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Research Paper

Performance and emissions characteristics of castor oil biodiesel fuel blends

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HIGHLIGHTS

- Castor oil biodiesel blends did not impact on engine thermal efficiency with relation to diesel.
- Castor biodiesel NOx penalty correlated to the biodiesel iodine value.
- The higher oxygen content of castor biodiesel did not improve PM emissions.
- Castor oil biodiesel PM, HC and CO emissions were load dependent due to poor atomization.

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ABSTRACT

This article comprises a series of experiments dedicated to the investigation of the operational effects of castor oil methyl ester blending into mineral diesel. Fuel blends containing 10 and 20% of biodiesel in volume were analyzed in tests conducted with a turbocharged diesel engine operating at steady state conditions. Soybean oil biodiesel fuel blends where also tested in order to provide a baseline to the expected behavior of a low viscosity first generation biodiesel. Exhaust gas concentrations of nitrogen oxides (NOx), unburned hydrocarbons (HC), carbon monoxide (CO), and total particulate matter (PM) were taken into account. The obtained results indicate that despite its unfavorable spray related properties, the castor oil methyl ester (COME) did not impact on engine thermal efficiency when compared to diesel fuel. The effects of COME upon HC and CO emissions were load dependable indicating a compromise between fuel oxygen content and poor breakup and evaporation properties. Both soybean and castor biodiesel blending into fossil diesel continuously increased the NO_x emissions with penalties correlated to the iodine number: Castor biodiesel emitted less NO_x than its soybean counterpart. The improved oxygen content with relation to the soybean biodiesel did not affect the PM emissions of the castor blends. A similar abatement of PM emissions with relation to fossil diesel was obtained with the castor and soybean fuel blends at mid and high engine load modes. At low load conditions, higher levels of PM were emitted for castor biodiesel blends when compared to soybean blends and the reference fuel.

1. Introduction

Current engine research has been focusing on simultaneously improving fuel consumption and reducing pollutant emissions. While the diesel engine operates with higher levels of efficiency and has a reliability reputation in comparison to the spark ignition engine, on the other hand, its combustion process is a major source of air pollutants and greenhouse effect gases. To reduce nitrogen oxides (NO_x) and particulate matter (PM) emissions in order to meet the current and future pollutant regulations constitutes a challenge of particular interest. This scenario demands further research to find sustainable and environmental friendly fuel alternatives for diesel engine application [1] and, at the same time, to successfully characterize the impacts of such alternatives upon engine fuel consumption and pollutant emissions.

Biodiesel plays a key role in this process and its use in the transport sector has continuously increased over the last years, mainly due to concerns about the depletion of fossil fuels and the interrelation of climate change with politics [2]. Accordingly, a considerable amount of research effort has been dedicated to the study of the influence of the molecular structure and

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thermophysical properties of biodiesel upon engine performance and pollutant emissions [3–7].

However, the expansion of the biodiesel industry has not gone unscathed by criticism. Carriquiry et al. [8], for instance, pointed that the initial broad support that biofuels enjoyed a decade ago has eroded as new studies have linked their production to rising food prices, questioned their ability to displace fossil energy, and analyzed their potential contribution to monoculture and deforestation. As a result, the search for non-edible feedstock options with characteristics such as lower land and water demands [9,10] as well as the use of agricultural residues [11] has received attention.

Castor bean or castor oil plant (Ricinus communis) is one of the promising non-edible oil crops [12]; it has low implementation and production costs and relative resistance to hydric stress, attributes that have enabled this oil plant to develop under adverse climate and soil conditions [13]. The oil extracted from the seeds of the ricinus communis plant contains about 90%, per mol, of ricinoleic acid (12-hydroxy-9-cis-octadecenoic acid). This long-chain fatty acid makes castor oil the only commodity oil with a functional group besides double bounds: a hydroxyl on the 12th carbon. This characteristic is well explored by chemical and pharmaceutical industries, and it causes castor oil biodiesel to be more polar than regular biodiesels. Under the perspective of engine use, castor oil biodiesel polarity induces high values of viscosity, surface tension and boiling point, which, by their turn, make fuel atomization more difficult and have an important impact into the subsequent evaporation and combustion processes. The extra oxygen contained in the hydroxyl group also causes castor oil biodiesel to burn in leaner conditions and reduces both its heating value and adiabatic flame temperature.

Perhaps more due to its remarkable chemical structure than for its attractiveness as a second-generation biodiesel, castor oil biodiesel characterization [12,14–16] and production [17–25] has gained increasing attention. The same cannot be stated about castor oil biodiesel engine performance and pollutant emissions testing. In a critical review of the prospects, feedstocks and challenges of biodiesel production from beauty leaf oil and castor oil, Azad et al. [26] concluded that scant literature can be found on engine performance and emissions for castor biodiesel, whereas further combustion research and performance tests are needed before recommending commercial scale biodiesel production from this source. In fact, current research results for castor oil biodiesel engine tests appear to be scarce and somewhat contradictory.

