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Assessment of the use of oxygenated fuels on emissions and performance of a diesel engine ☆

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ABSTRACT

Requirements as torque, power, specific fuel consumption and emitted compounds are highly influenced by the chemical composition of the fuel being burned. Thus, the aim of this study was to assess the use of oxygenated fuels on emissions of NO_x, CO, HC, CO_2 and particle number and size distribution (11.5 < Da < 365.2 nm). In this paper a cycle diesel engine coupled to a dynamometer bench was used, where three types of fuels were employed, B5 (diesel with 5% of biodiesel); B5E6 (ternary composition containing 89% diesel, 5% of biodiesel and 6% of ethanol); and B100 (100% of biodiesel). The performance of a diesel engine was also evaluated to see the impact of the oxygenated fuels in this kind of engine. The use of ethanol with high latent heat of vaporization and low cetane number added to the binary blend (B5) shown an increase in the HC emissions and a reduction in NO_x emissions when compared to B5. The use of pure biodiesel (B100) with high oxygen content showed a reduction in the HC emissions, but presented the highest emissions for both NO_x and particle number of smaller diameter among the studied fuels. The use of more oxygenated fuels reduced the power output and increased the fuel consumption, but the exergy analysis showed that the energy efficiency of these fuels could be considered similar to the B5 fuel.

1. Introduction

Diesel engines, due to its excellent drivability and fuel economy are the most common internal combustion engines. These basic machines are widely used in fixed and mobile systems, especially where there is a need of high power, improved fuel efficiency and high torque at low revs [1,2]. Its use is becoming more common and will become more intense with greater economic development [3].

These engines generate fewer emissions of most of the regulated compounds, carbon monoxide (CO), unburned hydrocarbons (HC) and carbon dioxide (CO_2), for example, they appear almost always with inferior values found in spark ignition engines [4]. However, the emissions from diesel engines contain considerable levels of nitrogen oxides (NO_x) and particulate matter (PM), and among the fossil fuels, diesel is the one with the highest emission factors of these compounds when compared to other fuels [5].

In recent years the legislation that regulates the pollutant emissions has established increasingly lower limits, the technological evolution of vehicles manufactured afforded the care of these increasingly stringent limits. In this scenario, fuels from renewable resources gained enough prominence and emerged as alternatives to fossil fuels [6]. Several tests have been performed with biodiesel to ascertain the impacts on engine performance, fuel consumption and the emission of pollutants mainly in relation to diesel [7–20].

Researchers have evaluated the impact of the mixture of various oxygenates to diesel fuel. The oxygenate additives commonly investigated are alcohols [10,19,21] and methyl or ethyl esters (biodiesel) [9,10,15,22]. The mixture of these additives to the oil provides the necessary oxygen to form CO_2 instead of carbon-rich particles. This, in turn, may cause a reduction of particulate matter emissions [23].

Many studies are found in the literature on the issue of HC, NO_x, PM and CO emissions, generated by diesel engines. However, it is not so simple to compare these results, since different types of engines, fuels, fuel blends, and working conditions are used. Theses factors have

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significant influence on the emission of compounds and engine performance [24,25].

Martins et al. [12] evaluated the emission of PM from heavy-duty engines fueled by diesel and biodiesel blend. In this study, PM was characterized by impaction from the emission of heavy vehicles fueled with a mixture of diesel/biodiesel (B3 — 3% biodiesel and 97% diesel) in Londrina, Brazil. Among the evaluated material the dominant particles were fine and ultrafine. The amount of fine and ultrafine particles from diesel burning was increased when compared to the results of tests when biodiesel were used.

Diesel burning can be considered the main emitter of particulate matter when compared with both ethanol and gasoline burning. In general, one can say that the concentration of PM emitted and the amount of chemical compounds adsorbed in their surface depend on the operating parameters such as speed, load, type and age of the engine, and the fuel composition, temperature and relative humidity [30]. The use of more oxygenated fuels could be a parameter that will interfere also in both chemical composition and size distribution of these particles.

