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Impact of waste cooking oil in biodiesel blends on particle size distributions from a city-car engine

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ABSTRACT

Using biodiesel as a blending component in diesel engine has demonstrated to reduce hydrocarbon and particulate matter emissions. Literature showed that biodiesel type, engine architecture and test conditions deeply affect performance and emission characteristics. Among suitable biodiesel fuels, waste cooking oil (WCO) is considered very attractive due to the reduced environmental impact without sacrificing engine performance.

This paper aims at investigating how mixing ratio of biodiesel from WCO and mineral diesel affects the particle size distributions of a current state of art small displacement diesel engine.

Experimental tests have been performed on an up-to date light common rail diesel engine. Its complete operative field has been investigated. The results obtained show that the use of biodiesel blends from WCO reduces the total number of particles emitted from the engine with respect to the diesel fuel; the reduction is more evident as the percentage of biodiesel in the blend increases. The number of particles in WCO biodiesel soot with diameter smaller than 10 nm is reduced as compared to diesel fuel; the same trend is observed for diameters larger than 200 nm; comparable particle numbers were obtained in the ultrafine range (Dp < 100 nm).

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1. Introduction

Carbonaceous particulate matters produced by incomplete combustion have been demonstrated to highly impact climate and human health. Environmental concern and fossil fuel depletion have stimulated researchers to explore and analyze performance of alternative fuels, such as biodiesel. The employment of biofuels offers the advantages of a reduced environmental impact and can be used in diesel engine without any hardware modification.

Previous studies demonstrated that particle size distribution, chemical composition, morphology and microstructure of particulate strongly depend on the physical and chemical properties of the fuel, on engine type and its operating conditions [1,2].

Because of the large variety of biodiesel fuels, many researches have been carried out with the aim to evaluate the effect on spray development, combustion progress, performance and exhaust emissions [3,4] of the different types. Furthermore, although the biodiesel content in diesel fuel is regulated in EU countries (7%, Directive 2009/30/EC [5]), investigations on how biodiesel to diesel ratio affects performance are still required. Devendra et al. [6] compared two different types of biofuels used unmixed with diesel fuel; Serrano et al. [7] investigates comparatively B7 and B20 fuel blends; Yehliu et al. [8] evaluates the impact of pure biodiesel (B100) on combustion process and soot production.

Among all suitable biodiesel fuels, waste cooking oil (WCO) is considered a promising option and has demonstrated its suitability as a biofuel [9–14]. WCO offers many benefits when it is used as a fuel source: WCO is 2–3 times less expensive than virgin vegetable oils [15]; the conversion of WCO into fuel also eliminates the environmental impacts caused by its disposal.

Peng [11] compared performance and exhaust emissions of waste edible oil with soybean oil, palm oil and pure diesel tests and found that the use of biodiesel reduced CO and HC emissions and smoke opacity; however, it increased fuel consumption as compared to petrol

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diesel. An et al. [13] investigated biodiesel derived from WCO with 3 different blend ratios (B10, B50 and B100): the use of biodiesel blends resulted in a higher brake specific fuel consumption, especially at low engine speed and partial load conditions. A slight reduction of HC and NO_x emissions was observed, but the opposite trend was shown at low engine speed. Can [14] examined the combustion characteristics of diesel engines fueled with biodiesel from WCO in different blend ratios (5% and 10% in vol). The maximum heat release rate and the in-cylinder pressure rise rate were slightly decreased and the combustion duration was generally increased with the biodiesel addition. Gopal et al. [16] conducted tests on a direct injection compression ignition engine fueled with WCO blends: they observed that diesel engine can perform satisfactorily in biodiesel with a significant reduction in CO, HC and smoke emissions as compared to diesel fuel. Attia et al. [17] experimentally evaluated the engine performance of various fuel blends containing WCO. Results demonstrated that the most recommended biodiesel blending ratios varied from 30% to 50% for better engine performance and emission characteristics. Cheung et al. [18] investigated the effect of WCO blends on the emissions of a diesel engine; the results showed a reduction of HC, CO and particulate mass and number concentrations, but also a NO_x increase. Hwang et al. [19] carried out an experimental study to compare the spray, combustion and emission characteristics of WCO with those of conventional diesel in an optically accessible single-cylinder direct injection diesel engine at 1400 rpm. A longer injection delay and a retarded combustion phase were observed for WCO than diesel fuel. WCO had the benefits of reduced CO, HC and PM.

