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Effect of Passive Pre-chamber Igniting Position on the Large Bore Natural Gas Engine Combustion Characteristics

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Abstract

To get rid of the combustion instability and knock in combustion of low-concentration coalbed methane in the large-bore engine, the combustion-supporting effect of passive pre-chamber was studied, exploring the influence of passive pre-chamber igniting position on the combustion in pre-chamber, jet characteristics and overall combustion. Three-dimensional fluid simulation was conducted to study the influence of igniting positions on the combustion performance of the engine by setting a fixed ignition time and changing the igniting position.The results show that as the igniting position lowers, the combustion rate in the pre-chamber slows down, the combustible mixture escaped from the nozzle hole during the cold jet duration decreases, and more heat is used for the hot jet to ignite the combustible mixture in the main combustion chamber. When the igniting position is 2mm away from the bottom of pre-chamber, the indicated thermal efficiency of the engine reaches its best, which is 1.6% higher than the one at original igniting position.

Keywords

Passive Pre-chamber; Jet Characteristics; Natural Gas; Combustion.

1. Introduction

With the upgrading of emission regulations and the pursuit of low-carbon power, improving the thermal efficiency of internal combustion engines in the combustion field has always been the focus of attention. In many technical routes of spark ignition (SI) engines, lean burn technology is an advanced combustion technology, which can improve combustion quality and reduce heat transfer loss, so that higher compression ratio can be applied[1]. Due to poor combustion stability and ternary catalyst incompatibility, lean burn has not been widely used. At present, the focus of lean combustion technology research is to enhance ignition, and promote lean combustion by increasing ignition energy and enhancing turbulence intensity, thereby increasing flame propagation speed. In this regard, ignition technologies such as ion igniter[2], laser-induced ignition[3], corona spark plug system[4] and turbulent jet ignition system (Turbulent Jet Ignition, TJI) are proposed to improve ignition ability and promote combustion.

TJI technology is achieved by introducing a prechamber structure : the mixture is ignited in the prechamber to form a hot gas, so that the hot gas is ejected from the channel between the pre-chamber and the main combustion chamber to achieve multi-point ignition and ' plume ' (or torch) -like multi-flame propagation, which is conducive to promoting the rapid propagation and development of the flame, and achieving a more stable combustion while expanding the rarefaction limit[5]. According to whether there is additional fuel added inside the prechamber, the prechamber is divided into an active prechamber and a passive prechamber. The active prechamber can form different proportions of fuel between the main combustion chamber and the prechamber, further improve the lean burn limit of the engine and improve the thermal

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efficiency of the engine. However, the structure of the precombustion chamber is relatively compact, and the technical difficulty is relatively high when installing the combustion supply system, which is still in the research stage. There is only a spark plug inside the passive pre-combustion chamber, and the concentration of the mixture in the pre-combustion chamber is the same as that in the main combustion chamber, so the ability to improve the lean burn limit of the engine is limited. However, due to its simple structure, it has a great application prospect.

At present, there are two jet ignition modes of jet flame ignition and jet spontaneous combustion ignition in passive prechamber engine[6-10]. The ignition mode of the pre-chamber is determined by the diameter of the jet hole. Most of the TJIs use a multi-hole pre-chamber jet structure, which can organize the distribution of jet flame in the main combustion chamber, improve the combustion condition of the main combustion chamber, the uniformity of flame development in the main combustion chamber, and accelerate the combustion rate [11-14].

Yonghao Zeng et al.[15] studied the effects of ignition position and ignition timing on in-cylinder combustion and emissions in a methanol-gasoline mixed fuel rotary engine. It was found that ignition position and ignition time changed the ignition and combustion process in the cylinder by changing the collision time between the jet flame and the rotor wall, the intensity of the jet flame and the position of the jet flame entering the cylinder. Changhao Lu et al.[16]discussed the effects of different ignition timings on the combustion characteristics and emission characteristics of the engine in the performance analysis of the passive pre-combustion chamber of a low-load lean-burn natural gas engine. It was found that when the ignition timing was 27 and 32^{o}CA BTDC, when λ=1.9, the COVIMEP was 2.36%, and the combustion was still stable. Ja´cson Antolini et al.[8] studied the effects of ignition timing on flame area evolution, cylinder pressure, heat release rate, flame development angle and combustion duration in a single-bar passive pre-chamber engine. It was found that the flame development angle of the main combustion chamber was the smallest under MBT conditions and increased with the shortening or extension of MBT. The combustion center is delayed with the decrease of ignition advance angle. Fanjia Sun et al.[17] found that the ignition angle and exhaust VVT have little effect on the combustion stability of the engine.

