Fuel 112 (2013) 224–235

Contents lists available at SciVerse ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Effects of injection parameters and EGR on exhaust soot particle number-size distribution for diesel and RME fuels in HSDI engines

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HIGHLIGHTS

- RME emitted lower concentration of soot particles than diesel.
- Increasing the injection pressure reduced the particle size and its concentration.
- EGR caused smaller particles to agglomerate to form larger size particles.
- The presence of oxygen in the fuel reduced the exhaust particle number concentration.

ARTICLE INFO

Article history:
Received 11 December 2011
Received in revised form 8 April 2013
Accepted 1 May 2013
Available online 29 May 2013

Keywords:
Diesel
Rapeseed methyl ester
Size distribution

ABSTRACT

The exhaust soot particles number size distributions obtained from the combustion of diesel and RME fuels were investigated in a high speed direct injection (HSDI) diesel engine for different engine operating conditions *viz.*, fuel injection pressure, injection timing, exhaust gas recirculation (EGR) and engine load. An Electrostatic Mobility Spectrometer (EMS) was used for characterising the exhaust soot particle number size distribution. Increasing the fuel injection pressure reduced the particle size and its number concentration in the accumulation mode under low and high load conditions, but an opposite trend was observed to the particle number concentration in the nucleation mode under higher load operation. The effect of fuel injection timings on the particle number concentration was not clear and consistent between diesel and RME fuels under low load operation. Under high load operation, the overall particle number concentration for RME decreased but for diesel only the nucleation mode decreased, while the accumulation mode remained unaltered when the fuel injection timing was retarded. The addition of EGR caused the particles to agglomerate and form larger size particles, which were observed mostly in the accumulation mode. Under most of the engine operating conditions RME emitted lower soot particle concentration than diesel under both nucleation and accumulation modes. The presence of oxygen in the fuel has the potential to lower the exhaust particle number concentration in diesel engines.

1. Introduction

Diesel engines are widely used owing to their high thermal efficiency and low fuel consumption. Despite these benefits, particulates and NO_x emitted from diesel engines are of major concern for the environment. Though the global air fuel mixtures are lean in diesel engines, the local equivalence ratios can be greater than 2. These locally rich regions within the combustion chamber leads to favourable conditions for the formation of soot particles, which eventually results in higher exhaust tail pipe soot emissions [1]. The soot emissions from diesel engines consist of millions of carbonaceous solid particles, which combine to form aggregates and appear as visible black smoke, if they are in high concentration. Stringent emissions regulations are proposed in Europe and US and around the globe to control and reduce the soot particulates. Expensive after treatments systems are used to meet these emission regulations. Effective working and regeneration of these after treatment systems results in a penalty of fuel cost. The number concentration of soot particles emitted from diesel engine has also been a major concern. Euro 5 and Euro 6 aim to reduce PM emission to 0.005 g/km for passenger cars but the future legislation has also introduced a limit on the particle number emissions [2].

The generation of soot in engines can be minimised by enhancing the mixing time to have a more premixed type of combustion, and also by operating the engine at conditions where the global

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http://dx.doi.org/10.1016/j.fuel.2013.05.013

in-cylinder temperatures are low enough to inhibit the in-cylinder soot formation. These conditions of improved mixing can be achieved through strategies such as high levels of EGR, high swirl and through advanced or retarded injection timing, which are normally referred to partially premixed or low temperature combustion [3–6]. The benefit of low soot emissions from these strategies are mainly limited to low and medium load operation, limited information is available in the literature about the exhaust soot particle number size distribution under these operating conditions for diesel and RME fuels. So this work is focused towards exploring the exhaust soot particle number and size measurements under the strategies that favour low temperature combustion.

