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EXPERIMENTAL TEST OF COMBUSTION AND EXPLOSION PRESSURE OF METHANE-AIR PREMIXED GAS

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Abstract: Methane, as a clean energy source, is increasingly widely used in industrial fields. The combustion and explosion characteristics of its premixed gas are crucial for efficient energy utilization and industrial safety. This paper presents experimental tests on the combustion and explosion of methane-air premixed gas. A 1000cc volume explosion device was designed and fabricated, and methane and air were sequentially filled into it. Four sets of combustion and explosion experiments were performed using methane–air premixed gas at different equivalence ratios, and the pressure variations throughout the entire combustion and explosion process were recorded. The results show that the peak pressure of the methane-air premixed gas combustion and explosion reaches 8-9 times the original premixed gas pressure. The experimental results provide important data support for the industrial application design of methane.

Keywords: Methane; Explosion device; Combustion and explosion experiment; Premixed gas

1 INTRODUCTION

As a core component of clean energy sources such as natural gas and coalbed methane, the premixed combustion and explosion characteristics of methane are key research topics in the fields of energy efficiency and industrial safety control. In recent years, domestic and foreign scholars have relied on numerical simulation, experimental testing, and other methods to conduct in-depth research on the combustion dynamics, flame evolution, and disaster prevention of methane-air premixed systems, gradually building a research system that combines theory and experiment.

In order to meet the high-temperature gas supply requirements of the hot jet wind tunnel test of the aircraft, scholars have carried out structural design and simulation research on the methane/air gas generator. After comparing different injection structures, it was confirmed that the coaxial DC scheme has better combustion performance and better uniformity of gas parameters [1]. At the same time, in view of the basic law of methane-air premixed gas explosion, the researchers have explored the control mechanism of ignition position, equivalence ratio and length-to-diameter ratio on explosion pressure rise rate and positive pressure duration by building an experimental system independently. Based on dimensional analysis, an overpressure prediction formula was constructed to lay a theoretical foundation for explosion power assessment [2]. On this basis, for the coal powder-blended dilute methane-air premixed flame, a two-dimensional axisymmetric model coupled with a discrete phase model (DPM) was used to carry out numerical simulation, analyze the influence of particle size and concentration on laminar combustion rate and flame structure, and verify the predictive reliability of the numerical model [3]. As for the interaction between the methane-air premixed flame and the wall, scholars compared different wall conditions through direct numerical simulation, clarified the influence of wall temperature and equivalence ratio on flame quenching and heat flow distribution, and established a scientific method for determining the quenching state by OH radical concentration [4].

The iterative upgrade of combustion diagnostic technology has further provided technical support for the accurate characterization of methane combustion and explosion process. By using constant volume combustion bomb to test the OH* and CH* chemi-luminescence signals of methane-hydrogen mixed combustion, non-contact real-time monitoring of combustion process can be realized [5]. To address the issue that temperature affects the accuracy of equivalence ratio measurements by laser-induced breakdown spectroscopy (LIBS), researchers have developed a hybrid correction method to enable simultaneous and accurate detection of both temperature and equivalence ratio in complex flame fields [6]. Combined with seasonal temperature differences to carry out explosion relief test, scholars analyzed the influence of length-to-diameter ratio and methane concentration on overpressure peak and impulse under winter and summer conditions. The established prediction model test error is controlled within 15%, which has strong engineering applicability [7]. In view of the heat transfer scenario of laminar methane-air flame jet impacting ribbed surface, the flow field interference mechanism of rib structure is analyzed by combining test and simulation. It is found that flow blockage and airflow separation will significantly reduce heat transfer efficiency [8]. Considering the discontinuity of fuel distribution in actual scenarios, closed pipeline tests show that shortening the intermediate air section will exacerbate flame propagation and explosion overpressure. When the air section is shorter than 500 mm, flame crossing and secondary explosions are more likely to occur. This finding provides a practical basis for the prevention and control of natural gas explosion accidents [9]. In addition, for the ammonia-hydrogen/methane-air multi-element mixed fuel system, through 20L spherical explosion test and dynamic simulation, the influence law of equivalence ratio and blending ratio on explosion intensity was revealed, and the regulatory role of core element reaction on combustion rate was clarified [10].