In summary, the research on the ignition position in the passive prechamber has relatively little influence. In addition, most of the related research is aimed at small-bore engines, and rarely involves large-bore engines. Compared with the ordinary size engine, the large cylinder diameter engine has 'scale effect' and is prone to knock. In this context, this paper uses CFD simulation software to model the passive prechamber large-bore natural gas engine, and explores the influence of ignition position on the combustion process and jet characteristics of the main and prechambers, providing a reference for the ignition matching of the large-bore passive prechamber engine.

2. Model and Methods

In this paper, a three-dimensional simulation model is established based on a passive pre-chamber type large-bore natural gas engine for power generation. The traditional spark plug is replaced by a passive pre-chamber with a volume of 469.5mm3.There are five jet holes in the pre-chamber. The four jet holes around the pre-chamber are evenly arranged at an interval of 90°, and the angle between the two jet holes is 140°. The diameter of the four jet holes around the prechamber is 1.6mm, and the diameter of the middle jet hole is 1.8mm. The engine parameters are shown in **Table 1**, the prechamber and engine model are shown in **Figure 1**. The simulation calculation includes four strokes of intake, compression, work and exhaust, totaling 720^{o}CA. In this paper, 0°CA is defined as the compression top dead center position, and the spark timing is set to 24^{o}CA BTDC. The intake and exhaust valves and pistons are defined

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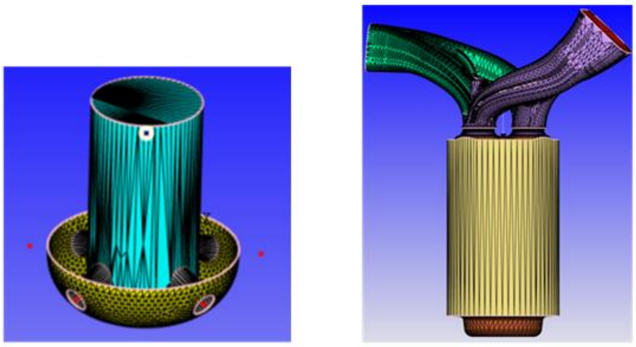
as moving walls, and the rest are fixed walls. The relevant boundary conditions are derived from the experimental data, as shown in **Table 2**. The calculation condition is rated condition, that is, speed 1000rpm, full load.

Table 1. Main specifications of the engine

Description	parameters
Stroke(mm)	320
Bore(mm)	210
Cylinder number	6
Compression ratio	11:1
Speed	1000rpm

In this paper, the SAGE model is used as the combustion model because it can simulate the combustion process based on the detailed reaction mechanism of the fuel. The fuel mechanism used in this paper is GRI 3.0, which is the most widely used methane reaction mechanism[18]. The RNG k-ε model is used to simulate the turbulent motion in the cylinder. The model can accurately predict the high-speed flow of the fluid and the complex flow of the working fluid such as the eddy current, and can accurately simulate the mixing and diffusion of methane and hydrogen in the cylinder, with good stability. The O 'Rourke and Amsden model was used to simulate the wall heat transfer process.



(a)Pre-chamber geometry model (b)Three-dimensional simulation model of engine

Figure 1. Pre-chamber and engine geometry model

Table 2. Boundary condition parameters

project	parameter
initial pressure (Mpa)	0.28
initial temperature(K)	884.0
inlet pressure(Mpa)	0.3
inlet temperature(K)	324
cylinder liner temperature(K)	438

After the grid independent line verification of the model, the basic grid size is set to 4 mm, and the two-level fixed encryption is carried out at the corner of the exhaust valve, and the minimum grid size is 1 mm. The main combustion chamber area, prechamber area and combustion grid size are 2mm, 1mm, 1mm. At the same time, monitoring points are set at the center of the overlap surface between each jet hole and the main combustion chamber to monitor the changes of pressure, temperature, turbulent kinetic energy and other parameters at the jet hole.

