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Characteristics and temporal evolution of particulate emissions from a ship diesel engine

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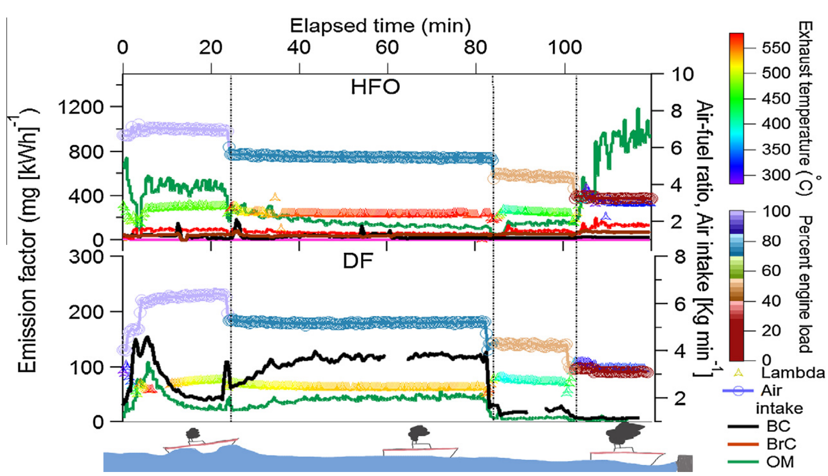
HIGHLIGHTS

- Marine sector is required to reduce particulate emission by using lower FSC.
- Medium speed engine with fuel switching capability for HFO and DF was used.
- Comprehensive characterization of emissions at different engine settings.
- Correlations of gaseous emissions with particulate emissions.
- Ship particulate emission can be reduced also by engine settings.

GRAPHICAL ABSTRACT



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ABSTRACT

Due to current and upcoming regulations to address the adverse impacts of particulate matter (PM) from shipping emissions, the maritime sector is required to find energy-efficient ways to comply mainly by using low fuel sulfur content (FSC) in regulated seas. We studied the PM emission from a research ship diesel engine with fuel switching capability, optimized for HFO used at cruising, operated at representative engine loads resulting to varying excess O_2 emission which was an indirect measurement of air–fuel mixture (λ), using heavy fuel oil (HFO, 1.6 S (%m)) and diesel fuel (DF, <0.001 S (%m)). We determined the

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characteristics and temporal evolution of the PM by using the High Resolution Time-of-Flight Aerosol Mass Spectrometry (HR-ToF-AMS) in combination with aethalometer, particle sizers, online gas phase, and filter measurements. The average emission factors were higher for HFO than for DF with relative percent differences of ~200, ~180, ~150, and ~145 for SO_4^{2-}, inorganic elements, organic matter (OM), and $PM_{2.5}$, respectively, while that for black carbon (BC) was similar for both fuels. The difference between HFO and DF in terms of carbonaceous emissions was higher at 100% and 25% than at 75% and 50% engine loads. The exhaust temperature (T) decreased with increasing λ leading to the enhanced emission of OM in HFO and reduced OM and BC emission in DF. Contributions of hydrocarbons and oxygenated hydrocarbons increased with λ for HFO and decreased with DF. Gas phase total hydrocarbon (THC) was well correlated with BC only for HFO and OM and BC for DF. Overall, using a lower FSC reduced average PM emissions, however, engine load, and λ were strongly linked to the characteristics and temporal evolution of major PM emissions. The information in this study may help the marine sector and policy-making process in evaluating and designing future solutions for shipping emission regulations and diagnostics.

1. Introduction

Shipping activities are of great economic importance, however, the resulting particulate emissions from ship engines pose a threat to ecosystems and public health [1,2]. Particulate matter from shipping emissions will likely exceed that of land-based in the future due to the tighter implementation of regulations on the latter [3]. Currently, not much is known regarding the effects of different operating conditions and fuel types on particulate emissions. This information is necessary to effectively evaluate and design current and future regulations in order to achieve energy-efficient ways that are environmentally-acceptable. This requires the knowledge of how particulate emissions evolve with engine operation and the common diagnostics such as temperature, pressure, excess oxygen, and exhaust gases concentration. Regulations are based on the general assumption that the $PM_{2.5}$ emissions decrease linearly with fuel sulfur content (FSC) [4]. Due to the legislations to further abate the ship emissions to be enforced by the year 2020, implementation of technological changes are being planned to compensate the expected economic impact [5].