Although literature review highlights considerable research activity on combustion and emission in engines fueled with many types of biodiesel, studies on the effect of biodiesel ratio on the particle size distribution is limited. Most of the investigations aim at evaluating the effect of biodiesel employment on smoke; results indicate that generally particulate emission decreases remarkably with increasing in biodiesel content in blends [3]. The type of biodiesel, the proportion of biodiesel in the blend, the engine type, operating conditions and tests conditions affect the percentage of reduction in smoke values. Characteristics and size of particulate matter play a key role in assessing the impact on the environment and human health. Due to this, emissions of particulate are regulated in EU in terms of both grams per kilometer and number of emitted particles. Therefore, there is the need to investigate how the use of biodiesel blends affects the particle diameters in the engine exhaust. Puzun et al. [2] investigated the particle size distribution due to different biodiesel blends from rapeseed oil. Sizes of particle emissions were mostly below 330 nm. Furthermore, a bimodal structure was observed for biodiesel; particle size distributions were affected by the proportion of biodiesel and the load conditions. Agarwal et al. [4] compared size and number distribution from B20 (blend of mineral diesel and fuel from bio-origin), mineral diesel and B100. Biodiesel gave a higher number particles than mineral diesel; B20 performed better as compared to B100: particle concentrations of B20 were comparable to those of mineral diesel and for some operating conditions they were even better than mineral diesel. Yehliu et al. [8] evaluated the impact of fuel properties on the PM size distribution from pure soybean methyl ester biodiesel. Biodiesel gave higher particle concentration than diesel fuel at low load for a single injection strategy. For the split injection strategy, a lower particle concentration and smaller particle diameter than for diesel fuel were observed. Kim et al. [20] examined the effect of biodiesel and bioethanol blended diesel fuel on particle emission from a common rail direct injection diesel engine. The use of biofuel-blended diesel fuel reduced the total number of emitted particles and determined a higher emission rate of particles having size below 50 nm as compared to diesel fuel.

For what concerns WCO employment, only few research works are devoted to investigate the effect of this type of biodiesel on soot particles. Hwang et al. [12] compared spray, combustion and emission characteristics of WCO with those of a conventional diesel in an optically accessible single-cylinder diesel engine at idling. They found that the diameter of primary particles in WCO soot was smaller than that in diesel fuel. Man et al. [21] performed a study on the influence of engine operating modes on the physico-chemical properties of the PM emitted by a diesel engine operating with WCO. More particles with larger size were found at lower engine speed. The impact of engine load at constant speed was more pronounced than the impact of engine speed.

From the published results, it is highlighted that even if experimentations were conducted just at some engine operative points, there is a tendency of biodiesel to increase the emission of smaller particles in the exhaust as compared to diesel fuel. These studies point out the need to better understand how blends from WCO affect the particle size distribution in the emissions from engines at the current state of art, in their complete operative field.

The purpose of this work was to investigate the impact of waste cooking oil percentage in blends with ultra-low sulfur diesel (ULSD) on the total number and size distribution of particle emissions from an up-to date light and compact direct-injection common-rail diesel engine, mainly used in urban micro-vehicles. A previous research activity on this engine was devoted to investigate performance and pollutant emissions [22]. It was observed an increase of NO_x emissions and a decrease of CO and HC concentration when the content of biodiesel in the blend increased as compared to ULSD. Particulate matter was slightly reduced when WCO blends were used. The influence of injection settings on engine power, specific fuel consumption and emissions was also analyzed.

2. Engine, fuels and tests

The engine is a small displacement common rail diesel engine LDW442CRS, whose main application is in micro cars and urban vehicles. The engine is not equipped with emission control systems. Table 1 reports the engine specifications.

Table 1
Engine specifications.

