

Article

Optimization of Marine Two-Stroke Diesel Engine Based on Air Intake Composition and Temperature Control

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Abstract: The influence of gas intake temperature, composition and the volume concentration of each gas component on diesel engine combustion, emission and the output power was studied by building a calculation model of the B&W 6S35ME-B9 marine two-stroke low-speed diesel engine, followed by a comprehensive optimization exploration. The results showed that under 295 K and 18.5% O₂ of intake gas, the engine's NO_x emission is only 4.5 g/kWh and reduced to 58% from the normal air gas intake condition. Moreover, their power output is very similar. In addition, the effect of CO₂ or H₂O added into the intake of the diesel engine on the performance of the diesel engine can be compensated by reducing the intake temperature. At the intake temperature of 295 K, the engine's NO_x emission with 20.58% O₂, 77.42% N₂ and 2% H₂O is 8.62 g/kWh, and 9.06 g/kWh under 20.79% O₂, 78.21% N₂ and 2% CO₂. It is lower than 11.77 g/kWh, which is under normal intake conditions (315 K, 21%O₂ and 79%N₂). The power output is also similar to the normal intake condition. Therefore, the comprehensive optimization of gas intake temperature, composition and concentration can effectively optimize the diesel engine's performance in terms of combustion, emission and power output. The research results have an important reference value for the optimization of diesel engine performance.

Keywords: marine diesel engine; combustion; emission; low temperature intake; oxygen reduction



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1. Introduction

The two-stroke marine low-speed diesel engine is widely used in ships because of its low fuel consumption, high efficiency, good economy and power output performance [1,2]. With the deterioration of the global environment and the rise of people's awareness of environmental protection, the emission of the diesel engine has attracted extensive attention, that of the marine diesel engine in particular [3,4]. The International Maritime Organization (IMO) and other maritime organizations have put forward more rigorous legal requirements regarding marine diesel engine emissions [5–7]. Therefore, the marine diesel engines' emission and power output performance have become the focus of ship owners' attention, and new technologies are urgently needed to comprehensively optimize diesel engines' performance.

In recent years, the development of new combustion technologies to reduce engine emissions has been very active. The combustion optimization technology of the internal combustion engine has become a hot topic in the industry at home and abroad [8,9]. The examples of such technology are as follows: low temperature intake [10], oxygen-enriched combustion [11], free-nitrogen combustion [12], nitrogen-enriched combustion [13], exhaust gas recirculation (EGR) [14], intake with humidification [15], etc. Studies have shown that the diesel engine's combustion efficiency improves by using low intake temperature to reduce the intake air gas density and increase charge coefficient [16,17]. Therefore, modern marine diesel engines mostly use inter-coolers to lower the temperature of engines' intake [18]. The increase of intake temperature can effectively increase the temperature of

the end of compression, shorten the period of ignition delay and improve the combustion process, although these cause the reduction of the amount of fresh air in the cylinder [19]. It has been proven that nitrogen reduction to enrich the oxygen concentration of the engines' air intake can significantly enhance its combustion efficiency and power output [20,21]. However, its NO_x emissions increase simultaneously. Studies revealed that exhaust gas recirculation, nitrogen-enriched, or humidification can effectively reduce NO_x emissions at the expense of the diesel engine's economy [22,23]. As a result, there appears to be a trade-off relationship between diesel engines' economy and NO_x emissions [24,25].

It has been revealed that the optimal no-smoke emission can be lowered by oxygen-enriched and EGR intake at the following full-load conditions: 1600 rpm, 30–40% EGR rate and 21.5–22.5% oxygen concentration; 2200 rpm, 20–45% EGR rate or 22–24% oxygen concentration [26]. Minimum total emissions can be achieved at 22% O₂, 2% CO₂ and 76% N₂ intake conditions [27]. Compared with normal air intake conditions, NO_x-soot emissions can be lowered by intake air humidification, EGR and shortened fuel injection time, and the indicated specific fuel consumption can be minimized as well [28]. A study has shown NO_x-soot emission can be effectively reduced by using EGR and optimizing intake air temperature [29]. At present, there are few studies on the optimization of the combination of intake air temperature, composition and concentration for marine diesel engines, and further systematic research needs to be conducted.

In this paper, based on the working process calculation model of the B&W 6S35ME-B9 marine two-stroke diesel engine, the power output and emission characteristics of diesel engine are studied by adjusting the intake temperature, intake composition (O₂\N₂\CO₂\H₂O), concentration, to find the way of reducing NO_x emission with little effect on its power output, and without affecting the external work capacity. It provides an important reference value for the optimization of air pollution emission and combustion performance for marine diesel engines.

2. Calculation Model

The model has taken the pressurized inter-cooled and two-stroke marine diesel engine of the B&W 6S35ME-B9 as the research object. The diesel engine's NO_x emission meets the requirement of IMO Tier II NO_x emission which is 14.4 g/kWh. The engine's technical parameters are shown in Table 1, which has the input parameter values for the calculation model. The working process calculation model is established in GT-Power as shown in Figure 1. According to relevant studies, the DIJET combustion model suitable for direct injection diesel engines was selected to study the combustion and emission performance of the diesel engine [8].

Table 1. Main technical parameters of the B&W 6S35ME-B9 marine diesel engine.

