NUMERICAL STUDY ON NO_X EMISSION REDUCTION MECHANISM OF HCCI MARINE DIESEL ENGINE FOR IMO TIER III EMISSION LIMITS

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SUMMARY

With the advantages of ultra-low emissions of oxides of nitrogen (NO_X) and high thermal efficiency, the homogeneous charge compression ignition (HCCI) mode applied to marine diesel engine is expected to be one of the technical solutions to meet the International Maritime Organization (IMO) MARPOL73/78 Convention-Annex VI Amendment Tier III requirement. According to the NO_X chemical reaction mechanism, taking a marine diesel engine as the application object, the numerical study on the NO_X formation characteristics of n-heptane for HCCI combustion process is performed. The results indicate that NO is usually the main component in the generation and emissions of NO_X with the n-heptane HCCI mode. The combustor temperature plays more important role in the proportion of NO generation and emission. Compared with the experimental data of conventional marine diesel engine, the emission reduction rate of NO_X can achieve an average of more than 95% in using HCCI technology.

1. INTRODUCTION

With the development of global economy and shipping industry, air pollution from marine diesel engine is becoming serious increasingly, especially for the air quality of coastal areas. These situations have attracted wide international attention. In the combustion process of diesel engine, the pollutant emissions mainly consist of oxides of sulphur (SO_X), oxides of nitrogen (NO_X), gaseous hydrocarbon (HC), carbon monoxide (CO) and particulate matters (PM). Among them, SO_X and NO_X are the components which are the biggest emitters, hazardous environmental and most tightly controlled. In recent years, it is estimated that the NO_X emissions from shipping occupied 18% to 30% of the total worldwide emissions according to the related statistical information on this topic (Wei, Y., 2013, Eyring, V., 2005, Øyvind, E., 2003). To control and reduce the air pollution from marine diesel engine, the Marine Environmental Protection Committee (MEPC) of the International Maritime Organization (IMO) has agreed upon progressively stricter limitations for NO_X emissions from vessels based on their date of engine installation with the standards of Tier I, Tier II and Tier III in October 2008. These standards have taken effect beginning on July 1, 2010. As shown in Table 1, the Tier III standard is the strictest mandatory requirement applied for the engine whose installation date later than January 1, 2016 in designated Emission Control Areas (ECA). Outside the ECA, the Tier II requirement is still performed. Compared with the requirements of Tier II and Tier I, NO_X emissions must decrease by 74% to 79% and 80% respectively to meet the Tier III requirement.

In face of the new increasingly stringent emission control regulations of IMO and many coastal countries, the development and application of effective NO_X emissions-reducing technology adapted in the marine diesel engine have already become the fundamental way in addition to the guidance of the government policies. This also has been becoming the most pressing problem to be solved indispensable for the shipping industry and marine diesel engine manufacturers.

Table 1. NO_X emissions limits in MARPOL73/78 Convention-Annex VI Amendment

Tier	Effective Date	NO_X Limit /g·(kWh)$^{-1}$		
		n<130	130≤n≤2000	n>2000
Tier I *	2000	17.0	$45\times n^{-0.2}$	9.84
Tier II	2011	14.36	$44\times n^{-0.23}$	7.66
Tier III **	2016	3.40	$9\times n^{-0.23}$	1.97

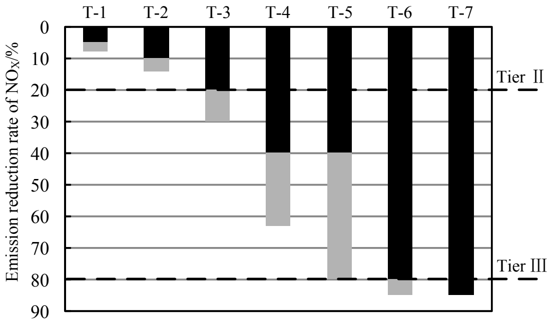
“n” refers to rated engine speed (r·min^{-1}).

All the NO_X emissions limits exclude ships with marine diesel engines less than a power output of 130 kW or ships solely for emergency use such as emergency diesel engine, lifeboat engines etc.

*Annex VI entered into force in 2004, but it applies retroactively to new engines larger than a power output of 300kW installed on ships on or after January 1, 2000.

** Tier III applies only in emission control areas.

The existing available emission reduction technologies on marine diesel engine are generally classified into two main types: internal purification and exhaust emissions after-treatment. The internal purification technologies include dual-fuel engine (Wärtsilä, 2013), alternative fuel technology, water-in-fuel emulsion and improvements of fuel and air intake system (U. S. Environmental Protection Agency, 2009). The exhaust emissions after-treatments mainly include selective catalytic reduction (SCR) method (Azzara, A., 2014), exhaust gas recirculation (EGR) (Raptotasios, S. I., 2015) and off-gas scrubbing (MAN Diesel & Turbo, 2013). The NO_X reduction effects of the main available technologies are presented in Figure 1. It is acknowledged that most of these technologies cannot meet the Tier III requirement.