Engine type	Four stroke, direct injection, naturally aspirated, water cooled
Cylinders	2
Displacement	440 cm^3
Bore	68 mm
Stroke	60.6 mm
Compression ratio	20:1
Maximum power	8.5 kW @ 4400 rpm
Maximum torque	25 Nm @ 2000 rpm

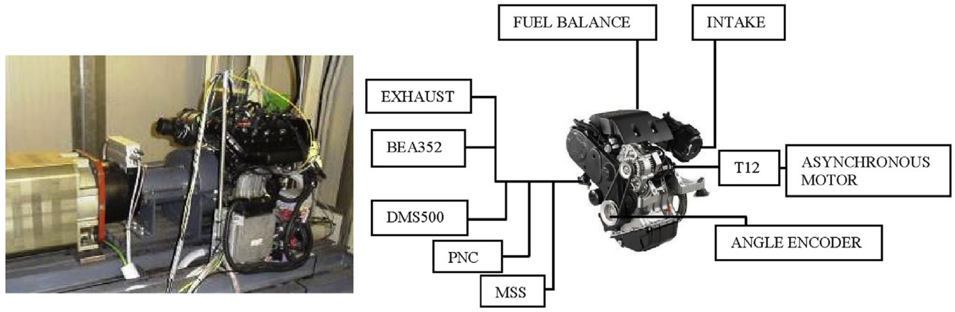

Fig. 1. Engine set-up.

As shown in Fig. 1, the engine was connected to an asynchronous motor. Transducers were installed to measure torque (HBM T12), fuel consumption (AVL Fuel Balance 733), pressure and temperature [23]. Exhaust gases were sampled at engine outlet by means of Bosh BEA352 in order to evaluate the exhaust emissions (CO, CO_2, HC, O, NO_x). The non-volatile particle number concentration in the size range of 23 nm to 2.5 μm was measured by AVL Condensation Particle Counter (PNC). AVL Micro Soot Sensor was used for soot concentration measurement. Particulate matter size was measured through the 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 or 32 channels per decade. The sampling system consists of two dilution stages and a sampling line (a heated pipe 5 m long, that connects the sampling point to the dilution stages and to the instrument). Primary and second dilution rates were set to 5:1 and 400:1, respectively. The diluted gas sample passes through a corona charger and then into the classifier column. The charged particles flow within a particle-free sheath flow and are deflected towards 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. The particles yield their charge to the electrometer amplifiers and the resulting currents are translated by the user-interface into particle number and size data.

A software developed by the authors in LabVIEW10 environment was used to manage the tests conditions; data acquisition was performed by a customized program [24].

During experimental tests, three fuels were used:

- ULSD: standard ultra-low sulfur diesel fuel;
- B20: ULSD 80%, biodiesel 20% by volume;
- B40: ULSD 60%, biodiesel 40% by volume.

Tests were carried out in the engine operative field 2300–3600 rpm; measurements were performed under stationary conditions, once oil and coolant temperatures have reached final steady-state thermal regime. In order to ensure the accuracy of the results, all signals were averaged over 25 engine cycles. Switching from one fuel to another was carried out by giving to the engine enough time to consume the remaining fuel in the supply system, before data acquisition started.

Biodiesel was produced from a mixture of waste oil. In order to make the biodiesel suitable as the products coming from refined vegetable oils, some pre-treatments were necessary with the aim to comply with the EN 14214 specification. Details of the procedure followed may be found in [22]. Table 2 reports biodiesel and ULSD properties. ECU injection settings were not modified during tests: a two-shot injection pattern was always imposed; a fixed quantity of 1 mm^3/stroke of fuel was delivered during the pre-injection process, regardless of the engine operative conditions. Timing and phasing of the shots were varied according to the selected engine operating conditions.

3. Experimental results and discussion

The performance characteristics of the engine measured during a previous research work highlighted that the available torque at full load condition depends on the percentage of biodiesel in the blend, due to the lower heating value of biodiesel as regards ULSD [22]. For this reason, it was established to perform tests at a maximum value of torque equal to 80% of the full load evaluated by using diesel fuel. This guaranteed the same load values with all tested fuels. 50%, 60% and 70% of load were also tested in the engine speed range 2400–3600 rpm, with a speed step of 300 rpm. Fig. 2 shows the effect of blend ratio on non-volatile particle number concentration (PNC) in the engine exhaust system. Each point in the plots represents the cumulative value of particles in the range from 23 nm to 2.5 μm. The data were computed by dividing the values of the particle number concentration (particles per cubic centimeter of exhaust gas) by the engine output at each operative point. The variation of PNC with the engine speed at a fixed load condition (80%) is presented in the left hand side plot. It can

Table 2
Biodiesel and ULSD fuel properties.

