ANALYSIS OF MARINE DIESEL ENGINE EMISSION CHARACTERISTICS UNDER BENCH TEST CONDITIONS IN CHINA

Zhongmin Ma[a] (Master, Lecturer)

Peiting Sun[a] (Doctorate, Professor)

Shulin Duan[a] (Doctorate, Professor)

Hui Xing[a] (Doctorate, Associate professor)

Hongfei Qu[a] (Bachelor, Associate professor)

Kai Wang[a] (Doctorate, Associate Professor)

[a] Dalian Maritime University, Dalian, 116026, China

(Corresponding author: mazhongmin1090@163.com)

Abstract

In order to accurately evaluate air pollution caused by ships, two main methods are usually used for calculation, such as, the method based on ship fuel consumption (top-down approach) and the method based on ship activities (bottom-up approach). Both of the methods require accurate diesel engine emission factors. If the underlying data is not accurate, the assess results will significantly depart from actual conditions and mislead policy decisions. In this paper, the emission characteristics of NOx, CO, CO_2 and THC from 198 domestic marine diesel engines were investigated under bench test conditions by standard emission measurement system which conformed to the requirements of the International Maritime Organization (IMO). The emission factors of marine diesel main engine (ME) and auxiliary engine (AE) were analyzed statistically. The ME's and AE's fuel-based emission factors and energy-based emission factors are given in detail and compared with the reference data given by IMO. The energy-based emission factors for different types of diesel engines are closely related to the diesel engine load, and the relationship between them can be expressed by quadratic polynomial or power function. In addition, the emission factors for marine high-speed engines are illustrated in detail. The results of this paper can provide valuable data for the estimation of waterway transportation exhaust emissions, emission regulation revise and comprehensive understanding of the emission characteristics of marine diesel engines.

Keywords: Fuel-based emission factor; Energy-based emission factor; Ship emissions; Specific emission

1. Introduction

Shipping not only brings great economic benefits to the global development, however, it also emits harmful substances into the atmosphere, which causes environment problems that have aroused widespread concern [1-3]. The ship emissions have always been considered as one of the important air pollution sources in port cities and inland river areas, which have brought serious negative effects on global climate and human health [4-6]. Therefore, more and more people pay attention to the ship emissions in recent years [7-9], and study the ship emission characteristics. At present, there are two main research methods for estimation ship exhaust emission: top-down approach based on ship fuel consumption and bottom-up approach based on ship automatic identification system (AIS) [10]. Both methods need to obtain effective emission factors. Currently, some international organizations or research institutions have provided emission factors for reference, such as the IMO, IPCC, USEPA and LR and so on. In addition, some researchers have also done more in-depth research on emission factors. Cooper et al. [11] tested the emission factors of 22 marine auxiliary engines from 6 ships at berth, and obtained the emission factors of NO_X, CO, THC, CO_2, SO_2 and PM. Chu-van et al. [12] tested a cargo ship exhaust emission, and gave the emission factors under different sailing conditions. Fu et al. [13] and Yin et al. [14], respectively took the freight ships in the Grand Canal as the research object and carried out a shipboard test on the emission factors of inland river transport ships in China, and preliminarily formed the emission factors of inland river ships under different operating conditions with the power under 300kW. Peng et al. [9] and Huang et al. [15] used portable equipment to measure the emission factors of the marine diesel engines, and gave the emission factors under different sailing conditions. In terms of the research status in China, although the research on the emission characteristics of Marine diesel engines is more in-depth, the emission test data is generally less, and it is difficult to provide sufficient data support for the establishment of emission inventory in China. Many scholars generally adopted foreign emission factors when studying the emission inventory of ships in coastal areas of China [16-19].

In this paper, 198 marine diesel engines manufactured in China were tested under bench test conditions. The fuel-based emission factors and energy-based emission factors were analyzed statistically, aiming to reveal and master the emission characteristics of ocean-going and inland river ship diesel engines.

2. Methodology

2.1 Emission measurement system and test bench

The HORIBA MEXA 1600DSEGR exhaust analyzer is mainly used for emission testing, which can obtain the contents of NO_X, CO_2, CO, THC and O_2 in exhaust. The measurement equipment is mainly composed of the following detection modules: Chemiluminescent detector (CLD) for NO_X, Non-dispersive infrared analyzer (NDIR) for CO_2 and CO, Heated flame ionization detector (HFID) for THC, and Paramagnetic detector (PMD) for O_2. In order to ensure the test results' accuracy, the test is usually carried out on a standard test bench, as shown in Figure 1.