In an experimental work based on steady state tests, Valente et al. [27] reported an increase of 3.2–7.1% in break specific fuel consumption (bsfc) for an engine operating with castor biodiesel blends up to B35. According to these authors, castor oil biodiesel also increased unburned hydrocarbons (HC) and CO emissions with relation to mineral diesel. However, fuel conversion efficiency, particulate matter and nitrogen oxides effects were not covered by Valente et al. [27]. In a similar experimental study, Panwar et al. [28] found thermal efficiency gains of 4.6% for B05, 14.1% for B10 and 6.4% for B20 fuel blend with relation to diesel, which were credited to better lubricity, lower friction loss and better combustion of the castor oil biodiesel blends when compared to mineral diesel fuel. Neutral NO_x effects at low load conditions and a slight penalty at full load were also reported [28]. Özcanli et al. [29] conducted engine tests with castor oil biodiesel blends in concentrations of B5, B10, B25, B50 and B100. These authors suggested the B25 castor oil biodiesel fuel blend as a suitable alternative fuel for diesel engines, in spite of 21.3% higher NO_x emissions being registered with this blend in relation to diesel fuel. As for performance, they report an average increase of 4.4% for the bsfc and a decrease of 1% in the fuel conversion efficiency by adopting the suggested B25 fuel blend. Unburned hydrocarbons and particulate matter aspects were addressed neither by Panwar et al. [28] nor Özcanli et al. [29].

Nevertheless, when one takes into account both the limited number of castor oil biodiesel performance and emissions studies, as well as the unusual properties of this biofuel, it becomes evident that further research is recommended from two distinct points of view. First, to better understand the operational effects of castor oil biodiesel blending into diesel fuel as a non-edible oil option. And second, to advance in the knowledge of the performance and emissions role played by biodiesel's molecular structure and thermo-physical properties by studying a case in which such variables assume extreme values. A series of steady state engine tests was conducted in the present paper with both this aims. Castor oil biodiesel blends into diesel fuel were analyzed in terms of fuel consumption, thermodynamic efficiency and pollutant emissions.

2. Materials and methods

2.1. Fuels

Soybean oil biodiesel was chosen here as a representative of low viscosity first generation biodiesels, being tested at the same operational conditions than castor oil biodiesel in order to provide reference results. Ultra-low sulfur mineral diesel (10 ppm) was used as baseline fuel and blends of 10% (B10) and 20% (B20) of each biodiesel, by volume, were prepared. Both soybean and castor oil methyl esters were produced by single-step homogeneous transesterification reactions according to the procedures described in [14]. Specific gravity values and kinematic viscosities were measured using a digital viscodensimeter Anton Paar SVM 3000-Stabinger, according to ASTM D-4052 and ASTM D-445, respectively. Flash point determination was run according to the ASTM D93 standard using a Tanaka (APM7) apparatus and the Pensky-Martens closed cup method. The fatty acid methyl ester content of each product was evaluated using gas chromatography with flame ionization detector (Varian), according to the EN 14103. The lower heating values (LHV) of the test fuels were determined with an IKA200 calorimeter, according to ASTM D 240-87 test method.

The relevant physicochemical properties of the test fuels are shown in Table 1. It is well accepted that the cetane number (CN), viscosity, and higher heating value increase with molecular weight and decrease with the number of double bonds, whereas density increases with decreasing molecular weight and increasing degree of unsaturation [30,31]. It can be noticed from Table 1 that castor oil methyl ester has three times the viscosity of its soybean counterpart, 20% higher surface tension, 5% higher density and 50 °C higher normal boiling point. These results may be related, not only to the effects of chain length and unsaturation degree, but mainly to the presence of the hydroxyl group in the ricinoleic methyl ester and its higher polarity tendency. Besides, while soybean biodiesel and most methyl esters contain about 11% oxygen by weight from the carboxyl group in their structure [32], in the case of castor oil this amount increases to 15.4% due to the additional oxygen in the hydroxyl group. As an indirect consequence of being more oxygen rich, castor oil biodiesel also has lower values of cetane number, adiabatic flame temperature and heating value in comparison to biodiesels from other sources.

2.2. Dynamometric bench experimental setup

A series of steady state experiments was performed in a direct injection turbocharged diesel engine model MWM 229-T6 with specifications shown in Table 2. Three different engine loads corresponding to break mean effective pressures (bmep) of 250, 500 and 750 kPa and constant speed of 1800 rpm were selected for the fuel

Table 1
Comparison of relevant thermophysical properties of diesel, soybean oil methyl ester (SOME), castor oil methyl ester (COME) and its blends.

