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Emission characteristics of offshore fishing ships in the Yellow Bo Sea, China

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ABSTRACT

Maritime transport has been playing a decisive role in global trade. Its contribution to the air pollution of the sea and coastal areas has been widely recognized. The air pollutant emission inventories of several harbors in China have already been established. However, the emission factors of local ships have not been addressed comprehensively, and thus are lacking from the emission inventories. In this study, on-board emission tests of eight diesel-powered offshore fishing ships were conducted near the coastal region of the northern Yellow Bo Sea fishing ground of Dalian, China. Results show that large amounts of fine particles (<0.5 μm, 90%) were found in maneuvering mode, which were about five times higher than those during cruise mode. Emission rates as well as emission factors based on both distance and fuel were determined during the cruise and maneuvering modes (including departure and arrival). Average emission rates and distance-based emission factors of CO, HC and PM were much higher during the maneuvering mode as compared with the cruise mode. However, the average emission rate of Nitrous Oxide (NO_x) was higher during the cruise mode as compared with the maneuvering modes. On the contrary, the average distance-based emission factors of NO_x were lower during the cruise mode relative to the maneuvering mode due to the low sailing speed of the latter.

Introduction

Maritime transport plays a central role in global trade. The impacts of the pollution caused by ships on the air quality of the sea, territorial waters and coastal areas have become more and more significant during the last few years. Consequently, shipping emissions have become a growing concern of the scientific community working on the environment. Thus, exhaust emissions from ships and their impact on the atmospheric environment have become a hot research

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field around the world, mainly taking two directions. One is based on real-world emission tests on certain types of ships (Winnes et al., 2015), while the other is focused on the development of emission inventories at the regional scale (Jena et al., 2015; Zhang et al., 2010).

The acquisition of accurate emission factors from the tests is the essential element to developing shipping emission inventories. Sinha et al. (2003) selected two representative diesel-powered ships in the southern Atlantic Ocean off the coast of Namibia and measured the emissions of trace gases and particles. The characteristics of particulate matter (PM) and gaseous emissions from a large cargo vessel operating on diesel were measured by Moldanová et al. (2009). Furthermore, Winnes and Fridell (2010) conducted experiments on the main engines of a ferry and a tanker, and measured the emission levels of NO_x and particles in maneuvering mode. Their emission inventories helped to evaluate the risks to the local environment caused by pollutants from the ships. Kesgin and Vardar (2001) have estimated that the total emissions of ships are 353,625 and 347,221 tons/year on the Bosphorus and the Canakkale Strait, respectively. It has also been reported that ocean-going ships, harbor tugs and commercial boats emit twice the amount of smog-forming emissions as emitted by all the power plants working in the area of Los Angeles (Mitchell, 2001). The NO_x emitted from ships made up a significant amount of the total NO_x levels in central Copenhagen (Saxea and Larsena, 2004). According to a research study, NO_x, SO_2, PM and GHGs (primarily CO_2) emitted from ships increased from 0.585 billion in 1990 to 1.096 billion tons in 2007 (Tzannatos and Kokotos, 2009).

Studies have also been performed in China to measure the emission factors and estimate the amounts of emissions contributed by ships in several large ports. Yang et al. (2007) developed an air pollutant emission inventory and estimated that the exhaust emissions such as NO_x, SO_2, Carbon Monoxide (CO), PM and volatile organic compounds (VOC) emitted from ships at Shanghai Port in 2003 were 44,270, 39,560, 34,220, 6290 and 17,570 tons, respectively. Emissions from the transport ships in Tianjin harbor were reported to be 5360 tons in 2006 (Jin et al., 2009). The maritime transport emission inventory of Qingdao established by Liu et al. (2011a, 2011b), indicated that ports and shipping lines contribute about 8.0% of the total discharges of SO_2 and about 12.9% of NO_x on an urban scale. Yau et al. (2012) also developed a detailed maritime emission inventory for ocean-going vehicles (OGVs) in Hong Kong. They showed that the total ship emissions from OGVs in 2007 were 17,097, 8190, and 1035 tons, accounting for 17%, 11%, and 16% of the total emissions of NO_x, SO_2, and PM_{10}, respectively. Fu et al. (2013) measured seven inland ships using different power engines, and thus calculated the emission factors of the ships.

The establishment of a coastal emission inventory has been included as one of the objectives of the Chinese government. However, the emission factors used in the ship emission inventory of the Chinese harbors are mostly based on the previously established European and US ship emission databases, which are not expected to reflect the real conditions of the local regions. Therefore, it is of great importance to determine the local emission characteristics of ships in China for an accurate shipping emission inventory.

