INVESTIGATION INTO PARTICULATE SIZE DISTRIBUTIONS IN THE EXHAUST GAS OF DIESEL ENGINES FUELLED WITH BIODIESEL BLENDS

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Abstract

Particulate matter (PM) size distributions in the exhaust gas of biodiesel blend fuelled diesel engines have been studied by experimenting firstly on a single cylinder equipped with a pump-line-injector injection system and secondly for comparison on a V6 DI engine equipped with a common rail fuel injection system. Both engines were operated with a biodiesel (RME) blend of B30 and ultra low sulphur diesel fuel (ULSD). Several engine load conditions with and without exhaust gas recirculation (EGR) were selected. Particulate number concentrations vs. the electrical mobility equivalent diameter were examined using a fast differential mobility spectrometer. The effect of engine operating conditions including EGR rates on particulate emissions has been investigated. It is found that PM sizes from combustion of B30 without EGR operation are generally smaller than those from ULSD while number concentrations are higher. This can result in lower PM mass estimates for the B30 case if due care is not taken. When EGR is applied to control nitrogen oxides emissions, both the total PM number and mass are increased and shifted toward the larger sizes for both fuels used in the test. The calculated total PM mass from B30 combustion is lower than in the ULSD case for all the tested engine operating conditions.

***Keywords**: Biodiesel, PM, combustion, diesel, PM size distribution*

1. Introduction

Several advantages of biodiesels such as low levels of aromatic compounds and near zero sulphur content along with properties comparable to fossil diesel fuel can facilitate reduction of engine-out HC/CO/PM emissions from combustion engines [6, 11]. For these reasons, many engine test programmes for higher proportions biodiesel blends (up to 30% by volume with standard diesel fuel) are underway, inline with the EU vision for 2030 to promote the use of bio-fuels for road transportation [7]. Some results of the studies by the authors concerning gaseous emissions have been reported previously [3-4].

Environmental and health concerns in relation to particulate matter emissions from engines have received increasing attention since a number of studies in epidemiology revealed a relationship between air-borne particulate matter and health effects such as heart diseases, respiratory and carcinogenic problems [8]. With the emergence of new engine technologies for vehicles the mass concentration of particulates in diesel exhaust has been reduced progressively over the past few decades [14]. For the same particulate mass, however, smaller particles yield a greater number of particulates. Therefore, it has become apparent in recent years that the particle number and size distributions should be considered to be more important than mass [13].

The typical particulate size characterisation of diesel aerosols described by Kittelson (1998) is generally in form of a tri-modal and log-normal distribution. The so-called nuclei mode is composed of spherical primary particles with diameters ranging from 5 to 50 nm. However, it covers more than 90% of particulates for a tiny amount of mass. In consequence the accumulation mode in which the diameter ranges from 50 to 1.000 nm has a lower number of particles but higher total particulate mass compared with the nuclei mode. Primary particles are agglomerated into aggregates, fairly similar to fractal-like shape with the fractal dimension in the range of 2 to 3 ($d_f \sim 2.4$ from 18). Therefore the size is then determined by the equivalent diameter of fractal-like particles. The coarse mode contains particles larger than 1.000 nm in diameter.

Particulate emissions from diesel engines have been studied previously in the authors' laboratory at Birmingham. Tsolakis et al. (2005) studied the particulates from the exhaust gas of a diesel-hydrogen fuelled engine, in which the particle size distribution was not affected considerably by diesel reforming into hydrogen, while the total particulate number and mass were reduced considerably compared with standard diesel fuel. Analysis of exhaust PM from the neat biodiesel fuel combustion with EGR was also accomplished [17].

The main objective of the present research is to study PM number and mass size distribution using a differential mobility spectrometer (DMS). A comparative experimental study of the effect of fuel properties on the exhaust gas aerosols from the combustion of diesel-biodiesel blends was devoted to the analysis of the measurement on a single-cylinder engine, with further studies conducted on a modern multi-cylinder production engine in order to assess the quantitative impact of high proportion biodiesel blends on exhaust emissions including particulate matter.

