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Particulate emissions from large-scale medium-speed diesel engines: 1. Particle size distribution

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ABSTRACT

This paper addresses particulate matter (PM) size distributions in large-scale diesel engine exhaust. The test engines were multivariable large-scale turbo-charged, after-cooled medium speed (~500 rpm, ~1 MW power per cylinder) direct injection diesel engines. Emissions measurements were carried out while burning heavy fuel (HFO) and light fuel (LFO) oils. Test modes for investigation were propulsion mode (marine) and generator mode (power plant), with load varying from 25 to 100%. PM was measured using a gravimetric impactor with four impactor stages plus a filter, classifying particles between 0.005 and 2.5 μm (aerodynamic diameter). The results show that HFO firing produces significantly higher PM emissions (more than factor of ~three on mass bases for high load operation) compared to LFO, especially for particles smaller than 0.5 μm. This is mainly due to higher ash-forming elements and sulphur content of HFO. For HFO, the fraction of the finest particles increases with load, more strongly for generator mode than for propulsion mode, with generator mode giving ~50% higher PM emissions than propulsion mode. With LFO firing, the largest amount of fine PM was emitted at the lowest load, for propulsion mode being lower and almost independent of load at higher loads, while for generator mode a steady decrease in emissions with increasing load is seen for all PM size classes measured.

1. Introduction

The use of large-scale diesel engines on sea-going ships and for the production of electricity at locations where the power grid cannot be accessed is steadily increasing, which has stressed the importance of addressing the emission of pollutants from the equipment. Besides the greenhouse gases CO_2, CH_4 and N_2O, the emissions of NO*x*, particulate matter (PM), SO*x* and unburned species CO and HC (hydrocarbons) should be monitored and minimised and, depending mainly on location and the type of fuel used, measures must be taken to reduce the emission of certain pollutants. Particle size and its distribution are important parameters for characterizing the behaviour of diesel engine PM emissions. An appreciation of how diesel exhaust particle matter properties vary with particle size is fundamental for understanding their formation and control. Typically the size of diesel PM is for 90% below 1 μm in diameter, known as $PM_{1.0}$ in health and safety regulations [1].

Diesel particulates consist principally of combustion generated carbonaceous materials (soot) on which some organic and inorganic compounds have become absorbed and condensed. Diesel fuel composition has an important influence on particulate diesel exhaust although also the catalytic converters widely used in small-scale systems play a role in sulphate particle nucleation. Besides this, also the lubrication oil and especially metal-based additives contribute to PM formation and emissions [1–8].

In direct injection diesel engines, the highest particulate concentrations are found in the core region of each fuel spray where local time-average equivalence rations are very high (i.e. mixture is very rich in fuel). This corresponds to a large fraction of the fuel carbon in the extremely rich fuel vapour core being present as soot particulate. The picture becomes more complicated as the rate of fuel injection increases with engine load [9]. The time available during the combustion process for the formation of solid particles (SOL) from a fraction of the fuel is on the order of milliseconds (ms). The fuel distribution, mixing and heat-release in the cylinder are highly non-uniform during the particle and soot formation.

Particle size distribution can be presented using either the mass or number of particles. In the mass size distribution, as given this study, the majority of the particulates i.e., the particulate mass, is found in the accumulation mode with particle diameter $d_p>0.1$ μm. The nuclei size fraction ($d_p<0.1$ μm) depending on the engine technology and particle sampling technique may be as low as a few mass percent, sometimes even less than 1%. Although most of the diesel PM mass is contained in the accumulation mode, most of the particles in the number size distributions can however be found in the nuclei mode (typically the size range below 30–50 nm). The number and size of these nuclei mode particles depends

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also on the particulate sampling conditions, such as dilution ratio(s) and sampling temperature applied during the measurement [10].

For this work, PM number distributions were not measured because the focus was on current emission regulatory that is based on PM mass. Moreover, a PM number measurement would give practically all particles are in the size range below 0.1 μm almost independent of engine and engine operation parameters, while this work aimed at particle sizes up to several micrometers, covering the accumulation mode size range.

There are not many publications on the size distribution and composition of particulate matter sampled from the exhaust of large-scale diesel engines firing heavy (HFO) or light (LFO) fuel oils. Due to differences in PM sampling and measurement methods used, it is not possible to give a reliable (unambiguous, explicit) quantification of PM emissions and size distribution that suits all needs [11]. The determination of particle size and number size distribution is much more sensitive to the measuring techniques and parameters than the quantification of particulate mass emissions, which in principle can be accomplished using a filter or other simple impactor [12].

For the determination of the particle mass-based size distribution approaches based on inertial impactors are very powerful, as also in this study. Most data by others (almost exclusively measured from the exhaust of small engines with <1 MW power output) suggest that the particle size distribution is not bimodal [13].