Fuel properties	Diesel	SOME			COME		
		B10	B20	B100	B10	B20	B100
Kinematic viscosity [cSt@40 °C]	2.53	2.56	2.82	4.16	3.01	4.20	14.50
Specific gravity [kg/m^3]	829.9	835.20	840.5	882.9	838.6	849.3	923.7
C atoms in chemical formula[a] [–]	10.80	11.31	11.87	18.83	11.27	11.78	17.96
H atoms in chemical formula[a] [–]	18.70	19.73	20.85	34.82	19.83	21.04	35.82
O atoms in chemical formula[a] [–]	0.00	0.13	0.27	2.00	0.19	0.39	2.86
Monounsaturated ester[a] [% mol]	–	–	–	24.65	–	–	91.41
Polyunsaturated ester[a] [% mol]	–	–	–	56.62	–	–	6.90
Iodine value [gI$_2$/100 g]	–	–	–	121.60	–	–	83.40
Higher heating value [MJ/kg]	45.56	45.02	44.50	40.48	44.64	43.75	37.34
Cetane index[b] [–]	49.9	50.1	50.3	52.1	49.9	49.9	50.0
Normal boiling point[c] [°C]	172.9	184.1	196.2	347.7	188.0	204.2	401.8
Flash point [°C]	64.0	66.2	67.2	176.7	67.0	68.2	273.1

[a] Calculated from fatty acid distribution.
[b] Cetane index from [49,31,50].
[c] Normal boiling point from [51].

Table 2
Engine specifications.

Configuration	Direct injection, turbocharged, water cooled, 4 stroke diesel
Maximum brake power [kW]	81 @ 2500 rpm
Maximum brake torque [N m]	350 @ 1800 rpm
Number of cylinders	6
Displacement [dm^3]	5.8
Bore/stroke [m]	0.102/0.120
Compression ratio	15.9:1
Fuel injection pump	Bosch inline pump
Fuel injector holes	4
Injector opening pressure [bar]	300
Piston crown shape	Re-entrant

tests. For the engine in use, these loads correspond to 33, 66 and 100% of the maximum brake torque, respectively. An automated test bed equipped with an AC dynamometer was used to control the engine operation and to identify its relevant performance and emissions parameters. Assemble averaged data was acquired within 10 min of the steady-state engine test in each operational condition. All engine tests were made in triplicate, with the data set corresponding to the central bsfc result being presented.

A schematic representation of the experimental setup is shown in Fig. 1. The engine load was controlled by a servo actuator directly connected to the fuel pump rack, while the engine speed was fixed by the dynamometer. The operational impacts of biodiesel blending into fossil diesel are not expressive at low biodiesel concentrations and, under uncontrolled experimental circumstances, the effects of intake air or fuel heat-up throughout a long engine test would difficult the interpretation of the obtained results. The control of intake air humidity from one engine test to another is also particularly important to ensure good reproducibility of NO_x measurements, for instance. Accordingly, specific subsystems were used to control the thermodynamic state of the intake air and the temperatures of the fuel, engine coolant and lubricant oil throughout the tests. The values adopted for the set-points and the maximum absolute deviations observed for each controlled variable within one typical experiment are listed in Table 3.

The total particulate matter (PM) including both soot and soluble fraction was measured with a mini-tunnel operating at 1/100 of the total exhaust volume. Two filters were used to capture the PM from the diluted exhaust gas sample at 50 °C, and concentrations of this pollutant were calculated in duplicate from the mass gained by each filter through 10 min of individual sample collection. Other sample was taken from the exhaust path and rou-