2. Experimental Systems and Test Procedures

Engine test rigs

The first engine (referred to as Engine 1 hereafter) was a single cylinder Lister-Petter TR1. The engine is naturally aspirated, air-cooled, DI and equipped with a pump-line-injector injection system. The standard injection timing for Engine 1 is 22° before top dead centre (BTDC). The fuel injection system (unmodified as provided by the manufacturer) has a three-hole nozzle with a hole diameter of 0.25 mm, located near the combustion chamber centre with an opening pressure of 180 bar. The piston is a bowl-in-piston design. A DC dynamometer with a load cell was coupled to the engine and used to load and motor the engine. The engine test rig has been described in detail in previous publications [3, 16].

The second engine used in this study(referred to as Engine 2 hereafter) was a Jaguar/Ford V6 diesel engine with a common rail direct injection system. Engine 2 is twin-turbocharged with intercoolers and equipped with cooled exhaust gas recirculation (EGR). The injection timing is varied with engine speed-load conditions as controlled by an engine management system (EMS). The fuel injection system has a six-hole Siemens-VDO piezo-actuated nozzle with a hole diameter of 0.36 mm and a nozzle cone angle of 156°. More detailed engine specifications for both engines are given in Tab. 1. For Engine 2, the test rig, previously described by Chuepeng et al. (2008), consists of an eddy-current type Schenck W230 dynamometer combined with an engine starter motor. For both test rigs, the ambient conditions in the test cells, i.e. temperature and humidity were recorded and used for emissions and in-cylinder pressure readings corrections. This comparative study was performed to assess the effects of the fuel blends that cannot be explained easily in the sophisticated V6 engine where a number of sensors and actuators are fitted, yielding difficulties in controlling independent variables.

Tab. 1. Engine specifications

	Engine 1*	Engine 2*
Bore	98.4 mm	81.0 mm
Stroke	101.6 mm	88.0 mm
Displacement volume	773 cm^3	2720 cm^3
Maximum torque	39.2 Nm @ 1800 rpm	435 Nm @ 1900 rpm
Maximum power	8.6 kW @ 2500 rpm	152 kW @ 4000 rpm
Compression ratio	15.5:11	7.3:1

* *Numbers 1 and 2 represent the single-cylinder Lister-Petter and V6 Jaguar diesel engines, respectively.*

Particulates collection and measurement

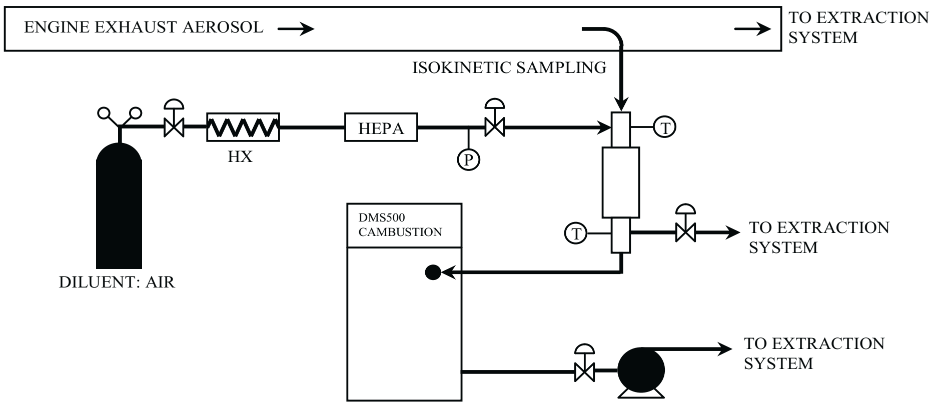


Fig. 1. PM sampling apparatus

The measurement of particulate matter was made using a partial flow dilution system. Exhaust gases were drawn at the locations described above into a mini diluter with constant 10-to-1 dilution ratio, where they were mixed with diluent (zero-grade air from bottle) under the controlled condition. The exhaust gases were thus diluted as in the real-world that vehicle engines emit exhaust gases which were mixed with ambient air. Also, with the limitation of the spectrometer in measuring PM number concentration, dilution and dilution conditions are crucial [1]. The diluted samples were then drawn into the electrical mobility spectrometer Cambustion DMS500 at a constant volume flow rate. The PM sampling system is shown schematically in Fig. 1.

