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Article

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Research paper

A comparison of particulate matter and gaseous emission factors from two large cargo vessels during manoeuvring conditions

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ABSTRACT

In this study, emission factors of both particle and gaseous phases are characterised on board two large cargo vessels operating on the east coast of Australia during manoeuvring conditions. In order to investigate the difference in particle number and mass size distributions, measurements were conducted on two 2-stroke engines of two vessels using Heavy Fuel Oil (HFO) with nearly the same sulphur content. Results showed that manoeuvring compared to ocean-going conditions resulted in higher emission factors for carbon monoxide (CO), carbon dioxide (CO_2), unburnt hydrocarbon (HC), particulate matter (PM) and particle number (PN), which can have significant negative effects on human health and the environment in coastal and port areas. Importantly, a significant difference was observed in particle number size distributions between the two vessels. Those observed for Vessel II were mono-modal with the peak at 40–50 nm and dominated by ultrafine particles (D < 100 nm), while for Vessel I a bimodal distribution with a nucleation peak at around 20 nm and a major peak at larger diameter of 60 nm was observed. The difference in particle number size distributions between the two vessels may be due to the difference in sampling location and/or marine engine characteristics, including age and technology. The effects of fuel sulphur content on PN and PM emissions observed in this study are also compared with the results available from previous measurements in the literature. Engine load was also found to be an important influence on all emission factors.

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1. Introduction

Compared to all other modes of transport, maritime transport is the optimum mode of transport (per tonne cargo transfer) in terms of cost effectiveness and lower environment emissions (Corbett, 2003). It accounts for over 80% of global trade and is forecast to grow in the coming years (IMO, 2009). However, exhaust emissions from ships have a profound impact on the environment, and consequently on human health, and have become a global issue over the last twenty years (Anderson et al., 2015; Blasco et al., 2014; Corbett et al., 2007; Di Natale and Carotenuto, 2015; Mueller et al., 2015; Reda et al., 2015; Ristovski et al., 2012; Winnes et al., 2016). Over 70% of ship emissions may cause impact up to 400 km inland and have become an important contributor to global anthropogenic emissions, especially in the vicinity of coastal and port areas (Eyring, 2005; Eyring et al., 2010). Recent papers by González et al. (2011) and Viana et al. (2014) have indicated that shipping-related emissions are responsible for causing increased levels of both particulate matter (PM) and gaseous pollutants in the atmospheric environment. PM is a complex mixture of extremely small solid and liquid particles. In particular, it consists of a number of components, including carbonaceous elements, acids, organic chemicals, metals, and soil or dust particles (Ristovski et al., 2012), which contribute strongly to climate change (Hallquist et al., 2013; Lack et al., 2011; Winnes et al., 2016). Besides the above-mentioned issues, shipping activities are one of the primary sources causing seawater acidification (Hassellöv et al., 2013). In 2012 diesel engine exhaust was classified as a carcinogenic substance to human health (Group 1, same as asbestos) by the International Agency

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for Research on Cancer (IARC), which is part of the World Health Organization (WHO). Corbett et al. (2007) estimated that on a global scale, shipping-related fine particle ($PM_{2.5}$) emissions are the cause of approximately 60,000 deaths annually resulting from cardiopulmonary and lung problems. Most deaths occurred in areas of high population density and high particle concentrations, such as Asia and Europe, and the number of annual mortalities was predicted to increase by 40% by 2012 (Corbett et al., 2007).

Emissions from ships at berth and during manoeuvring operations are responsible for a relatively small proportion of the overall pollution from shipping compared to the ocean-going mode, however they can cause adverse health effects on the surrounding population because of their proximity to areas of high population density (Cooper, 2003; Winnes and Fridell, 2010). In the literature, investigating emission factors during ship manoeuvring has been neglected over the years (Winnes and Fridell, 2010). Winnes and Fridell (2010) conducted manoeuvring measurements on two main engines with a focus on nitrogen oxides (NO_x) and particle emissions, and found an increase in levels of particle number (PN) throughout the manoeuvring period, especially for the start-up and shut-down of engines, but not for NO_x emissions. Nevertheless, further on-board measurement studies need to be carried out to add to the existing database of ship emissions, which can be used to diminish the uncertainty in quantification of ship emission factors. Measuring small-sized PN from ships during manoeuvring conditions is also beneficial, since it potentially enables the quantification of health impacts and hence may efficiently limit unexpected health risks in exposure areas such as ports or harbour cities (Winnes et al., 2016).

