Chapter 2

Effect of Waste Cooking Oil Biodiesel Blends on Performance and Emissions from a CRDI Diesel Engine

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Additional information is available at the end of the chapter

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Abstract

The employment of biofuels in blends with diesel oil proved to attain a reduced environmental impact without compromising the engine performance. Among biofuels, waste cooking oil offers the advantages of its reduced raw material cost in comparison with fresh vegetable oil cost; it also eliminates the environmental impacts caused by its disposal. Although a great number of researches has been devoted to biodiesel combustion in engines and pollutant emissions, few studies can be found on light duty diesel engine equipped with up-to-date technologies. This work aims at investigating the impact of waste cooking oil percentage in blends with diesel oil on the performance and emission characteristics of an up-to-date light and compact common rail diesel engine whose main application is in microcars and in urban vehicles. A comprehensive experimental activity was performed in the engine complete operative field. The comparison of the results with those obtained with standard ultralow-sulfur diesel highlighted that the engine performance was quite similar for B20 and diesel oil. B40 suffered for the lower caloric value in regard to diesel. A reduction in CO and HC was obtained with biodiesel blends, along with an increase in NO_x. Particulate emissions were also reduced for biodiesel blends; the mean size of particles was smaller as regards diesel oil.

Keywords: diesel engine, biodiesel blend, waste cooking oil, pollutant emission, particulate emission

1. Introduction

In the frame of complying with the emission regulations that become day by day more and more stringent, researchers have focused their interest on areas of fuel injection control strategies, exhaust gas recirculation, exhaust gas posttreatment devices, and also on areas of alternative fuels.

Alternative fuels from vegetable oils and animal fats have been proposed for a partial and total replacement of diesel fuel to reduce the environmental impact in terms of air pollution and dependence on fossil fuel.

Among these fuels, biodiesel from vegetable oils has received great attention for its renewability and its potential to reduce greenhouse gas emissions and soot formation [1–4].

Experimental investigations have highlighted that biodiesel used in blends with diesel is responsible for a reduction in unburned hydrocarbon, carbon monoxide, and particle emissions due to the increased oxygen content in the fuel [4–8]. In regard to NO_x emission, somehow contradictory conclusions were found, since there are numerous factors, each has its own relative importance according to the engine technology and operating conditions of the blended fuel [9–13]. Physical properties, chemical composition, and structure of the biodiesel alter the fuel injection and ignition process, and then the combustion development and the engine exhaust emissions [14–18]. Many studies proved that biodiesel feedstock and blend ratios have a large impact on obtained results. Peng [2] tested various types of biodiesel on a turbocharged diesel engine; he found smoke opacity, CO and HC decreased, but fuel consumption increased compared to petrol diesel. Serrano et al. [11] analyzed the behavior of an EURO 5 engine fuelled with two biodiesel blends (7 and 20% v/v). Fuel consumption was not consistently increased with biodiesel; NO_x emission with biodiesel use did not present significant rise. Yehliu et al. [19] investigated the impact of fuel properties and injection strategy on the combustion process and soot emission. Three fuels were tested on a turbocharged diesel engine, and particle size distribution was measured. Ajtai et al. [20] studied the effect of fuel type and engine condition on number and size distribution of diesel soot. They found that the biodiesel content in the total fuel amount can modify the characteristics of the exhaust particles.

Among all suitable biodiesel fuels, waste cooking oil (WCO) has been considered a promising alternative to vegetable fresh oil because of its reduced raw material cost (the price of WCO is two to three times cheaper than virgin vegetable oils [21]). Moreover, WCO conversion into fuel offers the advantage of eliminating the environmental impact caused by its disposal. Previous studies demonstrated the suitability of WCO as a biofuel. Attia and Hassaneen [12] studied the effect of various WCO blends on the performance of a single-cylinder diesel engine. The best value of a brake specific fuel consumption was attained at blended fuel containing 20% of WCO. A range of blending ratio between 20 and 50% v/v showed the best environmental behavior. Gopal et al. [22] investigated the performance and emission characteristics of a single-cylinder diesel engine designed for agricultural purpose fuelled with WCO and its blends. The study revealed that WCO has lower CO, HC, and smoke opacity than diesel. On the other hand, NO_x and specific fuel consumption were higher than diesel. An et al. [23, 24] evaluated the influence of WCO biodiesel/blends on combustion and exhaust emission characteristics of a four-cylinder turbocharged diesel engine. The results showed that the use of WCO resulted in higher brake specific fuel consumption with regard to the exhaust emissions; the use of WCO generally resulted in a lower CO_2 and HC; under most of the operating conditions, NO_x produced by biodiesel (100% v/v) was lower compared to that of diesel fuel. Can [25] experimentally investigated the combustion development of a single-cylinder diesel engine fuelled with WCO blended in 5 and 10% with diesel fuel. An increase in NO_x emissions and a decrease in smoke and HC was found. Cheung et al. [26] analyzed the impact on the emissions from a diesel engine at fixed engine speed fuelled with diesel blended with different proportions of biodiesel from WCO. The results showed that biodiesel leads to a reduction in HC, CO, and particulate mass concentration and number concentrations, but an increase in NO_x. Man et al. [27] studied the effect of diesel operating conditions on the particle size emitted by a diesel engine operating with WCO biodiesel. They found more particles with larger size at lower engine speed; primary particles tend to form at lower engine load. Hwang et al. [28] investigated the combustion and emission characteristics of WCO and conventional diesel fuel in an optically accessible diesel engine. WCO had the benefits in CO, HC, and PM reduction at low load. In the high engine load, the emission characteristic of WCO was deteriorated than that of diesel.

Although the research on biodiesel combustion and emissions is considerable and many studies are related to the usage of WCO in diesel engines, they mainly focused on multicylinder-diesel engine of large displacement. Only some works are devoted to light-duty diesel engines, designed for agricultural purpose, and the results are mainly related to a fixed value of engine speed and load.

The main aim of this research is to analyze in detail the impact of WCO used in different percentages with diesel oil in an up-to-date light and compact, common rail diesel engine whose main application is in microcars and in urban vehicles. A comprehensive experimental activity was performed in the engine complete operative field in order to characterize the engine performance and emissions. NO_x, CO, CO_2, HC, and soot concentration were analyzed. The influence of WCO content in the blend on the particle emissions was also investigated, in terms of soot particles' size distributions.

2. Apparatus and tests

2.1. Experimental setup

A common-rail water-cooled two-cylinder diesel engine was tested in this study. Its main technical data are presented in **Table 1**. The engine was connected to an asynchronous motor (Siemens 1PH7, nominal torque 360 Nm, power 70 kW) and was installed in the test bed of the Engineering Department at Roma Tre University.

Torque measurement was carried out by means of HBM T12 (it is a strain gauge transducer with an optical encoder).

AVL Fuel Balance 733 was used for fuel consumption measurement.

The in-cylinder pressure was measured with a piezoelectric transducer AVL GU13P.

Engine type	Common rail, naturally aspirated, water-cooled
Cylinders	2
Displacement	440 cm^3
Bore	68 mm
Stroke	60.6 mm
Compression ratio	20:1
Maximum power	6.7 kW @ 3600 rpm
Maximum torque	20 Nm @ 2400 rpm

Table 1. Engine specifications.

The engine exhaust emissions (CO, CO_2, HC, O_2, and NO_x expressed as NO equivalent) were measured with Bosch BEA352. AVL particle counter (APC) and AVL micro soot sensor were used to measure the nonvolatile particle number concentration in the size range 23 nm–2.5 μm and the soot concentration in the engine exhaust gas, respectively. Particulate matter size was measured through Cambustion DMS500. This device uses a classifier column to compute the particle size distribution in the range 5 nm–1 μm, with a size resolution of 16 channels per decade. Exhaust gas passes first through a cyclone separator in order to remove particles above the measurement range (1 μm). Two stages of dilution are applied before the sample gas passes through a corona charger and into the classifier column. Primary and second dilution rates were set to 5:1 and 400:1, respectively. The charged particles flow within a particle-free sheath flow and are deflected toward grounded electrometer rings by their repulsion from a central high voltage rod. Their landing position is a function of their charge and their aerodynamic drag. Further details may be found in Ref. [29].