According to the statistics of the China Fisheries Association, there were a total of about 452.5 thousand offshore fishing ships in China in the year 2012. In fact, nearly 70% of ship emissions occur within 400 km of land, leading to the potential of these emissions to affect the air quality of the coastal areas (Endresen et al., 2003; Eyring et al., 2005). Moreover, the use of residual oil characterized by high density, high viscosity, and high concentrations of impurities aggravates the emission conditions of the ships (Corbett et al., 1999; Mudway et al., 2004; Moldanová et al., 2009). This leads to the fact that the pollutants from the offshore fishing ships adversely affect the local atmospheric environment. However, the literature related to emissions of low tonnage offshore fishing ships is sparse, and thus there is a need to study these ships separately.

The objective of this study is to enhance the understanding of emission levels of offshore fishing ships in China and provide references for stricter regulations on marine pollution. The emissions from offshore fishing ships, such as CO, Hydrocarbons (HC), NO_x, and PM, were measured by using a portable emission measurement system (PEMS). These measurements were used to obtain emission factors of offshore fishing ships in the northern Yellow Bo Sea fishing ground off the coast of Dalian China. In addition to this, a comparison of the obtained fuel-based emission factors with those of previous studies is presented.

1. Experimental section

1.1. Instruments for measurements

In this study, we employed a portable emission measurement system (PEMS) to test the offshore fishing ships. The use of such systems on ocean ships has rarely been reported in the literature. This system, however, has been employed to measure the emissions from inland ships by Fu et al. (2013). In the current study, the use of PEMS was extended to investigate the pollutants emitted from the offshore fishing ships under real driving conditions.

This system consists of a SEMTECH-DS (DS, Sensor Inc., US), electrical low pressure impactor (ELPI) and some other useful accessories. The SEMTECH-DS is able to measure the instantaneous emissions of gaseous pollutants, such as CO_2, CO, HC, and NO_x, applying corresponding measurement modules (Dearth et al., 2005; Durbin et al., 2007). Environmental humidity, temperature, pressure, instantaneous location, speed of the ship, and some other parameters were measured and transmitted to a computer through a data line. Moreover, the SEMTECH-DS was zeroed and calibrated with pure nitrogen and standard gases respectively prior to each test to guarantee the accuracy of the measurements (Huo et al., 2012a, 2012b). The ELPI was used for the real-time monitoring of aerosol particle size distributions and providing second-by-second PM emission data with a minimum response time of less than 5 sec (Marjamäki et al., 2000). This instrument can measure airborne particle size distributions in the size range of 7 nm to 10 μm. The instrument should also be zeroed before starting a test. Table 1 shows the truncation diameter and median diameter level of the ELPI.

Table 1 – Particle diameter (D_p) and particle median diameter (D_i) levels of electrical low pressure impactor (ELPI).

Level	D_p (μm)	D_i (μm)	Density (g/cm^3)
1	0.0070	0.0214	1.20
2	0.0290	0.0407	1.00
3	0.0570	0.0759	0.85
4	0.1010	0.1291	0.75
5	0.1650	0.2051	0.70
6	0.2550	0.3166	0.60
7	0.3930	0.5003	0.50
8	0.6370	0.7941	0.40
9	0.9900	1.2625	0.35
10	1.6100	1.9901	0.30
11	2.4600	3.1251	0.20
12	3.9700	6.3479	0.10

Two ejector dilutors (dilutors, Dekati, Finland) were installed between the ELPI and the sampling probe. The exhaust gas was diluted by compressed air passing through the dilutors in series before entering the ELPI. The first dilutor was heated to 200°C and the second ejector dilutor was left at room temperature. This helped the mixture to avoid condensation in the first dilutor and then to be cooled in the second dilutor. The dilution ratio during testing was set to around 64:1. This has proved to be effective, particularly in inhibiting all post-dilution particles which may arise from coagulation and adsorption. This system has already been employed successfully on many occasions in diesel emission measurements in China (Zhang et al., 2009; Wang et al., 2008; Liu et al., (2011a, 2011b); He et al., 2011; Fu et al., 2013).

The SEMTECH-DS, ELPI, dilutor system and the generator were all installed and fixed on the deck of a ship, while a fuel consumption meter (Ono Sokki, Japan) was installed in the engine compartment. The fuel consumption meter is able to calculate the fuel consumed and transfer the data to a remote device, *via* an internet network. This instrument can measure fuel consumption in the range of 0 to 120 L/hr. Table 2 gives the detailed information of the tested instrument. Fig. 1 shows the experimental installation schematic diagram.