Technical Parameter	Value
Type of diesel engine	6S35ME-B9
Type of air intake	pressurized intercooled
Number of cylinder	6
Ignition sequence	1-5-3-4-2-6
Rated condition	142 rpm/3570 kW
Stroke/cylinder diameter	1550 mm/350 mm
Compression ratio	21
Injection time	2–4 °CA after top dead center
Air intake timing	–38/38 °CA
Exhaust valve timing	–64/98 °CA

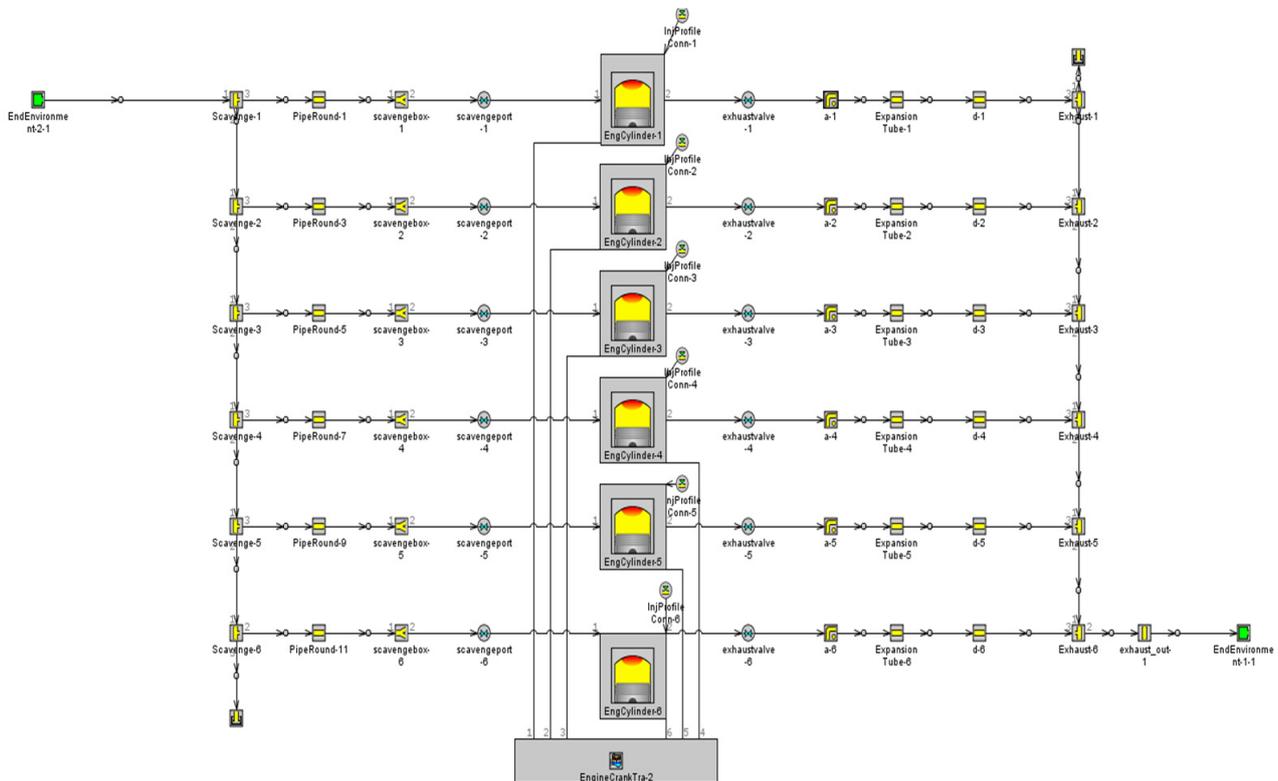


Figure 1. Calculation model of the B&W 6S35ME-B9 marine diesel engine in GT-Power.

The calculation model was checked and verified by taking the parameters of diesel engine speed, power, cylinder pressure, intake and exhaust temperature, intake and exhaust pressure and emissions at 100%, 75%, 50% and 25% load conditions. Figure 2 shows the comparison between the actual and simulated cylinder pressure curves of diesel engines under various working conditions, indicating that the calculated values are consistent with the experimental values. Key thermodynamic and emissions parameters under various working conditions are shown in Table 2. The diesel engine's emission values were collected by AVL i60 detection equipment. The cylinder pressure data were collected by Kistler pressure sensor, and then the average cylinder pressure of 100 cycles was used as the experimental value for this study. Other experimental data were collected by a special acquisition system. The deviations of pressure, temperature, NO_x and CO₂ emissions are all less than 5%. Therefore, this calculation model can be used to study the combustion and emission performance of this type of marine diesel engine.

Table 2. Comparison of experimental and simulated parameters of the B&W 6S35ME-B9 diesel engine.

