it is shown the fuel energy split between heat transferred to cooling water (Q_{CW}), heat transferred to outside of control volume (Q_{CV}), power produced (W_{CW}) and exhausting gases energy (E_{EX}).

$$\dot{E}_{\text{in}} = \dot{n}_{\text{F}}\left|\overline{\text{LHV}}\right| = \left|\dot{Q}_{\text{CW}}\right| + \left|\dot{Q}_{\text{CV}}\right| + \dot{W}_{\text{CV}} + \dot{E}_{\text{EX}} \tag{2}$$

For determination of heat exchanged between the engine and the environment, the First Law of Thermodynamics and mass balance were applied, Eq. (3), as in Canakçi and Hosoz [21] and Moran and Shapiro [24].

$$\begin{aligned} &\frac{\left(\dot{Q}_{\text{CW}} + \dot{Q}_{\text{CV}}\right)}{\dot{n}_{\text{F}}} - \frac{\dot{W}_{\text{CV}}}{\dot{n}_{\text{F}}} = \left(\bar{h}_{\text{P}} - \bar{h}_{\text{R}}\right) \\ &= \sum_{P} n_{\text{out}}\,(\overline{h_F^0} + \overline{\Delta h})_{\text{out}} - \sum_{R} n_{\text{in}}(\overline{h_F^0} + \overline{\Delta h})_{\text{in}} \end{aligned} \tag{3}$$

The enthalpy variation was determined by Eq. (4).

$$\overline{\Delta h} = \bar{h}(T) - \bar{h}(T_{\text{REF}}) \tag{4}$$

Formation enthalpies of the blends were determined from the general reaction for the complete combustion. The engine-generator energy efficiency (η), defined as the ratio of useful energy produced by the generator to the energy contained in the consumed fuel, was determined according to Eq. (5).

$$\eta\,(\%) = \left(\frac{\dot{W}_{\text{CV}}}{\dot{n}_F\left|\overline{\text{LHV}}\right|}\right) \times 100 \tag{5}$$

3 Results and discussion

In this section the magnitude of energy flows crossing the engine control volume as well as exhausting gases composition and temperature is evaluated.

3.1 Exhaust gas temperature

Figure 5 shows the exhaust gas temperature for the evaluated blends at three different loads (9, 18, and 27 kW). An increase in temperature was observed for higher loads. It can be explained by the larger quantity of fuel injected into the combustion chamber. The blend B5 generated the highest temperature at all loads, especially at 27 kW. This variation is not always significant, though. According to Hazar [25], biodiesel generates lower exhaust gas temperatures due to the larger quantity of fuel injected and to the lower ignition delay caused by biodiesel higher cetane number. Similar results were presented in Ozturk [26].

3.2 Exhaust emissions

In this section the results regarding the composition of emissions from the different blends at different loads will be discussed.

