Numerical simulation of in-cylinder combustion characteristics of LNG-diesel dual-fuel engine

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Abstract: Three-dimensional numerical simulation of diesel engine cylinder combustion process was carried out by using computational fluid Dynamics (CFD) software AVL-FIRE. The combustion characteristics of LNG under different ignition diesel ratio, cylinder pressure were studied. Through the simulation calculation of pilot diesel ratio, cylinder pressure, combustion heat release rate, the analysis results showed that the minimum value of pilot diesel ratio was not less than 0.5. During a cycle, there was no cliff-like change in cylinder pressure. CFD simulation has guiding significance for optimizing combustion chamber structure parameters and improving diesel engine performance. CFD simulation is instructive for the optimization of diesel engine performance.

1.Introduction
With the entry into force of the International Maritime Organization (IMO) regulations on diesel engine exhaust emissions, it has become one of the hot spots in diesel engine emission research to seek alternative fuels besides fuel oil and realize clean combustion. Dual-fuel combustion strategy is to combine diesel fuel system with natural gas fuel system. The mixture of air and natural gas are inhaled in cylinder, and then a small amount of diesel oil is injected into diesel injector for ignition. This dual-fuel combustion mode can further reduce emissions and achieve the goal of clean combustion[1]. Natural gas is considered as one of the most suitable alternative fuels because of its advantages of wide distribution, low price and good anti-storm performance[2,3]. Some achievements have been made in the research of LNG-diesel dual fuel combustion in China. Lin Zhiqiang et al. revealed the effects of factors such as pilot fuel quantity and excess air coefficient on combustion. They found that when the natural gas content in the cylinder was relatively thin, the stable ignition and combustion of natural gas can be realized by the ignition method of diesel natural gas[4,5]. Gansu University has studied the influence of different substitution rates on fuel economic and emission performance of diesel/natural gas dual-fuel engine. The results showed that with the increase of substitution rate, the effective fuel consumption rate of dual-fuel engine decreased. NO emission declined first and then climbed up. HC emission was rising, but CO and soot emissions were falling[6]. Long Yanxiang et al. found that the fuel consumption rate and HC rised in different degrees with the increase of LNG content. And NO and CO showed different rules at high and low loads[7].

Based on the current researches, there are few researches on diesel pilot quantity, dual fuel injection angle. Taking the marine medium-speed diesel engine as the research object, and using AVL-FIRE software, we simulated the combustion in cylinder and made a research on diesel pilot quantity, by the change of the condition such as the change of the dual fuel combustion characteristic.
With deep understanding of the mixture and combustion process of diesel oil and LNG, it helped to add to the dual fuel combustion characteristic research fundamentals, and deepen the understanding of the dual fuel combustion so as to guide the dual fuel engine performance optimization.

2. Computational model
The turbulent diffusion equation adopts $k-\zeta-f$ equation with high stability and good accuracy. The primary crushing model selects Blob Injection and KH-RT for the secondary crushing model. The evaporation model is Multi-component evaporation model. The Walljet 1 model suitable for hot wall is selected for the wall collision model. We chose the ECFM-3Z model for the combustion model which is specifically for the combustion of multi-component fuels. Considering the high temperature in the combustion chamber and the uneven distribution of fuel injected directly into the cylinder, the extended Zeldovich model is selected as the NO emission model.

3. Geometric Modeling and Grid Division

3.1. Initial parameters
In this paper, the marine medium-speed diesel engine is selected as the research object. The grid model is established according to the structure size of the diesel engine cylinder combustion chamber. The fuel injector is set as LNG/ diesel common fuel injection mode to simulate the combustion of dual-fuel engine. See table 1 for injector parameters.

| Main initial parameter                        | diesel oil |
|-----------------------------------------------|------------|
| Orifice diameter (mm)                         | 0.335      |
| Single cylinder injection per cycle/g         | 1.56       |
| Number of nozzle holes                        | 9          |
| Angle of spray hole/ ($^\circ$)               | 156        |
| Injection time                                | 710$^\circ$CA |
| Injection duration angle                      | 30$^\circ$CA |

3.2. Computational grid generation
The FIRE software ESE Diesel module is used to generate the model and mesh it. Because the injector studied in this paper has 9 holes and is centrosymmetric, 1/9 slice of the combustion chamber is selected for modeling. Fig. 1 is the combustion chamber grid when piston is at top dead center (TDC), 670$^\circ$CA and intake valve is closed.
3.3. Model verification

The calculated working condition is the rated working condition of the original engine. The boundary conditions used for calculation are shown in Table 2. Comparing the calculated curve of in-cylinder pressure with crank angle with the curve of in-cylinder pressure obtained by bench test, the pressure curves are basically consistent, indicating that the established model is correct, as shown in Figure 2.

