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Chemical composition and size distribution of particulate matters from marine diesel engines with different fuel oils

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ABSTRACT

In this work, detailed physicochemical characteristics of particulate emissions were investigated over ranges of fuel properties, particles size distribution, chemical compositions and toxicity based on dynamometry experiments with marine diesel engines. The results indicated that lower fuel sulfur content (FSC) can decrease the specific emissions of total particle matters (PM). Organic carbon (OC) emissions were more than elemental carbon (EC), especially for 2-stroke marine diesel engine with heavy fuel oil (HFO), and carbonaceous substances were found to be load and size dependent. The suppression effect of low-sulfur light diesel fuel (LSDF/DF) for PM mass emissions was exhibited mostly in the reduction of OC and sulfate, compared with high-sulfur light diesel fuel (HSDF). PM mass emissions with low-sulfur HFO were still higher due to larger OC emissions. Emissions of 16 priority polycyclic aromatic hydrocarbons (PAHs) were highest in particle-phase PAHs, among which 3 and 4-benzene ring PAHs were predominant. Flua and Pyr were the PAHs with the highest emissions in the PM emitted from marine diesel engines. The PAHs had very high toxic equivalent, with the highest contribution of BaP and DahA. According to benzene rings number, the proportion of 5-benzene ring PAHs had the highest equivalent toxic concentration. Size distribution of PAHs had high correlations with OC and the PM with small size had higher equivalent toxicity concentration.

1. Introduction

With the growth of the global economy, ship transportation accounts for over 80% of the total transportation, and the exhaust gas emission of ships is an important pollution source of environmental air in ports and coastal areas [1]. Those pollutant in exhaust gas emitted from ships causes serious damage to human body health, port and ocean atmospheric environment [2–6]. The harmful emissions mainly include sulfur dioxide (SO_2), and particulate matter (PM) due to the properties of heavy fuel oil (HFO) [7–9]. In addition to above emissions, nitrogen oxide (NOx), PAHs and metals are also generated, which are also hazardous to human health. Some metals and polycyclic aromatic hydrocarbons (PAHs) are usually existed in particles [10–14].

PM emissions have been more clearly related to the human health, such as lung disease. And the marine diesel aerosols has also attracted much attention due to the large PM emissions. According to the regulations implemented by International Maritime Organization (IMO), the allowed FSC in sulfur emissions control areas (SECAs) was 0.1%m/m. In global world or outside of ECAs, the FSC limitation of 0.5%m/m will be implemented in 2020 [15,16]. To comply with the FSC regulations, using low-sulfur fuels, cleaning fuels, or installing exhaust gas cleaning system (EGCS) were recommended. The limited value of NOx in regulations was 3.4 g/kW·h, and this regulation has been implemented since 2016 [17,18]. For particulate matters (PM) emissions, there is no uniform and clear regulation all over the world. Some countries and organizations have enacted regulations, especially United States Environmental Protection Agency (US EPA) and Ministry of Ecology and Environment of the People's Republic of China (PRC MEE) [19,20]. The FSC can affect the emissions of particulate matter in ships and reducing FSC is also used to control the emissions of particulate matter. The effect of burning low-sulfur HFO and light diesel oil (DF/LSDF) on reducing particulate matter is not clear.

During the past years, the emissions characteristics of PM emitted from marine diesel engines have been investigated. To improve the quality of marine fuels has been regarded as a method to reduce particles emissions. The total particle mass emissions from marine 2-stroke diesel engines with HFO (> 2.0%S) usually were about 1.09–2.12 g/kW·h [13,23], when the marine fuels (< 2.0%S) were used, the PM emissions values were about 0.23–0.76 g/kW·h [24]. The improvement of fuel quality was reflected in the decrease of FSC or viscosity of fuel, such as, changed from HFO 380 (2.6%S) to HFO180 (0.5%S), or from HFO to distillates. Speed was determined by the engine setup; however,

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the low-speed engines were 2-stroke engines, mainly used for big container ships with direct propeller drive, and the medium or high-speed engines were 4-stroke engines, usually installed in cruise ships or some inland and coastal fishing boats. The large power 2-stroke diesel engines could cause much PM emissions and the contributions of small ships installed many 4-stroke diesel engines may be bigger [25]. Sulfur was very important factor to PM emissions. There were no similar studies for PM chemical compositions emitted from marine diesel engines. Because of the absence of tests bench and rather expensive operation cost; and as typical marine fuel contains many substances, the sole effect of FSC can be hardly separated from other factors.

Carbonaceous particle-phase substances associated environmental pollution are known to be toxic, mainly including OC, EC and PAHs, and the 16 priority PAHs determined by US EPA have the highest toxicity [26]. In the previous study, the size distributions of particles number and mass emitted from marine diesel engines have been investigated [27,28]. However, the size distributions of carbonaceous substances (e.g. OC, EC and PAHs) have not been reported [10,21,22,32], and its effects on particulate toxicity and human health are very important.

