Experimental Study on the Explosion Characteristics of CH$_4$/O$_2$/N$_2$ Mixtures with Different Oxygen Enrichment Coefficients and Ignition Positions

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ABSTRACT: In this paper, the flame propagation characteristics and overpressure oscillation characteristics of CH$_4$ explosion were studied under different ignition positions (IPs) and oxygen enrichment conditions in a half-open tube. The distances between the IP and the closed end of the tube are 0, 250, 500, and 750 mm. The oxygen enrichment coefficient (φ) values used in the experiment are 0.21, 0.3, and 0.4. The experimental results show that the IP and oxygen enrichment coefficient have an important influence on the flame structure and overpressure oscillation. Only when the oxygen enrichment coefficient φ = 0.21, a tulip flame will be formed. The IP close to the outlet can make the air participate in the combustion more quickly. With the increase of the oxygen enrichment coefficient, the combustion-induced rapid phase transition phenomenon is more likely to occur, and the maximum overpressure value and the overpressure rise rate of flame will increase. It is worth noting that after increasing the oxygen enrichment coefficient, the IP has less influence than the oxygen enrichment coefficient on the overpressure rise rate.

1. INTRODUCTION

As traditional fossil energy is gradually consumed, people are looking for new energy alternatives. There is a large amount of methane in coal mining, and it is difficult to use it effectively because of the low methane concentration. Oxygen-enriched combustion technology is used to improve the combustion range of low concentration gas so that low concentration gas can partially replace fossil fuel.

In recent years, more and more scholars have studied the explosion mechanism and law of combustion. Askari et al. used a new differential-based multishell model and combined it with schlieren photography to study the laminar burning velocity and the flame structure of H$_2$/CO/air premixed. The results show that when the initial pressure increases, due to the significant decrease of flame thickness and the enhancement of hydrodynamic instability, the flame instability will occur earlier. Hu et al. conducted experiments and simulations on laminar burning velocity of the methane–hydrogen–air premixed flame at atmospheric pressure, high temperature, and low pressure. The non-stretching laminar burning velocity and Markstein length were obtained. The results show that the flame propagation velocity and laminar burning velocity increase with the increase of initial temperature and hydrogen content but decrease with the increase of initial pressure. Deng et al. used computational fluid dynamics methods to study the propagation of methane–air mixing flames in a half-open tube. The relationship between the specific surface area of the flame and the burned gas volume growth is used to study the flame tip speed evolution after the flame skirt contacts the wall.

Research studies show the dimensionless time interval from the flame skirt contacting the wall surface to the flame front reversal and the dimensionless speed of the flame skirt. Zheng et al. used the large eddy simulation (LES) method to study the structure changes of the tulip flame produced by the combustion of methane/air and hydrogen/air in the closed tube. The results show that the pressure wave can cause the structure of the tulip flame to change when the flame aspect ratio increased. Wen et al. studied the coupling effect of the explosion flame and pressure waves under different conditions. When the flame passes through different forms of obstacles, the flame structure changes, and the burned gas and unburned gas are rapidly mixed. This will increase the combustion reaction rate and overpressure, making the flame burn faster. Xiao et al. analyzed the change of the flame structure in the process of flame propagation by using hydrogen/air and other combustible gases. The flame reversed backward in the tube propagation process, and a twisted structure was generated after the appearance of a tulip flame. The second twisted tulip flame produced a series of dents, and the formation of the tulip flame was caused by Taylor’s instability.
More recently, Di Benedetto et al. found that the combustion of oxygen-enriched fuel will lead to serious explosion behavior when water is produced due to combustion. This phenomenon has been named combustion-induced rapid phase transition (cRPT). Combustion-induced rapid phase transition can explain many phenomena that cannot be explained by classical explosion theory. At the same time, Di Benedetto et al. have measured the behavior of oxygen-enriched oscillations in the high pressure (240 bar). The oscillation behavior can be attributed to the condensation and evaporation cycles of water which was generated during combustion. The culmination of this cycle is the rapid phase transition of the condensate, which leads to the peak value of over-adiabatic pressure. It is also found that the propagation direction of the pressure wave is consistent with that of the flame during combustion-induced rapid phase transition. Basco et al. theoretically analyzed the phenomena of combustion-induced rapid phase transition (cRPT) in H2/CO2/O2/N2 and CH4/O2/N2/CO2 and proposed a criterion to distinguish cRPT from deflagration and detonation. Their research shows that cRPT can be carried out not only in oxygen-enriched conditions but also in hydrogen doping conditions.

