Full Length Article

# Particle emissions characterization from a medium-speed marine diesel engine with two fuels at different sampling conditions

L. Ntziachristos [a,*], E. Saukko [a], K. Lehtoranta [b], T. Rönkkö [a], H. Timonen [c], P. Simonen [a], P. Karjalainen [a], J. Keskinen [a]

[a] Aerosol Physics Laboratory, Department of Physics, Tampere University of Technology, P.O. Box 692, 33101 Tampere, Finland
[b] VTT Technical Research Centre of Finland Ltd., P.O. Box 1000, 02044 VTT, Espoo, Finland
[c] Atmospheric Composition Research, Finnish Meteorological Institute, P.O. Box 503, 00101 Helsinki, Finland

## HIGHLIGHTS

- Non-volatile marine exhaust rather consists of metallic ash particles than soot.
- Heavy species not evaporating at 250 °C condense on the non-volatile particles.
- Exhaust aerosol mostly depends on fuel properties than combustion characteristics.
- Porous tube diluters provide a more stable exhaust aerosol than ejector-type ones.

## ARTICLE INFO

## ABSTRACT

Particle emission characteristics for a medium-speed four-stroke marine diesel engine were studied using a variety of sampling systems. Measurements were conducted at 25% and 75% load employing a heavy fuel oil (HFO) and a lighter marine distillate oil. The measurements, especially with HFO, revealed that marine exhaust particles mostly consist of nanometer sized ash particles on which heavy volatile species condense during exhaust dilution and cooling. The soot mode number concentration was low with both fuels tested, in particular when HFO was used. Total particle number emissions ranged in the order of 5.2–6.9 × $10^{15}$ per kg of fuel and formed a monomodal size distribution when a porous tube diluter combined with an ageing chamber and operating at low dilution ratio was used for sampling. The levels and size distributions obtained in the lab using a porous tube diluter were similar to the ones reported in the literature studying ship plumes following atmospheric dilution. Lab measurements with ejector-type diluters mostly led to bimodal distributions that did not well resemble atmospheric size distributions. Moreover, the nucleation mode formed with the ejector diluters was variable in size and concentration. When used with dilution air at ambient temperature, ejector diluters were inappropriate for primary dilution due to clogging.

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## 1. Introduction

There is a well-established link between elevated atmospheric particulate matter (PM) concentrations and negative health effects [1,2]. PM smaller than 10 μm in aerodynamic diameter is generally considered inhalable, while deposition models have shown that ultrafine particles (UFP) smaller than 0.1 μm ($PM_{0.1}$) reach blood-exchanging areas of the respiratory system [3]. Such small particles can therefore enter the circulation system, leading to cardiovascular problems [4], and can be translocated to other sensitive organs, including the brain, potentially impairing their operation [5].

Because of the significant health effects, regulations around the world set more stringent emission limits with time on anthropogenic sources of PM. Combustion is the prime source of UFP, including both direct primary emissions and secondary aerosol formed by photochemical reactions in the atmosphere [6]. For this reason, a range of regulations aim at controlling emissions from transport equipment, which commonly use combustion as a power source. Despite such regulatory efforts, PM air quality problems are persistent and exceedances of recommended ambient standards are regularly observed [7]. Shipping has been shown to moderately contribute to ambient PM levels in urban and coastal areas. In their review, Viana et al. [8] summarized that shipping activities contribution to ambient $PM_{2.5}$ levels in coastal areas is in the range of 1–14%, with higher levels in this range reached in the Mediterranean

area. In regions with high shipping activity, this contribution can be even higher with examples of 20% in Genoa [9], or 25% in Hong Kong [10]. In all cases, a significant fraction of shipping PM in the atmosphere comes from secondary sulfate particle formation, which can often exceed primary shipping $PM_{2.5}$ emissions [11,12].

Significant ambient PM contribution from maritime activities is to be expected in part because shipping PM emissions are not directly controlled. In fact, setting engine emission limits to ships, similar to road vehicles, is problematic. Ocean vessels and generally large ships operate on residual fuel (heavy fuel oil – HFO) containing high ash and sulfur content that manifest themselves as PM mass in the exhaust plume of the vessels [13]. Exhaust PM from an HFO operating vessel typically contains 60% direct fuel components in the form of inorganic ash and sulfate [14]. Therefore, several efforts to improve fuel are currently in place. Sulfur environmental control areas (SECA) in EU and the US aim at enforcing the use of low sulfur fuels to control acidification [15] and, in turn, they also have an impact on PM emissions [16]. A study in the port of Venice, which implements a voluntary agreement on low sulfur fuel use, showed that the ambient $PM_{2.5}$ contribution of ships operating on low sulfur fuel halved in five years, despite the significant increase in shipping activity [17]. International regulations also control fuel sulfur used by ocean-going shipping even outside of SECA, with fuel sulfur content dropping to 0.5% in 2020, from a maximum level of 3.5% today [18]. Such developments may lead to the gradual phasing-out of HFO and its replacement with lighter fuels [19].

