

The Particle Emissions Characteristics of a Light Duty Diesel Engine with 10% Alternative Fuel Blends

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ABSTRACT

In this study, the particle emission characteristics of 10% alternative diesel fuel blends (Rapeseed Methyl Ester and Gas-to-Liquid) were investigated through the tests carried out on a light duty common-rail Euro 4 diesel engine. Under steady engine conditions, the study focused on particle number concentration and size distribution, to comply with the particle metrics of the European Emission Regulations (Regulation NO 715/2007, amended by 692/2008 and 595/2009). The non-volatile particle characteristics during the engine warming up were also investigated. They indicated that without any modification to the engine, adding selected alternative fuels, even at a low percentage, can result in a noticeable reduction of the total particle numbers; however, the number of nucleation mode particles can increase in certain cases. For all the fuels tested, the increase of engine load results in a general reduction of particle numbers and an increase of particle mean diameters while increasing EGR leads to increased total particle numbers, which are mainly in the nucleation mode. The engine particle emissions suffer much higher numbers of the nucleation mode non-volatiles during warming up than during normal operations.

INTRODUCTION

The diesel engine is a widely-used power unit for vehicles for its great advantages, such as lower fuel consumption, lower carbon monoxide emissions and better torque characteristics. However, it is among the contributors to air pollutions due to

its considerable amount of particulate and NO_x emissions and controlling these emissions is one of the most important aspects of modern air quality management and engine design [1,2,3]. In 2007, Europe Union finalized its light-duty Euro 5 emission standards which had applied from September of 2009 (light commercial vehicles and special needs cars from September in 2010) for new models of cars and from January 2011 (light commercial vehicles and special needs cars from January 2012) for all new cars. Compared with Euro 4, it confines the emissions further for carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x) and Particulates Matter (PM) and the latter two had a 28% and 80% reduction respectively. While from 2014, Euro 6 will be carried into force, and that will put a major restrict on the NO_x and particle numbers. The change of the diesel tailpipe standards listed in [Table 1](#) reflects how diesel engine technology has to be developed accordingly.

See [Table 1](#) after last section of paper

Particulates are probably the most critical issue of all the emissions for diesel engines. They are tiny solid and liquid particles and are sometimes referred to as particulate matter (PM) or fine particles, and their sizes, which are strongly linked to the human health issues, vary from several nanometers to several hundred microns[5,6,7]. Generally, particles from engines can be categorized into three distinct types according to their sizes: nucleation mode (<100nm), accumulation mode (100-900nm) and coarse mode



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(100-900nm) [5]. Coarse mode particles are mainly composed of those forming from the other two modes or atypical rust and scale from the exhaust system. They can easily be stored and released in the exhaust system and this inconsistency makes its manner unpredictable and thus less studied [5]. For the past years, people have mainly concentrated on the accumulation mode particles, which consist of some basic blocks called primary particles or spherules. The spherules' diameters are around 20-50nm and their numbers determine the size of the particles. They are composed of solid core parts and some liquid or semi liquid materials attached to the surface of their aggregations, making them "wet". Nucleation mode particles are relatively less studied for their obscure and irreproducible nature. Some of them are volatiles and some are solids. The environmental and human health issues of them are outside the scope of this paper, but are delineated well by Peter Eastwood [5]. Based on the conceptual model recommended by him, particles can be divided into non-volatile/non-soluble, which are mainly generated in the engine, and volatile/soluble, which form later in the exhaust. The former includes the soot and ash fractions while the sulphate, organic and nitrate fractions are categorized in the latter. According to the UNECE GRPE Particulate Measurement Programme (PMP), which focuses on the nano-particles from vehicle engines, it is recommended to use a thermo-diluter to remove all the volatiles and have the non-volatiles' number concentration measured which correlate greatly to the effects on human health and this has prompted the shifting of the research pivot from the particle mass, where most previous researches were done [8], to the particle number.

Biodiesel is one of the new alternative fuels, whose use is driven by the fossil fuel shortage and promoted by the increasing nationally defined fiscal means. It is commonly produced from a variety of raw materials through reactions called 'transesterification' [9]. The transesterified biodiesel mainly contains mono-methyl ester of long chain fatty acids and compared with the conventional diesel, it has the following advantages: 1.Higher cetane ratings; 2.Virtually containing no sulphur content or aromatic hydrocarbons, with better lubricating properties; 3. More complete combustion in engines for containing more oxygen, although with lower calorific values; 4. Higher flash point for safer storage and delivery. 5. It can help to reduce emissions such as particulates. These have been proved in many studies [10,11].

