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Study on Combustion Characteristics of Low Concentration Coalbed Methane Induced by Hydrogen Jet based on Excess Air Ratio

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Abstract

Low concentration coal bed gas used for power generation is a better treatment scheme at present, which solves the problem of environmental pollution caused by the direct emptying of coal bed gas. Coal bed methane is a methyl alkyl fuel, and slow combustion rate will cause abnormal combustion phenomena such as large combustion cycle changes. The initial ambient gas concentration has a great influence on the development and propagation of the flame. In this paper, a constant volume bomb model is established to change the excess air coefficient of methane air premix in the initial constant volume bomb, and the change law of combustion heat release is analyzed. The results show that when hydrogen participates in the combustion stage, the combustion rate increases with the increase of excess air coefficient. When hydrogen is burned out, the combustion rate decreases with the increase of excess air coefficient.

Keywords

Coalbed Methane; Excess Air Ratio; Constant Volume Bomb; Combustion Heat Release Rate.

1. Introduction

Coalbed gas refers to the hydrocarbon gas stored in coal seam with methane as the main component, mainly adsorbed on the surface of coal matrix particles, and partly free in coal pores or dissolved in coal seam water. It is an associated mineral resource of coal, and belongs to unconventional natural gas. It is a clean, high-quality energy and chemical raw material rising in the world in the past 20 years.

The coal bed methane engine fuel is methyl alkyl fuel, which has some abnormal combustion phenomena such as high minimum ignition energy, slow flame propagation speed, poor thin combustion ability and knock [1, 2]. Hydrogen is an active gas. Using hydrogen jet to ignite low-concentration coalbed methane can provide higher ignition energy and increase the combustion speed greatly [3]. Hydrogen jet ignition of low-concentration coalbed methane has a strong dependence on the initial conditions in the cylinder, and the excess air coefficient of different methane air premixed gas leads to obvious differences in the formation and development of initial flame, which further affects the performance of the engine. When the ratio of the hydrogen injection pressure to the ambient pressure exceeds 2, the hydrogen jet is an underexpansion process, and the hydrogen tip jet will appear vortex ball [4-6].

Hydrogen jet can effectively improve the combustion speed of coalbed methane, and the selection of jet structure, jet pressure and environmental pressure is also crucial to the efficiency of the engine. With the increase of jet pressure, jet penetration distance will increase, and with the increase of environmental pressure, jet penetration distance will decrease [7-9].

Excess air coefficient is of great significance to the determination of antiknock and compression ratio of engine. The antiknock performance of spark ignition engines under different excess air coefficients is studied, and the relationship between excess air coefficient and compression ratio is also analyzed. The results show that with the decrease of excess air coefficient, it has greater knock resistance, and the further decrease of excess air coefficient will increase the required compression ratio[10]. Du et al. [11] studied the working characteristics of internal combustion engines under different equivalent ratios by means of experiment and numerical analysis, and the results showed that the indicated thermal efficiency of the engine showed a trend of first increasing and then decreasing as the equivalent ratio increased. The excess air coefficient will directly affect the combustion and emission of fuel. With the increase of the excess air coefficient, the indicated thermal efficiency of the engine is improved, and the emission of NOx is reduced [12, 13].

In summary, the study of jet combustion mainly focuses on the study of jet structure, in addition, the influence of different excess air coefficients on engine efficiency is also involved. The research on flame structure and heat release rate of combustion with different excess air coefficient can provide theoretical basis for the application of coal-bed methane combustion in engine. Therefore, in this paper, the combustion characteristics of low concentration coalbed methane ignited by hydrogen jet under different excess air coefficients are analyzed by numerical analysis.

