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TECHNICAL PAPER

Mechanical and emissions performance of a diesel engine fueled with biodiesel, ethanol and diethyl ether blends

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Abstract

In this work, the effects of the addition of ethanol and diethyl ether (DEE) in a 54 kW mechanical fuel injection diesel engine, operating with diesel–biodiesel blends, were evaluated. The fuel compositions tested were fossil diesel (D100), B20 (20% biodiesel and 80% diesel), B20E (90% B20 and 10% ethanol) and B20E + DEE (95% B20E and 5% DEE). DEE was used as a cetane improver for the ethanol–biodiesel–diesel blend. D100 and B20 were used as references. Its results showed few differences between them, considering performance and emissions. Considering the blends B20E and B20E + DEE, effective reductions in NO_x and PM emissions were observed, in relation to D100 and B20, especially in medium and high loads. MBT decreased as a result of the reduction in LHV. The engine efficiency for all the fuels was close, but at the high load the blend B20E + DEE presented the highest efficiency.

Keywords Diesel engine · Biodiesel · Ethanol · Diethyl ether · Emissions

1 Introduction

The intense use of fossil fuels is partly responsible for global warming, acid rain incidence and photochemical smog in urban centers. In addition to concerns on air pollution, the search for energetic matrix diversification drives the emerging needs for biofuels [1]. The European Union, by means of Directive 2009/EC, has decided that at least 10% of renewable fuels should be used in the composition of commercial fuel by 2020 as a way to reduce pollutant emissions and other negative impacts [2].

Among biofuels for compression ignition (CI) engines, biodiesel is a viable alternative for diesel engines, because it is widely available, oxygenated, non-toxic, renewable, biodegradable and sulfur free [3–5]. Neat biodiesel and blends with fossil diesel generally result in a higher flash point, cetane number (CN), viscosity and density, while lower aromatic content and energy density [6]. High viscosity can cause problems related to clogging and increases the size of fuel droplets during injection, reducing combustion quality [7].

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The addition of less viscous fuels, such as ethanol or DEE in diesel–biodiesel blends, can improve the spray characteristics such as atomization and droplet size in the combustion chamber [8, 9]. Zhan et al. [1] report that this leads to a condition similar to that of fossil diesel. However, the use of ethanol in diesel blends is limited due to its lower viscosity and lubricity, reduced ignitability, CN and limited miscibility with diesel [10]. In addition to this, the high enthalpy of vaporization generates a cooling effect, mainly at low loads, which decreases the combustion temperature and usually reduces NO_x emissions [2, 10–13]. However the results of NO_x emissions using ethanol in diesel engines are not consolidated in the literature. The NO_x formation may vary according to different factors such as the method of application, fuel blend, engine characteristics and technology [14].

Tutak et al. [15] observed an increase in NO_x emissions with the use of ethanol in mixtures with diesel (DE) and biodiesel (BE). The tests were conducted at full load and constant speed (1500 rpm), using ethanol fractions (EF) from 0 to 45% in volume. The highest NO_x emissions for the DE blend (5.5 g/kWh) were obtained using 30% of EF in blend and for the BE blend, (3.5 g/kWh), was obtained using an EF of 45%. With diesel and biodiesel pure, as a reference, the NO_x emissions were approximately 2.2 g/kWh.

In the study by Wei et al. [3], the authors observed simultaneous NO_x and PM reduction using blends of ethanol and biodiesel (BE5, BE10 and BE15) when compared to fossil diesel and with pure biodiesel. Experiments were conducted at five loads at 1800 rpm. The brake thermal efficiencies were higher in relation to diesel and biodiesel at intermediate and high loads. The authors indicated the low CN and high enthalpy evaporation as responsible for the reduction in NO_x emissions.

Guerreiro et al. [16] tested B5 (95% of diesel fossil with 5% of biodiesel), B5E6 (ternary composition containing 89% diesel, 5% of biodiesel and 6% of ethanol) and B100 (pure biodiesel) in a stationary diesel engine at 1800 rpm and 70% of full load. The use of ethanol shown an increase in the THC emissions and a reduction in CO and NO_x emissions when compared to B5 and B100.

Ferreira et al. [17] evaluated the effects of adding ethanol to B30 (70% diesel and 30% biodiesel) using a fumigation technique. The tests were carried out on a stationary diesel engine at 1800 rpm, connected to an electric generator under constant load. The addition of ethanol resulted in a consistent reduction in NO_x emissions and smoke opacity; however, an increase in CO and THC emissions were observed.

With regard to DEE, this has been the subject of much research due to its high CN ($\geq$ 125) when compared to fossil diesel [1]. Other characteristics, such as low viscosity, oxygen content, miscibility with diesel and other fuels and lower heating value (LHV) higher than ethanol, have attracted attention for application in blends in diesel engines [18]. In this context, DEE can be used as an additive in diesel–biodiesel–ethanol blends in order to increase the CN. Some studies have also shown improvements in NO_x and PM emissions with the application of DEE. In Kaimal and Vijayabalan [19], waste plastic oil (WPO) and blends with 5%, 10% and 15% DEE were examined in a single cylinder DI diesel engine at 1500 rpm and varying loads. The authors observed significant reductions in NO_x and PM emissions with DEE blends. The brake thermal efficiency also increases with increasing percentage of DEE.

