Simulation Analysis of Influence of Boundary Parameters on the Performance of Gasoline Compression Ignition Engine

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Abstract. In order to solve the problems of combustion instability and excessive discharge of gasoline compression ignition (GCI) engine at low load, three-dimensional numerical simulation software CONVERGE is used to establish engine simulation model, and the main factors controlling combustion such as the oxygen content and the intake pressure are simulated and analyzed. The results show that when the volume fraction of the oxygen content of intake is 23%, higher thermal efficiency and lower emissions can be achieved. When the intake pressure is 0.12MPa, the peak of heat release rate is the highest and the combustion efficiency is high. The research results provide basic data and theoretical basis for achieving stable combustion at low load conditions.

1. Introduction

Under the dual challenge of environment and energy, the technology of homogeneous compression ignition and the low temperature combustion has been widely studied at home and abroad in recent years. In order to achieve high efficiency and low emission of internal combustion engines, some scholars at home and abroad put forward homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), and premixed compression ignition (PCI) and reactivity control compression ignition (RCCI) and other new combustion method [1]. Based on the research of the above combustion modes, Kalghatgi and others [2,3] put forward the gasoline partial premixed compression ignition (GCI) combustion method, the long delay period and the better atomization performance of gasoline fuel are used to achieve compression ignition in diesel engines for higher thermal efficiency and lower NOx and Soot emissions.

Gasoline partial premixed compression ignition (GCI) has received extensive attention and research as a new combustion method. A series of research has been carried out by researchers at home and abroad represented by Johnasson, Retiz and Zhang Yuseng [4-8], and the research shows that the gasoline compression ignition (GCI) mode can achieve higher thermal efficiency and lower NOx and Soot emissions, but there are still some problems such as self ignition to catch fire is difficult at low load, and poor combustion stability and excessive emission.

Combustion fluctuations and excessive emissions are main technical challenges faced by GCI engines at low load conditions. Therefore, with the aid of three-dimensional CFD software CONVERGE platform, the numerical simulation method is used to optimize the combustion and emission performance of the GCI engine at low load by changing the combustion control strategy such as rich oxygen intake air and intake supercharging.
2. Establishment and validation of model

Based on the ZH1130 single cylinder diesel engine, the simulation model is established, and the specific parameters are shown in Table 1.

Table 1. The main engine parameters

| Bore  | Stroke | Connecting rod length | Compression ratio | Displacement | Intake valve close timing | Exhaust valve open timing |
|-------|--------|-----------------------|-------------------|--------------|---------------------------|----------------------------|
| 130mm | 120mm  | 0.185mm               | 17                | 1.592L       | -142°CA ATDC              | 125°CA ATDC               |

The main parameters for calculating the boundary conditions based on the test data are shown in Table 2.

Table 2. The main parameters of boundary conditions

| temperature | Swirl ratio | Kinetic energy | Turbulent dissipation rate | Injection pressure | Injection timing | Simulation duration |
|-------------|-------------|----------------|---------------------------|--------------------|------------------|---------------------|
| 383K        | 1.2         | 35m²/s²        | 6800m²/s²                 | 18MPa              | -20°CA ATDC      | -142~125 °CA ATDC   |

The simplified geometry model established by Catia was imported into CONVERGE for boundary conditions, physical models and combustion model settings. The simulation calculations yielded 66204 high-mass adaptive meshes. The calculation of the cross section of the grid is shown in Figure 1.

Figure 1. Calculate the grid at bottom dead center

Comparing the cylinder pressure and heat release rate curves obtained from the simulation with the test curves to verify the availability of the model, and the comparison result is shown in Figure 2. The cylinder pressure and heat release rate curves are basically the same in the compression stroke, but there is a slight deviation in the power stroke, and within 10%. The error range is acceptable, which indicate that the calculation model used is reliable and the calculation model can accurately reflect the engine's operating characteristics.

