

Experimental Study on Combustion of Hydrogen-blended Natural Gas Inhibited by Inert Gases

Bobo Zhang^{1*}, Xuewen Cao¹

¹*China University of Petroleum (East China), Qingdao, China*

**Corresponding Author. Email: 1431453943@qq.com*

Abstract. To address the fire and explosion safety hazards in the popularization and application of hydrogen-blended natural gas, and to explore the flame suppression effects and mechanisms of CO₂ and N₂ on its premixed combustion, an experimental platform integrated with an explosion pipeline, a high-speed camera and a pressure acquisition system was established. The influence laws of inert gas volume fractions (0%, 6%, 12%, 18%) and hydrogen blending ratios (0%, 20%, 40%) on explosion overpressure and flame suppression efficiency were systematically studied. The results show that CO₂ achieves flame suppression through the synergistic effect of thermodynamic dilution and chemical inhibition. Under the pure methane condition, 18% CO₂ can reduce the peak explosion overpressure from 0.21 MPa to 0.08 MPa with a reduction amplitude of 61.9%. When the hydrogen blending ratio increases to 40%, the overpressure reduction amplitude reaches 78% at the same CO₂ concentration. N₂ mainly exerts its effect through physical dilution; 18% N₂ in pure methane reduces the peak overpressure from 0.23 MPa to 0.08 MPa with a reduction amplitude of 65.2%, and the suppression efficiency is further increased to 68.4% at a high hydrogen blending ratio. The flame suppression efficiency of both inert gases increases with the rise of their own concentrations, and the increase of hydrogen blending ratio enhances their suppression effects, while the overall flame suppression performance of N₂ is weaker than that of CO₂. The research results provide experimental basis and technical reference for the explosion prevention and control of hydrogen-blended natural gas and the design of inert gas flame suppression systems.

Keywords: Hydrogen-blended natural gas, Carbon dioxide, Nitrogen, Flame suppression, Experimental study

1. Introduction

Driven by the global low-carbon energy transition and the goals of carbon peaking and carbon neutrality, hydrogen energy has become a core research direction in the energy field due to its advantages of high calorific value and zero carbon emission, and has significant application potential in the fields of transportation, industrial heating and so on. However, the large-scale application of hydrogen energy is restricted by the bottlenecks of high technical difficulty and high cost in storage and transportation, which limits its popularization [1-3]. Hydrogen-blended natural gas technology realizes the mixed utilization of hydrogen through the existing natural gas

infrastructure, which can not only efficiently consume green hydrogen and reduce carbon emissions, but also improve the combustion efficiency of natural gas. It has both economic and environmental benefits and is a highly potential hydrogen energy utilization scheme [4-6].

Relying on the effects of specific heat capacity, collision efficiency and dynamic regulation, inert gases can slow down the combustion rate and narrow the explosion limit of flammable gases. When the addition amount reaches the threshold, the mixed gas can be inerted to non-combustible to suppress explosion. In addition to physical flame suppression, active gases can also participate in the explosion chain branching reaction to consume key free radicals such as H, O and OH, thus enhancing the flame suppression effect. In typical research on flame suppression by gas-phase media, Lu Chang et al. [7] found that the flame suppression of hydrogen-rich methane explosion by CO₂ involves both physical inerting dilution and chemical effects: in the initial stage of explosion, CO₂ reacts with H to consume H₂ and generate CO, leading to the incomplete reaction of CH₄ and interfering with the propagation of chain reaction. Chen Xiaokun et al. [8] showed that CO₂ can effectively inhibit the deflagration of hydrogen-blended methane, slow down the flame propagation speed and reduce the peak explosion pressure, and the tulip flame structure disappears when the volume fraction reaches 15%. Wang et al. [9] explored the effect of N₂ addition ratio (0~0.2) on the deflagration characteristics of hydrogen-rich methane, and indicated that N₂ can narrow its explosion limit, and the explosion suppression effect on hydrogen-rich methane with a hydrogen addition ratio lower than 50% is significant when the addition amount exceeds 15%.