In Lee and Kim [20], DEE–diesel in percentages of 10%, 25% and 50% of DEE by mass were tested at 1000 rpm and several engines loads (0.2–0.8 MPa of IMEP). The experiment showed engine efficiency similar to that of fossil diesel and lower emissions of THC, CO and PM in the entire load range. However, higher NO_x emission was observed when DEE blends were used.

PATIL et al. [21] tested DEE–diesel blends (2%, 5%, 8%, 10%, 15%, 20% and 25% DEE by volume) at 1500 rpm and five loads. In general, reductions in NO_x, CO and smoke emissions were observed with the use of DEE in the blends. However, there was observed an increase in THC emissions.

Ibrahim [11] tested mixtures of 5% and 10% DEE with diesel and biodiesel (D70B25DEE5 and D70B20-DEE10) at constant speed of 1500 rpm and at different engine loads. Fossil diesel and B30 (70% diesel and 30% biodiesel) were used as reference. The author reported that 5% DEE in the blend has led to an increase in engine efficiency, while with 10% DEE the efficiency decreased. No emission tests were performed at the work.

The high CN of DEE can improve ignitability of the fuel. However, the high volatility and enthalpy of evaporation of DEE and its reduced LHV can produce a cooling effect in the combustion chamber, which can cause a longer delay in ignition when compared to diesel or diesel–biodiesel blends. Jeevanantham et al. [14] tested the DEE in blends with diesel–biodiesel (D50B45DEE5 and D50B40DEE10) at 1500 rpm and in four loads. The results showed an increase in the ignition delay with DEE mixtures compared to diesel and D50B50 blend that were tested as reference. According the authors, the cooling effect rather than higher CN of DEE had prevailed. Despite this, DEE blends showed significant NO_x reduction in relation to the other fuels and a lower CO and HC compared to diesel.

Venu and Madhavan [18] tested DEE at 5% and 10% by volume in blends with EBD (20% ethanol, 40% biodiesel and 40% diesel, in volume). The tests were performed on a single cylinder diesel engine at a constant speed of 1500 rpm and under 5 load conditions. The addition of 10% DEE in EBD also increased the ignition delay in relation to diesel, EBD and 5% DEE + EBD blend. DEE blends increased THC emissions and decreased NO_x, in relation to diesel and EBD.

Qi et al. [22] investigated the effects of using DEE and ethanol as additives to biodiesel–diesel blends. The tests were performance in an engine speed of 1800 rpm and several engine loads. The tested fuels were B30 (30% biodiesel and 70% diesel) as reference, BE-1 (5% diethyl ether, 25% biodiesel and 70% diesel) and BE-2 (5% ethanol, 25% biodiesel and 70% diesel) in volume. The results indicated that, in comparison with the B30, there was a reduction in the BSFC with the use of the BE-1 mixture. There was also a significant reduction in smoke opacity with BE-1 and BE-2 at high engine loads. Regarding NO_x emissions, a reduction was observed with the use of the BE-1, whereas there was a slight increase with the use of the BE-2 blend.

Paul et al. [4] tested diesel and blends of DEE–diesel and DEE–diesel–ethanol in a single cylinder diesel engine at 1500 rpm in 6 load conditions. The results showed that the use of ethanol along with DEE provided higher brake thermal efficiency and reduced NO_x and THC emissions, in relation to diesel and DEE–diesel blends.

This work was carried out using a 54 Kw MWM diesel engine, with four cylinders with mechanical direct fuel injection. The aim was to evaluate the influence of ethanol and diethyl ether in diesel–biodiesel blends. Diethyl ether was added to diesel–biodiesel–ethanol blend in order to increase the cetane number so that the adverse effects related to the use of ethanol in diesel–biodiesel blends can be overcome.

2 Methodology

2.1 The diesel engine

The tests were performed on a four cylinder, 54 kW, MWM stationary diesel engine coupled to a Foucault dynamometer. Tables 1 and 2 describe the main characteristics of the engine and the dynamometer.

The tests were performed in three engine brake power (BP) conditions: 8 kW, 16 kW and 24 kW, corresponding to 25%, 50% and 75% of the full BP. In all cases, the engine operated at constant revolution (1800 rpm). Table 3 describes the engine test conditions.