1.2. Tested ships

A great deal of care was taken in the selection of ships to make sure that the selected ships would be truly representative of the fleet. After a thorough investigation, it was determined that the engine power of the registered fishing ships in Dalian port mainly ranged from 200 to 400 kW. However, the use of 260 and 330 kW diesel engine ships is quite common here. These fishing ships usually operate on residual fuel oils, which are expected to adversely affect the engine combustion and performance. Residual oil is oil found in low concentrations naturally or in exhausted oil fields, often with high molecular weight, high viscosity and mixed with water. The ship engines normally have to be changed after about two to three years owing to the poor operating environment. When the residual oil is injected into the cylinder, large carbon particles can be formed due to lack of full combustion, which can cause clogging of the nozzle, which will affect the performance of the engine. Therefore, we installed a fuel filter before the fuel consumption meter, in the course of the experiment, to observe whether the fuel filter was blocked or not, and if it was blocked, replace the fuel filter in time. Table 3 gives the detailed information of the tested ships. Residual fuel oil consists of water ≤0.15%, ash 0.031% and sulfur ≤2.86%. The density of residual fuel oil is 0.992 kg/m^3 at 20°C and the viscosity is 180 mm^2/sec at 20°C.

Table 2 – Details regarding the test instrument of SEMTECH-DS.

Pollutants	Measurement range	Resolution ratio	Measurement accuracy
CO_2	0–20%	0.01%	±3%
Carbon Monoxide (CO)	0–8%	10 ppm	±3%
Total hydrocarbon	0–1000 ppm	1 ppm	±2%
Nitrogen Monoxide (NO)	0–2500 ppm	1 ppm	±3%
NO_2	0–500 ppm	1 ppm	±3%

1.3. Test operating modes

Offshore fishing ships generally depart for fishing in the open sea at about 4 p.m. and return back to the port the next morning. While on berth, life services are generally provided by storage batteries without power being taken from the ship engine. The direct current (12 V) is converted into alternating current (220 V). The operations of offshore fishing ships during a journey are divided into three modes: port departure, cruise and port arrival (Deniz and Durmusoglu, 2008; Winnes and Fridell, 2010; Lonati et al., 2010). Port departure is assumed to start from engine ignition to the moment when cruise speed has been reached, while port arrival is considered as the period when the ship is close to the port and thus begins to decelerate, and is assumed to end when the ship docks at the bank. The emissions from maneuvering, which include port departure and port arrival, comprise the lowest share of emissions of the total journey, but their influence on local air quality is of prime importance owing to the proximity to land (Winnes and Fridell, 2010). In this study, eight fishing ships were operated to simulate the entire process. They departed from the port after the installation of instruments, cruised in the open sea for about 2 hr, and finally returned to the port.

1.4. Data processing

The fuel-based emission factors were calculated using the carbon balance method, which assumes that all carbon is emitted as HC, CO and CO_2. Emission factors were defined as (Eq. (1)):

$$EF_{(g/kg)} = \frac{\sum\left(\rho_{(g/m^3)} \times Y \times V_{(m^3/\,sec)}\right)}{\sum\left(\rho_{diesel(g/m^3)} \times FC_{(L/\,sec)}\right)} \quad (1)$$

where EF_{fuel} (g/kg) fuel is the fuel-based emission factor, ρ is the density of the emissions in standard conditions, Y is the volume fraction of the emissions in standard conditions, V is

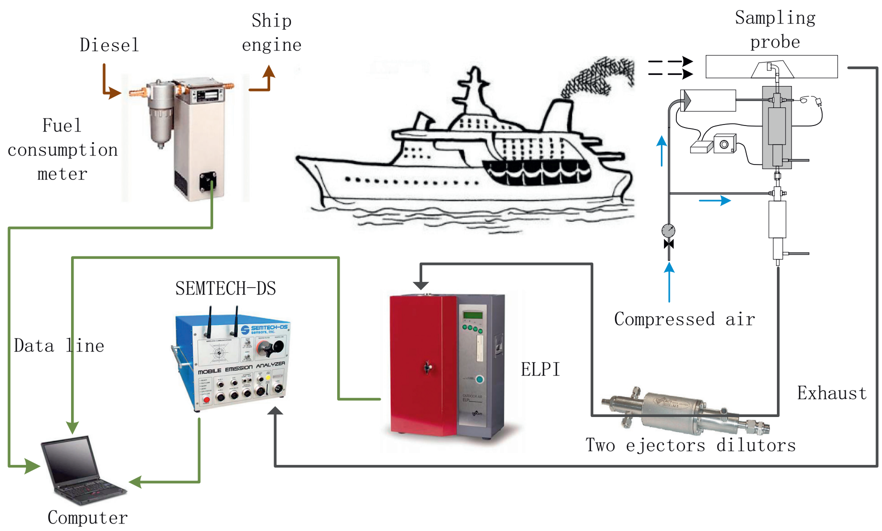

Fig. 1 – The experimental installation schematic diagram. ELPI: electrical low pressure impactor.

the exhaust volume flow rate in standard conditions, FC is the fuel consumption rate, and ρ_{diesel} is the density of the fuel in standard conditions.