T-1: Supercharge and inter-cooling, T-2: After injection, T-3: Water-in-Fuel Emulsion (WFE), T-4: Humid air motors (HAM), T-5: Exhaust gas recirculation (EGR), T-6: Selective catalytic reduction (SCR), T-7: Dual-fuel (DF Gas mode)
Figure 1. NO_X emission reduction effects of the main available technologies

Besides the techniques mentioned above, the homogeneous charge compression ignition (HCCI) (Mauya, R. K., 2012, Niat, P. M., 1983) technology has received increased attention for its potential to extremely reduce the emissions of NO_X and PM and enhance the thermal efficiency (Xue, L., 2014, Yao, M. F., 2009). This HCCI mode is expected to be one of the effective technical solutions to meet the IMO MARPOL73/78 Convention-Annex VI Amendment Tier III requirement if it is applied to marine diesel engine. A significant feature of HCCI is that the compression ignitions are happened in multiple regions. Therefore, the temperature inside the combustion chamber is relatively uniform, the cyclic variations are small and there are no obvious high-temperature zones in combustion process. With these characteristics, the combustion roughness and fuel economy can be improved. And the formations of NO_X and PM are controlled effectively. To promote the practical application of the HCCI technology, the combustion characteristic and optimal design have been studied. The cyclic variation of HCCI combustion phasing has been investigated by Maurya, R. K. (Maurya, R. K., 2013). Many experimental researches on HCCI combustion using various alternative fuels (Li, H. L., et 2007) and blended fuels (Bushby, S. R. M., 2005) have been conducted. Furthermore, both numerical simulation and experimental research show that the HCCI mode has potential for extremely low emissions of NO_X and PM (Yao, M. F., 2005). However, the studies on NO_X emissions reduction mechanism and influence factor for HCCI combustion are insufficient. So far, to the authors' knowledge, the study on the applicability of HCCI marine diesel engine to Tier III requirement is also a rare occurrence.

The elementary chemical reactions of diesel combustion in the cylinder are very complex and extremely large in quantity because of the multiple components and uncertainty component concentration in diesel fuel (Kim, Y. M., 2000, Turns, S. R., 2000). Consequently, the other single component fuels are always selected as replacements for diesel fuel in combustion simulation. N-heptane is one of the ideal alternative fuels which have the approximate cetane number with diesel fuel (Zheng, Z. L., 2006).

Applying the NO_X chemical reaction mechanism inside the cylinder, a numerical study on the NO_X formation of n-heptane for HCCI combustion process is performed taking the MAN-B&W6L23/30-A marine diesel engine as application object. On this basis, the characteristic features of NO_X formation and emission are displayed. Then the effects of emission reduction under various operating conditions are analyzed and discussed.

2. FORMATION MECHANISM OF NO_X AND COMPUTATIONAL MODEL

Based on mechanism of NO_X formation and emission, NO_X in diesel engine exhaust are created and discharged as a by-product of in-cylinder combustion process. According to the source of nitrogen element in NO_X, NO_X emissions are generally divided into three main types: thermal NO_X, fuel NO_X and prompt NO_X. The diesel fuel usually contains trace amounts of nitrogen element. During the running of diesel engine, the fuel NO_X is mainly generated by the volatile nitrogen which is formed from nitrogen element in fuel under high temperature, and the amount of volatile nitrogen is little. That is, NO_X from fuel oil is so little that it can be ignored in calculation. Therefore, it is generally considered that NO_X in diesel engine exhaust is almost entirely the thermal NO_X and prompt NO_X emissions which are produced from in-cylinder combustion chemical reaction involving the nitrogen (N_2).

2.1 FORMATION MECHANISM OF NO_X

The forms of thermal NO_X include nitric oxide (NO), nitrous oxide (NO_2), nitrogen dioxide (N_2O), dinitrogen trioxide (N_2O_3), nitrogen pentoxide (N_2O_5), nitrogen tetroxide (N_2O_4) and so on, which are the major contributors to local and regional air quality issues such as acidic nitrate deposition and health impacts such as lung irritation. Among them, NO_2 and NO are the majority components in NO_X emissions. The detailed formation mechanism of NO_X is very complicated. It is generally recognized that NO_X are produced in the zones of flame front and burned region. The NO_X formation chain reactions are proposed by Zeldovich, Y. B. in 1946 (Palmer, W. 2000, Zeldovich, Y. B., 1947).

Pyrolysis of O_2 under high temperature:

$$O_2 \rightleftharpoons O + O \quad (1)$$

Production of NO:

$$O + N_2 \rightleftharpoons NO + N \quad (2)$$

$$N + O_2 \rightleftharpoons NO + O \quad (3)$$

Production of NO_2:

$$2NO + O_2 \rightleftharpoons 2NO_2 \quad (4)$$

Another formation reaction of NO occurs in the conditions of over-rich mixture.

$$N + OH \rightleftharpoons NO + H \quad (5)$$

Under normal operating conditions of marine diesel engine, the mixture concentration is relatively low that the chemical reaction (5) is generally ignored.

For above chemical reactions, temperature is an important factor that affects the rate of chemical reaction (2), which ultimately influences the process and rates of the NO_X formation reactions. Therefore, the maximum flame temperature and maximum local flame temperature are the main influence factors that affect the formation rate of NO_X in combustion chamber. In addition, oxygen (O_2) concentration and chemical reaction time of oxygen (O_2) and nitrogen (N_2) in high temperature zone also have important effects on the generation of NO_X. It is summarized that the factors which affect the chemical reaction rates of NO_X formation mainly include combustion temperature, oxygen (O_2) concentration and chemical reaction time of oxygen (O_2), and nitrogen (N_2) in high temperature zone (Zhang, T., 2016).