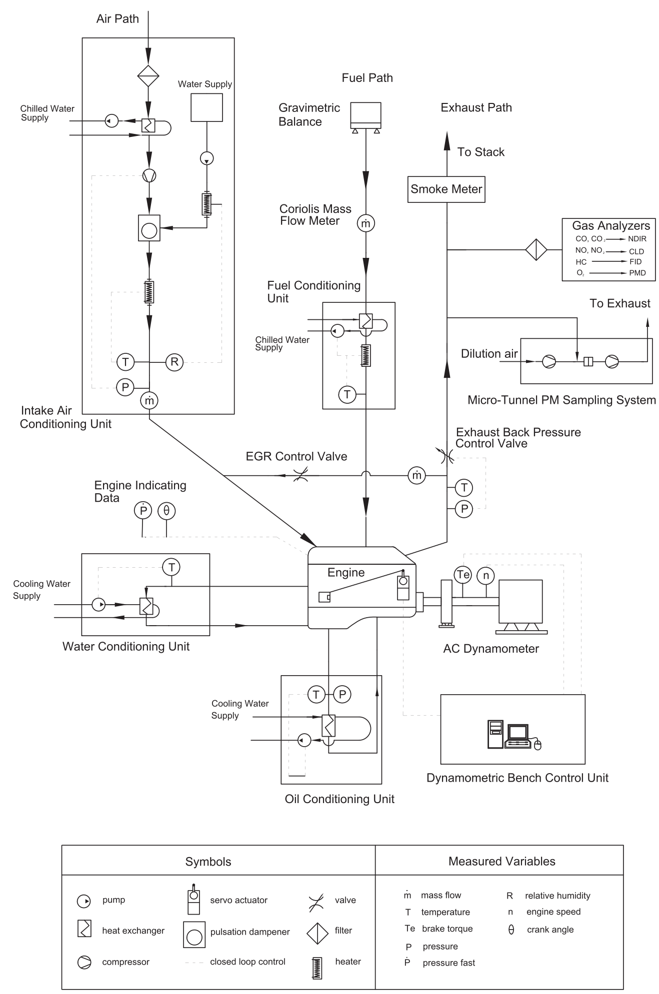


Fig. 1. Schematic representation of the experimental setup.

ted to a set of pollutant analyzers through a heated filter and individual heated lines. The unburned hydrocarbons were measured in THC mode by a heated flame ionization analyzer model CAI 600 HFID. The filter and the lines were maintained at 120 °C in order to limit the condensation of unburned hydrocarbons from the biodiesel, which may have high boiling points. Nitrogen oxides were detected in NO/NO_x mode with a CAI 600 HCLD heated chemiluminescence equipment. A Fuji ZPA analyzer combining

Table 3
Operational parameters set-points and maximum absolute deviations.

Operational parameter	Set-point/deviation
Engine speed [rpm]	1800 ± 4.9
Brake torque [N m]	350 ± 1.18
Intake air temperature [°C]	25 ± 0.06
Intake air pressure [kPa]	101.3 ± 0.11
Intake air relative humidity [%]	60 ± 0.42
Engine coolant temperature [°C]	84 ± 0.39
Engine oil temperature [°C]	95 ± 0.62
Fuel temperature [°C]	40 ± 0.16

the non-dispersive infrared method for CO and CO_2 and the paramagnetic method for O_2 completed the emissions measurement setup.

Two distinct procedures were used here to determine if the start of injection angle was modified with biodiesel blending: needle lift measurements and estimation from injection line pressure. Needle lift measurements are far more accurate than pressure line pressure comparisons but, in spite of that, studies based on line pressure comparisons predominate in the literature. Comparison of theoretical injection spray characteristics were conduced with basis on Sauter mean diameters (SMD) calculated at the instant of peak injection pressure. Fuel line pressure and engine indicating data were used to calculate the Suter mean diameter (SMD) values according to the El-Kotb correlation [33]. Engine fuel conversion efficiency (η_t), or thermodynamic efficiency, break specific consumption and specific pollutant emissions values were calculated according to the procedures shown in Ref. [34].

3. Results and discussion

3.1. Engine performance

It is widely accepted that the use of biodiesel blends does not significantly affect the engine thermal efficiency with relation to mineral diesel [35,36]. The results shown in Fig. 2a indicate that castor biodiesel B10 and B20 fuel blends also followed this tendency, in spite of their inferior spray related properties. In fact, the only consistent trend within the η_t data is a slight efficiency gain for both castor and soybean biodiesel blends at high load condition, whereas in low and medium loads the η_t deviations between the tested fuels are within the uncertainty margins.

Castor oil biodiesel has a lower heating value than its soybean counterpart and, as can be seen in Fig. 2, the foremost levels of break specific consumption were registered with its B10 and B20 fuel blends. This was an expected result, since most of the published studies report bsfc increases that are closely related to the penalty imposed by each biodiesel blend into the fuel heating value [35]. It is interesting to point out, however, that part of this tendency can be recovered in volumetric terms because castor oil biodiesel is 11.3% and 4.6% denser than diesel fuel and soybean biodiesel, respectively. In terms of engine performance, our results qualitatively agree with those of Valente et al. [27] and Ozcanli et al. [29], in opposite to the efficiency and fuel economy gains reported by Panwar et al. [28].

3.2. HC emissions

The results shown in Fig. 3a indicate that the specific unburned hydrocarbon were reduced for all tested fuels with the engine load and the fuel injection pressure increasing. Additionally, the substitution of diesel by soybean biodiesel caused a consistent HC abatement within all load conditions, and average reductions of 18% and 21% were registered for the B10 and B20 fuel blends, respectively. A similar trend was reported for soybean biodiesel blending into low sulfur diesel by Last et al. [37], that found HC reductions of 28% and 32% for B10 and B20 blends with relation to diesel fuel [37].

Two distinct factors are usually taken into account in order to support the sharp decreases in HC emissions that are characteristic for biodiesels [36]: oxygen availability at the combustion sites and fuel ignition quality. The first line of reasoning is well represented in the work of Rakopoulos et al. [38], where oxygenated fuels are believed to improve combustion and to decrease HC emissions by providing fuel oxygen into the combustion sites. The second hypothesis is based on the fact that a fuel with a high cetane number, like biodiesel, would shorten the ignition delay. A reduced ignition delay restricts the amount of HC prone fuel that has been mixed leaner than the flammability limit before the ignition event [39].