The exhaust volume flow was calculated using the following equation (Eq. (2)) (Fu et al., 2013):

$$VF_{EX(L/\,sec)} = \frac{FC_{(L/\,sec)} \times \rho_{diesel(g/m^3)} \times 1000 \times CWF_F}{0.866 \times Y_{HC} \times \rho_{HC(g/m^3)} + 0.429 \times Y_{CO} \times \rho_{CO(g/m^3)} + 0.273 \times Y_{CO_2} \times \rho_{CO_2(g/m^3)}} \tag{2}$$

where VF_{EX} (L/sec) represents the exhaust volume flow, FC (L/sec) represents the fuel volume flow, CWF_F represents the carbon content of the residual fuel oil, φ (ppm) and ρ (kg/m^3) represent volume fraction and standard density of the studied gas, including HC, CO and CO_2, respectively. 0.866, 0.429 and 0.273 are the mass fractions of carbon in HC, CO and CO_2, respectively. ρ_{diesel} and CWF_F were analyzed as 0.996 kg/L and 87.98%.

Error analysis used the standard deviation formula (Eq. (3))

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i-\mu)^2} \tag{3}$$

σ represents the standard deviation, *N* represents the total number of samples, *i* represents the sample number, x_i represents the measured value, and μ represents the average value.

Table 3 – Details regarding the test ships.

Identifier	Engine type	Built year	Engine rated power (kW)	Rated engine speed (r/min)
No. 1	6190ZLCA-1	2012–12	330	1200
No. 2	6190ZLCA-1	2012–12	330	1200
No. 3	6190ZLCA-1	2011–05	330	1200
No. 4	6190ZLCA-1	2011–04	330	1200
No. 5	6190ZLCA-1	2012–12	330	1200
No. 6	Z6170ZLC-5	2011–04	260	1200
No. 7	6190ZLCA-1	2012–12	330	1200
No. 8	Z6170ZLC-5	2011–04	260	1200

2. Results and discussion

2.1. Instantaneous emission

2.1.1. Instantaneous emissions of gaseous pollutants

The operations of offshore fishing ships during a journey are divided into three modes: port departure, cruise and port arrival. Different operating modes were separately measured to ensure the validity of the simulation. Emissions of trace gases and particles from all 8 fishing ships were measured in Dalian port. The instantaneous speed and emission characteristics during the journey are shown in Fig. 2. Only part of the data taken on cruise mode is displayed, as the duration was too long and the data measured during cruising was relatively stable. The ship speed was steady at a high level of about 20 km/hr on cruise mode, while rapid acceleration and deceleration occurred frequently in maneuvering mode (port departure and port arrival modes). The CO, HC and PM measurements indicated highly elevated instantaneous concentrations during maneuvering as compared to the average levels during cruise mode. It is clear from Fig. 2 that NO_x trends fluctuate during the maneuvering, but remain elevated and mostly stable during the cruise mode, relative to the two other modes. However, large peaks occur in maneuvering modes, which correspond to rapid acceleration and deceleration. As a matter of fact, the emission features were found to depend mainly on engine operating conditions. The operating conditions of ship engines varied greatly and frequently during maneuvering modes in order to meet the demands of adjustment of driving direction and speed. This variation caused instability in the essential combustion parameters such as air intake, fuel consumption and combustion temperature. However, the ships maintained cruise velocity and the engines were kept running steadily at high speed during cruise mode. Therefore, the different engine operating conditions resulted in significant differences in the above discussed emissions between maneuvering and cruise modes.

