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Emissions from several in-use ships tested by portable emission measurement system

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ABSTRACT

Seven ships were tested using portable emission measurement system. Particles from three ships were sampled using quartz-filters and analyzed using Thermal/Optical Carbon Analyzer and GC–MS. The emission factors of CO, HC, NO_x and PM are 11.00–84.60 g/kg, 22.75–98.88 g/kg, 0.72–5.83 g/kg and 0.15–9.53 g/kg, respectively. In most cases, the ships emit larger quantity of pollutants during cruising. For particle number, the majority is formed in the nucleation mode. The nucleation mode and the accumulation mode from ships during maneuvering increase by 2.63 and 3.52 times respectively, compared with those from ships during cruising. Particle mass is dominated by the accumulation mode and the coarse mode. Analysis of the samples shows that OC is the major composition of carbonaceous particle, whose mass fraction is 0.52–0.88. The emission factors of OC and EC are 0.29–1.44 g/kg and 0.04–0.64 g/kg, respectively. Most of the particle-phase PAHs are medium molecular weight PAHs, while high molecular weight PAHs are seldom observed.

1. Introduction

Ship transportation plays an essential role in globalization and its importance will continue to grow as the global market expands. Meanwhile, ships have been thought to be one of the most severe combustion sources for a long time (Corbett and Fischbeck, 1997). Main emissions from ships usually include carbon monoxide (CO), hydrocarbon (HC), nitrogen oxide (NO_x), sulfur oxide (SO_x) and particulate matter (PM).

Emission from ships has been studied worldwide. Corbett (2002) estimated that ships emit 9880 t of NO_x, 443 t of PM and 4672 t of SO_x in northwest America. Marr et al. (2007) made a survey on Aberdeen Habour and figured out ship emissions of CO, NO_2, SO_2 and PM in the harbor. Winther et al. (2014) calculated the emission inventory of ships in the Arctic, using the universal shipborne automatic identification system (AIS) to obtain the activity value. In China, emission inventories in some regions such as Bohai Rim (Zhang et al., 2014) and Shanghai Yangshan (Song, 2014) are reported. All the above literatures indicated great importance of emission factors (EFs) to calculate the emission inventory. However, most of the studies used data in the reports from IVL or Lloyds' Register. The data is based on limited tests and thus needs further collection. Hence a few studies provided EFs by portable emission measurement system (PEMS). Agrawal et al. (2007) provided EFs from a large ocean going vessel. Khan et al. (2012,2013) measured the emission from two containers in several trips, while Fu et al. (2013) measured seven ships on the Grand Canal in China.

Among the main emissions from ships, a growing attention has been paid to particles. In general, particles from diesel combustion sources are usually divided into three modes according to their diameters (D_p): the nucleation mode (from 3 nm to 50 nm), the accumulation mode (from 50 nm to 1000 nm) and the coarse mode (over 1000 nm) (Kittelson, 1998). Typically, the nucleation mode is believed to contribute little in mass but may be great in number. It is found of high toxicity to both the organisms in the ecosystem food webs (Maurer-Jones et al., 2013) and the humans (BéruBé et al., 2007). Therefore, many researchers studied particle size distributions (PSDs) from diesel combustion sources. A lot of

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these studies focus on the engine bench-test results. Millo et al. (2012) studied the PSDs in steady-state run and warming-up phase from a small displacement diesel engine. Ushakov et al. (2013) studied the PSDs from a heavy-duty diesel engine using low-sulfur marine fuel under different engine loads and engine speeds. Tan et al. (2014) studied the PSDs under transient condition from a light-duty diesel engine. As cases studied in the bench do not entirely represent the real-world operating conditions, PSDs from ships in different operating modes and ship speeds need further investigation.

Particle from ships contains carbonaceous particle, sulfate and ash, according to results from other studies (Khan et al., 2012, 2013). The carbonaceous particle, including organic carbon (OC) and elemental carbon (EC), is thought to be the dominate composition. OC and EC contain carcinogenic and mutagenic compounds, and may cause urban visibility impairment (Kim et al., 2006), climate change (Kigoshi et al., 2014) and monument discoloration (Bergin et al., 2015). In OC from diesel combustion sources, PAHs are among the major carcinogens, though it is in a small proportion (Lima et al., 2005). Hence it is important to study the EFs of OC, EC and particle-phase PAHs from ships. The emission of OC and EC may be estimated by sampling the air in port-area and modeling the motion path of the air (Zhang et al., 2014; Keuken et al., 2014). However, unavoidable assumptions from such estimation may influence the result. Therefore, samples directly from the ship exhaust were analyzed in this study to improve the understanding of shipping-derived carbonaceous compositions and PAHs.