Parameters	25%			50%			75%			100%		
	Experimental	Simulated	Deviation/%									
Speed(rpm)	89.5	89.5	0	112.8	112.8	0	129	129	0	142	142	0
Power(kW)	892	912	2.24	1795	1729	−3.6	2677	2547	−4.85	3575	3455	−3.4
Fuel consumption rate (g/kWh)	220.6	215.7	−2.22	190.6	197.8	−3.8	178.3	186.9	+4.82	180	186	+3.3
Scavenging pressure (MPa)	0.045	0.0438	−2.67	0.115	0.119	+3.5	0.188	0.191	+1.6	0.265	0.266	+0.4
Scavenging temperature (K)	314.5	317.6	0.99	311.5	312	+0.2	313.5	313.6	+0.03	318.5	310	−2.7
Compression pressure (MPa)	6.288	6.2	−1.40	9.528	9.56	+0.3	12.8	12.95	+1.2	16.3	16.4	+0.6
Combustion pressure (MPa)	7.891	7.89	−0.01	11.64	11.74	+0.9	15.69	15.84	+0.95	17.52	17.65	+0.7
Exhaust pressure (MPa)	0.039	0.0376	−3.59	0.102	0.105	+2.9	0.172	0.171	+0.58	0.24	0.242	+0.8
Exhaust temperature (K)	50.3	50.2	−0.20	53.35	53.5	+0.3	54.35	54.4	0	55.8	55.6	−0.4
NO _x (g/kWh)	15.96	15.31	−4.07	12.58	12	−4.6	12.88	12.3	−4.5	12.6	12.22	−3
CO ₂ (g/kWh)	691.2	674.8	−2.37	597	625	+4.7	559	586.8	+4.9	563.8	590.3	+4.7

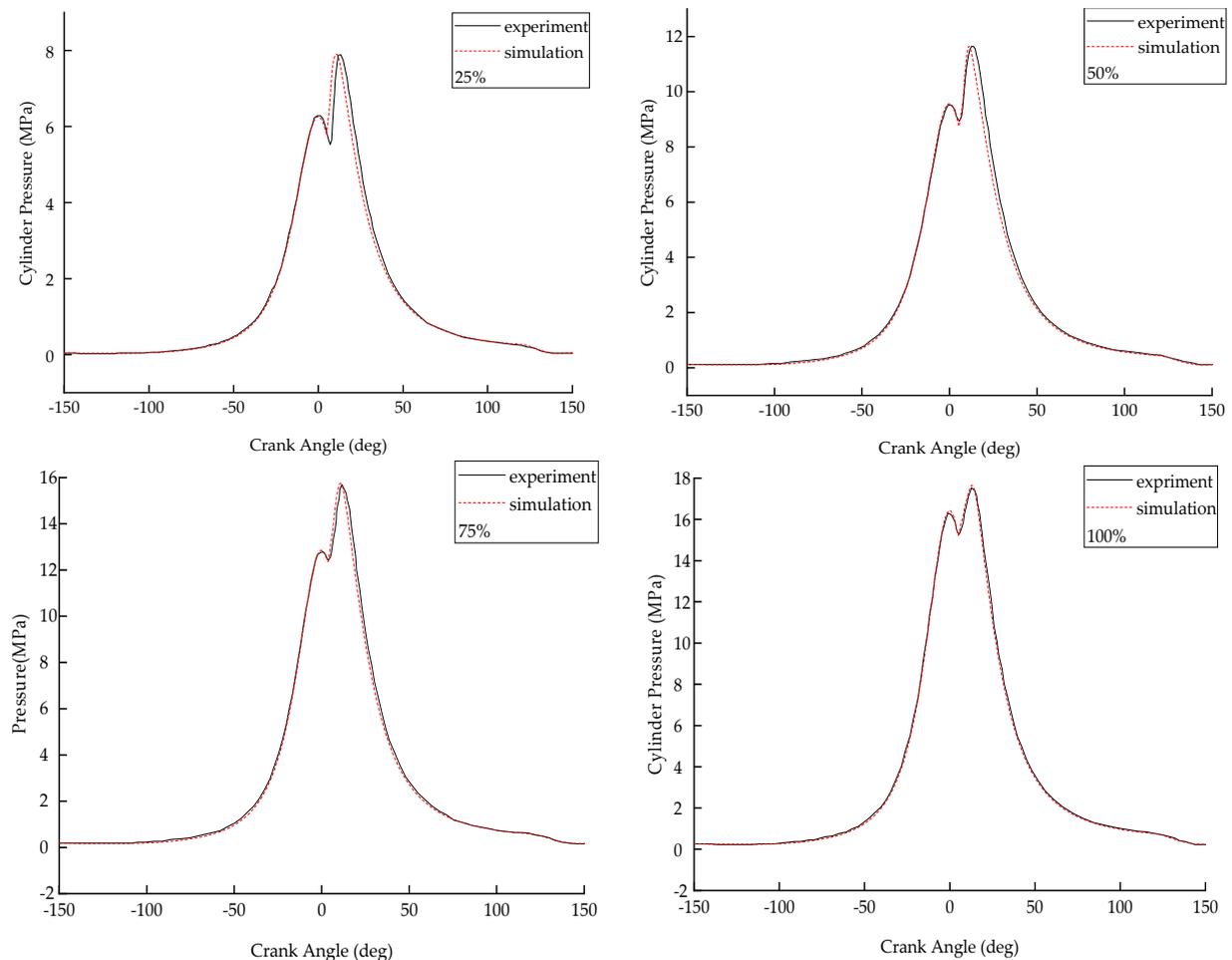


Figure 2. Comparison between experimental and simulation values of cylinder pressure of the B&W 6S35ME-B9 diesel engine.