For economic reasons, Heavy Fuel Oil (HFO) is the most commonly used fuel by ships (Mueller et al., 2015). Corbett (2003) found that HFO is the main fuel for over 95% of 2-stroke low-speed main marine engines and 70% of 4-stroke medium-speed engines. HFO combustion results in different compounds containing sulphate, organic carbon (OC), black carbon (BC), ash and heavy metals in emitted particles (Anderson et al., 2015; Moldanová et al., 2009; Winnes et al., 2016). The above-mentioned impurity content in HFO combustion results in the emission of particles with higher toxicity risks (Di Natale and Carotenuto, 2015). This can make ship emission-related issues become more serious, particularly in coastal areas (Mueller et al., 2011). Historically, the shipping industry has not used flow meters to monitor HFO fuel consumption. Such measurements were taken using HFO tank soundings, which have a larger error, are typically taken daily, and do not give instantaneous measurements. Current practice in the shipping industry is that all new ships are fitted with HFO flowmeters and almost all older ships have been retrofitted. (This is for managing fuel consumption because its price has significantly increased in the last decade.) Previously, shipping companies did not use flowmeters, and the responsibility for fuel consumption management was in the hands of the ship chief engineers who controlled engine speed to save fuel consumption and consequently optimise profit. But now, fuel consumption is strictly managed by the shipping companies on a global scale. HFO flowmeter data is reported to the company every day (called a "noon report") and feedback is given to the ship's chief engineer when required to optimise fuel consumption. Such advances in fuel consumption management help to reduce uncertainty of emission factors when on-board ship emission measurements were taken during each voyage. In the present study, fuel consumption information was obtained instantaneously by using HFO flowmeters installed on the measured vessels.

The International Maritime Organization (IMO) is a specialised branch of the United Nations (UN) which issues global regulations on the safety, security and environmental performance of global shipping. In particular, Annex VI of the International Convention for the Prevention of Pollution from Ships – the Marine Pollution Convention – MARPOL was adopted by the 1973 Convention, and then modified by the 1978 Protocol with regards to limiting the harmful impacts of ship emissions on air quality (IMO, 1997). These regulations were effective as of 19th May 2005, and reduce NO_x, sulphur oxides (SO_x) and PM from marine engines. Responding to the desire of some coastal nations for further reduction of SO_x emissions from ships in their regions, sulphur Emission Control Areas (ECAs) have been instituted, based on provisions contained in Regulation 14 of MARPOL Annex VI (Chu Van et al., 2019). ECAs consist of the Baltic Sea area, the North Sea area, the North American region (containing the coastal sector of the United States and Canada), and the United States Caribbean Sea areas (around Puerto Rico and the United States Virgin Islands). These regulations limit the marine fuel sulphur content to 0.1% by mass in ECAs by 2015, and to 0.5% globally by 2020, as shown in Fig. 1. The IMO does not particularly limit PM emissions, however, applying the fuel sulphur content requirements of Regulation 14 helps to reduce the sulphur-related portion of particulate matter formation. In addition to the regulations issued by the IMO, the fuel content limits and ship emission regulations have been introduced by other regions and countries, such as the State of California and the European Union (EU). In particular, from 1st January 2010, European directive 2005/33/EC demands all ships at berth or anchoring in European ports to use fuel oil with a sulphur content of less than 0.1% by weight (European Parliament, 2005). Further regulations, however, are needed because a fuel change to low sulphur was not enough to reduce small-sized PN emissions (Winnes and Fridell, 2012; Winnes et al., 2016). A very recent study by Chu Van et al. (2018) have found that fuel sulphur content resulted in PN, PM and sulphate fraction increases, and suggested that burning high sulphur HFO when ships are in port should be discontinued.

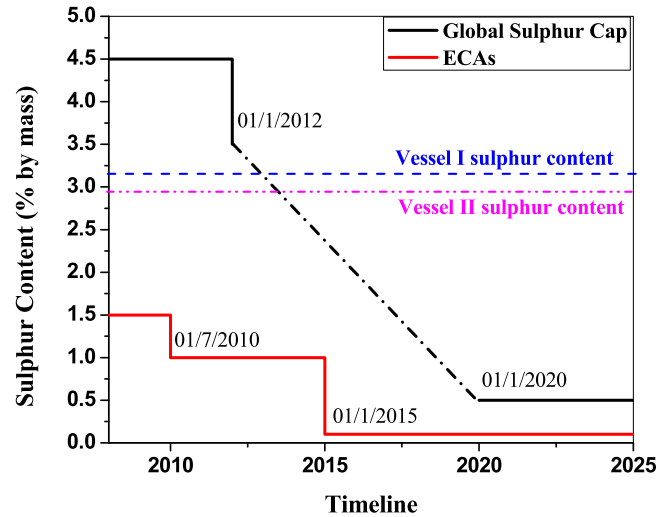

Fig. 1. Timeline for the reduction of sulphur content in marine fuels (globally and in SECAs) from MARPOL (IMO, 1999), and fuel sulphur contents of fuels used for two vessels.

In this study, a comparison of particulate and gaseous emission factors from two large-power 2-stroke low-speed main marine engines using HFO with 2.94% and 3.13% S, respectively, has been carried out. The study was conducted when the vessels were under manoeuvring conditions on the east coast of Australia. Practical on-board ship measurements have significant challenges of confined spaces, installing sampling points in exhaust systems of huge size and operational ship issues. It should be pointed out

Table 1
Brief information about the vessels, main engines and fuels used.