In order to verify the feasibility of the model, the combustion process of the engine is simulated under the condition of 1000r/min and full load. The experimental equipment is shown in **Table 3**. The fuel is methane, λ=1.6, and the ignition time is 24°CA BTDC. Through comparison, it is found that the peak cylinder pressure of the simulation and test is 12.78 Mpa and 12.83 Mpa respectively. The experimental value and the simulated value are in good agreement, and the error is within 5%. The model has high reliability and can be used for numerical simulation. The cylinder pressure curves of the test and simulation are shown in **Figure 2**.

Table 3. Main equipments of bench test

test system	type	accuracy of instruments
dynamometer system	Y1900 Hydraulic Dynamometer	torque measurement accuracy : ±0.2%
		velocity measurement accuracy : ±0.5%
air and fuel flow test system	TRIO-MASS mass flowmeter	mass flow accuracy : ±0.4%
		density accuracy : ±0.01%

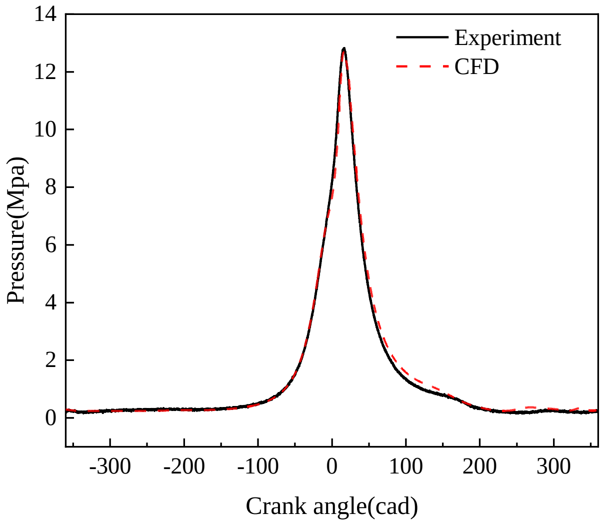


Figure 2. Validation of test and simulation results

3. Results and Discussion

1.1. Effects of Ignition Position on the Combustion Process of Pre-chamber

The residual carbon dioxide concentration at the spark plug and the distribution uniformity in the prechamber are also important indicators for evaluating the scavenging efficiency. The former can determine the ignition energy, and the latter can determine the stability of flame propagation[19]. Therefore, in order to study the influence of ignition position, taking the ignition position of 8mm as an example, the CO2 concentration and turbulent kinetic energy intensity in the prechamber before the spark plug work are analyzed in detail. From **Figure 3**, it can be seen that the concentration distribution of CO2 in the prechamber is relatively uniform, and the overall shows that the closer the CO2 concentration of the exhaust valve is, the thinner the CO2 concentration is. From top to bottom, the distribution of CO2 concentration on both sides of the middle is thin. The turbulent kinetic energy intensity in the prechamber is small, and the closer to the exhaust valve, the smaller the turbulent kinetic energy intensity, and the closer to the bottom of the prechamber, the greater the turbulent kinetic energy intensity.