Biswas et al. [26] observed substantial emissions reductions in particulate mass (>90%) when using a heavy diesel vehicle operating with advanced emission control technologies. This reduction was not observed for the particle number concentrations at cruise conditions, with exceptions hybrid — CCRT® and EPF vehicles, which were efficient in controlling emissions both in mass and in number.

So far, respiratory tract deposition of inhaled particles has been extensively investigated using computational works [27–30] and indicated that the tracheobronchial and the alveolar deposition fractions of nanoparticles are smaller at intense activity than at rest, but extrathoracic deposition increases during intense activity. Authors suggested that both particulate mass and the number concentration measurements are necessary to assess health effects of diesel exhaust particles.

Therefore, the aim of this study was to assess the use of oxygenated fuels on emissions of NO_x, CO, HC, CO_2, and particle number and size distribution (11.5 < Da < 365.2 nm). The performance of a diesel engine also was evaluated to see the impact of the oxygenated fuels.

2. Experimental

2.1. Fuels and chemicals

Three kinds of fuel were used in this work: (i) pure soybean oil biodiesel (B100); (ii) binary blend of diesel with 5% of biodiesel (B5); and (iii) ternary blend with 89% of diesel, 5% of biodiesel and 6% of ethanol (B5E6). The pure soybean biodiesel employed in the tests were kindly donated by Petrobahia (Distribuidora de Petroleo da Bahia S.A.); ethanol 99.3% was purchased from Pro-Análise®; commercial B5 was purchased from Petrobras Fuel Station (Petrobras Distribuidora, Brazil), and ternary blend was prepared using both fuels B100 and B5. The specifications of the fuels are listed in Table 1. The cetane number determined by the CFR test (ASTM D-613) using secondary standards. The lubricating oil used for all tests was Lubrax CI-4 (15W-40) produced by Petrobras ®.

Table 1
Fuel specifications for B5, B100 and ethanol.

Characteristics	B5	B5E6	B100	Ethanol
Density (g mL^{-1}, 20 °C)	0.853	0.821	0.870	0.790
Viscosity (cSt, at ^{40}C)	4.12	3.40	4.20	1.18
Latent heat of vaporization ($kJ\cdot kg^{-1}$)	270	350	200	840
Cetane number	48	41	56	6
Lower calorific value ($kJ\cdot kg^{-1}$)	42,820	41,733	36,395	28,300

2.2. Evaluation of the emission and performance of the diesel engine

A diesel engine, Agrale, model N790, speed rate of 1800 rpm, 4 strokes, operating in a stationary mode and with 70% of loading, coupled to a steady-state hydraulic dynamometer (SCHENK), was used for the tests. The engine's main characteristics are listed in Table 2.

The regulated pollutants including NO_x, CO, HC, and CO_2 were measured online with a TELEGAN TEMPEST-100 exhaust gas analyzer. The sampling time was 15 min at each operating condition. The relative standard deviations of the analyzer are less than 3.5% for NO_x, 4.5% for CO, and 2% for CO_2.

The particle number and size distribution (11.5 < Da < 365.2 nm) were measured for 10 min, with ten replicates for each fuel (B100, B5 and B5B6). The samples were collected by Particle Counter (TSI model 3910) connected at Dilution tunnel with constant volume sampling (Fig. 1), using an air:exhaust rate of the 20:1. Flexible, conductive tubing (Part 3001940, TSI Inc., St. Paul, MN) was used for sampling to avoid particle losses due to electrostatic forces.

The brake specific fuel consumption (BSFC) of the fuel blends was evaluated using a gravimetric method. A vessel with each test fuel was placed on a precision balance during the tests. The difference in mass observed during each period indicated on the balance was used to determine the mass consumption for each fuel. Thus, BSFC was defined as the ratio between the total consumption of fuel and energy consumed at a time and evaluated in g/kW. It was obtained according to Eq. (1).

$$\mathrm{BSFC} = \frac{m_f}{\dot{W}_{vc}\,.\Delta t} \tag{1}$$

Where:

m_f is the mass of the total fuel consumed;
$\dot{W}_{vc}$ is the average of the instantaneous power, measured in kW;
Δt is the sampling time in hours.