In this paper, a flame suppression experimental system with multi-parameter cooperative control was constructed to systematically study the regulation laws of inert gas types (CO₂, N₂), concentration gradients and hydrogen blending ratios on explosion characteristics. The key points are to reveal the coupling mechanism of physical dilution and chemical inhibition evolving with working conditions, clarify the specific flame suppression mechanism of inert gases in hydrogen-blended environment, and establish a quantitative correlation model between flame suppression efficiency and key control variables.

2. Experimental system structure and experimental procedures

2.1. Experimental system

The core components of the experimental platform include a hydrogen-blended natural gas explosion pipeline system, a premixed gas distribution system, an ignition system, a high-speed camera system, as well as a pressure and photoelectric signal acquisition system; the schematic diagram of its combustion experimental system is shown in Figure 1. Through this platform, real-time monitoring of dynamic characteristic parameters such as explosion overpressure, flame propagation morphology and propagation speed during the explosion of hydrogen-blended natural gas in the pipeline can be realized. It simulates the multi-component gas environment by precise gas distribution, captures explosion parameters in real time with sensors, and restores the entire explosion process with high-speed camera. It effectively breaks through the bottlenecks of difficult monitoring of explosion process and difficult analysis of multi-factor action mechanism, and provides reliable experimental support for in-depth exploration of the explosion characteristics of flammable gases and optimization of prevention and control strategies.

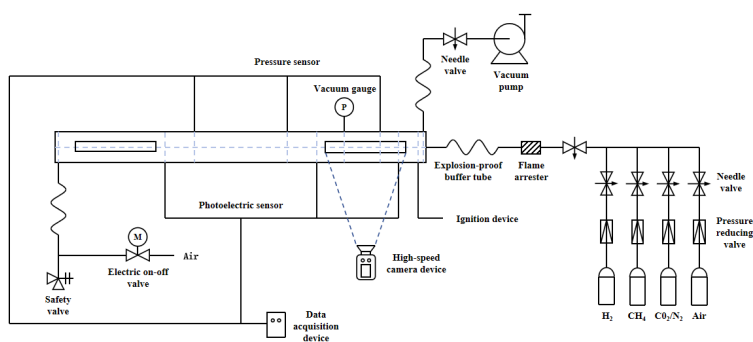


Figure 1. Schematic diagram of experimental system

2.2. Experimental procedures

The experimental operation is carried out in an orderly manner according to the following steps: (1) Pipeline connection and system debugging: Connect the pipelines, high-speed camera and data acquisition equipment according to the schematic diagram, debug the control program, verify the timeliness of ignition trigger, the continuity of pressure data storage and the image definition, and determine the adaptive acquisition frequency; Leak detection is conducted by the method of "vacuum pumping - standing pressure measurement": first, pump to vacuum and stand for 5 min without pressure rise, then fill with 0.2 MPa compressed air and stand for 5 min without pressure drop, then the pipeline tightness is judged to be good. (2) Premixed gas preparation: Pump the pipeline to the preset vacuum degree, fill methane, hydrogen, air and inert gases (CO_2 , N_2) in turn according to Dalton's law of partial pressures, maintain atmospheric pressure after mixing according to the designed ratio, and stand for 10 min to ensure uniform gas distribution. (3) Experimental execution and data recording: Start the control program, and synchronously start the high-speed camera, data acquisition and ignition; close the program after the explosion ends and data storage is completed. (4) Residual gas treatment and preparation: After the experiment, open the air extraction port and the vacuum pump pipeline, extract and discharge the residual gas for 5 min and keep the inner wall of the pipeline dry, close the relevant valves and open the gas inlet valve to prepare for the next experiment. (5) To ensure data reliability, 4~6 parallel experiments are repeated under each experimental condition, and abnormal values are eliminated after statistical analysis.

