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Emissions from a marine auxiliary diesel engine at berth using heavy fuel oil

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Abstract

This study presents an emission measurement campaign on commercial ships plying the east coast of Australia. Detailed investigation of engine performance and emissions from main and auxiliary marine diesel engines using heavy fuel were undertaken. Marine diesel engine gaseous (O_2, CO, CO_2, SO_2 and NO_x) and particle number and mass emissions were measured using research grade instrumentation. The measurements were performed in October and November 2015 on two large cargo ships at berth, manoeuvring and during travel between the ports of Brisbane, Gladstone and Newcastle. Detailed measurements on an auxiliary engine at berth are analysed in this paper, and include engine power and RPM, fuel oil consumption, exhaust gas temperature and exhaust particle and gaseous emissions. It was found that some ship emissions were up to several orders of magnitude higher than corresponding land-based diesel emission levels. Significant variations in emissions were also related to fuel sulphur content and engine load.

Introduction

Increasing diesel engine brake power, and reducing brake specific fuel oil consumption, exhaust gas and noise emissions occur by turbocharging a diesel engine, which is popular in many applications, including road, non-road, marine and industry [1]. For land-based applications, turbocharging has been incorporated into the engine design carefully, so as not to adversely affect emissions because of the strict framework for emission control including EURO and TIER used in the EU and USA, respectively. However, for marine applications the main motivation for turbocharging has been reduction in fuel consumption alone. Consequently, marine diesel emissions are an emerging issue and have become of global concern over the last decade.

Ship emissions, including gases and particulate matter (PM), have negative effects on both the environment and public health [2-6]. Physical and chemical characteristics of diesel particulate matter (DPM), and its respiratory health effects have been investigated by Ristovski [5]. Particle number (PN) and mass from diesel engines using both diesel fuel and marine gas oil (MGO) have also been investigated and compared [7]. Corbett et al. (2007) estimated that shipping-related PM2.5 emissions are the cause of approximately 60,000 deaths per year associated with cardiopulmonary and lung problems annually around the world [6]. Therefore, quantitative and qualitative estimation of pollutant emissions from ships and their distribution are becoming more important [4]. However, a very limited number of on-board measurement studies have been undertaken [4, 8] it investigates this problem.

Heavy fuel oil (HFO), which contains many impurities including sulphur and metal, is used by almost all medium and larger ships owing to its cost-effectiveness [3]. Corbett (2003) has estimated that the yearly amount of fuel consumption was almost 290 million tonnes globally, in which approximately 80% of fuel consumed by the world ship fleet was HFO. HFO is the main fuel for 95% of 2-stroke low-speed main engines and 70% of 4-stroke medium-speed engines [9]. This makes ship emission-related issues more critical, especially in port environments [10]. This study aims to investigate heavy fuel oil auxiliary marine diesel engine emissions during constant revolution conditions and load acceptance.

Ship Emission On-Board Measurement Campaign

An 11-day measurement campaign was performed in October and November 2015 on two large cargo ships of CSL shipping company at Ports of Brisbane, Gladstone and Sydney. The work was a collaboration of the Australian Maritime College (AMC), Queensland University of Technology (QUT), and Maine Maritime Academy (MMA). The first on-board measurements were performed on Vessel I from 26th to 31st of October, 2015 when she was running from Port of Brisbane to Port of Gladstone. The second measurements were conducted on Vessel II from 3rd to 6th of November, 2015 in her voyage from Gladstone to Newcastle. All measurements have been carried out on both main and auxiliary engines of the two ships for different ship operating conditions, such as at berth, manoeuvring, and at sea.

Measurements presented in this paper were performed on the auxiliary engine data from Vessel II while she was at berth. Instruments were arranged on a deck high up in the machinery room and the exhaust gas was sampled continuously from a hole cut in the exhaust pipe after the turbocharger of auxiliary engine No.1. The details of the measured engine can be seen in Table 1. At the sample point, one hole was created for the present measurements by a Testo 350XL and a DMS 500. The schematic diagram of sampling setup is shown in Figure 1. Data on engine power, engine revolution, fuel oil consumption, and exhaust gas temperature were measured by the ship's instrumentation. Characteristics of HFO used are presented in Table 2. The measurement procedure followed ISO 8178 standard [11, 12].

Table 1 Technical parameters of Main Diesel Generator.