For the purpose of characterising soot, devices based on electrostatic soot particles classification technique have been widely used. These systems are usually capable of detecting particle mobility diameters in the range from 10 nm to 1000 nm and their number concentration. It has been shown that the general soot particle number size distribution from diesel engines has a bimodal type of distribution [7,8]. The nucleation modes are described as those particles in a diameter range below 50 nm and normally they peak at about 10–20 nm. Besides soot, volatile organic fractions and particles that are formed from super-saturation of un-burnt hydrocarbons in the exhaust system are present in the nucleation mode, and the nuclei mode contains 1–20% of the particles mass and around 90% of the particles number [9]. The accumulation mode ranges in size from about 50 nm to 500 nm, in this mode, carbonaceous particles from the combustion grew up through the condensation of hydrocarbons or agglomeration with other particles. Particulate measurement techniques require simultaneous sampling and dilution of engine exhaust soot particles before they are actually classified in an electro static classifier. The dilution of the soot particles are carried out to prevent coagulation, condensation and also to reduce the concentration to the limit that can be handled by the electrostatic classifier and particle counting devices. Thus dilution ratio is one of the important factors that influence the measured particle size distributions and it is also influenced by other factors such as temperature of diluting gas, residence time, ageing and relative humidity, as all these factors cause significant artefacts to the measurement of soot particles. In the already published literature, it has been shown that at low dilution ratios (about 20–30), high number concentrations of particles were observed in the nucleation mode [9–11]. The ways through which the aerosol is diluted are of importance than the actual dilution ratio itself. It is mixing and cooling of soot with dilution gas in a controlled way that preserves the soot from further nucleation or coagulation. The process of mixing and cooling of soot particles had been done in different ways in different systems [12,13]. The most commonly used system for simulating atmospheric dilutions is the constant volume sampler (CVS). This method can be used as a full exhaust flow dilution tunnel (FEFD-tunnel), or partial exhaust flow dilution tunnel (PEFD tunnel). Another system that is used for dilution is the ejector diluter, which is based on the venturi nozzle principle, the compact design of this system allows couple of units to be operated in cascade to achieve different dilution ratios. The rotating disc dilutor discussed in [14] is capable of achieving a wide range of dilution ratios from 1:30 to 1:1000 by varying the speed of rotation, and this is an ideal dilutor for particles below 1000 nm. Lyyränen et al. [15] proposed a dilution system where the dilution gas flows through a porous tube and mixes with the sampled exhaust before it is fed to the classifier and it is referred as porous tube diluter. In this work a similar type of dilution system was used to preserve the engine out aerosol before it was allowed to pass through a differential mobility analyser and a faraday cup electrometer.

The strategies that leads to improved spray mixing process and their effects on the exhaust soot particle number size and size are very limited. So this work is focused towards exploring the exhaust soot particle number and their size measurements for the strategies such as varying the fuel injection timing, fuel injection pressures and the exhaust gas re-circulation (EGR) under low load and high load operation for both diesel and RME fuels.

2. Experimental apparatus and procedures

2.1. Experimental setup

All measurements were carried out in a four cylinder high speed direct injection (HSDI) diesel engine. The schematic of the experimental setup is presented in Fig. 1 and the specifications of the engine are provided in Table 1. The injectors are designed to have six holes with a nozzle hole diameter of 0.154 mm, and the fuel was pressurised using a common rail system. The engine control unit (ECU) and its software allowed controlling the engine parameters on real time basis. The exhaust gas analyser (Horiba, Mexa 7170DEGR) was used to determine the level of EGR and the level of dilution in the primary dilution system.

A detailed schematic of the exhaust soot particle number size analyser (tapcon & analysesysteme, Electrostatic Mobility Spectrometer EMS VIE-11) is presented in Fig. 2. The EMS consists of a neutralizer, differential mobility analyser (DMA) coupled to a faraday cup electrometer (FCE). The neutraliser (Am-241), with an alpha activity of 60 MBq was used in the EMS and this radioactive source is covered with a 2 μm thick layer of gold/palladium. The DMA used in this work is used to detect particles of sizes ranging from 5 nm to 650 nm.

The soot was sampled from the exhaust and diluted in two stages (primary and secondary dilution). In the primary dilution system, the sampled soot was first allowed to mix with the inert dilution gas (N_2) in a perforated concentric tube arrangement. Introduction of the inert gas at an early stage of sampling prevented further changes to the engine produced soot in the exhaust at high exhaust gas temperatures. The primary dilution ratio (PDR) for the home built system was determined by measuring CO_2 simultaneously in the exhaust tail pipe before and after the sampled soot had been mixed and diluted with N_2 in the concentric tube arrangement, and the PDR is calculated as described in [16] as follows:

$$\mathrm{PDR} = \frac{CO_{2m} - CO_{2a}}{CO_{2e} - CO_{2a}}$$

where CO_{2m} is the concentration of CO_2 in the mixture (after the mixing process), CO_{2e} is the concentration of CO_2 in the exhaust gas (before the mixing process) and CO_{2a} is the concentration of CO_2 in the ambient air.

While the secondary dilution system is based on a closed loop mixing tube dilute configuration and it is shown as a dilution probe in Fig. 2, this unit is coupled to an Electrostatic Mobility Spectrometer (EMS). The N_2 diluted exhaust gas after passing through the FCE are allowed to pass through an absolute filter in the EMS system. The filtered gas are heated to dilute the aerosol again in a closed loop secondary dilution system before they are allowed to pass through the charger, DMA and FCE. It is possible get up to ten different dilution ratios by using a combination of six critical orifices (CO_1, CO_2, CO_3, CO_4, CO_5 and CO_6) as shown in the schematic (Fig. 2). Always a constant amount of flow Q_s (2.57 L/min) was drawn into the neutraliser, classifier and the FCE through the operation of the pump P_2 in conjunction with the main critical orifice (CO) placed ahead of the pump as shown in Fig. 2. Different dilution ratios were achieved through the operation of one or several critical orifices at different combinations to vary the dilution gas flow to the sampling probe and this alters the exhaust flow