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Combustion characteristics of a lean-burned CBM engine with hydrogen direction injection

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Abstract: A 3D model of a CBM engine was established, and the combustion modes under different injection parameters and ignition matching conditions were studied by using methane PFI+ hydrogen DI injection method. Flame propagation, flame structure and engine indication thermal efficiency under the three combustion modes were analyzed. The results show that when the interval between injection and ignition is less than 10°CA, the flame structure of plume ignition will be formed; when the interval between injection and ignition is greater than 10°CA and less than 16°CA, the flame form of concentration stratification will be formed; when the interval is greater than 16°CA, the homogeneous flame structure will be formed. The flame propagation speed of plume ignition is significantly higher than that of the other two combustion modes. Under the three combustion modes, the injection and ignition schemes are adjusted several times. When the injection time is -8°CA ATDC and the ignition time is -2°CA ATDC, the flame structure is the plume ignition structure. The indicated thermal efficiency is higher than the other two combustion modes, and the indicated thermal efficiency of the engine is up to 52.8%.

Keywords: Lean burn; Direct injection; Plume ignition combustion.

1. Introduction

Coalbed methane (CBM) is a kind of hydrocarbon gas stored in coal seams. It takes methane as the main component and belongs to unconventional natural gas. As a clean energy source, China owns the world's third-largest CBM resources, estimated at approximately 30.05×1012 m3 [1]. CBM has the advantages of large reserves, high hydrogen carbon ratio, and high-octane number, so it is considered to be a promising alternative fuel for large bore engines for power generation. The higher antiknock performance enables the CBM engine to achieve higher compression ratio and lean combustion, thus improving the thermal efficiency of the engine [2]. CBM with methane concentration higher than 30% belongs to high concentration coalbed methane, and the commercial application technology has been mature. Low concentration coalbed methane (LCCM) generally refers to CBM with CH4 concentration lower than 30%. The volumetric heat value of LCCM is low, and the CH4 concentration is close to the limit of lean burning. Long-distance transportation is not only dangerous, but also has no cost advantage. Local power generation after LCCM extraction is the most desirable and the most common practice at present, and the spark ignited large-bore engine is good way for power generation [3]. CH4 concentration of LCCM is low and unstable, which leads to frequent misfire, increased knock risk and other problems of engines [4]. In addition, the engine large bore makes the flame propagation distance increase, and the engine low speed makes the turbulent movement in the cylinder relatively weaker, which will weaken the flame propagation in the cylinder [5].

Hydrogen has the advantages of low ignition energy, high laminar burning velocity and wide flammability range. Both hydrogen and CBM are gaseous fuels, easy to premix with each other. Hydrogen blending can improve the problems of ignition difficulty and slow flame propagation speed for LCCM. A spark ignited engine with blended fuel of H2 and CBM/natural gas is called HCNG engine [6]. He et al. [7] conducted experimental researches on the combustion and emission characteristics of a CNG engine with different hydrogen blending ratios. The research shows that hydrogen-blending can improve the ignition stability and fuel economy, reduce cycle variations and HC emissions. However, this kind of HCNG is still based on the model of "homogeneous combustion", and a larger proportion of blended hydrogen is easy to cause backfire of the engine.

In order to realize the stable ignition of lean combustion and accelerate the flame combustion speed, scholars [8-9] put forward the technology of stratified charge combustion. Stratified charge combustion is one of the most important ways to realize lean combustion. It means that the fuel concentration stratification or active stratification is formed in the combustion chamber. After ignition, the flame kernel is first formed in the richer area in the cylinder and then the flame spreads to the surrounding lean mixture. When the overall mixture is lean in the stratified charge combustion system, it can ensure the high efficiency and low emission of the engine.