The emission reductions in newer diesel engines are primarily due to lower accumulation mode size PM emissions [10,14]. New diesel engines have a higher fuel injection pressure, a higher turbocharger boost pressure and a better intercooler system. It is known that diesel engines sometimes produce a three-modal PM size distribution [13]. It has been suggested [15] that this might be due to the presence of metal compounds in diesel exhaust particles. As will be confirmed below by our data on large-scale engines, practically all particulates have sizes significantly less than d_p 2.5 μm (aerodynamic size), defined as $PM_{2.5}$ and to a large extent also finer than 1.0 μm, $PM_{1.0}$[12].

Considering particle formation during and after combustion it is of much interest to know how fuel type and engine load determine and affect the resulting complex mixture of diesel PM and its concentration. Several researchers (working on much smaller engines than those considered here) found that increasing load results in a widening of the PM size distribution as a result of more primary particles (i.e. nucleation sources) formed with higher fuel input [16,17], whilst others found a (linear) relation between diesel fuel sulphur content and emissions of soot and/or PM [18]. Note, however, that the combustion and other processes that lead to pollutant formation in smaller engines will differ in many ways from that in large engines.

This paper investigates the mass-based emission of diesel particulates and their mass size distribution from large-scale (~1 MW per cylinder) diesel engines burning heavy and light fuel oil (HFO and LFO). In addition, the effect of generator and propulsion mode at different loads on the particle mass size distribution and particle formation was studied. Mass size distributions were measured using a gravimetric impactor and presented as particle mass concentration in this study. While this part 1 focuses on PM size distributions, part 2 of this paper [19] will focus in more detail on the chemical composition of the PM size fractions.

2. Experimental procedure

2.1. The engine, fuels and test conditions

The experimental set-up for the tests is shown in Fig. 1. The test engines used were turbo-charged, after-cooled and trimmed 6–18 cylinder diesel engines (about 300 different engines of both L and V type) with power output ~1 MW per cylinder (Table 1). Engine tests were carried out according to Dekati [12], MARPOL 73/78 [20] and ISO 3046-1 [21] test conditions and procedures (which include accounting for differing ambient conditions), see Table 2 for engine operation conditions. No effect was found of the size (i.e. number of cylinders) or type (L or V) of the engines used. All engines were new when tested (after allowing for 8–10 h to reach a steady state) and had the same power output per cylinder Fuel properties are given in Table 3. Fuel temperature to injector (fuel pump) was ~120 °C for HFO and ~60 °C for LFO, respectively (the higher viscosity of HFO required a higher fuel temperature) and injection pressure was ~130 MPa. The exhaust gas flow was ~30 kg/s maximum on full load, at ~350 °C, 100 kPa, with manifold diameter 1.6 m. The sampling point for PM and soot (FSN) was located 10 m from the engine exit (turbocharger leading to exhaust manifold). After dilution by a factor of seven (7, vol/vol) [22], the PM aerosol sample was fed through heated sampling (150 °C) lines to the impactor. More discussion on the dilution is given in part 2 of this paper [19].

2.2. Engine operation, propulsion and generator mode

The propulsion mode of operation is used only in marine applications and implies operation with varying engine speed. The generator mode of operation, with constant speed, is used in marine applications and as power utility and typically produces power for an electricity generator [23]. Matching (which implies that the surging of the turbocharger is avoided, by increasing the air flow through the cylinder) the marine diesel engine for running in propulsion mode has a relatively strong influence on exhaust emissions. Matching implies a compromise between performance at low load and at high load, with the optimal load at about 82%. If the diesel generator is required for base load operation, the engine matching will be rated at full load when it comes to exhaust emissions minimisation [24].

Important are the different air flow rates for the two modes for a given load, which will affect the mixing processes, the combustion temperature and hence the formation and destruction of pollutants. For example 40% load gives 25% of the power (~0.25 MW/cylinder) for propulsion mode while with generator mode this power requires 25% load. Less air gives smaller flows and less turbulent (mixing) flow. Optimum specific fuel consumption will occur at load 75–85%, where mechanical friction losses are lowest. But, as regards to exhaust emissions the PM will increase for low load (power) for both the propulsion and the generator mode as will be shown below. Note that turbocharger operation is different for propulsion or generator mode.

2.3. Measuring procedures and test cycles

The measurements were made in compliance with the emission limits in accordance with regulation MARPOL 73/78, Annex VI [19], ISO 3046 [21], ISO 8178 [25] for diesel engines. When an engine operates on diesel oil the emissions shall be determined in accordance using the relevant test cycles and measurement methods.

For constant speed diesel engines under generator mode (including diesel electric drive) test cycles shall be applied in accordance with the following table:

•	Speed%	100	100	100	100
•	Power%	25	50	75	100
•	Load%	25	50	75	100

For the propulsion mode operation the main engines' test cycles shall be applied accordance with the following table:

•	Speed%	63	80	91	100
•	Power%	25	50	75	100
•	Load%	40	63	82	100

Note that "load" means for generator mode (constant speed): x% load = x% of the max. power (=1 MW/cylinder); for propulsion mode: x% load = x% of the BMEP at the given speed. The maximum variations in load were ~10% at 25% load, ~5% at 50% load, and ~3% at 75% and 100%, respectively.