Improving fuel properties will reduce PM by decreasing ash and sulfate particles but will also have an impact on soot particles produced by the engine itself. Typical marine diesel engines operate at low speed compared to smaller on-road ones. Based on international $NO_x$ standards [18], medium and large size marine engines can be distinguished as those with a maximum speed of 2000 rpm and 130 rpm, respectively. Such low operation speed gives combustion much more time to complete than in smaller engines, potentially leading to significant differences in the characteristics of the PM emitted. Hence, inferring impacts of fuel properties on marine PM exhaust by tests on non-marine diesel engines, like the studies of Nabi et al. [20] and Ushakov et al. [21,22] may be generally instructive but is not representative of the real-world. On the other hand, fuel quality effects on PM emissions and particle characteristics on actual marine engines have been studied only in a few studies [14,23–28] and, out of those, even less explain fuel impacts on particle physical characteristics.

Given the already on-going fuel switching in ship engines, understanding fuel effects on marine exhaust particle characteristics becomes crucial. Moreover, use of lighter fuels gradually opens the field for direct control of marine PM emissions. Current procedures to measure PM need therefore to be assessed with regard to their appropriateness for marine exhaust PM emission standardization. In that respect, the present study examines PM emissions from a medium-speed marine diesel engine using both heavy and light fuel oils. Particle samples are collected with different sampling systems and a range of sampling conditions and physicochemical characteristics are discussed. The results of the study are useful to understand current trends in marine PM emissions and the impact that the change of regulations will have to those.

## 2. Methods

### 2.1. Engine and fuels

The engine used for studying PM emissions was a Wärtsilä Vasa 4R32, a four-stroke four-cylinder medium speed diesel engine with a bore × stroke of 320 mm × 350 mm, constant speed of 750 rpm, and a brake nominal power of 1640 kW.

The main specifications of the two fuels employed in this study are shown in Table 1. The heavy fuel oil (HFO) was a low sulfur grade (1% wt.) produced by Neste under the commercial name "Neste heavy fuel oil 420". The light fuel was a Shell "Thermocity" distillate oil, conforming to EN590:2009 specifications. The HFO contained, amongst others, significant quantities of nitrogen and ash, and heavy fuel markers such as V and Ni. This was a rather high quality HFO with sulfur, ash, water and V content much below the maximum levels allowed by the engine manufacturer.

### 2.2. Testing and sampling

The gaseous emissions as well as the PM mass were measured according to the ISO 8178 method. A chemiluminescence (CLD) analyzer was utilized to measure $NO_x$. HC emissions were measured by a flame ionization detector (FID), and CO and $CO_2$ with a non-dispersive infrared (NDIR) analyzer. The primary PM filter temperature was retained between 42 °C and 52 °C per ISO 8178-1:2006 specifications. One should note that the ISO 8178 PM measurement method is applicable only for fuel sulfur levels up to 0.8%, which is slightly less than the 1% nominal sulfur level for the HFO fuel in this study.

PM filters were further analyzed for sulfates, and organic and elemental carbon. For sulfate analysis, preparation of the samples was carried out according to the IP method 416/96. This included extraction with a mixture of water and 2-propanol. The extracts were then collected and analyzed by capillary electrophoresis. Sulfates analysis assumed hydrated sulfate ($H_2SO_4$. 6.5 $H_2O$), typically considered for marine PM [29].

The OC/EC samples were collected on quartz filters. The OC/EC analysis was performed using the thermal optical method described by Birch and Cary [30]. This was divided into two phases. First, the sample was heated in a helium atmosphere using a certain temperature ramp, and the released organic carbon was oxidized to $CO_2$ and, further, reduced to $CH_4$, determined by a flame ionization detector (FID). In the second phase the sample was heated in a helium/oxygen atmosphere using a second temperature ramp. During this phase the EC and the pyrolyzed OC was oxidized to $CO_2$ and yet again reduced to $CH_4$ and measured by the FID. The measured $CH_4$ concentrations were used to calculate the OC/EC-content of the sample. With the online optical measurement of the sample, the pyrolyzed OC was defined and added to the total OC fraction. Without the optical measurement the pyrolyzed OC would be erroneously allocated to the EC portion.

**Table 1**
Main specifications of fuels used in this study.

| Measure | HFO | LFO |
|---|---|---|
| Density 15 °C, kg/m³ | 1003 | 840 |
| | ISO 12185 | ISO 12185 |
| Viscosity, mm²/s | 302 (@50 °C) | 3.1 (@40 °C) |
| | ASTM D341 | ISO 3104 |
| Lower heating value, MJ/kg | 40.42 | 42.85 |
| | ASTM D240 | NM112 |
| Flash point, °C | 90 | 65 |
| | ISO 2719 | EN 22179 |
| Sulfur content, wt.% | 1.0 | 0.0008 |
| | ISO 8754 | ASTM D3120 |
| Ash, wt.% | 0.03 | <0.001 |
| | ISO 6245 | ISO 6245 |
| N, wt.% | 0.4 | n.a. |
| | D5291 | |
| Ni, wt. ppm | 31 | n.a. |
| | ISO 10478 M-ICP | |
| V, wt. ppm | 66 | n.a. |
| | ISO 10478 M-ICP | |