Data post-processing

The particle number concentration corresponding to the given measurement is presented in terms of ($dN/d\log D_p$) with the unit of number per cubic centimetre and as a time-averaged PM size spectra. The area under the graph of ($dN/d\log D_p$) plotted against $\log D_p$ is the total number of particles (number per cubic centimetre) in the aerosol which can be calculated by integrating over the size range from 5 to 1.000 nm.

The mass-sized spectral concentration is obtained by re-weighting the number concentration:

$$\frac{dM}{d\log D_p} = \frac{dN}{d\log D_p} \cdot \rho_p \cdot S \cdot (D_p)^{d_f}\,, \tag{1}$$

where:

($dM/d\log D_p$) - unit of $\mu g \cdot cm^{-3}$,
ρ_p - particle density,
S - shape factor,
D_p - particle electrical mobility diameter,
d_f - particulate fractal dimension.

In this study, the particulate fractal dimension was assumed to be 3 and the particle density was assumed to be 1.000 kg·m^{-3} [2]. This is because those values are dependent of particulate diameter [19] and are not readily known. For the total PM mass, the integration of the mass concentration over the size range as the total number calculation is also applied.

As the spectrometer used in the test is able to measure aerosol in real-time, the PM number and mass size weighted distributions shown in the following sections are averaged from 30 seconds that are representatives for each steady-state engine test condition. Also, the following particulate number and mass size distributions were corrected for dilution and are shown as engine undiluted exhaust gas emissions.

Fuels used

The experimental study was performed using two different fuels: pure ultra low sulphur diesel (ULSD) and volumetric blend of 30% rapeseed methyl ester (RME) with 70% ULSD. The latter will be referred to as B30 in the following sections. The base fuels were provided by Shell Global Solutions UK and conform to the EN 590 and EN 14214 fuel standards for ULSD and RME, respectively. Some of the main fuel properties are given in Tab. 2.

Tab. 2. Fuel properties

	Test method	ULSD	RME
Cetane number	ASTM D613	53.9	54.7
Density at 15^{o}C (kg·m^{-3})	ASTM D4052	827.1	883.7
Viscosity at 40^{o}C (cSt)	ASTM D445	2.467	4.478
LHV (MJ·kg^{-1})		42.7	39.0
Sulphur (mg·kg^{-1})	ASTM D2622	46	5
Sulphur (mg·kg^{-1})		24.4	-
C (% wt.)		86.5	77.2
H (% wt.)		13.5	12.0
O (% wt.)		-	10.8

Tab. 3. Engine test conditions

Engine Condition	Engine[(a)]	Speed (rpm)	IMEP (bar)	EGR(vol.%)
C1	1	1500	2.0	0
C2	1	1500	4.0	0
C3	1	1500	4.0	10
C4	1	1500	4.0	20
C5	1	1500	5.0	0
C6	2	1500	5.1	0
C7	2	1500	5.1	48[(b)],45[(c)]
C8	2	1500	6.9	0
C9	2	1500	6.9	34[(b)],32[(c)]
C10	2	1850	6.5	0
C11	2	1850	6.5	37[(b)],36[(c)]

[(a)] *Numbers 1 and 2 represent the single-cylinder Lister-Petter and V6 Jaguar engines, respectively*
[(b)] *For ULSD case*
[(c)] *For B30 case*

Test conditions

The engine speed-load conditions used in this study for both engines are shown in Tab. 3. For Engine 1, the engine conditions C1, C2 and C5 were chosen covering a major range of the load conditions at this engine speed (1500 rpm). The volumetric flow rate of EGR was calculated according to the reduction in the air volumetric flow rate. The steady-state engine conditions C7, C9 and C11 for Engine 2 are extracted from the New European Driving Cycle while the EGR percentages were calculated and controlled by the engine management system.