Most of the above studies on explosion and combustion-induced rapid phase transition are about H2 and CO and are carried out in a closed tube. Due to the influence of air, the effect of oxygen content on methane deflagration is more complex in the half-open tube. No one has yet studied the coupling effect of different oxygen contents and different ignition positions (IPs) on methane deflagration characteristics. The significance of this paper is to improve the combustion characteristics of methane at low concentrations under complex conditions. Therefore, this paper designed a set of CH4 combustion test platform with a half-open tube and studied the CH4 combustion with different oxygen enrichment conditions and IPs.

2. EXPERIMENT

As shown in Figure 1, a self-made experimental device is established to analyze the characteristics of CH4 combustion. It consists of four parts: a gas distribution system, an ignition system, an experimental tube, and a data collection system. The cross-section size of the experimental tube is 80 × 80 mm, and the length of the experimental tube is 1000 mm. The tube is made of transparent plexiglass with a thickness of 30 mm, and the maximum pressure resistance limit is 2.5 MPa. The left end of the tube is a 5 mm thick steel plate. The steel plate is equipped with an ignition head and an inlet valve, and the PVC membrane is on the right side of the tube. Previous studies have shown that the PVC membrane has little effect on flame propagation. In order to study the influence of the IP on CH4 combustion, the ignition system consists of four ignition devices, which were set at 0, 250, 500, and 750 mm away from the closed end of the tube. The gas distribution systems are composed of the ALICAT 21 gas mass flow controller and high-pressure cylinder. The gas mass flow controller is used to adjust the gas flow so that the oxygen enrichment coefficients of combustible gas in the tube are 0.21, 0.3, and 0.4. The data acquisition system consists of an image device part and a pressure collection device. The flame propagation image is captured by the Miro M310 high-speed camera, and the image acquisition frequency is 3200 frames/s. An MH-90 pressure sensor collects pressure data, and the working frequency of the pressure sensor is 200 kHz. A computer is used to store images and pressure data.

In this work, the method of controlled variables is used to conduct experiments. When the oxygen enrichment coefficient (φ) is a fixed value, adjust the IP to 0, 250, 500, and 750 mm and record the image and pressure data of methane combustion. Then, adjust the oxygen enrichment coefficient and repeat the above experimental steps. The oxygen enrichment coefficient, φ, is calculated as

$$\phi = \frac{V_{O_2}}{V_{O_2} + V_{N_2}}$$

where \(V_{O_2}\) is the volume of oxygen and \(V_{N_2}\) is the volume of nitrogen.

CH4, O2, and N2 are supplied by a high-pressure cylinder. The purity of the experimental gas reached 99.9%. The mixed gas with 4 times the volume of the tube was filled to discharge the air in the tube. The time for discharging air is 10 min. According to Amaget’s law of partial volume, the volume flow rates of CH4, O2, and N2 at different stoichiometric ratios are calculated. Each set of experiments was repeated three times. The experimental conditions are shown in Table 1.

3. RESULTS AND DISCUSSION

3.1. Influence of the IP on Flame Propagation. As shown in Figure 2, the flame propagation picture of the premixed gas deflagration process is shown when oxygen enrichment coefficient \(\phi = 0.21\) and IP = 0 mm, in which four

| IP (mm) | \(\phi\) | CH4 (%) | O2 (%) | N2 (%) |
|--------|--------|--------|--------|--------|
| 0      | 0.21   | 9.50   | 19.00  | 71.50  |
| 0      | 0.30   | 13.70  | 27.40  | 58.90  |
| 0      | 0.40   | 16.70  | 33.30  | 50.00  |
| 250    | 0.21   | 9.50   | 19.00  | 71.50  |
| 250    | 0.30   | 13.70  | 27.40  | 58.90  |
| 250    | 0.40   | 16.70  | 33.30  | 50.00  |
| 500    | 0.21   | 9.50   | 19.00  | 71.50  |
| 500    | 0.30   | 13.70  | 27.40  | 58.90  |
| 500    | 0.40   | 16.70  | 33.30  | 50.00  |
| 750    | 0.21   | 9.50   | 19.00  | 71.50  |
| 750    | 0.30   | 13.70  | 27.40  | 58.90  |
| 750    | 0.40   | 16.70  | 33.30  | 50.00  |
classic phases of flame propagation dynamics can be observed. The flame structure developed into a hemispherical structure at 3 ms. At 3–31 ms, the flame expands into a finger-shaped structure. At 45 ms, the flame skirt touches the wall, and the front of the flame forms a flat flame. The flame collapsed in the opposite direction of the flame propagation at 78–107 ms and formed a tulip flame structure. In the tulip flame structure, the initial position of the blue flame does not change with the development of flame, indicating that the tensile speed of the flame is of the same speed as the propagation.