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

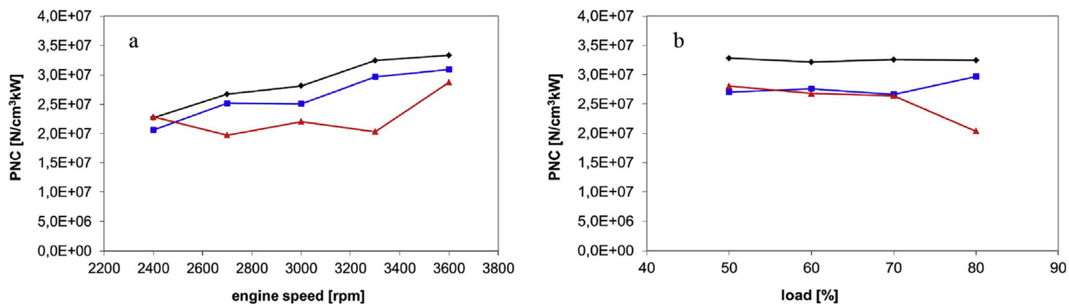

Fig. 2. a): Variation of particle number concentration with the engine speed at 80% load; b): variation of particle number concentration with the load at 3300 rpm; ◆ diesel fuel, ■ B20, ▲ B40.

be noted that the employment of B20 slightly reduced the soot emissions with respect to the baseline fuel. With B40, the particulate matter further decreased.

The right hand side plot shows the variation of PNC with blends at a fixed value of engine speed (3300 rpm) and for different load values. It can be observed that WCO blends significantly reduced soot particle number concentration at all load conditions.

In order to explain the obtained trends, several concurrence aspects must be taken into account:

- the higher cetane number of WCO with respect to ULSD shortened the ignition delay and elongated the duration of mixing-controlled combustion;
- the higher oxygen content of biodiesel promoted the combustion, especially for the higher engine load conditions and favored the soot oxidation;
- the higher viscosity and density deteriorated the fuel atomization (smaller spray cone angle, larger droplet size and larger fuel penetration length); literature reports studies demonstrating that it is not only the biodiesel blending ratio but also the injection settings that have a significant effect on the emissions [17,19].

Fig. 3 presents the variation of soot concentration in the exhaust emission as a function of the engine speed for diesel fuel and biodiesel blends.

The increase of soot concentration in the exhaust with the engine speed value for all fuels agrees with literature [3,8]. Such a trend is to be ascribed to a balance between:

- reduced time for air-mixing and combustion, which, in turn, is responsible for a less uniform mixture and more incomplete combustion, and consequently in a higher particle concentration [8];
- increase in the turbulent effects with the increase of engine speed, which enhances the extent of complete combustion process [3].

As the percentage of biodiesel in the blend increased, the particulate emission decreased significantly. According to many experimental investigations, this was caused by the increase of the oxygen content, which enables a more complete combustion, even in the regions of the combustion chamber with fuel-rich diffusion flames, it also favors the oxidation of the already formed soot. Moreover, the different structure of particles from biodiesel and diesel may facilitate the soot oxidation [3,8,20].

The following figures from 4 to 12 show the soot particle diameter and their number distribution obtained during experimental tests in which ULSD, B20 and B40 were used to investigate how blend ratio affects particles emitted in the exhaust when a variation of the operating conditions is imposed on the engine. In all the plots, the particle number concentration is expressed as size spectral density, $dN/dlogD_p/cc$. This choice allows an easy integration over the size range to give the total particle concentration; the log term arises from the fact that the size classes are logarithmically spaced. Fig. 4 presents the variation of particle size with the engine speed at a fixed value of load condition (80%) and with the load at a fixed value of engine speed (3300 rpm). The data have been obtained by fueling the engine with ULSD.

The graphs highlight a bimodal distribution of the particle size; in all trends, accumulation mode dominates.

The plots highlight also that:

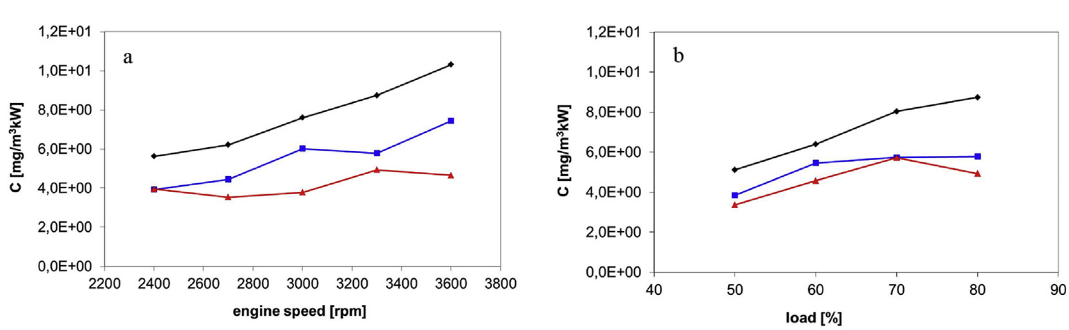

Fig. 3. a): Variation of soot concentration with the engine speed at 80% load; b): variation of soot concentration with the load at 3300 rpm; ◆ diesel fuel, ■ B20, ▲ B40.