The engine speed was measured using an angular sensor (AVL 364C) with 2880 pulses/revolution.

Figure 1 shows the complete engine setup.

The sampling frequency was varied according to the engine speed in order to ensure a fixed angular resolution of the signals.

Data acquisition was controlled by means of LabVIEW software, by using a custom program [30].

2.2. Fuel

A second-generation biodiesel was used in the experimentation. It was obtained starting from a mixture of waste cooking oils. Due to its poor quality, it required some treatments in order to become similar to a product obtained from refined vegetable oils. A first-stage self-cleaning disk separator was used to remove 90% of the water containing the water-soluble matter and solids; a second-stage disk separator machine was used to remove the left over water. Physical deacidification was also needed to remove free fatty acids (FFA) due to product deterioration as a consequence of the use in food cooking. The neutralized products were then converted via

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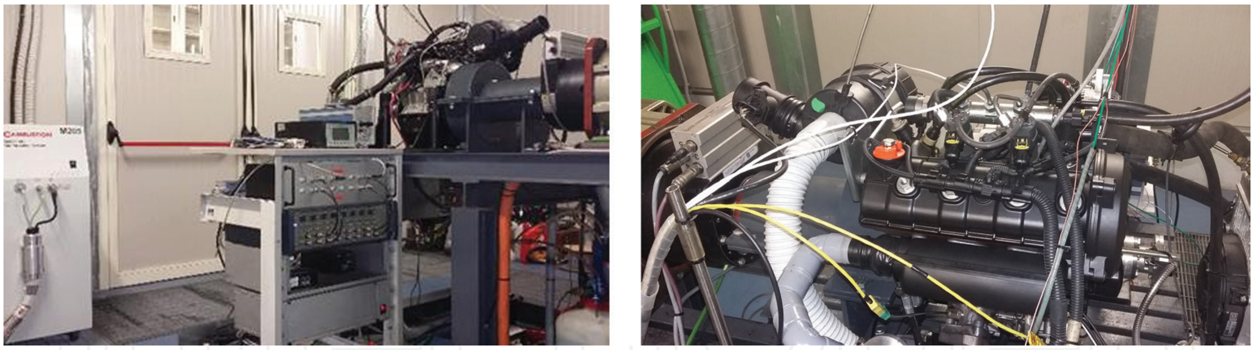

Figure 1. Engine setup.

a transesterification process. The resulting raw biodiesel, coming from poor raw material, was distilled in order to comply with the reference specifications of biodiesel (EN 14214). Details of the procedure may be found in Ref. [31]. The properties of the biodiesel and ultralow-sulfur diesel (ULSD) are listed in **Table 2**. The chemical composition of WCO is reported in **Table 3**.

2.3. Experiments

Since the aim of this work was to investigate the potential use of biodiesel blends in a small displacement diesel engine, some preliminary investigations were performed with the objective of selecting the maximum percentage of WCO in the blend that was able to be tested without the need of modification to the engine hardware. It was established that 40% of WCO in the blend was the highest quantity of biodiesel that could be tested, since higher percentage of biodiesel in the blend caused a degradation of the rubber hoses/seals in the engine fuel system. The experimentation was thus performed with a biodiesel percentage lower than 40% by volume: standard ultralow-sulfur diesel, B20 (80% ULSD and 20% biodiesel, by volume), and B40 (60% ULSD and 40% biodiesel, by volume) were tested. This allowed the investigated blends to be ready for use in actual engine. Before each new fuel was tested, sufficient time was given to the engine to consume the remaining fuel in the supply system.

Engine speed was varied in the engine complete operative range (2400–3600 rpm).

Load condition was varied in the field 50–80% as regards the available torque at full-load condition evaluated using diesel fuel. The maximum value was established by testing the engine with the different blends and by computing the load that are able to ensure the same value for all the tested fuels.

	ULSD	Biodiesel
Density [kg/m^3 at 15°C]	830	877
Viscosity [cSt at 40°C]	2.5	4.4
Lower heating value [MJ/kg]	43.1	37.1
Cetane number	52	56

Table 2. Biodiesel and ULSD fuel properties.

Mass fraction	Biodiesel
Carbon	0.812
Hydrogen	0.065
Oxygen	0.117
Sulfur	0.006

Table 3. Biodiesel composition.

The data acquisition started after the engine warm-up in order to let the engine reach nominally stationary conditions. For each running condition, 25 engine cycles were used to average the signal, thus to attenuate the engine cycle irregularities (the increase in this number did not change the feature of the trends).

3. Results

Experimental results obtained with WCO blends are shown and discussed with the aim of highlighting the characteristics of performance (torque, brake specific fuel consumption, brake thermal efficiency) and pollutant emissions (NO_x, CO, CO_2, HC, soot concentration, particle number concentration, particle size distributions).

Figure 2 shows the variation of engine torque with speed at full-load condition for diesel fuel, B20, and B40. The torque trend at full-load condition depends on the percentage of biodiesel in the fuel; since WCO has a lowering heating value than ULSD, the engine torque values related to B40 are the lowest at all engine speeds.

In order to allow the comparison between data obtained for the different fuels, it was established to perform tests at 80% of full load evaluated using diesel fuel, so as to impose the same value of load to the engine for all tested fuels.

Figure 3 shows the variation of brake specific fuel consumption (BSFC) with engine speed for 100% load. The fuel consumption increases with the content of WCO in the fuel. This is to attribute to the reduction in energy content in the biodiesel as regards diesel fuel. The average increase in BSFC over all engine speed values is 3.9% for B20 and 7.1% for B40.

Brake thermal efficiency (BTE) versus engine speed is plotted in **Figure 4**. It was evaluated by computing the ratio of the brake power to the power provided by the consumed fuel at full-load condition. The differences in the B20 and B40 averaged values are only about 1% as compared to diesel fuel.

Exhaust temperature is a very important indicator of the combustion process and has a key role in the formation of pollutants. **Figure 5** presents the variation of exhaust temperature with engine speed obtained with ULSD, B20 and B40 at 80% of load. The thermocouple was placed just downstream junction of the two-branches that connects the cylinders to the exhaust duct. All fuels are characterized by an increase of temperature with engine speed. The trends show a reduction in exhaust temperature with the increase in biodiesel ratio in the blend. This behavior

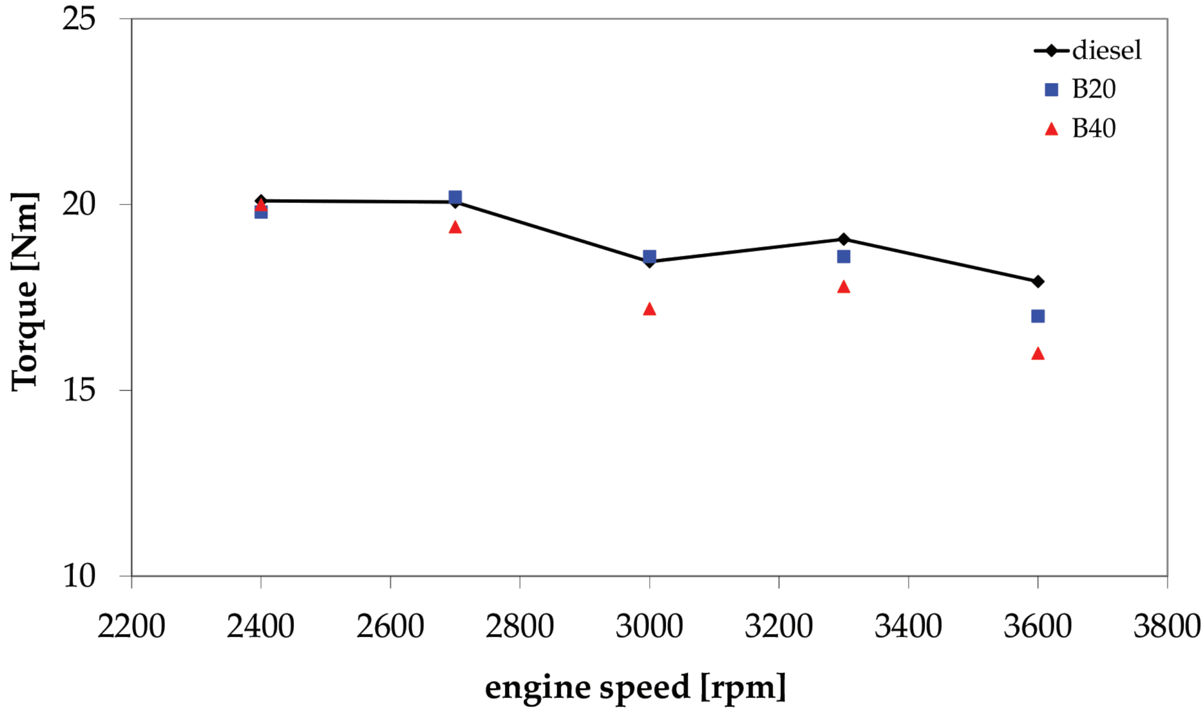

Figure 2. Variation of engine torque with engine speed [31].