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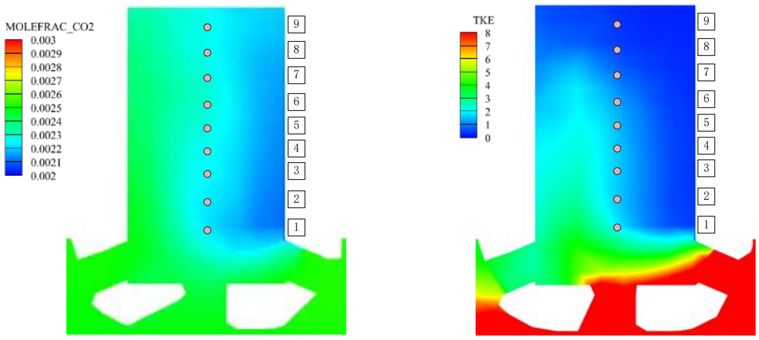
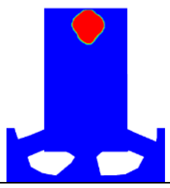
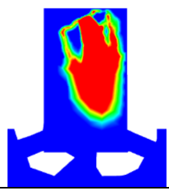
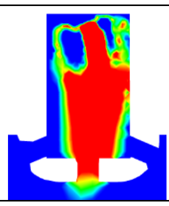
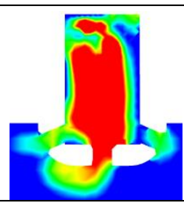
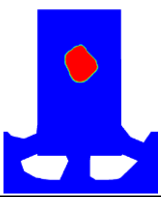
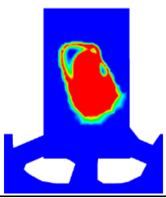
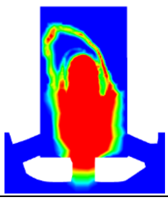
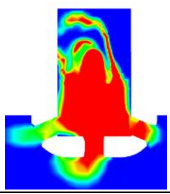
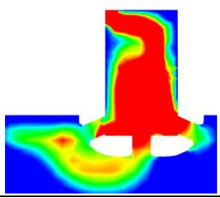
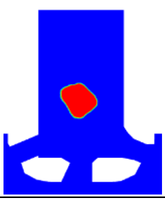
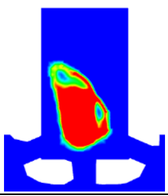
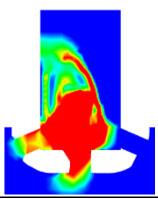
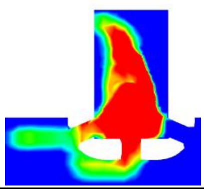
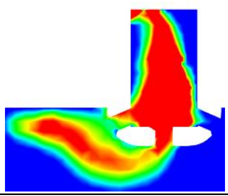


Figure 3. Distribution of CO2 concentration and turbulent kinetic energy intensity with prechamber before ignition

The OH radical is an important intermediate product of the combustion chain reaction. Its initial appearance can characterize the beginning of combustion. **Table 4** shows the flame propagation in the prechamber after ignition at three ignition positions of 9,6, and 3mm[19]. The flame propagation speed is the fastest when the ignition position is 6mm, and the flame propagation speed is the slowest when the ignition position is 9mm during the ignition of the spark plug (24°CA BTDC) to 17°CA BTDC. This is because when the ignition position is 6mm, the CO2 concentration is the thinnest and the turbulent kinetic energy intensity is slightly stronger. This ignition condition promotes the initial flame propagation. The turbulent kinetic energy intensity is 0 at the ignition position of 9mm, which inhibits the propagation of the initial flame. In the late combustion process of the prechamber, as the ignition position decreases, the flame propagation speed slows down. This is due to the fact that at the lower ignition position, the later flame propagates from bottom to top near the intake valve side, and then to the side near the exhaust valve. When the flame propagates from the bottom up, it is greatly disturbed by the flow field in the prechamber, and the flame propagation speed is weakened. And the lower the ignition position, the greater the interference of the flow field on the flame propagation velocity in the later stage of combustion in the prechamber.

Table 4. Main equipments of bench test

Development course	23°CA BTDC	20 °CA BTDC	17°CA BTDC	14°CA BTDC	11°CA BTDC
9					
6					
3					

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Due to the small volume of the prechamber, the combustible mixture content in the prechamber is low, resulting in a small pressure difference between the prechamber and the main chamber. Therefore, this study does not analyze the cylinder pressure in the combustion stage of the prechamber in detail. **Figure 4** shows the instantaneous heat release curve of the combustion stage of the pre-chamber at different ignition positions. When the ignition position of the spark plug is located at 8mm, the maximum heat release peak appears in the prechamber. After that, as the ignition position decreases, the heat release peak of the prechamber gradually decreases, the phase of the heat release peak continues to advance, and the heat release rate duration continues to increase. Among them, the main reason for the increasing heat release rate duration of the prechamber is that the combustion speed is small in the later stage, and the flame propagation is greatly disturbed by the internal flow field.

