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Computational study of NO_x reduction on a marine diesel engine by application of different technologies

Xiuxiu Sun[a], Xingyu Liang[a]*, Peilin Zhou[b], Hanzhengnan Yu[c]， Xinyi Cao[a]

[a]*State key Laboratory of Engines, Tianjin University, Tianjin 300072, China*
[b]*Naval Architecture, Ocean &Marine Engineering, University of Strathclyde, Glasgow G4 0LZ, UK*
[c] *China Automotive Technology & Research Center, Tianjin, China, 300300*

Abstract

The simulation model of two-stroke heave fuel oil marine diesel engine was developed in this paper. The model was validated with the experimental data. The ability of NO_x reduction was researched for exhaust gas recirculation, humid air motor and miller cycle based on the simulation model. The results show that the EGR has the most potential to reduce the NO_x emission. It can make the quantity of NO_x meet the requirement of Tier III. The reduction value of NO_x was less for miller cycle. The HAM can be reduced the NO_x. However, the depth of HAM was limited.

Keywords: heavy fuel oil; marine diesel engine; EGR; HAM; miller cycle

1. Introduction

The two-stroke marine diesel engine has been widely used in the marine transport, due to the high thermal efficiency and lower cost. However, it also produces more pollutants than the vehicles. The international maritime organization (IMO) require the NO_x of marine engine reduce to 3.4 g/kWh in environment control area (ECA), which was applied in 2006 [1]. All kinds of methods were researched to reduce the emissions of the marine diesel engine, such as exhaust gas recirculation (EGR), humid air motor (HAM), miller cycle, injection strategies and so on [2].

* Corresponding author. Tel.: +86-022-2789 1285; fax: +86-022-2789 1285
E-mail address: lxy@tju.edu.cn

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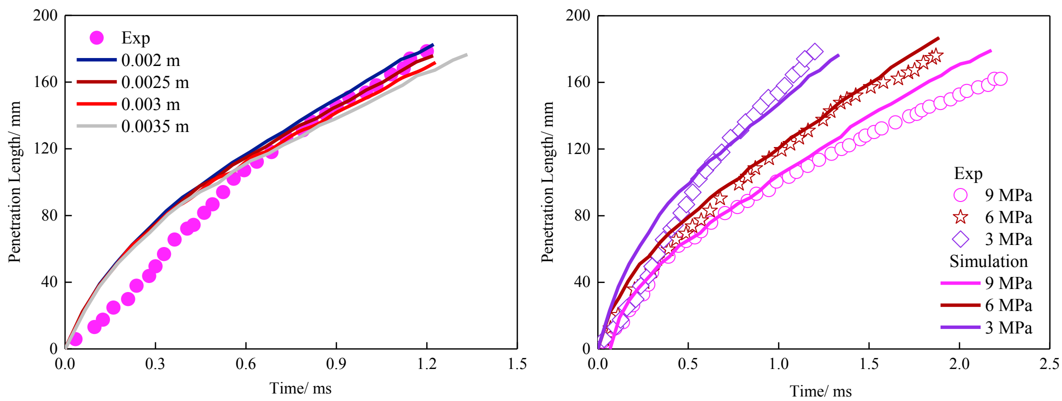
Verschaeren et al. [3] researched the EGR and miller timing to reduce the NO_x on a medium speed heavy duty diesel engine. The results showed that the EGR system is an essential part of an engine concept in order to fulfill IMO Tier III NO_x requirements. However, further investigation was needed to address its inherent drawbacks. Zhou et al.[4] researched the miller cycle and fuel injection direction strategies for low NO_x emission in the marine two-stroke engine. To improve fuel consumption, the injection direction must be carefully adjusted within certain limits. With optimized exhaust valve closed timing and injection direction, lower NO_x emission can be realized with no penalty of fuel consumption. Raptotasios et al.[5] researched the effect of EGR on the in-cylinder combustion and NO_x formation using a multi-zone combustion model of two-stroke marine diesel engine. The results showed that the NO_x can meet the requirements of Tier III when the EGR rate close to 40 % at 75 % load.