Table 1 Engine specification

Manufacturer and model	MWM 229.4
Engine type	Four cylinder, in line; aspirated
Maximum power	54 kW @ 2500 rpm (NBR-1585)
Compression ratio	17:1
Cylinder bore × stroke	102 × 120 mm
Injection type	Mechanical, direct injection
Injection pressure (MPa)	23
Displacement (L)	3.92

Table 2 Dynamometer specification

Manufacturer	Logs electronics systems
Model	EC-150
Type	Foucault break
Maximum power (kW)	150

Table 3 Engine test conditions

RPM	Torque (Nm)	Brake power (kW)
1800	42.4	8
	84.9	16
	127.3	24

For each fuel tested, the engine was warmed up for 25 min in order to maintain the stability of the engine operation condition.

2.2 Instrumentation

The fuel mass flow rate was obtained by gravimetric method using a digital scale. For each fuel test, six cycles of measurements were performed with a sampling time of 5 min to determine the fuel consumption.

The exhaust gas emissions were determined by two gas analyzers. One of them evaluated the concentration of CO and NO_x in ppm, while the other measured the concentration of total unburned hydrocarbons (THC) in hexane basis. A total of five measurements were performed to determine the emissions for each fuel. The main characteristics of the instruments used are given in Table 4.

The particulate matter (PM) measurements were obtained by gravimetric method using a dilution tunnel type CVS (constant volume sampling) (Fig. 1). The dilution ratio of air/exhaust was of 20:1 in volume. Fiberglass filters, with 0.7 μm (mesh) and external diameter of 47 mm, manufactured by Milipore®, were used to collect the PM. The exhaust gas flow rate through the filters was set to 10 LPM, as indicated by the Brazilian standard ABNT-NBR14489. All the filters were placed on a silica gel dryer for 24 h at a temperature of 25 °C and relative humidity of 50% before being weighed. The filters were weighed before and after the PM sampling. Figure 1 shows the assembly details and the dilution system piping (CVS).

The PM was collected at 105, 75 and 45 min at the engine loads of 8 kW, 16 kW and 24 kW, respectively. The collection time was shorter at higher loads, since at

Table 4 Instrumentation specifications

Measuring quantity	Instrument	Manufacturer (model)	Range	Uncertainty
Exhaust gas temperature	Digital thermometer	Minipa (MT-525)	0 to 700 °C	± 5 °C
Ambient humidity	Digital hygrometer	Icel (HT-208)	0 to 100 %	± 3%
Fuel consumption	Digital scale	Mettler Toledo (9094)	0 to 45 kg	± 2%
Exhaust gas (NO_x)	Gas analyzer	COSA (Optima 7)	0–1000 ppm	± 5%
Exhaust gas (CO)	Gas analyzer	COSA (Optima 7)	0–4000 ppm	± 5%
Exhaust gas (THC)	Gas analyzer	NAPRO (PC-Multigás)	0–500 ppm	± 3%