2.2 THERMODYNAMIC MODEL

In this modeling, it is assumed that the thermodynamic pressure, thermodynamic temperature and composition concentration of inflammable mixture are completely uniform in combustion chamber (Figure 2). The thermodynamic state of inflammable mixture (working fluid) is determined by the pressure P, thermodynamic temperature T and mass M. And the engine working process can be simulated on the basis of energy conservation equation, mass conservation equation and state equation of ideal gas.

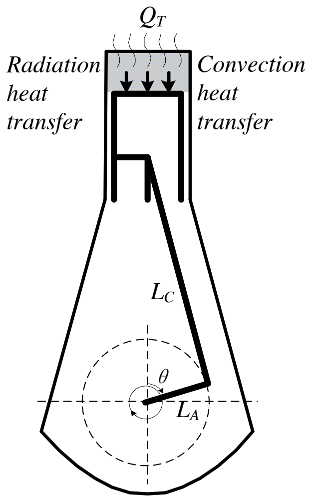


Figure 2. Modeling of HCCI diesel engines; L_C: length of connecting rod, L_A: radius of crank arm, θ: crank angle

2.3 HEAT TRANSFER MODEL

The convection heat transfer and radiation heat transfer of cylinder wall are considered. The heat transfer model is described by the following empirical formula (Woschni, G., 1967):

$$Q_T = 129.8 B^{-0.2} P^{0.8} T^{-0.55} w^{0.8} A_S \cdot \Delta T_m \tag{6}$$

Where Q_T is heat flux of the cylinder, B is cylinder bore, P is in-cylinder pressure, T is combustor temperature, A_S is equivalent heat transfer area, ΔT_m is temperature difference, and w is the average velocity of in-cylinder flow.

2.4 PISTON MOTION

The inflammable mixture in cylinder, which is from system boundary, and residual exhaust gas are supposed to be thoroughly mixed instantaneously during the intake stroke. The change of cylinder volume caused by piston motion is simplified to a slider-crank mechanism, which is expressed as:

$$\frac{V(\mathrm{t})}{V_C} = 1 + \frac{\varepsilon - 1}{2}\left[\frac{L_C}{L_A} + 1 - \cos\theta - \sqrt{\left(\frac{L_C}{L_A}\right)^2 - \sin^2\theta}\right] \tag{7}$$

Where $V(t)$ is cylinder volume, V_C is cylinder clearance volume, ε is geometry compression ratio

The diesel engine power is expressed as the arithmetic product of the output power of piston and transmission mechanical efficiency of connecting rod and crankshaft. The chemical reaction kinetics of NO_X formation is implemented based on CHEMKIN. The NO_X emissions, reduction rate and the other calculations are mainly performed in MATLAB.

3. RESULTS AND ANALYSIS

In this research, MAN-B&W6L23/30-A marine medium-speed diesel engine in marine power plant laboratory of Dalian Maritime University is chosen as the simulation object. Table 2 shows the structural specifications of MAN-B&W6L23/30-A diesel Engine.

Table 2. Structural specifications of MAN-B&W6L23/30-A diesel Engine

Items	Specification parameter
Cylinder bore/mm	225
Length of stroke/mm	300
Number of cylinders	6
Geometry compression ratio	13:1
Connecting rod length/mm	600
Cylinder clearance volume /m^3	9.94×10^{-4}
Release valve open phase degree /°CA (BDC)	-37
Rated speed / r·min^{-1}	900

In the simulation calculation, the TDC (Top Dead Center) of the intake stroke is set as the zero point of crank angle (0°CA). The computational domain starts from the starting point of compression stroke, ends with terminal point of expansion stroke. So the range of crank angle is from 180°CA to 540°CA. The fuel injection way adopts the port fuel injection.

3.1 IMPACT ANALYSIS OF COMPRESSION RATIO

Figure 3 and Figure 4 show the NO_X concentration in cylinder and NO_X emissions with the compression ratios. According to the observation, the compression ratio affects the NO_X emissions greatly. With the rise of compression ratio, the NO_X emissions increase continuously and the increase rate is accelerated. When the compression ratio is less than 12, the NO_X emissions tend towards zero. When the compression ratio exceeds 18, the NO_X emissions have already reached 4.5g·$(kWh)^{-1}$ that achieves the level of the conventional diesel engine. As shown in Figure 5 and Figure 6, this phenomenon is result from the case that the high compression ratio would cause higher combustor temperature and O_2 concentration in cylinder. The percentage of NO in the NO_X emissions rises from 69.4% at compression ratio of 11 to 99.4% at compression ratio of 18.

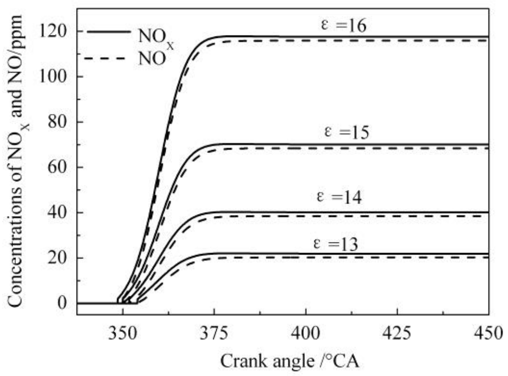


Figure 3. Effect of the compression ratio on concentration of NO_X and NO in cylinder. (Intake pressure p_0=0.25 MPa, intake air temperature T_0=320 K, excess air coefficient λ=2.8, engine speed n=900 r·min^{-1}.)