The reduction of NO_x was researched using EGR, HAM and miller cycle on the marine diesel engine using heavy fuel oil (HFO). The simulation model was validated with the experimental data. The in-cylinder pressure, NO_x emission and indicated specified fuel consumption (ISFC) were compared using different methods. The technology lines were provided for the marine diesel engine to meet the requirement of Tier III.

2. Model Validation

The simulation model was based on a marine diesel engine (6S35ME-B9). The structure of marine diesel engine has been introduced in published paper [6]. The experimental data were obtained when the engine speed was 142 r/min using HFO. The spray model and combustion model were validated with experimental data due to the different physical properties of diesel and heavy fuel oil [7]. The physical properties of HFO were obtained from the Kyriakides's model, which includes the dynamic viscosity, surface tension, vapor pressure, heat of evaporation and specific enthalpy [8]. The spray model was validated with the experimental data in a rotational flow constant volume combustion chamber [9, 10].

The validation of HFO spray model is shown in Fig.1. The effect of grids was shown in Fig.1(a) on the penetration length of HFO spray. The penetration length was close to the experimental data when the grids set to less 2.5 mm. The base grids set to 2 mm in a simulation model. The penetration lengths of HFO were compared with the experimental data at different environment pressure, 9 MPa, 6MPa, and 3MPa. The results are shown in Fig.1 (b). The penetration length increases with increasing the environment pressure. It can be seen that the simulation results are in good agreement with the experimental data. The spray model of constant volume combustion chamber will be used in the simulation model of the marine diesel engine.



(a) grids sensitive (b) spray model validation

Fig. 1. The validation of spray model for the HFO

The HFO marine diesel engine was simulated using the CONVERGE CFD software. The detailed chemical mechanism was used in the combustion model of the simulation model. The in-cylinder pressure was validated with the experimental data, which is shown in Fig.2. The emissions were not compared between the simulation and experimental data, due to the lack of experimental data. The trend of in-cylinder pressure was in good agreement with the experimental data. The errors of maximum compress and combustion pressure were less 1 % compared with the experimental data. The simulation model can be used to research the EGR, HAM and miller cycle.

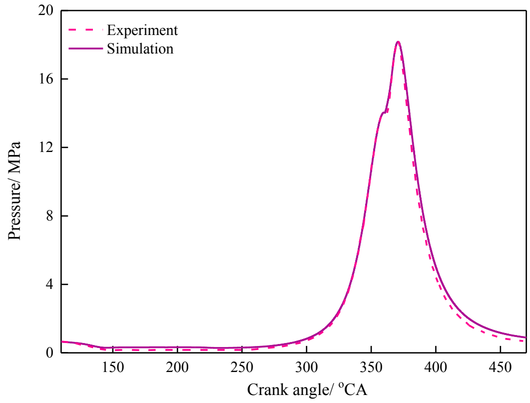


Fig. 2. The validation of simulation model with the experimental data in HFO marine diesel engine

3. Results and Discussion

3.1. Exhaust Gas Recirculation

The effect of EGR rate has been researched to reduce the NO_x emission. The boundary conditions were obtained from the calculated results of GT-power. The comparisons of in-cylinder pressure are shown in Fig.3 using different EGR rate. It can be seen that the in-cylinder pressure decreases with increasing EGR rate. It causes the ISFC increases. The maximum combustion pressure was lower 0.15 MPa than the result of original engine when the EGR rate set to 28%. The ISFC increases 5.8 g/kWh compared with the value of original engine.

The comparisons of NO_x emissions are shown in Fig.4. The quantity of NO_x emissions decreases with increasing EGR rate. It can be seen that the quantity of NO_x can meet the requirements of Tier III when the 28 % EGR rate was used in the marine diesel engine. The EGR technology is the useful method to reduce the NO_x emissions. However, the increased ISFC is the disadvantage for using the EGR to reduce the NO_x emissions. The EGR technology can be coupled with others methods to resolve the problem.

