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Research Article

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Simulation study of high load diesel-methanol dual fuel marine engine

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Abstract Methanol alternative fuels have greater potential in the marine sector. A simulation study of a diesel-methanol dual-fuel marine engine was conducted using a 6-cylinder turbocharged intercooled marine diesel engine as a prototype and a computational fluid dynamics approach combined with a chemical reaction kinetic mechanism. The results show that the peak cylinder pressure is lower in the dual-fuel mode than in the diesel mode, and the ignition delay is longer than in the diesel mode. As the engine load increases, the engine cylinder pressure increases and the ignition delay decreases. The dual fuel mode is lower in NOx emissions and higher in HC emissions than the diesel mode. Moreover, NOx emissions increase and HC emissions decrease with increasing engine load.

Keywords Dual fuel, Combustion, Emission

1. Introduction

Diesel engines are widely used in the transportation industry because of their high efficiency and reliability. However, pollutant emissions of diesel engines have a huge impact on the environment and human health. Therefore, the requirements of marine diesel engine emission standards are becoming more and more strict, and it is imperative to study various emission reduction strategies. [1] On the other hand, with the development of transportation industry, the demand for energy is also increasing. In response to environmental and energy issues, renewable energy sources such as natural gas [2], biodiesel [3], alcohols [4], hydrogen [5] and ammonia [6]are studied, methanol has unique advantages over other fuels. Methanol is a renewable energy source that can be made from captured carbon dioxide and photolytic hydrogen. [7] Moreover, methanol is a liquid at room temperature and pressure, which makes it easy to store and transport, and it has low production cost. Due to the high oxygen content of methanol and the absence of carbon-carbon bonds, particulate matter emissions can be greatly reduced. Meanwhile, methanol has a higher flame propagation speed, resulting in efficient and clean combustion in internal combustion engines. [8]

Considering the high latent heat of vaporization of methanol, the current applications of methanol in diesel engines are diesel/methanol blends, methanol port injection and methanol direct injection. [9] However, because of the different properties of methanol and diesel, they are incompatible with each other and require a co-solvent to help blend methanol and diesel, which increases the cost of the fuel. The use of direct in-cylinder injection for methanol and diesel requires a redesign of the cylinder head as well as an increase in the fuel supply system, which is a major modification to the original diesel engine. Methanol port injection means that methanol enters the cylinder with air during the intake process and diesel fuel is injected for ignition when the piston runs to the top dead center. However, methanol absorbs a lot of heat when it is injected to the intake manifold, because of the high latent heat of vaporization of methanol, causing engine misfires. To solve this problem, Professor Yao proposed that the concept of diesel/methanol Combined Combustion (DMCC) [4]. The engine was started with pure diesel fuel and after the engine was warmed up, the methanol valve was opened to use diesel/methanol dual fuel. This method is used in this study because it is less modifying to the engine, less costly and effective.

In order to further explore the operating range of diesel-methanol dual fuel mode in marine engines and analyze the engine performance and emissions under different operating conditions. In this paper, based on CONVERGE software combined with the kinetic mechanism of diesel methanol chemical reaction, a numerical simulation model of engine in-cylinder was established and the reliability was verified. Through the method of computational fluid dynamics, the in-cylinder combustion and emission performance under high load in diesel mode and dual-fuel mode are analyzed with emphasis, which provide theoretical basis for the actual engine design and modification.

2. Numerical Model

The diesel-methanol dual-fuel engine was modeled using CONVERGE software combined with the kinetic mechanism of the diesel-methanol chemical reaction. The engine used in this study is a six-cylinder water-cooled turbocharged marine diesel engine produced by Zichai. The main parameters of the engine are shown in Table 1. Because the injector is used with six holes, a model of one-sixth is used to save calculation costs. The geometry built using Creo software is shown in Figure 1, and the computational model built by CONVERGE is shown in Figure 2.