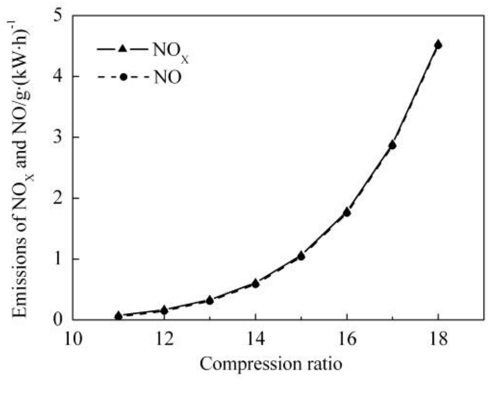


Figure 4. Effect of the compression ratio on NO_X emissions. (Intake pressure p_0=0.25 MPa, intake air temperature T_0=320 K, excess air coefficient λ=2.8, engine speed n=900 r·min^{-1}.)

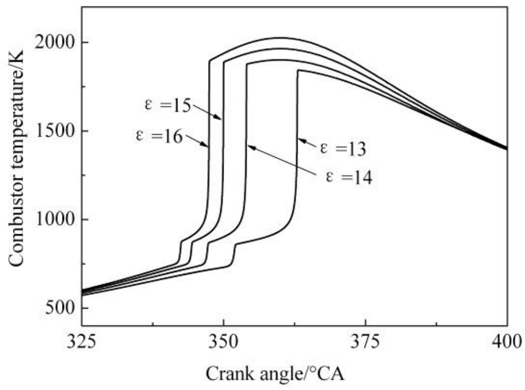


Figure 5. Effect of the compression ratio on combustor temperature. (Intake pressure p_0=0.25 MPa, intake air temperature T_0=320 K, excess air coefficient λ=2.8, engine speed n=900 r·min^{-1}.)

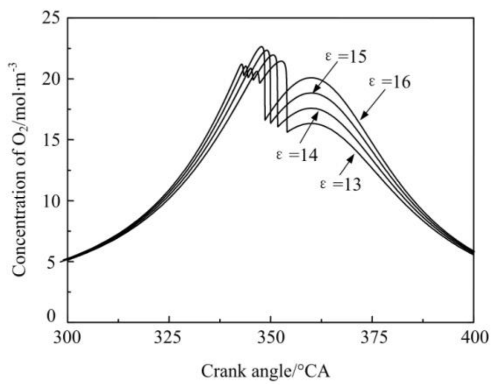


Figure 6. Effect of the compression ratio on concentration of O_2 in cylinder. (Intake pressure p_0=0.25 MPa, intake air temperature T_0=320 K, excess air coefficient λ=2.8, engine speed n=900 r·min^{-1}.)

The modern marine diesel engine commonly adopts high compression ratio which is unfavorable for the reduction of NO_X emissions in HCCI mode. But due to high combustion efficiency of this combustion mode, the NO_X emissions have the potential to be reduced moderately in the operating condition of low compression ratio without affecting the thermal efficiency and fuel economical efficiency significantly.

3.2 IMPACT ANALYSIS OF INTAKE AIR TEMPERATURE

Figure 7 and Figure 8 show the NO_X concentration in the cylinder and NO_X emissions with the intake air temperature. The NO_X emissions increase with the rise of intake air temperature in the case of unchangeableness of the other initial conditions. The effects of the intake air temperature on combustor temperature and concentration of O_2 are given in Figure 9 and Figure 10, higher intake air temperature often result in higher combustor temperature and lower concentration of O_2. It is obvious that the combustor temperature plays more important role in the chemical reaction rate of NO_X formation under the simulating operating conditions.

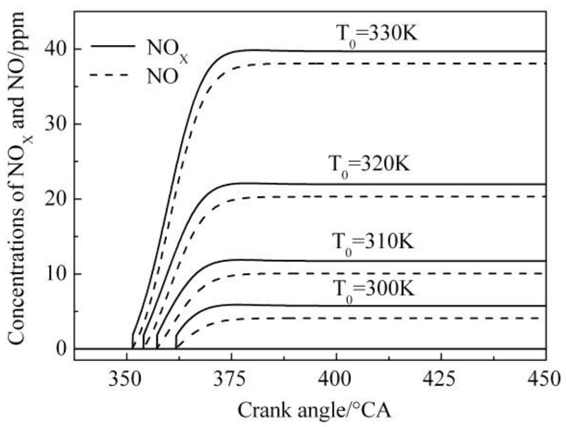


Figure 7. Effect of the intake air temperature on concentration of NO_X and NO in cylinder. (Intake pressure p_0=0.25 MPa, compression ratio ε=13, excess air coefficient λ=2.8, engine speed n=900 r·min^{-1}.)

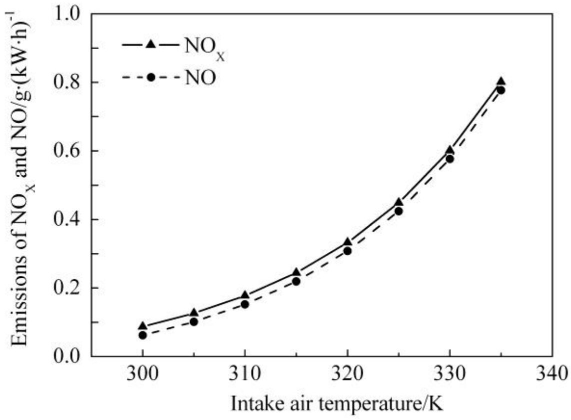


Figure 8. Effect of the intake air temperature on NO_X emissions. (Intake pressure p_0=0.25 MPa, compression ratio ε=13, excess air coefficient λ=2.8, engine speed n=900 r·min^{-1}.