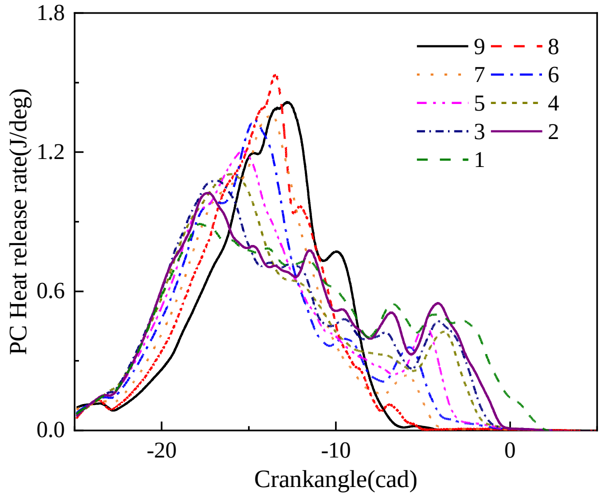

Figure 4. Heat release rate curve of prechamber with different ignition positions

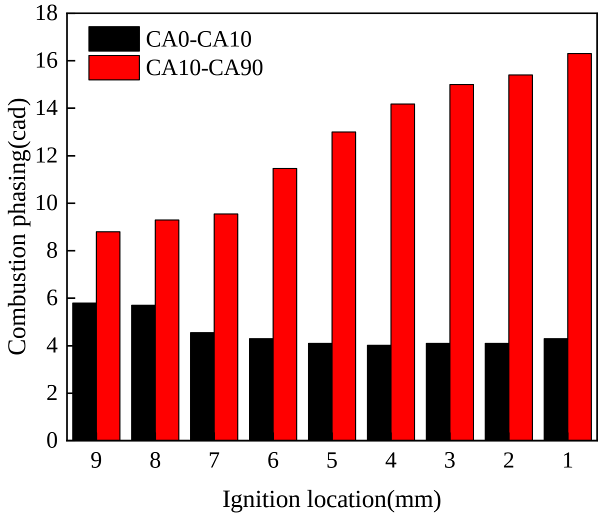

Figure 5. Variation of combustion phase in prechamber with different ignition positions

This paper defines the flame development period from the ignition time to the fuel release at 10% of the total amount, and the heat release from 10% to 90% is the rapid combustion period. **Figure 5** shows the variation of combustion phase in the prechamber at different ignition positions. As the ignition position decreases, the flame development period of the prechamber gradually shortens. When the ignition position of the spark plug is located at 4mm, the flame development period in the prechamber is the shortest, the ignition position continues to

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decrease, and the flame development period gradually increases. This is because as the ignition position decreases, the CO2 concentration increases slightly, and the turbulence intensity increases. The turbulence intensity at the ignition position of 4mm and above plays a major role in the enhancement of flame development. When the ignition position is located below 4mm, the inhibition of CO2 concentration on flame development is enhanced. In addition, as the ignition position decreases, the flame propagation in the prechamber is more obviously disturbed by the flow field in the later stage of combustion, the combustion speed becomes slower, and the rapid combustion period increases.