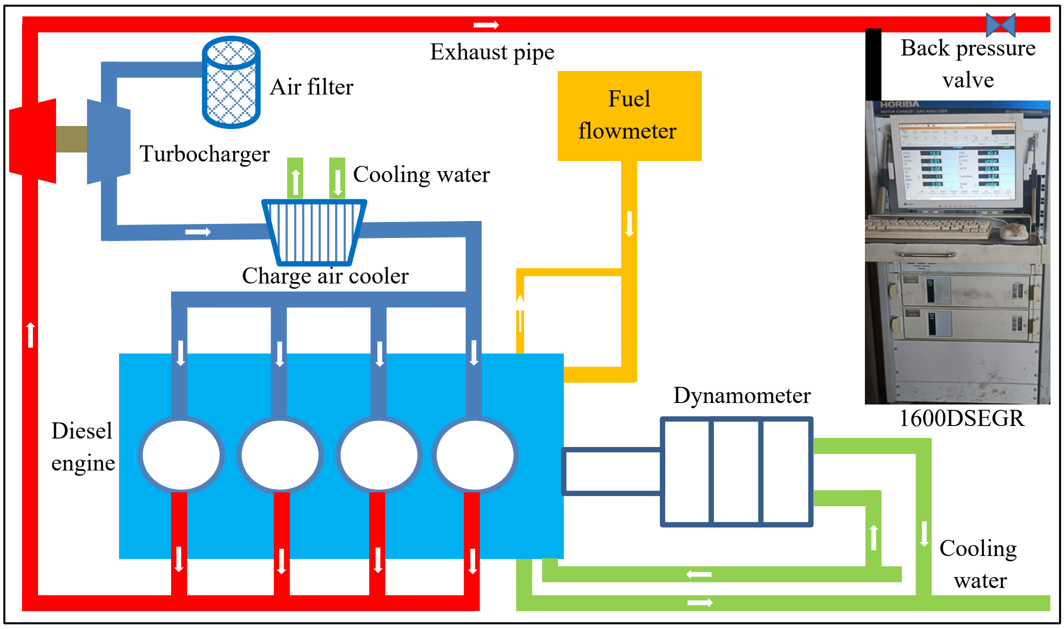

Figure 1. Schematic diagram of diesel engine bench emission test

2.2 Test engines

In this paper, a total of 198 marine diesel engines were tested under bench test conditions and analyzed statistically. According to the statistical results, the slow-speed diesel (SSD) power range was between 4320 kW and 26000kW, and the speed range was between 67.6 rpm and 120rpm. The medium-speed diesel (MSD) power range was between 330 kW and 4500kW, and the speed range was between 600rpm and 1000rpm. The high-speed diesel (HSD) power range was between 130 kW and 1816kW, and the speed range was between 1000rpm and 2425rpm. All tested diesel engines were completely able to meet the IMO NOx Tier II emission standard, which was executed since January 2011, and more stringent rule of Tier III in ECAs was executed from January 2016.

2.3 Emission factor calculation method

The fuel mass flow rate and engine power can be measured during the diesel engine emission bench test. The mass flow rate of individual exhaust gas component can be calculated according to carbon balance method [20,21]. The fuel-based emission factor and energy-based emission factor and can be calculated based on the above conditions. The calculation method is as follows:

$$EF^{f} = \sum_{i=1}^{n} Q_{mags,i} \cdot W_{F,i} / Q_{mf,i} \tag{1}$$

$$EF^{e} = \left(\sum_{i=1}^{n} Q_{mags,i} \cdot W_{F,i}\right) / \left(\sum_{i=1}^{n} P_i \cdot W_{F,i}\right) \cdot 10^3 \tag{2}$$

where: EF^f: fuel-based emission factor(kg/t-fuel); Q_{mags}: emission mass flow rate of individual gas (kg/h); Q_{mf}: fuel flow rate(t/h); W_F: weighting factor; i: test power point; EF^e: energy-based emission factor (g/kW•h); P: power of each test load point (kW).