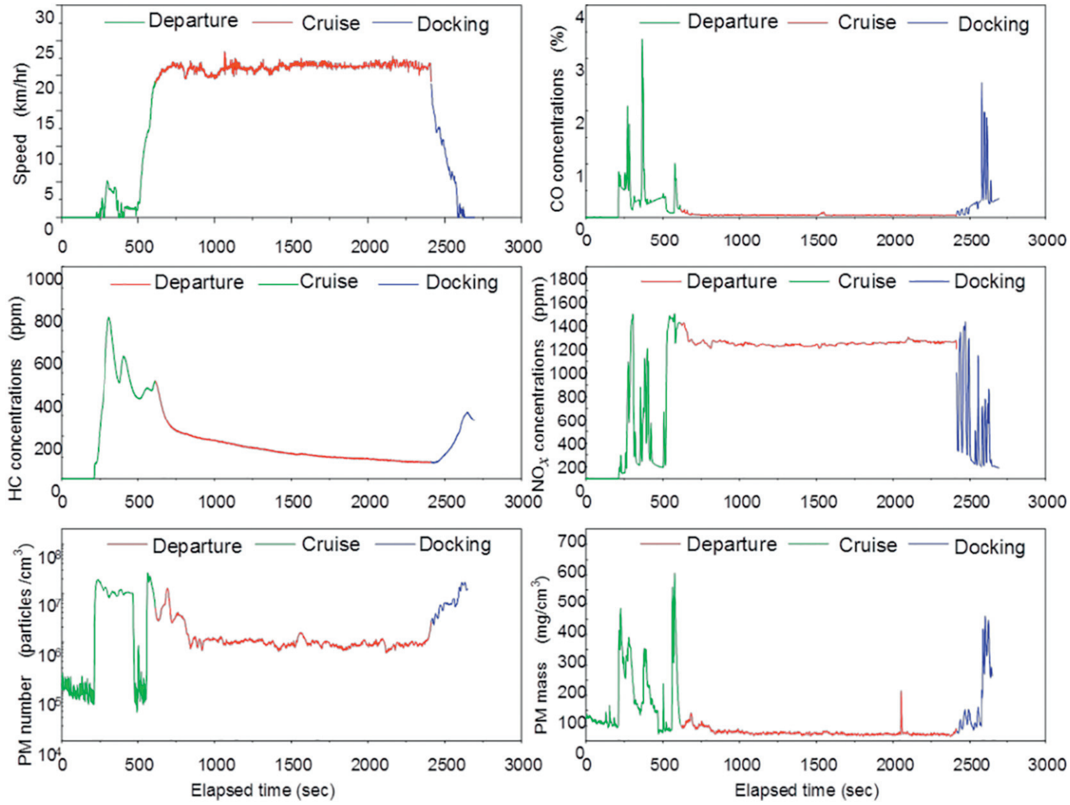

Fig. 2 – Instantaneous ship speed and emission concentrations in different operating modes. PM: particulate matter.

2.1.2. Size distributions of PM

Generally, PM emissions are divided into three modes, called nucleation mode (condensation of HC volatiles) with the size range 0.01–0.1 μm; accumulation mode (carbon species and adsorbed material) with size 0.1–1 μm; and the coarse mode (re-entrained particles) with size 1–10 μm (Cooper, 2003;

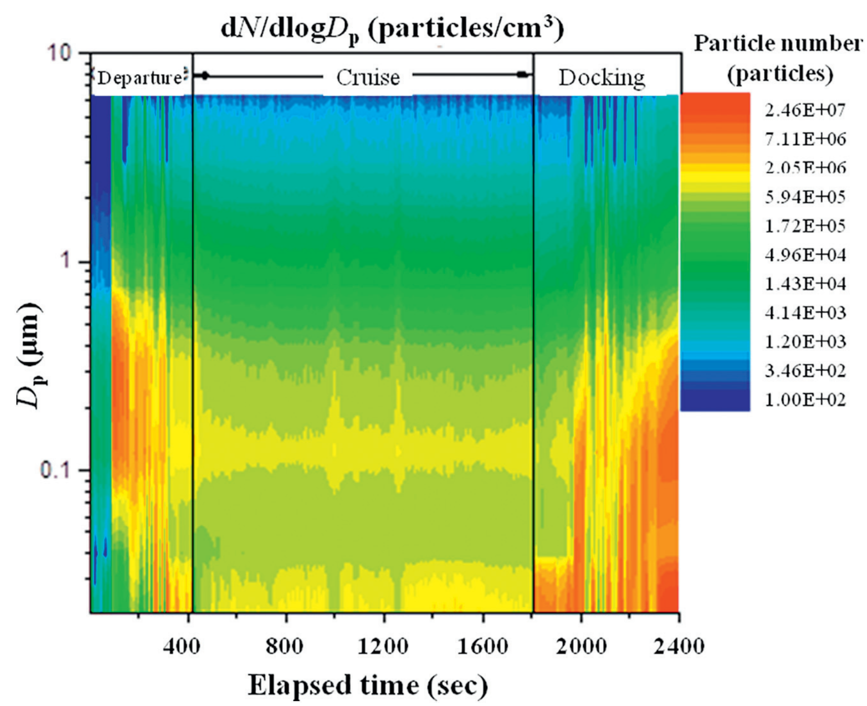

Fig. 3 – PM number distribution from three typical operational modes. dN/dlogD_p: number per unit of particulate size; D_p: particle diameter range.