Biffiger et al. [10] compared the combustion characteristics of HCNG port fuel injection (PFI) and methane PFI + methane direct injection (DI) modes in reciprocating piston internal combustion engines. After adjusting the phases of direct injection and ignition, they found that the stratified charge combustion also existed in PFI+DI mode. Yu et al. [11] comparatively studied the combustion and emission characteristics of spark ignition engines in gasoline PFI+ gasoline DI and gasoline PFI+ hydrogen DI modes, and found that the combination of gasoline PFI+ hydrogen DI engine had significantly better rapid combustion characteristics than gasoline PFI+ gasoline DI engine. The experimental results show that the fuel concentration stratification alone cannot change the shortcomings of the fuel itself, and the combustion rate in the cylinder can be improved by replacing the DI direct injection fuel with a more active fuel. In order to further explore ways to improve the shortcomings of LCCM, such as not easy to ignite and slow combustion speed, Ji et al. [12]

and Pan et al. [13] studied the combustion characteristics of natural gas PFI + hydrogen DI rotor engine. The results show that the amount of hydrogen injection, the time of hydrogen injection and the ignition time are the three key factors affecting the flame morphology and combustion characteristics.

Wallner et al. [14] and Kawanabe et al. [15] found that ignition near the internal injection time of hydrogen direct injection engine would form multi-point ignition like diesel compression ignition and multi-flame surface ignition to improve ignition stability. Oikawa [16] called this model of jet flame ignition the “plume ignition combustion concept” (PCC). Soon after, Ali et al. [17] also found the plume flame structure in CNG engine and called it gas jet ignition (GJI). Both PCC and GJI have good ignition properties. However, these are all studied in the flame structure of GDI engines, and there are still few studies in the combined injection system of PFI+DI.

At present, the research on hydrogen jet and jet flame characteristics is mainly based on air atmosphere and hydrogen/air premixed atmosphere, and the research on thin CBM atmosphere is still lacking. Based on large bore CBM engine and PFI+DI injection system, this paper studies the influence of interval of time between hydrogen injection timing and ignition timing on flame structure, and compares the combustion characteristics and emission characteristics of the engine under different flame structure. The purpose of this work is to clarify the effects of different flame structure on combustion in cylinders and engine performance, and to provide ideas for plume ignition optimization and engine injection system design of lean natural gas engines.

2. Model and Simulation

2.1. Model

The formation and combustion process of the mixture in the cylinder of the internal combustion engine is carried out under the turbulent state, which determines the distribution and transportation state of each component in the cylinder. In order to reflect the complex transient flow movement in the cylinder more truly, the appropriate turbulence model should be selected during the simulation calculation. Various turbulence models are provided in AVL-Fire software. In this paper, the K-zeta -f four-equation model is chosen for simulation calculation, which has good accuracy and stability, and is suitable for all applications. In this study, because of the dual-fuel combustion, the ECFM-3Z in the coherent flame model is used to calculate the combustion process of the engine, and the Muti-component model is used to describe the heat and mass transfer of fuel evaporation. The above two models can be well applied to all types of multi-component combustion. The O-Rourke model was used to characterize the particle interaction process. The impact characteristics of gaseous particles can be accurately represented by Walljet0 model. For emissions performance, the extended Zeldovich model performs the calculation of NO emissions.

Table 1. Main performance parameters

parameters	value
Bore	160 mm
Stroke	240 mm
Compression ratio	10.5 : 1
Number of valves	4

This study takes a natural gas engine as the prototype to establish a simulation model. The main performance parameters of the original engine are shown in Table 1.

2.2. Boundary conditions

Table 2. Main boundary conditions

boundary	type	value
intake	input	0.24Mpa/314K
hydrogen injection	input	300K
piston	moving wall	500K
head	fixed wall	550K
liner	fixed wall	550K

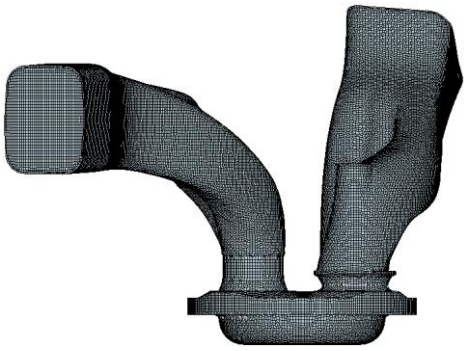


Figure 1. Grid model (top dead center)

2.3. Model validation

In this part, the validity of the model is confirmed by comparing the experimental and simulated cylinder pressure results under the same conditions. As shown in Figure 2, slight differences appear after TDC, generally within 5%, and the simulation results of this model are reliable.