3. Calculation, Results and Analysis

To facilitate the study, the connection between the hollow cooler in the original model and the scavenging air main pipe was disconnected. Furthermore, the intake temperature, intake gas type and the volume percentage of each gas component were directly modified and set as the boundary conditions of the intake of scavenging air main pipe. Based on the initial working conditions of 75% diesel engine load, the results are as follows: 129 rpm with 10.285 g fuel injection for one cylinder each time, scavenge pressure is 0.29 MPa, scavenge temperature is 315 K, and air intake (21% O₂ and 79% N₂). The following calculation studies were carried out. First, the influences of single factors on diesel engine power output, NO_x, CO and soot were studied by changing the intake temperature or the volume percentage of N₂ in the intake. Second, a combined optimization of intake temperature and N₂ volume percentage was conducted to find the optimization method of diesel engine performance. Third, based on the aforementioned two aspects of research regarding the replacement of N₂ in the intake gas with H₂O or CO₂, studies of the influence of H₂O or CO₂ on diesel engine performance were performed.

3.1. Influence of Intake Temperature or Oxygen Volume Fraction

3.1.1. Influence of Intake Temperature

Taking the air of 21% O₂ percent with 295 K, 315 K and 335 K as the initial intake conditions, the influence of scavenging temperature on the diesel engine's power output and emissions performance was analyzed by comparing the calculated results. As shown in Figure 3, the increase of intake temperature effectively increases the temperature of cylinder gas in the diesel engine compression stage. However, the rate of the temperature rise in the cylinder after top dead center (TDC) remains almost unchanged. Moreover, the beginning time of fuel combustion and heat release does not change with the change of intake temperature, either. That is because the modern two-stroke marine diesel engine adopts a high compression ratio and fuel injection at high pressure. Furthermore, the gas temperature in the cylinder at the injection time after TDC is high enough to ensure fuel particle refinement and ignition combustion, so the difference in the intake gas temperature is not big enough to significantly affect the start time of the ignition combustion. The rise of the gas temperature in the cylinder is conducive to the propagation of the combustion flame and accelerates and improves the combustion process, thus leading to the increase of the maximum combustion temperature in the cylinder. The temperature of the gas in the cylinder is also significantly higher in the later period of combustion, which is consistent with the conclusion in reference [16]. However, Figure 4 shows that the compression pressure and the maximum combustion pressure decrease with the increase of intake temperature. This is because the rise of temperature leads to the reduction of gas in the cylinder. The gas compression pressure is lower under the same compression workload. The combustion efficiency lowered by the reduction of oxygen in the cylinder is more than the effect of high-temperature optimized combustion, so its maximum combustion pressure is lower. Its power output and NO_x emission decrease with the increase of intake temperature, while its soot and CO emissions increase. Therefore, the marine diesel engine can optimize the scavenge temperature by adjusting the cooling effect of the air cooler according to its sailing area, to reduce the emission of NO_x while not affecting its power output. The minimum intake temperature is limited by seawater temperature, and the maximum sweep temperature is limited by the performance of the diesel engine and supercharger. In addition, Figure 5 shows that, under the normal air conditions, the engine's NO_x emission is 11.77 g/kWh with 315 K intake, and the NO_x emission is 11.9 g/kWh at 295 K and 11.6 g/kWh at 335 K, indicating that the effect of reducing NO_x emission simply by changing intake gas temperature is not good.

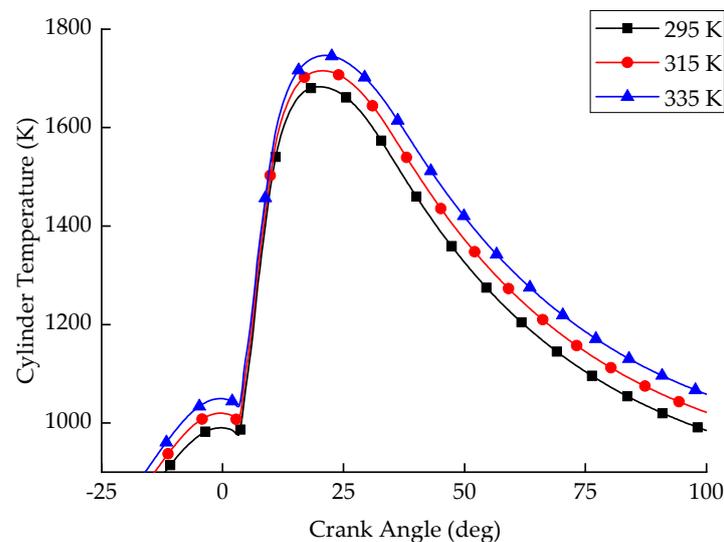


Figure 3. Comparison of temperature in cylinder under air intake at different temperatures.