2. Model and Methods

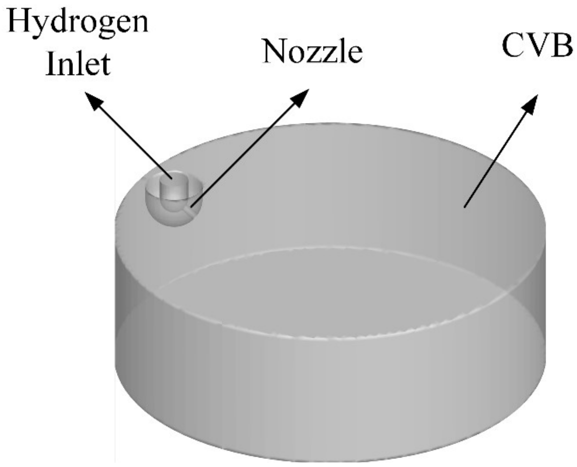

Figure 1. Constant volume bomb calculation domain

In this paper, a constant-volume projectile (CVB) model is established as shown in Figure 1 The diameter of CVB is D=60mm, the height H=20mm, and the diameter of the nozzle is 1mm. In this paper, RNG k-ε model is selected for turbulence model, O 'Rourke and Amsden model for wall heat transfer model, Source/Sink model for ignition model, SAGE model for combustion model, and GRI mech 3.0 for chemical reaction mechanism are selected. This mechanism has been widely used in natural gas combustion simulation [14, 15]. In order to verify the reliability of the model, the penetration distance calculated by simulation is compared with the experimental results of Yip[16] et al. As shown in Figure 2 compared with the experimental results, the simulation penetration distance is slightly larger than the experimental results, but the error is less than 5%, indicating that the model is more accurate.

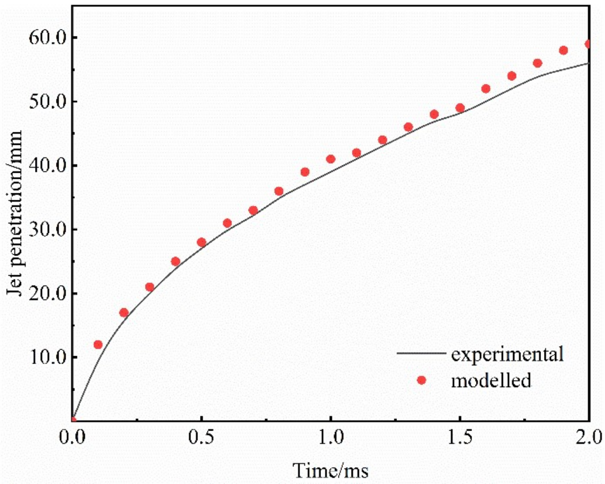

Figure 2. Comparison of penetration distance between simulation and experiment

In order to explore the influence of different initial methane concentrations on combustion characteristics, five ambient atmospheres were set as excess air coefficient Φa=1.6, Φa=1.7, Φa=1.8, Φa=1.9 and Φa=2.0 to study the influence of excess air coefficient on combustion characteristics. Detailed experimental conditions are shown in Table 1.

Table 1. Experiment condition

project	parameter
ambient pressure (MPa)	0.1
ambient temperature(K)	300
Hydrogen injection pressure(MPa)	0.5
Duration of hydrogen injection(ms)	1.5
excess air coefficient	1.6,1.7,1.8,1.9,2.0

3. Results and Discussion

This paper mainly analyzes the effect of excess air coefficient of methane air premixed gas on the combustion characteristics of low concentration coalbed methane ignited by hydrogen jet. The development of fire nucleus under different excess air coefficient was observed from the ignition time, and the variation law of fire nucleus diameter with excess air coefficient was obtained. The flame structure obtained by simulation calculation is used to analyze the flame development process under different excess air coefficients. In addition, the combustion duration under different excess air coefficients is studied by combining the heat release rate curve.

3.1. Development of Fire Core under Different Excess Air Coefficients

The formation and development process of the initial ignition nucleus is directly related to the initial environmental atmosphere. In order to explore the change law of the development of the initial ignition nucleus under different excess air coefficients, this paper calculates the ignition under three kinds of constant volume bomb environmental atmospheres: excess air coefficient Φa=1.6, Φa=1.8 and Φa=2.0. Define the diameter of a spherical isosurface with a molar fraction of OH of 0.0001 as the diameter of the fire core.

The ignition time is the same as the hydrogen injection time, and it takes some time for the hydrogen jet to reach the ignition position, so the ignition is not hydrogen but the methane air premix gas inside the constant volume bomb. The development of the ignition nucleus varies with different excess air coefficients. The changes of the diameter of the ignition nucleus with excess air coefficients Φa=1.6, Φa=1.8 and Φa=2.0 after ignition are shown in Figure 3. In the initial stage of ignition, the core diameter increases rapidly from 0mm to 7mm, and the change trend of the core diameter under different excess air coefficients is basically the same; After ignition 0.2ms, the diameter of the core increases from 7mm to 11.5mm in the period from 0.2ms to 1.3ms in the environment of Φa=1.6, and increases from 7mm to 12.5mm in the period from 0.2ms to 1.3ms in the environment of Φa=2.0. The trend of fire core change is not as big as the initial stage.