Fridell et al., 2008). The particle number distribution in different operating modes is presented in Fig. 3. It is obvious that large amounts of small size particles with diameter below 0.5 μm were emitted from the engine during the journey. In an alternative way, the average PM number and mass size distributions during different operating modes are depicted in Fig. 4. It can be found that about 75.1% particles were in nucleation mode, while 24.8% particles were in accumulation mode during the departure mode. The corresponding proportions of particles were 94.1% and 5.7% during cruise mode, whereas 72.8% and 26.7% during port arrival mode, respectively. However, the mass distribution of particles reveals that the particles in nucleation and accumulation modes contribute about 27.4%, 13.1% and 14.2% of total mass emitted during port departure, cruise and port arrival modes, respectively. The number of particles is clearly higher during maneuvering mode as compared to cruise mode.

2.2. Emission factors for different operating modes

2.2.1. Emission rates for different operating modes

The emission factors of ships were found to be varied due to different engines and driving conditions. Therefore, average emission factors were introduced to evaluate the emission levels of offshore fishing ships in Yellow Bo Sea fishing grounds. Table 4 presents the average emission rates of CO, HC, NO_x and PM for different operating modes. The relative standard deviations of the average emission rates among the eight ships were in the range of 7.3% to 10.6%. The CO, HC and PM average emission rates during maneuvering mode were mostly higher as compared to those during cruise mode, while for NO_x the average emission rates were just the opposite. Particles and NO_x are the main emissions from ship engines using residual oil. Emission rates of PM during port departure and port arrival mode were 5.1 and 1.7 times greater on average than those during cruise mode, respectively. The average emission rates of NOx in the cruise process were 2.8 and 3.3 times greater than those in the port departure and arrival process, respectively. The possible reason may be that the rapidly changing engine speed and engine load during the maneuvering process may cause poor combustion, which results in higher emission rates of CO, HC and PM, but on the contrary, lower emission rates for NO_x. Since NO_x emissions from ships are temperature-dependent (Sinha et al., 2003), operation for long periods of time at higher temperatures during cruise mode leads to higher NO_x emission.

Table 4 – Average emission rates for different operating modes.

	Operating mode		
	Departure	Cruise	Docking
Carbon Monoxide (CO) (g/hr)	7812 ± 811	1620 ± 134	5040 ± 534
Hydrocarbons (HC) (g/hr)	418 ± 43	234 ± 22	140 ± 12
Nitrogen Oxide (NO_x) (g/hr)	2160 ± 178	6012 ± 470	1800 ± 165
PM (g/hr)	684 ± 51	133.2 ± 10	223.2 ± 18
Average speed (km/hr)	4 ± 0.6	19.6 ± 2.8	5.2 ± 0.7

PM: particulate matter.

2.2.2. Distance-based emission factors for different operating modes

The definition of distance-based emission factors is pollutant mass divided by the ship driving distance; these have already been successfully adopted on many occasions in establishing vehicle emission inventories (Wang et al., 2008; Chen et al., 2007). Since the sailing velocity was rather stable during the cruise mode, the distance-based emission factors could also be introduced in establishing the ship emission inventories. Table 5 shows the distance-based emission factors of CO, HC, NO_x and PM for different operating modes calculated on the basis of their emission rates and sailing speed. The relative standard deviations of emission factors based on the average

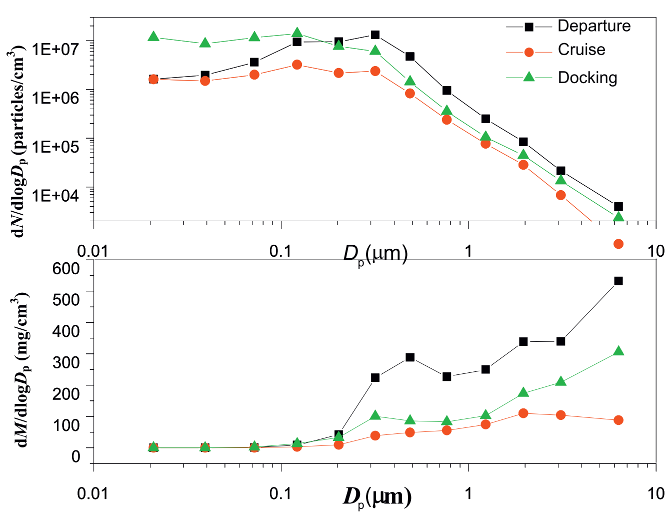

Fig. 4 – Average particle number and mass size distributions from three typical operational modes. dM/dlogD_p means mass per unit of particulate size.