	Vessel I	Vessel II
Owner of Ship	CSL Australia	CSL Australia
Type of Ship	General cargo	Bulk carrier
Build Year	1981, converted 2008	2002
Main engine (Power/rpm)	Mitsui B&W 6L80GFCA (12 080 kW/102 RPM)	HHM-Man B&W 6S50MC (6880 kW/102 RPM)
Fuel used (S content)	HFO (2.94% S)	HFO (3.13% S)
IMO regulations	Not applicable	Tier I

that the main focus of the present study is to conduct the real time on-board ship emission measurements of both gases and particulate matter which are rarely found in the literature (especially during manoeuvring conditions) and make comparisons where possible. This study also attempts to provide a full range of power-based emission factors under actual operating conditions, which will be beneficial for future estimates of ship emission inventories and quantifying air quality, climate change and human health impacts. Moreover, the present study compares the PN and PM results available from previous studies to investigate the relationship between fuel sulphur content and emission factors. The different methods used for PM measurements from on-board, test-bed and ship plume studies are also discussed herein.

2. Experimental methods and equipment setup

The measurements were performed in October and November 2015 on two large cargo ships (called Vessel I and Vessel II) manoeuvring in and travelling between the Ports of Brisbane, Gladstone and Newcastle. The first on-board measurement was performed on Vessel I when she was sailing from Port of Brisbane to Port of Gladstone. The second measurement was conducted on Vessel II during her passage from Gladstone to Newcastle. All measurements were carried out on both main and auxiliary engines of the two ships for different operating ship conditions, experienced at berth, manoeuvring and cruising. The on-board measurements presented in this paper were performed on the main engines of both vessels I and II during manoeuvring conditions. These conditions refer to an operation in which a ship arrives at or departs from a berth or a port, and crosses other ships on her way in the port traffic zones. The working conditions of a main engine vary greatly from high to partial load conditions or vice versa to meet the ship speed requirements during manoeuvring conditions. In other words, the operation of the main engines is generally more a transient during manoeuvring conditions. The request letter for assistance on measuring and assessing ship emissions at port can be seen in the study of Chu-Van et al. (2017). Table 1 presents the brief information about the vessels, main engines and fuels used. More detailed information about the two measured vessels in this campaign can be seen in Table S1. Further technical parameters of the main engines of the two vessels can be seen in Table S2. The main engines were both two stroke marine engines, although the engine for Vessel II was approximately 20 years newer than that for Vessel I, had an improved and higher pressure fuel injection system and was certified to Tier standards. HFO with a similar S content was used for both vessels (Table 1), and more detailed characteristics of fuels can be seen in Table S3. The fuel characteristics were obtained both from Bunker Delivery Receipts and the Central Analytical Research Facility (CARF) laboratory analysis at Queensland University of Technology (QUT).

Emission sampling measurement instruments were located on a deck high up in the machinery room where exhaust gas from main engines was sampled and measured continuously from different sampling positions in the exhaust channel. The sampling position for Vessel I was located before the economiser that is approximately 10 m of exhaust pipe length from the exhaust manifold of the main engine, while the other was about 0.5 m after the turbocharger of the main engine for Vessel II. A schematic diagram of the different sampling positions for the two vessels is shown in Fig. S1. At each exhaust sampling position, two sampling holes were cut in the exhaust channel for both particle and gaseous phase measurements in the same configuration for the two vessels. The schematic picture of the experimental setup at each sampling position is shown in the study of Chu-Van et al. (2017). The raw hot exhaust gas was sampled directly to the DMS 500 (Cambustion, Cambridge, UK) dilution systems (2-stage dilution systems) from the first sampling hole. In particular, raw exhaust was first diluted with hot air at a temperature of 150 °C and at a fixed dilution ratio (DR) of 5. The diluted sample was then transferred to the second dilution stage via a heated sampling line to prevent condensation of water and volatile organic compounds (VOCs). The secondary dilution stage was a high ratio rotating disc diluter with a DR range of 20–500. A DMS 500 was used to measure particle number size distributions in the size range of 5 nm – 1.0 μm with a sample frequency of 1 Hz. Further details on the dilution conditions can be seen in Table S4. The second sampling hole was used for measurements by a Testo 350 Portable Emission Analyser, and by a DustTrak™ Aerosol Monitor 8530 (TSI Incorporated, Minnesota, USA) and Sable CO_2 Monitor through an Ejector Diluter (Dekati, Kangasala, Finland). The concentrations of gases, including sulphur dioxide (SO_2), NO_x, carbon monoxide (CO), oxygen (O_2), unburned hydrocarbons (HC) and CO_2 in the raw exhaust were measured by a Testo 350 Portable Emission Analyser, while a DustTrak™ Aerosol Monitor 8530 was used to measure mass concentrations of PM_{10}, $PM_{2.5}$ and $PM_{1.0}$. More specifications of measurement devices used in the present study can be seen in the study of Chu-Van et al. (2017).

Data on engine power, engine revolution and fuel oil consumption were measured by the ships' instrumentation (Table S4). In the engine control room, all engine parameters including engine power and speed information that were presented on the screen of the engine control system were continuously recorded by a video camera for both vessels under real world conditions. Data was extracted from these recorded videos at a frequency of every five seconds. Fuel oil consumption information was obtained from a flowmeter installed after supply pumps of the HFO fuel oil system. The emission factor (EF) calculation method is explained in the Supporting Information (S8). The measurement procedure is in line with the ISO 8178 standards (ISO8178-1, 2006; ISO8178-2, 2008).