In this paper, the flame propagation velocity is calculated by the following formula

\[
v_t = \frac{p_t - p_i}{d_t}
\]

where \(v_t\) is the flame propagation speed of the flame at time \(t\); \(p_t\) is the distance of flame front to the ignition device at time \(t\) in the picture; and \(d_t\) is the shooting interval of a high-speed camera, which is 1/3200 s.

As shown in Figure 3, the flame propagation picture of premixed gas deflagration process is shown when oxygen enrichment coefficient \(\varphi = 0.21\) and \(IP = 250\) mm. Figure 3a shows that before the flame front passes out of the tube, the flame develops into a sphere structure at 17.50 ms, and the flame continues to spread, forming a finger-shaped structure at 40.62 ms. At 43.15 ms, the left flame moves to the right, which is because the pressure on both sides of the flame remains the same when the flame develops freely. However, due to the closure of the left side of the tube, the pressure increases gradually during the flame propagation. Under the condition of high pressure, the left flame is pushed to the right side, and the flame continues to spread to the left side and is pushed to the right side again by the pressure, so as to form the oscillation of the flame. Because the density and temperature of the burned gas are different from those of the unburned gas, the pressure wave will reflect when passing through the interface of the two gases, which will cause the pressure wave to oscillate back and forth between the closed end of the tube and the flame front, which will also induce the flame oscillation. At the same time,
the oscillation of the flame will lead to the fluctuation of the heat release rate, which will produce acoustic oscillation in the closed tube and further lead to the oscillation of the flame. Figure 3b shows the flame structure after the flame front comes out of the tube. The flame on the left side continues to spread, and the right side is connected with the atmosphere. Under the effect of air buoyancy, the flame is lifted, resulting in faster combustion at the top of the tube.

As shown in Figure 4, the flame propagation picture of the premixed gas deflagration process is shown when the oxygen enrichment coefficient $\phi = 0.21$ and IP = 500 mm. Figure 4a shows that with the development of flame, the left side gradually forms a finger-shaped flame from the spherical flame and the flame surface oscillation. The reason for flame oscillation is the same as that of flame oscillation when IP = 250 mm. It is worth noting that the flame on the left side develops from the spherical flame to finger-shaped flame at 40.63 ms and then rapidly transforms into a tulip flame structure. This is quite different from the propagation of the left flame when IP = 250 mm. Figure 4b shows the propagation structure of the right flame front after the exit tube. It can be found that the flame oscillates obviously because of the combustion-induced rapid phase transition. With the combustion going on, a large amount of water vapor is generated from the combustion on the left side. When it contacts the low-temperature wall, the water vapor condenses and the volume decreases rapidly, which makes the pressure on the left side decrease, and the flame propagates to the left side. At the same time, the flame propagating to the left will vaporize the condensed water again, causing the pressure to rise, and the flame will be pushed to the left, thus causing the flame surface to oscillation.