In summary, after ignition, the diameter of the fire core increases rapidly in the initial stage, and then the increase speed of the fire core diameter gradually slows down. At the same time, with the increase of excess air coefficient, the diameter of the core decreases.

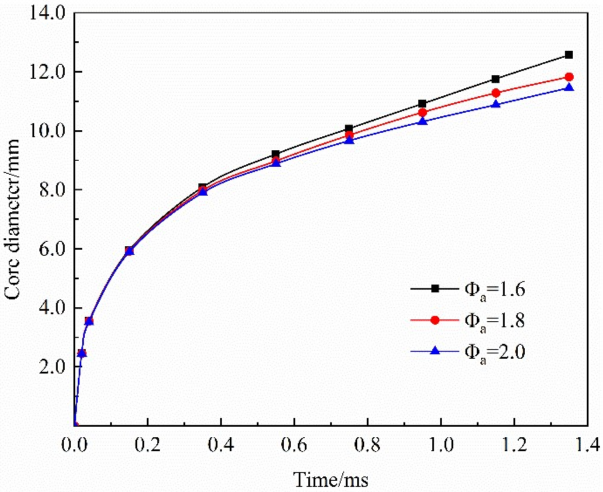

Figure 3. Fire core diameter development

3.2. Analysis of combustion Characteristics in Different Ambient Atmospheres

In order to ensure more accurate simulation analysis of hydrogen injection process during combustion calculation under different excess air coefficients, both hydrogen injection and ignition are set to start at 0.5ms and last for 1.5ms. In order to avoid the hydrogen jet blowing off the initial fire core, the ignition position is set below the axis of the jet hole as shown in Figure 4 In the figure, a rectangular coordinate system is established with O point as the origin, and the ignition position coordinates are (5mm,-7mm).

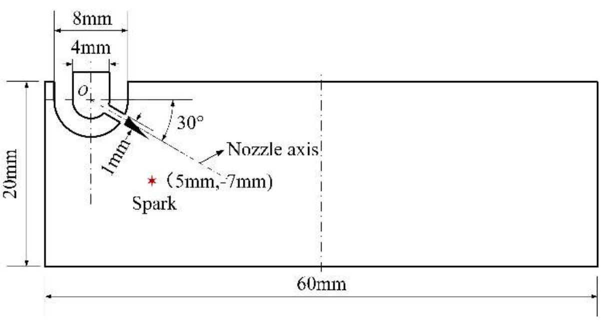

Figure 4. ignition position

Figure 5 shows the flame development cloud diagram after ignition, in which OH radical, the intermediate product of combustion reaction, is used to represent the flame surface. When t=0.5ms, ignition and hydrogen injection start at the same time. Because it takes some time for the hydrogen jet to reach the ignition position, the methane air premix gas in the constant volume bomb is ignited first. When t=0.6ms, a spherical premix flame appears. When t=1.0ms, the hydrogen jet has developed to 0.5ms, and the methane air premixed flame ignites the hydrogen jet, and the hydrogen jet flame begins to spread along the direction of the hydrogen beam development to form the jet flame. With the development of hydrogen injection time, the hydrogen jet will have axial and radial diffusion and mix with the methane air premix in the constant volume bomb. In the core column area inside the hydrogen jet, the hydrogen concentration is higher, and the temperature of the hydrogen cold jet is low, so the jet flame will not develop into the hydrogen beam, and grooves will appear on the flame surface. When t=2.0ms, the jet flame reaches the bottom surface of the constant volume projectile and begins to spread along the bottom of the constant volume projectile under the barrier of the wall. At this time, because the hydrogen injection has just finished, the hydrogen concentration in the core column of the hydrogen jet is still high, and the jet flame will develop in two parts. When t=3.0ms, the jet flame starts to reverse diffusion after striking the side wall of the constant volume projectile. Meanwhile, combustible mixture has formed in the core column area of the hydrogen jet, and the flame begins to develop inside the jet. When t=10.0ms, the flame has basically spread to the entire constant volume bomb.