MAIN DIESEL GENERATOR			
AUXILIARY DIESEL ENGINE		**GENERATOR**	
Type	Four-stroke, trunk piston type marine diesel engine with exhaust gas turbo charger and air cooler	Type	Protected drip proof type (FE 41A-8)
Output	425 kW	Output	531.25 kVA x 450V x 60 Hz x 3Φ
Revolution	900 RPM	Revolution	900 RPM
Max Combustion Press	165 bar		
Mean Effective Press	16.7 bar		
No. Cylinder	4		
Cylinder Bore x Stroke	200 x 280 mm		
Maker	Wartsila Diesel Mfg Co., Ltd	Maker	Taiyo Electric Co., Ltd

The Testo 350XL was calibrated on 10th, August 2015 by the Techrentals Company and was used to measure gaseous emissions. Particle number size distributions in the size range 5 nm – 1.0 µm in the hot exhaust gas were analysed with a time resolution of 10 Hz (0.1 s) using a DMS 500 MKII – Fast Particulate Spectrometer with heated sample line, and build in dilution system (Cambustion). All auxiliary engines used on board ships work at load characteristic. This means that a marine diesel engine is working at a constant speed while the torque load is varied. Engine load depends on electric loads of electric equipment of ship. In this case, we investigated exhaust emissions at different engine loads, including 0, 24, 35, 55, 70, 83, and 95% load by means of alternating the load between two auxiliary engines. This can be seen in Figure 2.

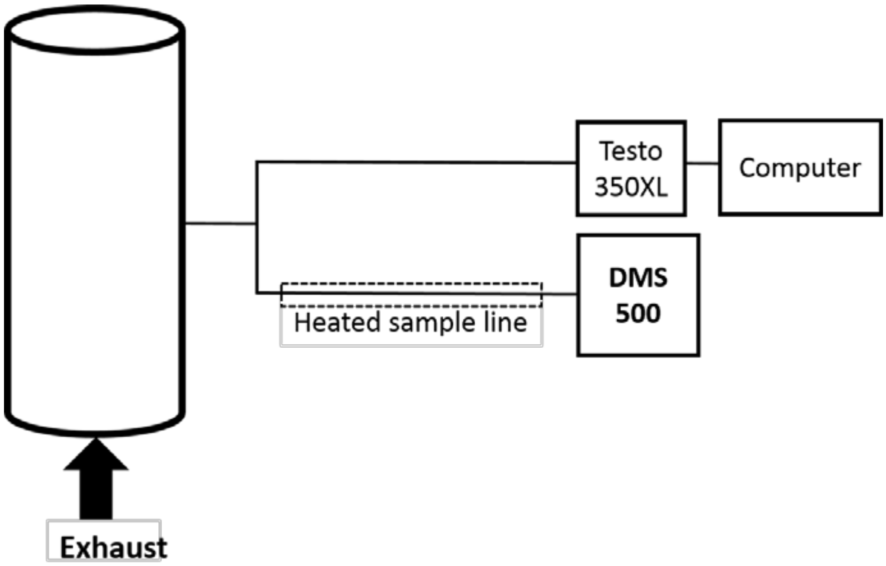

Fig. 1 The schematic diagram of exhaust emission sampling setup

Table 2 Main chemical composition and physical properties of HFO.

Parameter	Units	Method	Bunker receipt	Laboratory
Density at 15^0 C	kg/m^3	ISO 3675	986.2	-
Viscosity at 50^0 C	mm^2/s	ISO 3140	377	-
Micro - carbon residue	% mass	ISO 10370	14.65	-
Sulphur (S)	% mass	ISO 2719	3.13	-
Carbon (C)	% mass	AR 2816	-	88.14
Hydrogen (H)	% mass	-	-	-
Nitrogen (N)	% mass	AR 2816	-	0.68
Ash	% mass	ISO 6245	0.064	-
Vanadium (V)	mg/kg	IP 501	141	-
Nickel (Ni)	mg/kg	IP 501	34	-
Asphaltenes	% mass	IP 143/D6560	7.42	-

Results and Discussion

The emission ratios (ERs) were calculated using the co-emitted CO_2 (g of emissions/g of CO_2) and used to express the emission data. Such an approach does not require the instantaneous engine fuel consumption to be known. This is particularly helpful for the auxiliary engine used in this case because the engine load could not be held perfectly constant. It should also be noted that ERs do not require knowledge of the fuel properties.