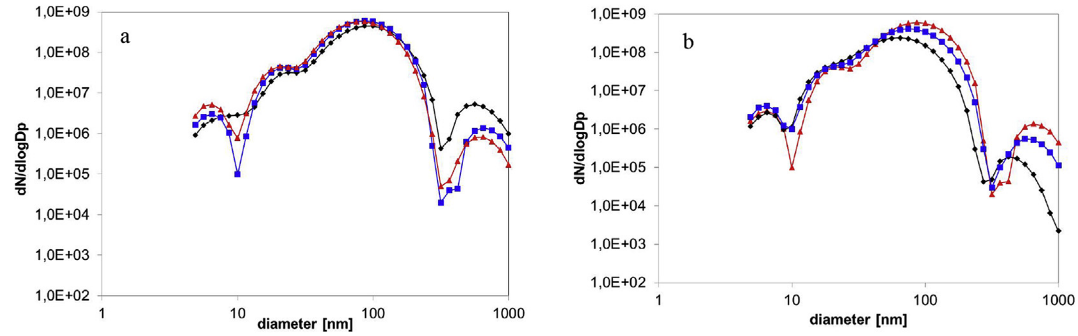

Fig. 4. a): Variation of particle number concentration with the engine speed at 80% load for ULSD, ◆ 2700 rpm, ■ 3300 rpm, ▲ 3600 rpm; b): variation of particle number concentration with the load at 3300 rpm for ULSD, ◆ 50% load, ■ 70% load, ▲ 80% load.

- the distribution of particle diameter gradually decreases with the engine speed increase: higher concentration of particles is emitted under 100 nm and lower concentration of particles is emitted above 100 nm as the rpm increases;
- the increase in engine load corresponds to an increase of number of particles of highest diameters, in agreement with [4].

The comparison among the trends points out that lower values of engine speed and higher values of load are responsible for the increase in the number of particles in the portion of larger diameters (>200 nm).

The effect of biodiesel from WCO in the blend with diesel fuel is shown in the following figures (from 5 to 9), in terms of particle size distributions for ULSD, B20 and B40. The objective of the analysis is to understand how particle emissions are affected by the quantity of WCO in the fuel and to deeper insight into the smoke emissions from WCO blends (that have demonstrated to be reduced as compared to Diesel fuel, as shown in Figs. 2 and 3).

Figs. 5–7 show the data related to a variation of the engine speed at fixed value of load condition (80%). Figs. 8 and 9 compare data related to a fixed value of engine speed and variable load conditions. B20 and B40 data are almost always lowest than ULSD values; in some diameter ranges, the number of particles for the fuels is comparable (Figs. 6–9). At 3600 rpm and 80% of load (Fig. 5), ULSD, B20 and B40

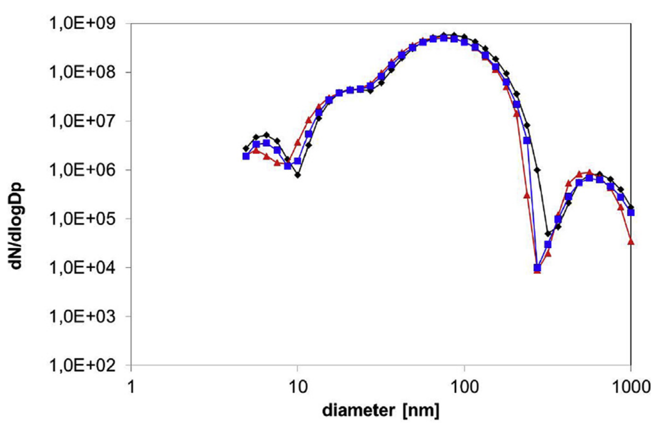

Fig. 5. Particle number concentration at 3600 rpm, 80% load: ◆ ULSD, ■ B20, ▲ B40.