3. Results and discussion

3.1. Voyage description

A ship voyage during operating conditions normally consists of three major parts: at berth, manoeuvring and cruising (Winnes and Fridell, 2010). During the running from Port of Brisbane to Gladstone for Vessel I and from Port of Gladstone to Newcastle for Vessel II (Fig. 2), gas-phase and particle emission factors during manoeuvring (Man) conditions were investigated. For each ship, the first manoeuvring condition consisted of the initial start-up, manoeuvring when leaving the harbour, and acceleration out of the port area, while the second phase included deceleration and manoeuvring when approaching the harbour, and shut-down. Both particulate matter and gaseous emission concentrations of the first and second manoeuvring phases for two vessels are

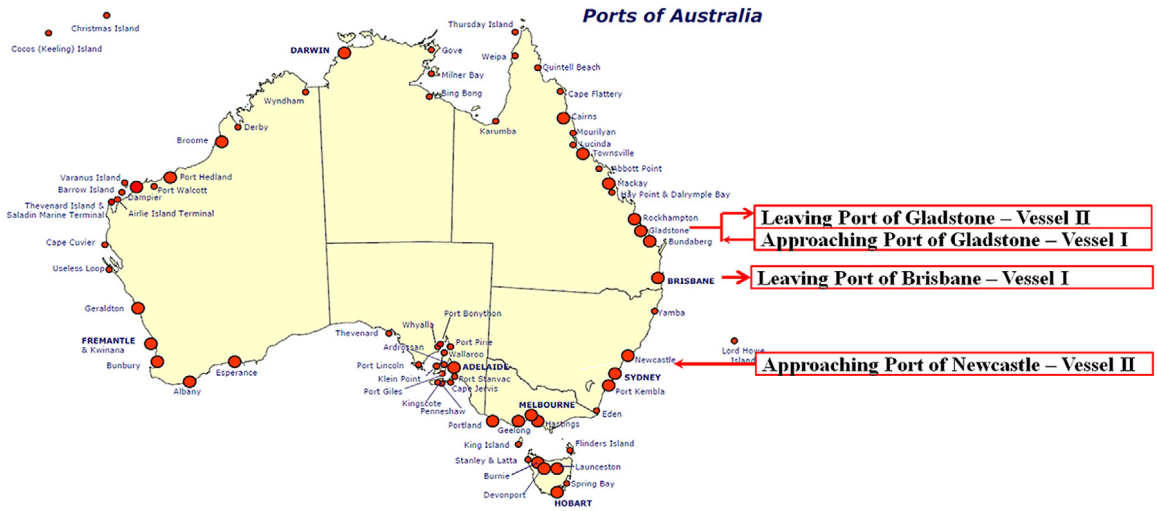

Fig. 2. Map of Australian ports, and port locations of Brisbane, Gladstone and Newcastle (Australian Ports, 2017).

presented in the Supporting Information. Further details about the four-emission measurement campaigns during arriving and leaving the three ports under manoeuvring conditions for the two vessels can be seen in Table S5.

3.2. Gaseous emissions

The main gaseous emission species of interest in the marine diesel engine exhaust channel were NO_x, SO_2, O_2, CO_2, CO and HC. The real-time on-board measurement of these gaseous concentrations during manoeuvring conditions of Vessel I can be seen in Fig. S3 and in the study of Chu-Van et al. (2017) for Vessel II. These figures present the relationship between the variation of emissions, engine power and speed against measured time. The results of gas-phase emission factors for NO_x, SO_2, CO_2, CO and HC in terms of g/kWh of the two measured ships under manoeuvring conditions against engine load conditions are presented in Fig. 3. The relationship between engine load, specific fuel oil consumption (SFOC) and engine speed can also be seen in Fig. 3. For both vessels, engine-propulsion configuration is a direct drive combination in which a main marine diesel engine is connected with a direct shaft to drive a fixed-pitch propeller. As a result, the relationship between engine power, SFOC and engine speed will follow a cubic relationship or propeller law (Carlton, 2019), as can be seen in Fig. 3a. A significantly higher SFOC is normally observed during ship manoeuvring compared to ocean going conditions. This is largely because manoeuvring conditions generally occur when the engine speed or load is low, such that SFOC reaches the higher values, as can be seen clearly from Fig. 3a. The reason for higher SFOC at low engine speed or low engine load conditions may be due to the sub-optimum operation of the diesel engines, such as low fuel injection pressure, more leaking of fuel at fuel injection pumps, and low engine thermal efficiency during these conditions. In addition, during manoeuvring conditions, engine working conditions are continuously and instantaneously changed to adapt with the ship's practical requirements. This means diesel engines experience transient working conditions, which are known to promote SFOC (Zare et al., 2017).