The engine efficiency (EE) defined as the energy produced by the generator and the energy contained in the BSFC was determined according to Eq. (2).

$$\mathrm{EE}(\%) = \left(\frac{\dot{W}_{vc}}{m_f \cdot LHV_f}\right)\cdot 100 \tag{2}$$

Where:

m_f is the mass of the total fuel consumed;
$\dot{W}_{vc}$ is the average of the instantaneous power, measured in kW;
LHV_f is the lower calorific value of the fuel tested in kJ/kg.

The tests were performed at a temperature of $29 \pm 2\ ^\circ$C, while the humidity was kept constant at $58 \pm 2\%$. For each cycle, the engine was heated for 30 min. The lubricating oil was substituted for each fuel test.

Table 2
Main characteristics of the diesel engine.

Characteristics	Diesel engine
Model	N790
Number of cylinders	2 verticals
Swept volume (cm^3)	1272 cm^3
Compression ratio	20:1
Fuel g injection system	Direct
Potency NF (NBRISO 1585) (Cv kW^{-1} rpm^{-1})	19.8
Engine cooling system	Air

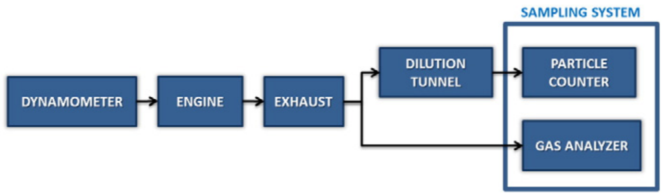

Fig. 1. Scheme of the sampling system for particles matter and gases.

3. Results and discussion

3.1. Evaluation of the emissions profile of fuel blends

Fig. 2(a) shows the results of CO_2 emissions measured in percentage on dry basis (v/v). The values obtained for CO_2 emissions from burning the fuels studied can be considered statistically equal. However, the emissions generated by biofuels during combustion in internal combustion engines can be considered "recyclables" due to the vegetable photosynthesis. The CO_2 is released into the atmosphere when the biofuel is burned and it is recycled by the growing plants, which are later processed into the fuel [31].

The results for emissions of HC are shown in Fig. 2(a). Burning B5E6 showed an increase of HC emissions. This fact may be associated with lower cetane number of the fuel compared to the others and consequently weak ignition and reducing the temperature of the combustion chamber. Thus, the addition of ethanol in the B5 fuel increases incomplete combustion favoring the formation of HC. This result is in agreement with the data obtained by other researchers Lei et al. [32] and Tsang et al. [33]. The use of B100 had lower HC emissions compared to other fuel mixtures. This is due to the fact that the B100 fuel presents high oxygen content and high cetane number, which best feature your ignition. The reduction of HC emissions with use of biodiesel fuel was also confirmed by Di et al. [34]. However Lin et al. [35] found no significant variation in the HC emissions with the increase content of biodiesel into to diesel fuel.