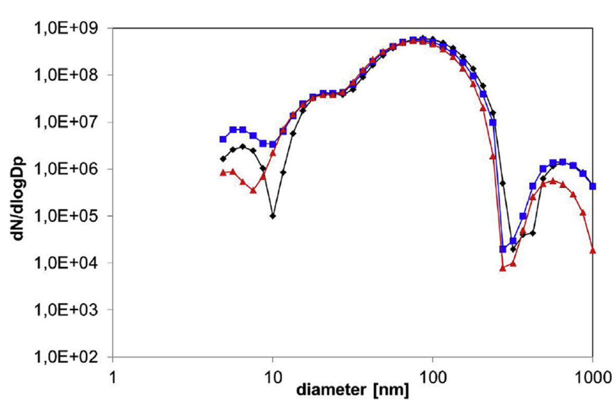

Fig. 6. Particle number concentration at 3300 rpm, 80% load: ◆ ULSD, ■ B20, ▲ B40.

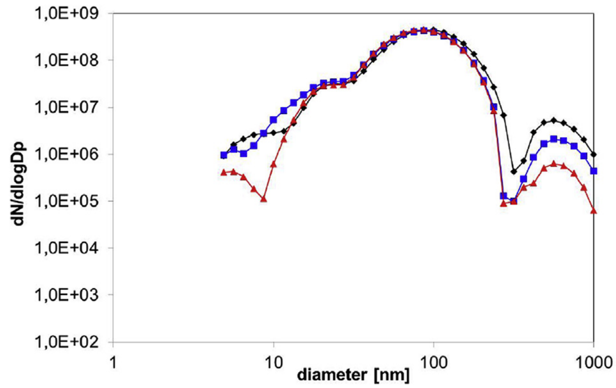

Fig. 7. Particle number concentration at 2700 rpm, 80% load: ◆ ULSD, ■ B20, ▲ B40.

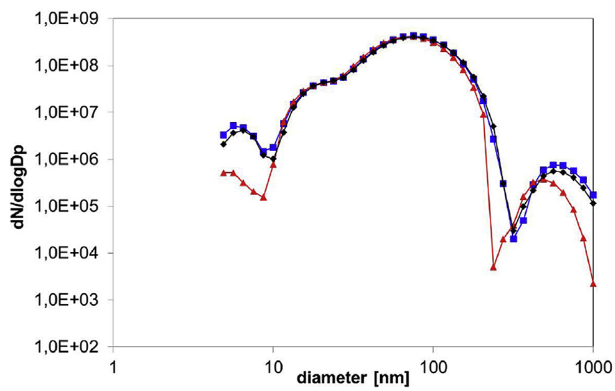

Fig. 8. Particle number concentration at 3300 rpm, 70% load: ◆ ULSD, ■ B20, ▲ B40.

have a comparable number of emitted particles lower than 20 nm and in the range 300–1000. Abrupt decreasing trends of number of particles at diameters in the range and greater than 1 μm are observed for B20 and B40 with respect to ULSD fuel. Such a behavior is in agreement with literature data, where it is reported that the employment of biodiesel was responsible of a reduced number of fine particles (D_p < 2.50 μm). This result can be explained by considering that the oxygen content of biodiesel fuel favors the completeness of the combustion process in the region with fuel-rich diffusion flames. The resulting more complete combustion promotes the oxidation of the already formed soot and inhibits the soot growth.

Figs. 10–12 compare the data obtained by fueling the engine with B20 and B40 under varying the engine operative conditions. B20 trends agree with the corresponding data obtained from ULSD fuel tests: the increase of the engine speed is responsible for the decrease of soot particle concentration with diameters larger than 100 nm. Some small differences may be noted for nanoparticles trends (diameters lower than 10 nm). Plots related to B40 show an increase of concentration of particles with diameters under 100 nm and larger than 200 nm with the engine speed value increase. The trends highlight the abrupt decrease of particle number concentration in the range of diameters around 1 μm. The increase of load at a fixed value of engine speed caused an increase of the dimensions of emitted particles when B20 and B40 blends were employed.