Manoeuvring conditions consequently resulted in a large variation of engine power, engine speed, particulate matter and exhaust gas concentrations during these periods, as seen in Figs. S2, S3 and S4. The SO_2 and NO_x emission factors against engine load conditions can be seen in Fig. 3b. SO_2 emissions show a similar trend to SFOC in Fig. 3a and are proportional to fuel S content. SO_2 emission factors observed in Vessel I are slightly higher than that of Vessel II, although S content of Vessel I (2.94%) is slightly lower than that of Vessel II (3.13%). This may be due to SFOC being higher for Vessel I compared to Vessel II. NO_x emission depends on the combustion temperature inside the engine combustion chamber, and thus the emission of NO_x presented in Fig. 3b shows a dependence on engine loads, where low engine load during manoeuvring conditions generates less emissions. In comparison to Vessel I, NO_x emissions for Vessel II are significantly lower than that of Vessel I, perhaps due to the effect of MARPOL Annex VI NO_x emission requirements on Vessel II. This is because Vessel II was produced after 2000, making her subject to the "Tier I" NO_x rule of Annex VI, which requires NO_x emissions lower than the limit of 17 g/kWh at engine speeds less than 130 rpm. In comparison to the SO_2 and NO_x results available in the literature, the results of the present study are congruous with previous measurements. Winnes and Fridell (2010) conducted on-board measurements on a main engine using HFO (1.6% S), and found higher NO_x with increasing in engine loads, while lower SO_2 was observed. The same trends for SO_2 and NO_x are also observed in other studies (Cooper and Gustavsson, 2004; Entec UK Limited, 2002).

Higher emission factor values of CO and HC were observed at low engine load compared to high engine load conditions, as can be seen in Fig. 3c. This is because partial engine load conditions during manoeuvring can lead to incomplete combustion, which in turn leads to higher CO and HC compared to steaming conditions. Emission factors of CO and HC emitted from Vessel I were significantly higher than that observed in Vessel II, which may be due to the effect of engine age on engine emissions, where an older main engine was used in Vessel I when compared to Vessel II; thus more emissions are generated. Another reason that may contribute to higher CO and HC emissions at low load conditions is the lack of oxygen for combustion due to ineffective operation of the turbo-chargers for the main marine diesel engines at low engine speed conditions. It can clearly be seen in Fig. 3d that emission factors of O_2 were lower for decreasing engine loads. The fuel-dependent specific emissions of CO_2 show a higher value for Vessel I compared to Vessel II during manoeuvring conditions, as presented in Fig. 3d. This is most likely due to the higher SFOC of Vessel I compared to Vessel II, noting that the fuel carbon content of both HFOs used was almost identical as shown in Table S3. In comparison to the literature, an increase in CO and HC emissions under manoeuvring conditions compared to ocean-going conditions was also observed in previous studies (Agrawal et al., 2008a; Huang et al., 2018; Khan et al., 2013; Moldanová et al., 2013).