1.2. Effects of Ignition Position on Jet Characteristics

After the spark ignition in the prechamber, the turbulent flame develops rapidly in the pre-chamber, and the temperature and gas pressure in the prechamber rise rapidly. The combustible mixture in front of the flame flows into the main chamber through the outlet of the connecting channel to form a cold jet[20]. The jet characteristics of the prechamber directly affect the combustion in the main chamber. The unburned gas spilled during the cold jet and the turbulent kinetic energy generated in the main chamber inhibit and enhance the combustion in the main chamber, respectively. The hot jet is directly used for ignition in the main chamber[21]. Therefore, the influence of ignition position on jet characteristics is studied in detail in this paper. **Figure 6** compares the energy distribution of cold and hot jets in the pre-chamber at different ignition positions. It can be seen from the diagram that as the ignition position continues to decline, the energy contained in the cold jet and the energy of the unburned mixture escaped through the nozzle continue to decrease, the energy contained in the hot jet continues to increase, and the energy used for ignition in the main chamber continues to increase. As the ignition position continues to decline, the distance from the ignition position to the nozzle hole decreases, and the energy required for the flame to propagate to the nozzle hole (i.e., the energy contained in the cold jet) decreases. Because the combustible mixture covered by the ignition position to the bottom of the prechamber is reduced, the combustible mixture that can escape in front of the flame is reduced after the spark ignition.

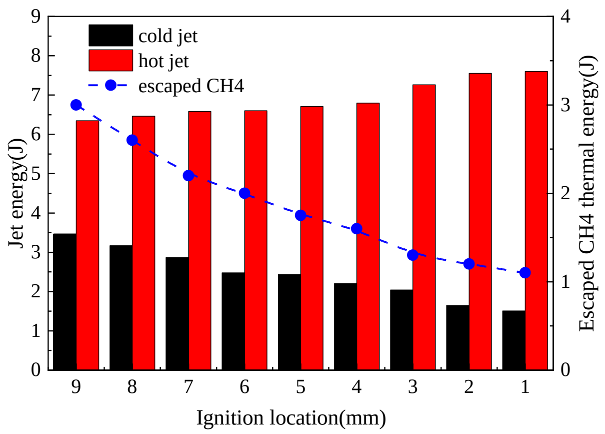

Figure 6. Distribution of cold and hot jet energy with different ignition positions

Figure 7 shows the duration of cold and hot jets at different ignition positions. It can be seen from the figure that as the ignition position decreases, the distance from the flame to the nozzle hole continues to decrease, the time of the cold jet and the hot jet appearing in the main chamber continues to advance, and the duration of the cold jet continues to shorten. As a result, the energy used for the cold jet and the heat of the combustible mixture escaping from the nozzle hole are reduced, so that more energy is used for the hot jet to ignite the main chamber and the hot jet enters the main chamber earlier, and the main chamber ignition is advanced. Because the flame propagation in the prechamber is disturbed by the flow field in the later stage of combustion, the combustion speed is slow, resulting in the continuous growth of the hot jet duration as the ignition position continues to decline.

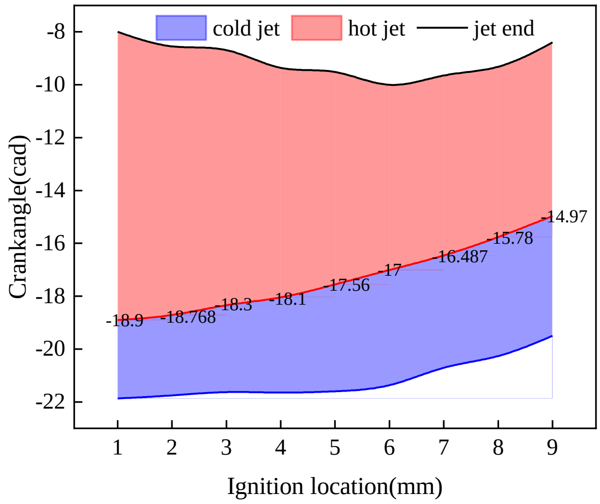

Figure 7. Variation of the duration of cold and hot jets with different ignition positions

Figure 8 compares the variation of the average velocity during the jet duration under different spark plug ignition positions. As the ignition position continues to decline, the average velocity of the jet shows a trend of rising first and then falling. The maximum average velocity of the jet appears at 7 ignition positions, and the higher the ability of the larger penetration distance in the main room.