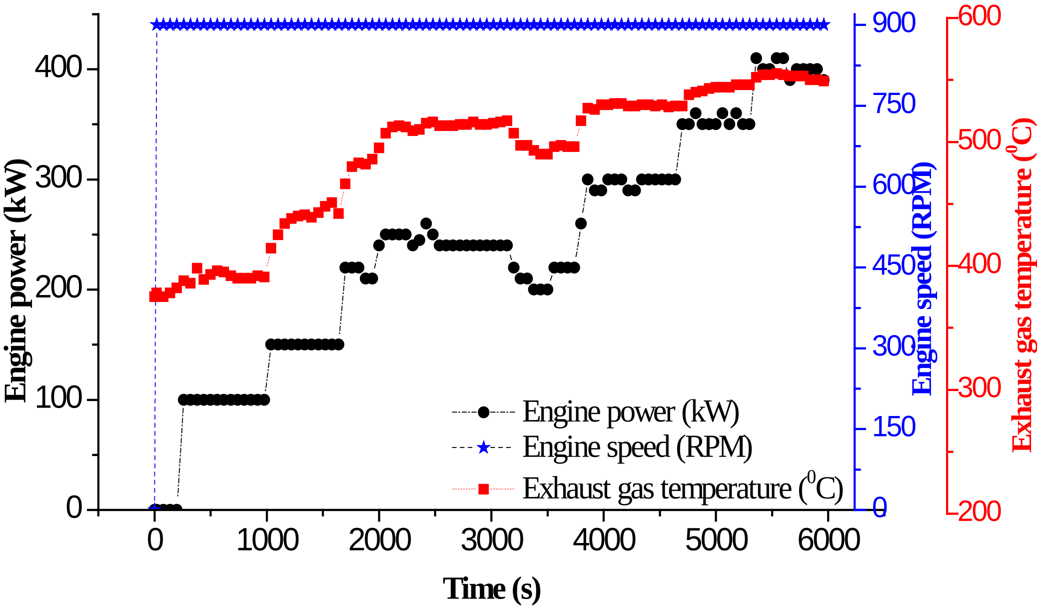

Fig. 2 Auxiliary engine (at berth) speed, power output and exhaust gas temperature with time

The relationship of gaseous ERs with engine power in percentage of full load is shown in Figures 3a, 3b, 3c and 3d. Generally there is a significant relationship between the ERs and engine load, except for SO_2 emissions in Figure 3c. This is because sulphur emissions are directly related to fuel sulphur levels which do not change during the operation of the engine. There was an initial peak in CO concentration at start-up in cold start period – which can be seen in Figure 3a. This is due to the cold start of the engine and the low engine load condition, which leads to incomplete combustion and contributes to carbon monoxide reaching its highest level. CO concentration then significantly decreases and reached a stable value when the engine load was at a high level. If the engine test was repeated at warm up condition ERs of CO/CO_2 at 0 and 25% load would most likely be smaller than that in the cold start.

A decreasing trend of O_2 emissions with power was observed in Figure 3b. This may be due to the engine revolution being constant, which makes the amount of air stable while the engine load is increased. Thus, more fuel is required and a rich fuel-air mixture combustion condition is reached. The SO_2 and CO_2 emissions in Figure 3c are generally proportional to the fuel carbon and sulphur content, and therefore the ER of SO_2/CO_2 seems to be constant as was expected. The theoretical and measured curves of the ER of SO_2/CO_2 had a difference in value of 20 – 25%. This difference is likely to arise from a combination of combustion and measurement issues including not all the Sulphur in the fuel being converted to SO_2 and the high levels of Sulphur in the exhaust gas being at the far end of the Testo instrument range. Of most interest in this study is the ER of SO_2/CO_2 which is significantly higher than that in the research of Agrawal [8] and Cooper [13], as a result of higher sulphur content fuel used in this research (3.13 % mass). Their fuel sulphur contents were 2.05 and 2.2% by mass, respectively. The emission of NO_x will depend on the engine temperature, and thus the ER for NO_x presented in Figure 3d shows a dependence on engine load in which high engine load produces the highest temperature and therefore the highest emission. However, the ER of NO_x/CO_2 was much lower than that of compared studies. This may be due to differences in engine types and working conditions.

For particle emissions, PN and PM ERs in Fig 3e and 3f were observed at a high level at low and medium engine load working conditions, especially at the cold start of the engine compared to the high load condition. However, these values then significantly dropped at higher engine loads. The

ER of the PM in this study was significantly smaller than that of compared studies. Available data concerning PN is extremely limited to just a few papers as shown in Figure 3.