In summary, existing research has analyzed the core characteristics of methane-air premixed systems from multiple dimensions from basic flame behaviors and combustion diagnosis methods to explosion evolution laws and engineering equipment applications. However, systematic experimental research on the combustion and explosion pressure test of methane-air premixed gas is still rarely reported. With increasingly severe resource depletion and environmental pollution problems, methane, as a clean energy source, is finding increasingly wider applications in industry and defense. Its combustion and explosion pressure characteristics are crucial for engineering safety design and risk control. Therefore, this paper conducts a series of experiments on the methane combustion and explosion process to systematically obtain basic characteristic parameters of methane combustion and explosion. The research results can provide important theoretical reference and data support for related industrial applications.

2 EXPERIMENTAL PROCESS

2.1 Experimental Apparatus and Conditions

A cylindrical sealed cavity with a diameter of 100mm and a depth of 131.4mm was designed. Two pressure measuring heads, one charging valve, and one exhaust valve were installed on the explosion device wall. The entire internal cavity of the explosion device also housed ignition devices and other components. After removing all internal components, the cavity volume of the explosion device was 1000cc.

2.2 Experimental Operation Procedures

First, methane is injected into the explosion device through the gas inlet, and the mass of injected methane is controlled by the pressure gauge. Next, high-pressure air is injected into the explosion device, and the amount of compressed air injected is also controlled by the pressure gauge. The ratio of methane to air mass is strictly controlled, as the methane-air ratio for explosion is 1.5%~9.5%. Finally, the explosion is ignited by a remote explosion device, and the methane deflagrates in the explosion device. By testing the pressure change pattern inside the explosion device, the characteristics of methane combustion and explosion can be obtained. Figure 1 shows the actual image of the explosion device tested on site.

Figure 1 Actual Image of the Explosion Device

3 EXPERIMENTAL RESULTS

To obtain more abundant data, multiple sets of explosion device experiments were designed. Four sets of experiments with different methane and air ratios were conducted. The specific data on the ratio of methane charging pressure to air charging pressure are shown in Table 1.

Table 1 The Charging Pressure of Air and Methane

Serial Number	Methane pressure (MPa)	Methane-air mixture pressure (MPa)
Experiment 1	0.5	4.82
Experiment 2	0.21	2.24
Experiment 3	0.25	2.68
Experiment 4	0.26	2.87

A high-sensitivity pressure testing instrument was used to collect the gas pressure inside the cavity of the explosion device in real time, with a sampling frequency of 0.02ms. The collected pressure was displayed as a graph. Figures 2-5 show the pressure change curves of the explosion device corresponding to the operating conditions of Experiments 1-4, respectively.

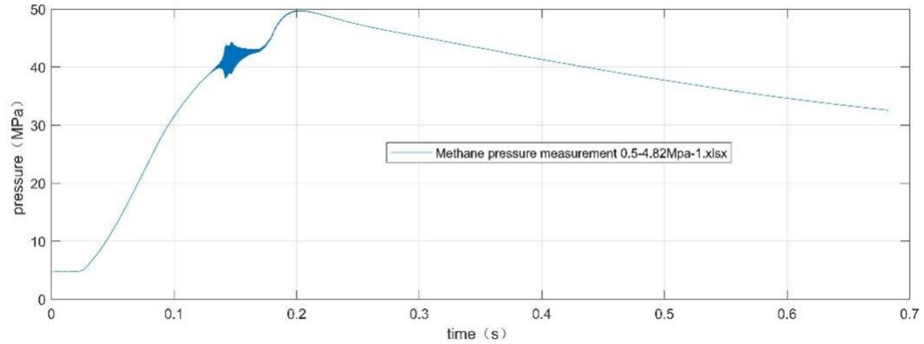

Figure 2 Pressure Test Curve of Methane Explosion Device under Experiment 1 Condition

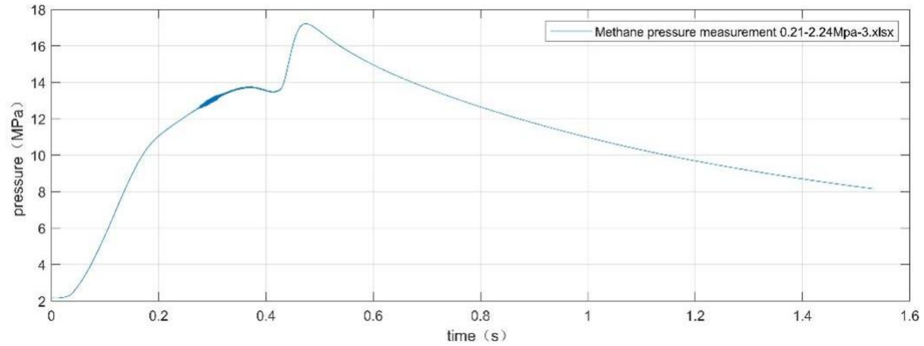

Figure 3 Pressure Test Curve of Methane Explosion Device under Experiment 2 Condition