The purpose of this study is to figure out the real-world EFs and particle emission characteristics of ships with medium rated speed from 750 rpm to 1500 rpm and rated power from 880 kW to 2648 kW. In this study, CO, NO_x, HC and PM from the ships in different operating modes were tested using PEMS. Fuel-based EFs in different operating modes are provided. The annual emissions of each ship are calculated. PSDs measured by ELPI are demonstrated and compared. Particle samples from three ships are collected. The carbonaceous compositions are analyzed by DRI Thermal/Optical Carbon Analyzer, while the particle-phase PAHs are analyzed by GC–MS (Agilent 5975-6890).

2. Methodology

2.1. Test instruments

As shown in Fig. 1, a PEMS consisting of a Semtech-DS, an Electric Low Pressure Impactor (ELPI) and some relevant accessories was employed in this study. A filter-based sampler was also employed in testing three ships.

The Semtech-DS was used for measuring gaseous pollutants. This instrument is able to test CO and CO_2 by non-dispersive infrared (NDIR), NO and NO_2 by non-dispersive ultraviolet (NDUV), and total hydrocarbon (THC) by flame ionization detector (FID) (Fu et al., 2012). A weather station to detect ambient temperature, humidity and pressure was connected to the Semtech-DS. A Global Positioning System (GPS) was also used to obtain the speed and the latitude of tested ships. In addition, an exhaust flow meter (Semtech-EFM) was installed behind the exhaust port to measure the exhaust flow rate and exhaust temperature. To ensure the accuracy, the Semtech-DS was zeroed and calibrated before each separate test.

The ELPI was used to detect real-time particle number concentration and particle size distribution. This instrument, made by Dekati Ltd., is able to measure airborne particle size distribution ranged from 7 nm to 10 μm by 12 channels and a filter stage. The ELPI also calculates the corresponding particle mass in each channel using appropriate values of particle density (Guo et al., 2014). In this study, particle mass is determined by the 1st to the 11th channels ($D_p < \sim 3.1$ μm). Results from other studies showed a good agreement among ELPI and other particle measuring instruments (Zervas and Dorlhène, 2006), and a good transient test performance for ELPI (Maricq et al., 2000). In this study, the ELPI was installed behind a two-stage diluter which was used to dilute the exhaust using a dilution ratio of 64. The diluted exhaust in the first stage was heated up to 190°C while the diluted exhaust in the second stage was not heated. The dilution air, whose pressure was kept at 0.2 MPa, was supplied by an air-compressor. To ensure the accuracy, the ELPI was zeroed before each separate test.

For each operating mode, two quartz filters in the filter-based sampler were used to collect the particulate matter. The total flow rate in the sampled tube was 10 L/min and the sampled time was 10 min. A 0.5 cm^2 area of each sample was punched and analyzed by DRI Thermal/Optical Carbon Analyzer following the IMPROVE-A temperature protocol. The punched areas were placed in helium

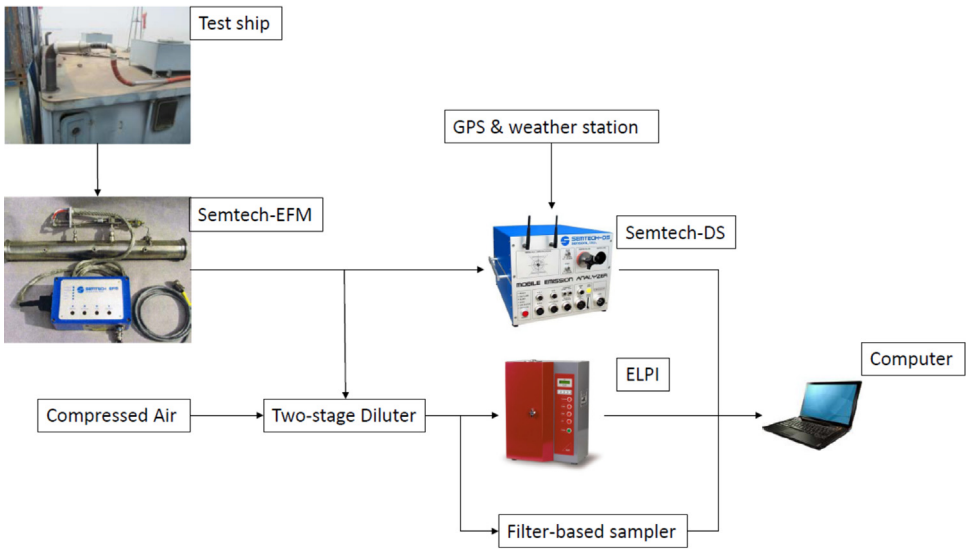

Fig. 1. Schematic diagram of test system.