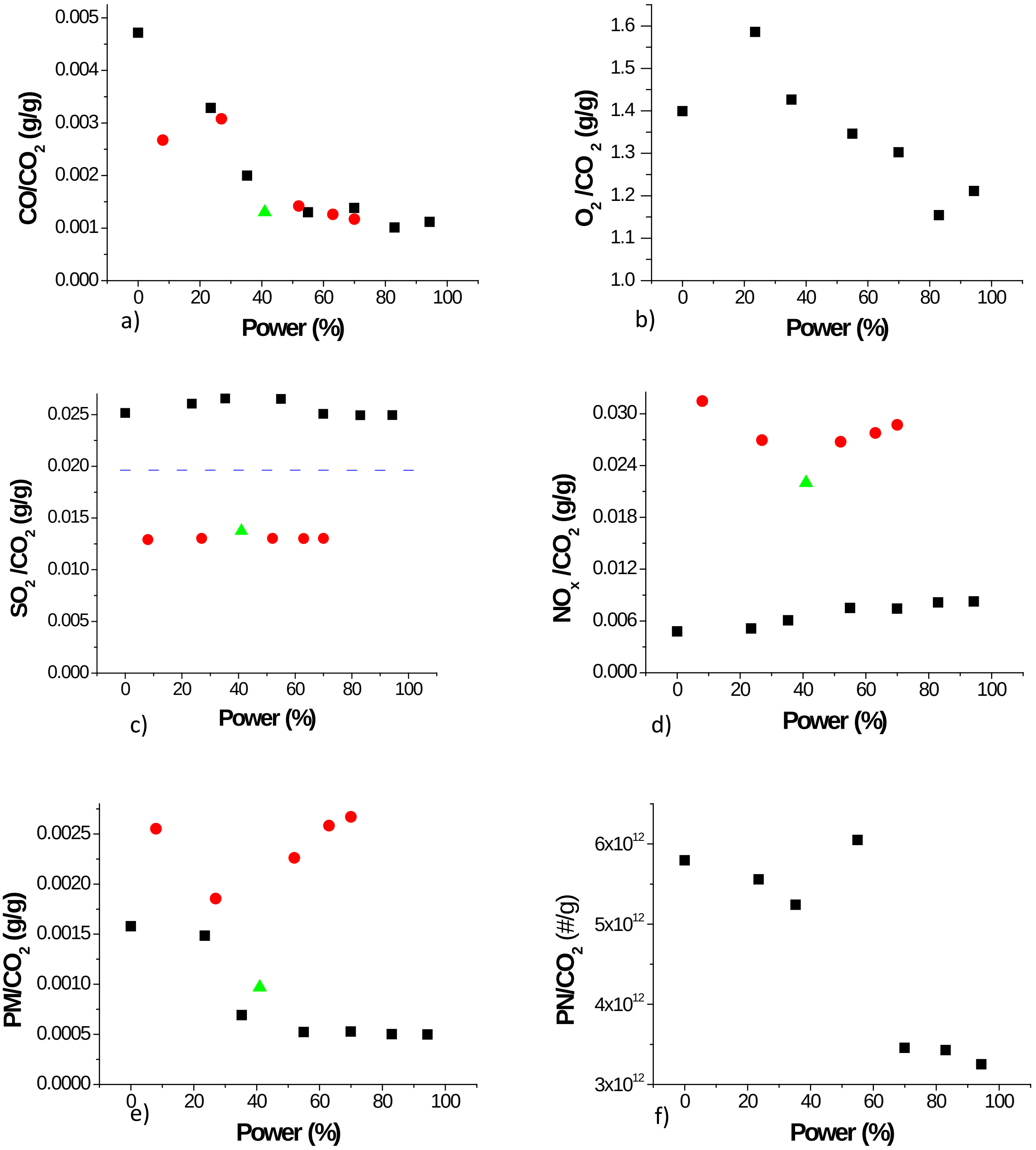

Fig. 3 Auxiliary engine at berth emission ratios of a) CO, b) O_2, c) SO_2, d) NO_x, e) PM, and f) PN (g/g AND #/g CO_2) with engine power. ■ this study, ● Agrawal 2008 [8], ▲Cooper 2003 [13]. The dashed line in Figure 3c illustrates the theoretical curve of gSO_2 /gCO_2 according to the fuel sulphur and carbon content.

Conclusion

To improve the limited knowledge regarding marine engine emissions, a measurement campaign on two commercial ships plying the east coast of Australia was conducted and has been described. Engine performance and emissions (gaseous and particle) of an auxiliary engine while in berth, were measured on-board the ship during actual harbour stopovers. The ERs (g of emissions/g of co-emitted CO_2) were used to present the emission data. From cold start exhaust emissions experienced a high level when compared to the stable working condition and were closely related to the fuel sulphur level.

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