2.4 Fuel information

The fuel used in all the bench tests was diesoline. According IMO NO_X technical code, the fuel was sampled and sent to a special testing institution for elemental analysis after each test. Elemental analysis included carbon(C), hydrogen(H), oxygen(O), nitrogen(N), sulfur(S). According to the analysis report, C, 85.22~86.83%; H, 12.47~14.12%; N, 0.01~0.41%; O, 0.02~0.77% and S, 0.00~0.19%.

3. Results and discussion

3.1 Fuel-based emission factors

The fuel-based emission factor of NO_X, CO, CO_2 and THC of each type of diesel engine can be calculated according to formula (1), as shown in Table 1. As it can be seen from Table 1 that the NO_X fuel-based emission factors are all smaller than baselines given in the IMO research report. The slow-speed and middle-speed ME NOx fuel-based emission factors are 5.79% and 7.86% lower than the baseline values respectively. And the medium-speed and high-speed AE NOx fuel-based emission factors are 19.34% and 18.09% lower than the baseline values respectively. The CO fuel-based emission factors are all higher than baselines. For the ME, the

CO fuel-based emission factors are 55.23% and 11.95% higher than baselines. And for the AE, the CO fuel-based emission factors are 29.53 and 105.88% higher than baselines. The CO_2 fuel-based emission factors are all lower than baselines. In this paper, the carbon conversion rate is between 97.27% and 98.65%. The THC fuel-based emission factors are either higher or lower than baselines, without obvious rule.

Table 1 Fuel-based emission factor (kg/t-fuel)

Eng speed/ type	EF^f_{NOx}			EF^f_{CO}			EF^f_{CO2}			EF^f_{THC}		
	x±s [1)]	n [2)]	Base-line [10]	x±s	n	Base-line	x±s	n	Base-line	x±s	n	Base-line [3)]
SSD-ME	69.48± 8.17	27	73.75	4.30± 2.49	27	2.77	3163±30	27	3206	1.23± 0.44	26	3.08+ 0.06
MSD-ME	45.11± 2.82	22	48.96	2.81± 1.23	22	2.51	3119±21	21	3206	2.25± 0.86	22	2.33+ 0.05
HSD-ME	35.40± 4.03	46	na	3.98± 2.79	49	na	3140±21	47	na	1.23± 0.90	46	na
MSD-AE	37.41± 4.09	35	46.38	3.09± 1.14	33	2.38	3118±24	35	3206	2.87± 1.17	34	1.76+ 0.04
HSD-AE	27.81± 5.91	59	33.95	4.90± 2.91	59	2.38	3142±21	55	3206	1.31± 0.90	56	1.76+ 0.04

1) x represents the mean, and s represents the standard deviation; 2) n represents the number of samples; 3) EF^f baseline including: NMVOC baseline before + and CH_4 baseline after +.

In addition, the emission characteristics of different diesel engines under different loads are studied. It can be seen from Figure 2 and 3 that the CO_2 fuel-based emission factors depend on the fuel carbon content and are independent of diesel type and load. Therefore, if the shipping industry continues to use petroleum fuels, it will be difficult to achieve the ambitions of the initial IMO strategy, which are to reduce the carbon intensity of international shipping by 70% and the total annual GHG emissions by at least 50% by 2050, compared to 2008 [22].