By taking either, diesel or the soybean biodiesel blends as a reference, it can be noticed from Fig. 3a that the HC emissions of the castor biodiesel blends deteriorated with engine load reduction, showing similar results to soybean at high load and worse results than diesel at low load. Two aspects call for attention here: castor

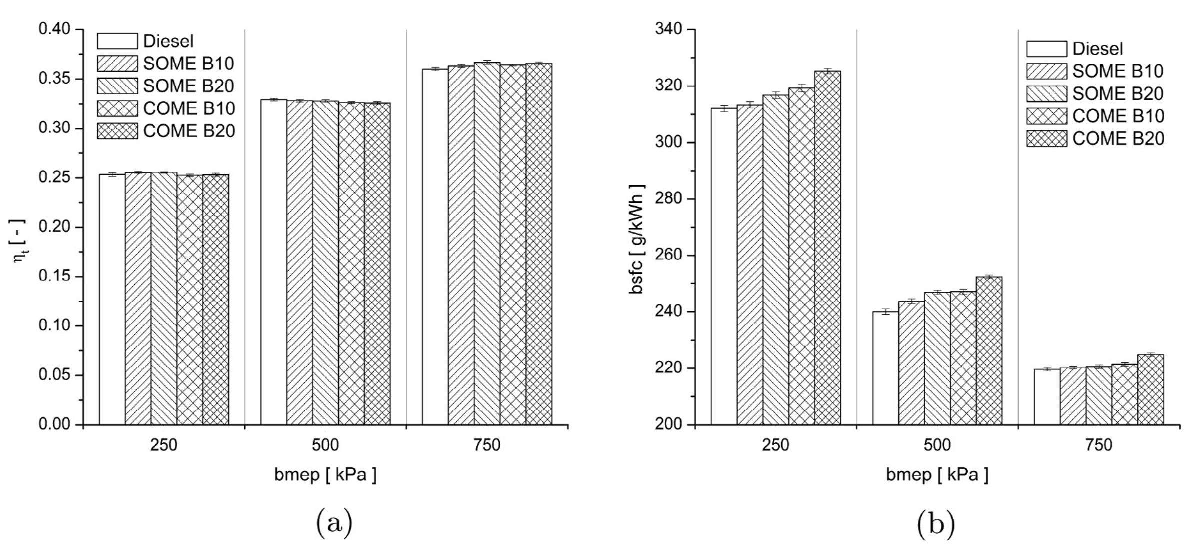


Fig. 2. Thermal efficiency and specific fuel consumption data for the tested fuel blends.

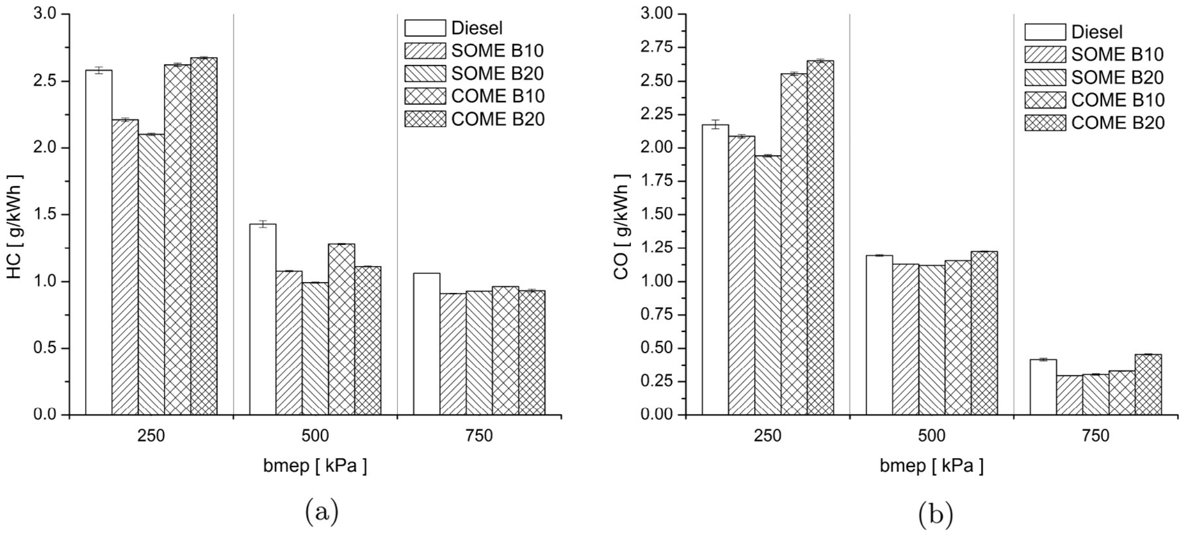


Fig. 3. Engine out specific unburned hydrocarbons and carbon monoxide emissions for the tested fuel blends.

oil biodiesel has a 40% higher oxygen content with respect to the soybean biodiesel and its cetane index is the central of the three considered fuels. Thus, while the HC levels at bmep's of 500 kPa and 750 kPa could be justified by a preeminence of cetane number effects over oxygen content, a third factor that is characterized by load dependance is needed in order to explain the obtained results at 250 kPa.