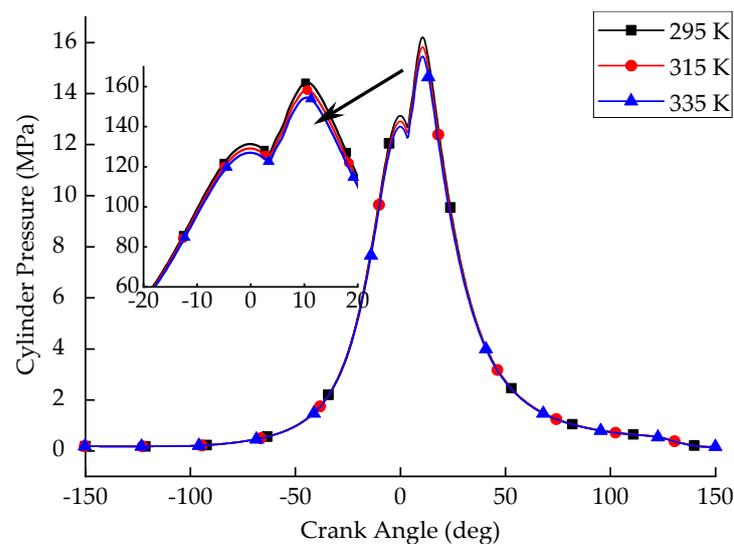


Figure 4. Comparison of pressure in the cylinder under air intake at different temperatures.

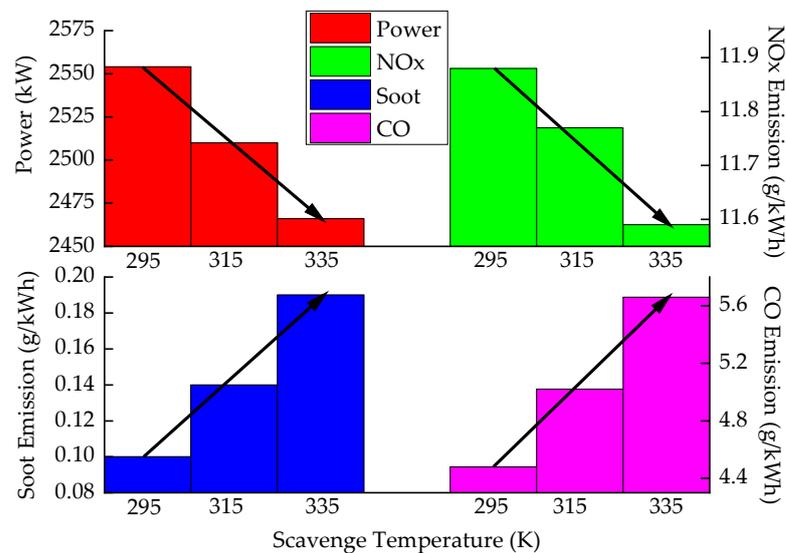


Figure 5. Comparison of emissions under air intake at different temperatures.

3.1.2. Influence of Oxygen Volume Fraction

At the intake temperature of 315 K, the volume fractions of oxygen and nitrogen in the intake gas were adjusted. We analyzed the diesel engine's cylinder combustion pressure and emissions by the O_2 percentage of the intake gas in the calculation model set at 19%, 21% and 23%. The results are shown in Figures 6 and 7. Soot is 0.63 g/kWh, CO is 6.89 g/kWh, NOx is 5.67 g/kWh, the highest combustion pressure is 15.2 MPa, and the output power is 2476 kW under the conditions of 19% O_2 and 81% N_2 . Soot is 0.14 g/kWh, CO is 5.13 g/kWh, NOx is 11.77 g/kWh, the highest combustion pressure is 15.8 MPa, and the output power is 2510 kW under air (21% O_2 and 79% N_2) intake conditions. Under the conditions of 23% O_2 and 77% N_2 intake, the engine's soot is 0.08 g/kWh, CO is 3.84 g/kWh, NOx is 17.86 g/kWh, the highest combustion pressure is 16.3 MPa, and the output power is 2527 kW. Therefore, the in-cylinder combustion is improved with the increase of oxygen concentration, the highest combustion pressure, and power increase, whereas the engine's soot and CO emissions decrease. However, the improvement of the combustion process causes the increase of the combustion temperature in the cylinder, thus accelerating the NOx generation in the cylinder. It is consistent with the research conclusions in reference [11,20]. At 295 K and 335 K, the emission parameters, maximum

combustion pressure, and the power output of diesel engines have the same variation trend. Therefore, the emission parameters and work performance of diesel engines can be effectively changed by adjusting the oxygen concentration in the cylinder. Or vice versa, the development of air separation technology, the study of oxygen volume fraction in internal combustion engine intake is effectively promoted.

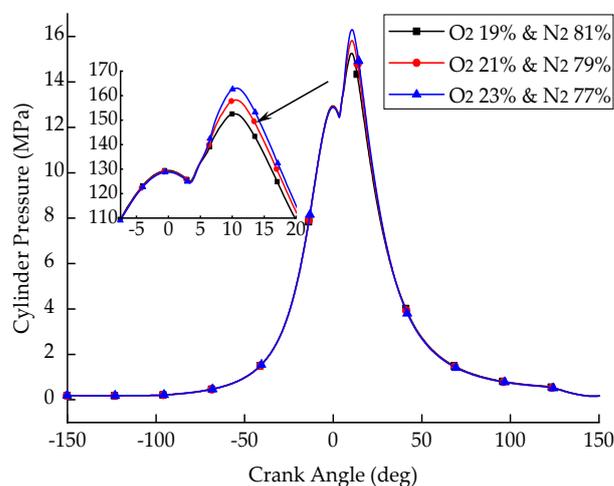


Figure 6. Cylinder pressure comparison at 315K and different O₂ volume fractions.