However, its physical and chemical characteristics make it face challenges when to be used in commercial engines. A major disadvantage of biodiesel is the reduced oxidation stability, compared with mineral diesel. There is also a potential impact on fuel injection equipment components, as described by FIE manufacturers [12]. One of the workable ways is to blend it with the commercial diesel at a relatively low percentage [11,13,14,15]. According to the ACEA agreement on biofuels made in 2008, it was agreed that 7%

was the maximum permissible blend level for commercial diesel engines without making any modifications. Nowadays, the new diesel supplies from fuel companies have bio-components up to 7%.

Unlike biodiesel, Gas to Liquid (GTL) diesel is not yet widely available for the public use. However, for its abundant resources, there is a growing demand and the developing conversion technologies are making it another option to be the future alternative of the conventional diesel [16]. Similar to biodiesel, GTL produces fewer emissions than fossil diesel, and having it blended with fossil diesel is a possible way in the near future. GTL is produced by converting natural gas or other gaseous hydrocarbons into longer-chain hydrocarbon diesel, through methods such as Fischer-Tropsch (US Energy Information Administration). Compared with conventional diesel, GTL has the following advantages: 1.Higher cetane ratings; 2.Virtually containing no sulphur content or aromatic hydrocarbons; 3. Can help to reduce emissions such as carbon monoxides, particulates and etc. The density and viscosity of GTL is normally lower than a typical EN590 compliant mineral diesel, and this limits the amount that can be blended without stepping outside the density / viscosity limits prescribed in the EN590 standard. These were presented in [17,18].

The present study aims to investigate the particles characteristics from the combustion of 10% blend of RME and GTL (comparable to the 2020 fuel blends target) on a Euro 4 engine without any modification. The measurement has been taken using 2 methods: one is without thermal dilution, used for all the steady engine conditions, the other is based on the UNECE GRPE Particulate Measurement Programme, with thermo-dilution, used for the engine warming up from cold. The experiment was carried out in the Future Engines and Fuels Lab in the University of Birmingham.

EXPERIMENTAL SYSTEM

The tests were conducted on a current production diesel Ford Engine. It is turbocharged, with a common-rail direct injection system and cooled EGR. The overall experiment set-up is shown in [Figure 1](#). Exhaust gases from the engine flow through a Diesel Oxidation Catalyst (DOC) and then a Catalyzed Diesel Particulate Filter (DPF). The aerosol sample is drawn through the 'Pepper Pots' drilled at the end of the ¼ inch stainless steel tubes at the sampling point upstream the DOC. The specification of the engine is given in [Table 2](#).

See [Figure 1](#) after last section of paper

Engine and Testing Rig-The Engine is coupled with an FCL EC38TA Eddy Current Dynamometer from CP Engineering. The Data Acquisition (DAQ) System is set up through two NI DAQ Cards: one USB 6218 for the in-cylinder combustion

pressure measurement and one PCI-6251 for the measurement of test rig temperatures and pressures. Both are installed in a desktop computer, and the acquisition of data is managed by in-house developed programs in LabVIEW environment.

See [Table 2](#) after last section of paper

Test Fuels-the properties of the fuels used are listed below. In the test, 10% RME and 10% GTL diesel were blended with the mineral diesel (labeled as RME 10, GTL 10 respectively in this paper).

See [Table 3](#) after last section of paper

SMPS and the diluter-A Scanning Mobility Particle Sizer (SMPS) (Model 3936) from TSI was used in the test to measure the particulate size distribution and concentration. It consists of a Model 3080 Electrostatic Classifier (EC), a Model 3775 Condensation Particle Counter (CPC) and two DMA's, one long DMA and one nano DMA. The long DMA was used in the experiment. The diluter was a 379020A Model from Matter Engineering AG and the dilution ratio was set to 90. For the thermo-dilution, another diluter was used, Model ASET15-1, with an integrated MD19-2E rotating disk diluter mounted in. It supplied thermo-dilution by heating the dilution air to 300 °C (from A-C-D in [Figure 2](#)) and removed the volatiles which had a great influence to the particle number measurement. The dilution ratio was set to 181 for the primary dilution and 3 for the secondary one, which gave an overall dilution ratio of 542. The reason for this arrangement was to get sufficient dilution to avoid the volatiles nucleation during C-D phase [\[19\]](#).