Table 1: Specification of Models in stage

Parameter	**Value**
Bore × Stroke	170 × 200 mm
Compression ratio	14.5
Rated power	450 kw @ 1500 r/min
IVC	-140 °CA ATDC
EVO	115 °CA ATDC
Nozzle number	6

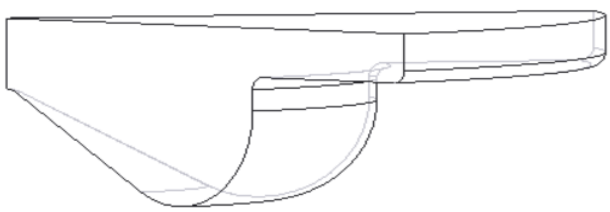

Figure 1: The geometric of combustion chamber

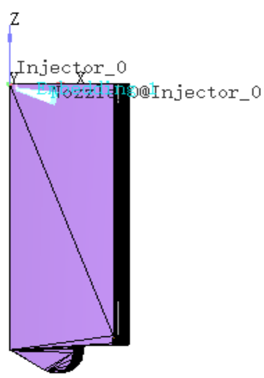

Figure 2: Computational Models

In order to better predict the physical and chemical changes in the cylinder, the RNG k-ε model was chosen as the turbulence model, the KH-RT model was chosen for the droplet fragmentation model, the Wall film model was used to simulate the spray-wall interaction, and the NTC collision model was used to calculate the droplet collision. And the SAGE model is used to calculate the reaction rate of combustion. Besides, the chemical kinetic mechanism of methanol/n-heptane combustion proposed by Liu et al.[11] was used in this study, including 52 species and 182 reactions. Meanwhile, Hiroyasu soot model was used to calculate the carbon soot generation and Extended Zeldovich NOx model was used to calculate the NOx formation.

Bench tests were performed prior to the simulation calculations, and the resulting test data were added to the calculations, such as the mass flow rate of diesel or methanol. The calculation time is from the IVC (intake valve closing) to the EVO (exhaust valve opening), without considering the intake and exhaust process. And the lower surface of the cylinder head, the cylinder wall, and the upper surface of the piston are the boundaries. In the adaptive grid encryption, the temperature from the beginning of oil injection (-5°CA ATDC) to the end of the calculation is set with 2 levels of adaptive mesh refinement, and the spray holes are set with 3 levels of fixed embedding. The substitution rate is the ratio of methanol energy to total energy and is given by the following equation.

$$MSR = \frac{m_M \times LHV_m}{m_D \times LHV_D + m_M \times LHV_m} \times 100\%$$

where, $m_D$and m_M are the mass flow rate of diesel and methanol respectively, LHV_D and LHV_m are the lower heating value of diesel and methanol separately.

Figure 3 shows the experimental and simulated in-cylinder pressures. Although there are some differences between the experiments and simulations, the model has good accuracy.

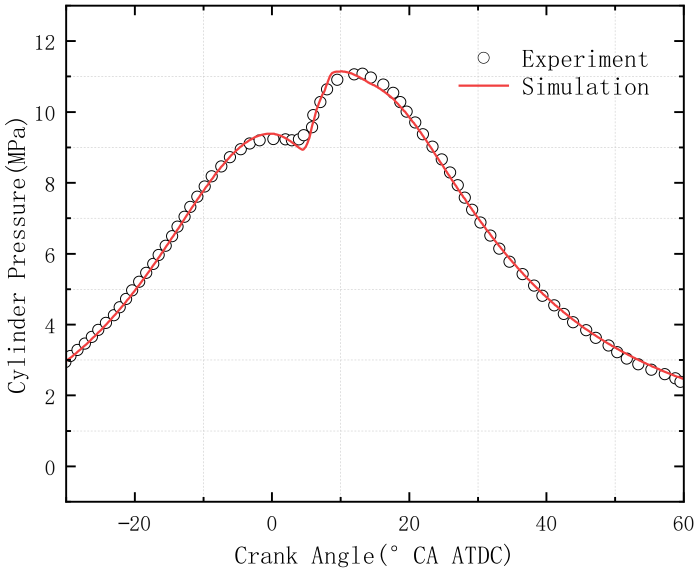

Figure 3: Model validation of the dual fuel model

3. Results and Discussion

3.1. Combustion Characteristics

Figure 4 and Figure 5 show the cylinder pressure and heat release rate curves at 75% load, respectively.