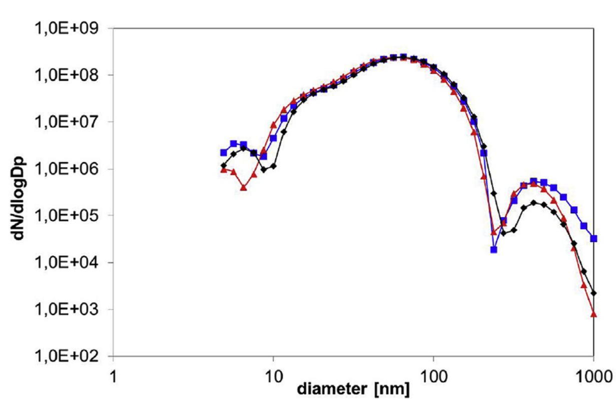

Fig. 9. Particle number concentration at 3300 rpm, 50% load: ◆ ULSD, ■ B20, ▲ B40.

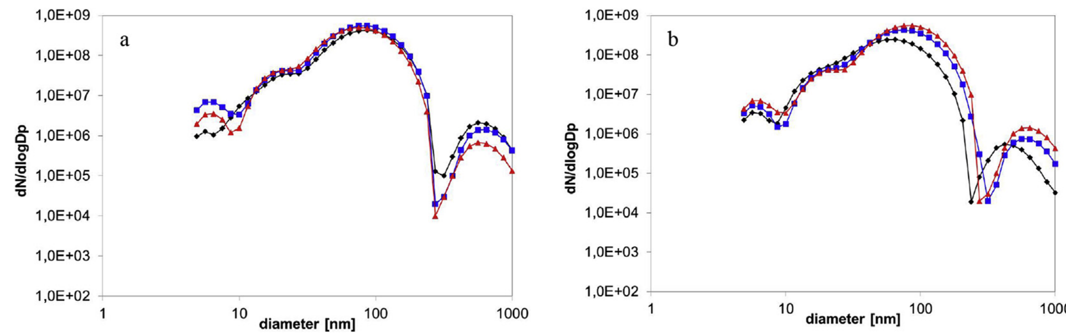

Fig. 10. a): Variation of particle number concentration with the engine speed at 80% load for B20, ◆ 2700 rpm, ■ 3300 rpm, ▲ 3600 rpm; b): variation of particle number concentration with the load at 3300 rpm for B20, ◆ 50% load, ■ 70% load, ▲ 80% load.

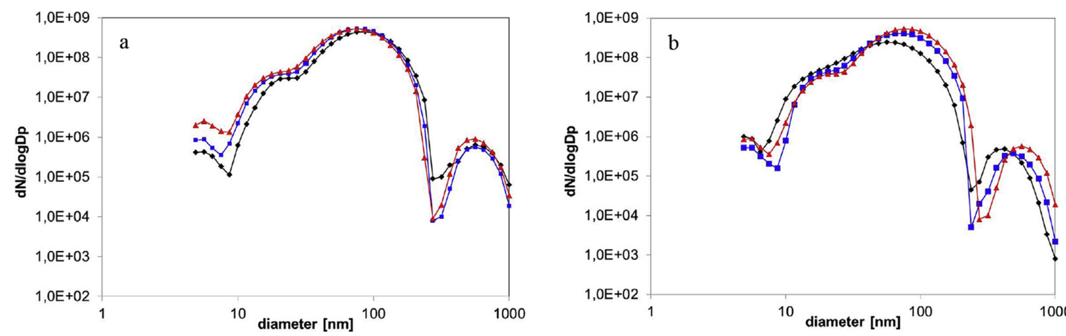

Fig. 11. a): Variation of particle number concentration with the engine speed at 80% load for B40, ◆ 2700 rpm, ■ 3300 rpm, ▲ 3600 rpm; b): variation of particle number concentration with the load at 3300 rpm for B40, ◆ 50% load, ■ 70% load, ▲ 80% load.

Fig. 13 shows the variation of mean size of accumulation mode as function of the engine speed at constant load (80%) and as function of the engine load at constant speed (3300 rpm).

As the engine speed increased at constant load conditions, the court mean diameter decreased. For all tested blends, load increase at a constant engine speed determined an increase in the court mean diameter. B20 and B40 were characterized by a lower mean diameter in their exhaust than ULSD. For almost all the engine operative conditions, B40 had a smaller mean particle diameter than that in B20. By comparing these trends with those of Figs. 5–9, it is possible to observe that such a behavior was caused by the lower number of particles of diameter larger than 200 nm.