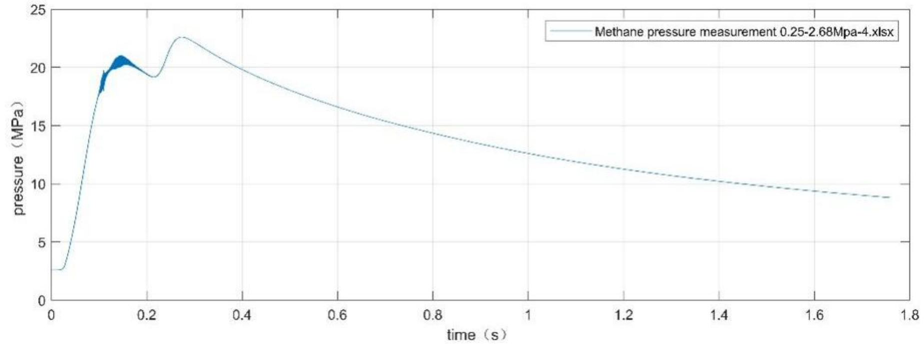

Figure 4 Pressure Test Curve of Methane Explosion Device under Experiment 3 Condition

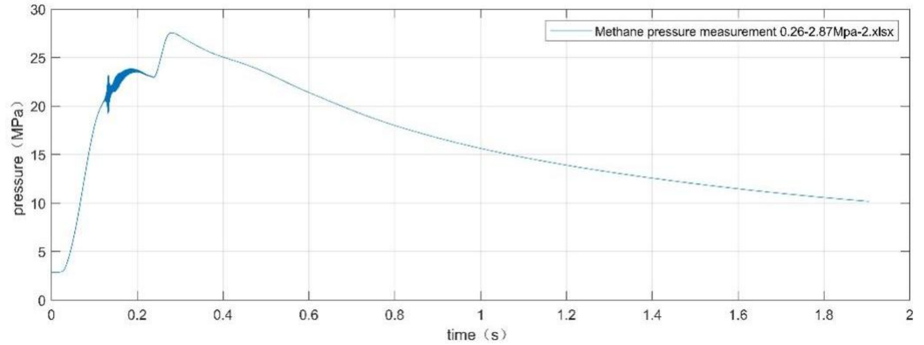

Figure 5 Pressure Test Curve of Methane Explosion Device under Experiment 4 Condition

4 RESULTS AND DISCUSSION

From the above four pressure curves, it can be seen that the pressure inside the explosion device showed a pressure peak, indicating that the methane-air mixture under all four conditions underwent combustion and explosion. Each pressure curve exhibited a rapid initial rise followed by a gradual decline. Owing to the rapid explosion triggered by combustion, the pressure inside the explosion vessel reached its maximum immediately after the explosion, corresponding to the peak of the curve. Subsequently, the combustion of the mixture inside the explosion device was completed, and the gas temperature and pressure were at their highest. As time progresses, the high-temperature gas inside the explosion device conducts heat outward through the walls of the explosion device, gradually dissipating the heat and causing the temperature of the post-combustion gas to gradually decrease, resulting in a slow pressure drop. Table 2 shows the premixed gas ratio and the maximum pressure value after combustion and explosion under four experimental conditions.

Table 2 The Premixed Gas Ratio and the Maximum Pressure Value

Serial Number	Methane (g)	Air (g)	Peak pressure of combustion (MPa)	Peak time (s)
Experiment 1	2.5953	51.9796	50	0.2
Experiment 2	0.7137	25.049	17.2	1.3
Experiment 3	0.9732	29.7531	22.56	0.82
Experiment 4	1.0381	31.8699	27.57	1.1

4.1 Experimental Results

Through the pressure-time curves obtained from the methane-air premixed gas combustion and explosion experiments under different experimental conditions, it can be seen that the entire premixed gas process fully presents the entire process of premixed gas ignition - combustion and explosion pressure rise - pressure oscillation - pressure relief and decay. The core characteristics are as follows:

4.1.1 Ignition and pressure rise stage

After the mixture is ignited, the pressure rises rapidly from the initial value, reaching the first peak value in about 0.3s. The pressure rise rate is extremely high, reflecting the rapid chemical reaction and rapid volume expansion characteristics of the methane-air premixed gas, which is consistent with the pressure rise law of combustible gas deflagration.