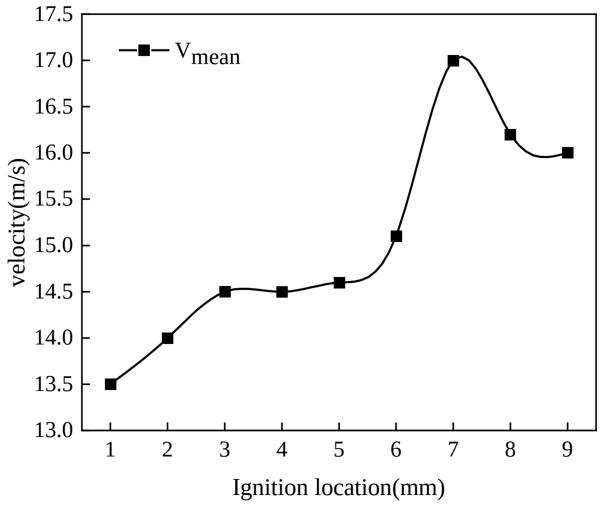

Figure 8. Variation of the average velocity of the jet with different ignition positions

1.3. Effect of Ignition Position on the Combustion Process of the Main Chamber

Figure 9-10 compares the variation of cylinder pressure and instantaneous heat release rate of the main combustion chamber under different ignition positions. Due to the decrease of the distance between the ignition position and the nozzle hole, the duration of the cold jet is shortened, the mass of the unburned mixture is reduced, the energy contained in the hot jet is increased and the time to enter the main combustion chamber is advanced. Therefore, the peak values of cylinder pressure and instantaneous heat release rate of the main combustion

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chamber increase continuously and the corresponding phases advance. However, the average velocity of the jet at the ignition position of 1mm is smaller than that at the ignition position of 2mm, and the heat jet energy at the two ignition positions is the same. Therefore, the peak cylinder pressure and instantaneous heat release rate of the main combustion chamber at the ignition position of 1mm are smaller than those at the ignition position of 2mm.

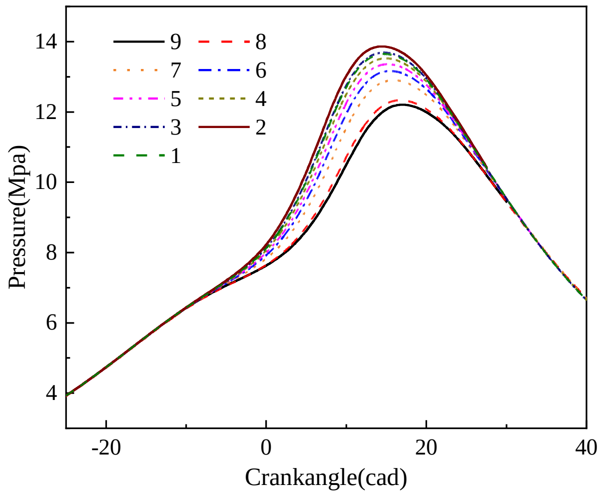

Figure 9. Cylinder pressure variation curves of main combustion chamber under different ignition positions

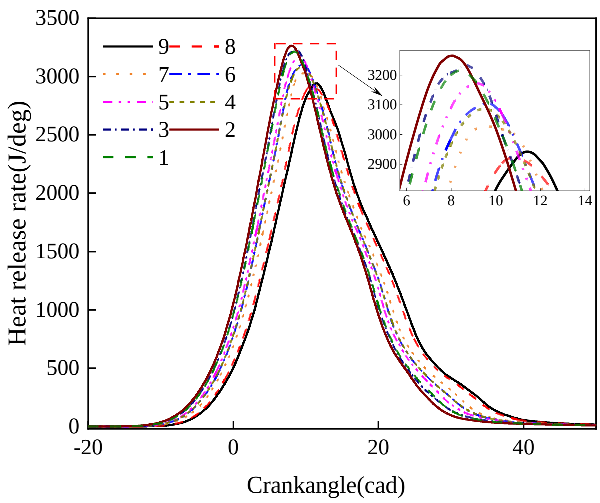

Figure 10. Heat release rate of the main chamber with different ignition positions

Figure 11 compares the variation of combustion duration of CA0-10 and CA10-90 in the main combustion chamber under different spark plug ignition positions. Due to the small volume of the prechamber, the methane content entering the prechamber during the compression stroke is small, and the ignition delay is large. CA0-10 is greater than CA10-90 at different ignition positions. The flame development period and rapid combustion period of the main combustion chamber change similarly with the ignition position. When the ignition position of the spark plug decreases from 9mm to 2mm, the hot jet energy of the prechamber increases and the main chamber appears earlier, which accelerates the combustion speed of the lean mixture in the main combustion chamber, so that the combustion duration generally shows a downward trend.