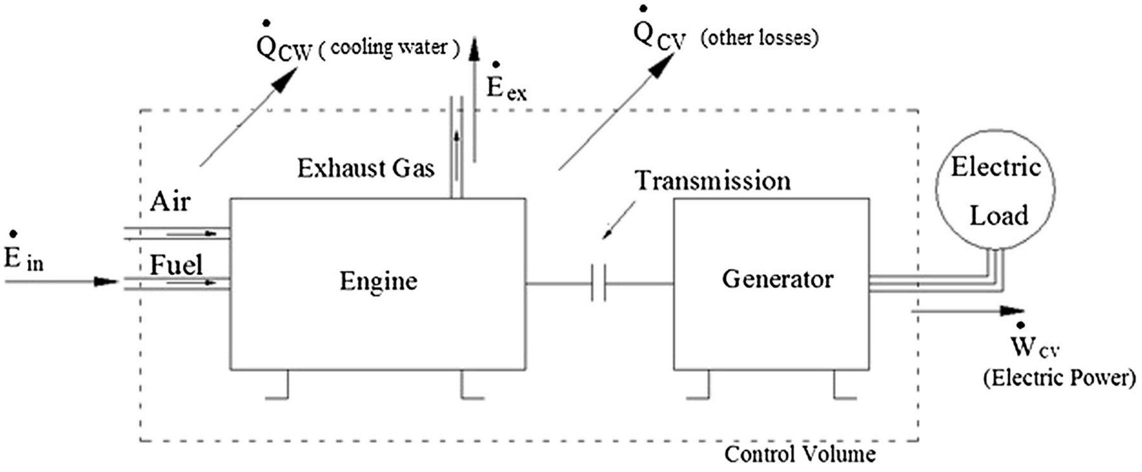

Fig. 4 Energy flows crossing engine control volume

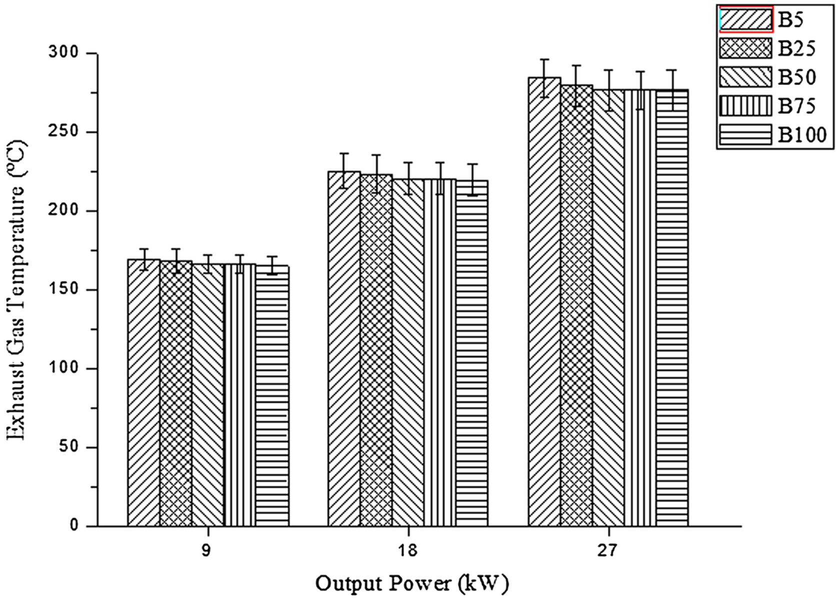

Fig. 5 Exhaust gas temperature as function of output power for the tested blends

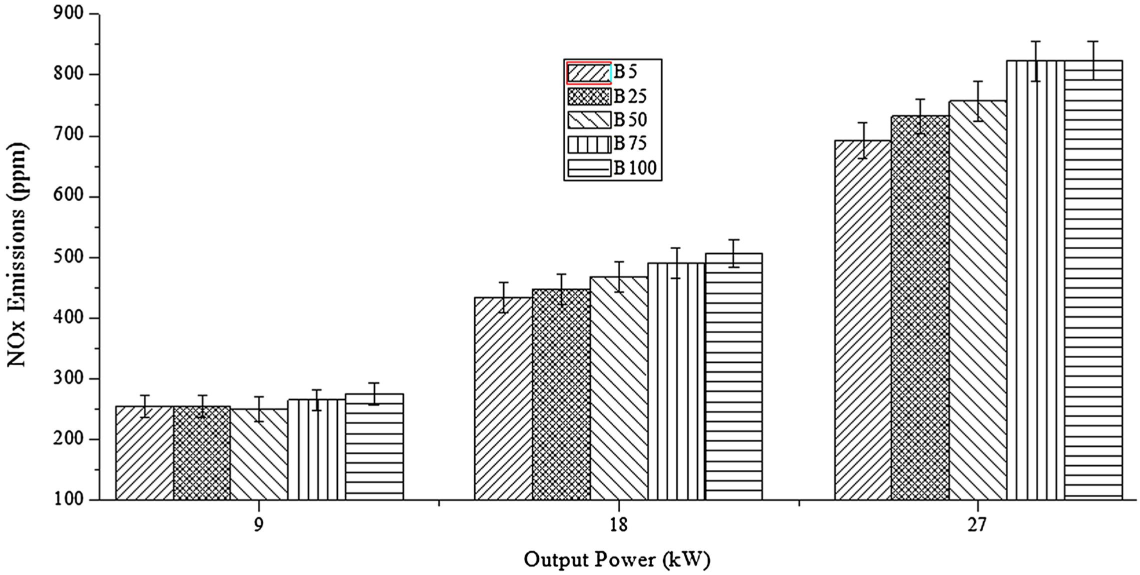

Fig. 6 NOx Emissions using different biodiesel blends for different load conditions

3.2.1 NOx emissions

The formation of NOx in Diesel engines is driven mainly by thermal mechanism. As the temperature raises in the combustion chamber NOx emissions also rises. When the load is increased at constant speed (1800 rpm) more fuel is injected into the combustion chamber; thus it is possible to infer that higher temperatures will be obtained during combustion. In Fig. 6, this tendency can be observed.

Furthermore, Fig. 6 shows an increase in NOx emissions with biodiesel content for the three different loads. An increase of 17% was found when the engine was operated using B100 in comparison to B5. As discussed in Nabi et al. [13] biodiesel has more oxygen in its composition increasing the temperature in the combustion chamber and then the NOx concentration in the exhaust gases. Besides that, larger quantities of oxygen also increase NO formation rate. In addition to that, the engine used in this work has an in line pump projected for neat diesel injection; thus, as discussed in Hoekman and Robbins [27], the injection process becomes slightly advanced when biodiesel is used due to its higher bulk modulus.

3.2.2 CO emissions

The increase in load causes an increase in fuel/air ratio which leads to higher CO emissions. Still, as discussed in Di Yage et al. [1], the increase in load also increases the combustion chamber temperature. Thus, a higher conversion rate of CO into CO2 is expected. Figure 7 shows that CO emissions decreased as the load increased, indicating the dominance of temperature influence over the influence of fuel/air ratio.

Higher CO emissions (up to 20% at 9 kW) were found for blends with higher biodiesel content. This may be caused by the higher viscosity of biodiesel, which leads to a poor injection spray, as appointed by Xue et al. [5] and Hoekman and Robbins [27]. Fattah et al. [12] and Fazal et al. [28] have found opposite results and they justified the reduction in CO emissions by the oxygen content of biodiesel.

3.2.3 CO_2 emissions

Figure 8 shows a reduction in CO_2 emissions when the load required by the generator was reduced as result of lower