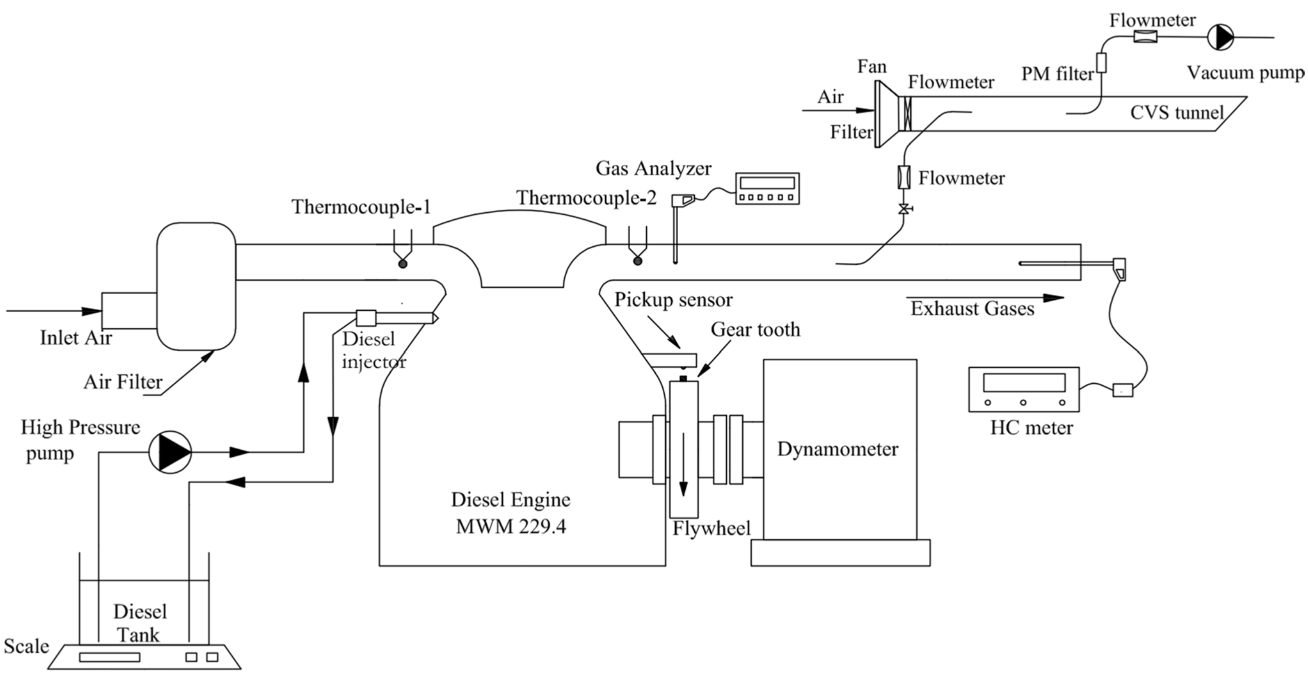

Fig. 1 Assembly and CVS details

higher loads the PM emissions are higher, avoiding filter saturation

2.2.1 Uncertainty analysis

In the experimental tests, several chances for errors and uncertainties are possible, due to factors as calibration, observation of the operator, working condition and weather condition. In order to enhance the confidence level of the experiments, the tests were carried out under similar system conditions for all fuels, such as engine temperature and weather (ambient temperature, 26± 4 °C and relative humidity of 64 ± 4%).

All tests were performance in triplicates. In each test, five measurements were performed. In the assessment of uncertainties, the single-sample method described in MUFFAT [23] was used as a reference. The graphics presents the main value and the confidence interval at the error bars. The uncertainties present for the various instruments used are given in Table 4.

2.3 Maximum torque and power

The maximum engine torque and power were evaluated for each fuel at five engine speeds: 1400, 1600, 1800, 2000 and 2200 rpm. The engine was kept at full load in each engine speed for 3 min. These tests were performed at an ambient temperature of 26± 1 °C and humidity of 64 ± 2%.

2.4 Fuel composition and properties

The primary fuels used for blends were fossil diesel (D100), soybean biodiesel (B100), ethanol (99.3% purity) and diethyl ether (DEE) (99.7% purity). The fossil diesel used was an S-10 class (maximum sulfur content of 10 ppm). The diesel and biodiesel were supplied by Petrobahia®. Table 5 shows the properties of the primary fuels.

Fossil diesel, ethanol, biodiesel and diethyl ether (DEE) were mixed in varying proportions, resulting in four fuels for the experimental tests, as given in Table 6.

Table 5 Properties of the primary fuels used in the tests

Property	Diesel (D100)	Biodiesel (B100)	Diethyl ether (DEE)	Ethanol (99.3%)
Oxigen content (% wt)	0	10.8	21.6	34.7
Density (20 °C)	0.8400	0.8778	0.7130	0.7860
Viscosity (cSt)	3.30	4.95	0.23	1.20
Flash point (°C)	96	158	− 45	15
Cetane number	46.0	55.9	125	6.5
Low heating value (MJ/kg)	42.50	37.46	36.87	28.40
Enthalpy of vaporization (kJ/kg)	260	200	356	836

Table 6 Volumetric composition of fuels and their lower calorific value

Fuel	D100 (%)	B100 (%)	Ethanol (%)	DEE (%)	H/C	LHV (MJ/kg)
D100 (S10)	100	0	0	0	1.80	42.50
B20	80	20	0	0	1.79	41.46
B20E	72	18	10	0	1.76	40.24
B20E + DEE	68.4	17.1	9.5	5	1.83	40.09

The ethanol and DEE properties were obtained by the literature review [18, 24]. For the D100 and B100, properties were determined experimentally. The CN was determined based on the standard ASTM-D613-CFR-ce-tane. An automatic calorimeter model C-2000 manufactured by IkaWorks was used to determine the LHV based on the standard ASTM-D240-87. The fuel density was obtained using a densimeter model 5000 manufactured by DMA-Anton Paar®. The viscosity of the samples was measured by a capillarity viscometer model P manufactured by Techmeter®. The properties flash point and latent heat of vaporization were obtained by the literature review. Oxigen content was calculated based on the molecular composition.

The LHV values given in Table 6 were calculated based on the values presented in Table 5. The fraction of biodiesel applied (20%) was chosen in order to permit the miscibility between diesel and ethanol, which is limited to low quantities [10, 13, 25]. The amount of ethanol in the blend B20E was chosen to avoid major differences in viscosity, LHV and CN in relation to fossil diesel. The fraction of DEE was chosen based on the previous literature reviews which reported better results using lower fractions of DEE in EBD blends [11, 18].