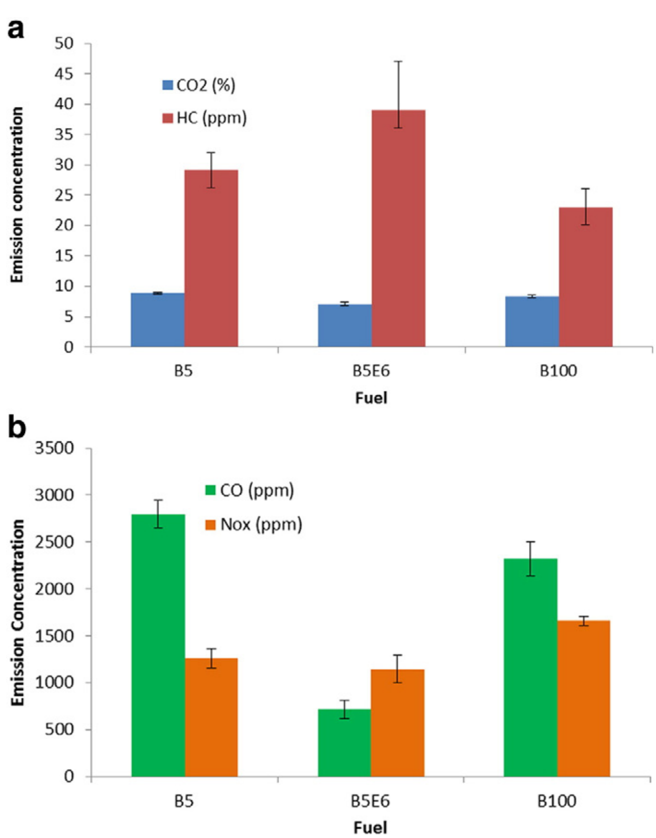

Fig. 2. (a) The CO_2 (%) and HC (ppm) emission concentration; and (b) CO (ppm) and NO_x (ppm) emission concentration for all fuel.

The results for emissions of NO_x and CO are shown in Fig. 2(b). The addition of ethanol (B5E6) caused a slight reduction of NO_x emissions. The NO_x formed in the combustion chamber by the heat released by the fuel and thus is the high latent heat of vaporization and low calorific ethanol contribute to the reduction of NO_x [36]. Many researchers reported significant benefits of using ethanol blend fuels in terms of NO_x reduction [37–39]. However, the low cetane number of ethanol and its high oxygen content favors the increase in emissions of nitrogen oxides. Factors such as the high latent heat of vaporization of ethanol and Lower Calorific Value (LCV) may have excelled over other fewer dominants, causing a reduction of the peak pressure and temperature in the combustion chamber, reducing thus NO_x emissions [21]. Among tested fuels, B100 (fuel that has higher oxygen content) showed higher NO_x emissions and it presents a high modulus of volumetric compressibility [40] that has its early injection compared to petroleum diesel, which enhances the premixing combustion promoting the temperature increase of the chamber and the formation of NO_x [35].

Carbon monoxide is a toxic, odorless and generally formed when the engine operates in a condition rich equivalence ratio of fuel/air. Addition of ethanol in the mixture B5 presented a small reduction in CO emissions, which can be considered statistically equal, possibly due to low concentration (Fig. 2b). Ethanol can provide a more efficient combustion; it may take a greater amount of oxygen to some parts of the combustion chamber. Guarieiro et al. [10] found similar results for ethanol content of 5% in the mixture, while Tsang et al. [33] observed conflicting results, reporting increased emissions of CO with increasing ethanol content injected into the engine.

The particle material mass size distributions (df/f ∗ dlog dp versus dp where f is the mass fraction of PM concentration in a certain size interval) from burning of three studied fuel (B5, B5E6 and B100) are shown in Fig. 3. The burning of fuels showed concentrations of particles trendy accumulation of $50 < Da < 200$ nm (Fig. 3). In general, particles emitted from diesel engines are in the size range 20–130 nm [41]. The geometric mean obtained for both fuels B5 and B5E6 was $\delta = 86.6 \pm 3.7$ nm, with a total number of particles of 9.6×10^6 particles/cm^3 for the B5 and 1.1×10^7 particles/cm^3 to the B5E6. The B100 showed geometric mean of $\delta = 78.1 \pm 3.1$ nm with total number of particles of 1.4×10^7 particles/cm^3.

Applying a principal component analysis (PCA) on the data matrix of the samples, it was found that the cumulative variance for PC1 and PC2 was 84.21% with the formation of three distribution groups (Fig. 4).

As a result of PCA analysis, it is possible to identify the group with greater values and negative scores (B5) showed increased particle emissions with larger diameter, while other fuels B100 and B5E6 (shifted more to the right of the graph) showed greater particle emissions

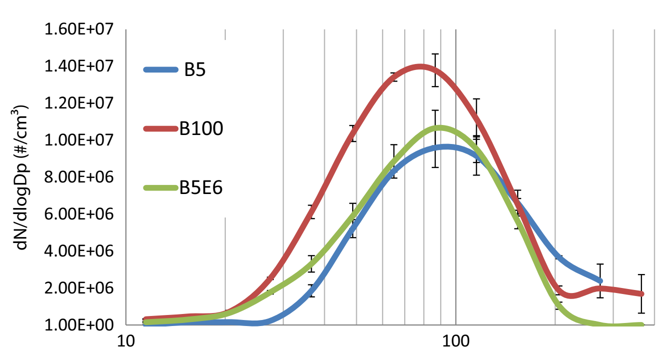

Fig. 3. Distribution of number and size particles for fuels: B5, B5E6 and B100.