In dual fuel mode, the peak in-cylinder pressure decreases and the peak heat release rate increases. Moreover, the in-cylinder pressure during the compression stroke of the dual-fuel mode is lower than that of the diesel mode. Because of the high latent heat of vaporization of methanol, the inlet gas temperature decreases, while the temperature in the cylinder also decreases, and the ignition delay is prolonged, resulting in a decrease in cylinder pressure. Because the ignition delay period, the more evenly diesel, methanol and air are mixed, and the higher the peak of heat release rate. Figure 6 and Figure 7 show the cylinder pressure and heat release rate curves at 100% load, separately. In both modes, the engine in-cylinder pressure increases with increasing engine load. And, as the load increases, the ignition delay in dual fuel mode decreases. The peak heat release rate is higher for 75% load than 100% load in dual fuel mode due to the substitution rate limitation, but the ignition delay is smaller for 100% load than 75% load.

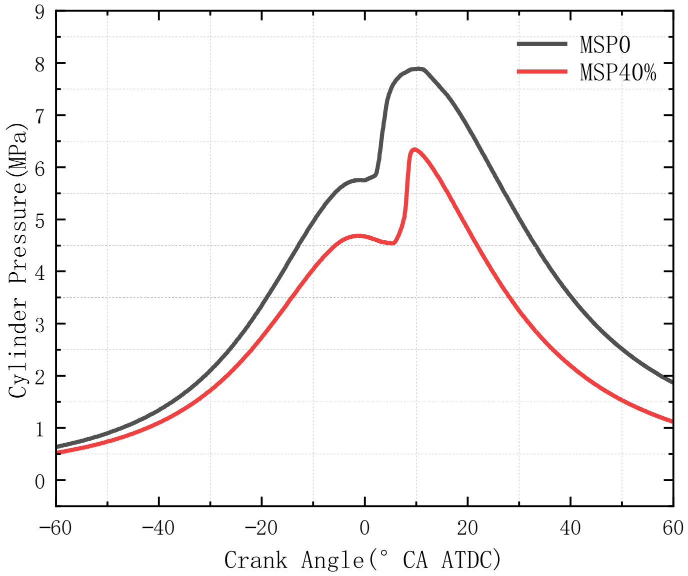

Figure 4: In-cylinder pressure at 75% load.

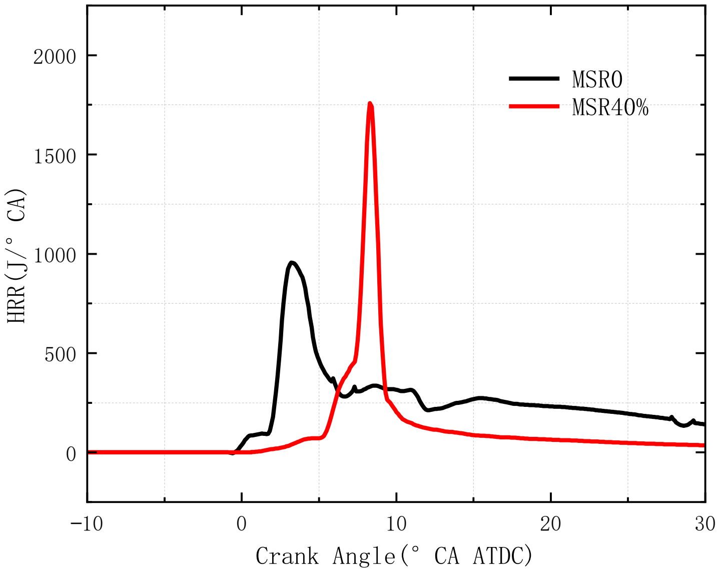

Figure 5: Heat release rate at 75% load.