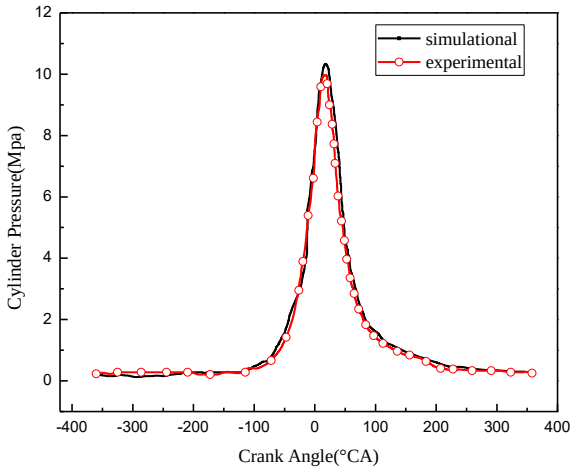


Figure 2. Cylinder pressure comparison between simulated value and test value

3. Results and discussion

3.1. Analysis of mixture distribution and flame structure

In this paper, to explore the influence of matching hydrogen injection and ignition time on flame structure, the ignition time was fixed as -2°CA after top dead (ATDC), the hydrogen injection time was changed, the injection duration was 10°CA, the hydrogen content was 10% (hydrogen with calorific value equivalent to 10% was injected instead of part of methane), and the injection start time was -4°CA ATDC, -8°CA ATDC, -15°CA ATDC,-20°CA ATDC, -25°CA

ATDC(labeled as Scheme A, B, C, D, and E). OH radical is a highly reactive chemical factor and an important intermediate product of combustion chain reaction. The initial appearance of OH can represent the beginning of combustion.

As shown in Table. 3, at the ignition timing, 2°CA and 6°CA were injected in scheme A and scheme B respectively, and both schemes were continuously injected, so the hydrogen of the two schemes was concentrated in the center, while the hydrogen near the spark plug in scheme B was more concentrated and the combustion was more intense. Scheme C has stopped the hydrogen injection when it's fired but the hydrogen doesn't spread out, it's still in the center. In scheme D and F, the hydrogen is already diffused.

As shown in Table. 4, hydrogen is still sprayed when the interval between hydrogen injection and ignition is about 0°~10°CA (Schemes A and B), so the flame obviously spreads outward in a plume structure. Compared with Plan A, the hydrogen in plan B is injected for a longer period of time, and there is more concentrated hydrogen in the cylinder at the time of ignition. In the same time after ignition, plan B diffuses more first and burns more intensely. What is interesting is that in scheme A, we can clearly see that the outer outline of the hydrogen beam burns first instead of the hydrogen beam itself. This is because the hydrogen beam itself is fast, and the newly ejected hydrogen cannot form a mixture with oxygen in the cylinder in time, so the outline burns first. In the mass fraction diagram of CH4 at 5°CA ATDC, it can also be seen that CH4 mixed with hydrogen beam has a combustion lag. In the diagram of 5°CA ATDC in plan B, hydrogen has stopped spraying, so the middle part of hydrogen beam mixed with oxygen also starts to burn rapidly, which also explains the reason. Such morphology greatly increases the surface area of the ignited hydrogen beam to form multi-point ignition and improve the ignition energy, which is more conducive to its ignition source to ignite the thin coalbed methane.

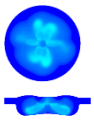
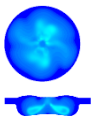
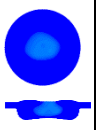
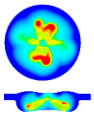
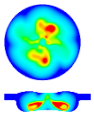
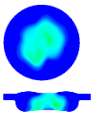
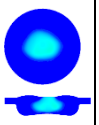
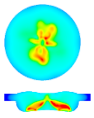
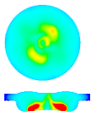
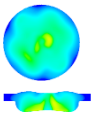
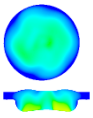
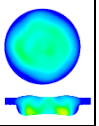
When the interval between hydrogen injection and ignition is about 10°~16°CA (Scheme C), it is obvious that there is a flame form of stratified combustion. After injection, the hydrogen that has not been diffused is concentrated near the spark plug. During ignition, the spark plug firstly ignites the concentrated hydrogen in the middle and then leads to the thin coalbed methane combustion outward.