Figure 2. simulation model validation
3. Analysis of Combustion Control Strategy

3.1. The Effect of Rich Oxygen Intake on Combustion and Emission

Rich oxygen intake can change the composition of the air-fuel mixture and accelerate combustion at low temperature and enhance the burnout property. It is effective on improving the performance of the engine. It is the main method to achieve stable combustion at low load. In order to study the effect of oxygen-enriched air intake on the engine's low load conditions, the conditions such as speed \( n = 1400 \) r/min, the fuel equivalent ratio is \( \varphi = 0.43 \), the injection time is \( 20^\circ \text{CA} \) BTDC are selected to simulate. The oxygen volume fraction is 21\%, 23\%, 25\% are selected to compare and analyze.

Figure 3 shows the influence curve of oxygen-enriched intake air on cylinder pressure and average temperature in the cylinder and instantaneous heat release rate of engine.

As shown in Figure 3, increasing the oxygen concentration can improve the fuel combustion performance and the combustion efficiency. When the oxygen volume fraction increases from 21\% to 23\%, the oxygen content in fuel and air mixture increase, which reduces the duration of combustion phase. Increasing oxygen content leads to combustion advance, and the energy release is concentrated, and the peak of heat release rate increases. Increasing the in-cylinder pressure and the average temperature can accelerate the combustion rate and stabilize the combustion process. When the oxygen volume fraction is 25\%, the oxygen content in the cylinder is high, excessive oxygen content is also detrimental to combustion for the GCI combustion mode. As shown in Figure 3(c), excessive oxygen content makes energy release too concentrated, and the peak of heat release rate increase rapidly, which lead to a drastic expansion of the working medium and worsen the combustion process. Under the influence of shock waves in the cylinder, the force of the piston is violent and the service life of the parts is reduced.

![Figure 3. Cylinder pressure, average temperature in the cylinder and heat release rate curve in rich oxygen intake](image-url)
The effect on NOx and Soot emissions of rich oxygen intake is shown in Figure 4.

Figure 4 shows that at the same crank angle, with the oxygen concentration increases, the NOx mass increases significantly. After 30°CA ATDC, it tends to be stable. With the increase of oxygen content, the average temperature in the cylinder increases and the high temperature oxygen enrichment is the ideal environment for the formation of NOx. Therefore, when the volume fraction is 25%, the NOx mass increases dramatically, and the emission is almost 3 times of 21%. Figure 4(b) shows that increasing the oxygen content has a significant effect on reducing Soot emissions. High temperature anoxia is the ideal environment for the formation of Soot. When the volume fraction is 21%, the average temperature in the cylinder is the lowest, but the reduction of oxygen content of combustion at the later stage, which results in the highest Soot mass. When the volume fraction is 25%, there is almost no area of oxygen anoxia during the combustion process, so the Soot mass is the lowest. Increasing the oxygen content in the cylinder can accelerate the combustion rate and increase the combustion efficiency, and promote the mixture combustion, and further inhibit the formation of Soot.

In summary, when the oxygen volume fraction increases from 21% to 23%, the combustion performance of the fuel is improved, and the GCI combustion is more stable at low load, and the mass of NOx increases, but the mass of Soot decreases. When the volume fraction of oxygen is 25%, the ignition is rapid and the heat release is too concentrated. The rate of pressure rise is too high, and the probability of knocking is large, and the combustion is unstable. After comprehensive analysis and comparison, oxygen volume fraction of 23% is more conducive to combustion at low load conditions.

3.2. Effect of intake supercharging on combustion and emissions

Intake supercharging is an effective means to expand the range of low load operating conditions for PPC combustion of high octane fuel. The intake supercharging can increase the intake air volume, and improve the combustion structure in the cylinder, and provide a more suitable combustion environment for the combustion of the engine. In order to study the effect of intake supercharging on the engine's low load conditions, the conditions such as speed n = 1400 r/min, the fuel equivalent ratio is φ = 0.43, the injection time is 20°CA BTDC are selected to simulate. The intake pressure is 0.1MPa, 0.12MPa, 0.15MPa are selected to compare and analyze.