Given the singular properties of castor oil biodiesel, we believe that difficulties involved into its atomization and subsequent evaporation can be related to that undesirable HC behavior. As the fuel jet momentum is reduced at low engine loads, fuel atomization and vaporization become critical with peak injection pressures of about 380 bar being measured, in contrast to the 750 bar normally attained at high load conditions. Taking the Sauter mean diameter as a qualitative reference for the quality of the atomization process, one can see from Table 4 that the COME B20 blend causes the SMD to increase in 9.2 μm (*ca.* 40%) with relation to the baseline diesel fuel, whereas for SOME B20 this increase is of 1.7 μm (8%) only. Besides, the 401 °C normal boiling point of castor biodiesel would impose an additional difficulty to the subsequent droplet evaporation.

3.3. CO emissions

It becomes evident from the results depicted in Fig. 3b that CO and HC emissions are correlated. Since carbon monoxide is also a product of incomplete fuel oxidation, it was expected from the previous discussion that the higher values of viscosity, surface tension and boiling temperature of the COME fuel blends would impact their emissions when compared to those of SOME blends. It can be noticed that the CO impact was even higher then what was observed for HC, as the COME B20 blend emitted more carbon monoxide than the baseline fuel in all tested modes. At low engine load only 10% of COME blending was sufficient to worsen the CO emissions.

Table 4
Sauter mean diameters (SMD) at peak injection pressure calculated from [33].

bmep [kPa]	Diesel (μm)	SOME B20 (μm)	COME B20 (μm)
250	21.0	22.7	30.2
500	17.2	18.7	24.1
750	14.2	15.4	19.4

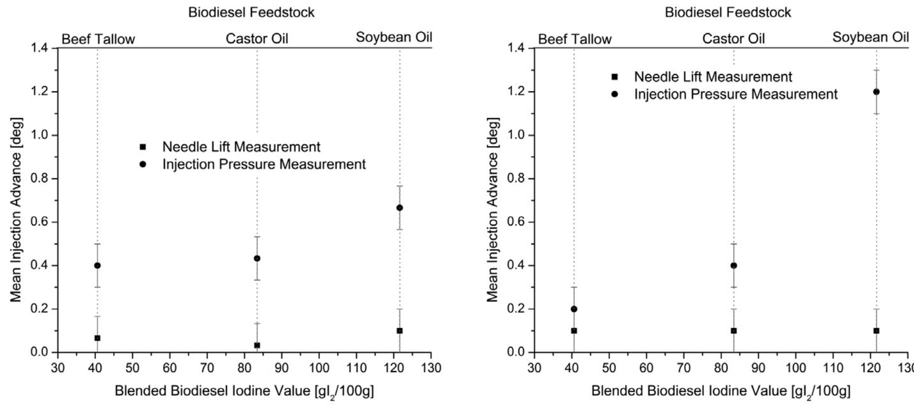
The results obtained here are at an intermediary position with relation to the scarce literature currently available for castor oil biodiesel. Considering biodiesel blends up to B20, Valente et al. [27] found higher HC and CO emissions levels for soybean blends followed by castor and mineral diesel. Those authors justified their results pointing soybean biodiesel chemical structure and castor atomization difficulties as roots of the increased emissions. On the other hand, according to Ref. [29] blending castor biodiesel into diesel fuel continuously decreased the CO emissions, what was justified by increased fuel oxygen content. An explanation that agree with our findings can be found in the work of Pinzi et al. [6], who correlated the HC and CO emissions abatements obtained with rapeseed and low-chain methyl esters taking both into consideration: oxygen content as a positive effect and boiling temperature as a detrimental issue.

3.4. NO_x emissions

3.4.1. Injection timing

Several reports explain the NO_x biodiesel penalties through an advance of the injection timing that is caused by fuel compressibility dissimilarities [40–42]. The values of bulk modulus of biodiesel are usually higher than those of fossil diesel, and it is credited to advancing the injection point by increasing the travel speed of the pulses that occur within the mechanical injection systems. The bulk modulus is another property that increases with the biodiesel unsaturation degree. Still from the previous works, it was believed that the resulted advanced injection would increase the peak combustion temperature [40,41] and/or advance its angle of occurrence [42], setting favorable conditions to NO_x formation. Since biodiesel bulk modulus is known to increase with unsaturation, a number of previous works correlated the NO_x penalty to the iodine value (IV) of the biodiesel in use [35].