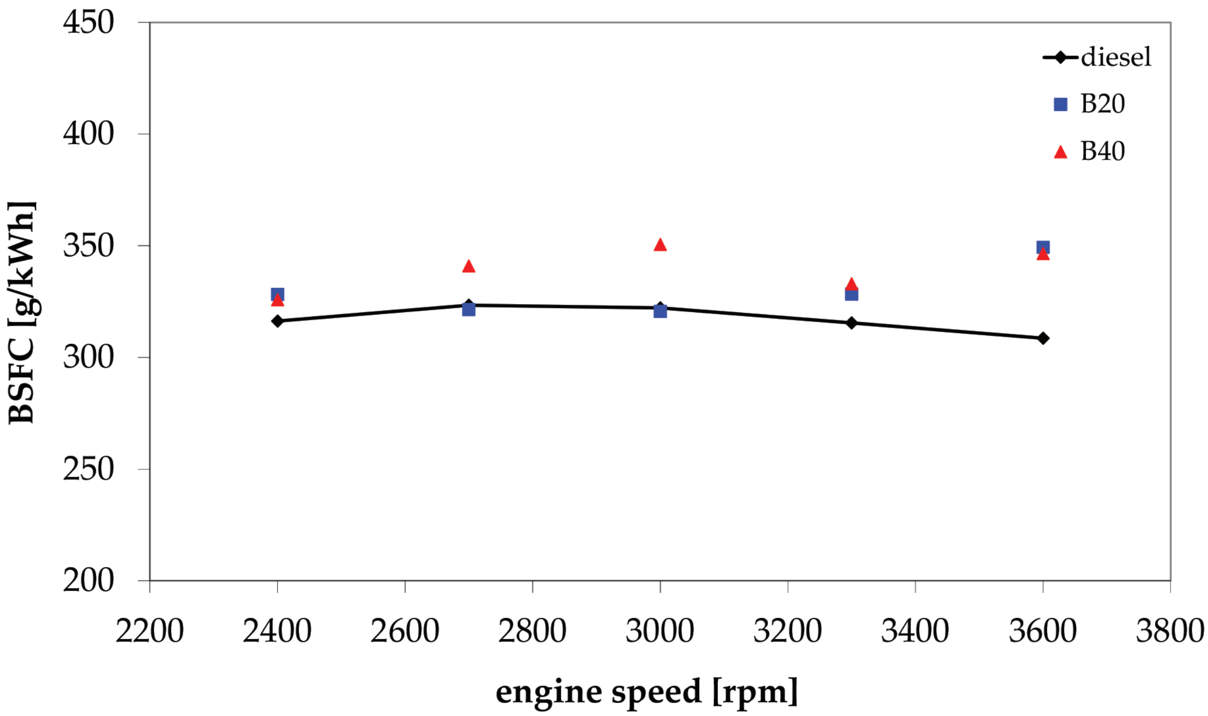

Figure 3. Variation of brake specific fuel consumption with engine speed [31].

is ascribed to the lower heating value of biodiesel, which reduces the amount of total energy released, thus reducing the combustion peak temperature and then the exhaust temperature. Data from literature are contradictory: some authors report that biodiesel has a higher combustion temperature as regards diesel fuel [13]; other authors assert the opposite behavior [23].

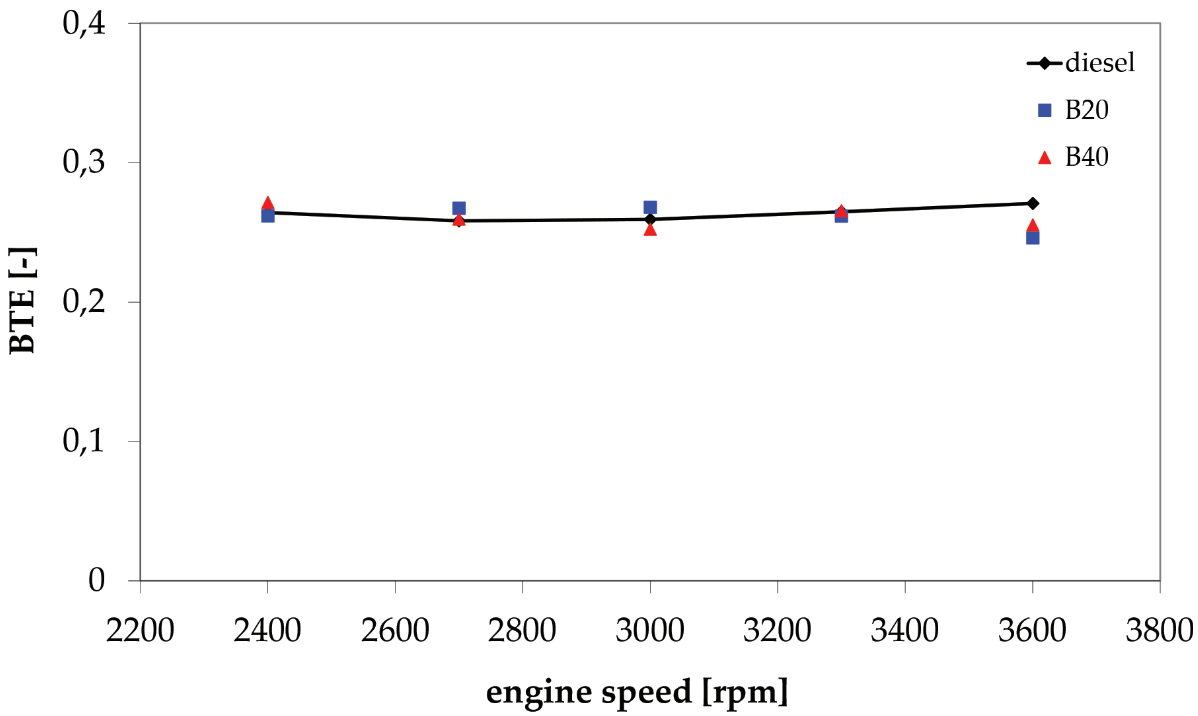

Figure 4. Variation of brake thermal efficiency with engine speed [31].