As shown in Figure 5, the flame propagation picture of the premixed gas deflagration process is shown when oxygen enrichment coefficient $\phi = 0.21$ and IP = 750 mm. Figure 5a shows that before the flame front passes out of the tube, similar to the flame structure of IP = 500 mm, the left flame tends to form a tulip flame at 47 ms. Because the right flame is connected with the atmosphere, the stable flame propagation environment is destroyed, and the tulip flame cannot continue to form. Comparing the flame propagation on the left side of IP = 250 mm and IP = 500 mm, when the flame position is closer to the closed end surface of the tube, the pressure spreads rapidly between the flame and the closed end surface. The left flame surface is greatly affected by the closed end surface of the tube and cannot be forming a tulip flame. When the IP moves to the right, the flame surface on the left becomes farther away from the closed end surface of the tube, and the flame surface easily forms a tulip flame structure. In Figure 5b, the flame oscillates obviously after the right flame front passes out of the tube, which is caused by the rapid phase transition of water vapor induced by combustion.
No flame oscillation occurred after the IP = 250 mm flame burst out of the tube, but the flame oscillation occurred at IP = 500 mm and IP = 750 mm. This is because the closer the IP is to the outlet of the tube, the faster the flame can come into contact with the air. More air causes the flame to burn violently, and easier CPT phenomenon will occur, resulting in flame oscillation. This is evidenced by the color change of the flame. The closer the IP is to the exit, the higher the brightness and temperature of the flame.

### 3.2. Influence of Oxygen Enrichment Coefficient on Flame Propagation

As shown in Figure 6, the flame propagation picture of the premixed gas deflagration process is shown when IP = 250 mm and oxygen enrichment coefficient ($\phi$) is 0.3 and 0.4. Compared with Figure 3, with the oxygen enrichment coefficient gradually increasing, the brightness of the flame gradually increases, and the flame propagation speed accelerates. When the oxygen enrichment coefficient is 0.21, it takes 81.25 ms for the right flame to reach the tube outlet, while when the oxygen enrichment coefficient increases to 0.4, it only takes 15.62 ms for the right flame to reach the tube outlet. Figure 7 shows the change of the flame front position on the left and right sides of the IP with time. With the increase of oxygen enrichment coefficient, the flame propagation speed increases obviously. At the same time, when the oxygen enrichment coefficient is the same, the propagation speed of the right flame will also increase with time. Due to the closure of the left tube, the left flame does not propagate to the left but oscillates at a fixed position.

When the oxygen enrichment coefficient is 0.3 and 0.4, combustion-induced rapid phase transition will occur in the flame rushing out of the tube, resulting in flame oscillation, which has the same characteristics as the accelerated flame contact with air, which will make the flame burning more violent, so that a combustion-induced rapid phase change occurs.

In this section, in order to verify the repeatability of the experimental data, Figure 7 shows the positions of the flame front surface at different oxygen enrichment coefficients at the same IP. The error bars are the standard deviation of the flame front position recorded during the repeated experiments. As shown in Figure 7, the results of multiple experiments are very consistent. In the early stages of flame propagation, there was little difference in the position of the flame front in the three experiments. The maximum error occurs when $\phi = 0.4$, but the maximum error is also less than 7%. Thus, the experimental data in this study are repeatable, and the accuracy of the experimental data is verified.

### 3.3. Influence of Oxygen Enrichment Coefficient and IPs on Overpressure

Figure 8 is a pressure diagram of different IPs when the oxygen enrichment coefficient $\phi = 0.21$. As shown in the Figure 8, the IP has a significant effect on the pressure curve. At the beginning of the combustion reaction, as the reaction proceeded, the pressure gradually increased. The pressure of the four groups of reactions decreased significantly at the time of 16 and 20 ms, which was due to oscillation of pressure caused by the rupture of the PVC membrane. After the rupture of the PVC membrane, a small pressure peak appeared in the reaction with IP = 0 mm, then the pressure gradually decreased, and there was no pressure oscillation in the later stage of combustion. The results show that the combustion reaction with IP = 250 mm has a regular pressure oscillation after the rupture of the PVC membrane, and the peak pressure decreases with the reaction progress. When IP = 500 mm, the pressure oscillated obviously after the membrane was broken. The pressure rose rapidly within 40–90 ms, reaching the maximum amplitude, and then, the pressure decreased rapidly. In the stage of pressure rising, the frequency of pressure oscillation is relatively regular. In the stage of pressure drop, the frequency of pressure oscillation becomes smaller. The combustion reaction with IP = 750 mm also shows obvious oscillation. The pressure rose rapidly within 40–180 ms and then decreased rapidly. The oscillation frequency of pressure is similar to that of IP = 500 mm, but the maximum overpressure is greater than that of IP = 50 mm.