When the interval between hydrogen injection and ignition is above 16°CA (Schemes E and F), the injected hydrogen gas and the thin coal seam gas in the cylinder have formed a relatively homogeneous HCNG mixture. When ignited, the flame in the cylinder gradually expands into a fireball shape, which is consistent with the combustion pattern of premixed ignition fuel.

Table 3. Image of H_2 mass fraction under different schemes

schemes	A	B	C	D	E
OH/1° CA ATDC					
	H2[-] Mass Fraction 0 0.008 0.016 0.024 0.032				

Table 4. Image of CH4 and OH [-] mass fraction under different schemes

schemes	A	B	C	D	E
OH/1° CA ATDC					
CH_4					
OH/5° CA ATDC					
CH_4					
OH/9 °CA ATDC					
CH_4					
	CH4[-] Mass Fraction 0 0.0064 0.0128 0.0192 0.0256 0.032 OH[-] Mass Fraction 0 0.0008 0.0016 0.0024 0.0032 0.004				

This article defined from the ignition time to 10% of the total quantity of heat release of the time for the development of flame, 10% to 90% of the heat release for rapid combustion period, as shown under the three different forms of the flame of rapid combustion period were similar, while the flame development difference is bigger, according to the homogeneous ignition burning, burning, smoke plume, in turn, shorter, compared with homogeneous combustion, The flame development time of stratified combustion is about 20% shorter. This is because the hydrogen around the spark plug is more concentrated during the ignition of stratified combustion, so the initial combustion speed is faster. Compared with stratified combustion, the flame development time of plume ignition is more than 50% shorter. This is because not only the hydrogen is more concentrated during ignition, but also the hydrogen jet strengthens the turbulence intensity in the cylinder and accelerates the combustion speed further. In Fig.5, it can be seen that the rate of heat release of the plume ignition increases very fast before the hydrogen injection ends, and then continues to rise after a sudden drop after the hydrogen injection ends (2°CA ATDC).

As shown in Fig. 5, the variations of pressure in the cylinder of the three flame structures, it can be seen that because the hydrogen injection timing (-32°CA ATDC) of homogeneous combustion is the earliest, the hydrogen injection makes the pressure in the cylinder rise to the highest. Although the stratified combustion is earlier than the plume ignition, the pressure in the cylinder rises faster after the plume ignition, and the maximum cylinder pressure is also higher than the stratified combustion.

The main pollutant generated during engine combustion is NO, which is discharged into the atmosphere and slowly reacts with O2 under atmospheric conditions to form NO2, which is one of the main factors for the formation of photochemical smog and acid rain. Fig. 6 shows the NO mass fraction of different flame structures. As shown in the figure, the generation rate of NO mass fraction in plume ignition at the beginning of ignition is significantly higher than that of the other two flame structures, because the initial combustion reaction speed of plume ignition combustion is very fast. In

the figure, “homogeneous” combustion generated the most NO, followed by “stratified charge”, and “plume ignition” is the least, because the final amount of NO generated is positively correlated with the duration of high temperature. However, Among the three flame structures, the ignition advance angle of “homogeneous” combustion is the largest, followed by “stratified charge”, and “plume ignition” is the least.