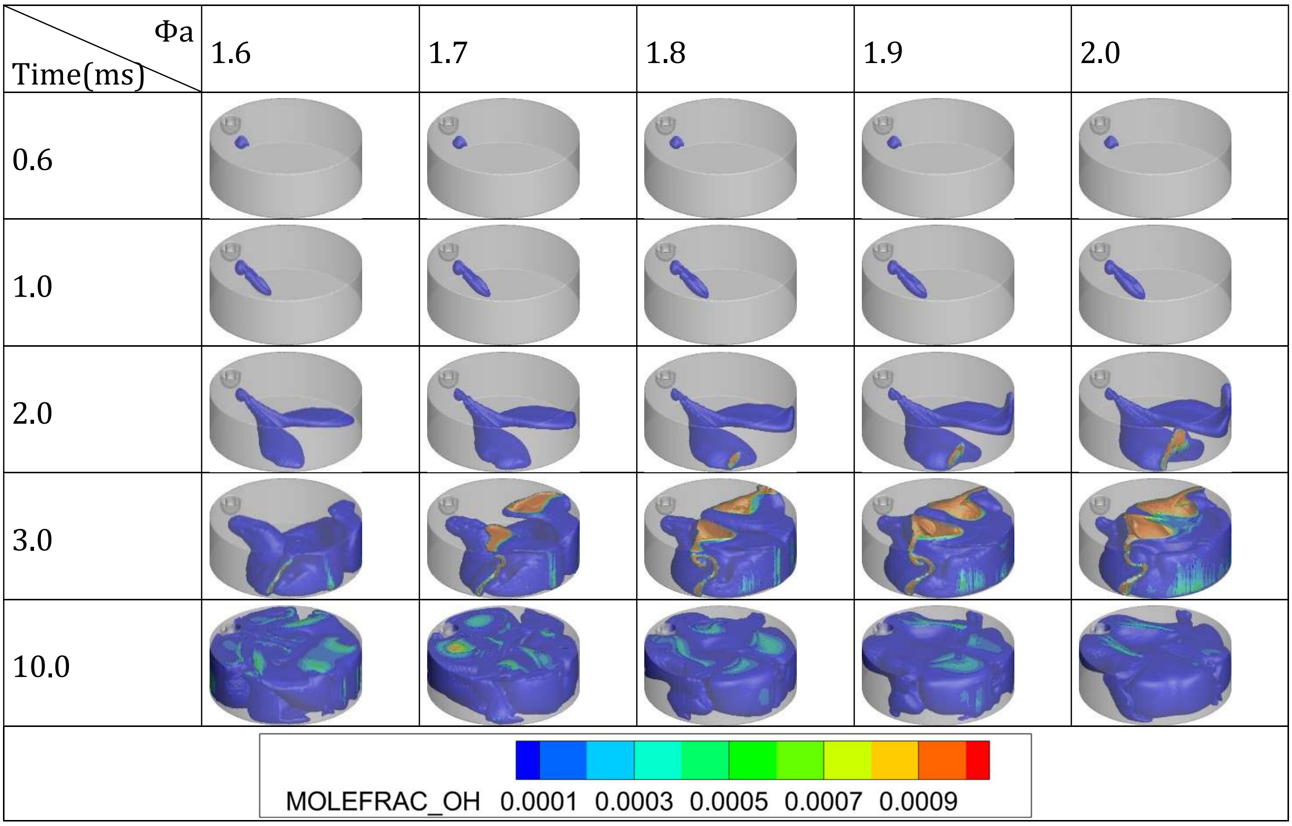

Figure 5. image of flame development

There are also differences in flame development under different excess air coefficient atmospheres. As shown in Figure 5, the flame development trend is basically the same under different excess air coefficients before t=1.0ms, and obvious differences have appeared at t=2.0ms. In the ambient atmosphere of Φa=1.6, the jet flame has not yet spread at the bottom of the constant volume projectile, while in the ambient atmosphere of Φa=2.0, the jet flame has not yet touched the side wall of the constant volume projectile. The flame has hit the side wall of the constant volume projectile. When t=3.0ms, under the ambient atmosphere of Φa=1.6, the flame has just collided with the side wall of the fixed volume bomb and then reversed diffusion, and under the ambient atmosphere of Φa=2.0, the flame has occupied two-thirds of the space of the fixed volume bomb. When t=10.0ms, the development of the flame has different changes.

Under the ambient atmosphere of Φa=1.6, the flame has basically spread to the whole space of the constant volume projectile, while under the ambient atmosphere of Φa=2.0, the flame surface has not been distributed to the entire constant volume projectile.

