FLAME PROPAGATION OF PREMIXED GAS EXPLOSION WITH DIFFERENT EQUIVALENT RATIO UNDER CORRUGATED FIRE-RETARDANT CORE

by

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Based on the self-built experimental set-up, the propagation law of explosion flame of hydrogen/methane premixed gas with different hydrogen volume fractions in different equivalent ratios was investigated under the action of a corrugated fire-retardant core. The experimental study shows that the flame isolation and suppression effect of the corrugated fire-retardant core at different equivalence ratios is either promoted or suppressed, the hydrogen/methane premixed gas explosion flame is quenched without hydrogen mixing when $\phi = 0.8$ and 1.0, and also quenched when $\phi = 1.2$ in different hydrogen volume fractions. The corrugated flame-retardant core significantly affected the extinguishing of the explosion flame of the premixed gas when $\phi = 1.2$, the flame propagation speed and overpressure showed a similar trend under different volume fractions of hydrogen. When the flame is quenched, the flame is depressed inward to form a reverse spherical cell flame, reverse diffusion combustion phenomenon occurs, and it lasts a long time, eventually, the combustion reaction extinguished. The flame penetrated the corrugated fire-retardant core during the rest of conditions. When $\phi = 1.0$, the flame reaction of the hydrogen/methane premixed gas explosion under the action of the corrugated fire-retardant core is the most violent, and its propagation speed and overpressure jump rapidly until it reaches a peak.

Key words: *corrugated fire-retardant core, hydrogen/methane premixed gas, chain reaction, reverse diffusion combustion*

Introduction

Hydrogen is an essential carrier for building a diversified energy supply system based on clean energy in the future [1-4], and the transportation of hydrogen through existing natural gas pipeline corridors is an important way and means of hydrogen storage and transport [5, 6]. Due to the special physicochemical properties of hydrogen, low ignition energy, ease to be ignited, and hydrogen embrittlement phenomenon will affect the integrity of steel components pipeline, when the premixed combustible gas leaks and explodes during the long-distance pipeline transportation, it will cause serious production safety accidents, resulting in serious casualties and

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property damage [7, 8]. Flame arresters are widely used in explosion isolation and suppression of gas pipelines due to their special arrangement of fire-retardant cores, the good extinguishing performance of the explosion flame, and the attenuation performance of the explosion pressure.

Duan *et al*. [9, 10] found that porous materials with different porosity have two different effects on the explosion flame and overpressure to promote or inhibit the larger porosity, diffusion combustion phenomenon occurred. Li *et al*. [11] studied the propagation of the explosion flame of hydrogen methane mixture through the perforated plate with different apertures. Lin *et al*. [12] obtained the effect of different working conditions on the propagation velocity and explosion pressure of hydrogen explosion flame entering the flame arrestor and the corresponding flame extinguishing results. Yue *et al*. [13] showed that the diameter of the quenching section and the parameters of the long triangular gap were the key factors affecting the quenching characteristics. Jin *et al*. [14] studied the flame-quenching behavior of premixed hydrogen/air flames under the action of a wire mesh in a closed tube, and the flame-quenching performance increased significantly with the increase of the wire mesh volume, and the wire mesh had a more effective suppression effect on the fuel-rich case. Mahuthannan *et al*. [15] analyzed the effect of methane-air, propane-air, and ethylene-air flame velocities on quenching distance and discussed the effect of flame curvature and turbulence from quenching theory. Sun *et al*. [16] studied the propagation and quenching processes of propane-air, ethylene-air, and hydrogen-air through a convoluted tape flame arrestor in a closed horizontal pipe. The quenching mechanisms of gases with different reactivity were related to the porosity and thickness of the flame arrestor element and the length-to-diameter ratio of the pipe. Wan *et al*. [17] studied the quenching distance of a perforated plate with different perforation lengths and channels, and the effect of the perforated plate on premixed hydrogen-air flame quenching under the initial pressure in the channel. The flame speed depends on the length of the perforated plate.

Although the aforementioned scholars at home and abroad have conducted relevant studies on corrugated fire-retardant core and achieved certain results, it's still a lack of research on hydrogen/methane premixed gas under the action of corrugated fire-retardant core, and also need to improve the standard for developing flame arrester cores for premixed gas blended with hydrogen. This paper investigates the flame propagation law of the explosion of hydrogen/methane premixed gas under the action of corrugated fire-retardant core with different equivalence ratios and provides theoretical support for the future explosion isolation and suppression technology in the gas pipeline network.