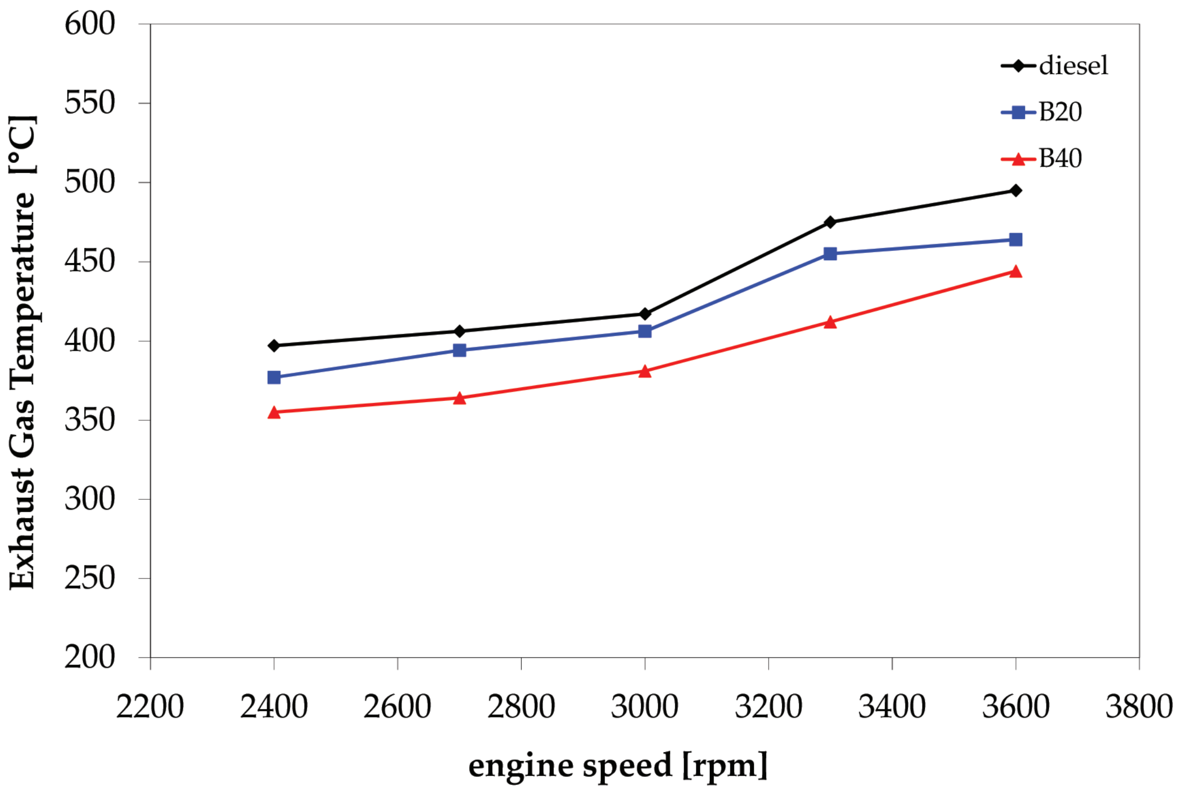

Figure 5. Variation of exhaust temperature with engine speed [31].

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Figure 6 shows the variation of NO_x emission with engine speed at a fixed value of load condition (80%). It is expressed as NO equivalent. All fuels exhibit a decrease in NO_x with the increase in engine speed, in agreement with literature [32]. This trend is due to the increase in the gas motion in the cylinder at higher engine speed that is responsible for a faster mixing between fuel and air and a shorter ignition delay. At higher engine speed, the residence time of high temperature within the cylinder is shortened and this causes a reduction in NO_x emission, in spite of the temperature trends shown in **Figure 5**. The traces in **Figure 6** do not exhibit remarkable differences; B40 shows the greatest increase in NO_x, which is evident for values greater than 3000 rpm. Such increase in NO_x emission can be explained by considering the effect of temperature, the differences in fuel chemistry, spray properties, and ignition delay that affect the duration of premixed and diffusion burn regimes [4, 9, 19].

In **Figure 7**, CO emission trends obtained at 80% load are shown. The oxygen content in the biodiesel blends enhances the mixing process between air and fuel, thus allowing a reduction in CO emissions for B20 and B40 as regards diesel fuel, in agreement with results from literature [7, 33].

Figure 8 presents the variation of HC emission with respect to the engine speed. The WCO content in the blend causes a reduction in emissions as regards diesel fuel, according to published data [7, 18].

CO_2 emission trends are shown in **Figure 9**. Similar behavior has been obtained for all tested fuels. The literature reports contradictory results in this field. Some authors [34] obtained

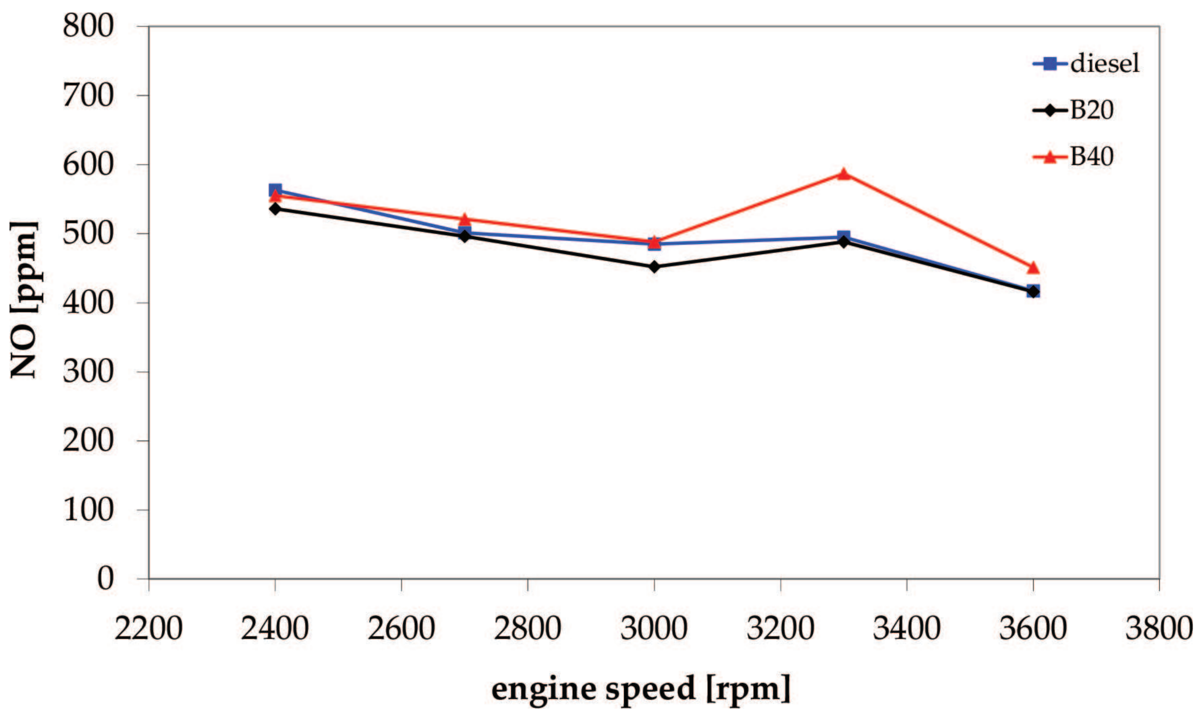

Figure 6. Variation of NO_x emission with engine speed [31].

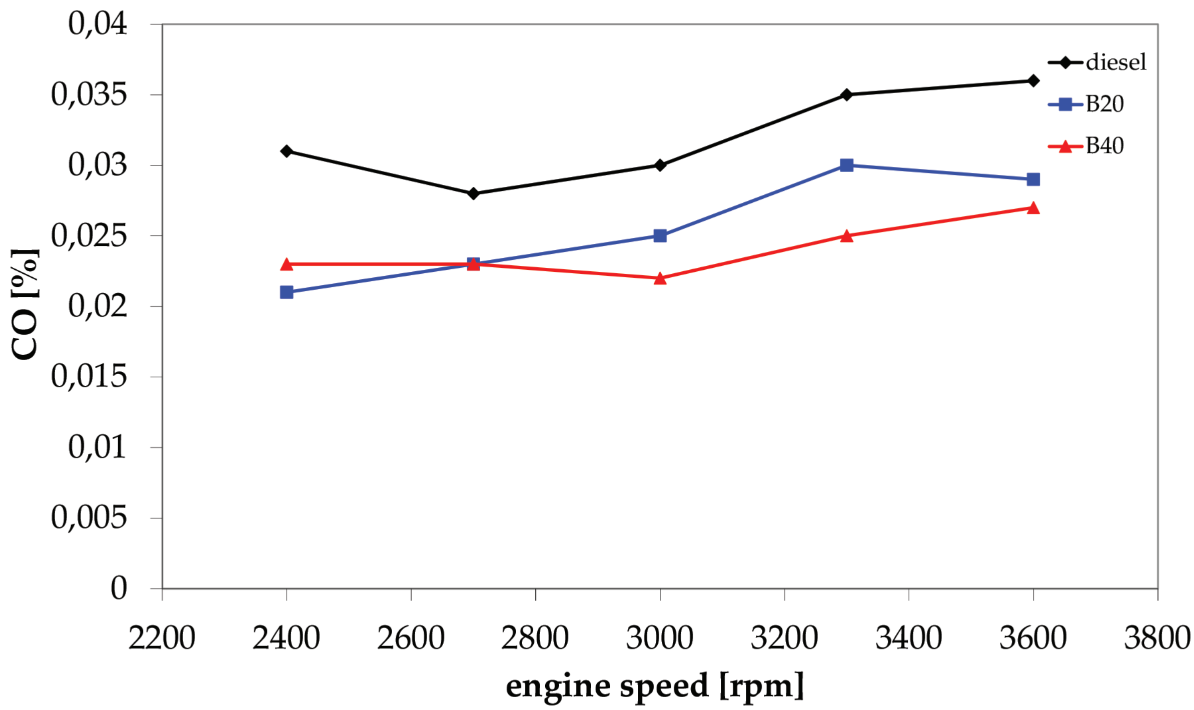

Figure 7. Variation of CO emission with engine speed [31].