To sum up, it can be preliminarily judged that the entire combustion process is divided into two stages. The first stage is: at the initial stage of the combustion reaction, the flame propagation speed increases with the increase of the excess air coefficient; after a period of time, it enters the second stage, where the flame propagation speed decreases with the increase of the excess air coefficient. In order to further analyze the combustion characteristics of the two stages, the combustion heat release curve and fuel change curve under different excess air coefficients are combined with the image of flame development.

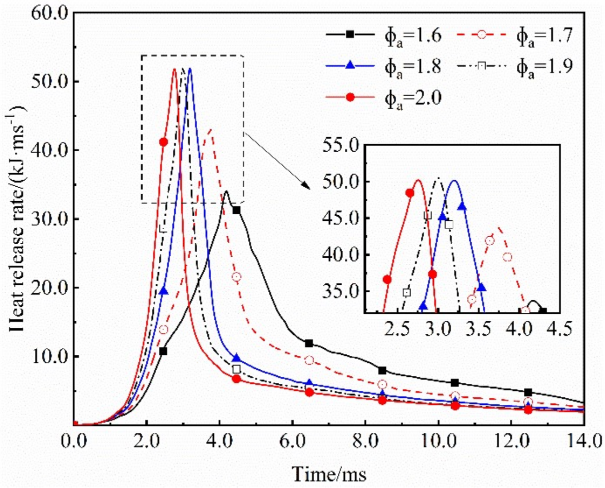

Figure 6. Heat release rate with different excess air coefficient

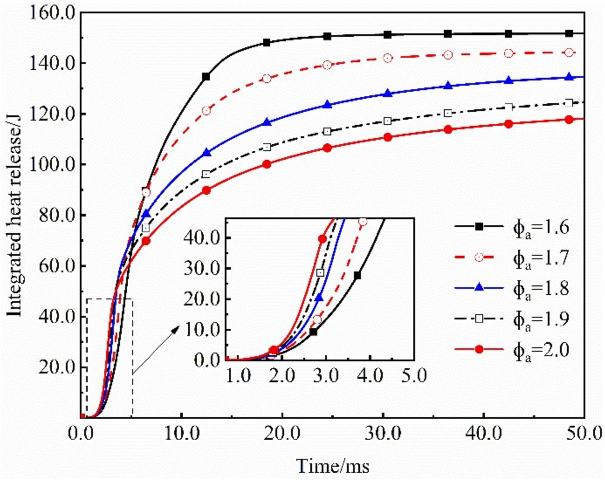

Figure 7. Integrated heat release with different excess air coefficients

The instantaneous heat release rate curves under different excess air coefficients are shown in Fig.6. The instantaneous heat release rate curves all show a trend of first increasing and then decreasing. There is a significant difference in the time when the peak value of the instantaneous heat release rate appears under different excess air coefficients. The peak instantaneous heat release rate is about 50kJ·ms-1. With the decrease of excess air coefficient, the time when the instantaneous heat release rate reaches the peak is delayed successively. In the ambient atmosphere of Φa=1.6, the time when the instantaneous heat release rate reaches the peak is the latest, and the peak value is the lowest, about 34 kJ·ms-1. When the excess air coefficient is in the range of 1.6-1.8, the peak value of instantaneous heat release rate changes significantly, increasing from 34 kJ·ms-1 to 50 kJ·ms-1. When the excess air coefficient is greater than 1.8, the peak value of instantaneous heat release rate changes little. The cumulative heat release rate curve under different excess air coefficients is shown in Figure 7. During the period from 0ms to 5ms, the greater the excess air coefficient, the faster the cumulative heat release growth rate; after 5ms, the cumulative heat release growth rate decreases with the increase of excess air coefficient.

The hydrogen mole fraction curve under different excess air coefficient environments is shown in Figure 8. When the boundary conditions are divided in the CONVERGE simulation software, there is hydrogen atmosphere inside the nozzle, so there is a small amount of hydrogen before t=0.5ms. When t=0.5ms, hydrogen injection begins, and the molar fraction of hydrogen increases rapidly. When t=2.0ms, hydrogen injection ends, and the molar fraction of hydrogen reaches the maximum value. Since the ignition and hydrogen injection time are the same, some hydrogen has participated in the combustion during hydrogen injection. The fuel consumption rate is different in the ambient atmosphere with different excess air coefficient. When the excess air coefficient is larger, the fuel is in a more oxygen-rich condition, increasing the collision and combination of oxygen and hydrogen, and the reaction is faster. With the increase of excess air coefficient, the hydrogen consumed in the process of hydrogen injection will increase, and the phenomenon of different maximum molar fraction of hydrogen as shown in the figure will appear. Because the hydrogen combustion speed is fast, the hydrogen molar fraction decreases rapidly after the hydrogen injection, and the decreasing speed increases with the increase of excess air coefficient.