In the intake air temperature range of 300K to 335K, the NO_X emissions are consistently lower than 0.8 g·(kWh)$^{-1}$. The most mass of chemical component is NO which contributes the NO_X emissions of percentage of about 71.2% to 97.0%. The other components in NO_X emissions are mainly NO_2. Moreover, the percentage of the NO increases with the intake air temperature. That is because the temperature has obvious influence on the NO formation reaction.

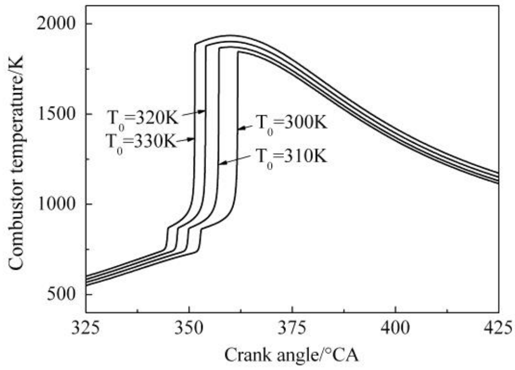


Figure 9. Effect of the intake air temperature on combustor temperature. (Intake pressure p_0=0.25 MPa, compression ratio ε=13, excess air coefficient λ=2.8, engine speed n=900 r·min^{-1}.)

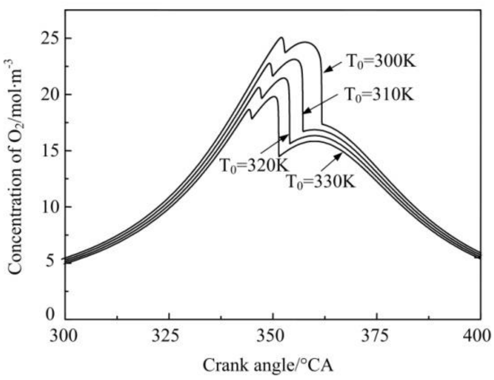


Figure 10. Effect of the intake air temperature on concentration of O_2 in cylinder. (Intake pressure p_0=0.25 MPa, compression ratio ε=13, excess air coefficient λ=2.8, engine speed n=900 r·min^{-1}.)

3.3 IMPACT ANALYSIS OF INTAKE PRESSURE

Figure 11 and Figure 12 show the NO_X concentration in the cylinder and NO_X emissions with the intake pressure. It is shown that the NO_X emissions exhibit an approximate linear increase with the intake pressure. When the intake pressure is in the range of 0.15 MPa to 0.45 MPa, the NO_X emissions are relatively low. It is also shown that NO is the major chemical component in NO_X emissions. The percentage of NO decreases from 95.7% to 86.9% in the chosen range of intake pressure.

Figure 13 and Figure 14 show the effects of the intake air temperature on combustor temperature and concentration of O_2 in cylinder. The increase of intake pressure leads to rising of concentration of O_2 and extension of chemical reaction time of O_2 and N_2 in high temperature zone. Due to the combined effects of the two factors, the NO_X emissions tend to grow rapidly.

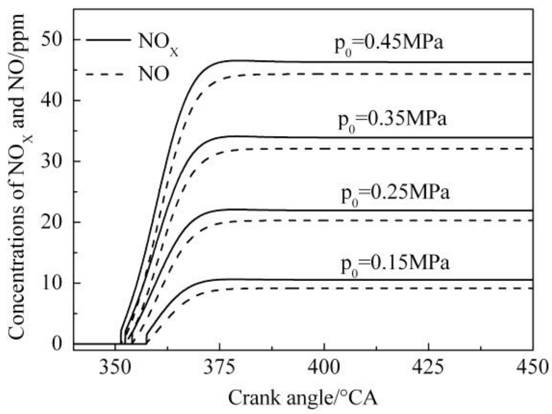


Figure 11. Effect of the initial pressure on concentration of NO_X and NO in cylinder. (Intake air temperature T_0=320 K, compression ratio ε=13, excess air coefficient λ=2.8, engine speed n=900 r·min^{-1}.)

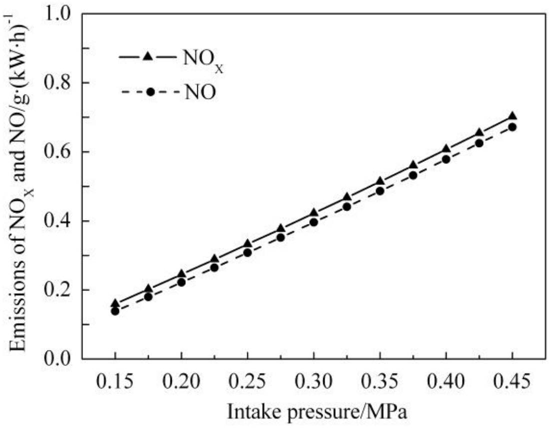


Figure 12. Effect of the initial pressure on NO_X emissions. (Intake air temperature T_0=320 K, compression ratio ε=13, excess air coefficient λ=2.8, engine speed n=900 r·min^{-1}.)