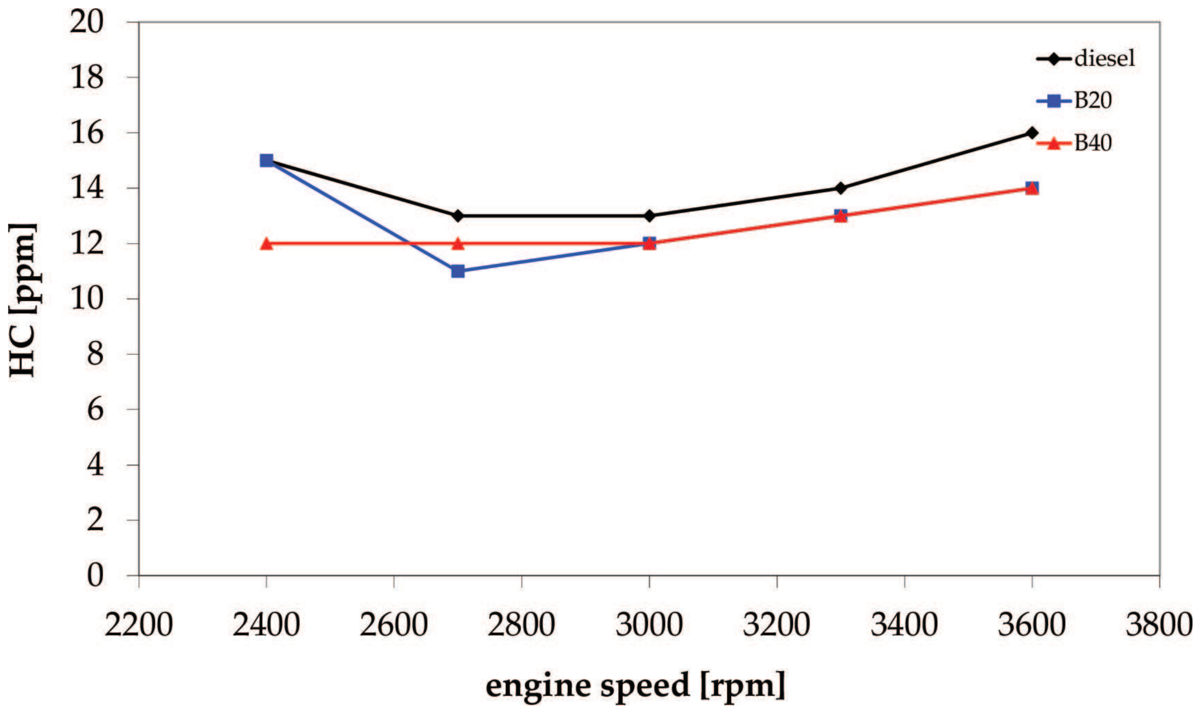

Figure 8. Variation of HC emission with engine speed [31].

an increase in CO_2 emission for biodiesel probably due to the higher density of biodiesel in comparison with diesel fuel, that increases the overall mass. Some studies [5, 23] report the opposite behavior as a consequence of the lower carbon to hydrogen ratio and the increase in oxygen content in the biodiesel blend.

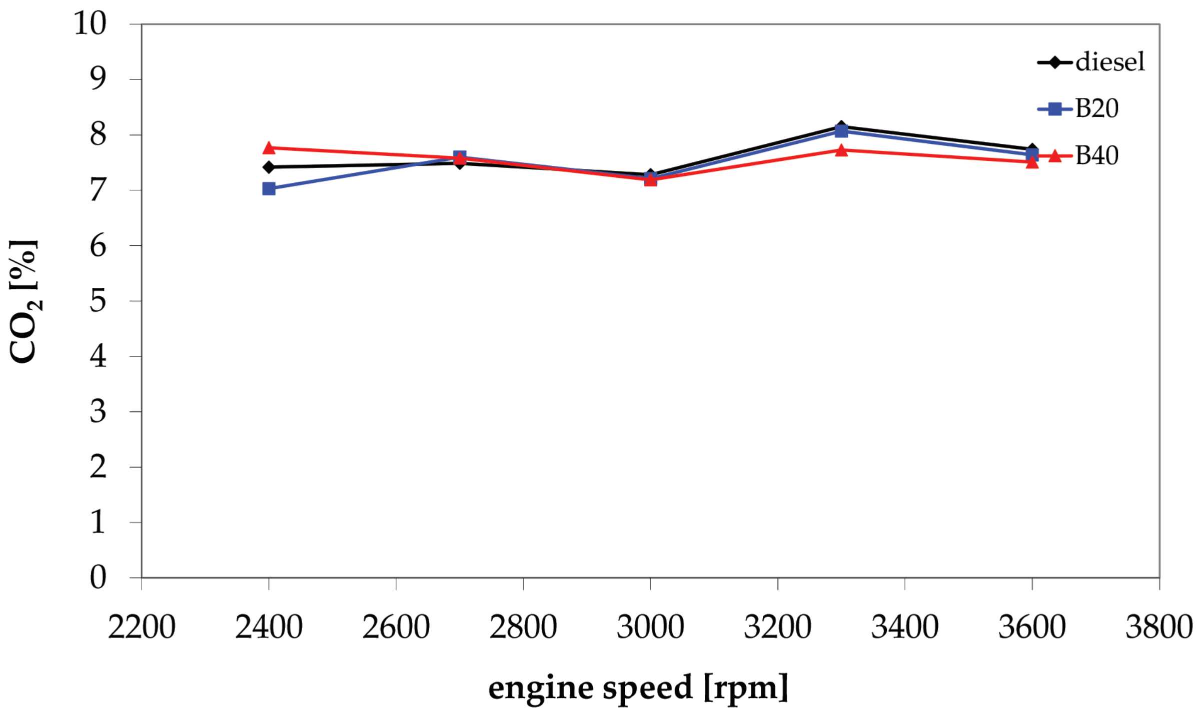

Figure 9. Variation of CO_2 emission with engine speed [31].

The following figures are devoted to analyze how the WCO content in the fuel affects the particle emission of the engine. **Figure 10** shows the nonvolatile particle number concentration (PNC) in the exhaust (all data have been normalized by the corresponding available engine output value). Each point is a cumulative value of particles in the range 23 nm–2.5 μm. The left-hand-side plot shows the variation of PNC with the engine speed at a fixed value of load (80%). The right-hand-side plot shows the effect of load condition at a fixed value of engine speed (3300 rpm). The traces highlight the reduction in soot emission obtained with B20 as regards diesel fuel. The increase in WCO ratio in the blend causes a further decrease in PNC. The obtained results are explained by accounting for many aspects. The higher density and viscosity of WCO blends as regards diesel oil are responsible for a variation of the injection process (smaller spray angle, larger droplet size, and fuel penetration length). Studies [12, 28] report that the injection setting has also a significant role in particle emission. Furthermore, the higher cetane number of WCO as regards diesel fuel causes a reduction in ignition delay and an increase in the mixing-controlled combustion duration. The higher oxygen content of biodiesel as regards ULSD promotes the combustion process and favors soot oxidation.