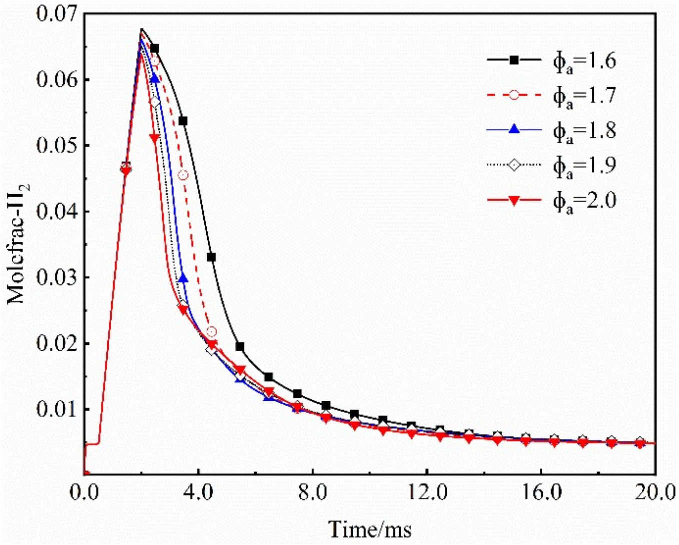

Figure 8. Hydrogen mole fraction change curve

The low calorific value of hydrogen is 119.7MJ·kg-1, while the low calorific value of methane is 45.8 MJ·kg-1. In the early stage of the combustion reaction, hydrogen burns rapidly, and the molar fraction of methane also decreases rapidly in the rapid combustion stage of hydrogen. With the consumption of hydrogen, the reaction rate of methane also slows down, as shown in Fig.9. The change of molar fraction of methane is also different under different excess air coefficient, and the change of molar fraction of methane is affected by the combustion rate of hydrogen in the reaction stage. Due to the different excess air coefficient, the initial value of methane molar fraction in the constant volume bomb is different. In the reaction stage of hydrogen combustion, the decrease rate of methane molar fraction increases with the increase of excess air coefficient. At about t=6.0ms, the molar fraction of hydrogen drops to 0.01, and the main combustion reactant is methane air premixed gas. At this time, the change rate of methane molar fraction decreases with the increase of excess air coefficient.

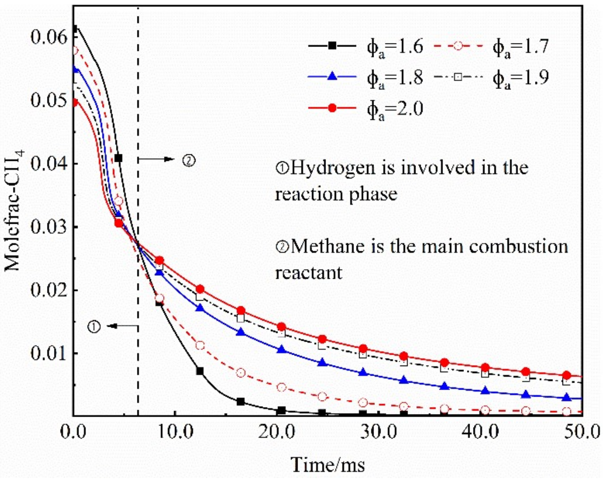

Figure 9. Methane molar fraction change curve

4. Conclusion

In this paper, the combustion characteristics under different excess air coefficients are studied by numerical analysis. By comparing the combustion heat release rate, core diameter and molar fraction of methane and hydrogen under different excess air coefficient conditions, the following conclusions are drawn:

(1) At the same time, under the environmental condition of Φa=2.0, the radius of the fire core is smaller, while under the environmental condition of Φa=1.6, the radius of the fire core is slightly smaller. The initial core radius decreases with the increase of excess air coefficient.

(2) The combustion process of coalbed methane piloted by hydrogen jet can be divided into two stages: hydrogen main combustion and methane main combustion. In the hydrogen main combustion stage, the combustion speed increases with the increase of excess air coefficient; During the main combustion period of methane, the combustion speed decreases with the increase of excess air coefficient.

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