Table 5 – Distance-based emission factors for different operating modes.

	Operating mode		
	Port departure	Cruise	Docking
Carbon Monoxide (CO) (g/km)	2190 ± 333	130 ± 18	1638 ± 241
Hydrocarbons (HC) (g/km)	170 ± 25	18.9 ± 25	57.3 ± 7
Nitrogen Oxide (NO_x) (g/km)	819 ± 80	479 ± 71.5	582 ± 68
PM (g/km)	270 ± 36	10.8 ± 1.2	78 ± 10

distance of eight ships were in the range of 9.8% to 14.9%. The distance-based emission factors of CO, HC, NO_x and PM were all higher during maneuvering modes relative to cruise mode. This is attributed to the lower speeds in the port.

2.2.3. *Fuel-based emission factors for different operating modes*

Ships have been reported to be the world's highest polluting combustion sources per unit fuel consumed (Corbett and Fischbeck, 1997). Fuel-based emission factors are also widely used in inventory studies, as this is a good way to get rid of the influence of engine size (Sinha et al., 2003; Marr et al., 2007; Moldanová et al., 2009; Yao et al., 2011). Table 6 presents the fuel-based emission factors for different operating modes. The relative standard deviations of the average fuel-based emission factors of the eight ships were in the range of 8.2% to 12.8%. It is clear that emission factors of CO, HC and PM on maneuvering mode were higher than those on cruise mode, but the situation was the opposite in the case of NO_x emissions. The main reason is incomplete combustion during the maneuvering process caused by low fuel utilization. The fuel used in the tested ships is a residual fuel that contains many impurities in it. Residual fuel refers to a broad category of low-grade fuels, ranging from crude oil to a fuel from which some of the impurities have been removed, particularly those that may cause excessive engine wear. Residual fuels are generally characterized by higher viscosity and density, and higher concentrations of impurities such as sulfur (Corbett et al., 1999). Relative to the distillates, residual fuels give incomplete combustion with the consequent emissions of products other than CO_2.

Table 6 – Fuel-based emission factors for different operating modes.

	Operating mode		
	Port departure	Cruise	Docking
Carbon Monoxide (CO) (g/kg)	226 ± 29	16.7 ± 1.8	218 ± 24
Hydrocarbons (HC) (g/kg)	9.5 ± 0.8	2.4 ± 0.3	9.0 ± 0.9
Nitrogen Oxide (NO_x) (g/kg)	48.6 ± 4.3	75.6 ± 7.5	69.7 ± 8.6
PM (g/kg)	20.9 ± 1.9	3.27 ± 0.3	11 ± 1.0

2.3. *Comparison of fuel-based emission factors with previous studies*

A comparison of the fuel-based emission factors of the current study with those of other studies (Sinha et al., 2003; Marr et al., 2007; Moldanová et al., 2009) is presented in Fig. 5. The physico-chemical properties of fuel used in this study are more or less similar to those of other studies selected here for comparison. The major characteristics of the fuels include their high viscosity, density and sulfur content. In addition to this, the studies involved similar operating modes under real-world cruise conditions. It can be seen that there is no HC and PM emission data in Marr's and Sinha's studies, respectively. The fuel-based emission factors of HC, NO_x and PM of the current study (A) are all in the middle levels in contrast with those in the other studies, while the emission factor of CO is slightly higher than that of Marr's study (study E with ferry B).

As far as NO_x is concerned, it has drawn considerable attention from researchers with the increase of marine transportation such as ships. According to the International Maritime Organization Diplomatic Conference held in September 1997, the Regulation 13 of Annex VI was implemented starting 1st January 2000. As per Regulation 13, all the diesel engines being used to operate the ships and having individual power outputs of greater than 130 kW were required to comply the NO_x emission limits as of January 1, 2000 (Kowalski and Tarelko, 2009). The NO_x limit of marine engines given in Tier 1 as 17 g, was ratcheted down to 14.4 g in Tier 2 for such engines manufactured after 2011. The Tier 2 standard unfortunately could not be implemented successfully due to the lack of efficient engine technologies such as engine timing, engine cooling, and advanced computer controls. Furthermore, the Tier 3 standard focused on sulfur control is scheduled to be implemented in the year 2016. The Chinese Classification Society (CCS) also developed the measurement methods and test guidelines for NO_x emitted from marine diesel engines in 2010. According to the CCS, the ships manufactured after 9th January 2000 are required to meet the Tier 1 emission standard. In this study, the authors have estimated the fuel-based NO_x emission factors by using the emission standard, as there are no Tier 1–3 NO_x emission standards in terms of g/(kg fuel). The Ministry of Environment Protection (MEP) of China has also implemented a number of emission regulations for on-road vehicles since 2000. However, nationwide there are no mandatory emission regulations for the newly built ship engines.