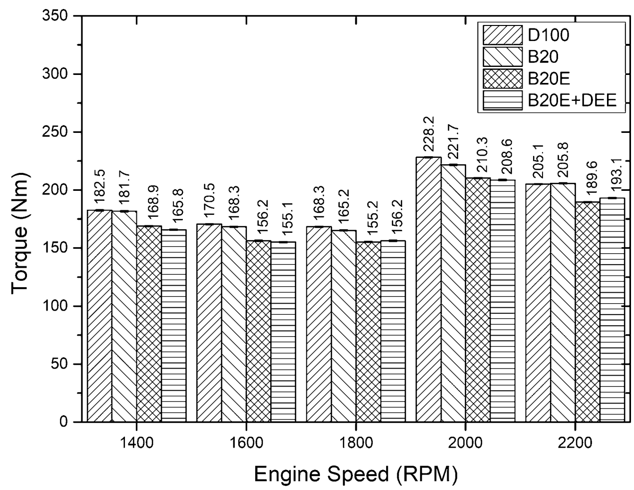

Fig. 2 Maximum brake torque for the fuels

3 Results and discussion

3.1 Engine performance

3.1.1 Torque measurement

The maximum brake torque (MBT) results obtained for each fuel are presented in Fig. 2. A reduction in torque was observed when the diesel was mixed with biofuels at all engine loads. These results can be explained by the significant reduction in LHV when biodiesel, ethanol and DEE are added to the blends, and considering a mechanical fuel injection system.

The MBT observed for all fuels occurred at the engine speed of 2000 rpm. The air entrance (volumetric efficiency) is probably optimized in respect to the engine design configuration (valve diameter, combustion chamber design, air induction system) at this speed.

The use of the blend B20 decreased the torque (1.3% to 4.3%), in relation to D100, except at the engine speed of 2200 rpm, in which the torque increased by about 3.0%. The reduction in torque can be explained by LHV reduction in the blend B20 in relation to D100 (approximately 2.5%).

The elevation in torque at 2200 rpm, despite a lower energy content, can be explained by the higher CN and oxygen content, which can be used in the combustion, reason for a more complete combustion, especially in fuel-rich zones [26]. In addition, other properties such as higher viscosity (less internal leakage in the fuel pump), density, bulk elasticity modulus and sound velocity of biodiesel blend tend to increase the fuel density injected into the engine. Similar torque results using diesel and biodiesel blends have been reported in the literature [3, 26, 27].

The blends B20E and B20E + DEE presented similar torque results (differences less than 2.0%), despite the lower LHV (about 3.6%) of B20E + DEE. This can be explained by the higher volatility, CN, and oxygen content of B20E + DEE, which may cause a shorter ignition delay in relation to B20E, improving combustion quality [18]. These characteristics also may explain the higher MBT obtained for B20E + DEE at 1800 and 2200 rpm.

3.1.2 Brake-specific fuel consumption

Brake-specific fuel consumption (BSFC) is the ratio between mass fuel consumption and brake effective power. The BSFC is shown in Fig. 3.

The BSFC comparison is made at the same engine load and speed, which is translated into the same engine torque and power. Therefore, the BSFC values are effectively directly proportional to the fuel mass flow rate [22]. The different trend that appears in the BSFC test reveals the fuel conversion efficiencies.

In the case of B20, the blend presented an elevation of BSFC in relation to D100 in all engine load conditions (2.8% to 5.3%). This can be explained by the lower LHV. Considering the B20E and B20E + DEE, at 16 kW and 24 kW loads, the BSFC of B20E + DEE was lower than B20E. This better use of fuel energy can be attributed to the positive effects of the DEE properties of the blend, such as the higher CN and oxygen content compared to B20E, as well as lower viscosity and density, which can lead to diameter fuel droplet reduction, and thus, better atomization and air–fuel mixing, especially under higher load conditions [17, 28].

3.1.3 Engine efficiency

Figure 4 presents the engine efficiency obtained for all the fuel combinations tested.

At lower engine loads, a reduced wall temperature and residual gas temperatures prevail, which can lead to a lower charge temperature and increased ignition delay (ID) [18]. Considering the engine test condition of 8 kW, the D100 presented the highest engine efficiency. It can be assumed that, due to the longer ID caused by higher enthalpy of vaporization and lower CN, combustion starts later for B20E and B20E + DEE in comparison with D100 and B20.

As the load increases, the engine efficiency increases for all fuels. At higher engine loads, the magnitude of the cylinder temperature and pressure increase providing a better environment for fuel atomization and combustion quality [28]. In addition, there is a decrease in ID and an increase in the duration of combustion (DOC) for diesel and blended fuels. The ID is reduced due to higher in-cylinder temperature and the DOC increase is due to more fuel injection at higher loads [29].