As can be seen from Fig. 4, it was not possible to devise any injection advancement superior to the encoder resolution (0.1 deg) from the needle lift data obtained here for beef tallow, castor and soybean B10 and B20 blends. Accordingly, it will not be reasonable to credit mean injection advances of only 0.1 deg as the root cause of NO_x results obtained here for both, castor and soybean oil biodiesel blends. Beef tallow biodiesel data from [43] were depicted in order to provide low iodine values (42 gI_2/100 g), whereas the scatters at 83 gI_2/100 g and 121 gI_2/100 g represent castor and soybean biodiesel, respectively.



(a) B10 fuel blends (b) B20 fuel blends

Fig. 4. Average injection advance of B10 and B20 blends with relation to diesel fuel.

Average results from the three engine loads were adopted in each point of the figure. For the sake of comparison, the injection advance was also estimated by the less precise fuel injection line method. Still in Fig. 4, it is interesting to notice that an earlier injection that can be correlated to the biodiesel iodine number is obtained from injection line pressure information. An explanation to these opposing results can be found in the interesting work by Caresana [44], where it is shown that pressure pegging difficulties cause the timing advances induced by biodiesel to be overestimated by adopting injection line pressure comparisons.

3.4.2. Biodiesel structure and properties

Higher NO_x levels were observed to the biodiesel blends with relation to fossil diesel, as can be seen from the results shown in Fig. 5. In fact, it can be stated that the emissions were scaled with the iodine value (see Table 1) and the concentration of each biodiesel blended into the fuel. Soybean biodiesel blends (IV = 121.6) emitted more NO_x than castor (IV = 83.4) blends. However for the concentration effect, an exception was observed for COME B20 producing less NO_x than COME B10 at bmep = 250 kPA, indicating that the previously mentioned atomization difficulties reduced the charge temperature within this specific test mode at a point that it was effective for NO_x mitigation.

Besides its correlation with the injection phenomena, the biodiesel iodine value (unsaturation degree) also plays a major role in the kinetics of biodiesel combustion. In the low temperature regime C=C double bonds reduce the overall rate of reaction, thereby reducing the cetane number of unsaturated biodiesel [30,45], while at high temperatures the C=C double bonds accelerate the overall rate of combustion [5]. Cetane number is pointed as a key parameter for nitrogen oxides formation in [4,6,46], while a particularly interesting point of view involving additional factors is presented by Schönborn et al. [46]. These authors stated that the nitrogen oxides formation is controlled by three layered effects: The CN and ignition delay of the fuel molecules plays a dominant role by changing the heat release history and the combustion stoichiometry; The adiabatic flame temperature appears as a secondary effect, which only became clearly visible when the effect of ignition delay was removed by the authors; Soot-radiative heat transfer plays a tertiary role in the formation of NO_x according to their results.

Incidentally, the two biodiesels utilized here have a minor dispersion of CN with relation to diesel fuel (+0.2% to SOME and +4.4% to COME), which tends to lose significance at B10 and B20 blending levels. Thus, it is believed that increased flame temperature effects due to accelerated combustion at the high temperature regime could explain the results obtained here for castor and soybean biodiesel B20 blends. It is considered that both castor and soybean blends accelerated the combustion with relation to fossil diesel via double bonds influence, however the higher unsaturation degree of soybean biodiesel has accentuated this effect. Besides, castor biodiesel has a higher oxygen content in comparison to soybean, what is known to reduce its heating value and flame temperature. The results obtained here qualitatively agree with previous studies, where COME effects range from a minor increase [28] to 21.3% higher NO_x emissions at B25 fuel blending [29].

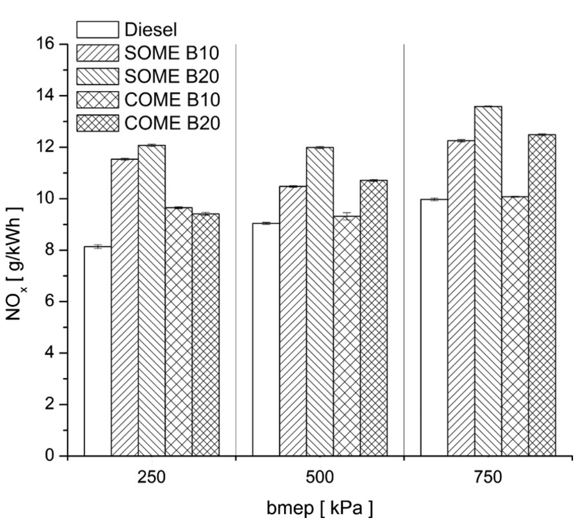


Fig. 5. Engine out specific nitrogen oxides emissions for the tested fuel blends.