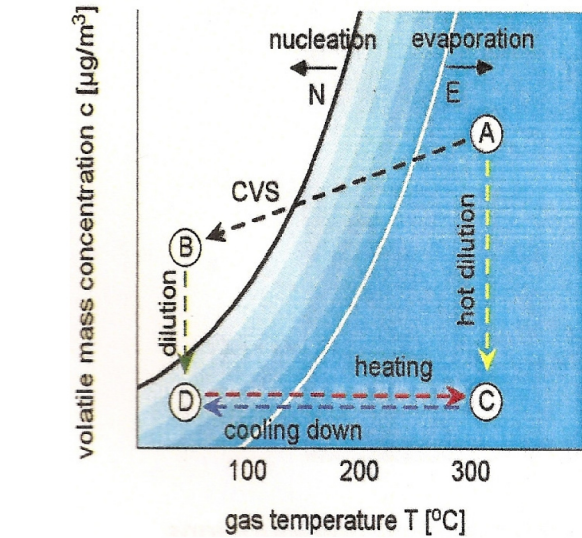


Figure 2. Thermo Dilution [\[19\]](#)

AVL Smoke Meter-An AVL Smoke Meter 415SG002 was used to measure the smoke in the exhaust of the engine. The result of its measurement was displayed as Filter Smoke Numbers

SEM-A Jeol JSM-7000F FE-SEM with Schottky emitter was used for the research. It has a resolution of 1.2 nm at 15 kV, 3.0 nm at 1kV and a Magnification of 10 - 500,000.

Horiba MEXA-7100 DEGR-the emission gas of the engine was directly sampled and the concentrations of CO, HC and NOx were measured using the gas analyzer.

Engine Test Modes and Procedures-[Table 4](#) shows the 8 engine test modes selected and recommended by the supplier of the engine for this study, which covered different speeds and loads. EGR was used in Mode 2, 3 and 6, and the EGR valve opening for the diesel fuel was also listed in [table 4](#). For all the three types of fuels, the engine was running at the same speed and torque. The injection strategies were adjusted automatically by the ECU calibrated for diesel fuel without any modification. The sampling and measurement were finished at the same test point upstream the DOC after 10 minutes engine stabilization. For each mode, measurements were carried out three times in a row and the results were averaged.

Table 4. Engine Test Modes

Mode	Engine Speed (rpm)	Torque (Nm)	Load (%)	EGR Valve Opening (%)
1	800	2.1	0.68	0
2	1800	30	9.68	30.91
3	1800	30	9.68	15.45
4	1800	30	9.68	0
5	1800	134	43.23	0
6	3100	35	11.29	18.18
7	3100	138	44.52	0
8	3100	230	74.19	0

RESULTS AND DISCUSSION

PARTICULATE NUMBER CONCENTRATION

See [Figure 3](#) after last section of paper

Effect of alternative fuel blends--[Figure 3](#) shows the total exhaust particulate number concentration of the eight engine modes when fuelled with diesel, RME 10 and GTL 10 respectively. It is very clear that adding either of the two alternative fuels, even at a percentage as low as 10%, could

reduce the particle numbers in a similar way and this effect was even more significant when the engine was running in the middle speed range and high speed range with low loads. As shown in mode 2, mode 5 and mode 6, RME 10 reduced the particle number by 28%, 32% and 28% and GTL 10 by 32%, 34% and 29%, respectively, compared with diesel. In the idle mode, GTL 10 emitted the least particles, 33% less than diesel, while RME 10 showed little improvement. This effect has been illustrated in many papers and it is believed that for the high cetane number and aromatics and sulphur - free characteristics, the 10% GTL diesel blend could improve the PM emission, while the oxygen contents contained and also the aromatics-free characteristics of the 10% RME could achieve similar PM reduction.