3. Experimental conditions

To study the effects of inert gas volume fraction and hydrogen blending ratio on the explosion suppression effect of hydrogen-blended methane premixed gas, carbon dioxide and nitrogen were selected as the inert gases. The volume fractions of carbon dioxide and nitrogen were designed as 0%, 6%, 12% and 18%, and the hydrogen blending ratios were designed as 0%, 20% and 40%. The detailed working conditions are shown in Experimental Scheme Table 1.

Table 1. Experimental conditions under different CO₂/N₂ volume fractions and different hydrogen blending ratios

CO ₂ /N ₂ /%	φ=0%			φ=20%			φ=40%		
	H ₂ /%	CH ₄ /%	Air/%	H ₂ /%	CH ₄ /%	Air/%	H ₂ /%	CH ₄ /%	Air/%
0	0	9.50	90.50	2.20	8.80	89.00	5.22	7.83	86.95
6	0	8.93	85.07	2.07	8.27	83.66	4.91	7.36	81.73
12	0	8.36	79.64	1.94	7.74	78.32	4.59	6.89	76.52
18	0	7.79	74.21	1.80	7.21	72.99	4.28	6.42	71.30

4. Analysis of experimental results

4.1. Effect of carbon dioxide on the deflagration attenuation characteristics of hydrogen-blended natural gas

Explosion overpressure is one of the key factors causing damage to the surrounding environment by the deflagration of hydrogen-blended methane gas. It is closely related to the intensity of deflagration and can effectively characterize the hazard degree of hydrogen-blended methane gas deflagration. Taking it as an index can clearly evaluate the suppression effect of inert gases on deflagration and provide a scientific basis for practical application. The following analyzes the effect of carbon dioxide on the deflagration attenuation characteristics of hydrogen-blended natural gas.

4.1.1. Analysis of flame suppression effect of carbon dioxide under pure methane condition

Figure 2 shows the effect of different CO₂ volume fractions (0%, 6%, 12%, 18%) on the explosion overpressure evolution process of methane when the hydrogen blending ratios are 0%, 20% and 40%. The experimental data clearly reveal the key role of CO₂ as an inert gas in inhibiting explosion intensity and slowing down the combustion dynamic process, and its influence mechanism is mainly reflected in three dimensions: peak overpressure, pressure rise rate and explosion development time.

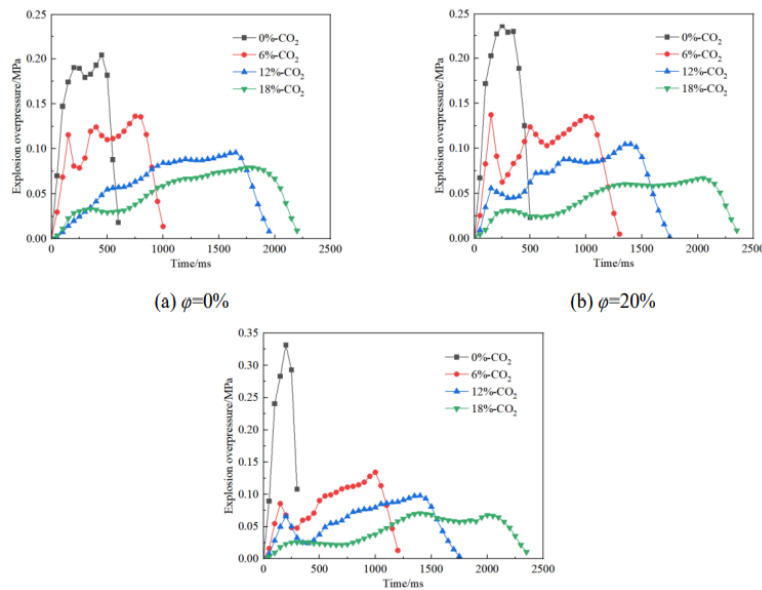


Figure 2. Effect of inert gas CO₂ volume fraction on explosion overpressure of hydrogen-blended methane premixed gas under different hydrogen blending ratios