Heavy fuel oil (HFO) contains residues of fuel refining process such as sulfur and metals, and is mainly used as fuel by ships due to economic reasons. HFO is a mixture of residues and distillates derived from various processes during refinery. As such, it is highly viscous and requires heating prior to injection in the engine. Ships fueled with HFO emit considerable amounts of pollutants to the atmosphere. Many particle-associated pollutants actually are transferred from the fuel to the emissions. Recent regulations have been implemented to reduce the harmful emissions from ships which affect the type of fuels that can be used, especially near harbors [6]. Improvement of fuel quality has been deemed as a solution to reduce emissions of critical pollutants, leading to the establishment of sulfur emission controlled areas (SECA) in some regions [6,7]. In accordance with sulfur regulations, ships are required to use fuel with lower sulfur content such as diesel fuel within 200 nautical miles of the coastline. To comply with current regulations, ship engines may be equipped with fuel switching capability so that they are able to operate with HFO during cruising and switch to cleaner fuel such as distillates when near the harbor or entering the SECAs [8]. Also regulating engine speed may be beneficial to the environment [4,9]. Speed is determined by the engine setup, either direct propeller drive or indirect drive via an electrical generator. The former is mainly used for big container ships with 2-stroke engines capable of speed reduction while the latter used for ferries and cruise ships operates at nominal speed and varying engine load. In a previous study, it was shown that in terms of gaseous emissions, there were no significant differences between 2-stroke and 4-stroke ship engines [10]. However, the relative contributions of small ships powered by 4-stroke engines to emission factors may be bigger due to their large numbers [11]. Ships usually operate during cruising at intermediate engine loads, typically between 50 and 75% load, and at low loads, typically between 10% and 30% when idling or docking at harbors. Full engine load is only applied for short times when for example encountering icy waters in the sea or accelerating. Characteristics of emitted PM emissions have been observed to depend on the engine operation for a ship engine [12–17]. Variation in engine load can impact the cylinder conditions, hence, the combustion conditions and the resulting emissions [18]. Characteristics of exhaust gases have been correlated to engine technical malfunctions [19]. However, these measurements are still insufficient to match the engine operation with the profiles and temporal evolution of emitted shipping PM.

Carbonaceous compounds classified as organic and elemental carbon (OC and EC) are some of the major fractions of PM that are emitted by shipping activities and dispersed into the atmosphere [20–23]. Concentrations of these fractions were found to be enhanced up to 4–5 times at the coast line when ships were passing by Ref. [24]. Carbonaceous aerosols associated with air pollution are known to be toxic [25]. Diesel exhaust particles are hazardous due to their small size and high surface area enabling them to efficiently deposit in the human lung and interact with the biological interface [26]. The surface of combustion particles can also serve as a mechanism for deposition in the lungs of toxic or carcinogenic compounds such as polycyclicaromatic hydrocarbons (PAHs) or metals associated with HFO. Aromatic compounds and their alkylated derivatives were found to be prominent in HFO and DF aerosols [27,28] as well as high concentration of volatile organic compounds [29].

Further improvement of fuel quality by decreasing FSC to 0.1% by 2015 is already implemented for the SECA as of January 2015. However, previous laboratory studies indicate that the PM emissions between FSC = 0.5% which is the intended global limit for 2020 and FSC = 0.1% which is just implemented in the SECA did not differ significantly from each other [30]. The use of lower FSC led to reduction of OM and SO_4^{2-} emissions but the BC emission was not reduced [31]. BC emission factors were found to be dependent on engine load and engine settings and not on the FSC [32]. The reduction of PM did not lead to reduction of gaseous species as well. It was shown that although SO_2 emissions decreased, NO_x emissions increased in the SECA in the North Sea [33]. NOx emissions depended mainly on the combustion process [34] such as changes in temperature, pressure, residence time in the combustion zone [19] and lower rotational speed such as those in 2-stroke engine [35]. To facilitate fast and easy monitoring of FSC compliance, scientists proposed remote sensing methods for both NO_x and SO_2 emission in the ECA [36,37]. From a survey, ships