3.5. PM emissions

Particulate matter emissions results are shown in Fig. 6. As expected, the relative weight of this pollutant increased with engine load due to limited oxygen availability. Soybean biodiesel blending reduced the particulates at all engine load modes with relation to diesel fuel, whereas for castor there was a slight penalty at the low load mode. It is interesting to notice, however, that both biodiesel feedstocks presented a similar performance at mean and high load levels. A continuous abatement of PM with biodiesel blending was noticeable at a break mean effective pressure of 750 kPa only.

Biodiesel blending into diesel fuel is generally believed to reduce total particulate matter emissions in agreement with the

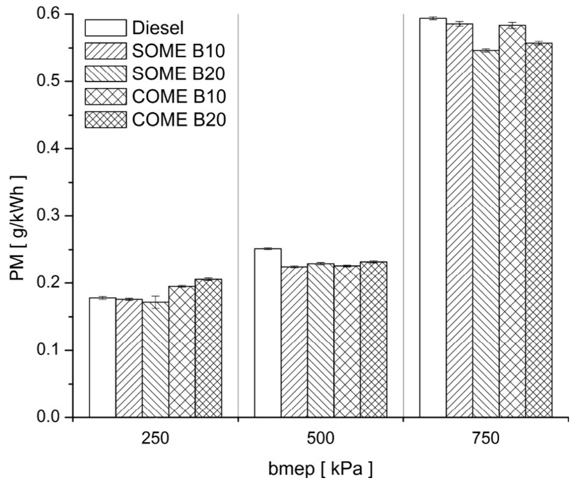


Fig. 6. Particulate matter specific emissions for the tested fuel blends.

results obtained here for the soybean blends [3,6,47,46]. By introducing oxygen into the fuel and reducing the aromatics content, biodiesel is credited to simultaneously reduce soot formation and enhance soot oxidation [35]. Therefore, a biodiesel with increased fuel oxygen content, as the castor one, would have an improved potential to soot elimination.

However, other factors must be taken into consideration for a proper discussion of the obtained results. Soot emission is also correlated with the number of double bonds present in the biodiesel structure because of ethene and ethyne formed during the fuel thermal decomposition [3,46], both of which are known precursors to carbonaceous soot [48]. Zhu et al. [3] also established a linear relationship between fuel saturate fraction and particulate matter SOF. Particulate matter was also found to increase with deprecated spray related properties, which can amplify the probability of soot or volatile matter to form from hydrocarbons unable to vaporize [6]. Furthermore, Schönborn et al. [46] correlated the concentration of nucleation mode particles in the exhaust gas with the boiling points of the biodiesel molecules, that indicates that the high number of nucleation mode particles produced by biodiesel combustion may consist of small fuel droplets.

No previous works addressing the particulate matter effects of castor biodiesel were known to the authors. By taking the soybean biodiesel blends as a reference, castor biodiesel has two positive aspects related to soot formation: a higher oxygen content and a lower saturation degree. On the other hand, the same boiling point and viscosity factors that affected HC and CO emissions were credited above to increase soot nucleation and soluble fraction. From the obtained results, it appears that a compromise between these aspects rendered similar results to castor and soybean biodiesel blends at mid to high engine loads. Whereas at low load mode the atomization related difficulties have made COME B10 and B20 blends achieve higher levels of PM than the soybean blends and the reference diesel fuel. It is interesting to point out, however, that at low engine load the COME B20 blend also emitted less NO_x than the COME B10 one, which suggests that an appreciable charge temperature reduction occurred for the B20 blend in this test mode.

4. Conclusions

1. In spite of its unfavorable spray related properties, the castor oil biodiesel B10 and B20 blends did not impact on engine thermal efficiency with relation to diesel fuel;
2. The effects of castor oil biodiesel upon HC and CO emissions were load dependable indicating a compromise between fuel oxygen content and poor breakup and evaporation properties. The results were favorable to the castor biodiesel blends at high and mid engine loads while adverse at low engine load;
3. Castor oil biodiesel blending into diesel fuel did not advance fuel injection for the engine in use, and the same can be said for the soybean blends.
4. Both soybean and castor biodiesel blending into fossil diesel continuously increased the NO_x emissions. The nitrogen oxides penalties were correlated to the biodiesel iodine value: Castor biodiesel emitted less NO_x than its soybean counterpart;
5. The cetane index of the tested fuels had similar values and it is believed that castor biodiesel reduced the flame temperatures in relation to soybean thus reducing nitrogen oxides emissions;
6. Soybean biodiesel blending reduced the particulates at all engine load modes with relation to diesel fuel;
7. The improved oxygen content with relation to the soybean biodiesel did not affect the PM emissions of the castor blends;
8. In fact, a similar abatement of PM emissions with relation to fossil diesel was obtained with the castor and soybean fuel blends at mid and high engine load modes, while at low load castor biodiesel blends emitted higher levels of PM than the soybean blends and the reference fuel.

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