4.1.2 Pressure oscillation stage

After the initial peak, the pressure briefly drops, then climbs again to the highest peak of the entire cycle, and finally falls back to the trough, forming a significant secondary fluctuation. This oscillation is a typical phenomenon of the shock wave generated by combustion and explosion being reflected and superimposed in a closed container, reflecting the propagation and dynamic pressure response characteristics of the combustion and explosion wave.

4.1.3 Pressure relief attenuation stage

After the oscillation subsides, the pressure enters a continuous and stable linear attenuation process. The attenuation rate is uniform and without sudden changes, which is consistent with the law of high-pressure gas slowly releasing pressure through the seal of the explosion device after combustion and explosion.

4.2 Discussion and Analysis

4.2.1 Physicochemical mechanism of combustion and explosion process

Rapid Pressure Increase Stage: After the methane-air premixed gas reaches the ignition conditions, a chain oxidation reaction occurs, releasing a large amount of heat instantaneously, causing the gas temperature and pressure to rise sharply, forming a positive pressure wave. The pressure increase slope directly reflects the combustion and explosion reaction rate and the flame propagation speed. The extremely fast pressure increase rate in this experiment indicates that the mixture is in a strong combustion and explosion (close to detonation) state under this condition, with violent reaction and concentrated energy release.

Pressure Oscillation Stage: The shock wave generated by the combustion and explosion is reflected and superimposed multiple times at the container wall structure, forming pressure pulsations and secondary peaks. Oscillation amplitude and period are the core parameters for evaluating the impact strength of combustion and explosion and the dynamic response of containers, providing experimental basis for the impact resistance design of explosion-proof structures.

Pressure relief attenuation stage: The pressure decreases steadily and linearly, and there are no abnormalities in the sealing structure of the explosion device. The release process conforms to the basic law of isothermal pressure relief of high-pressure gas.

4.2.2 Correspondence between experimental conditions and combustion and explosion characteristics

As shown in Experiment 3, the initial premixed gas pressure of the explosion device is 2.68 MPa, and the actual peak combustion pressure reaches 22.56 MPa, which is much higher than the initial pressure. This reflects the strong combustion and explosion pressure boosting effect of the methane-air premixed gas: the pressure gain generated by the combustion of the premixed gas can reach 8 to 9 times the initial pressure, indicating that the methane-air premixed gas has a very strong combustion and explosion force.

4.2.3 Engineering application and safety significance

Explosion-proof design basis: The peak pressure, pressure rise rate and oscillation characteristics obtained in this experiment are key measured data for the explosion-proof structure design and safety margin verification of methane transportation and storage systems (such as coal mine gas pipelines, gas pipelines, and gas storage tanks). They can be used to optimize the size of the explosion relief port, the selection of explosion-proof valves, and the design of container wall thickness.

Explosion risk assessment: The curve fully reflects the pressure evolution of the mixture from ignition to depressurization, providing experimental support for the explosion risk classification and safe operation procedure formulation of methane-air premixed gas, and has reference value for the prevention and control of coal mine gas explosion and gas pipeline explosion accidents.

Optimization direction: If it is necessary to reduce the explosion impact, the intensity of the shock wave can be weakened, the pressure rise rate can be shortened, and the system safety can be improved by optimizing the explosion relief structure (such as adding explosion relief plates and buffer chambers), adjusting the mixture concentration, and adding flame arresters.

Power propulsion drive design: Methane is a clean energy source and is easy to access. It provides key measured data for the design of long-range fire extinguishing bombs and other launch devices by replacing gunpowder and other dangerous goods with methane-air premixed gas.

4.2.4 Experimental errors and limitations

The small local fluctuations in the curve are mainly due to the dynamic response delay of the pressure sensor, data acquisition noise, and heat loss of the container wall, which are normal experimental errors and do not affect the overall trend and the validity of the core conclusions.

5 CONCLUSION

This methane-air premixed gas combustion and explosion experiment successfully obtained the full-cycle pressure-time curve, clearly presenting three typical stages: rapid pressure rise, pressure oscillation, and stable pressure release. The patterns conform to the basic principles of combustible gas combustion and explosion dynamics. The combustion and explosion pressure of the methane-air premixed gas is as high as 8 to 9 times the original premixed gas pressure. The experimental data truly reflects the combustion and explosion pressure rise characteristics and shock wave response of the mixture, and can provide reliable experimental support for the explosion-proof design, risk assessment, safety control, and power generation device design of methane-related systems.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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