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Research Paper

Performance and emission evaluations in a power generator fuelled with Brazilian diesel and additions of waste frying oil biodiesel

Anderson Antunes de Paulo, Ronaldo Silvestre da Costa, Sérgio Barbosa Rahde, Felipe Dalla Vecchia, Marcus Seferin, Carlos Alexandre dos Santos *

Pontifícia Universidade Católica do Rio Grande do Sul – PUCRS, Av. Ipiranga, 6681, Porto Alegre, Rio Grande do Sul 90619-900, Brazil

HIGHLIGHTS

- Brazilian diesel with additions of waste frying oil biodiesel was evaluated.
- Electric diesel power generator fuelled by diesel–biodiesel blends was studied.
- In the fuel consumption, the smallest value was observed to B20.
- In the generated power, the best performance was achieved by B5 and B20.
- In the flue gas emissions, a decrease of NO_2, SO_2 and C_xH_y was observed.

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ABSTRACT

Performance and emission evaluations in a diesel power generator fuelled with Brazilian commercial diesel (petroleum diesel with 5% biodiesel), pure waste frying oil-based biodiesel (B100), and additions in order to obtain 20%, 30%, 50%, 75% biodiesel blends were performed. Biodiesel was produced by two-step alkaline catalyzed transesterification. The pure biodiesel was characterized considering methyl ester content, density and flash point. Blends were analyzed to quantify biodiesel added in petroleum diesel. Electrical performance of the engine-generator group (two-cylinder, 13 kVA) was determined using a resistive load bank, monitoring total power and individual phase power. During the tests, the engine was instrumented using a gas analyzer in the exhaust system. A precision gravimetric balance was used to determine fuel consumption. Best power performances was achieved by B5 and B30, whereas B20 showed the higher thermal efficiency and the lowest fuel consumption as well. Increasing concentrations of CO_2 and NO_x and decreasing concentrations of CO, NO_2, SO_2 and C_xH_y in the flue gases were observed as the amount of methyl ester added to fossil diesel was raised from B5 to B100.

1. Introduction

The increasing energy demand due to population growth and life style change during the last decades has triggered environmental preoccupation related to climate changes as consequences of greenhouse gases (GHC) emissions. The need for replacing fossil diesel fuel for renewable fuels or energy sources, such as biomass derived fuels, hydro, geothermal, solar and wind is the aim of several works [1–3].

Biodiesel offers a number of technical and environmental benefits when compared to conventional fossil fuels, making it attractive as an alternative fuel for the transport sector and power generation [4–14]. The main benefits included in the economic impacts are sustainability, fuel diversity, manufacturing jobs increase, development of new technologies, and international competitiveness. Regarding environmental impacts, biodiesel tends to be lesser GHC emission intensive than fossil diesel fuels when the whole life cycle of the fuels are considered. Besides that, biodiesel biodegradability, lower sulfur and aromatic emissions, and less toxicity are often referred. Finally, in the energy impacts, the benefits are supply reliability, higher flash point, fossil fuels reduction and renewability [15]. Currently, green energy has been used as an alternative term for energy from renewable sources, being the green power the electricity supplied from these renewable sources [1].

In the transport sector, several works have been reported considering either light vehicles like typical passenger cars [4–7], or heavy vehicles, such as buses and trucks [8]. For all mentioned studies, the operation of diesel engines fuelled with biodiesel blends generally emitted lower carbon monoxide (CO), sulfur dioxide (SO_2) and particulate matter (PM) levels when compared to conventional diesel, but distinct carbon dioxide (CO_2) and nitric oxides (NO_x) emissions pattern were observed.

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* Corresponding author. Tel.: +55 51 3353 4058; fax: + 55 51 3320 3500.
E-mail address: carlos.santos@pucrs.br (C.A. dos Santos).

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For energy and power generator sector, literature presents results regarding to boilers and generators fuelled with biodiesel blends. The study presented by Ghorbani and collaborators [9] showed a comparison of combustion efficiency and flue gas emissions of B5, B10, B20, B50, B80 and B100 blends to conventional diesel fuel over wide input air flows at two energy levels in an experimental boiler. They concluded that diesel efficiency was higher than biodiesel efficiency at higher energy, and biodiesel blends were more efficient than diesel at lower energy. Concerning gas emissions, biodiesel blends emitted less pollutant than diesel, except for NO_x.

Regarding to generators, there are works investigating the nature of vegetable oil feedstocks for biodiesel production, different engines, as well as different engine-generator groups and their influence on the overall generator performances and emission patterns. Some works analyzed heating and blending of biodiesel to decrease fuel viscosity in order to eliminate various operational difficulties [11–13]. Others works have investigated the use of EGR (exhaust gas recirculation) to reduce NO_x emissions, as well as smoke, due to low flame temperature in the combustion chamber [14]. In all studies, results showed that biodiesel could be used as an alternative fuel to run diesel engines with no modifications.

Brazil has developed a government program (National Program for Production and Use of the Biodiesel – PNPB) that incentives biodiesel addition to fossil diesel, where in 2010, it was established a content of 5% biodiesel to be added in the commercial diesel. The preferential oil and fat sources for the Brazilian biodiesel production are soybean, animal fats and cotton, since the supply chain for this products is well structured. Although medium or large biodiesel plants are responsible for this biofuel production, small plants that could employ alternative raw materials like used cooking oil are now emerging as fuel sources for power generation for structures that presents low energy requirements. Despite the amount of available studies focusing on diesel power generator fuelled with biodiesel–diesel blends, the effect of addition of waste frying oil-based biodiesel to Brazilian commercial diesel, containing 5% biodiesel, has not been reported. The objective of the present work is to evaluate the best diesel–biodiesel blend in an engine-generator group operating with different fuels. The influence of additions of 20%, 30%, 50%, 75% of waste frying oil-based biodiesel to commercial diesel (fossil diesel with 5% soybean biodiesel) was performed. Electrical and mechanical performances and exhaust emissions were analyzed.