Without the addition of CO₂, the peak explosion overpressure is about 0.21 MPa, reflecting the violent combustion and concentrated energy release of the pure methane-air mixture. With the increase of CO₂ volume fraction, the peak overpressure shows a monotonous decreasing trend: it drops to 0.14 MPa at 6% CO₂, about 0.10 MPa at 12% CO₂, and only 0.08 MPa at 18% CO₂, with a reduction amplitude of 61.9%. This phenomenon stems from two mechanisms: one is the thermodynamic dilution effect, CO₂ as a triatomic molecule has a high specific heat capacity, which can absorb combustion heat, reduce the adiabatic flame temperature of the system and weaken the explosion intensity; the other is the chemical inhibition effect, CO₂ decomposes into CO and O₂ at high temperature, and also undergoes termination reactions with active free radicals such as H, O and OH (e.g., CO₂+H→CO+OH), thus interrupting the progress of chain reaction.

4.1.2. Effect of hydrogen blending ratio on the suppression effect of carbon dioxide

Plotting the peak explosion overpressure in Figure 2 as a curve of peak explosion overpressure changing with inert gas CO₂ volume fraction under different hydrogen blending ratios, as shown in Figure 3, the following conclusions can be drawn.

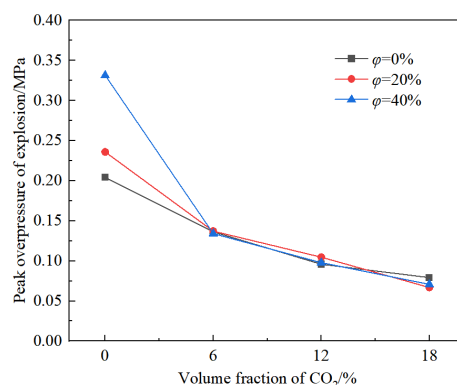


Figure 3. Variation of peak explosion overpressure with inert gas CO₂ volume fraction under different hydrogen blending ratios

The hydrogen blending ratio significantly enhances the basic explosion overpressure of methane deflagration. Under the same CO₂ volume fraction (e.g., 0% CO₂), when the hydrogen blending ratio increases from 0% to 40%, the peak overpressure rises from 0.20 MPa to 0.33 MPa with an increase amplitude of 65%. This is due to the core characteristics of hydrogen: first, the laminar flame speed of hydrogen is much higher than that of methane, which can accelerate the progress of combustion chain reaction; second, the lower heating value of hydrogen is significantly higher than that of methane, which promotes the increase of adiabatic flame temperature; third, the molecular diffusion coefficient of hydrogen is 4 times that of methane, which can promote the premixing of unburned mixture gas and the turbulization of flame front.

The suppression efficiency of CO₂ on gas explosion has a significant linear relationship with the hydrogen blending ratio, and its action mechanism covers both physical and chemical paths: on the physical level, the high specific heat capacity of CO₂ reduces the combustion temperature through heat absorption, and at the same time dilutes the concentration of flammable gas to delay the propagation of combustion wave; on the chemical level, CO₂ can promote the recombination of free radicals and quench the combustion chain reaction.

4.2. Effect of nitrogen on the deflagration attenuation characteristics of hydrogen-blended natural gas

Figure 4 shows the effect of different N₂ volume fractions (0%, 6%, 12%, 18%) on the explosion overpressure evolution process of hydrogen-blended natural gas when the hydrogen blending ratios are 0%, 20% and 40%. The experimental data clearly reveal the key role of N₂ as an inert gas in inhibiting explosion intensity and slowing down the combustion dynamic process, and its influence mechanism is mainly reflected in three dimensions: peak overpressure, pressure rise rate and explosion development time.