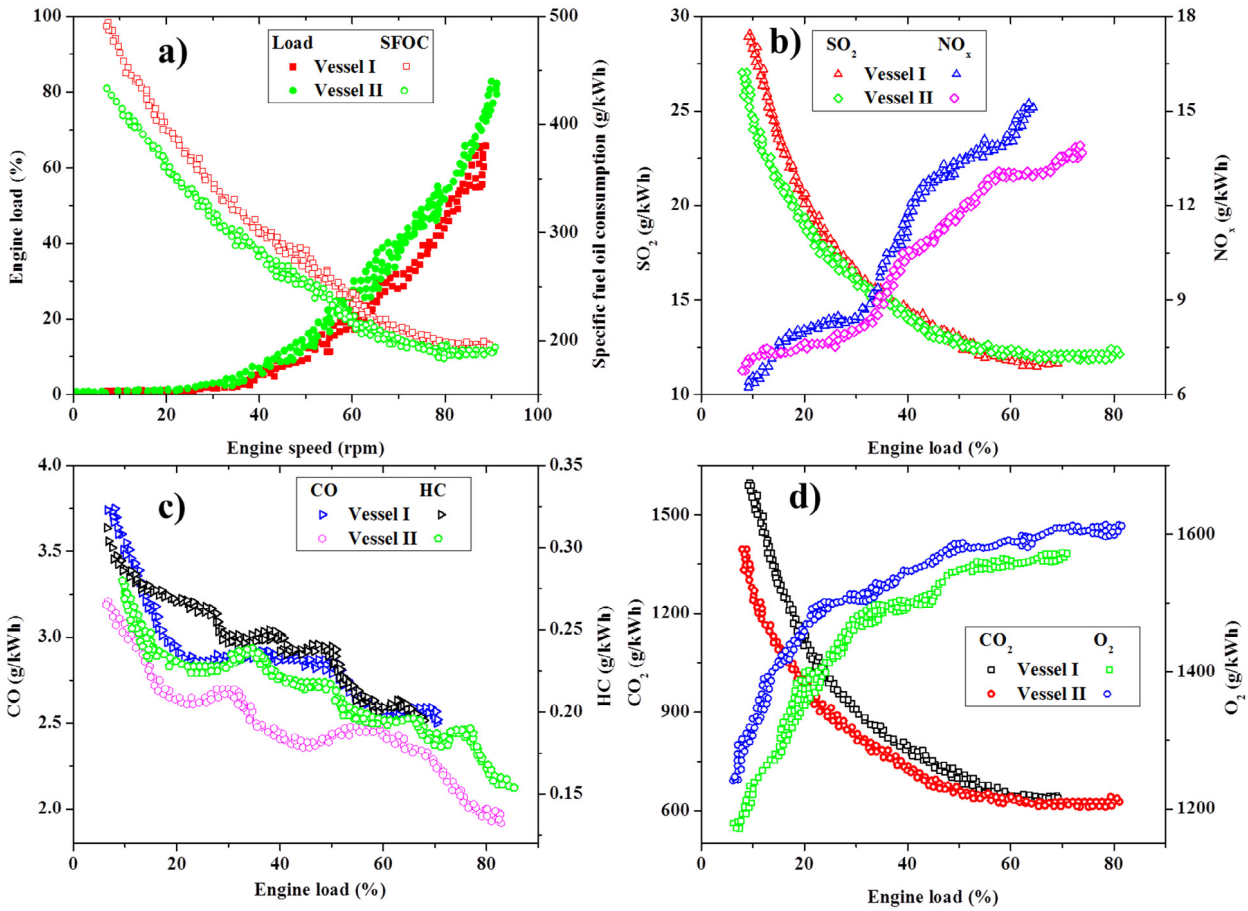

Fig. 3. Emission factors of NO_x, SO_2, CO_2, CO and HC in g/kWh from two vessels during manoeuvring conditions.

3.3. Particle emissions

In the literature, research on ultrafine and nanoparticles with respect to PN, and number size distributions emitted from HFO combustion-related marine engines operating during manoeuvring conditions is poorly investigated (Anderson et al., 2015). In this study, a DMS 500 was used to measure the particle number size distributions with a range of 5 nm to 1000 nm, while PM concentrations of PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ were measured by using a DustTrak™ through a dilution system with dilution ratios in the range of 13–20. Figs. S2 and S4 present total PN, nucleation and accumulation mode concentrations (#/cm^3), PM concentrations (mg/m^3), and count median diameter (CMD) of both nucleation and accumulation modes (nm) during manoeuvring conditions for the two measured vessels. Results showed that higher PN concentrations were generated in nucleation mode during transient diesel engine conditions compared to stable diesel engine load conditions. Emitted PN concentrations for Vessel I were dominated by nucleation mode particles, while PN mostly in the accumulation mode was found for Vessel II.

Fig. 4a shows the number and mass size distributions from the two measured vessels, including the standard deviation calculated for each size channel diameter, while Fig. 4b presents PN and PM emission factors against engine loads. The particle number size distributions observed in the case of Vessel II were unimodal with a peak at around 40–50 nm, while a bimodal number size distribution with a minor peak of 15–25 (nucleation mode) and a major peak of 50–60 nm (accumulation mode) were obtained from Vessel I during manoeuvring phases. In comparison with the literature, a bimodal size distribution for HFO, that is consistent with results observed for Vessel I, has been observed in previous studies (Anderson et al., 2015; Hallquist et al., 2013; Petzold et al., 2008). In particular, Anderson et al. (2015) observed a bimodal number size distribution with modes at 6–10 and 100–110 nm when running a marine diesel engine fuelled by HFO in a test-bed engine laboratory. The test rig study of Petzold et al. (2008) also found a bimodal number size distribution with modes of 15 and 50 nm from a 4-stroke marine diesel engine using HFO. The on-board measurements of Hallquist et al. (2013) showed a bimodal number size distribution with a major mode at 10 nm and the other at 30–40 nm. A uni-modal particle size distribution with a mode at around 50 nm, as observed in the Vessel II case, was also found both in test-bed measurements (Kasper et al., 2007; Lyyranen et al., 1999; Streibel et al., 2016), as well as in on-board measurements (Zetterdahl et al., 2016).

A number of factors could be contributing to the differences in the PN emissions for the two vessels. They may consist of the dilution system used, fuel sulphur content, engine characteristics and load conditions, all of which have a strong impact on PN emissions. In the present study, however, a two-stage dilution system, with the first stage heated, was used for both vessels. Moreover, fuel S contents (2.94 and 3.13% S), and engine characteristics and load conditions (2-stroke marine main engines working during manoeuvring conditions) were very similar. Therefore, the differences in the particle number size distributions between the two vessels during manoeuvring conditions observed in this study most likely may be due to the differences in the sampling point positions or/and engine age. In particular, the sampling point positions were placed directly after the turbo-charger of the main engine for Vessel II, while for Vessel I sampling was before the economiser, about 10 m from the main engine exhaust gas manifold. This distance may influence particle