Figure 9 shows the pressure diagram of different IPs at $\phi = 0.3$ and $\phi = 0.4$. The flame is similar to that at $\phi = 0.21$ at the initial stage of combustion. There is a pressure rise process, and the pressure oscillations occur as the PVC membrane ruptures. Different from $\phi = 0.21$, the pressure will oscillate violently at all IPs in the later stage of flame combustion because with the increase of oxygen enrichment coefficient, it is easier for the combustion-induced rapid phase transition to occur, resulting in pressure oscillation. Under different oxygen enrichment coefficients, the amplitude of pressure oscillation and the speed of attenuation are different. When $\phi = 0.21$, the pressure oscillation frequency of all IPs is relatively uniform in...
40–220 ms; when \( \phi = 0.3 \), only IP = 750 mm can be observed and the pressure oscillation period is relatively stable. It is worth noting that the pressure oscillation frequency with IP = 0 mm is not stable in the early stage of combustion but gradually stable in the later stage of combustion. When \( \phi = 0.4 \), no stable pressure oscillation cycle was found in all IPs. This is because, when the flame rushes out of the tube, air will enter the tube to participate in the combustion, and the oxygen content in the air is 21\%. If the oxygen enrichment coefficient differs greatly from 21\%, the incoming air will cause the oxygen enrichment coefficient in the tube to occur changes, resulting in different oxygen contents in the tube at each moment in the late combustion period, thus creating an unstable pressure oscillation cycle.

Figure 10 shows the influence of the IP and oxygen enrichment coefficient on the maximum overpressure of the explosion and its arrival time. When \( \phi = 0.21 \), the maximum overpressure at IP = 500 mm and IP = 750 mm is significantly greater than IP = 0 mm and IP = 250 mm maximum overpressure. As the previous analysis, when the IP is close to the open end, CH\(_4\) burning in the tube produces cRPT phenomenon, resulting in increased pressure. Because the IP of IP = 750 mm is closer to the open end, the air outside the tube can participate in the reaction more quickly, so the maximum pressure value of IP = 750 mm is greater than that of IP = 500 mm. At the same time, because the outside air has little effect on the oxygen enrichment coefficient and the pressure propagation is stable, the time for the maximum overpressure to reach the sensor also has a positive correlation with the IP. When \( \phi = 0.3 \), the maximum overpressure value of each IP and the time to reach the maximum overpressure are the same, so when \( \phi = 0.3 \), the influence of different IPs can be minimized. When \( \phi = 0.4 \), the time for each IP to reach the maximum overpressure is the same as when \( \phi = 0.3 \). The maximum overpressure value at different IPs is greater than the other two groups, and the overpressure value reaches the maximum when IP = 500 mm. This is because when the oxygen enrichment coefficient is 0.4, the incoming air will cause the oxygen enrichment coefficient to decrease so that the intensity of CH\(_4\) combustion decreases, resulting in the decrease of the maximum pressure value at IP = 750 mm.

4. CONCLUSIONS

In this work, we have studied the combustion of CH\(_4\) in a half-open tube, verified the four stages of flame morphology evolution, compared the effects of different IPs and oxygen enrichment coefficients on flame morphology changes, and discussed the burning speed of the lower flame, the pressure change, the maximum overpressure value, and the overpressure rise rate in different situations. The main results can be summarized as follows:

1. With the increase of oxygen enrichment coefficient, the burning speed and brightness of CH\(_4\) gradually increase, and only when the oxygen enrichment coefficient \( \phi = 0.21 \), the tulip flame can be observed.

2. When the oxygen enrichment coefficient \( \phi = 0.21 \), only when IP = 500 mm and IP = 750 mm, the obvious cRPT phenomenon will occur in the combustion of CH\(_4\), resulting in overpressure oscillation. Increasing the oxygen enrichment coefficient will cause cRPT at all IPs.

3. When the IP is at the closed end of the tube, the flame has only one burning direction, cRPT phenomenon is not easy to occur, and the maximum overpressure value is small; when the IP is a certain distance away from the closed end of the tube and closer to the open end, cRPT phenomenon easily occurs.

4. In this experiment, when the oxygen enrichment coefficient \( \phi = 0.3 \), the maximum overpressure value and the overpressure rise rate of the flame are affected by the IP to a minimum. Because air entering the tube changes the oxygen concentration and the IP has less influence than the oxygen enrichment coefficient on the overpressure rise rate, the maximum overpressure arrival time at all ignition locations is reduced and very close when \( \phi = 0.3 \) and \( \phi = 0.4 \).

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