3. Results and discussion

Influence of biodiesel blends without EGR

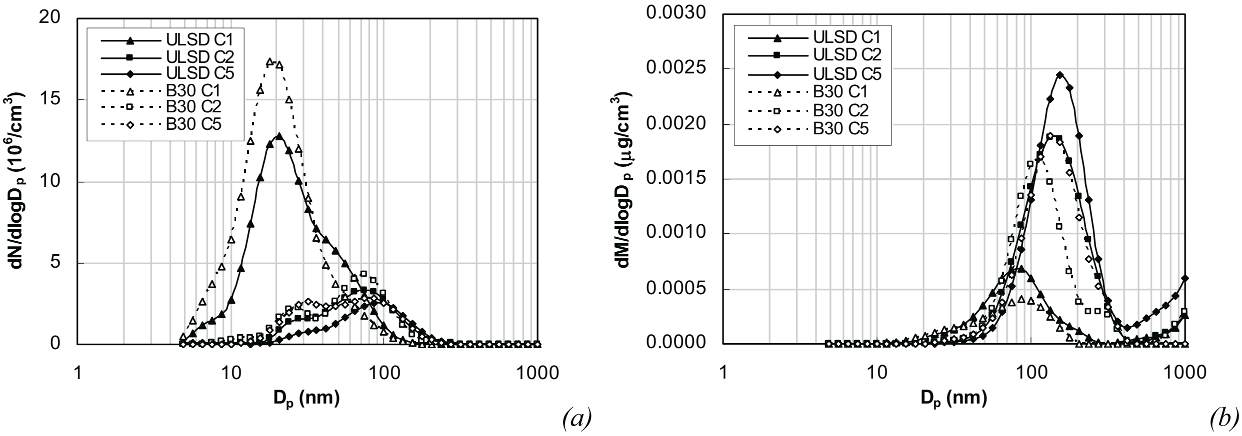


Fig. 2. Influence of biodiesel blended fuel on particle (a) number concentration - and (b) mass concentration - size distribution. Engine 1: Engine Condition C1 (2 bar IMEP, 1500 rpm), Engine Condition C2 (4 bar IMEP, 1500 rpm) and Engine Condition C5 (5 bar IMEP, 1500 rpm)

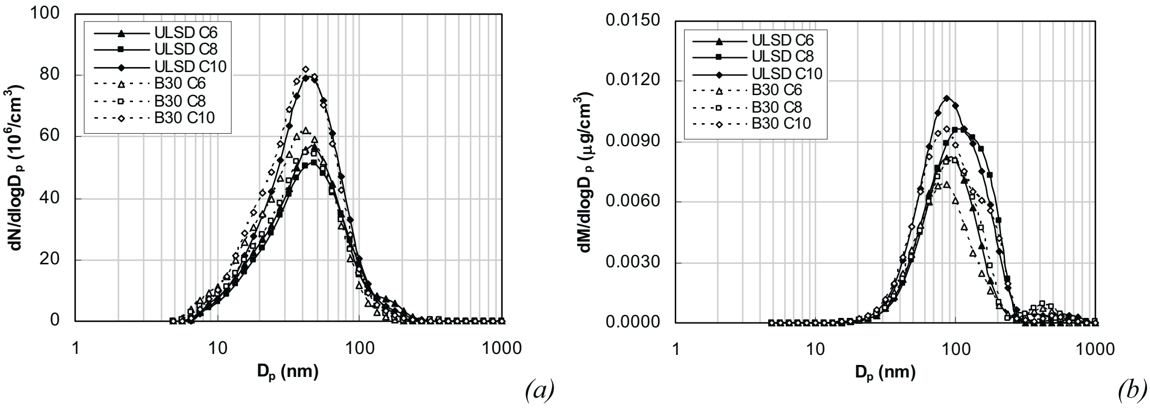


Fig. 3. Influence of biodiesel blended fuel on particle (a) number concentration- and (b) mass concentration- size distribution. Engine 2: Engine Condition C6 (5.1 bar IMEP, 1550 rpm), Engine Condition C8 (6.9 bar IMEP, 1550 rpm) and Engine Condition C10 (6.5 bar IMEP, 1850 rpm)

For the particulate matter emissions with ULSD and B30, the number and mass distributions over the size for Engine 1 are shown in Fig. 2a-2b respectively. Generally the particulate numbers of exhaust aerosol from B30 combustion are significantly higher in smaller diameter (nuclei mode) compared with ULSD combustion aerosol. This difference is much smaller for the measurement in Engine 2, as shown by Fig. 3. One of the main reasons for the increase in the particulate number in small size can be attributed to the increase in fuel injection pressure for RME shown by Fig. 4. This yields better fuel atomisation by increasing droplet number and shifting to smaller droplet size. In addition, the higher relative air-to-fuel ratio achieved locally in the combustion chamber as a consequence of increasing injection pressure facilitates the reduction of particle number in accumulation mode [5].