Figure 11 shows the effect of engine speed and load on soot concentration in the engine exhaust. The plots highlight the increase in the values as the engine speed increases for all tested fuels. Such a behavior is in agreement with similar results from literature [5, 19], and it is due to the concurrence aspects that have to be taken into account: a reduced time for air-mixing and combustion that penalizes the mixture uniformity and the combustion completeness. In addition, the increase in engine speed is responsible for an enhancement of the turbulence, which promotes the extent of complete combustion.

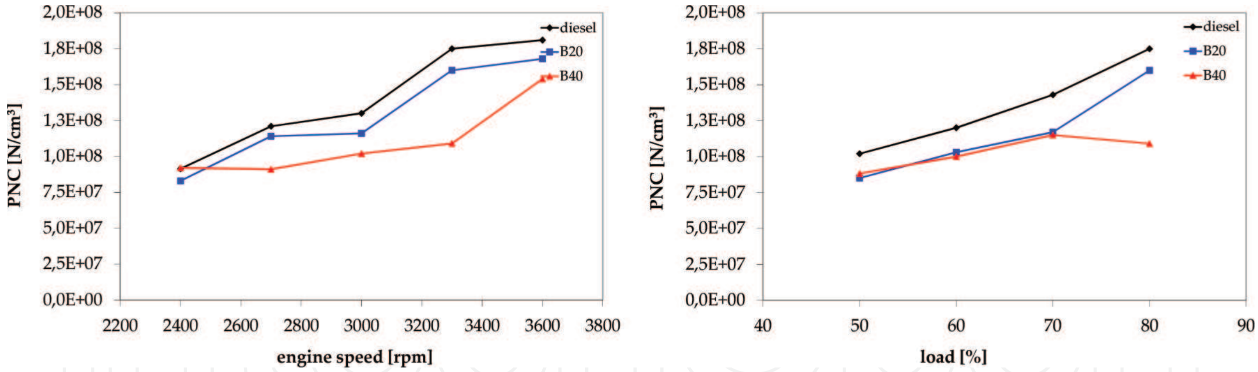

Figure 10. a): Particle number concentration at 80% load; b): particle number concentration at 3300 rpm [35].

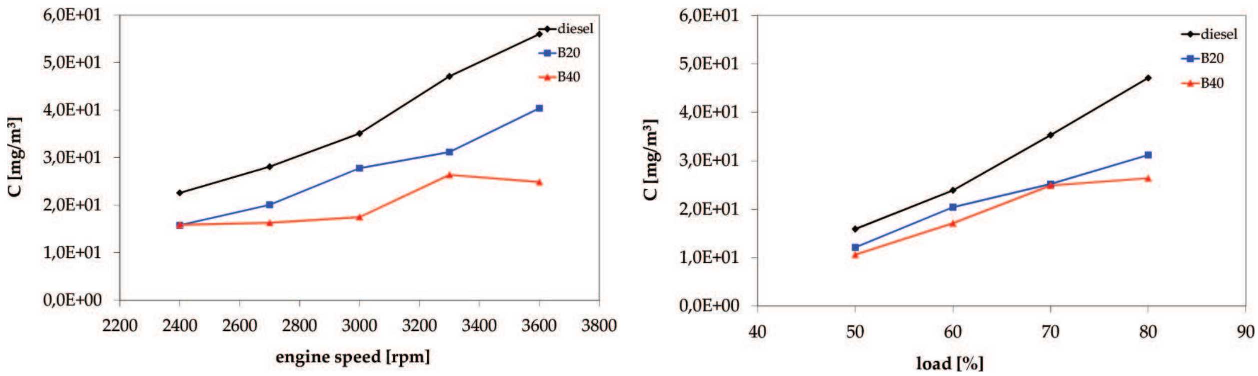

Figure 11. a): Soot concentration at 80% load, b): soot concentration at 3300 rpm [35].

The content of biodiesel in the fuel is responsible for a reduced particulate emission. This effect is ascribed to the increase in oxygen content in the blends that is responsible for a more complete combustion process and further oxidation of the already formed soot, according to Refs. [4–6, 8, 14, 19].

Figures 12–14 present the effect of blend ratio on the distribution of soot particles' diameters obtained during tests in which the engine was fuelled with ULSD, B20, and B40, respectively. In all plots, the data are expressed as size spectral density ($dN/dlogD_p/cc$). The left-hand-side plots show the variation of particle size obtained during tests in which the engine speed was varied at a fixed load condition (80%). The right-hand-side plots show the variation of particle size obtained during tests in which the load condition was varied at a fixed engine speed value (3300 rpm).

All trends exhibit a bimodal distribution of the particle size: 'nucleation' mode is comprised primarily of condensed volatile materials, mainly sulfate and heavy hydrocarbons, with particle sizes that are typically less than 30 nm; 'accumulation' mode is comprised mainly of carbonaceous particles of sizes larger than 30 nm [36]. The engine type, the operation condition, and the dilution needed prior sampling deeply affect the particle size distribution [4, 24].

The graphs highlight that accumulation mode dominates in all tested conditions. ULSD shows a decrease in particle diameters as engine speed increases: the number of particles of

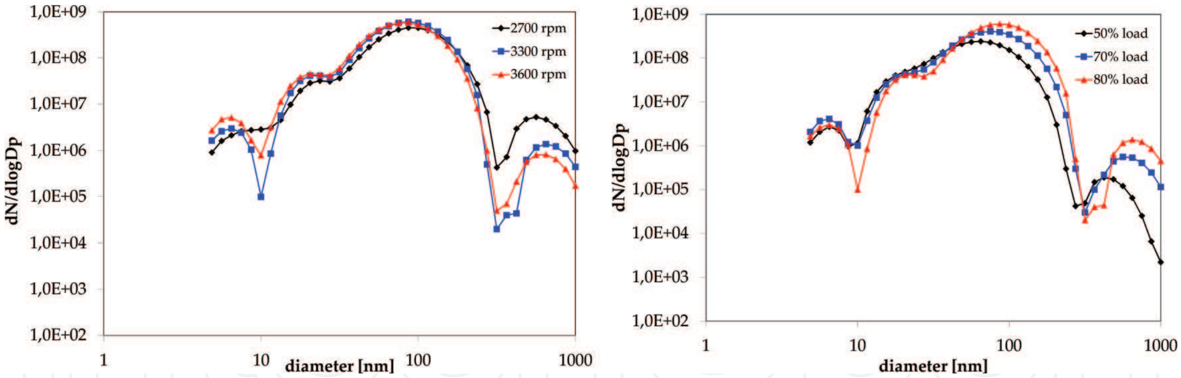

Figure 12. a): Particle number concentration at 80% load for ULSD, b): particle number concentration at 3300 rpm for ULSD [35].

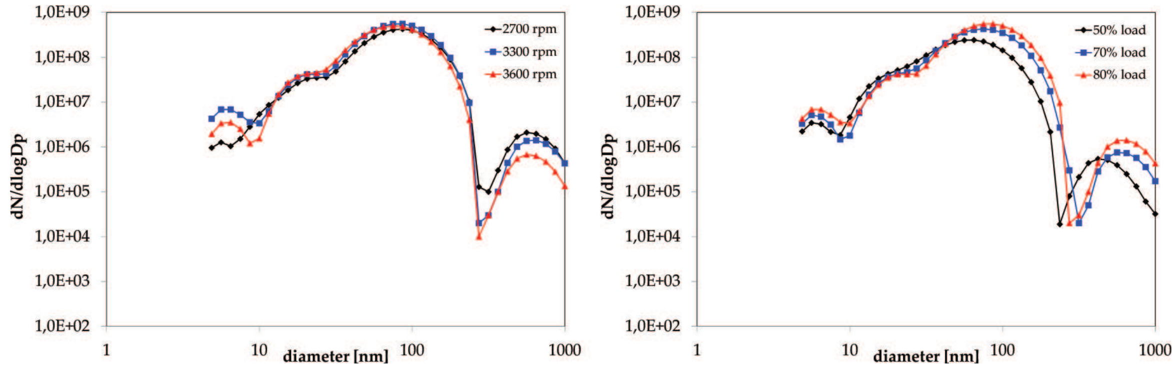

Figure 13. a): Particle number concentration at 80% load for B20, b): particle number concentration at 3300 rpm for B20 [35].