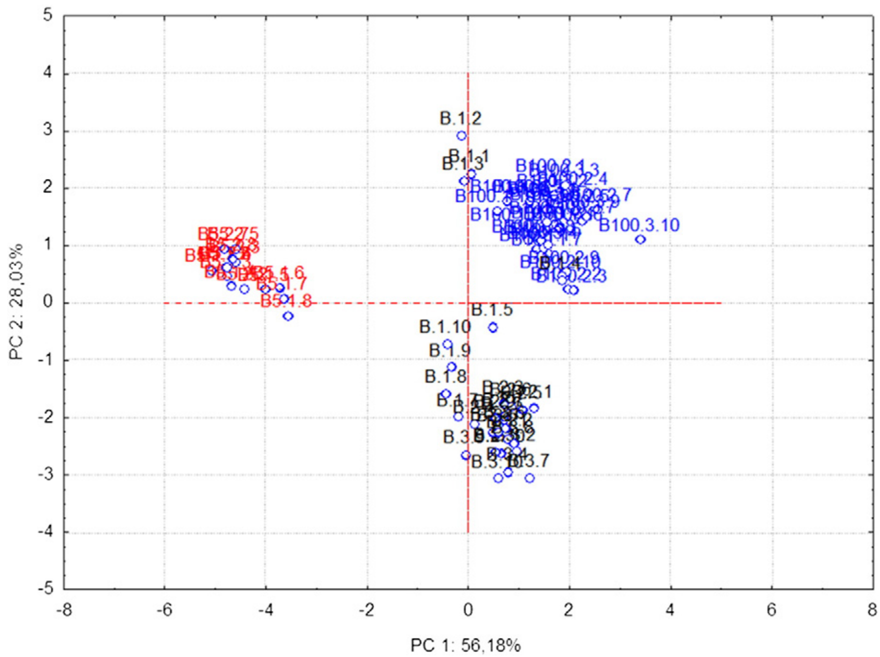

Fig. 4. Results of the scores for the B5 (red), B5E6 (black) and B100 (blue) fuels.

with lesser diameters (Fig. 4). These observed results is according with the data obtained by Tsolakis [42] and Cheng et al. [43], where was observaded also an increase in the number of smaller particulate emissions when biodiesel is used instead blends diesel with alcohol fuel. As the engine used in this work has mechanical injection, an anticipated injection can happen due to high modulus of volumetric compressibility of the B100, and this makes it longer to mix with the air. Thus, there is an increase in premixed combustion fraction due to the ignition delay that can generate a lesser incomplete burning, reducing the size of the particles and consequently increasing their concentration [43]. However, the nucleation, condensation and coagulation of the HC in the engine exhaust will generate some particles, leading to more particulate, both in number and in mass, than the B5 and B5E6.

On the other hand, Young et al. [44] examined the number emission characteristics of 10–1000 nm nonvolatile particles from a heavy-duty diesel engine, operating with various waste cooking oil biodiesel blends (B2, B10 and B20) and engine loads. This research showed the number of particles decreased with increasing biodiesel blend at 0% load. At 25% and 50% loads, the number of soot particles decreased with increasing biodiesel blend. Therefore, the number reduction with increasing biodiesel blend was not limited to soot particles but also included the particles. This is likely due to the increased oxygen content, lower aromatic content, prolonged soot oxidation time, and lower final boiling point with increasing biodiesel blend [40,41,45].

3.2. Evaluation of engine efficiency

Fig. 5 shows the results from power output of the motor for each fuel tested. Binary mixture B5 showed higher power output by having a superior calorific value to other fuels. As biodiesel has lower calorific value among the three fuels tested, it showed lower power output. Çetinkaya et al. [46] found similar results reporting slight power loss with the use of pure biodiesel. The ternary mixture (B5E6) had the lowest measures of powers, although having intermediate calorific value among the tested fuels. A discrete formation of microbubbles in the fuel tank for run times higher at one o'clock indicating the small fuel vaporization injection with hot fuel line was verified. The high volatility of ethanol can promote their vaporization in the return line, which can harm the injection process in diesel direct injection engines. The low cetane number of ethanol may also explain this significant reduction.