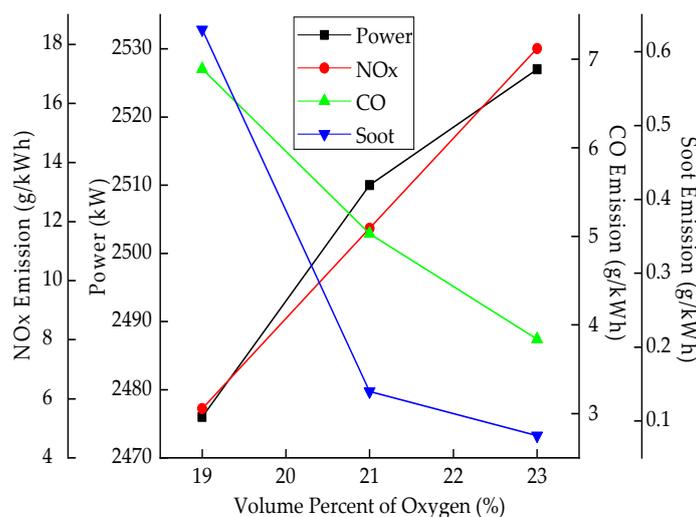


Figure 7. Emission comparison at 315K and different O₂ volume fractions.

Based on the research discussed above, the decrease of intake temperature or the increase of intake oxygen volume concentration can effectively improve the in-cylinder combustion process and the power output of diesel engines, though causing the increase in NO_x emissions. With the increase of intake temperature or the decrease of intake oxygen concentration, the NO_x emission of the diesel engine can be reduced, but its power output is lower as well. The intake temperature and the intake oxygen concentration of diesel engine power output and NO_x emissions are not the same. We can study the performance of diesel engines through either the combination of high intake temperature and oxygen enrichment or low intake temperature and oxygen deficiency.

3.2. Integrated Optimization with Intake Temperature and Oxygen Volume Fraction

3.2.1. High Intake Temperature and Enriched Oxygen

Under the intake temperature of 335 K and changed volume percentage of O₂ and N₂ with 23% O₂, 29% O₂ and 40% O₂ were used as boundary conditions, which corresponds

to conditions 2, 3 and 4 in Figures 8 and 9, respectively. The results were compared with the normal intake condition 1 (315 K, 21% O₂). As shown in Figure 8, the compression pressure in condition 1 is higher than the one in condition 2 and there is a slight difference in compression terminal pressure in conditions 2, 3 and 4, which is consistent with the results from Section 3.1.2. In working condition 2, oxygen-enriched air intake is used to promote combustion and compensate for the weakening of the combustion process caused by the intake temperature increase, so its maximum combustion pressure is similar to that in condition 1. Compared with conditions 1–3, O₂ concentration increases from 23% to 29%, the combustion in the cylinder is further improved, and the maximum combustion pressure increases significantly.

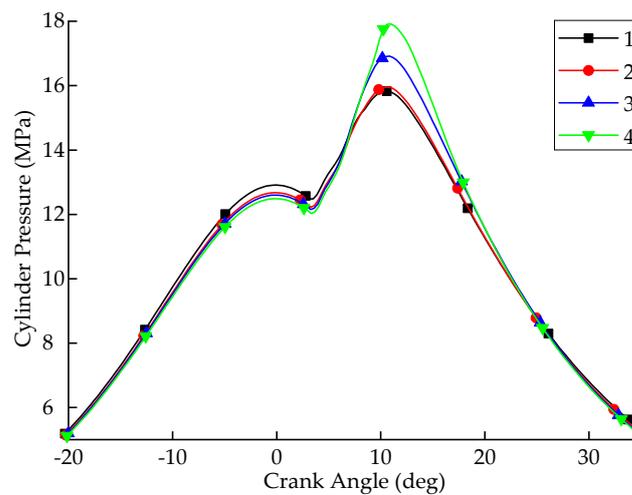


Figure 8. Cylinder pressure comparison at high temperature and oxygen enriched.

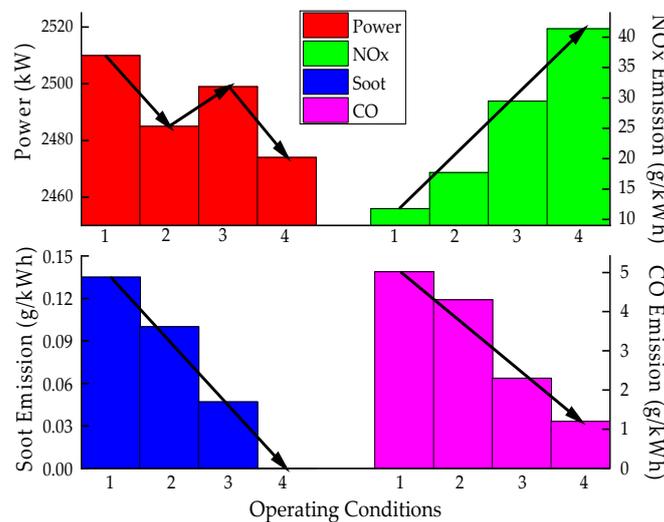


Figure 9. Emission comparison at high temperature and oxygen enriched.