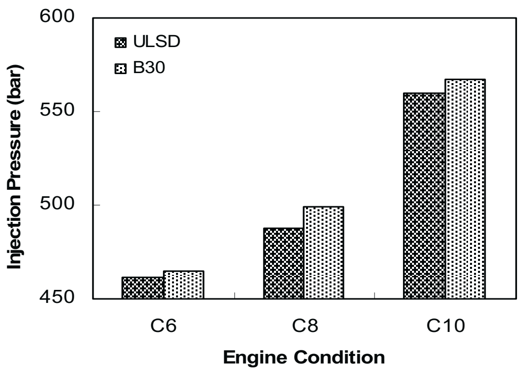


Fig. 4. Fuel injection pressure. Engine 2: Engine Condition C6 (5.1 bar IMEP, 1550 rpm), Engine Condition C8 (6.9 bar IMEP, 1550 rpm) and Engine Condition C10 (6.5 bar IMEP, 1850 rpm)

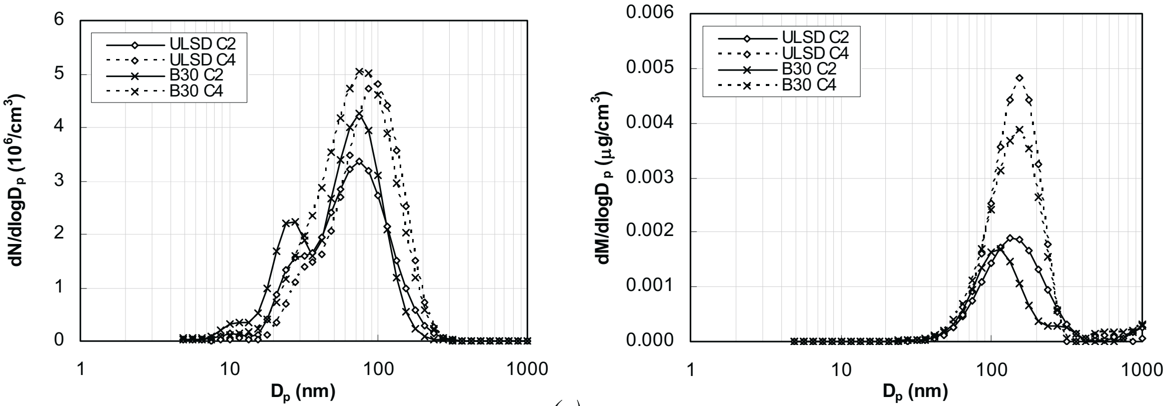
For B30 combustion in the engine combustion chamber, the oxygen-contained fuel mixture also reduces unburned hydrocarbons by lowering the rate of gas-to-particulate conversion [15]. This has resulted in the lower PM mass that is observed from the mass concentration-size distributions in Fig. 2b-3b and also the total particle mass in agreement with the literature [6, 11, 4]. For this study there appears to be trade-off, as reported by [15], between the total particle number and mass for both engines. In addition, the oxygenate fuel such as RME has contributed to a better fuel oxidation in the fuel-rich zone where the soot forming regions are located along the centre line of fuel jets. This leads to the reduction of both total PM mass and size [12]. Furthermore, the significantly lower sulphur in RME, which also has lower aromatics, can reduce the total particle mass from the B30 combustion, although the individual effect of aromatics on the particle characteristics can be examined further.

Influence of exhaust gas recirculation

At constant engine load and speed, the EGR addition was also found to affect the characteristics of the aerosol exhaust particles in terms of size, number and mass. Fig. 5 shows the particle number and mass size distributions over mobility equivalent diameter of the exhaust aerosol from Engine 1 for 0% and 20% EGR. The number and mass of particles in accumulation mode have been increased whereas the nuclei mode is reduced by the EGR for both fuels as reported by Kreso et al. (1998). Without EGR, the count mean diameters of aerosols from ULSD and B30 combustion were approximately at 64 nm and 59 nm respectively, but as the EGR rate increased to 20%, the count mean diameter has shifted toward larger sizes of around 84 nm and 71 nm for ULSD and B30 aerosol, respectively.