3.2. Emission Characteristics

Figure 8 shows the NOx emissions at both loads. The generation of NOx is related to the temperature in the cylinder, the oxygen content and the duration of the high temperature. First, the latent heat of vaporization of methanol is high, which lowers the intake air temperature and in-cylinder combustion temperature. As a result, the methanol ignition delay becomes longer, the burning rate of the fuel becomes faster, the in-cylinder temperature will increase, but the combustion duration is shortened. On the other hand, the oxygen atoms in methanol may increase NOx, and various factors interact with each other. As can be seen from Figure 8, NOx emissions are significantly reduced in the dual-fuel mode compared to the diesel mode.

Figure 9 shows the HC emissions at both loads. Because the higher latent heat of vaporization lowers the cylinder temperature, the thickness of the quenched layer in the cylinder increases, the methanol is not completely burned, and some of the unburned methanol is exhausted with the exhaust gas. Moreover, the lower in-cylinder temperature reduces the oxidation rate of HC, so the dual-fuel mode produces higher HC emissions than the diesel mode. However, the HC decreases with increasing load, because the cooling effect of methanol decreases with increasing load.

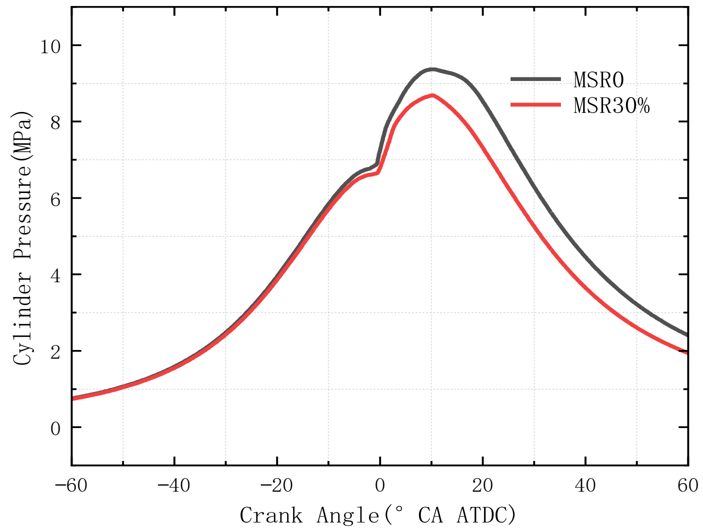

Figure 6: In-cylinder pressure at 100% load

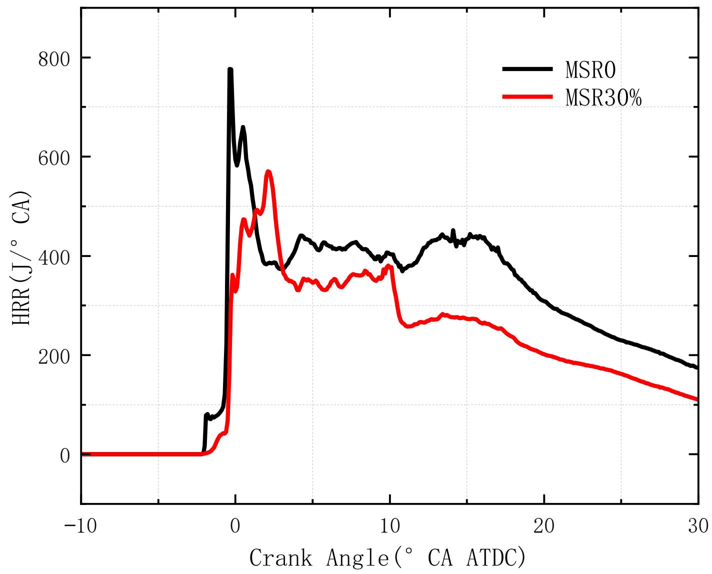

Figure 7: Heat release rate at 100% load.