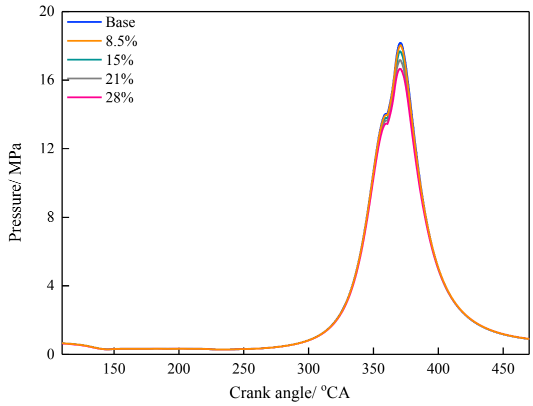


Fig. 3. The comparisons of in-cylinder pressure using different EGR rate

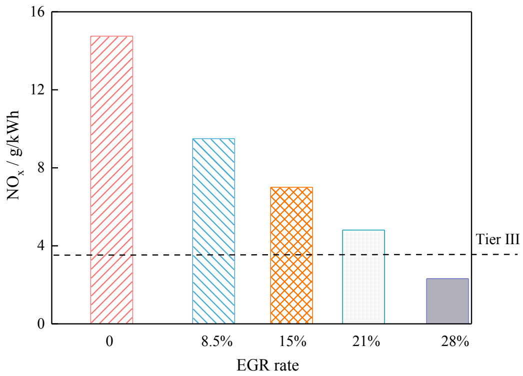


Fig. 4. The comparisons of NO_x emissions using different EGR rate

3.2. Humid Air Motor

The air contains more H_2O in the operation environment of ships, which has a large effect on the performance of marine diesel engine. The HAM is a useful method to reduce the NO_x for the marine diesel engine. However, the quantity of HAM depends on the pressure and temperature of inlet gas. The quantity of HAM (W/F) can be defined as:

$$W / F = \frac{m_{H2O}}{m_{fuel}}$$

It is important to ensure the vapor water into the cylinder instead of liquid water. So, the maximum value of W/F was set to 2 in this paper. The potential of HAM was researched on the reduction NO_x of the marine diesel engine.

The simulation results of in-cylinder pressure are shown in Fig.5. The maximum compress pressure is lower 0.26 MPa than the results of without HAM when the W/F set to 2. It decreases with the increasing depth of HAM. The reduced value of maximum combustion pressure is lower than that of the maximum compress pressure. That is to say: the HAM has little effect on the in-cylinder pressure. The power and fuel consumption has a relationship with the pressure. The HAM technology will not cause a reduction of power compared with the results using EGR.

The comparisons of NO_x are shown in Fig.6 using different HAM. It can be shown that the quantity of NO_x has large decrease with the increasing depth of HAM. The quantity of NO_x can reduce to 6.57 g/kWh when the W/F set to 2. The HAM makes the content of vapor water increasing. The content of oxygen decreases 1.31% compared with the value of oxygen content without HAM when the W/F set to 2. The specific heat capacity of mixture gas increase, which makes the increasing of absorbs heat. The in-cylinder temperature decreases. The region of higher temperature and rich oxygen become reduction with the increasing depth of HAM. It is a good method to reduce the NO_x for the marine diesel engine.