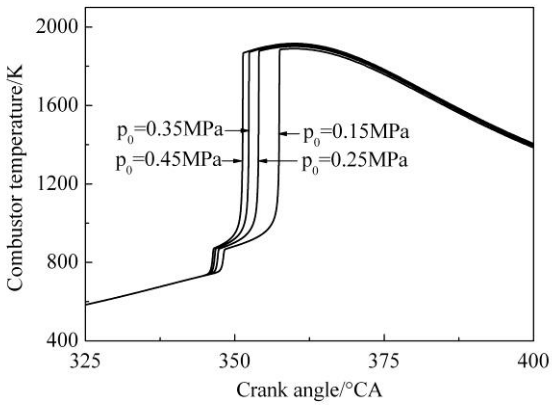


Figure 13. Effect of the initial pressure on combustor temperature. (Intake air temperature T_0=320 K, compression ratio ε=13, excess air coefficient λ=2.8, engine speed n=900 r·min^{-1}.)

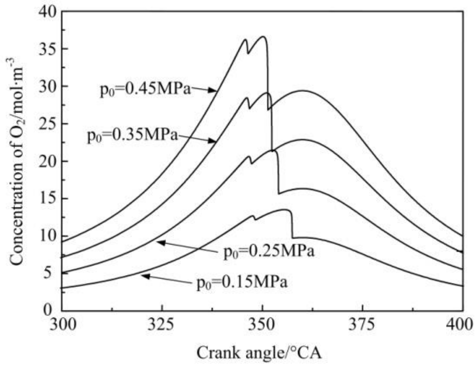


Figure 14. Effect of the initial pressure on concentration of O_2 in cylinder. (Intake air temperature T_0=320 K, compression ratio ε=13, excess air coefficient λ=2.8, engine speed n=900 r·min^{-1}.)

3.4 IMPACT ANALYSIS OF EXCESS AIR COEFFICIENT

Figure 15 and Figure 16 show the NO_X concentration in the cylinder and NO_X emissions with the excess air coefficient. The impacts of excess air radio to the NO_X emissions are remarkably. Overall, the NO_X emissions decrease with the increase of the excess air radio. When the excess air radio is less than 2.3, the NO_X emissions decrease very quickly but far exceed the emission level of conventional diesel engine, and the components in NO_X emissions are almost entirely NO. When the excess air radio is greater than 2.3, the NO_X emissions decrease slowly relatively. The other components of NO_X emissions, except NO, account for a certain proportion. When the excess air radio is greater than 3.2, the NO_X emissions have approached zero.

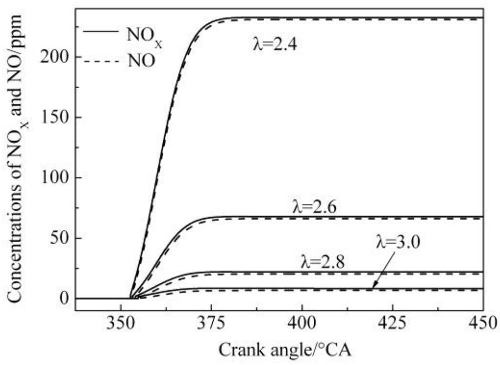


Figure 15. Effect of the excess air coefficient on concentration of NO_X and NO in cylinder. (Intake air temperature T_0=320 K, intake pressure p_0=0.25 MPa, compression ratio ε=13, engine speed n=900 r·min^{-1}.)

Figure 17 and Figure 18 show the effects of the intake air temperature on combustor temperature and concentration of O_2 in cylinder. The simulation results confirm that, with the increase of the excess air radio, the declines of combustor temperature and chemical reaction time of O_2 and N_2 in high temperature zone are significant. But the increase of concentration of O_2 is generally less pronounced. Their synthesis results are that the NO_X emissions are cut down dramatically at a larger excess air coefficient. Therefore, it can be seen that HCCI engine has extraordinarily lower NO_X emissions with the dilute homogeneous air and fuel mixture. The NO_X emissions of HCCI marine diesel engine can be controlled by adjusting the excess air radio.

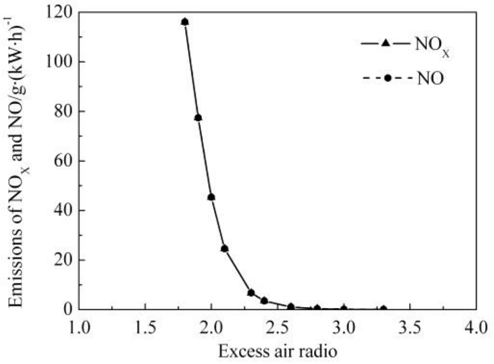


Figure 16. Effect of the excess air coefficient on NO_X emissions. (Intake air temperature T_0=320 K, intake pressure p_0=0.25 MPa, compression ratio ε=13, engine speed n=900 r·min^{-1}.)