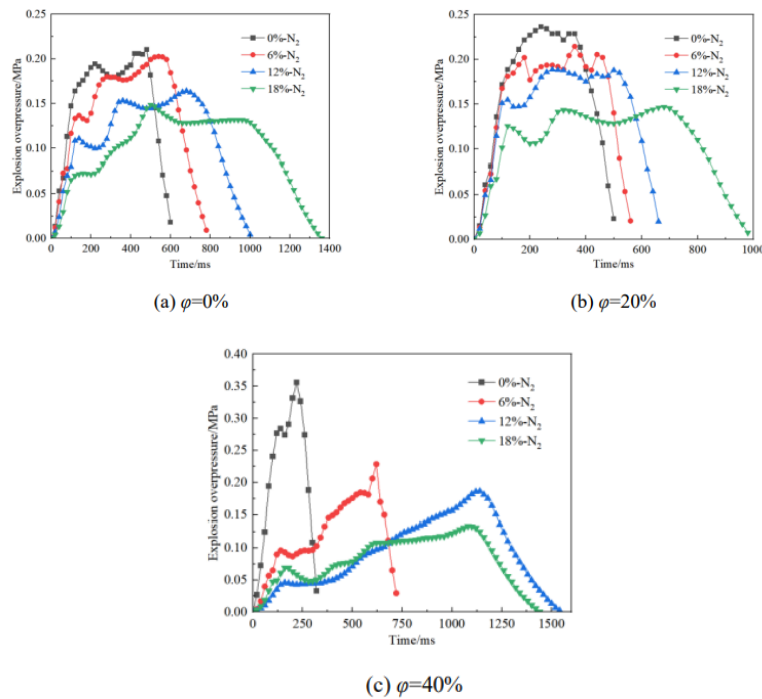


Figure 4. Effect of inert gas N₂ volume fraction on explosion overpressure of methane/hydrogen premixed gas under different hydrogen blending ratios

4.2.1. Analysis of flame suppression effect of nitrogen under pure methane condition

Figure 4-a shows the effect of different N₂ volume fractions on explosion overpressure under the working condition of 0% hydrogen blending ratio (pure methane). It can be seen from the curve that the peak overpressure is about 0.23 MPa without N₂, and drops to 0.08 MPa when the N₂ volume fraction increases to 18%, with a reduction amplitude of 65.2%, indicating that the physical and chemical effects of N₂ effectively inhibit the explosion intensity. N₂ not only reduces the peak pressure, but also significantly delays the pressure rise: the 0% N₂ curve reaches the peak at about 200 ms, while 18% N₂ takes 800 ms, which shows that N₂ reduces the explosion risk by slowing down the combustion speed; in addition, under higher concentrations such as 12% N₂ and 18% N₂, an obvious "plateau stage" appears in the pressure curve, reflecting that N₂ inhibits the free radical chain reaction, leading to slow and incomplete combustion.

4.2.2. Effect of hydrogen blending ratio on the suppression effect of nitrogen

Figure 4-b shows the variation law of overpressure when the hydrogen blending ratio is 20%, and the overpressure variation under this working condition is significantly different from that of pure methane. Under the same N_2 concentration, the peak overpressure with 20% hydrogen blending is generally higher; for example, at 6% N_2 , the peak overpressure with 20% hydrogen blending is about 0.18 MPa, while that of pure methane is only 0.15 MPa, with an increase amplitude of 20%. This is due to the high diffusion coefficient and fast combustion characteristics of hydrogen, which can maintain a high combustion rate even in the presence of N_2 , making the peak arrival time of all curves 30-50 ms shorter than that of pure methane. Figure 4-c shows the explosion characteristics under high hydrogen blending ratio (40%), and the explosion law under high hydrogen blending ratio is more complex. First, the overpressure amplitude increases significantly, the peak overpressure reaches 0.38 MPa without N_2 , an increase of 65% compared with pure methane, which confirms the enhancement effect of hydrogen on explosion intensity; second, the suppression effect of N_2 is limited, although the overpressure decreases with the increase of N_2 concentration (dropping to 0.12 MPa at 18% N_2), the absolute pressure at the same N_2 concentration is still higher than that under low hydrogen blending ratio conditions.