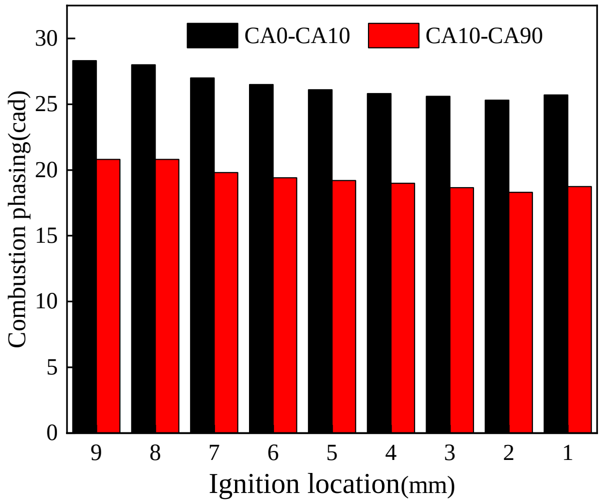

Figure 11. Variation of combustion phase in the main combustion chamber with different ignition positions

Figure 12 compares the variation of indicated thermal efficiency under different spark plug ignition positions. As the ignition position continues to decline, the indicated thermal efficiency of the engine generally increases first and then decreases. When the ignition position of the spark plug is located at 2mm, the indicated thermal efficiency has a maximum value, which is 1.6% higher than the original ignition position.

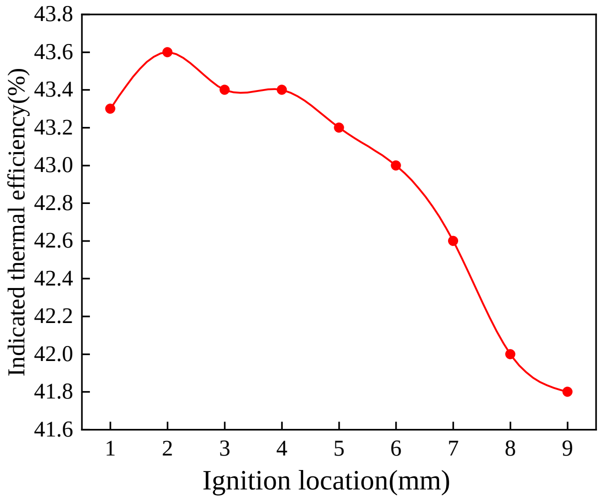

Figure 12. Variation of indicated thermal efficiency with different ignition positions

4. Conclusion

In this paper, a calculation model of a large-bore passive prechamber engine is established, and the influence of ignition position on prechamber combustion, jet characteristics and overall combustion is studied. Through the analysis of the simulation results, the following three conclusions are obtained :

(1) As the ignition position decreases, the combustion speed of the prechamber slows down. Although the flame propagation speed of the prechamber becomes faster in the initial stage after the ignition position decreases, the flame propagation speed gradually slows down in the later stage due to the interference in the prechamber.

(2) The ignition position continues to decline, and the combustible mixture escaping through the nozzle hole during the duration of the cold jet decreases, and more heat is used to ignite the

combustible mixture in the main combustion chamber by the hot jet. In addition, the occurrence time of the hot jet in the main combustion chamber is advanced with the decrease of the ignition position.

(3) The effect of ignition position on the overall combustion of the engine is mainly achieved by changing the hot jet energy and the time in the main combustion chamber. When the ignition position of the spark plug is located at 2mm, the indicated thermal efficiency of the engine is the largest, and the thermal efficiency is increased by 1.6% compared with the original ignition position.

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