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Emission factors of particulate and gaseous compounds from a large cargo vessel operated under real-world conditions[☆]

Cheng Huang [a, *], Qingyao Hu [a], Hanyu Wang [b], Liping Qiao [a], Sheng'ao Jing [a], Hongli Wang [a], Min Zhou [a], Shuhui Zhu [a], Yingge Ma [a], Shengrong Lou [a], Li Li [a, **], Shikang Tao [a], Yingjie Li [a], Diming Lou [c]

[a] *State Environmental Protection Key Laboratory of Cause and Prevention of Urban Air Pollution Complex, Shanghai Academy of Environmental Sciences, Shanghai, 200233, China*
[b] *School of Naval Architecture, Ocean & Civil Engineering, Jiaotong University, Shanghai, 200240, China*
[c] *School of Automobile Studies, Tongji University, Shanghai, 201804, China*

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ABSTRACT

On-board emissions measurements were performed on a Handysize-class bulk carrier operating under real-world conditions. Emission factors (EFs) were determined for criteria pollutants such as NO_x, CO, total hydrocarbons (THC), and PM; PM composition, including organic and elemental carbon (OC and EC), inorganic species, and a variety of organic compounds and VOC species (including alkanes, alkenes, single-ring aromatics, and oxygenated VOCs) were also analyzed. To investigate the impacts of engine type, fuel, and operating conditions on emissions, measurements were conducted on one main and one auxiliary engines using low- and high-sulfur fuels (LSF and HSF) under actual operating conditions, including at-berth, maneuvering, and cruising at different engine loads. OC was the most abundant PM component (contributing 45–65%), followed by sulfate (2–15%) and EC (1–20%). Compounds with 3 or 4 aromatic rings, including phenanthrene, fluoranthene, pyrene, and benzo[b+k]fluoranthene, dominated the particulate polycyclic aromatic hydrocarbons (PAHs) emitted from the ship, accounting for 69–89% of the total PAHs. Single-ring aromatics constituted 50–78% of the emitted VOCs and were dominated by toluene. In this study, switching from HSF (1.12% S) to LSF (0.38% S) reduced emitted PM by 12%, OC by 20%, sulfate by 71%, and particulate PAHs by 94%, but caused an increase in single-ring aromatics. The power-based EFs generally decreased with increasing engine loads. However, decreasing the ship engine load also reduced the vessel speed and, thus, decreased emissions over a given voyage distance. Herein, a Vessel Speed Reduction (VSR) from 11 to 8–9 knots decreased NO_x and PM emissions by approximately 33% and 36%, respectively, and OC, EC, sulfate, and particulate PAHs in PM emissions by 34%, 83%, 29%, and 11%. These data can be used to minimize uncertainty in the emission factors used in ship emissions calculations.

1. Introduction

Particulate and gaseous emissions from ships have attracted increasing attention for their potential impacts on air quality (Gaston et al., 2013; Aksoyoglu et al., 2016; Marelle et al., 2016; Becagli et al., 2017; Liu et al., 2017), climate change (Olivié et al., 2012; Liu et al., 2016), and human health (Brandt et al., 2013; Broome et al., 2016). Particulate matter (PM) emitted from ships consists of a number of components, including carbonaceous substances, inorganic salts (such as sulfate and nitrate salts), organic compounds, and metals, that can greatly impact visibility (Seinfeld and Pandis, 2006; Pitchford et al., 2007). PM also participates strongly in climate forcing through both direct and indirect effects (Lack et al., 2011; Thomson et al., 2018). The organic fraction emitted from ships may contain a number of toxic components, including polycyclic aromatic hydrocarbons (PAHs), which possess mutagenic and carcinogenic properties and pose a significant risk to human health (Diesch et al., 2013; Czech et al., 2017; Manoli

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[☆] This paper has been recommended for acceptance by Charles Wong.
[*] Corresponding author.
[**] Corresponding author.
E-mail addresses: huangc@saes.sh.cn (C. Huang), lili@saes.sh.cn (L. Li).

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et al., 2017). Due to increasing emissions of NO_x and volatile organic compounds (VOCs) from ships, ship emissions may explain, at least in part, the high ozone concentrations measured in air masses with marine back-trajectory origins (Eyring et al., 2010; Velchev et al., 2011; Tagaris et al., 2017). However, measurements of VOCs from ships are relatively few, which may hinder VOC ozone formation potential calculations.

Ocean-going cargo vessels, including container ships, cargo carriers, tankers, etc., contribute significantly to global air pollutant emissions from ships, accounting for 84, 88, and 87% of global marine NO_x, SO_x, and $PM_{2.5}$ emissions, respectively (Johansson et al., 2017). Ocean-going cargo vessels are primarily fueled with heavy fuel oil (HFO). Currently, vessels are required to switch from HFO to distillate fuel (DF) in sulfur emission control areas (SECAs) to satisfy sulfur regulations. However, the SECAs are generally limited to Europe and some parts of North America, and vessels in other areas use predominantly HFO. Global HFO consumption totaled ~195 million tons in 2015, constituting 71% of the total fuel consumption for global shipping, and has been increasing at a rate of 2.1% per year (Johansson et al., 2017). Previous research has indicated that emissions of unregulated hazardous species with air quality and human health impacts (e.g., sulfate, OC species, PAHs, and transition metals) are significantly higher from HFO than from DF at all engine loads (Sippula et al., 2014).