2. Experimental procedure

2.1. Engine-generator group

An engine-generator group, Ruggerini 191 model, nominal power 13 kVA, was adapted for monitoring exhaust emissions (flue gas composition and temperature) and electrical performance (effective power) using a resistive load bank, as shown in Fig. 1. The fuel consumption was determined by the weight loss of a 20 liters fuel tank coupled with a metallic support positioned over a precision gravimetric balance with 1 g resolution.

Table 1
Engine specifications [16].

Ruggerini 191 – Lombardini Srl	
Engine type	2 Cylinders, air-cooled
Fuel injection system	Indirect injection
Maximum rated power (kW@3600 rpm)	13
Maximum rated torque (N.m@2400)	40.5
Bore/stroke (mm)	85 / 75
Displacement volume (cm^3)	851
Compression rate	19:1

Engine technical specifications are given in Table 1, and it is commonly used for small-scale power generation. The engine operated at constant rotation of 3600 rpm. In all cases, engine was fully warmed up for 15 minutes to purge any remaining fuel from the engine fueling system.

The generator electrical performance was obtained using three-phase resistive bench as electrical load. The applied electrical load was approximately 85% of the generator maximum power (220V – 16 A – 11,000 W). Electrical current and voltage were monitored to determine the total power and the effective power demanded by each phase.

To measure the electrical consumption (power, current and voltage), a digital device was installed in the input of the resistive load bank. This digital device has a frequency of 1 Hz and functions with current transformers (TCs) and potential transformers (TPs), analyzing global parameters and parameters separated by phases. The power factor in the calculations was considered 1, meaning that each 1 kVA corresponds to 1 kW.

The ambient conditions were monitored by a thermometer and a barometer. Before each test, engine was operated during 5 minutes for stabilization, and results were collected after that. To determine fuel consumption, volume values were calculated by conversion of mass values obtained in the tests using the specific mass for each blend fuel.

During tests, engine was instrumented using a gas analyzer (O_2, CO, CO_2, NO, NO_2, NO_x, SO_2, C_xH_y) and a thermocouple installed in the exhaust system. Exhaust gas analyzer specifications are presented in Table 2. For CO_2 emission measurement, the basic principle is non-diffractive infrared radiation (NDIR), and for O_2, CO, NO, NO_2, SO_2 and C_xH_y, it is electrochemical method. A test was performed

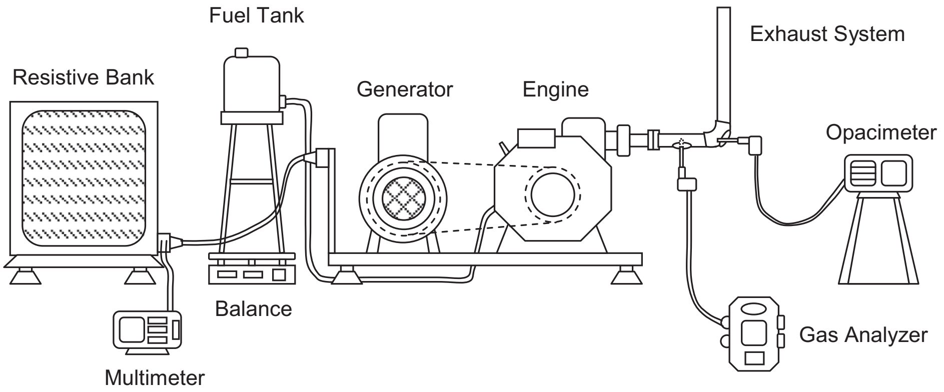


Fig. 1. Schematic diagram of experimental apparatus.

Table 2
Specifications of the gas analyzer [17].

TESTO XL 350	Detection limit	Response time (s)	Resolution	Accuracy
O_2	0.1%	<20	0.01%	<0.2% m.v.
CO	1 ppm	<40	1 ppm	<5% m.v.
CO_2	0.02%	<10	0.01%	<1.5% m.v.
NO	1.8 ppm	<30	1 ppm	<10% m.v.
NO_2	0.5 ppm	<40	0.1 ppm	<2% m.v.
SO_2	0.5 ppm	<30	1 ppm	<5% m.v.
C_xH_y	100 ppm	<35	10 ppm	<2% m.v.

m.v., measured value.

on engine disconnected to the generator, and these values were taken as reference for the pollutant emissions.

2.2. Biodiesel characterization

The fuels under study were Brazilian commercial diesel (fossil diesel with 5% soybean biodiesel – B5) and its blend with waste frying oil-based biodiesel achieving volumetric concentrations of 20% (B20), 30% (B30), 50% (B50), 75% (B75), as well as pure biodiesel (B100). Biodiesel was produced by two-step transesterification process [18–20] with methanol and sodium hydroxide, purification by water, using a 380 liters capacity pilot plant. After production, the biodiesel ester content [21], density [22] and flash point [23] were evaluated before and after its addition to B5. Before tests, blends were analyzed by infrared spectrometry to quantify the proportion of biodiesel in fossil diesel [24].

a) Methyl ester content by infrared spectrometry –the following diesel–biodiesel blends were analyzed: B5 (commercial-Shell), B20; B30, B50; B75 and B100. Analyses were performed on an InfraSpec^{TM} VFA-IR Spectrometer, model EB, Wilks Enterprise Inc [25]. The InfraSpec operates accordingly to ASTM D7371-12 standard [24].

Table 3
Results of diesel/biodiesel contents in the different blends.

Sample	Average % (v/v)	Standard deviation (v/v)
B5 (commercial)	4.50	0.10
B20	17.80	0.00
B30	28.83	0.06
B50	48.63	0.06
B75	73.30	0.10
B100 (pure biodiesel)	96.60	0.17

b) Density – analyses were performed on a picnometer calibrated with water at 17.1 °C using an analytic balance, temperature at 16.8 °C and relative humidity of 54% accordingly to EN ISO 6883:2014 standard [22].
c) Flash point – analyses were performed on a HFP 339 – Pensky Martens analyzer [26]. Analyses were performed using 75 mL for each fuel, 120 °C as reference flash point, and 120 °C ± 20 °C as ignition point. Due to the unknown of flash point for each fuel, it was used as the pre-test function with an ignition test for each 2 °C.