Most of the ships still use fossil fuel, because of the limitation of emissions regulations, low-sulfur fuels are also used by part of the ships. For marine diesel engines, it is not certain whether the low-sulfur fuels meet the coming stringent emission regulations of particulate matters. The aim of this study is to investigate how using the fuel with limited FSC will affect PM emissions and to determine the PM emissions characteristic of marine diesel engines with different fuels. In this study, PM mass emissions, chemical compositions and size distribution were investigated for 2-stroke diesel engine with HFO (0.5%m/m S) and 4-stroke diesel engine with light diesel oils (LSDF/DF, < 0.1%m/m S and HSDF, 3.09%m/m S), the effect of FSC on PM emissions was also studied for 4-stroke marine diesel engine. The chemical compositions of PM mainly include organic carbon (OC), elemental carbon (EC), sulfate, polycyclic aromatic hydrocarbons (PAHs). The toxicity of the PAHs has also been determined.

2. Experimental process and methods

2.1. Tested engines and fuel properties

Measurements were conducted on tested engines according to the propeller-law-operated test mode. One was a 2-stroke, low-speed marine main engine with HFO 180 (0.5%m/m S), and HFO 180 was a heavy fuel oil containing 0.5% sulfur, with the viscosity of 180 mm^2/s at 50 °C; the other was a 4-stroke, medium-speed marine diesel engine with LSDF/DF (0.1%m/m S) and HSDF (3.09%m/m S). The specification of the tested diesel engines and properties of tested fuels were shown in Tables 1 and 2 respectively. The LSDF was common diesel fuel oil wildly used in cruise ships or some inland and coastal fishing boats in China. The HSDF was blended products by adding sulfur-containing lubricant additives to common diesel fuel and the sulfur-containing substance was not lube oil, but one additive with high sulfur content. The blended product was mixed by a professional company, Shanghai Teao Lubricating Oil co. LTD. The property was steady, very close to common diesel fuel oil. And when HSDF was used in this experiment, the specific fuel oil consumption (SFOC), exhaust gas temperature and maximum cylinder pressure were much the same as common diesel fuel oil at all engine loads. Therefore, we thought that the sole effect of FSC was separated from other factors. Those tests were carried out at bench. The 4-stroke diesel engine (WD10C190-15) was made by Weichai Heavy Machine Co., Ltd. in 2015 and the 2-stroke diesel engine (6S35ME-B) was made by CSSC Marine Power Co., Ltd. in 2012.

Table 1
Specification of the test diesel engines.

Specification	WD10C190-15	6S35ME-B
Type	4-stroke	2-stroke
Cylinder	6	6
Rated power (kW)	140	3570
Rated speed (r/min)	1500	142
Bore × stroke (mm × mm)	126 × 130	350 × 1550
Emission standards	Tier II	Tier II
Year of manufacture	2015	2012

Table 2
Properties of test fuels.

Properties	LSDF/DF	HSDF	HFO 180
Density (20 °C, kg/m^3)	845	875	932
Sulfur content (%wt)	< 0.1	3.09	0.5
Carbon content (%wt)	86.49	83.95	87.6
Hydrogen content (%wt)	13.44	12.48	12.5
Nitrogen content (%wt)	–	< 0.3	–
Lower heating value (MJ/Kg)	42.52	42.38	–

2.2. Particulate emissions measurement and analysis methods

Fig. 1 was the schematic diagram of marine diesel engines exhaust emissions test setup.

The raw exhaust gas flowed from engines exhaust pipe by a J-shaped sampling probe located about 6–10 times of exhaust pipe diameter away from turbo-chargers. The sampling method was completely in accordance with the regulations [20], as described below: PM was sampled on a 47 mm diameter quarts filters under stable engines loads conditions. These samples were collected from the diluted exhaust from the partial dilutor. The obtained dilution ratio (DR) was calculated from the continuous simultaneous measurements of NOx in the exhaust channel and in the diluted sample after the dilutor for every particle sample. The DR was approximately 8–10 and the sampling time was

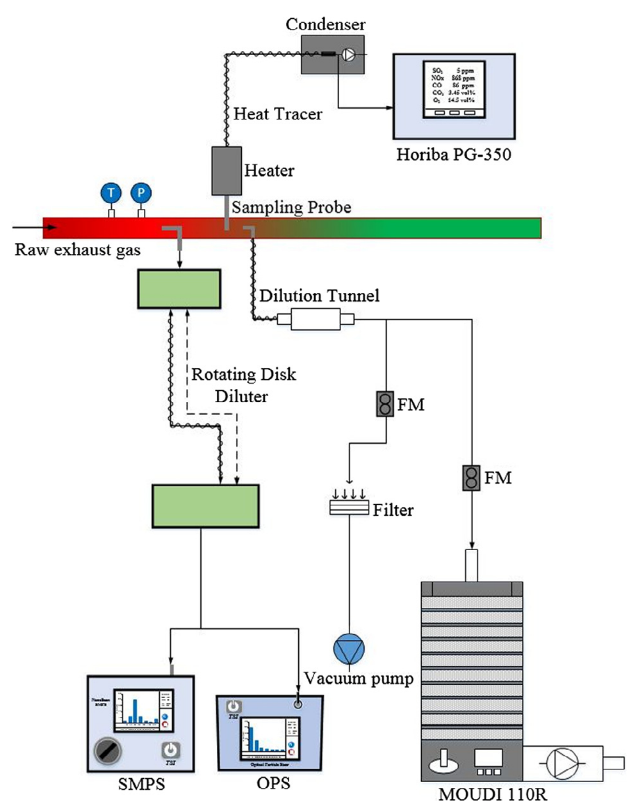

Fig. 1. Schematic diagram of marine diesel engines exhaust emissions test setup.