4. Conclusions

Biodiesel produced from WCO represents a sustainable source of energy. Although there have been a number of research activities focusing on engine performance and emissions from WCO blends in diesel engines, literature research highlighted a lack of knowledge in the characterization of particle size distribution and the need of a better understanding of how the percentage of WCO in diesel fuel might affect the particles dimensions in the exhaust of engine at the current state of art. This paper was devoted to investigate two different blending ratios (B20 and B40) and to analyze the effect of the engine operative conditions on the particle diameters as compared to diesel fuel.

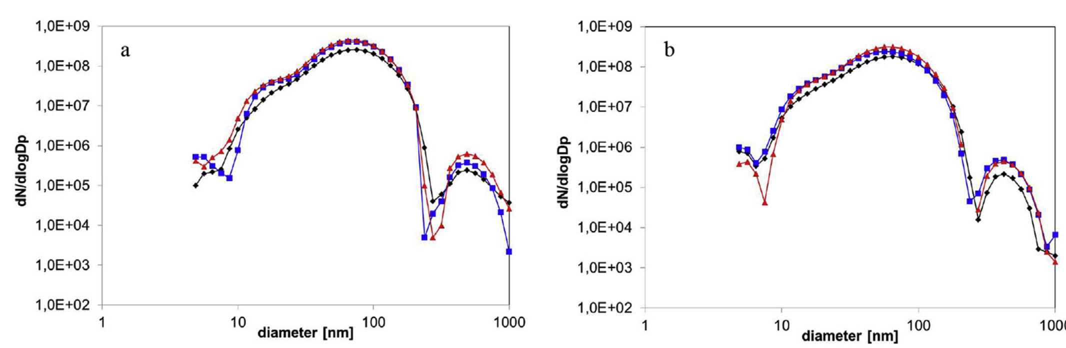

Fig. 12. a): Variation of particle number concentration for B40 at 70% load, ◆ 2700 rpm, ■ 3300 rpm, ▲ 3600 rpm; b): variation of particle number concentration for B40 at 50% load, ◆ 2700 rpm, ■ 3300 rpm, ▲ 3600 rpm.

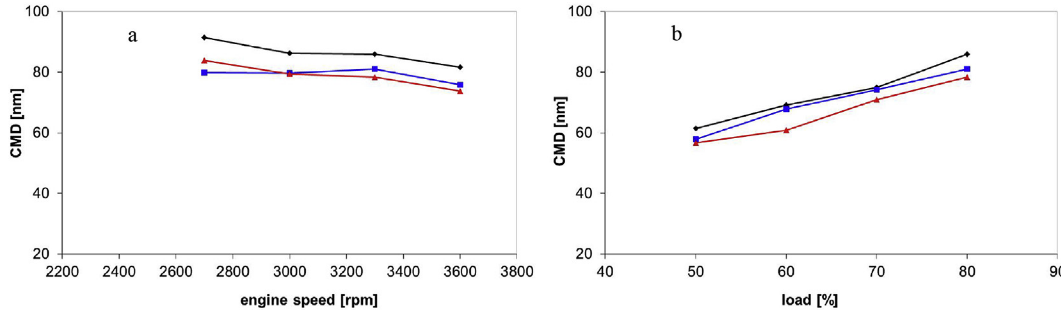

Fig. 13. a): Variation of accumulation mean diameter with the engine speed at 80% load; b): variation accumulation mean diameter with the load at 3300 rpm; ◆ ULSD, ■ B20, ▲ B40.

The main concluding remarks may be summarized as follows:

- the use of biodiesel blends from WCO reduces the total number of particles emitted from the engine with respect to the diesel fuel;
- the reduction is more evident as the percentage of biodiesel in the blend increases;
- the number of particles in WCO biodiesel soot with diameter smaller than 10 nm is reduced as compared to diesel fuel;
- the same trend is observed for diameters larger than 200 nm; comparable particle numbers were obtained in the ultrafine range (Dp < 100 nm);
- a bimodal distribution of the particle size is observed for all the fuels; accumulation mode dominates in all trends;
- the mean size of accumulation mode in B20 and B40 is lower than that one in ULSD; B40 has smaller mean particle diameter than that in B20 in almost the complete engine operative field.
- the engine operative conditions affect the particle size distribution: an increased load leads to a decrease of the portion of smaller diameters, while increasing the engine speed leads to a reduction of the particle diameters.

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