3. Results and discussion

3.1. Biodiesel characterization

Results about methyl ester content on the blends determined by infrared spectroscopy are presented in Table 3. As can be observed, there is a small divergence between calculated contents and obtained values, with maximum difference around 10%. Analyses were performed three times, and it showed average of these results as well as standard deviation.

Densities are shown in Fig. 2a. For commercial diesel (fossil diesel with 5% biodiesel – B5), it was determined to have a density of 843.3 kg/m^3, and for pure biodiesel (B100), a maximum value of 885.8 kg/m^3. With these values of densities in relation with biodiesel blends (Bx), it was possible to build a trend curve according to equation:

$$\text{Density} = 0.4429 \cdot (\text{Bx}) + 840.97 \quad [\text{kg/m}^3] \tag{1}$$

Flash point values are also presented in Fig. 2a, where for B5 the lowest value (38 °C) was observed and the highest value (144 °C) for B100. Using the same methodology applied to density, it was possible to obtain two tendency lines, given by:

$$\text{Flash Point} = 0.4137 \cdot (\text{Bx}) + 36.487 \quad (\text{B5-B75}) \quad [^\circ\text{C}] \tag{2}$$

$$\text{Flash Point} = 3.04 \cdot (\text{Bx}) - 160 \quad (\text{B75-B100}) \quad [^\circ\text{C}] \tag{3}$$

where Eq. (2) is valid for the range between B5 and B75, and Eq. (3) is valid for the range between B75 and B100.

Both results are showed in Fig. 2a. With these data, it is possible to estimate the higher heating value (HHV) using equations presented in literature [27] as a function of density (ρ):

$$\text{HHV} = -0.0259 \cdot \rho + 63.776 \quad [\text{MJ/kg}] \tag{4}$$

resulting in the calculated values as shown in Fig. 2b.

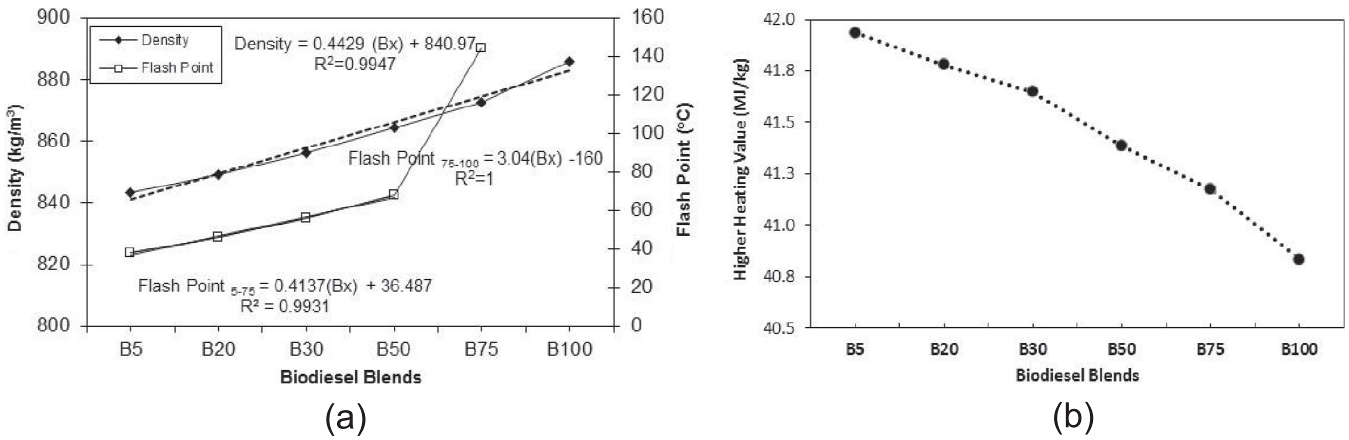


Fig. 2. (a) Densities and flash points for different diesel–biodiesel blends, and (b) higher heating value (HHV) as a function of density for different diesel–biodiesel blends.

Table 4
Biodiesel properties from this work *vs* literature.

Biodiesel	Density $[kg/m^3]$	Flash point [°C]	References
B100 – waste frying oil (this work)	885.8	144	–
B100 – waste frying oil	880–887	146–178	6, 20, 28
B100 – Soybean	882–885	163–178	6, 9, 27, 28
B100 – rapeseed	882	80	27
B100 – soybean 40% + rapeseed 60%	884	135	8
B100 – Palm	870–880	140–183	12, 27
B100 – coconut	858	118	12
B100 – Karanja	879–890	163–187	27, 29, 30
B100 – jatropha	864–917	163–238	10, 29

Table 4 presents a comparison between biodiesel properties obtained in this work and results presented in literature, including other vegetable sources. As can be observed, obtained results for density and flash point in this work are in agreement with those reported in literature.

Considering the higher heating value (HHV) as a function of density, it is observed that values decrease with increasing biodiesel content. These values agree with those presented by Habibullah et al. [12]. These values will be used to determine the brake thermal efficiency (BTE), as given:

$$BTE = (3600/(BSFC \cdot HHV)) \cdot 100\% \tag{5}$$

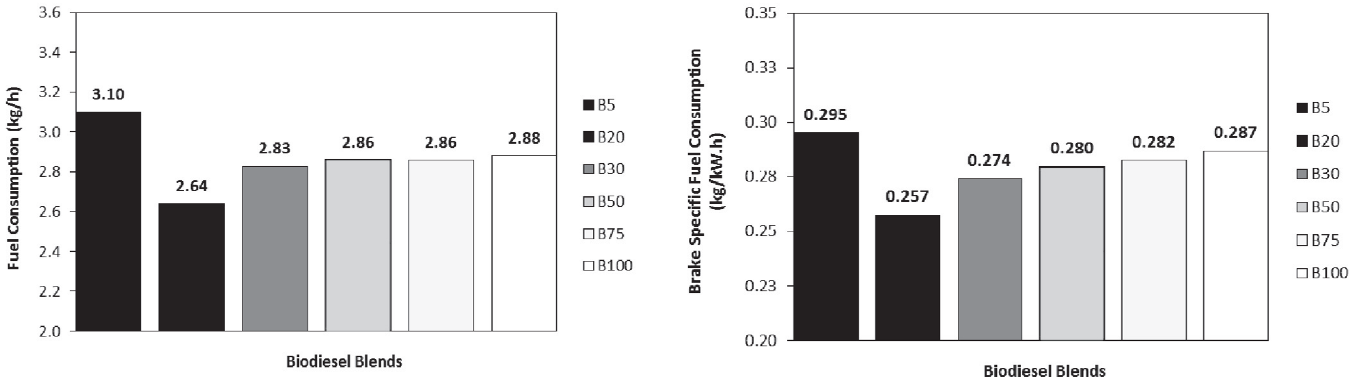
where BSFC is the brake specific fuel consumption [kg/kW.h].