As shown in Section 3.1.1, the increase in intake temperature will reduce the diesel engine’s power output and NO_x emissions. Figure 9 shows that the engine’s power output increased by oxygen percentage changes from 23% to 29% at 335 K. However, it is still lower than the normal intake condition 1. Although its combustion pressure at 40% O₂ condition is higher than the normal intake conditions, its power output is still lower than that of 23% O₂. The increase of oxygen was not enough to make up for the influence of the rise of intake temperature on the diesel engine’s power output, and it is difficult to achieve the power output under normal intake conditions. The engine’s NO_x emission increases exponentially

with oxygen percentage from 23% to 29%, and its influence is significantly greater than the one of intake temperature. Therefore, it is difficult to optimize the performance of diesel engines' power output and emissions through the combination of high temperature and oxygen-enriched intake.

3.2.2. High Intake Temperature and Low Oxygen

Under the intake temperature of 295 K, changed volume percentage of O_2 and N_2 with 20% O_2 , 19% O_2 and 18% O_2 were used as boundary conditions, which corresponds to conditions 2, 3 and 4 in Figures 10 and 11, respectively. The results were compared with the normal intake condition 1 (315 K, 21% O_2). As shown in Figure 10, the compression pressure of conditions 2, 3 and 4 are higher than condition 1, which is consistent with Section 3.1.2. Moreover, low oxygen intake can effectively slow down the combustion process and reduce the maximum combustion pressure. The maximum combustion pressure is even lower than the one in condition 1.

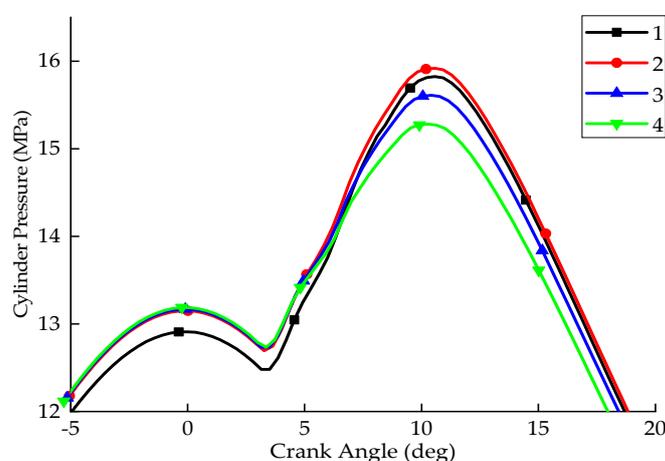


Figure 10. Cylinder pressure comparison at low temperature and low oxygen.

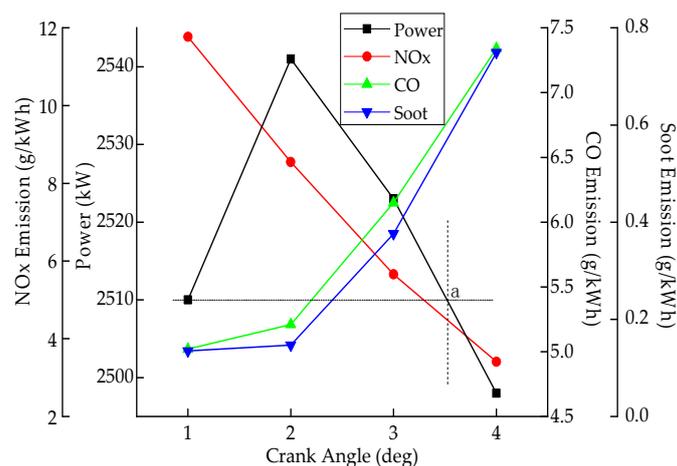


Figure 11. Emission and power comparison at low temperature and low oxygen.

Figure 11 shows that the power output and NO_x emission both decrease when the oxygen concentration changes from 20% O_2 to 18% O_2 at 295 K intake temperature, which is also consistent with the conclusion in Section 3.1.2. The engine's power output in condition 2 is higher than the normal intake in condition 1, and its NO_x emission is only 50% of that in condition 1. With the oxygen concentration further reduced to 18%, its NO_x emission is only 3.41 g/kWh less than 3.44 g/kWh which is the requirement of IMO NO_x emission Tier III. However, its power output has 12.5 kW lower than the normal intake condition. Therefore,

when the intake temperature is 295 K and the O₂ volume fraction is adjusted to about 18.5%, the engine's NO_x emission can be effectively reduced by 58% to 4.5 g/kWh, which is slightly higher than the emission of Tier III. Moreover, its power output remains unchanged with normal intake condition 1, as shown in position 'a' of the line in Figure 11. Therefore, the performance of the diesel engines can be effectively optimized by low temperature and low oxygen intake combination.

3.3. Effects of Different Intake Components

Based on the previous research results, the effects of different gas components on the diesel engine power output and emissions performance were explored via low temperature and low oxygen. According to the characteristics of the marine diesel engine, it can recycle exhaust gas or directly add water steam from the boiler to dilute the oxygen concentration in the intake air. Different proportions of CO₂ or H₂O gas into the intake were set in the calculation model. The calculated power output and NO_x emissions are shown in Figure 12, its conditions from 1 to 6 are as follows: 1 (295 K, 20% O₂ and 78.8% N₂), 2 (295 K, 20% O₂ and 79.4% N₂), 3 (295 K, 20% O₂ and 80% N₂), 4 (295 K, 20.58% O₂ and 77.42% N₂), 5 (295 K, 20.79% O₂ and 78.21% N₂), 6 (315 K, 21% O₂ and 79% N₂).

