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Effects of dilution conditions on diesel particle size distribution and filter mass measurements in case of marine fuels

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ABSTRACT

Particle emission characteristics were studied from heavy-duty diesel engine operating on fuels with sulfur levels relevant to marine operation, i.e. 0.05% S and 3% S respectively. Effects of primary dilution temperature (PDT) and primary dilution ratio (PDR) were investigated together with effect of filter media and time of filter conditioning. PDT increase was found slowing down nucleation rate due to increase of saturation vapor pressures of volatile species. In turn, increasing PDR reduces partial pressure of exhaust species and hence weakens both homogeneous and heterogeneous nucleation. All these effects are amplified by high sulfur content in marine fuels which increases available amount of nucleation-prone vapor-phase semivolatile compounds. At the same time, water condensation artifact was observed at PDR = 3. No filter type was found to be overwhelmingly superior as certain positive and/or negative measurement artifacts are inherently associated with all filter materials. The filter conditioning time was also found to cause substantial PM mass variation, as control over VOC take up from (or lost to) laboratory air and hydration of sulfuric acid is required. The standard 24 hour conditioning time was found insufficient to reach complete PM mass equilibrium, so longer time is required when measuring from high-sulfur fuels.

1. Introduction

Diesel engines are likely superior to any other power-production device used for transportation purposes in terms of torque, driveability, and overall efficiency, but at the same time they suffer from inferior performance in terms of noise, NO_x and particulate matter (PM) emissions [1]. The recent technology improvements like common rail, direct injection, turbocharging, and multiple fuel injections enhanced combustion and helped not only to overcome the low power density and high noise disadvantages [2,3], but also allowed to reduce the levels of emitted pollutants. Nevertheless, engine manufacturers are still constantly challenged by emission legislation authorities that continuously toughen national and international emission standards for oxides of nitrogen, which adverse effects are well-known and comprehensively understood, and particulate matter. These actions are needed and highlighted especially by an increasing number of toxicological and epidemiological studies [4–7] that confirm the existence of the link between the daily mortality and morbidity and the exposure to inhalable PM (alone and/or combined with other pollutants in the air).

Both coarse ($D_p > 2.5\,\mu m$) and fine ($D_p < 2.5\,\mu m$) particles accumulate in human respiratory system and are associated with numerous adverse health effects; for example, cardiac arrhythmias [8,9] and emphysema. Fine particles have been more clearly linked to the most serious health effects [10], with people having lung disease, the elderly, and children being most at risk. These small particles promote changes in lung function [11], lung inflammation [12], elevate blood pressure, increases vascular inflammation [13,14], causing lung cancer [15], some other diseases, and may lead to premature death [16]. Ultrafine ($D_p < 100\,nm$) particles have been identified as a particular concern for human health [17,18] with some laboratory studies showing that particles which are non-toxic at $D_p \sim 1\,\mu m$ can be toxic when $D_p \sim 10\,nm$ [19–21]. Moreover, nanoparticles ($D_p < 50\,nm$) can penetrate very deep into the human lungs and enter the circulatory system together with blood cells [22,23], having a potential to deposit in vital organs such as brain or heart [24]. Another concern of PM is its environmental impact which is primarily related to reduced visibility, deposition on vegetation and impacts on ecosystems, as well as damage to paints and building material [10].

Taking into account all the aforementioned negative PM effects, it is rather obvious why the topic of diesel aerosols has attracted so much attention. During the past years, various researchers have investigated PM number concentrations and size distributions emitted from diesel engines [e.g. 25–28]. The diesel exhaust particle size distributions often consist of two distinctive modes, so-called nucleation mode and accumulation (soot) mode. Accumulation mode is typically in the range of 30–500 nm and composed primarily of in-cylinder originated soot agglomerates with condensed and adsorbed on them hydrocarbon (HC) and sulfur compounds formed in the cooling dilution process. This mode typically contributes 80–90% from the overall particle mass [29].

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The nucleation mode particles are typically <30–50 nm in diameter, mainly volatile, and consists of HC and sulfur compounds that homogeneously nucleate during dilution process [30,31] or condense on preexisting non-volatile cores [32–34]. Normally, only less than 10% of PM mass is found in the nuclei mode, but it might contain up 90% of particle number [25,35]. The size of nucleation mode is clearly dependent on dilution conditions, while accumulation mode is independent of them [34,36]. Comprehensive characterization of diesel particle emissions should address both accumulation and nucleation mode particles [37]. Moreover, one should take into account that formation of nuclei-mode particles is strongly influenced by dilution parameters like primary dilution temperature, primary dilution ratio, residence time and relative humidity of dilution air, which were investigated in number of studies [e.g. 25,38–41].

At the same time, there are not so many studies concerning PM emissions from marine diesel engines (MDE) [e.g. 42–45]. The shipping is known as one of the most effective ways of cargo transportation (in terms of tonnage kilometers), but huge amounts of transported goods together with majority of ships driven by non PM-optimized engines and operation mainly on residual fuels containing up to 3.5% of sulfur (by mass) making shipping a significant contributor to PM air pollution [46–48]. Differences between automotive and MDEs are significant; first of all, they operate on totally different types of fuels with cars and trucks using distilled fuels, and MDEs operating mostly on heavy fuels. Moreover, their geometrical dimensions and operating parameters are also very different. So taking into account all the mentioned dissimilarities, one should expect pronounced difference in PM emission characteristics between them as was reported earlier by Kasper et al., [42]; on the other hand, there might be certain similarities not only in shape of size distributions, but also in overall particle concentrations and mode diameters, especially in case of 4-stroke engines [45].