At intermediate test condition, 16 kW, the highest engine efficiency was obtained with D100 (similar with the blend B20E + DEE). The improved spray atomization and faster fuel vaporization by the DEE in the blend may result in higher engine efficiency [1, 30]. Additionally, the higher CN (in relation to B20E) and oxygen content of the B20E + DEE improve the combustion process. Damodharan

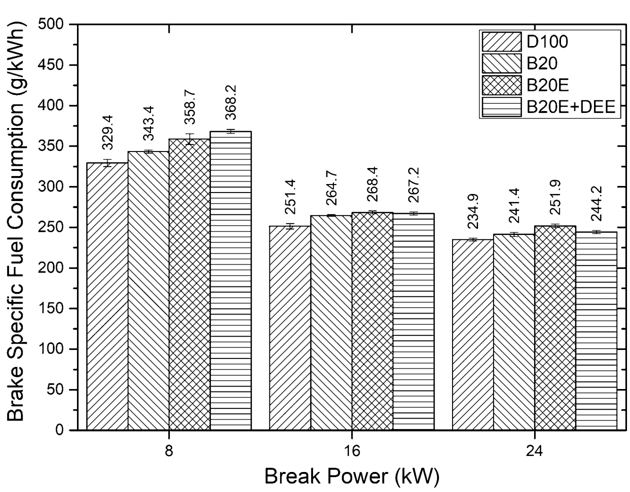

Fig. 3 Brake-specific fuel consumption

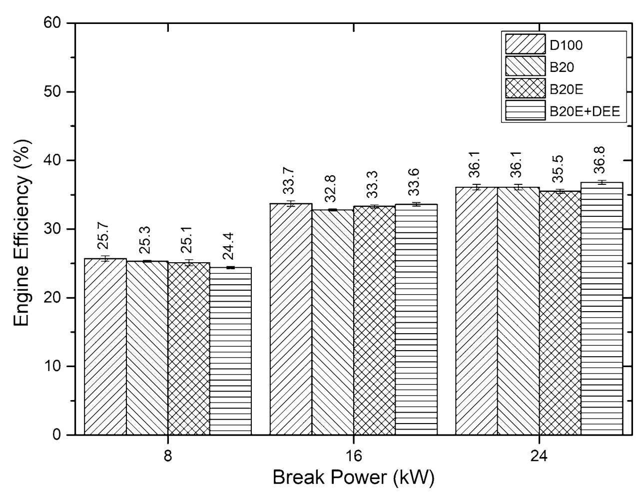

Fig. 4 Engine efficiency

et al. [31], report that the better oxygenated nature of the fuel enables provision of additional oxygen even at fuel-rich zones delivering a better combustion quality. At a BP of 24 kW, the highest engine efficiency was observed with the blend B20E + DEE. This highlights some characteristics for the good performance of the mixture, such as fuel jet viscosity, CN and high volatility, which overcame technical drawback that may influence the engine efficiency negatively. In general, the engine efficiency of the biofuels was higher at higher loads.

3.2 Emissions analysis

3.2.1 NO_x emissions

NO_x formation depends on factors such as peak combustion temperature, local oxygen concentration and oxidation of intermediate combustion products such as hydrogen, carbon and nitrogen content in the fuel [6]. Figure 5 represents the NO_x emissions obtained for all the fuels tested. According to Fig. 5, there is an increase in NO_x emissions for all fuels with increased load. This is due to a higher in-cylinder combustion temperature which increases the NO_x formation by the thermal mechanism [9, 32]. At low engine loads, more air cools down the combustion chamber, resulting in lower NO_x emissions.

Considering blend B20, the NO_x emissions increased when compared to D100, about 13.1% (8 kW), 0.9% (16 kW) and 3.2% (24 kW), respectively. This is probably attributed to the higher temperature caused by the greater quantity of fuel that results from an advanced fuel injection which is derived from the physical properties of the biodiesel, such as viscosity, density, compressibility (bulk modulus of elasticity) and sound velocity [10]. Additionally, the higher oxygen content and CN of B20 may also

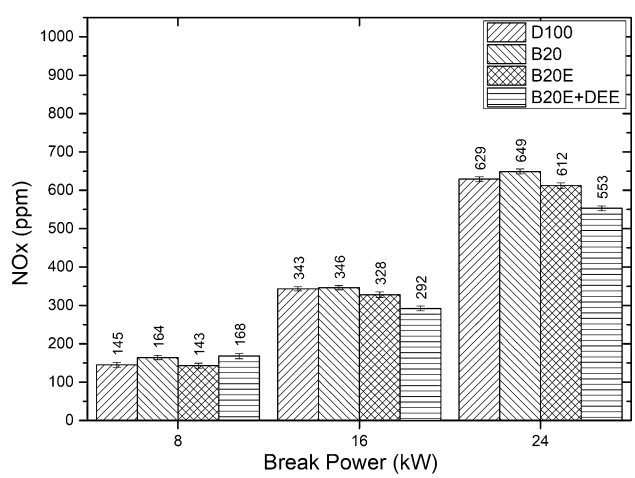

Fig. 5 NO_x emissions

anticipate the start of ignition, reducing ID, improving combustion which increases the in-cylinder temperature and NO_x emissions [5]. Similar results for NO_x increase using similar biodiesel–diesel blends were also obtained by Abed et al. [9] and Kim and Choi [33].