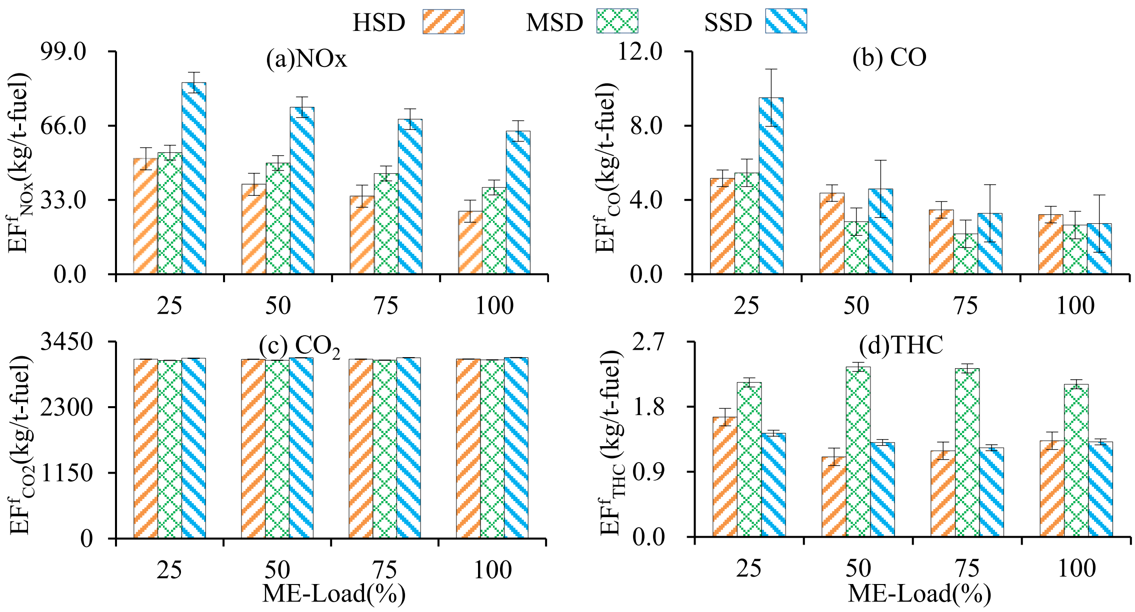

Figure 2. ME's fuel-based emission factors under different load

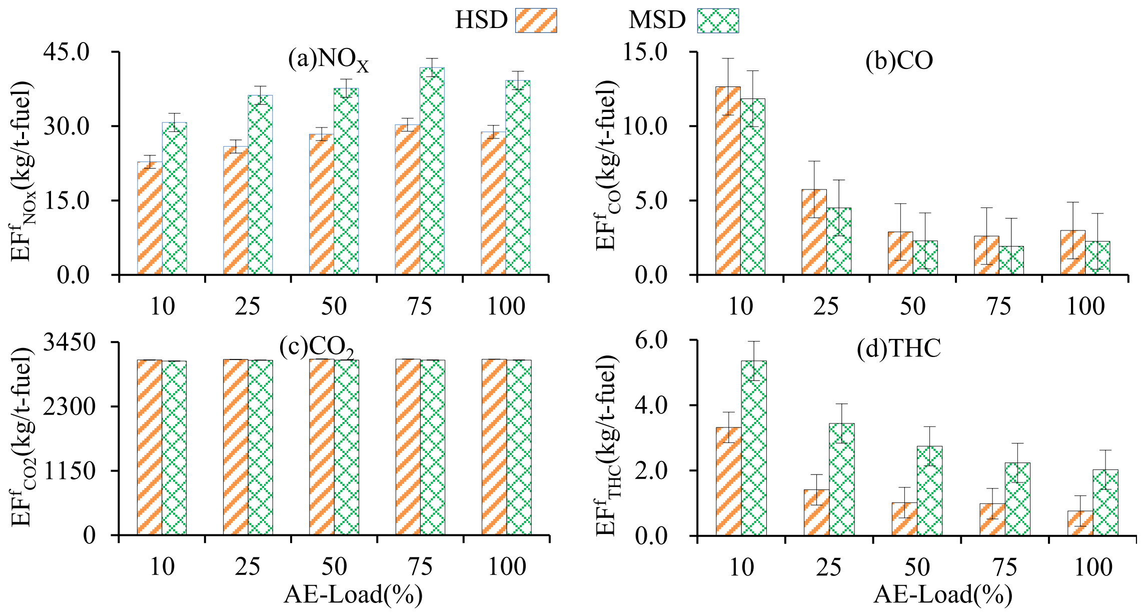

Figure 3. AE's fuel-based emission factors under different load

3.2 Energy-based emission factors

Based on individual exhaust gas mass flow rate and each test load point power of marine diesel engine, the energy-based emission factors of NO_X, CO, CO_2 and THC can be calculated according to formula (2), as shown in Table 2.