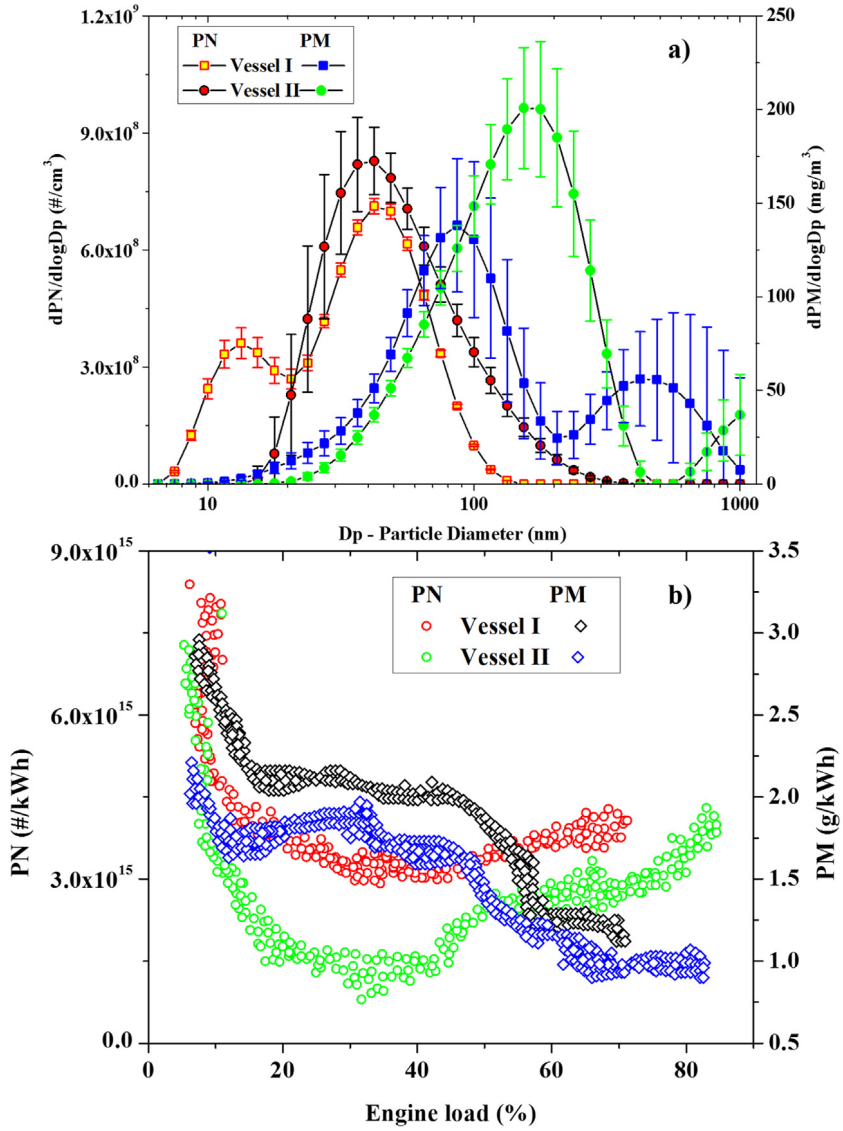

Fig. 4. (a) Particle number and mass size distributions of measured particles in the range of 5–1000 nm from main engines as the vessels are in manoeuvring conditions. Standard deviation was used to express the variation of measured data for both PN and PM emissions; (b) PN and PM emission factors against engine load conditions.

size by increasing the particle diameter, as shown in Fig. S2b for Vessel I compared to Vessel II in Fig. S4b. This can be explained by a previous study of Hallquist et al. (2013), who showed that initial real-world dilution conditions and plume ageing can reduce the concentration of nucleation mode particles by means of adsorption, condensation, or coagulation, which leads to a decrease in particle number in the nucleation mode. However, a smaller peak at 15–25 nm (nucleation mode) was also observed in Vessel I, as presented in Fig. 4. This volatile mode is most likely formed from sulphuric acid condensing and undergoing nucleation in the expanding plume (Petzold et al., 2008; Song et al., 2003). The availability of particles in nucleation mode observed in the case of Vessel I can also be clearly seen in Fig. S5, which presents the relationship between PN and PM concentrations for the two measured vessels.

In addition to the difference in sampling positions, differences in engine age and technology should not be ignored when considering the differences in the particle number size distributions between the two vessels during manoeuvring conditions. Specifically, the main engine used in Vessel I is more than 20 years older than that of Vessel II. A previous study on heavy-duty diesels stated that ultrafine and fine PM emissions generally increased with vehicle age (Robert et al., 2007). One reason for the reduction of PM in newer diesel engines is their improved diesel injection systems. These higher injection pressure systems produce a smaller atomisation diameter and therefore more complete combustion. Therefore, the effect of engine age on particle number size distributions in this study should be taken into account as an important factor. However, it may not be possible to provide a full explanation at this stage of the engine age effects and further investigation is needed in this area. Fig. 4b shows a clear effect of engine load on PM emissions, but not for PN emissions. Increasing engine load mostly resulted in lower PM emission factors on a g/kWh basis. For the PN case, PN emissions were observed to be at high values for both low and high engine load conditions. In conclusion, higher PN and PM emissions are strongly associated with manoeuvring conditions in which the engine normally operates in sub-optimum conditions. The relationship between PM and NO_x concentrations for the two vessels was presented in Fig. S6. For the same NO_x value, more PM is emitted from Vessel I compared to that of Vessel II, which may

be due to use of an older engine in the former vessel compared to the later one.

In order to compare results from this study and previous studies found in the literature, including on-board measurements, test-bed measurements and ship plume measurements, Table 2 is presented. Measured emission results of these studies were used to plot Fig. 5a and b that indicate the relation between the sulphur content of the fuel used and emission factors of PM in g/kWh and PN in #/kg fuel consumed, respectively. Thus, these important emission factors measured at different stages of exhaust emission evolution can be compared. Fig. 5a shows that PM emissions increase with an increase in fuel sulphur content, while the dependence of PN emission factors on fuel sulphur content is unclear. There is also a large variation of particle number emission factors, which is likely due to limited available data on PN and differences in fuel used, engine modes, working conditions and instruments used for PN measurement (Hallquist et al., 2013). A previous on-board measurement study by Winnes et al. (2016) indicated that other fuel characteristics, such as polycyclic aromatic hydrocarbons (PAH), metals, ash content and viscosity, rather than the fuel sulphur content, have a large influence on ultrafine particle formation. However, a recent study conducted by Chu Van et al. (2018) found a strong impact of fuel sulphur content, which caused an increase in PN, PM and sulphate fraction in particles. This illustrates the important role of IMO regulations in limiting marine fuel S content to reduce ship emissions.