The introduction of ethanol, blend B20E, led to a reduction in NO_x emissions in relation to D100 (1.4–4.4%) and B20 (2.4–12.8%). This reduction may be attributed to the lower LHV and higher latent heat of evaporation of the ethanol, which cause a reduction in the combustion peak temperature [34]. The higher latent heat of vaporization of ethanol has a dominant effect of reducing the combustion temperature; however, the oxygen content and lower cetane number may cause a longer ID, leading to higher temperatures during the premixed combustion phase [35].

The lowest NO_x emissions with the loads of 16 kW and 24 kW were observed when blend B20E + DEE was used. A combined action of DEE and ethanol further increases the latent heat of vaporization and the volatility of the mixture and this forms several ignition centers within the combustion chamber, which reduces the overall mixing and reaction time followed by lowered combustion duration [16].

At the lowest load (8 kW), the NO_x emission of B20E + DEE increased by about 13% in relation to B20E. At this load (leanest mixtures), it is supposed that a more pronounced O_2 concentration, higher CN easier evaporation should have improved oxidation and the combustion rate for the blend B20E + DEE. A similar result for NO_x emissions with EBD and DEE blends was observed in Venu and Madhavan [18].

3.2.2 CO emissions

In general, diesel engines operates well over the lean mixture zone. Blends using ethanol and DEE result in changes in combustion characteristics as ignition timing, fuel spray atomization, oxygen content, oxidation rate, cylinder temperatures and ignition center formation, which influences the CO formation [18].

Figure 6 presents the results of CO emissions of the fuels. The increase in CO at the lowest load is due to lower in-cylinder temperature and consequent delayed combustion process, that may suppress the oxidation process even though enough oxygen is available for combustion [35].

The blend B20 presented a reduction in CO emissions compared to D100: 3.8%, 12.1% and 9.1%, at 8, 16 and 24 kW, respectively. This can be explained by the higher CN and oxygen content of B20 which improve the combustion quality [9, 18]. The decrease in CO emissions using B20 blends was also observed in Karabektas et al. [32].

In the case of the blend B20E, despite the increase in oxygen content in the blend, the CO emissions increased in relation to B20. This may be attributed to the decrease in

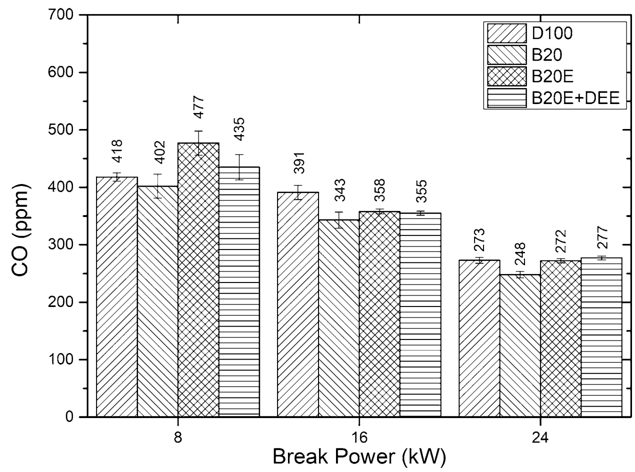

Fig. 6 CO emissions

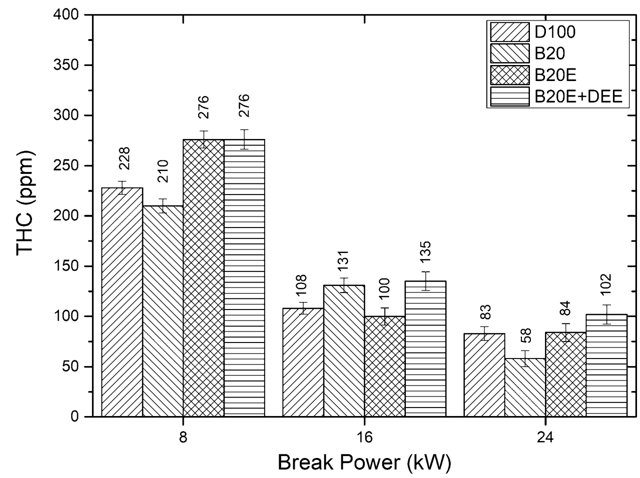

Fig. 7 THC emissions

combustion temperature due to the high latent heat of the evaporation of ethanol [15, 35]. Another reason is the lower CN of blend B20E, which increases the combustion ID and reduces the high temperature duration, which reduces the CO oxidation [36].

Regarding blend B20E + DEE, it presented lower CO emissions at the loads of 8 kW and 16 kW in comparison to B20E. This reduction, comes from the higher CN, volatility and easier evaporation of the DEE, allied with the higher oxygen content of the resultant blend. This leads to a more complete combustion, thus, decreasing CO emissions [37]. A small increase was observed for the load of 24 kW, however.

3.2.3 THC emissions

Figure 7 shows the THC results obtained for the fuels. A decrease in THC levels can be observed when the load is increased.