3. Conclusions

In this study, we tested five diesel-powered offshore fishing ships in the northern Yellow Bo Sea fishing ground off the coast of Dalian by using a portable emission measurement system (PEMS). The results proved that PEMS can be used for measuring the emissions of fishing ships. Peak concentrations of CO, HC, NO_x and PM during maneuvering modes (including departure and docking modes) were recorded from ship engines once per second. Average emission rates and

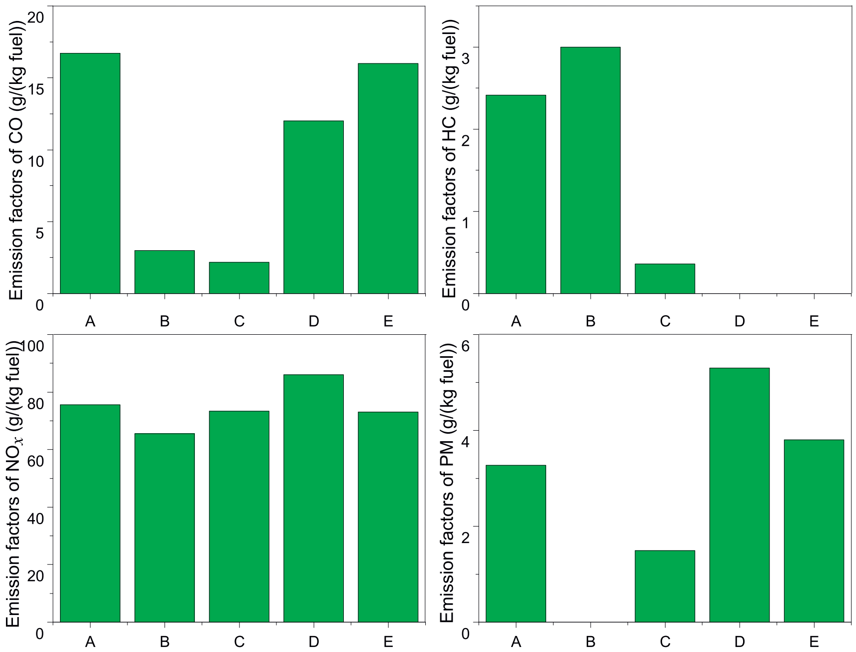

Fig. 5 – Fuel-based emission factors of Carbon Monoxide (CO), Hydrocarbons (HC), Nitrous Oxide (NO_x) and PM on cruise mode of several studies. A is the fuel-based emission factors for cruise mode from this study; B is emission factors of a container ship named MSC Giovanna from Sinha et al. (2003); C is emission factors of a large cargo vessel from Moldanová et al. (2009); D and E are the fuel-based emission factors of two ships (ferry A and ferry B) studied by Marr et al. (2007).

distance-based emission factors of CO, HC and PM were higher during maneuvering than during cruise mode. Average emission rates of NO_x for cruise mode were higher than those for maneuvering modes. However, the average distance-based emission factor of NO_x in cruise mode was lower than those for maneuvering mode because of the low sailing speed in maneuvering. During port departure and port arrival, the fishing ships need to adjust parking position, waiting for the stopping position, in order to overcome the impact of ocean currents; the engine is continuously working, but the driving distance is very short.

According to the tests, about 87%–97% of the particles are in the size range 0.01–0.4 μm in the three typical operational modes, while they only represent about 0.09%–0.14% of the total particle mass. These particles, formed in nucleation mode and accumulation mode, are mainly composed of condensing hydrocarbon volatiles, carbon species and adsorbed material, and have a great effect on human health and air quality (Liu et al., 2016; Lelieveld et al., 2015; Corbett et al., 2007).

The average fuel-based emission factors of CO, HC, NO_x and PM on cruise mode in this study are in the middle levels compared with those from previous studies. The higher emissions of CO, HC and PM can be attributed to poor combustion conditions, while higher pressure and temperature result in high levels of NO_x. Therefore, advanced engine technologies, such as improvements in engine timing, engine cooling and engine after-treatments, are necessary to reduce the exhaust emissions. In addition, combustion of low sulfur content marine fuels instead of residual fuels would also be effective for the reduction of pollutants, especially SO_x.

More offshore fishing ships should be measured in further studies to understand their emission levels. In addition, more information on ship activity and fuel consumption are needed to provide detailed information for developing an offshore fishing ship emission inventory in China.

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