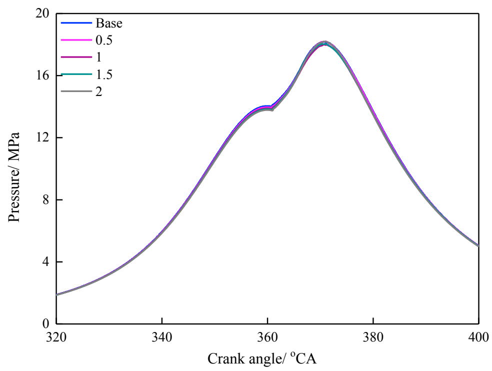


Fig. 5. The comparisons of in-cylinder pressure using different HAM

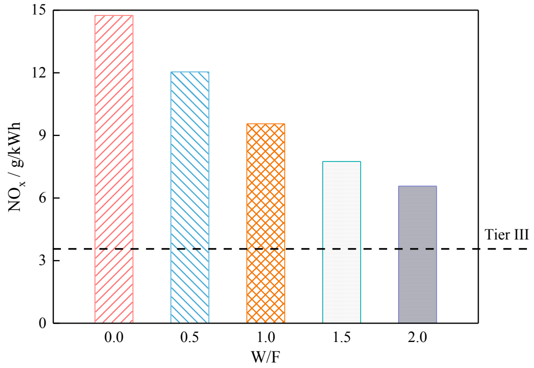


Fig. 6. The comparisons of NO_x emissions using different HAM

3.3. Miller cycle

The miller cycle has been widely researched to reduce the quantity of NO_x. The case is name M10 when the exhaust valve delay 10 °CA to close. The inlet pressure increase to make up the loss of fresh charge due to the delay close time of exhaust valve.

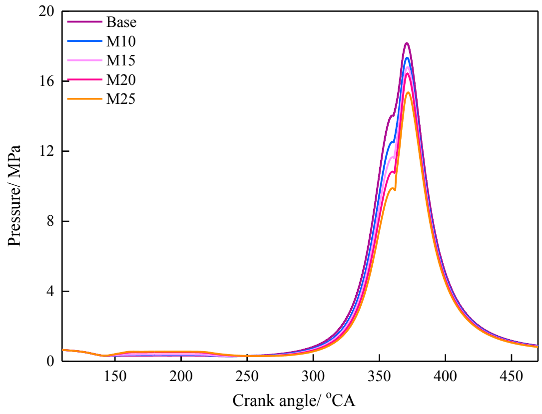


Fig. 7. The comparisons of in-cylinder pressure using different miller cycle

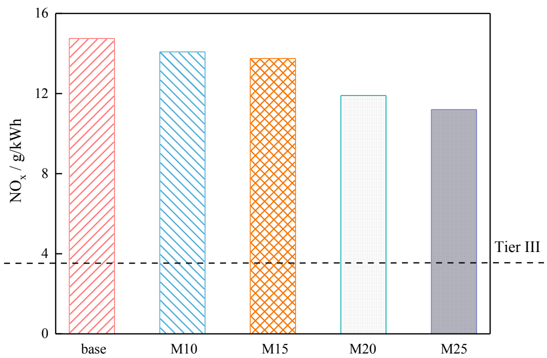


Fig. 8. The comparisons of NO_x emissions using different miller cycle

The comparisons of in-cylinder pressure are shown in Fig.7 using different miller cycle. It can be shown that the in-cylinder pressure has a large decrease with the depth of miller cycle. The maximum compress pressure decreases

4.6 MPa compared with the result of the original engine when the exhaust valve delay 25 °CA to close. The maximum combustion pressure also has a large decrease, which is about 2.83 MPa. The in-cylinder pressure is an index to evaluate the performance of engines. The in-cylinder pressure becomes worse than the results of using EGR and HAM.

The reductions of NO_x are shown in Fig.8 with the increasing depth of miller cycle. It can be seen that the quantity of NO_x has small decrease with the increasing depth of miller cycle. The quantity of NO_x emissions was 11.2 g/kWh when the M25 was used in the marine diesel engine. The value has a large difference with the requirements of Tier III. The effect of reducing NO_x is not obvious using miller cycle in the marine diesel engine.

4. Conclusions

The simulation model of the marine diesel engine was established in this paper. The model was validated with the experimental data. Then, the effect of EGR, HAM and miller cycle were investigated on the combustion and emission of the marine diesel engine. The results as follows:

1) The NO_x emissions have large improved when the EGR was used in the marine diesel engine. The quantity of NO_x can meet the requirement of Tier III when the EFR rate close to 30 %. However, the power of engine decreases.
2) The NO_x reduction using HAM is less than the results of using EGR. The power has less effect for the HAM method. The HAM is an effective method to reduce the NO_x. However, the depth of HAM is limited by the vapor water.
3) The decreasing of NO_x is limited using miller cycle. And, it decreases the in-cylinder pressure largely. The miller cycle cannot reduce the NO_x to meet the requirement of Tier III.
4) The EGR coupling with HAM is an optimal technology to reduce the NO_x. It is not only reducing the NO_x, but also keeping the power. The results improve a direction for marine diesel engine to reduce the NO_x.

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