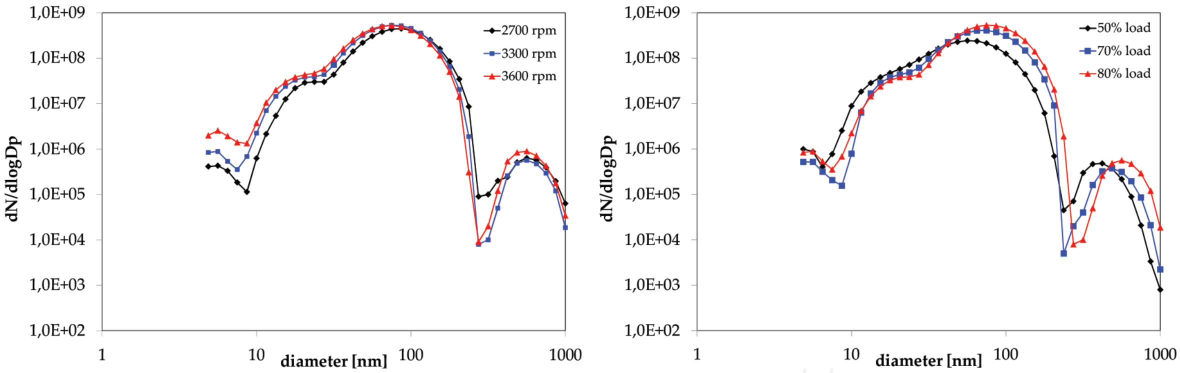

Figure 14. a): Particle number concentration at 80% load for B40, b): particle number concentration at 3300 rpm for B40 [35].

diameter larger than 100 nm decreases; the number of particles of diameter lower than 100 nm increases. Load condition affects the particle size distribution; load increase causes a greater number of larger particles, in agreement with Ref. [14].

Figures 13 and **14** show the data obtained with B20 and B40, respectively. The engine operative conditions affect the particle size distribution. B20 traces agree with those related to diesel fuel; the increase in engine speed causes a decrease in soot particle concentration with diameters

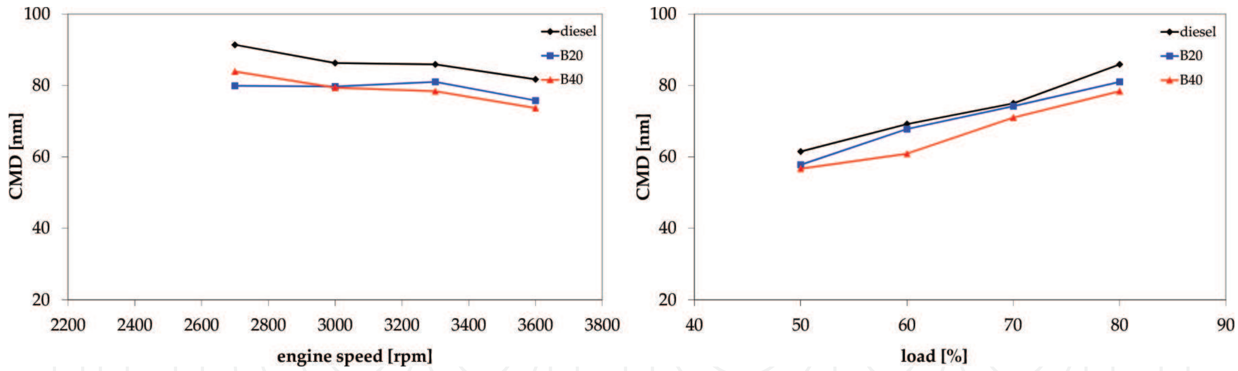

Figure 15. a): Accumulation mean diameter at 80% load, b): accumulation mean diameter at 3300 rpm [35].

larger than 100 nm. B40 trends show that the increase in engine speed is responsible for an increase in the concentration of particles of diameters under 100 nm and larger than 200 nm. The traces highlight the abrupt decrease in particle number concentration in the range of diameters around 1 μm. The increase in load (at constant engine speed) is responsible for the increase in particles' sizes for both B20 and B40.

The comparison between the particles' distributions points out that B20 and B40 are characterized by lower number of particles than ULSD in almost all diameters. This behavior agrees with literature data. Studies report that the employment of biodiesel blends produces an increased number of nanoparticles and a reduced number of ultrafine and fine particles in comparison with ULSD [6, 37, 38]. It can be explained by the oxygen content of WCO that favors the combustion completeness in the region of fuel-rich diffusion flame and then promotes the oxidation of the already-formed soot and inhibits the soot growth [19].

In **Figure 15**, the variation with engine operative conditions of the mean size of accumulation mode is shown. For all tested fuels, the court mean diameter decreases with increasing engine speed at constant load value. The increase in load condition causes an increase in the court mean diameter.

WCO biodiesel blends have lower mean diameter in their exhaust than diesel fuel. B40 has smaller particle mean diameter as regards B20 for almost all tested conditions.

4. Conclusion

Biodiesel from waste cooking oil was tested to investigate the impact of WCO percentage in blends with ultralow-sulfur diesel oil in the performance and emission characteristics of an up-to-date light and compact common rail diesel engine, whose main application is in microcars and in urban vehicles.

The engine performance (in terms of available torque, brake specific fuel consumption, brake thermal efficiency) with biodiesel blends was found quite similar for B20 and diesel fuel. B40 suffered for the lower caloric value of the blend in comparison with ULSD.

For what concerns the exhaust emissions, a reduction in CO and HC was observed for biodiesel blends, which was more significant with the increase in WCO in the fuel.

A reduction in particulate emissions was attained for WCO blends, along with a corresponding increase in NO_x, according to the well-known trade-off between NO_x and particulate. Particle size distributions were characterized by a bimodal distribution, in which accumulation mode dominated. A slight reduction in the particulate number concentration was observed as compared to diesel oil. The reduction was more evident as the WCO content in the fuel increased. The mean size of particles in B20 and B40 was smaller than that obtained with ULSD. For all fuel, engine load and speed conditions affected the particle size distribution: the increase in engine speed was responsible for a reduction in particles' diameters; the increase in load led to a reduction in the number of smaller particles.

Acknowledgements

We acknowledge the fundamental contribution of AVL which provided the instrumentation for the particle matter measurements (AVL Particle Counter and AVL Micro Soot Sensor) used during the research activity.

Nomenclature

B20	80% ULSD and 20% WCO, by volume
B40	60% ULSD and 40% WCO, by volume
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CMD	count mean diameter
D_p	particle diameter
FFA	free fatty acids
PNC	nonvolatile particle number concentration
ULSD	ultralow-sulfur diesel
WCO	waste cooking oil

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References

[1] Demirbas A. Progress and recent trends in biodiesel fuels. Energy Conversion and Management. 2009;**50**:14-34. DOI: 10.1016/j.enconman.2008.09.001

[2] Peng D. Exhaust emission characteristics of various types of biofuels. Advances in Mechanical Engineering. 2015;**7**(7):1-7. DOI: 0.1177/1687814015593036

[3] Puzun A, Wanchen S, Guoliang L, Manzhi T, Chunjie L, Shibao C. Characteristics of particle size distributions about emissions in a common-rail diesel engine with biodiesel blends. Procedia Environmental Sciences. 2011;**11**(C):1371-1378. DOI: 10.1016/j.proenv.2011.12.206

[4] Lapuerta M, Armas O, Rodriguez-Fernandez J. Effect of biodiesel fuels on diesel engine emissions. Progress in Energy Combustion Science. 2008;**34**(2):198-223. DOI: 10.1016/j.pecs.2007.07.001

[5] Xue J, Grift TE, Hansen AC. Effect of biodiesel on engine performances and emissions. Renewable and Sustainable Energy. 2011;**15**:1098-1116. DOI: 10.1016/j.rser.2010.11.016

[6] Kim H, Choi B. The effect of biodiesel and bioethanol blended diesel fuel on nanoparticles and exhaust emissions from CRDI diesel engine. Renewable Energy. 2010;**35**:157-163. DOI: 10.1016/j.renene.2009.04.008

[7] Kegl B. Influence of biodiesel on engine combustion and emission characteristics. Applied Energy. 2011;**88**(5):1803-1812. DOI: 10.1016/j.apenergy.2010.12.007