Table 2 Energy-based emission factor (g/kW•h)

Eng speed/ type	EF^e_{NOx}			EF^e_{CO}			EF^e_{CO2}			EF^e_{THC}		
	x±s [1)]	n [2)]	Base-line	x±s	n	Base-line	x±s	n	Base-line	x±s	n	Base-line[3)]
SSD-ME	11.38 ±1.22	27	14.38	0.61± 0.30	27	0.54	532.90 ±11.89	27	607	0.22± 0.05	24	0.60+ 0.01
MSD-ME	8.91± 0.53	21	10.53	0.55± 0.32	23	0.54	636.69 ±12.79	20	670	0.46± 0.18	22	0.50+ 0.01
HSD-ME	6.96± 0.87	47	na	0.78± 0.57	49	na	659.20 ±24.76	50	na	0.25± 0.18	46	na
MSD-AE	8.17± 0.80	35	10.53	0.55± 0.23	34	0.54	662.31 ±19.36	35	707	0.56± 0.22	34	0.40+ 0.01
HSD-AE	6.31± 0.91	56	7.71	0.76± 0.37	56	0.54	687.28 ±40.40	59	707	0.22± 0.13	54	0.40+ 0.01

1) x represents the mean, and s represents the standard deviation; 2) n represents the number of samples; 3) EF^e_{THC} baseline consists of two parts: NMVOC baseline before + and CH_4 baseline after +.

Table 2 shows that the NO_X energy-based emission factors are all within the IMO Tier II limit and lower than the baselines [10]. The ME NO_X energy-based emission factors are 15.38% to 20.86% less than the baselines, and the AE NO_X energy-based emission factors are 18.16% to 22.41% less than the baselines. The CO energy-based emission factors are 1.85% and 40.74% higher than the baselines. The CO_2 energy-based emission factors are between 87.79% and 97.21% of the baselines. The THC energy-based emission factors are either higher or lower than baselines, without obvious rule. For different type of diesel engines, the energy-based emission factors at each test load point are calculated and averaged. The relationship between engine load and energy-based emission factors is shown in Figure 4 and 5.

