Available online at www.sciencedirect.com
ScienceDirect
Atmospheric Environment 42 (2008) 5504–5510
ATMOSPHERIC ENVIRONMENT
www.elsevier.com/locate/atmosenv

Technical note

# In-use gaseous and particulate matter emissions from a modern ocean going container vessel

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Received 2 January 2008; received in revised form 22 February 2008; accepted 23 February 2008

**Abstract**

Ocean going vessels are one of the largest uncontrolled sources of pollutants and the emissions data from these sources are scarce. This paper provides the emission measurements of gases, particulate matter (PM), metals, ions, elemental and organic carbon, conducted from the main engine of an ocean going PanaMax class container vessel, at certification cycle and at vessel speed reduction mode, during actual operation at sea. The weighted emission factor ($g\,kW^{-1}\,h^{-1}$) of PM and $NO_x$ were 1.64 and 18.2, respectively, for the main engine operating on a 2.05 wt% sulfur heavy fuel oil (HFO). The $NO_x$ emissions at the vessel speed reduction mode (8% of full load) are 30% higher than at 52% engine power, the normal cruise speed. The composition of PM, from main engine is dominated by sulfate and water bound with sulfate (about 80% of total PM) and organic carbon constitutes about 15% of the PM. Sulfur, vanadium and nickel are the significant elements in the exhaust from the engine running on the HFO. At the point of sampling 3.7–5.0% of the fuel sulfur was converted to sulfate.


*Keywords:* Ship; Emissions; Main engine; Particulate matter; Elemental carbon; Organic carbon; Sulfate; Ocean going vessel; Heavy fuel oil; Vessel speed reduction

## 1. Introduction

Ships are a significant source of particulate matter (PM), sulfur oxides ($SO_x$) and nitrogen oxides ($NO_x$) emissions in many areas of the world (Corbett and Fischbeck, 1997). The high levels of PM and $SO_x$ emissions from slow-speed marine diesel engines are primarily associated with high levels of sulfur in the heavy fuel oil (HFO), used in these engines. The fuel sulfur, during combustion, is oxidized into different oxides of sulfur, mainly $SO_2$ and $SO_3$, typically in ratio of 15:1 (MAN B&W, 2004). $NO_x$ are formed when fuel nitrogen and nitrogen in air react with oxygen at high temperatures in the burning fuel spray (MAN B&W, 2004). Particulate emissions in the exhaust originate from a number of sources like agglomeration of very small particles of partly burned fuel, partly burned lubricating oil, ash content of fuel oil and cylinder lubricating oil, sulfates and water (Heywood, 1988).

A few studies in past have focused on developing emission inventories from the low-speed marine diesel engines (ENTEC, 2002; Lyyranen et al., 1999; Chen et al., 2002; Sinha et al., 2003; Petzold et al.,

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1352-2310/$ - see front matter 
doi:10.1016/j.atmosenv.2008.02.053

2004, 2007; Kasper et al., 2007). Recently, Petzold et al. (2007) measured microphysical and chemical properties in the exhaust gas of a four-stroke marine diesel engine under various load conditions. Kasper et al. (2007) have presented results from tail pipe emissions of PM from a two-stroke marine diesel engine from a test rig study. Corbett and Koehler (2003) published a comprehensive study on emissions from marine engines focusing on gaseous emissions. ENTEC (2002) presents a comparison of various services data for main engine marine emission factors. Measurement of emissions from ship plume studies by researchers in past (Chen et al., 2002; Sinha et al., 2003) provides additional insight into particle number and gaseous emission factors from diesel powered ships.

Currently, the US Environmental Protection Agency (EPA) offers only limited guidance regarding the development of port emission inventories. Many current emission inventories suffer from poor quantification of port activity and use of outdated emission factors to assess the impact of ports on regional and global air qualities (USEPA, 2006).

Few engine studies which have contributed to emissions data from slow-speed marine diesel engines have been performed either on engine test rigs or are plume measurement studies. While the emissions data presented in these studies give insight into the emissions profile of low-speed marine diesel engines, the current study focuses on developing emission factors for in-use marine diesel engine, during its actual operation at sea.

This study presents the emission factors of various gases and speciated PM from the main engine (low-speed, two-stroke marine diesel engines) of an ocean going container vessel. Measurements were made while the main engine operations approximated the modes in the ISO 8178 E-3 (ISO 8178-1, 1996) certification test cycles and while the vessel followed the voluntary vessel speed reduction (VSR) program implemented by the California Air Resources Board (CARB) (CARB, 2001). Emission factors from this study should be helpful in developing emission models and inventory calculations.

## 2. Experimental methods

### 2.1. Engine description

The sampling was conducted on a PanaMax class container ship equipped with one main engine: a MAN B&W Model 11K90MC-C. This is a large two-stroke, slow-speed engine of the MC generation. The engine was manufactured in 1995 and is rated at 50,270 kW and 104 rpm.

### 2.2. Fuel properties

The main engine burned HFO meeting ISO 8217 specifications (ISO 8217, 2005). Fuel was typical of normal supply. A fuel sample was obtained during the course of the emissions testing. A 1 liter fuel sample was drawn from the main engine final filter drain, immediately upstream of the injector rail. This sample was subsequently analyzed for a number of fuel properties. Selected data from the analysis of fuel are presented in Table 1.

### 2.3. Test cycle

The "in-use" emission testing in this study was carried out with the engine operating on a vessel during an actual sea voyage. The emissions were measured while following the modes for the ISO certification cycle (ISO 8178-4, 1996). These emissions data would verify that the engine was operating at design and values from these tests could be compared with certification data from similar sources. Testing for the main engine followed the EPA guidance and the ISO 8178-E3 four-mode test cycle, except that testing was not carried out at the 100% power due to practical limitations. The actual achievable load points were determined at the time of testing which depends on several factors; including operational constraints, sea current, wave pattern, wind speed/direction, and cargo load. Efforts were made to conduct the emissions measurements at loads as close as possible to those specified in ISO 8178-E3. The testing was conducted at the 8%, 27%, 52%, 63% and 70% of the full engine load. The engine load in this study is determined from the engine computer. The 8%

Table 1
Selected fuel properties

| Fuel type | HFO |
|---|---|
| Density ($kg\,m^{-3}$) at 15 °C | 990.8 |
| Viscosity ($mm^2\,s^{-1}$) at 50 °C | 296.8 |
| Micro-carbon residue ($\%m\,m^{-1}$) | 14.5 |
| Sulfur ($\%m\,m^{-1}$) | 2.05 |
| Ash ($\%m\,m^{-1}$) | 0.072 |
| Vanadium ($mg\,kg^{-1}$) | 259 |
| Nickel ($mg\,kg^{-1}$) | 26 |