3.2. Fuel consumption and performances

Analyzing the average fuel consumption during all tests (Fig. 3a), the highest fuel consumption was observed for B5, decreasing to B100 (7.09%), B75 and B50 (7.74%), B30 (8.70%), and B20 (14.83%). When comparing B20 to B30 and B50, an increase was observed in the fuel consumption about 6.71% and 7.69%, respectively. Considering B75 and B100, the increase was about 0.69%. These results are averages of three repetitions for each fuel, and difference between values for each test was less than 5%. Similar behavior was found by Mujahid et al. [11] using a generator (27.5 kVA) that runs at 1500 rpm at various loads. They compared diesel to pure biodiesels (B100) produced from fresh oil and waste vegetable oil. The diesel fuel consumption was higher than pure biodiesels as a function of fuel calorific value reduction. However, Karavalakis et al. [6] have reported that fuel consumption increases with biodiesel content (10%, 20% and 30%) produced from soybean oil, palm and coconut oils, and rapeseed and waste cooking oils due to lower energy content in biodiesel blends when compared to diesel.

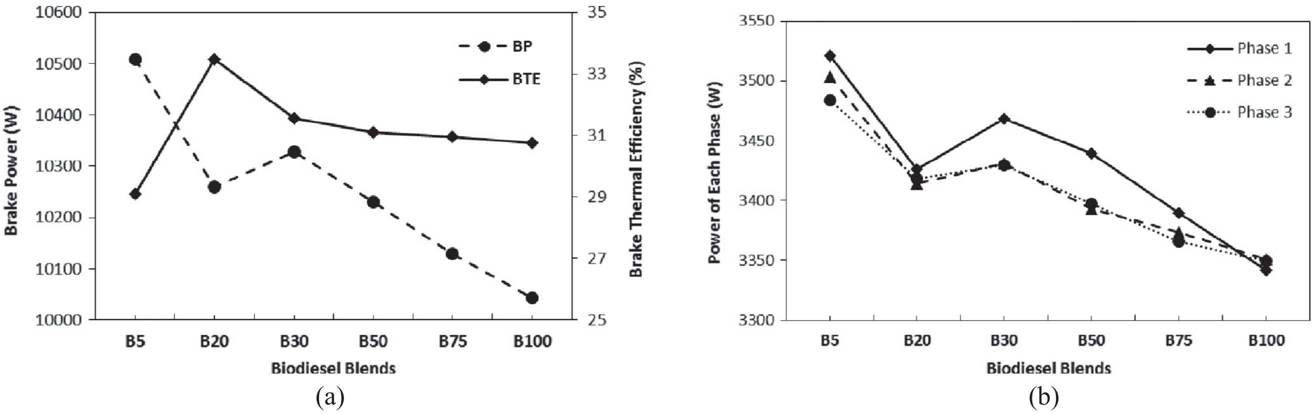
For the brake specific fuel consumption (BSFC), considering fuel consumption (kg/h)/brake power (kW), the highest value was observed for B5, followed by B100, B75, B50, B30 and B20 that showed the lowest value (Fig. 3b). When comparing only diesel to pure biodiesels, Mujahid et al. [11] observed BSFC values of 0.18 kg/kWh for waste vegetable oil biodiesel, 0.19 kg/kWh for fresh oil biodiesel and 0.20 kg/kWh for diesel at 100% rated load. Less fuel was required for same power output when biodiesel was used in place of diesel due to better combustion. When comparing only rice bran oil biodiesel blends (B10, B20 and B50) in a generator (9kW) with EGR system, Agarwal et al. [14] have found that BSFC increases with increasing of biodiesel content on the diesel. They attributed this behavior due to lower calorific value of biodiesel blends when compared to diesel, similar to results shown in Fig. 2b. Exception was found to B20 that presented the lowest BSFC due to the highest thermal efficiency for this blend, mainly at lower loads. Another work also concluded that B20 presents the lowest BSFC when comparing biodiesel blends (B20 and B50) from soybean oil, palm oil and waste frying oil using a generator (80kW) and variations in loads [28]. In the study of Habibullah et al. [12] with a generator (10kW) at full load and various speed using different 30% diesel–biodiesel blends (30% palm biodiesel + diesel, 30% coconut biodiesel + diesel, 15% palm + 15% coconut + diesel), the lowest BSFC was found by 15%–15% biodiesel blend, followed by 30% palm biodiesel and 30% coconut biodiesel. Results about BSFC have shown that biodiesel blends presented higher BSFC than diesel, behavior attributed to lower heating value and high viscosity of biodiesel blends.

Electrical performance analyses were conducted for two conditions (Fig. 4). The first was performed considering brake power (BP) as a function of different biodiesel blends, and it is possible to observe that brake power decreases with increasing biodiesel content from B5 to B100 (Fig. 4a). An exceptional behavior was observed for B20, which presented lower BP when compared to B30. However, this difference was lower than 5%. The lower energy content per unit volume of biodiesel when compared to diesel, as well as combustion conditions affect by higher viscosity, higher density and poorer atomization, can contribute for reducing brake power, as reported by Habibullah et al. [12]. However, using biodiesel produced from fresh oil and wasted vegetable oil for electricity generation, Mujahid et al. [11] observed high overall efficiency for biodiesels than diesel due to complete combustion and reduction in fuel calorific value. The disagreement of the results obtained in the present work with those reported by Mujahid et al. [11] may be due to engine type and operating conditions. A review about engine performance characteristics was reported by Ashraful et al. [29] using different



(a) (b)

Fig. 3. (a) Average fuel consumption, and (b) brake-specific fuel consumption.