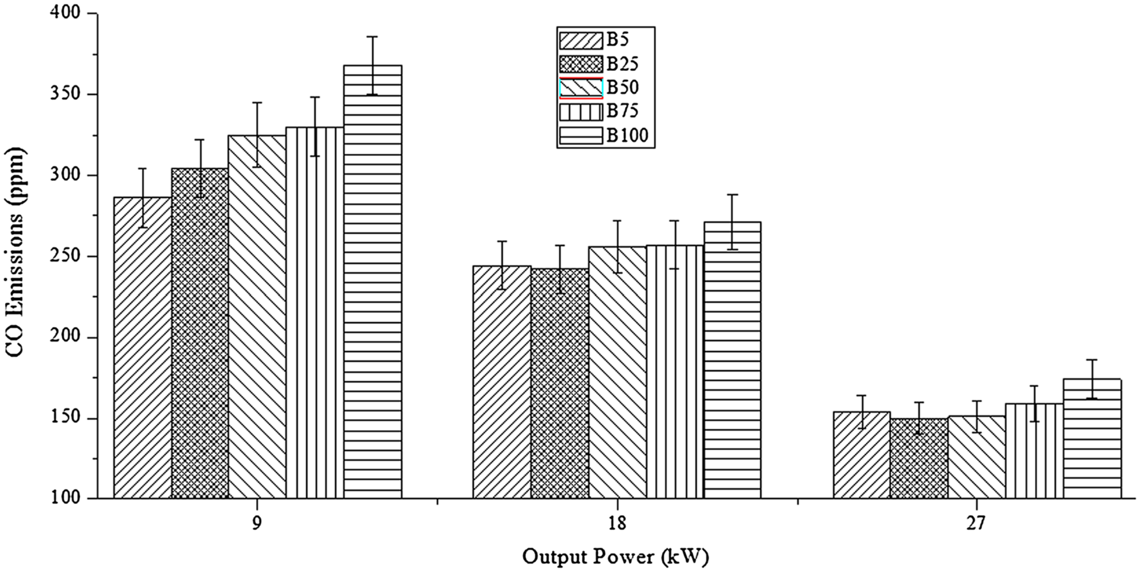

Fig. 7 CO emissions using different biodiesel blends for different load conditions

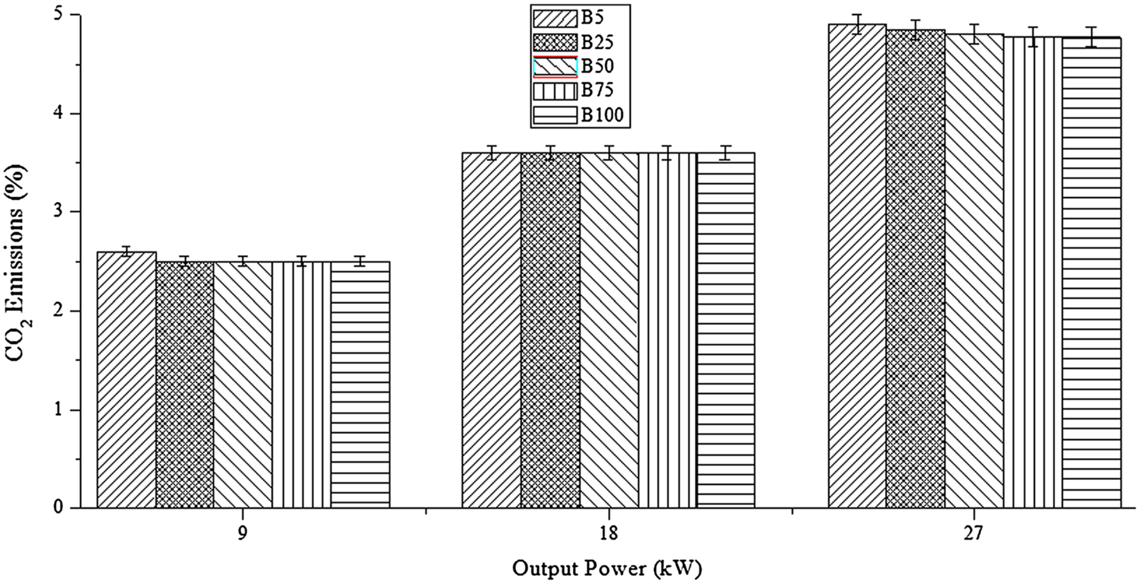

Fig. 8 CO_2 emissions using different biodiesel blends for different load conditions

fuel consumption in these conditions. It is not possible to note any significant variation in CO_2 emissions with biodiesel content for low and medium loads. For high load, however, a slight reduction in CO_2 emissions for blends with higher biodiesel content can be noted. The measurements uncertainties make more accurate conclusions impossible for this case.