The effect of hydrogen blending ratio on the suppression effect of N_2 on peak explosion overpressure can be further analyzed from Figure 5. With the increase of N_2 volume fraction (0%, 6%, 12%, 18%), the peak explosion overpressure under different hydrogen blending ratios (0%, 20%, 40%) all shows a downward trend, indicating that N_2 can suppress explosion by diluting the flammable mixture gas and reducing the reaction activity, which is a common law under all hydrogen blending ratio conditions.

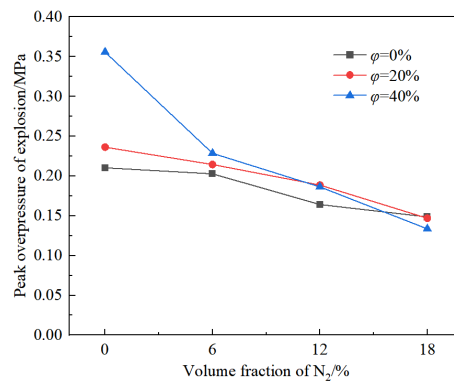


Figure 5. Variation of peak explosion overpressure with inert gas N_2 volume fraction under different hydrogen blending ratios

When the hydrogen blending ratio is 0%, the peak overpressure is about 0.28 MPa at 0% N_2 volume fraction and drops to about 0.20 MPa at 18%, with a relatively stable suppression effect. Without the participation of additional hydrogen, the simple physical dilution of N_2 plays a leading role. When the hydrogen blending ratio is 20%, the initial (0% N_2) peak overpressure is about 0.25 MPa, and the reduction amplitude with the increase of N_2 is larger than that at 0% hydrogen blending ratio. The flammability and high reaction rate of hydrogen change the activation energy and reaction path of the explosion system. The higher the hydrogen blending ratio, the stronger the initial reaction activity of the system. N_2 has a more obvious suppression effect on the high-activity system by reducing the concentration of reactants and absorbing reaction heat, that is, the increase of hydrogen blending ratio enhances the suppression effect of N_2 on peak explosion overpressure,

which is essentially the difference in the coupling effect between the reaction characteristics induced by hydrogen and the physical and chemical inhibition of N₂.

5. Conclusions

In this chapter, the flame suppression effects of CO₂ and N₂ on the premixed combustion of hydrogen-blended natural gas were explored through experiments. The effects of hydrogen blending ratio and inhibitor volume fraction on explosion overpressure, flame suppression efficiency and explosion range were analyzed emphatically, the action laws and mechanisms of each inhibitor were revealed, which provides experimental basis for explosion prevention and control.

(1) CO₂ has both thermodynamic dilution and chemical inhibition effects: under the pure methane condition, 18% CO₂ reduces the peak overpressure from 0.21 MPa to 0.08 MPa with a reduction amplitude of 61.9%, slows down the pressure rise rate and prolongs the peak arrival time, which is attributed to its heat absorption and temperature reduction as well as the reaction of its decomposition products with active free radicals to interrupt the chain reaction. The increase of hydrogen blending ratio enhances the suppression efficiency of CO₂; at a hydrogen blending ratio of 40%, 18% CO₂ reduces the overpressure with an amplitude of 78%, because hydrogen increases the combustion temperature and strengthens the effects of free radical quenching and heat absorption.

(2) N₂ is mainly based on physical dilution, and its flame suppression effect is synergistically enhanced with the increase of hydrogen blending ratio: 18% N₂ in pure methane reduces the peak overpressure from 0.23 MPa to 0.08 MPa with a reduction amplitude of 65.2%, reflecting the effects of dilution and thermal buffering. At a hydrogen blending ratio of 20%, the overpressure reduction amplitude is 60% at the same N₂ concentration but the absolute pressure is higher; at a hydrogen blending ratio of 40%, 18% N₂ reduces the overpressure from 0.38 MPa to 0.12 MPa with a reduction amplitude of 68.4%.

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