(a) (b)

Fig. 4. (a) Brake power and brake thermal efficiency, and (b) power per individual phase.

vegetable oils to produce biodiesel. In this review, presented results show both increasing and decreasing of power using biodiesel and their blends, reinforcing that variation can occur depending on raw materials, engine types and combustion conditions.

For the brake thermal efficiency (BTE), it increases from B5 to B20, which presented the highest value, and decreases from B20 to B100 (Fig. 4a). However, these values remain higher than B5, showing the lowest value. Some works have reported that biodiesel thermal efficiency is higher than diesel at higher load and lower blend ratio [11,29], while others have reported that biodiesel thermal efficiency is slightly lower than diesel and reduces with increasing of biodiesel [12,14]. A possible reason for reducing in BTE is attributed to higher viscosity and density of biodiesel resulting in poor atomization into the combustion chamber. However, engine model, operating settings and biodiesel can also play an important role on BTE and lead to diverging results. It is important to note that in the present work, the engine runs in normal condition set up to diesel, with no any adjusting in operational parameters as a function of biodiesel fuel. This could be the reason for difference with results reported in literature.

For the second analysis, when analyzing the individual phases (Fig. 4b), a small difference was observed among them, mainly between Phase 1 with Phase 2 and 3. Phase 1 shows the highest values, and Phase 2 and Phase 3 show lower and similar values. All presented results were obtained as average of three measurements in each condition.

3.3. *Exhaust gas emissions*

Fig. 5 shows examples of results for exhaust gas emissions with constant load during 1250 seconds in tests performed on B5 and B100. As can be observed for B5, O_2 and CO_2 levels were kept almost constant in 12% and 6%, while CO presented variation between 1300 ppm and 2450 ppm, and C_xH_y between 750 ppm and 1200 ppm. For NO_x, NO and NO_2, values of 350 ppm, 320 ppm and 30 ppm, respectively, were observed, and about 8 ppm for SO_2. The combustion of B100 presented similar behavior for O_2 emission, with slightly higher values for CO_2, NO_x and NO and lower values for CO, NO_2, SO_2, and C_xH_y than B5.

Average exhaust gas temperatures are shown in Fig. 6. As can be observed, temperature of the engine during tests increased from 440 °C to 480 °C as the biodiesel amount in the blends was raised from B5 to B100. For reference condition (B5 with no load), the average temperature of the exhaust gas was about 377 °C.

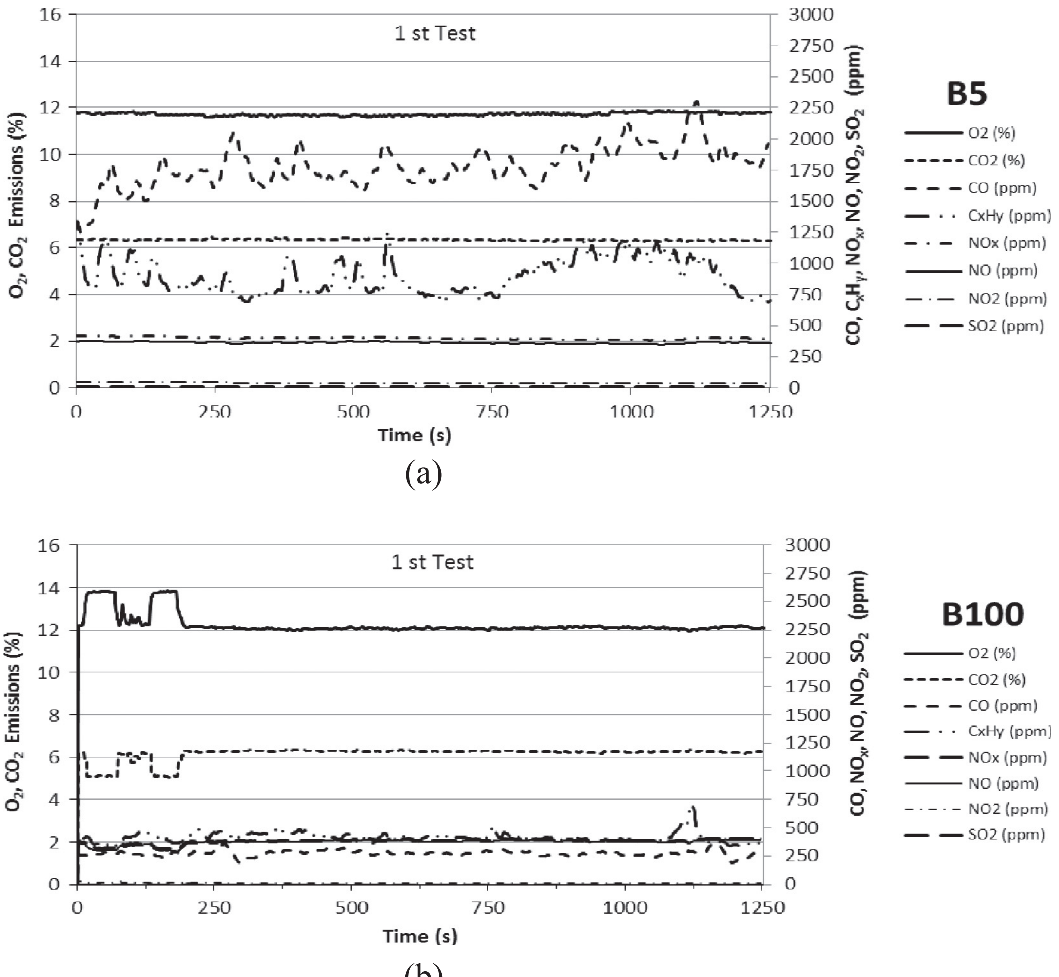
Fig. 7 shows average values for each gas (CO_2, CO, NO_x, NO, NO_2, SO_2 and C_xH_y) obtained during all tests for each fuel. It is important to note that average values for each gas were obtained after three measurements for each fuel. These data allow analyzing emission behaviors immediately after engine start and during the steady-state regime until test end. In the case of CO_2 (Fig. 7a), an increase was observed from B5 to B100, where B75 showed the highest value when compared to others fuels. Despite higher values for B75, the difference is lesser than 5% when compared to B100, and the tendency is to approach to others biodiesel blends during tests. For CO (Fig. 7b), the lowest values were observed for B100, B75 and B50, and the highest for B5, with B20 and B30, showing an intermediate and similar behavior. The highest variation during test was observed to B5, while others fuels presented behaviors almost constant. For NO_x and NO (Fig. 7c and d), values decreased from B5 to B50, and then increased from B75 to B100, where B100 showed the highest value. A higher variation is observed during test mainly for lower blend ratio (from B5 to B50), with a tendency to decrease along time. For NO_2 (Fig. 7e), average values showed a decrease from B5 to B100 in all cases, mainly comparing B75 to B100, as well as decrease during test. SO_2 and C_xH_y emissions (Fig. 7f and g) decreased from B5 to B100.