Different methods used for PM measurements from on-board, test-bed and ship plume studies are presented in Table S6. PM emission factors in g/kWh from these studies were used to plot Fig. S6. The figure shows PM emission factors from on-board measurements, test-bed measurements and ship plume measurements, with different PM measurement methods used against sulphur contents of fuel. It can be observed that different measurement methods are scattered across the range of measurements in Fig. S6. No significant difference in the different methods used for measuring PM emissions is observed, presuming confidence in the reliability of all instruments used. It should be noted that due to the wide variation of published BC emission factors, the International Council on Clean Transportation (ICCT) has recently funded studies that have looked at the impacts of instrument variation on PM measurements. Overall, results found good agreement between different BC measurement methods (ICCT, 2016).

4. Conclusion

In order to improve the limited knowledge available regarding marine engine emissions, especially for particle number size distributions, an on-board measurement campaign on two commercial vessels operating on the east coast of Australia was conducted during manoeuvring conditions. Emission factors for both particulate matter and gaseous emissions against engine load conditions have been investigated. In addition, based on the results of previous studies, the effect of fuel sulphur content on particle mass and number concentration was evaluated to assess the effectiveness of IMO Annex VI regulations on sulphur content of marine fuels. Results showed that significant differences observed in particle number and mass size distributions are most likely due to the difference in the position of sampling points arranged in the two measured vessels or/and the age of the main marine diesel engine. Particle size distributions for Vessel II were unimodal with a peak at 40–50 nm and dominated by ultrafine particles, while those for Vessel I were bimodal with a smaller peak at around 20 nm and a major peak at larger diameter of 60 nm, which has more influence on PM. Manoeuvring conditions also resulted in high levels of emissions for pollutants, such as CO, HC, PM and PN, compared to ocean-going modes. Such a high level of pollutants from ships during manoeuvring conditions may significantly contribute to air pollution in coastal and port areas, and consequently has negative impact on human health.

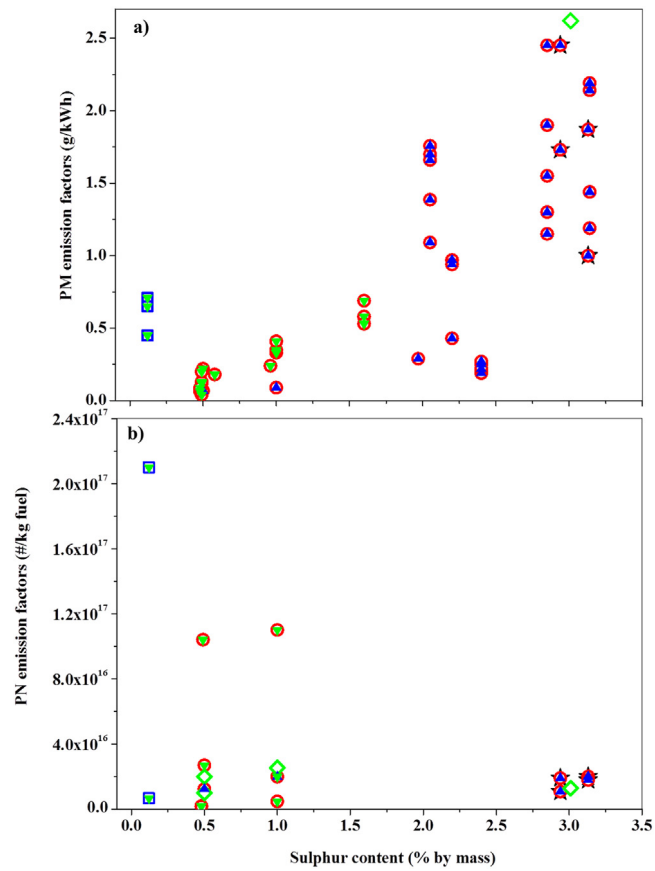

Fig. 5. (a) PM emission factors in g/kWh; (b) PN emission factors in #/kg fuel from on-board measurements, test-bed measurements and ship plume measurements against sulphur contents of fuel used in % by mass.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2019.10.001.

Table 2
This study and previous ship emission measurements found in the literature.

	On-board measurements	Test-bed measurements	Ship plume measurements[a]
2-stroke engines	This study Agrawal et al. (2008a) Agrawal et al. (2008b) Fridell et al. (2008) Khan et al. (2013) Moldanová et al. (2009) Winnes et al. (2016)		Jonsson et al. (2011) Murphy et al. (2009) Lack et al. (2009)
4-stroke engines	Entec UK Limited (2002) Hallquist et al. (2013) Moldanová et al. (2013) Winnes and Fridell (2010) Winnes and Fridell (2012) Winnes et al. (2016) Zetterdahl et al. (2016)	Anderson et al. (2015) Streibel et al. (2016)	

[a]No information regarding ships' engine types (for example: 4-stroke or 2-stroke engines).

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