Measurements of ship EFs for particulate and gaseous components are essential for compiling emission inventories and quantifying the impacts of emissions on air quality, climate change, and human health. In the last decade, numerous measurement campaigns have been conducted to determine EFs for ocean-going vessels. The EFs measured for regulated pollutants such as SO_2 and NO_x (Agrawal et al., 2008a, 2008b; 2010; Khan et al., 2013) are comparable to Lloyds service data (ENTEC, 2002) and EF estimates from the USEPA (2009) and CARB (2008). Recent studies have also focused on emissions of unregulated chemical compounds (Agrawal et al., 2008a, 2008b; Moldanová et al., 2013); correlations between such compounds and various fuel types (Jayaram et al., 2011; Lack et al., 2011; Celo et al., 2015), engine loads (Agrawal et al., 2010; Sippula et al., 2014), and after-treatment technologies (Lack and Corbett, 2012; Lehtoranta et al., 2015) have been discussed in previous studies. However, in comparison to on-road vehicles, emissions of particulate and gaseous species from HFO-fueled vessels remain poorly understood, especially under real-world operating conditions.

In this study, the EFs of particulate and gaseous species were determined for a large, modern bulk carrier via on-board measurements at sea. Measurements were performed during all of the operational modes typically experienced over the course of a voyage, including at-berth, departure, ocean and inland cruising, and arrival. Several different cruise speeds were designated to investigate the impact of cruise speed on the EFs of particulate and gaseous species.

2. Materials and methods

2.1. Emission measurement campaign

The measurements were performed in July 2017 on a large cargo vessel during an actual sea voyage. The ship, a Handysize-class bulk carrier, was built in 2012 and features a deadweight of 45,308 t and gross tonnage of 31,113 t. The ship is equipped with one main engine, four auxiliary engines, and an auxiliary boiler. In this study, emissions were measured from one main engine and one auxiliary engine; the major technical specifications of the main and auxiliary engines are presented in Table 1. The ship used RMG 180 grade HFO for both the main and auxiliary diesel engines. China has executed legislation that requires ships to use LSF (<0.5 wt% S) when at berth beginning January 1, 2017. Therefore, the engines burned LSF with 0.38 wt% S when at berth and during departure; HSF with 1.12 wt% S was burned during other operational modes. It should be noted that the fuel sulfur content limit in Chinese SECAs (<0.5%) is quite a bit looser than the limits in North America and Europe (0.1%). Therefore, the LSF used in this study differs from the DF used in emission control areas in North America and Europe; the physicochemical properties (e.g., metal and asphaltene content, viscosity, etc.) of the LSF used herein are not fundamentally superior to those of HFO, as shown in Table S1.

Table 1
Major technical specifications of the main and auxiliary diesel engines.

Specifications	Main engine	Auxiliary engine
Engine type	2-stroke diesel engine	4-stroke diesel engine
Model	MAN B&W 6S50ME-C8	MAN B&W 6L16/24
Power	7948 kW	660 kW
Rotation rate	127 $r \cdot min^{-1}$	1200 $r \cdot min^{-1}$

The ship traveled from Huanghua port in Bohai Bay, China through the Bohai Sea, Yellow Sea, and East China Sea to the Yangtze River, eventually arriving at Zhenjiang port (See Fig. S1). Measurements were taken during various operational modes throughout the voyage, including at-berth, departure, cruising, and arrival. At-berth and arrival tests were each performed one time, while departure tests were performed twice, once while departing from Huanghua port and once while departing from an anchorage near the Yangtze Estuary. The ship features five cruising speed gears, namely “Max,” “Full,” “Half,” “Slow,” and “Dead Slow.” During ocean and inland sailing, the gear was usually set between “Full” and “Max” to enhance economy; thus, most of the samples collected in the ocean and inland seas feature these operational modes. The impact of cruise speed on emissions was investigated by intentionally setting the ship to specific modes, including “Max,” “Full,” and “Half,” during measurement. The operational modes and their corresponding speeds, engine rotation rates, engine loads, and specific fuel oil consumption (SFOC) rates are presented in Table S2.

2.2. Sampling and analysis

A schematic of the sampling apparatus is shown in Fig. 1. The sampling instruments were placed on a deck below the chimneys. Exhaust gas was diverted to the deck through a stainless-steel air duct 108 mm in diameter; to avoid particle precipitation due to thermophoresis, the exterior of the air duct was wrapped in thermal insulation. Two sampling inlets were installed at the end of the air duct approximately 15 m downstream from the chimney. The

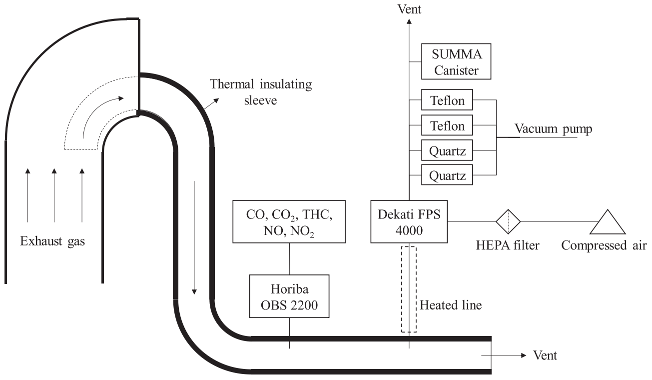

Fig. 1. Schematic diagrams of sampling setup.