For CO_2, results agree with those found by Valente et al. [13] and Karavalakis et al. [6] that reported concentration of CO_2 increases with high biodiesel content, mainly at low loads, independent of raw material used to produce biodiesel.

In the case of CO, literature describes that CO emissions for biodiesel are smaller to fossil diesel, mainly at lower loads [6,12,14], due to higher oxygen content and lower carbon content in biodiesel, leading a better combustion. At higher loads, a rich air–fuel mixture is burned into the combustion chamber, and due to lack of oxygen, more CO can be produced [12,14]. Few woks have reported that CO increases with biodiesel content, and this behavior is attributed to poor fuel atomization due to high viscosity and density of biodiesel [7,13,28].

For NO_x and NO, a decrease was observed between B5 and B50, and an increase for higher biodiesel content between B75 and B100. A decrease for NO_2 was observed with the increase of biodiesel blends. According studies, NO_x is a mixture of gases with approximately 95% NO, formed by combustion at elevated temperatures [3]. Engine heating during tests that increases from 440 °C to 480 °C with the increase of biodiesel blends (Fig. 6) can explain the higher amount of NO when compared to NO_2, as well as the higher loads can explain the decreasing of NOx [4] for lower biodiesel blends. As the variation of NO_x, NO and NO_2 depends on a series of factors, as reported in literature [4,9,13,14], a more detailed study is necessary to explain this behavior, mainly that related to physical–chemical properties of the biodiesel.

As the diesel hydrocarbons are substituted for the biodiesel methyl esters, the C_xH_y emission tends to be lowered. Some works



(a)

(b)

Fig. 5. Exhaust gas emissions: (a) B5 and (b) B100.

reported that this reduction is probably due to the fact that adding biodiesel to fossil diesel decreases the oxygen amount required for combustion [4,6] as a function of the higher oxygen content in the biodiesel, or due to high cetane number of biodiesel [12]. Research also shows that C_xH_y emissions tend to decrease at higher loads [7,13], and increase with increasing of biodiesel content when the air–fuel mixture is richer, promoting an incomplete combustion [14].

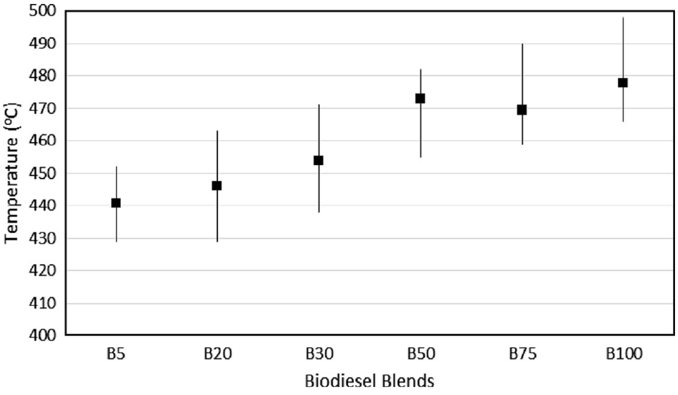
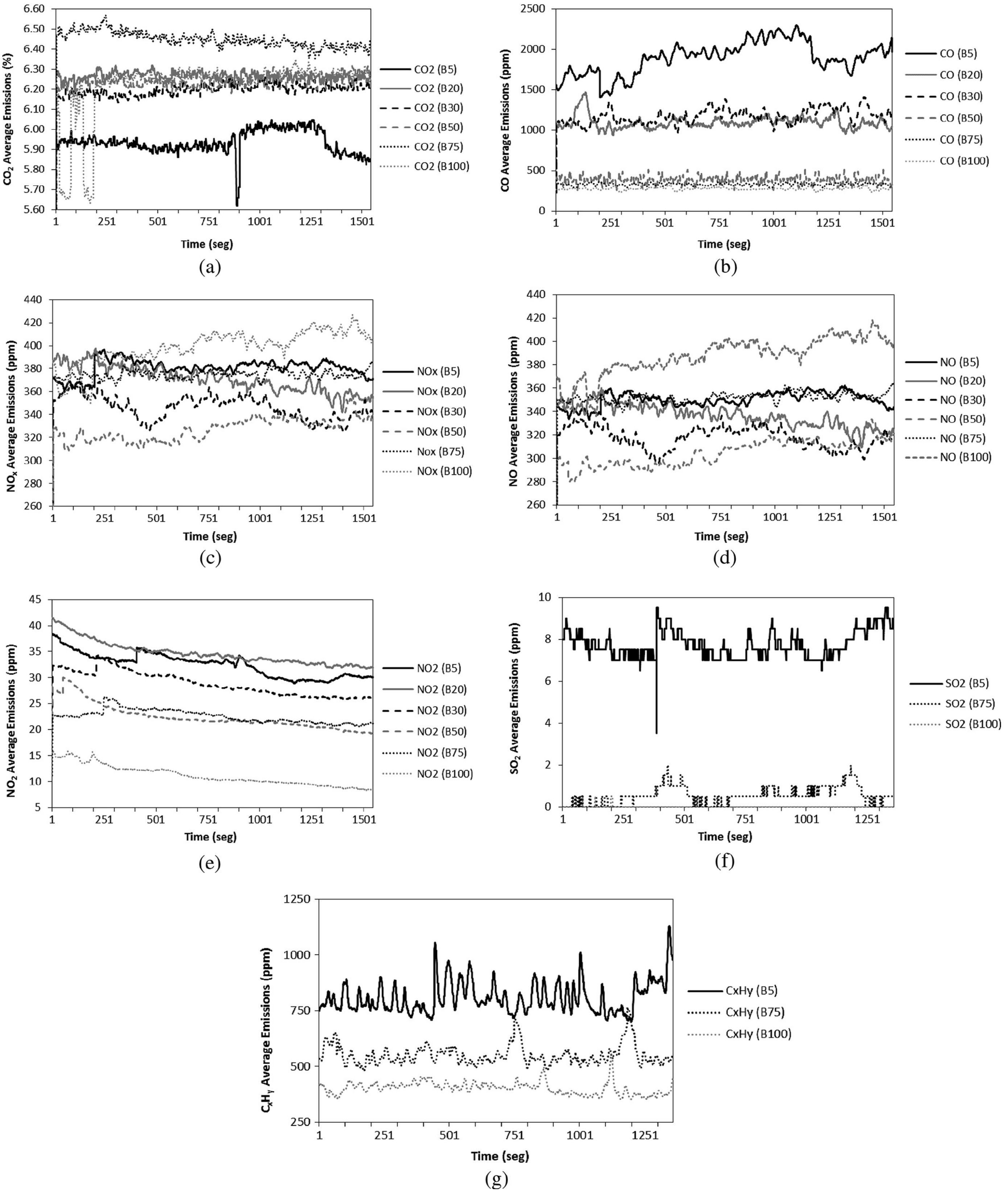