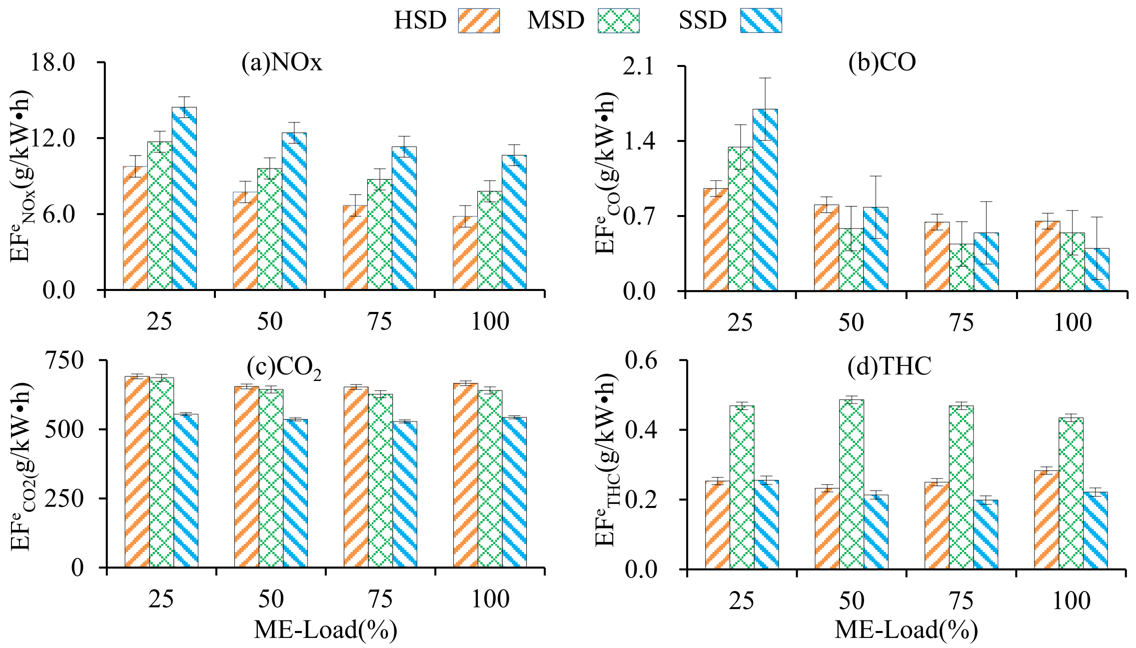

Figure 4. ME's energy-based emission factors under different load

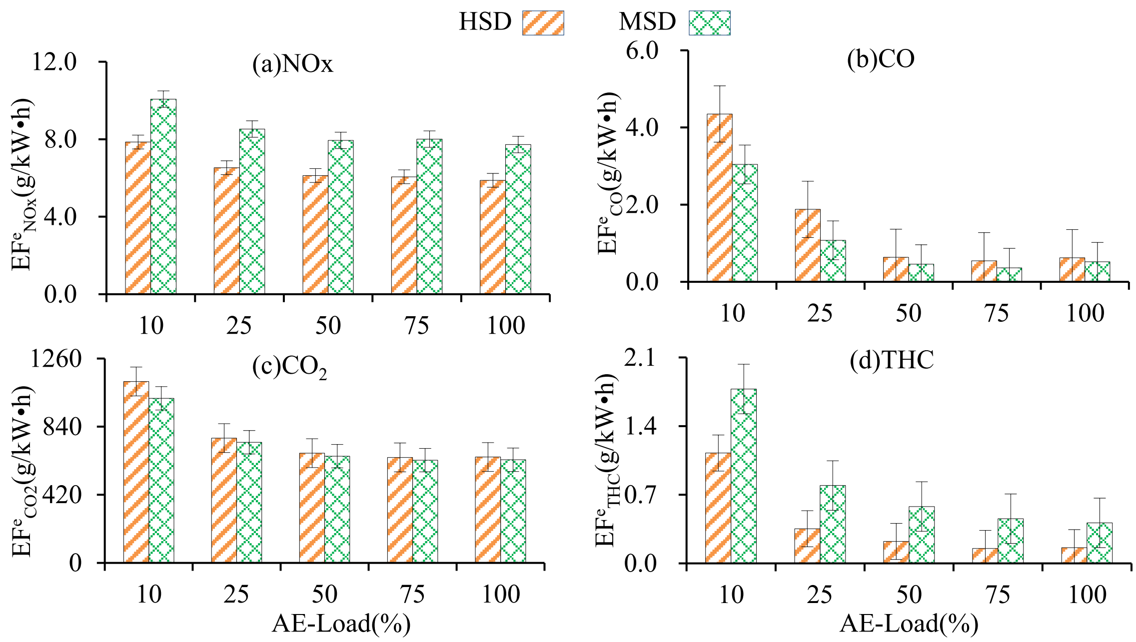

Figure 5. AE's energy-based emission factors under different load

Figure 4 and 5 show that the energy-based emission factors are closely related to the diesel engine type and load. The diesel engine operated under low load will lead to a higher NOx energy-based emission factor. This is because when the diesel engine works at low load, the amount of fuel injection per cycle is reduced, but the oxygen content in the cylinder is increased, thus promoting the generation of NOx. Similarly, under 10% load, the AE CO and THC energy-based emission factors are obviously higher than other loads. It shows that when the AE operates under low load, the oxygen content in the cylinder increases and the fuel gas is diluted, which promotes the THC formation. At the same time, the temperature in the local area of the cylinder is too low, the CO lost the temperature condition and can't be oxidized to CO_2.

3.3 Energy-based emission factors regression analysis

In addition, a regression analysis of the relationship between diesel engine load and energy-based emission factors was carried out. Under the maximum coefficient of determination (R^2), the relationship between diesel engine load and energy-based emission factors can be fitted by quadratic polynomial and power function, as follows:

$$EF^r = a \bullet LP^2 + b \bullet LP + c \tag{3}$$

$$EF^r = a \bullet LP^{-b} \tag{4}$$

Where, EF^r: regression analysis energy-based emission factor (g/kW•h); *LP*: load percentage; *a, b* and *c*: equation coefficient.

The obtained equation coefficients are shown in Table 3. It should be noted that the fitting of the relationship between diesel engine load and energy-based emission factors in this paper is only a statistical result. As can be seen from Table 3, for the ME, there is a power function relationship between NO_X energy-based emission factor and engine load, and there is a quadratic polynomial relationship between CO, CO_2 and THC energy-based emission factor and engine load. For the AE, the relationship between the energy-based emission factor and engine load is a power function.