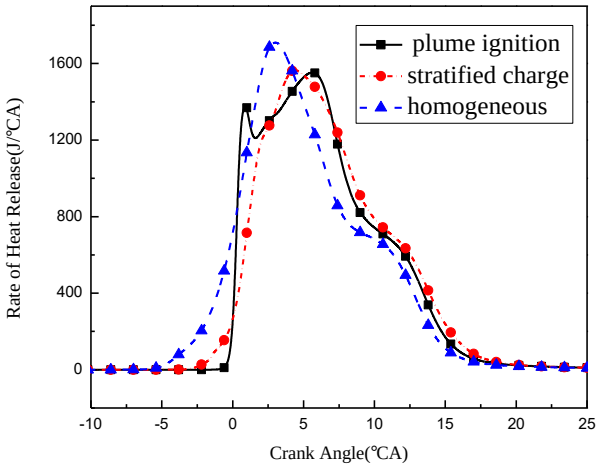


Figure 3. Rate of heat release of different flame structures

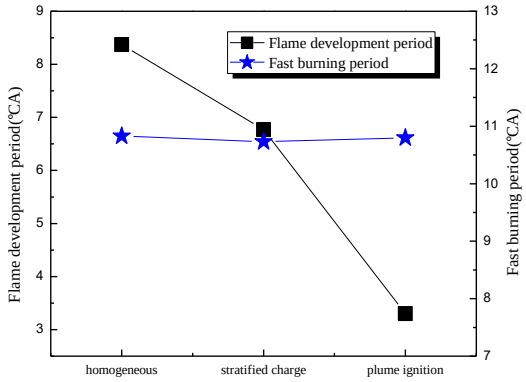


Figure 4. Combustion duration of different flame structures

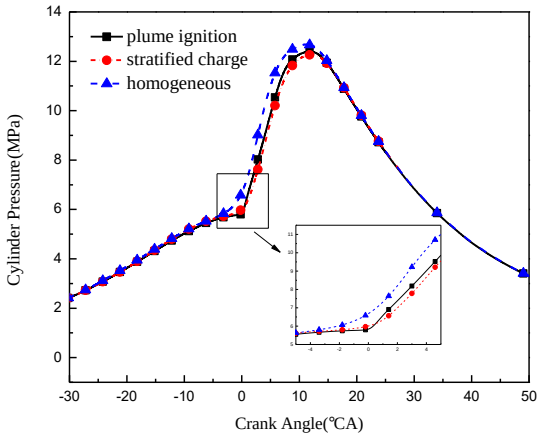


Figure 5. Cylinder pressure of different flame structures

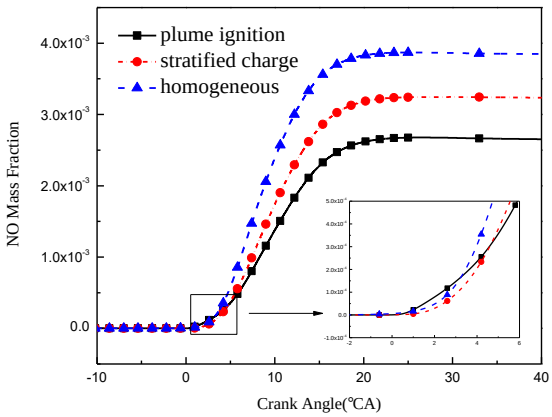


Figure 6. NO mass fraction of different flame structures

4. Conclusion

In this paper, a calculation model of a large bore dual-fuel engine is established. Methane PFI+ hydrogen DI injection method is adopted to study the flame structure and engine performance under different matching conditions of hydrogen direct injection and ignition under the same excess air coefficient. The main research conclusions are as follows:

(1) Under the condition of excess air coefficient is 1.6 and full load at rated speed, different flame forms will be formed with the change of hydrogen injection and ignition time interval. When the interval between injection and ignition is less than 10°CA, the smoke plume ignition flame will be formed in the cylinder; when the interval is greater than 10°CA and less than 16°CA, the active stratified flame will be formed; when the interval is greater than 16°CA, the homogeneous flame will be formed.

(2) The flame development period of the plume ignition mode is significantly shorter than that of the other two flame modes, indicating that the plume ignition flame propagation speed is fast, which is conducive to the formation of the initial fire core and can improve the ignition stability.

(3) By adjusting the injection and ignition schemes, under several injection and ignition schemes, the highest indicated thermal efficiency in the plume ignition combustion mode is 52.8%, and the corresponding schemes are -8°CA ATDC injection time and -2°CA ATDC ignition time.

(4) Due to the small ignition advance Angle, the NOX generation is significantly less than the other two flame forms, and the emission is better.

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