Figure 5 shows the impact curve of intake supercharging on engine cylinder pressure and the average temperature in-cylinder and instantaneous heat release rate.

As shown in Figures 5(a) and 5(b), the intake supercharging has a significant effect on the pressure and average temperature in-cylinder. Intake supercharging makes the peak of pressure in the cylinder increase significantly, and the energy of the mixture increases, and the ignition timing advances. When the intake pressure is 0.15MPa, the pressure in cylinder increases drastically at 3°CA BTDC, and piston movement is affected. Intake supercharging will increase working medium charge in cylinder, and make the loss of heat transfer and exhaust loss increase, which result in a decrease in the average temperature in the cylinder. As figure 5(c) shows that when the inlet pressure is 0.12MPa, the peak of
the heat release rate is the highest, and the combustion efficiency is better. When the inlet pressure is 0.1MPa, the ignition point is formed at 2°CA ATDC, and the ignition is late. The flame propagation and heat release are suppressed, which increases the combustion fluctuation. When the intake pressure is 0.15MPa, the ignition is too early, and heat release basically complete before the piston reaching the top dead center, which causes serious mechanical loss. Proper intake supercharging will increase the frequency of collisions between molecules, and reduce the average time of molecular motion and accelerate the spontaneous ignition of the fuel, and make the cylinder combustion more complete, which is conducive to stable combustion at low load conditions.

Figure 5. cylinder pressure, average temperature in cylinder and heat release rate curve during intake supercharging.

The effects of intake supercharging on NOx and Soot emissions are shown in Figure 6.

Figure 6. curves of NOx and Soot mass for intake supercharging

Figure 6(a) shows that at the same crank angle, the NOx mass first rises and then decreases with the increase of the intake pressure, and it tends to be stable after 40°CA ATDC. High temperature
oxygen enrichment is the ideal environment for the formation of NOx. When the inlet pressure is 0.12MPa, the temperature and oxygen are most suitable, and the NOx mass is the highest. When the inlet pressure is 0.15MPa, the temperature in the cylinder is the highest, but the oxygen content is relatively low, which inhibits the formation of NOx. When the inlet pressure is 0.1MPa, the temperature in the cylinder is the highest, but the oxygen content is relatively low, which inhibits the formation of NOx. Figure 6(b) shows that the Soot mass gradually decreases as the inlet pressure increases. When the inlet pressure is 0.1MPa, the ignition time is late, and the mixture combustion is poorly and the combustion efficiency is low, which result in increasing Soot mass.

In summary, appropriate intake supercharging can increase the energy of the mixture, and adjust the combustion phasing, which result in more efficient combustion. Appropriate intake supercharging is conducive to combustion at low load conditions, but NOx emissions will increase. Through comprehensive analysis and comparison, the intake pressure of 0.12MPa is more appropriate for combustion at low load conditions.

4. Conclusion
(1) Appropriately increasing the oxygen content of the intake air can improve the combustion performance of the fuel, and it will accelerate ignition and combustion at low temperature, and it will improve the combustion pressure and temperature and combustion efficiency. When the oxygen volume fraction is 23%, high thermal efficiency and low emission can be achieved. The cylinder pressure and average temperature and heat release rate are moderate during combustion, and fuel combustion is sufficient, and combustion efficiency is high. Soot emissions are ideal, and NOx emissions are significantly lower than when the oxygen volume fraction is 25%.

(2) Proper intake pressurization can increase the energy of the mixture; and it will optimize the combustion structure in the cylinder to achieve stable combustion at low load conditions. When the intake pressure is 0.12MPa, the cylinder pressure and the average temperature in the cylinder are moderate, the peak of heat release rate is highest and combustion efficiency is high and Soot emission is low. Although NOx emission is the largest, it is in an acceptable range.

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