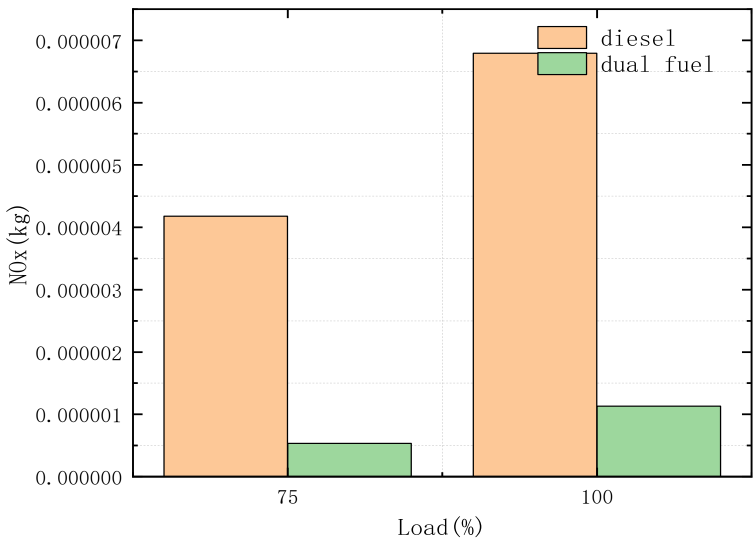

Figure 8: NOx emission

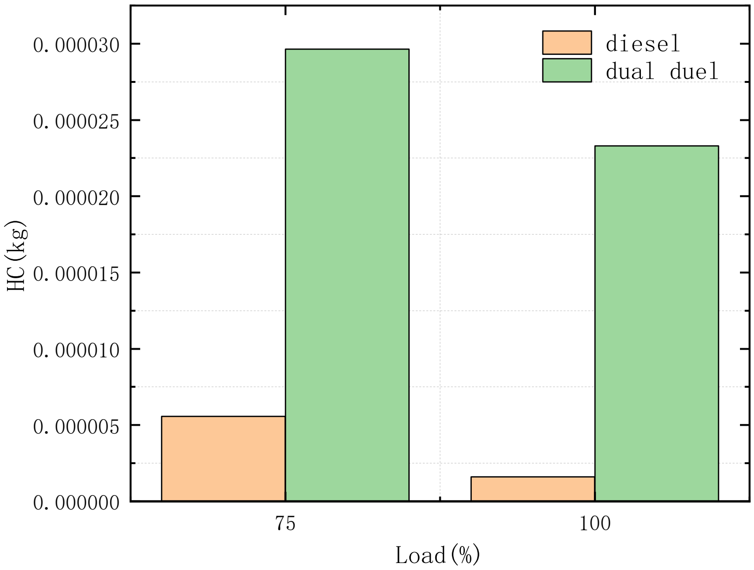

Figure 9: HC emission

4. Conclusion

In this article, the in-cylinder combustion and pollutant emissions of marine diesel engines in high-load diesel mode and diesel/methanol dual-fuel mode were studied by means of simulation. The main findings are as follows:

The peak cylinder pressure of dual-fuel mode is lower than that of diesel mode, and the cylinder pressure gradually increases as the load increases, with a small difference in cylinder pressure between the two modes at 100% load. And, the ignition delay is longer in dual-fuel mode than in diesel mode, with the gap decreasing as the load increases. Moreover, the peak heat release rate of dual-fuel mode is higher than that of diesel mode at 75% load and 40% substitution rate, and the peak heat release rate of dual-fuel mode is slightly smaller than that of diesel mode at 100% load and 30% substitution rate. The NOx of dual-fuel mode is significantly less than diesel mode, but the HC is higher than diesel mode, and the NOx increases and the HC decreases with increasing load.

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