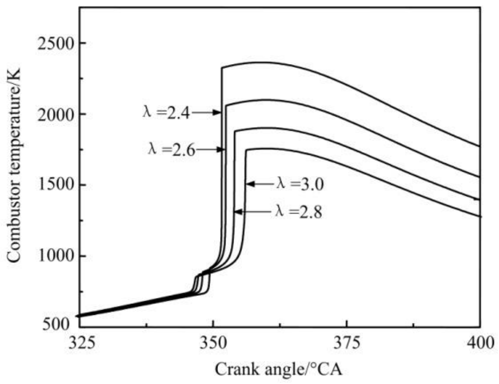


Figure 17. Effect of the excess air radio on combustor temperature. (Intake air temperature T_0=320 K, intake pressure p_0=0.25 MPa, compression ratio ε=13, engine speed n=900 r·min^{-1}.)

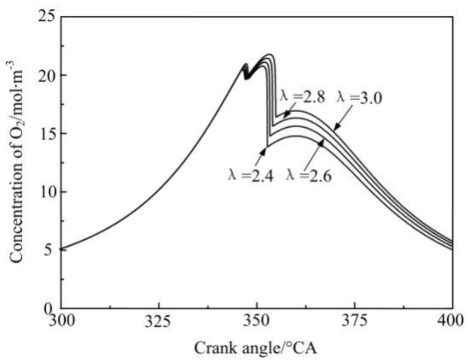


Figure 18. Effect of the excess air radio on concentration of O_2 in cylinder. (Intake air temperature T_0=320 K, intake pressure p_0=0.25 MPa, compression ratio ε=13, engine speed n=900 r·min^{-1}.)

3.5 IMPACT ANALYSIS OF ENGINE SPEED

Figure 19 and Figure 20 show the NO_X concentration in the cylinder and NO_X emissions with the engine speed. It is shown that the NO_X emissions decrease continually with the increase of engine speed, but all in low level in the simulated conditions. The percentages of NO in NO_X emissions are in the range of 97.3% to 91.6%.

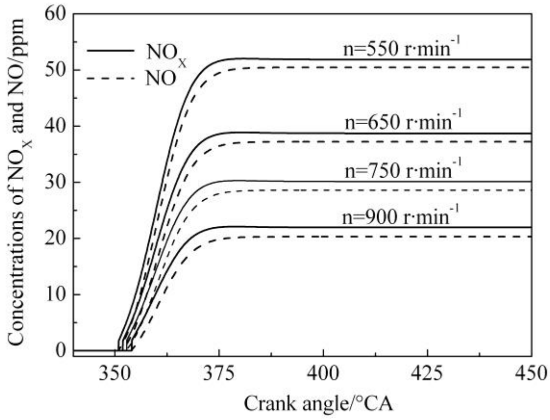


Figure 19. Effect of the engine speed on concentration of NO_X and NO in cylinder. (Intake air temperature T_0=320 K, intake pressure p_0=0.25 MPa, excess air coefficient λ=2.8, compression ratio ε=13.)

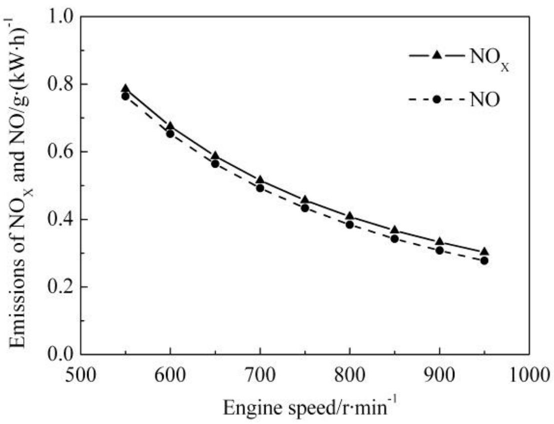


Figure 20. Effect of the engine speed on NO_X emissions. (Intake air temperature T_0=320K, intake pressure p_0=0.25MPa, excess air coefficient λ=2.8, compression ratio ε=13.)

Figure 21 and Figure 22 display the effects of the engine speed on combustor temperature and concentration of O_2 in cylinder. The rise of engine speed shortens the chemical reaction time of O_2 and N_2 in high temperature zone. But the combustor temperature and concentration of O_2 are not changed obviously in the crank angle of exceeding 350°CA. The NO_X emissions and the percentage of the NO emissions decrease as a whole.

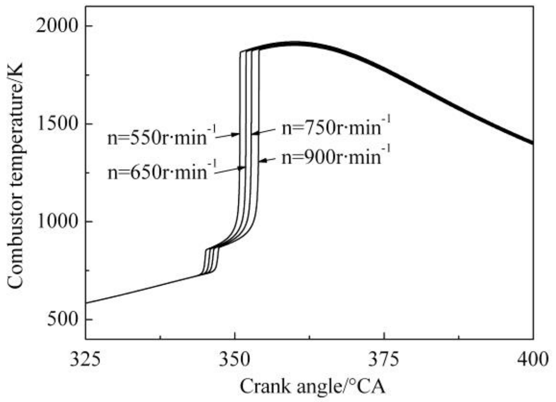


Figure 21. Effect of the engine speed on combustor temperature. (Intake air temperature T_0=320 K, intake pressure p_0=0.25MPa, excess air coefficient λ=2.8, compression ratio ε=13.)