Since sulfur was found to be very important in relation to overall PM emissions [49,50], it has become one of the most studied parameters of on- and off-road diesel engines [e.g. 51–53]. There were no similar studies for marine diesel engines, first of all, because only few research laboratories have them in their disposal ready for full-scale tests and they are rather expensive in operation; secondly, as typical marine fuels normally contain significant quantities not only sulfur, but also some other impurities, like ash compounds [42], so the sole effect of sulfur content in fuel can be hardly separated from other factors; thirdly, there have been very limited interest in studying the effects of various dilution parameters on particle size distributions and gravimetrically collected PM mass from high-sulfur marine fuels as there are actually no direct PM regulations for marine engines [47].

In current study a low-sulfur marine gas oil, considered as base fuel, was artificially doped with dimethyl disulfide ($C_2H_6S_2$) to the level of 3% (by weight) to reproduce, if not exactly to initiate, the molecular structure and content of natural sulfur-bearing compounds [50,54,55] in marine heavy fuel oils. The objective of this work was to evaluate the effects of dilution parameters (PDR and PDT) on particle size distribution and PM mass measurements at different load conditions for two fuels: base fuel, 0.05% S, and artificially doped fuel, 3% S (by weight) representing conventional low sulfur-level MGO and high sulfur level in HFO respectively. Moreover, we also evaluated how filter media and filter conditioning time affect the measured particle mass concentrations.

2. Experimental

2.1. Test engine, fuel and conditions

The engine operated during current research study was a 4-stroke high-speed heavy-duty turbo-charged diesel engine equipped with an aftercooler and fully complied with Euro 2 emission tier (Table 1). The experiments were carried on a test bed based on dynamometer water brake for constant engine speed of 1800 rpm at low (22.5 kW/10% of maximum load) and high (140 kW/50% of maximum load) load conditions.

Table 1
Specifications of the test engine.

Parameter	Value	Unit
Engine model	Scania DC1102	
Combustion system	DI, swirl supported	
Aspiration	Turbocharger	
Engine type	In-line 6-cylinder	
Displacement	10.64	l
Cylinder diameter	127	mm
Stroke	140	mm
Maximum power	280	kW
Maximum torque	1750	Nm
Rated speed	1800	rpm
Rated torque speed	1080–1500	rpm
Min. spec. fuel consumption	191	g/kWh

The conventional marine gas oil, which forms the baseline fuel of the study, was supplied by A/S Norske Shell, representing typical low-sulfur MGO. It is a distilled fuel, containing 0.05% S and is almost free of asphaltenes and ash with the properties making it very similar to #2 diesel fuel. An analytical grade, 99% purity, dimethyl disulfide (DMDS; $C_2H_6S_2$) was used in current study as a sulfur-additive compound. DMDS was blended with the base fuel at blending ratio of around 1/27 (by volume), which resulted in 3% S (by mass) artificial fuel representing high sulfur content in heavy marine fuels. The preliminary tests of solubility properties were performed at blending ratios 1/1 and showed no signs of phase separation, hence the emulsifying agent was not required. The properties of all test fuels and DMDS are summarized in Table 2.

2.2. Sampling and dilution procedures

The overall setup for particle measurements is shown on Fig. 1. As seen, exhaust gas sample was extracted from the tailpipe system with the help of J-shaped open-ended probe through the separate port located approximately 3 m away from the engine turbo-charger. To minimize the particle losses caused by thermophoretic effects [26,56,57] and to keep the volatile species in a vapor phase, the sampling lines were eclectically heated to 400 °C and insulated. Moreover, correction procedures accounting for various particle losses [58] inherently associated with sample gas transport were applied.

Dilution of the exhaust gas samples was performed with two-stage dilution unit, commercially available by Dekati Ltd., Finland. The primary dilution was accomplished inside a porous tube diluter, where dry particle-free dilution air flows though a porous tube (pore size 20 μm) into the inner tube, thus sheathing the aerosol flow from deposition and thermophoresis [59,60]. More detailed information about advantages and disadvantages of this type of diluter can be obtained in some earlier studies [37,41,61]. The secondary dilution was carried out in an ejector diluter [62] also available from Dekati Ltd. [63]. Two very important sampling parameters were independently controlled from each other in this study: PDR & PDT.

PDR was varied in the range of 3–11 and was controlled by varying the ratio of dilution air flow rate to that of raw exhaust. The overall dilution ratio, which is a product of dilution ratios in primary and secondary dilutors, was kept in the range of 50–90 during the experiment for all test points, and remained constant during data acquisition on each of them. Both primary and overall dilution ratios were calculated from the ratio of NO_x concentrations in raw exhaust to that in diluted gas, and were measured by portable multi-gas analyzers (PG-250, Horiba Ltd.) using a chemiluminescence detector with cross-flow modulation technique.

PDT refers to the temperature of air that dilutes exhaust sample and in current work possessed two distinct values of 30 °C and 400 °C, resulting in so-called 'cold' and 'hot' dilution respectevely [48]. The