Effect of engine speed and torque--For the eight engine modes, the particle numbers varied from $5619/\text{cm}^3$ to around $1 \times 10^6/\text{cm}^3$. The engine emitted the least concentration of particles in Mode 5 for all the three types of fuels when it was running at 1800 rpm, 134 N-m and no EGR was used. Mode 4 and Mode 5 had the same speed of 1800 rpm, with no EGR and when the torque was increased from 30 N-m to 134 N-m, the particle numbers were decreased by 68% for diesel, 73% for RME 10 and 73% for GTL 10 respectively. Under high speed engine conditions, the total particle numbers increased slightly with the load for RME 10, while for diesel and GTL 10, the trend of change was not clear. The increase of speed could result in more particles, as in Mode 7 the particle number was 10 times more than that in Mode 5.

Effect of EGR--EGR is mainly used for the reduction of NO_x and its impact on the particulates has been discussed by many people such as [20]. EGR's particle-producing effects were caused by its oxygen-replacement, higher heat capacity and radicals-supply effects. From Mode 2 to Mode 4, the EGR valve opening was reduced from around 31% to 0% (no EGR), and the particle numbers were reduced by 70% for diesel, 66% for RME 10 and 65% for GTL 10 respectively. In Mode 3, when the EGR valve was 15% opened, the effect of the alternative fuel blends to the particle numbers was least significant.

Mass--Figure 4 (a) is the Filter Smoke Number (FSN) of all the engine modes. Its trend of variation is not quite the same as the particle numbers shown in Figure 3. It indicates that when a smoke meter used the particle opacity for the calculation of mass, it not necessarily correlates to the particle numbers. This is particularly clear in high speed mode (from Mode 6 to Mode 8); although in certain conditions (from Mode 2 to Mode 5), they might seem relevant. The trade off between smoke and NO_x for different EGR (under 1800 rpm, 30 N-m) is also indicated in Figure 4 (c) for all the three fuels.

See Figure 4 after last section of paper

PARTICULATE MEAN DIAMETER

Figure 5 is the counted mean particle diameters of the eight engine test modes, derived from the SMPS results. The influences of the fuel properties to the diameters are not clear, although RME 10 seem to show the smallest mean diameter for most of the engine modes. For all the three fuels, the increase of engine torque led to an increase of the particle mean diameter. This is caused by the reduction of nucleation mode particle numbers in the middle speed range while the increase of accumulation mode particles in the high speed range, referring to the particle size distribution from Figure 6, Figure 7, Figure 8. Also from the particle size distribution, shown in Figure 9, it can be seen that the increase of the particle mean diameters with the increase of EGR is contributed by the production of large numbers of nucleation mode particles.

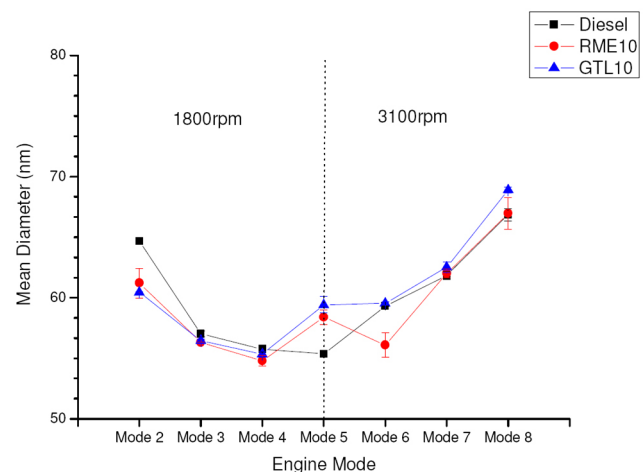


Figure 5. Particle mean diameter

PARTICULATE SIZE DISTRIBUTION

Figure 6 is the number weighted particle size distributions for the engine idle mode when fuelled with diesel, RME 10 and GTL 10 respectively. They are very similar and all show a bimodal size distribution. For the three types of fuels, the nucleation mode particles had two peaks, one at around 80 nm while the other varied. It is very clear that, adding either RME or GTL to diesel could reduce the particle numbers; however, there was an increase in the number of particles at diameter of around 20nm with the addition of 10% RME. This corresponds to the small difference in total particle numbers between diesel and RME 10 in Figure 3 and the reduction of particle number for GTL10 was contributed by the reduction of nucleation mode particles with a diameter of 10nm.