[8] Buyukkaya E. Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics. Fuel. 2010;**89**:3099-3105. DOI: 10.1016/j.fuel.2010.05.034

[9] Song H, Tompkins BT, Bittle JA, Jacobs TJ. Comparisons of NO emissions and soot concentrations from biodiesel-fuelled diesel engine. Fuel. 2012;**96**:446-453. DOI: 10.1016/j.fuel.2012.01.004

[10] Devendra S, Subramanian KA, Singal KS. Emissions and fuel consumption characteristics of a heavy duty diesel engine fueled with hydroprocessed renewable diesel and biodiesel. Applied Energy. 2015;**155**:440-446. DOI: 10.1016/j.apenergy.2015.06.020

[11] Serrano L, Loopes M, Pires N, Ribeiro I, Cascão P, Tarelho L, Monteiro A, Nielsen O, Gameiro da Silva M, Borrego C. Evaluation on effects of using low biodiesel blends in a EURO 5 passenger vehicle equipped with a common-rail diesel engine. Applied Energy. 2015;**146**:230-238. DOI: 10.1016/j.apenergy.2015.01.063

[12] Attia AMA, Hassaneen AE. Influence of diesel fuel blended with biodiesel produced from waste cooking oil on diesel engine performance. Fuel. 2016;**167**:316-328. DOI: 10.1016/j.fuel.2015.11.064

[13] Sun J, Caton JA, Jacobs TJ. Oxides of nitrogen emissions from biodiesel-fuelled diesel engines. Progress in Energy and Combustion Science. 2010;**36**(6):677-695. DOI: 10.1016/j.pecs.2010.02.004

[14] Agarwal AK, Gupta T, Kothari A. Particulate emissions from biodiesel vs diesel fuelled compression ignition engine. Renewable and Sustainable Energy Reviews. 2011;**15**(6):3278-3300. DOI: 10.1016/j.rser.2011.04.002

[15] Hwang J, Jung Y, Bae C. Spray and combustion of waste cooking oil biodiesel in a compression-ignition engine. International Journal of Engine Research. 2015;**16**(5):664-679. DOI: 0.1177/1468087415585282

[16] Szybist JP, Song J, Alam M, Boehman AL. Biodiesel combustion, emissions and emission control. Fuel Processing Technology. 2007;**88**:679-691. DOI: 10.1016/j.fuproc.2006.12.008

[17] Rakopoulos CD, Antonopoulos KA, Rakopoulos DC, Hountalas DT, Giakoumis EG. Comparative performance and emissions study of a direct injection diesel engine using blends of diesel fuel with vegetable oils or bio-diesels of various origins. Energy Conversion & Management. 2006;**47**:3272-3287. DOI: 10.1016/j.enconman.2006.01.006

[18] Lee CS, Park SW, Kwon S. An experimental study on the atomization and combustion characteristics of biodiesel-blended fuels. Energy & Fuels. 2005;**19**:2201-2208. DOI: 10.1021/ef050026h

[19] Yehliu K, Boehman AL, Armas O. Emissions from different alternative diesel fuels operating with single and split fuel injection. Fuel. 2010;**89**(2):423-437. DOI: 10.1016/j.fuel.2009.08.025

[20] Ajtai T, Pintér M, Utry N, Kiss-Albert G, Gulyás G, Pusztai P,Puskás R, Bereczky A, Szabados G, Szabó G, Kónya Z, Bozóki Z. Characterisation of diesel particulate emission from engines using commercial diesel and biofuels. Atmospheric Environment. 2016;**134**:109-120. DOI: 10.1016/j.atmosenv.2016.03.046

[21] Phan AN, Phan TM. Biodiesel production from waste cooking oil. Fuel. 2008;**87**(17-18): 3490-3496. DOI: 10.1016/j.fuel.2008.07.008

[22] Gopal KN, Arindan P, Sharma S, Samanchi C, Sathyanarayanan K, Elango T. Investigation of emission and combustion characteristics of a IC engine fuels with waste cooking oil methyl ester and diesel blends. Alexandria Engineering Journal. 2014;**53**(2):281-287. DOI: 10.1016/j.aej.2014.02.003

[23] An H, Yang WM, Chou SK, Chua KJ. Combustion and emission characteristics of diesel engine fueled by biodiesel at partial load conditions. Applied Energy. 2012;**99**:363-371. DOI: 10.1016/j.apenergy.2012.05.049

[24] An H, Yang WM, Maghbouli A, Li J, Chou SK, Chua KJ. Performance, combustion and emission characteristics of biodiesel derived from waste cooking oils. Applied Energy. 2013;**112**:493-499. DOI: 10.1016/j.apenergy.2012.12.044

[25] Can O. Combustion characteristics, performance and exhaust emissions of a diesel fueled with a waste cooking oil and biodiesel mixture. Energy Conversion and Management. 2014;**87**:676-686. DOI: 10.1016/j.enconman.2014.07.066

[26] Cheung CS, Man XJ, Fong KW, Tsang OK. Effect of waste cooking oil biodiesel on the emissions of a diesel engine. Energy Procedia. 2015;**66**:93-96. DOI: 10.1016/j.egypro.2015.02.050

[27] Man XJ, Cheung CS, Ning Z. Effect of diesel engine operating conditions on the particulate size, nanostructure and oxidation properties when using wasting cooking oil biodiesel. Energy Procedia. 2015;**66**:37-40. DOI: 10.1016/j.egypro.2015.02.020

[28] Hwang J, Bae C, Gupta T. Application of waste cooking oil (WCO) biodiesel in a compression ignition engine. Fuel. 2016;**176**:20-31. DOI: 10.1016/j.fuel.2016.02.058

[29] Chiatti G, Chiavola O, Recco E, Palmieri F. Soot particles experimental characterization during cold start of a micro car engine. Energy Procedia. 2016;**101**:662-669. DOI: 10.1016/j.egypro.2016.11.084

[30] Chiatti G, Chiavola O, Palmieri F, Piolo A. Diagnostic methodology for internal combustion diesel engines via noise radiation. Energy Conversion & Management. 2015;**89**:34-42. DOI: 10.1016/j.enconman.2014.09.055

[31] Chiatti G, Chiavola O, Palmieri F, Albertini S. Combustion and emissions characterization of biodiesel blends in a city-car engine. Energy & Fuels. 2014;**28**(8):5076-5085. DOI: 10.1021/ef501023q

[32] Altun S, Bulut H, Oner C. The comparison of engine performance and exhaust emission characteristics of sesame oil-diesel fuel mixture with diesel fuel in a direct injection diesel engine. Renewable Energy. 2008;**33**:1791-1795. DOI: 10.1016/j.renene.2007.11.008

[33] Qi DH, Chen H, Geng LM, Bian YZH, Ren XCH. Performance and combustion of biodiesel-diesel-methanol blend fuelled engine. Applied Energy. 2010;**87**:1679-1686. DOI: 10.1016/j.apenergy.2009.10.016

[34] Ng JH, Ng HK, Gan SY. Engine-out characterization using speed-load mapping and reduced test cycle for a light-duty diesel engine fuelled with biodiesel blends. Fuel. 2011;**90**:2700-2709. DOI: 10.1016/j.fuel.2011.03.034

[35] Chiatti G, Chiavola O, Recco E, Palmieri F. Impact of waste cooking oil in biodiesel blends on particle size distributions from a city-car engine. Journal of Energy Institute. DOI: 10.1016/j.joei.2016.11.009

[36] Myung CL, Park S. Exhaust nanoparticle emissions from internal combustion engines: A review. International Journal of Automotive Technology. 2012;**13**(1):9-22. DOI: 10.1007/s12239−012−0002−y

[37] Neer A, Koylu UO. Effect of the operating conditions on the size, morphology, and concentration of sub-micrometer particulates emitted from a diesel engine. Combustion and Flame. 2006;**146**:142-154. DOI: 10.1016/j.combustflame.2006.04.003

[38] Tsolakis A. Effects on particle size distribution from the diesel engine operating on RME-biodiesel EGR. Energy & Fuels. 2006;**20**:1418-1424. DOI: 10.1021/ef050385c