The BSFC results are shown in Fig. 6. Although the ternary mixture (B5E6) has presented a lower power among studied fuels, this fuel had low absolute consumption, providing an intermediary specific consumption between the B5 and the B100. Zhu et al. [36] also found similar results, reporting an increase in specific consumption in the ethanol content. The author justified this increase by reducing the calorific

Fig. 5. Power output for B5, B5E6 and B100 fuels.

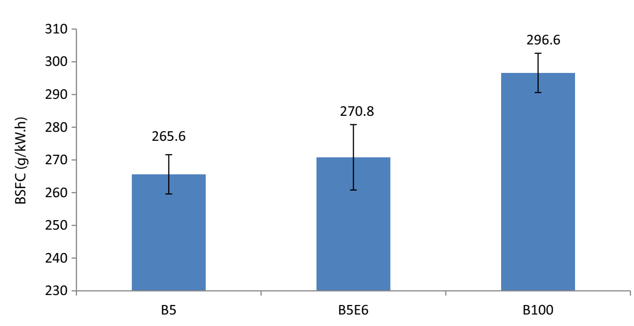

Fig. 6. Brake specific fuel consumption for B5, B5E6 and B100 fuels.

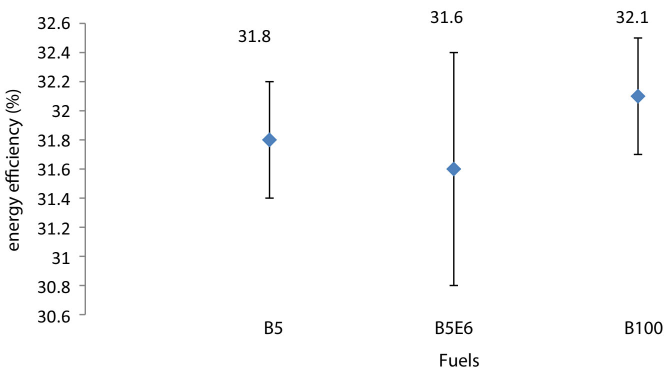

Fig. 7. Thermal efficiency for B5, B5E6 and B100 fuels.

value of the fuel. The biodiesel has lower calorific value, obtained higher specific consumption, a fact also reported by Whalen et al. [47].

The B100 fuel showed higher thermal efficiency, though having higher BSFC (Fig. 7). This fuel had power output very close to the binary mixture (B5) and a lower calorific value among all tested fuels. Canakcı et al. [48] found similar results, justifying the increase of energetic and exergetic income with the use of biodiesel, due to the high cetane number and oxygen content present in this fuel. The use of ethanol can led to a significant reduction in power, which contributed to decrease the EE. Law et al. [32] found similar results to those obtained in this present work. However these researchers reported a small increase in efficiency for low concentrations of ethanol. Even with low cetane number of alcohol, the oxygen present in the ethanol molecule can contribute to improve the efficiency of the combustion process.

4. Conclusions

The impact evaluation of the emissions from the use of fuels with higher content of oxygen added to B5 (commercial fuel) presented, for addition of 6% ethanol (B5E6), an increase in the emission of HC and number of smaller particles and a reduction in CO, CO_2 and number of larger particles. While emissions of NO_x could be considered statistically equal. The burning pure biodiesel (B100), with higher oxygen content than the both B5 and B5E6 fuels, showed an increase in emissions of NO_x and particle number of smaller diameter and reduced emissions of HC, CO and particle number of larger diameter. Emissions of CO_2 could be considered statistically equal.

The use of more oxygenated fuels (B5E6 and B100) can cause a reduction in power output and increased fuel consumption, but the exergy analysis showed that even with these results described above, the EE of these fuels can be considered similar to the B5 fuel.

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