Fig. 6. Exhaust gas temperatures for different biodiesel blends.

Average gas emissions were plotted against biodiesel content in Fig. 8 (average values, and bars showing minimum and maximum values) and Fig. 9 (relative global analysis). The average values observed for B5 with no load were taken as reference: O_2 – 15.91%, CO_2 – 3.74%, NO_x – 86.95 ppm, CO – 1529 ppm, and SO_2 – 0.01 ppm.

A decrease of 73.0% for CO, 2.5% for NO_x, 4.1% for NO, 43% for SO_2 and 4.1% for C_xH_y, and an increase of 6.3% for NO_2 and 5.2% for CO_2 were observed when comparing B5 to B20. Comparing B5 to B50, CO_2 was the only flue gas constituent that has its concentration increased by 4.8%, while a decreasing of 392.0%, 16.5%, 15.1%, 44.8%, 329% and 35% for CO, NO_x, NO, NO_2, SO_2 and C_xH_y concentration is observed, respectively. When comparing B5 to B75, a decrease of 477.8% for CO, 1.6% for NO_x, 44% for NO_2, 980.8% for SO_2 and 46.6% for C_xH_y, and an increase of 0.5% and 7.9% for NO and CO_2 were observed, respectively. Regarding B5 and B100, an increase of 4.5%, 9.6% and 4.5% for NO_x, NO and CO_2, respectively, and a decrease of 590.2% for CO, 191.5% for NO_2 were observed, more than 2000% for SO_2 and 101.1% for C_xH_y. Comparing B20 to B30, it was possible to observe a decrease of 7.2%, 6.0%, 20.1%, 1.1%, 87.5% and 25.1% for NO_x, NO, NO_2, CO_2, SO_2 and C_xH_y, and an increase of 6.6% for CO. When comparing B30 to B50, a decrease of 204.5%, 6.0%, 4.3%, 28.7%, 60% and 3.7% for CO, NO_x, NO, NO_2, SO_2 and C_xH_y was observed, and similar values for CO_2. Comparing B50 to B75, an increase of 12.8% for NO_x, 13.5% for NO, 0.6% for NO_2 and 3.3% for CO_2, and a decrease of 17.4%, 151.9% and 8.6% for CO, SO_2 and C_xH_y were observed, respectively. Finally, when comparing B75 to B100, a decrease



(a)

(b)

(c)

(d)

(e)

(f)

(g)

Fig. 7. Average exhaust gas emissions for different biodiesel blends: (a) CO_2, (b) CO, (c) NO_x, (d) NO, (e) NO_2, (f) SO_2, (g) C_xH_y.