3.2.4 PM emissions

PM was collected only at high load (27 kW) since at lower loads the quantity of PM is too small for accurate measurement using the scale available. Figure 9 shows a reduction of PM emissions (down to 45%) when biodiesel content increases. As discussed in Lapuerta et al. [3], the use of biodiesel can lead to oxygen-rich areas in the cylinder during the combustion process. Also, biodiesel does not present sulfur in its composition, which is a soot precursor, and thereby biodiesel reduces the particulate matter formation.

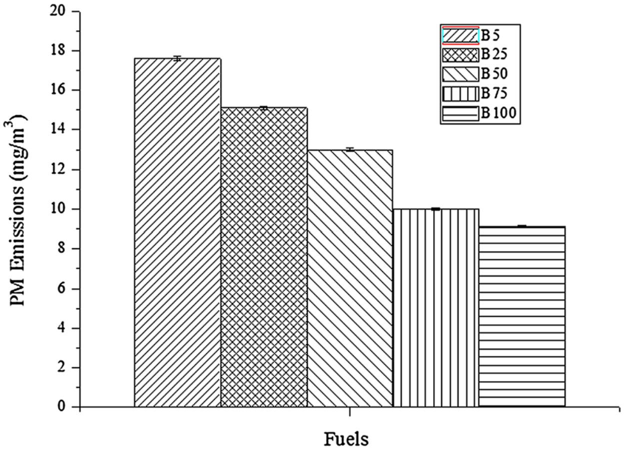

Fig. 9 PM emissions at 27 kW using different biodiesel blends

3.3 Fuel consumption

Figure 10 shows the results for the specific fuel consumption. There is a noticeable reduction in specific fuel consumption for all blends tested with load increasing. Also, an increase in the engine-specific fuel consumption with increasing of biodiesel content is observed. These results are expected due to the lower heating value of biodiesel.

3.4 Energy analysis

The values of energy flows crossing the control volume of the engine system are shown in Table 6. It is worth noting the increase in the engine efficiency with load. For 9 kW, it can be noted a slight reduction in the input energy as result of the increase in the quantity of biodiesel. The higher cetane number and the oxygen content of biodiesel can improve combustion, thus justifying these results. It is clear from Table 6 that approximately 33% of energy input is lost in cooling water at the load of 9 kW. This percentage decreases as the load increases reaching 20% at 27 kW. The exhaust gases temperature was almost the same for all blends and it increases as load increases. The exhausting gases' energy represents 28% of energy input and differently from cooling water; these gases are at high temperatures, e.g. 275 °C at 27 kW. Thus, it has significant capacity for power generation (high exergy) when the engine is operating at high loads. This capacity could be used to