Blend B20 presented the lowest THC emissions among all the fuels at loads of 8 kW and 24 kW. This can be explained by the increases in the oxygen content and CN due to the presence of biodiesel, which may improve the combustion quality in relation to D100.

The blends B20E and B20E + DEE presented increases in THC emissions in relation to D100 and B20. This can be explained by the high latent heat of vaporization and low CN of ethanol, which may result in a cooling effect and incomplete combustion, resulting in more THC emissions for the blend B20E. Damodharan et al. [30], reported that the high heat of evaporation (enthalpy of evaporation) by alcohol causes flame quenching zones where combustion cannot occur easily, resulting in an increase in hydrocarbons. Even with the introduction of DEE, the cooling effect of ethanol seems to have a predominant effect on THC emissions, despite the elevation of CN and volatility due to the DEE [18].

3.2.4 PM emissions

Particulate matter is a result of incomplete combustion from the CI engine due to factors such as higher fuel viscosity, higher C/H ratio, poor atomization, excessive fuel accumulation in the combustion chamber or a low combustion temperature [16]. Figure 8 shows the results of PM emissions for the fuels tested.

In general, PM mass is lower for the biofuels blends compared to fossil diesel. As biodiesel is free of aromatics, lower affinities with smoke for biodiesel blends reducing particulate matter are expected [27]. In addition, the oxygen content leads to more oxygen areas in the combustion process and sulfur free of biodiesel (which is a soot precursor) which are

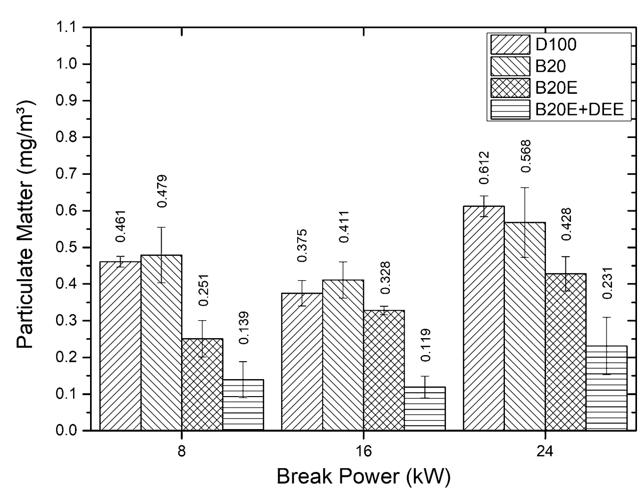

Fig. 8 PM emissions

also responsible for PM reduction [38]. The tests performed using B20 presented a PM reduction at the load of 24 kW of 7.2% in relation to D100. However, the results were higher than D100, about 4.2% and 9.4% at loads of 8 kW and 16 kW, respectively. Poorer atomization during injection has been indicated as the main cause for the increase in PM emissions in these conditions [39].

The blends B20E and B20E + DEE presented a reduction in PM compared to D100 and B20, at all tested loads. The elevated oxygen content of ethanol and DEE effectively delivered oxygen to the pyrolysis zone, reducing PM and smoke generation [40]. Additionally, the OH radicals of ethanol contribute to the reduction in soot precursors. Furthermore, the low surface tension may improve the fuel spray quality, reducing the overall PM emissions [11]. The blend B20E + DEE showed the lowest PM emissions in all test conditions. In addition to the effects of the ethanol in the blend, the higher CN, volatility and additional oxygen content of the DEE contribute to better fuel burning and therefore a reduction in PM [20].

4 Conclusions

An experimental study was conducted in order to evaluate the effects of the introduction of ethanol and DEE in blends with fossil diesel and biodiesel using a four cylinder MWM mechanical injected diesel engine. The performance and emissions were compared to those obtained with fossil neat diesel (D100) and B20. The introduction of ethanol (10% v/v) in a B20 blend resulted in an average 7.8% and 6.7% reduction in maximum torque in relation to D100 and B20, respectively. The lower energy content of ethanol can explain these results. Reductions in NO_x and PM emissions in relation to D100 and B20 were observed in all engine conditions. The high latent heat of vaporization and the oxygen content of ethanol may explain these results. CO and THC emissions increased at low loads (8 kW) in relation to D100 and B20. At 16 kW and 24 kW, the results did not show any clear trend.

The addition of DEE (5% v/v) in a diesel–biodiesel–ethanol blend did not significantly change the maximum torque value. A high cetane number and the additional oxygen of DEE probably compensated for the low energy content of the fuel. The NO_x emissions presented the lowest values for B20E + DEE at loads of 16 kW and 24 kW. With regard to the CO emissions, these did not show a clear trend, with variations depending on the load, while THC emissions presented the highest values at all loads for B20E + DEE. PM emissions drastically decreased (down to 71%) due to the high cetane number, volatility and the additional oxygen content of DEE. The engine efficiency was similar for all the fuels tested, and at higher engine loads, B20E + DEE presented the highest efficiency.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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