Table 3 Coefficients of fitting formulas for energy-based emission factors

Coefficients / Eng. type	EF^r_{NOx}				EF^r_{CO}				EF^r_{CO2}				EF^r_{THC}			
	a	b	c	R^2	a	b	c	R^2	a	b	c	R^2	a	b	c	R^2
SSD-ME	10.6	0.22	-	0.99	3.08	-5.51	2.85	0.98	136	-187	593	0.99	0.26	-0.37	0.33	0.99
MSD-ME	7.9	0.29	-	0.99	3.46	-5.34	2.45	0.99	223	-341	758	0.99	-0.21	0.21	0.43	0.99
HSD-ME	5.92	0.37	-	0.99	0.64	-1.24	1.23	0.98	198	-278	747	0.98	0.22	-0.23	0.30	0.98
MSD-AE	7.59	0.11	-	0.91	0.34	0.88	-	0.89	598	0.21	-	0.92	0.38	0.63	-	0.98
HSD-AE	5.76	0.12	-	0.93	0.46	0.95	-	0.93	607	0.24	-	0.90	0.13	0.87	-	0.96

4. Conclusions

In this paper, emission bench tests of 198 diesel engines were carried out on the bench, including NO_X, CO, CO_2 and THC. The ME's and AE's fuel-based emission factors and energy-based emission factors are analyzed statistically and the research results can provide benchmark data for the ship emission inventory in China's coastal areas.

ME is a major source of ship emissions leading to air pollution. If the IMO's reference value is adopted, the estimation result of NOX will be high and the estimation result of CO will be low. Therefore, reasonable emission factors should be selected during the establishment of China's ship exhaust emission inventory.

The energy-based emission factors under different loads are analyzed. The energy-based emission factors are closely related to the diesel engine type and load. The oxygen enrichment in the cylinder is an important reason leading to a higher energy-based emission factor when diesel engine works at low load. However, the CO_2 fuel-based emission factor is independent of engine load and type, but closely related to the fuel carbon content.

Based on the regression analysis of the relationship between the diesel engine load and the energy-based emission factors, the results show that the relationship between the emission factors and the diesel engine load can be fitted by the quadratic polynomial or power function, used for predicting diesel engine emissions under different loads.

Acknowledgements

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Presenting author biography

My name is Zhongmin Ma, 35 years old. I have taken up teaching since I graduated from Dalian Maritime University. I have been working for 8 years. At present, I am still a doctoral student, mainly engaged in the research of marine diesel engine emission test and exhaust treatment. At the same time, I am also a member of the Exhaust Gas Analysis Center of Dalian Maritime University, and have been engaged in the research of marine diesel engine exhaust emission test for many years.

Cover letter

Dear Editor:

I would like to submit the enclosed manuscript entitled "Analysis of marine diesel engine emission characteristics under bench test conditions in China", which I wish to be considered for publication in "IAMUC AGA21". No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication.

I would like to declare on behalf of my co-authors that the work described is original research that has not been published previously, and not under consideration for publication elsewhere. All the authors listed have approved the manuscript that is enclosed.

We deeply appreciate your consideration of our manuscript, and I would like to express my thanks to reviewers for their opinions. If you have any queries, please don't hesitate to contact me at the address below.

Thank you and best regards.

Yours sincerely,

Zhongmin Ma, Peiting Sun, Shunlin Duan, Hui Xing, Hongfei Qu and Kai Wang

Corresponding author: Zhongmin Ma

E-mail: mazhongmin1090@163.com

Point-by-point response to the reviewers' comments

First of all, thank you very much for the reviewers' valuable comments. The author has read every comment carefully and revised the manuscript as required.

Reviewer 1:

After receiving your comments, the authors carefully reviewed and revised the manuscript language.

Reviewer 2:

1. The manuscript was carefully revised as required by the AGA 2021 template.
2. According to the suggestions of the reviewer, the author revises the repeated data in the manuscript and deletes the relevant repeated data.
3. The author proofread the manuscript carefully, making corrections for confused sentences and grammatical errors.
4. The author revised the conclusion part of the manuscript and deleted the repeated content.
5. According to the suggestions of the reviewer, the author added the schematic diagram of the test bench and equipment photos to the manuscript.
6. Revisions have been made according to the comments in the reviewed manuscript.

Reviewer 3:

1. The abstract has been shortened according to the reviewer's comments.
2. The new IMO emissions regulations, or proposals, have been added to the manuscript.