Fig. 10 Specific fuel consumption for different blend at different loads

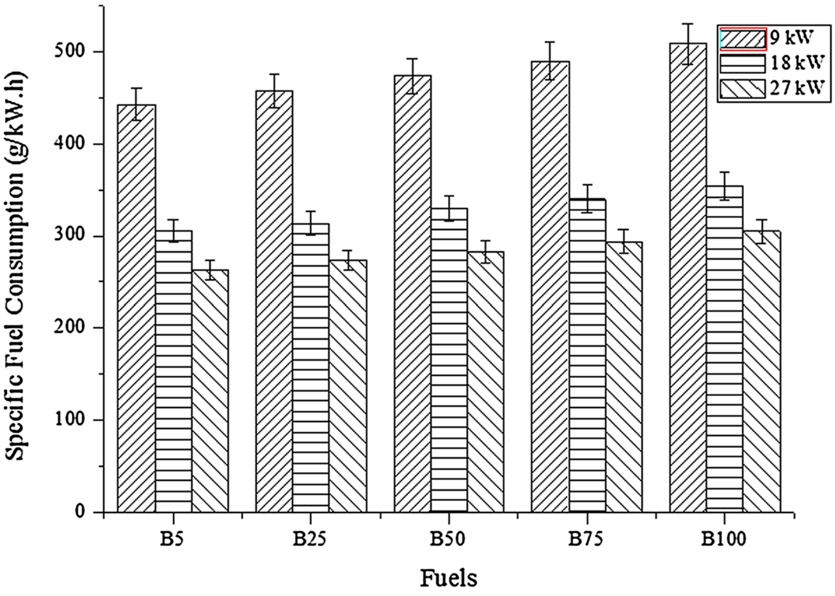

Table 6 Energy flow values through engine control volume

Output power	Blend	Inlet energy (kW)	Cooling water energy (kW)	Exhaust gas energy (kW)	Other losses (kW)	Energy efficiency (%)
9 kW	B5	48.0	16.4	13.3	9.3	18.8
	B25	47.8	16.1	13.5	9.2	18.8
	B50	47.7	16.0	13.6	9.1	18.9
	B75	47.6	16.0	13.6	9.0	18.9
	B100	47.5	15.9	13.7	8.9	18.9
18 kW	B5	65.8	16.8	18.7	12.3	27.4
	B25	65.8	16.9	18.6	12.3	27.4
	B50	65.7	16.8	18.7	12.2	27.4
	B75	65.8	16.9	18.7	12.2	27.4
	B100	65.8	16.3	18.8	12.3	27.4
27 kW	B5	85.1	17.3	24.2	16.6	31.7
	B25	85.3	17.3	24.1	16.9	31.6
	B50	85.2	17.3	24.1	16.8	31.7
	B75	85.2	17.2	24.1	16.8	31.7
	B100	85.1	17.3	24.0	16.8	31.7

drive a turbo-compressor, for heating purposes or even for electricity production by using cycles specially designed to deal with low-grade energy sources such as organic Rankine cycles and Kalina cycles.

The larger content of CO in the exhaust gases resulted in a slight increase of exhaust gas energy for biodiesel richer blends. This trend can be specially noted at lower loads.

3.5 Additional remarks

By summarizing the main results, it is possible to indicate that with increase of biodiesel content in the mixture:

- The temperature of exhausting gases decreased as in Hazar [25] and Ozturk [26];
- The concentration of NOx increased as in Nabi et al. [13] and Hoekman and Robbins [27];
- The content of CO increased in agreement with Xue et al. [5] and Hoekman and Robbins [27];
- PM emission decreased in agreement with Lapuerta et al. [3].

These tendencies were observed for the 3 loads evaluated with few exceptions (NOx with B50 at 9 kW and CO with B5 at 18 and 27 kW) that may be caused by measurements errors.

4 Conclusions

The use of biodiesel can be a valuable alternative to reduce conventional diesel consumption in Diesel engines. Characteristics of biodegradability, low toxicity and renewability make it an important source of energy not only for the Brazilian energy mix (characterized by high use of road transport fuels), but also for the global energy mix. This paper presented the exhaust emissions and energy analysis of a diesel engine coupled to an electric generator using several diesel/biodiesel blends and compared the results to those from a blend composed of 5% of biodiesel that is commercially supplied in the Brazilian market. An increase in biodiesel content from 5% to 100% generated an increase of 20% in CO emissions for the lowest load tested (9 kW). NOx emissions were increased up to 17% when pure biodiesel was used at 27 kW. This is usually explained by the increase in the oxygen content in the fuel which leads to higher temperatures in the combustion chamber and also increases NO formation rate. Also, the use of biodiesel generates a slight advanced injection in Diesel engines equipped with mechanical injection due the higher bulk modulus of biodiesel, which also results in temperature increase. An in-house developed system was used for PM measurements. Its measurements showed that the use of pure biodiesel resulted in a reduction of 45% in PM emission at the highest load tested (27 kW). The energy analysis revealed no appreciable variation in engine efficiency with the addition of biodiesel in the mixture. An increase in specific fuel consumption was observed as result of the reduction in the mixture LHV caused by the addition of biodiesel. It may increase fuel transportation costs for stationary engines and reduce the vehicle autonomy for vehicle engines.

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