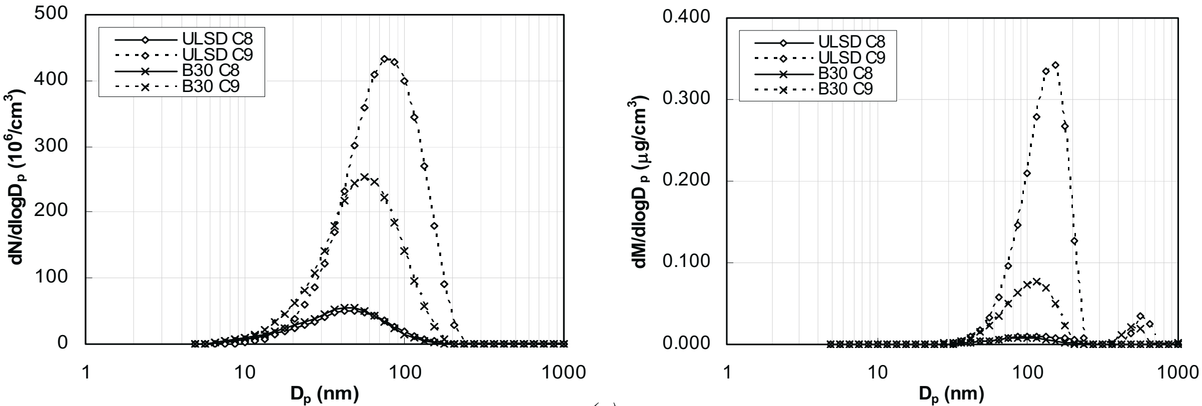
The particle number and mass distributions over the size of the exhaust aerosol from Engine 2 with EGR in comparison with the previous cases of without EGR are shown in Fig. 6. The trends are the same as in Engine 1 but there is a noticeable increase of the particle number mainly in the diameter range of 40-200 nm for both fuels when EGR is applied. The peaks of number concentrations are about 8 times for ULSD and 5 times for B30 higher respectively than those without EGR. In this case, the greater amount of EGR rate applied for ULSD (34%) may have been responsible for the higher number and mass of ULSD aerosol in bigger diameter, compared with 32% EGR for B30.

Fig. 5a indicates the effect of EGR on particles - for ULSD, it makes little difference to the particle number at mobility diameter smaller than 50 nm (nuclei mode), but for B30, it reduces considerably the number of particles in the nuclei mode. Potentially, reducing or maintaining the particle number at low mobility diameters can be proficiently carried out by optimising EGR addition. However, care has to be taken since this process may increase the total PM number and mass in larger sizes. In contrast, with biodiesel, this can bring benefits to the reduction of total particle number and mass at high mobility diameters for modern electronic-controlled diesel engines with common rail injection system such as Engine 2.



(a) (b)

Fig. 5. Influence of EGR on particle (a) number concentration - and (b) mass concentration - size distribution. Engine 1: 4 bar IMEP: 1500 rpm: Engine Conditions C2 (0% EGR) and C4 (20% EGR)



(a) (b)

Fig. 6. Influence of EGR on particle (a) number concentration- and (b) mass concentration- size distribution. Engine 2: 6.9 bar IMEP: 1550 rpm: Engine Conditions C8 (0% EGR) and C9 (34% EGR for ULSD and 32% EGR for B30)

4. Conclusions

Experimental studies on particle size distributions of exhaust gas aerosol of B30 and ULSD using diesel engines with different design features have revealed the conclusions as follows:

- generally the particle size of B30 combustion aerosol without EGR is smaller than that of ULSD while giving higher number concentration. The particle mass for B30 is likely to be underestimated,
- when EGR is applied, the total particle number and mass are increased along with the increase in particle size for both B30 and ULSD,
- the total calculated particle masses of B30 combustion aerosol are lower than those of the ULSD case, with consistent tendencies for both of the engines with different design features. Reducing or maintaining the particle number at low mobility diameter is potentially viable by the optimisation of EGR operation.

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