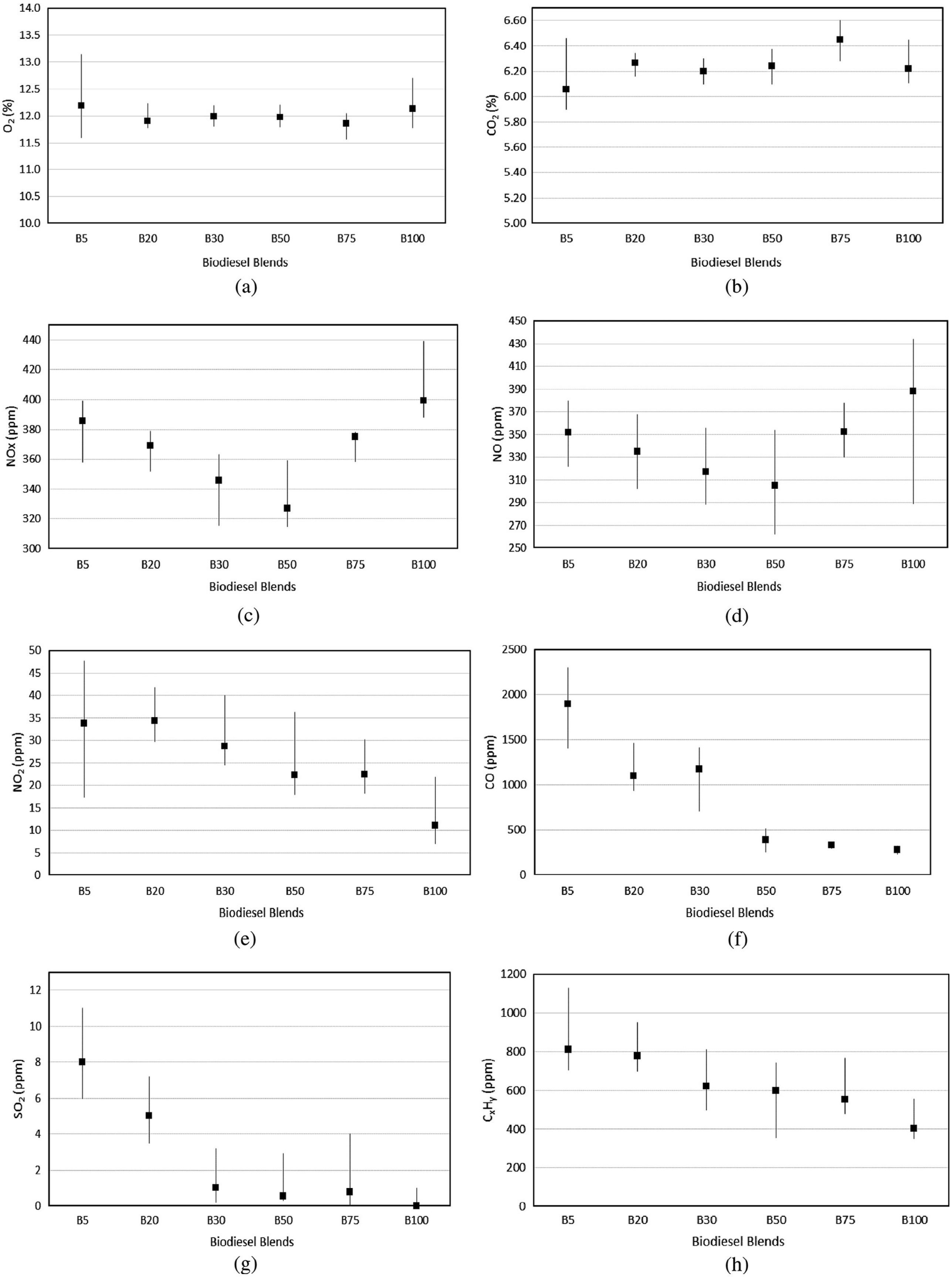
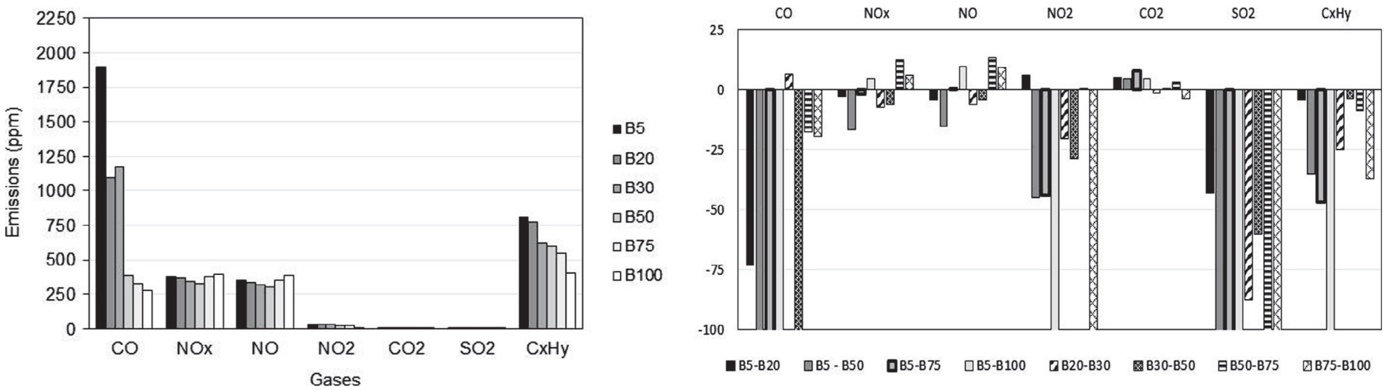


Fig. 8. Variation of the exhaust gas emissions: (a) O_2, (b) CO_2, (c) NO_x, (d) NO, (e) NO_2, (f) CO, (g) SO_2, (h) C_xH_y.



(a) (b)

Fig. 9. Analysis of the exhaust gas emissions: (a) average, (b) differences.

of 19.5% for CO, 101.3% for NO_2, 3.7% for CO_2, more than 2000% for SO_2 and 37.1% for C_xH_y, and an increase of 6.0% for NO_x and 9.1% for NO were observed.

4. Conclusions

According to the results, the following conclusions could be drawn:

- For the brake power (BP), the best performance was observed for the combustion of B5 (10.51 kW) and the worse for B100 (10.04 kW), with difference lesser than 5%;
- Increasing values for brake thermal efficiency (BTE) were observed for the fuel range from B5 to B20, with the highest value for B20 (33.48%) and lowest for B5 (29.10%). When the biodiesel amount in the blends was raised from B30 to B100, BTE has decreased;
- For the fuel consumption, the highest consumption was obtained for B5 (3.10 kg/h), and the lowest was obtained for B20 (2.64 kg/h), with a decrease about 14%. For higher biodiesel content blends, higher fuel consumption was observed as the methyl ester content was raised;
- For the brake specific fuel consumption (BSFC), the best performance was obtained to B20, followed by B30, B50, B75, B100 and B5;
- For the exhaust gas emission temperatures, an increase with the increase of biodiesel blends from 440 °C for B5 to 480 °C for B100 was observed;
- For pollutant emissions, CO_2, NO_x and NO emissions were found to be slightly increased with biodiesel blends, while CO, NO_2, SO_2 and C_xH_y showed opposite behavior;
- For this study, the best behavior considering fuel consumption, power and emissions was obtained for B20.

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