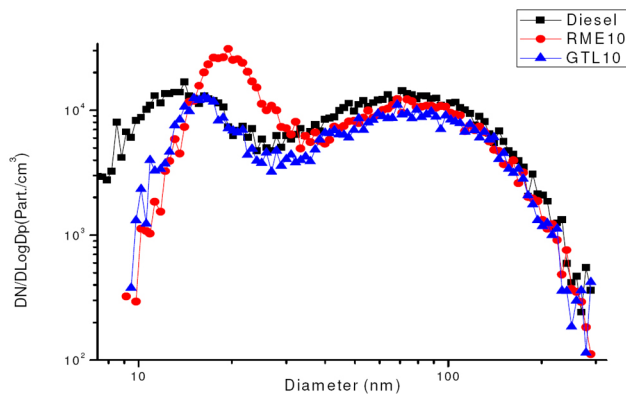


Figure 6. Number weighted particle size distributions at 800 RPM

Figure 7 shows the number weighted particle size distribution with two different loads at 1800 RPM. Unlike the idle mode just presented, the particle numbers at this speed all peaked at around 55 nm and showed a more monomodal feature for all the three fuels. The engine load had a great impact on the particle numbers and reduced the peak by half an order of magnitude when it was increased from 10% to 43%. This might be caused by more solid surface areas being produced for the volatiles to be attached to as high engine load favors carbonaceous particulates while low engine load favors organic ones.

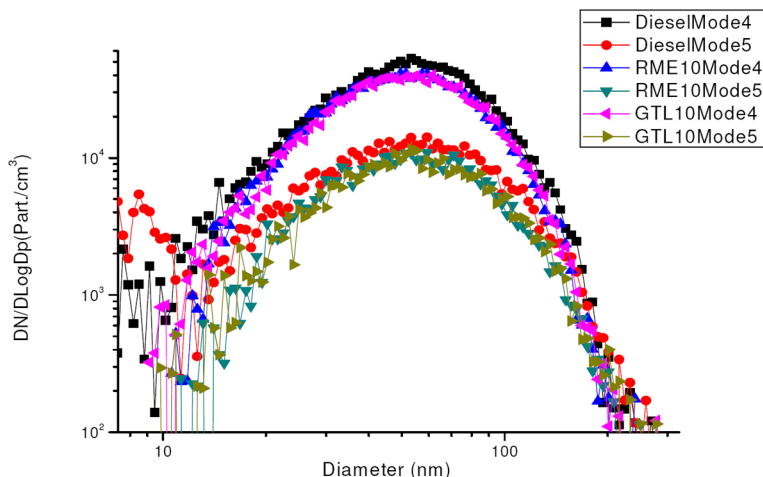


Figure 7. Number weighted size distributions at 1800 RPM

Figure 8 shows the number weighted particle size distribution at 3100 RPM and the particles all peaked around 55-60nm. The addition of RME or GTL reduced both accumulation mode and nucleation mode particles for all the three different loads, and this effect was especially evident at high load as (c). The influence of the engine load to the particle numbers is inconspicuous. However, the increase of the load tended to

produce larger particles, as Figure 8 (d) shows, which led to the increase of the particle diameters illustrated in Figure 5.

See Figure 8 after last section of paper

EGR--As mentioned earlier, for all the three tested fuels, reduced EGR corresponded to a decrease in both the total particle numbers and the mean diameter, shown in Figure 3 and Figure 5. It might also increase the particles in the smallest size range with a diameter of around 10nm according to Figure 9. This was particularly apparent with diesel.

See Figure 9 after last section of paper

PARTICLE MORPHOLOGY

A set of SEM images under different resolutions were taken for the particles from the three tested fuels and three typical ones, under the same magnification of 65000, are shown in Figure 10. All the samples were captured using 47mm circle glass microfiber filters from Whatman for a period of 10min under engine Mode 4 (1800rpm, 30nm) condition. Comparing the images of Figure 10(a), (b) and (c), it is clear that particles from diesel combustion had more clusters than those from the RME10 or GTL10. They also give an indication that the primary particle size from the combustion of all the three fuels is around 20-50 nm, as measured from the images.

See Figure 10 after last section of paper

NON-VOLATILE PARTICLES FROM ENGINE'S COLD START AND WARMING-UP

The non-volatile particulate size distribution was investigated during the warming up and RME10 was used in this test. Here SMPS was only employed to show the trend of change of the particles within a period of time as the condition is not constant. After the engine was started, it was kept idling (800rpm, 2.1N-m), and the data were recorded with an 8 minutes interval (labeled as Point 1- 6 in Figure 11) until the engine coolant temperature reached a constant of 80°C.