| Cylinder wall temperature/K | Cylinder head temperature/K | Piston top temperature/K | Initial temperature in cylinder/K | Diesel injection temperature/K |
|-----------------------------|-----------------------------|--------------------------|----------------------------------|-------------------------------|
| 520                         | 450                         | 550                      | 341                              | 404                           |

Fig. 2 Measured pressure curve and simulated pressure curve

4. Analysis of Simulation Results

4.1. The influences of different proportions of pilot diesel oil on the ignition of liquefied natural gas (LNG) in cylinders
Different proportions of pilot diesel directly affect the ignition boundary of in-cylinder combustion, and then affect the combustion process in the combustion chamber. In this paper, we analyze the cylinder combustion process at different crank angles when the proportion of pilot diesel oil is 0.3%, 0.4% and 0.5%. Figure 3 demonstrates the combustion temperature distribution of different proportions of pilot diesel oil in the combustion chamber. When the amount of pilot diesel oil is 0.3%, the diesel oil in the cylinder cannot be compressed and ignited, and LNG in the cylinder cannot be ignited due to low diesel content. When the proportion of pilot diesel oil is 0.4%, diesel oil is compressed and burn in the cylinder, but with the injection of LNG the combustion flame is covered by LNG and LNG absorbs a lot of heat. The heat provided by diesel oil combustion is not enough to ignite LNG, which leads to the ignition of pilot diesel oil being extinguished. When the proportion of pilot diesel oil is 0.5%, the heat generated by the combustion of pilot diesel oil reaches the combustion point of LNG, thus igniting LNG and realizing dual fuel combustion. In a nutshell, when the proportion of pilot diesel oil is 0.5%, it is a safe amount to ignite LNG, and when it’s less than 0.5%, it cannot ignite LNG.

| Pilot diesel fuel ratio | Crankangle /°CA |
|------------------------|-----------------|
|                        | 716             | 718             | 730             |
| 0.3%                   |                 |                 |                 |
| 0.4%                   |                 |                 |                 |
| 0.5%                   |                 |                 |                 |

Fig 3 Temperature distribution when the ratio of pilot diesel is 0.3% , 0.4% and 0.5%

4.2. The influence of different proportion of pilot diesel oil on the combustion characteristics of LNG in cylinder

After simulation, it is confirmed that LNG in the cylinder can be ignited only when the proportion of diesel oil is 0.5%. Further research can be conducted to explore the influence of different proportions of pilot diesel oil on in-cylinder combustion. Figure 4 and Figure 5 are the curves of cylinder average pressure and heat release rate under different crankshaft angles respectively. During the operation of piston at 680-840 CA, the in-cylinder pressure curve is smooth. There is no cross-sectional increase or decrease, and no deflagration phenomenon. At 710°CA, the increase rate of in-cylinder pressure starts to rise. When it reaches 730°CA, the combustion pressure in the cylinder with a pilot diesel ratio of 10% is the largest. As the pilot diesel ratio decreases, the corresponding pressure curves decrease in sequence. The heat release rate curve shows that the combustion is mainly divided into two processes. At 713°CA, it is mainly diesel combustion. The heat release peaks for the first time. As the combustion is completed, the heat release rate gradually decreases. At this time, the natural gas has not yet started to burn. With the completion of combustion, the heat release rate gradually decreases. At this time, natural gas has not yet started to burn. After 718°CA, it starts to rebound after reaching the
trough. At this time, LNG starts to burn. With the combustion going on, the second peak appears and keeps releasing heat continuously. At 740°C, the heat release rate starts to decline sharply. The final combustion is complete.

![In-cylinder pressure curves with 2%, 6% and 10% pilot diesel fuel](image)

Fig. 4 In-cylinder pressure curves with 2%, 6% and 10% pilot diesel fuel

![In-cylinder heat release rate curves with 2%, 4% and 6% pilot diesel fuel](image)

Fig. 5 in-cylinder heat release rate curves with 2%, 4% and 6% pilot diesel fuel

5. Conclusion
In this study, we use the CFD software to establish the model, and obtain the objective theoretical data by simulating the combustion chamber, which has guiding significance for the optimization of diesel engine performance.

Through the simulation calculation of software, we get that the lowest proportion of pilot diesel oil in liquid natural gas is 0.5%. With the increase of the proportion of pilot diesel oil, the pressure in the cylinder increases. In a cycle, the cylinder changes smoothly without any cliff change. In the process of cylinder combustion, both diesel and gas combustion have a peak and then reach the maximum heat release effect respectively.

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