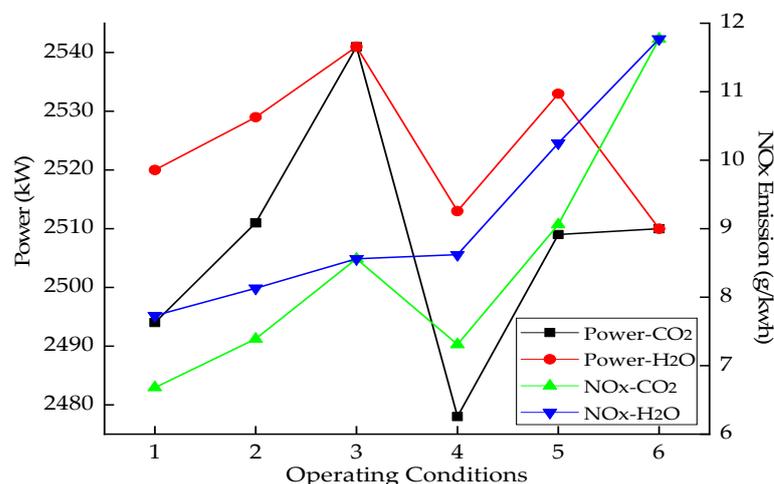


Figure 12. Comparison of power and emissions at different intake conditions.

As shown in Figure 12, when CO₂ or H₂O gas is added in the same proportion (other conditions remaining unchanged), the engine's power output and NO_x emission in CO₂ conditions are both lower than those in H₂O gas conditions, which is caused by the difference in the thermal physical properties of CO₂ or H₂O gas. The heat absorption of the combustion process in the cylinder is different as well. The comparison between conditions 2 and 3 shows that nitrogen is replaced by 0.06% CO₂ or H₂O gas when oxygen concentration is 20%. The engine's power output and NO_x emission are lower than pure O₂ and N₂ in condition 3 (2541 kW and 8.56 g/kWh), condition with H₂O gas is 2529 kW and 8.13 g/kWh, and the lowest in the condition with CO₂. In condition 2, replacing nitrogen in the intake with 0.06% CO₂, the engine's power output is 2511 kW, which is slightly higher than the power output of 2510 kW in the normal intake condition 6. However, its NO_x emission is only 7.39 g/kWh, which is significantly lower than 11.77 g/kWh in the normal intake condition. Therefore, NO_x emission can be reduced by reducing the intake temperature and the low oxygen intake combination optimization, while ensuring that the power output fluctuates only slightly.

According to the comparative analysis of conditions 4, 5 and 6 in Figure 12 with Figure 11, there are some intake conditions (adding CO₂, H₂O gas or N₂ to reduce O₂ concentration at 295 K) which make the diesel engine output unchanged and NO_x emissions reduced. Based on the studies carried out, it is confirmed that the 4.5 g/kWh NO_x emission is the smallest, which is achieved by adding nitrogen to reduce O₂ concentration to 18.5%.

NOx emission in condition 4 with 20.58% O₂, 77.42% N₂ and 2% H₂O gas is 8.62 g/kWh. 9.06 g/kWh NOx emission is relatively higher in condition 5 with 20.79% O₂, 78.21% N₂ and 2% CO₂. NOx emissions in the above conditions are significantly lower than 11.77 g/kWh in normal intake conditions.

4. Conclusions

This study investigates the potential ways of optimizing the marine diesel engine's performance while reducing the impact of its emissions on the environment, all in response to the rising global environmental awareness. Based on the analyses elaborated above, the main conclusions of the study are as follows:

(1) With the increase of intake temperature, the oxygen content per unit of volume in the cylinder decreases, the engine's power output and NOx emissions of the marine diesel engine decrease, with no apparent effect on reducing NOx emissions.

(2) With the increase of oxygen volume fraction in the intake, the marine diesel engine fuel combustion is perfected, combustion temperature in the cylinder increases, and power output is enhanced. Furthermore, the soot and CO emissions are reduced. However, its NOx emissions show a certain degree of increase.

(3) The NOx emissions can be reduced by nearly 58% with the power output remaining nearly unchanged by optimizing the low temperature and low oxygen intake which is under 18.5% O₂ and 81.5% N₂ at 295 K, is about 4.5 g/kWh. NOx emission is only 3.41 g/kWh when O₂ concentration is further reduced to 18% by adding N₂. It is lower than 3.44 g/kWh, which is the requirement of IMO NOx emission Tier III.

(4) Under 295 K intake temperature, the engine's NOx emission under some different components' intake is significantly better than 11.77 g/kWh with normal air intake conditions (315 K, 21%O₂ and 79% N₂) such as 20.58% O₂, 77.42% N₂, 2% H₂O gas and 20.79% O₂, 78.21% N₂, 2% CO₂. Especially, the NOx emission is only 8.62 g/kWh under H₂O gas conditions. Moreover, the diesel engine power output under the above conditions are consistent with the normal intake conditions.

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