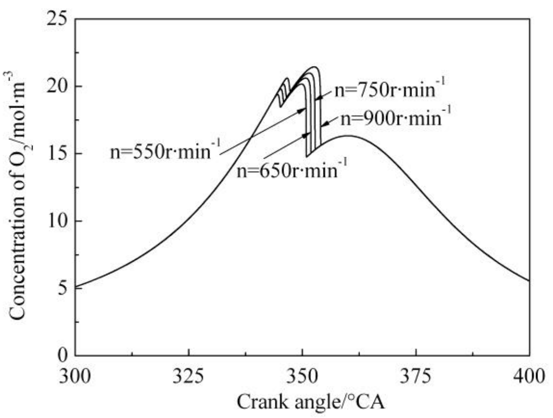
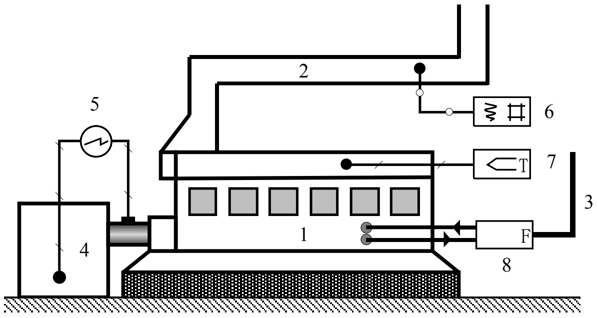


Figure 22. Effect of the engine speed on concentration of O_2 in cylinder. (Intake air temperature T_0=320 K, intake pressure p_0=0.25MPa, excess air coefficient λ=2.8, compression ratio ε=13.)

4. ANALYSIS OF NO_X EMISSIONS REDUCTIONS

At present, the conventional compression-ignition engine diesel and spark-ignition engine, each of which has reached its limit in improvement of fuel efficiency and decrease of harmful emission. The HCCI technology with the features of homogeneous mixture and low temperature reaction are expected to not only improve the engine cycle thermal efficiency, but significantly reduce the pollutant emission of NO_X.

In this paper, the MAN-B&W6L23/30-A marine diesel engine is chosen as application object. The experimental data of NO_X emissions are obtained from Dalian Maritime University. The schematic diagram of the diesel engine test is shown in Figure 23 (Xu, L. P., 2003). The effects of NO_X emissions reduction on n-heptane HCCI mode which is applied to the marine diesel engine are analyzed with the same structural specifications and operating conditions. As shown in Table 3 and Table 4, the E_1 and E_2 cycle of marine diesel engine are the test cycle modes according to the IMO MARPOL73/78 Convention-Annex VI.



1: MAN-B&W6L23/30-A marine diesel engine
2: exhaust pipe
3: fuel pipe
4: hydraulic dynamometer system
5: power measuring instrument
6: flue gas analyzer CLD/PMD
7: temperature tester
8: fuel consumption instrument.

Figure 23. Schematic diagram of the diesel engine test

In Table 3 and Table 4, it is shown that the effect of NO_X emissions reduction on HCCI mode applied to the marine diesel engine is extraordinary obvious. Under these operating conditions, the average NO_X reduction rate can surpass 95% and the emission values can fully meet the limits of Tier III requirement.

5. CONCLUSIONS

(1) Results from simulation show that NO usually accounts for the largest proportion in NO_X formation and emission of HCCI mode marine diesel engine under various simulated conditions. The combustor temperature always plays more important role in the proportion of NO.
(2) The operating conditions of the low compression ratio, low intake air temperature, low inlet pressure, large excess air coefficient and high engine speed are beneficial in reducing NO_X formation and emission of HCCI diesel engine. The above changes of operating conditions primarily influence the factors of combustion temperature, oxygen concentration and chemical reaction time of oxygen and nitrogen in high temperature zone, which affect the chemical reaction rate of NO_X generation.
(3) The HCCI combustion mode tends to have extremely remarkable low NO_X emissions performance. Compared with the experimental data of actual marine diesel engine, simulation results show that the emission reduction rate of NO_X can achieve an average of more than 95% in the n-heptane HCCI mode.

Table 3. Effect of NO_X emissions reduction of marine diesel engine in E_2 cycle on HCCI mode

Items	Operating condition 1	Operating condition 2	Operating condition 3	Operating condition 4
Engine speed /r·min^{-1}	900	900	900	900
Scavenging temperature/°C	41	50	50	56
Scavenging pressure/bar	0.03	0.36	1.35	1.8
Experimental data of NO_X emissions / g·(kWh)$^{-1}$	10.58	9.72	9.72	9.13
HCC simulation data of NO_X emissions/ g·(kWh)$^{-1}$	0.053	0.194	0.399	0.566
NO_X emissions limits of Tier III requirement / g·(kWh)$^{-1}$	1.883	1.883	1.883	1.883
NO_X reduction rate /%	99. 5	98.0	95.9	93.8

Table 4. Effect of NO_X emissions reduction of marine diesel engine in E_3 cycle on HCCI mode

Items	Operating condition 1	Operating condition 2	Operating condition 3	Operating condition 4
Engine speed /r·min^{-1}	565	713	820	900
Scavenging temperature/°C	47	48	51	56
Scavenging pressure/bar	0.25	0.71	1.38	1.8
Experimental data of NO_X emissions / g·(kWh)$^{-1}$	11.89	10.77	10.13	9.13
HCC simulation data of NO_X emissions/ g·(kWh)$^{-1}$	0.333	0.377	0.476	0.566
NO_X emissions limits of Tier III requirement / g·(kWh)$^{-1}$	2.095	1.986	1.923	1.883
NO_X reduction rate /%	97.2	96.5	95.3	93.8

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