Laboratory equipment

Experimental parameter settings

The experimental conditions were calculated by setting the premixed gas equivalence ratios ϕ = 0.8, 1.0 and 1.2 . Table 1 shows the required experimental conditions for this experiment are calculated.

Experimental set-up

The experimental set-up, as shown in fig. 1, consists of the following five systems, including explosive surge tube, premixed gas distribution system, high-speed flame image acquisition system, pressure acquisition system, and high-frequency pulse ignition system.

The explosion surge tube size is 1000 × 100 × 100 mm^3, made of a plexiglass plate, with a maximum pressure resistance of 2 MPa, which equipped with a pressure sensor and a vent above. Premixed gas distribution system connected with valves, gas inlet piping, gas flow meter (range of 0-5 Lpm) and combustible gas cylinder. High-speed flame image acquisition

Table 1. Volume fraction of premixed gases

φ	Equivalence ratio ϕ = 0.8		
	v(H_2) [%]	v(CH_4), [%]	v(Air) [%]
0%	0	7.79	92.21
10%	0.84	7.53	91.63
20%	1.81	7.23	90.96
30%	2.95	6.88	90.17
φ	Equivalence ratio ϕ = 1.0		
	v(H_2) [%]	v(CH_4)/ %	v(Air) [%]
0%	0	9.55	90.45
10%	1.02	9.22	89.75
20%	2.20	8.78	89.02
30%	3.58	8.35	88.07
φ	Equivalence ratio ϕ = 1.2		
	v(H2) [%]	v(CH4) [%]	v(Air) [%]
0%	0	11.25	88.75
10%	1.21	10.85	87.94
20%	2.60	10.38	87.02
30%	4.22	9.84	85.94

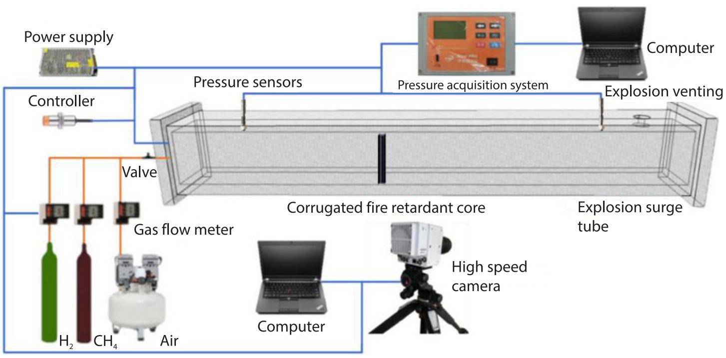


Figure 1. Schematic diagram of the experimental setup

system consists of Phantom V710L high-speed camera connected to a computer, with a maximum sampling frequency of 7400 fps and a maximum resolution of 1280 × 800 pixels. Pressure acquisition system consists of a high-frequency pressure sensor (–0.1-0.1 MPa), a pressure tester and a computer. High-frequency pulse ignition system consists of power supply, ignition switch, and high-voltage pulse device. Determine the corrugation gap according to the MESG value and define the corrugation gap as 1.0 mm [18]. The size of the corrugated fire-retardant core is 100 × 100 × 10 mm^3, as shown in fig. 2.

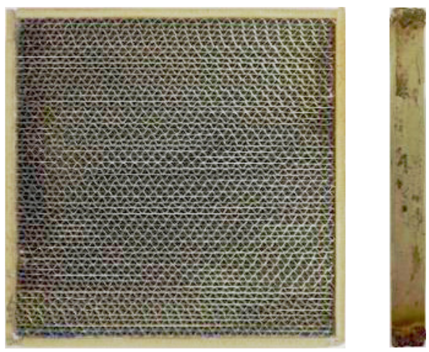


Figure 2. Corrugated fire-retardant core

Analysis of experimental results

Flame propagation characteristics

The explosion flame diagram of hydrogen/methane premixed gas under the action of corrugated fire-retardant core with different equivalent ratios is shown in fig. 3, hydrogen/ methane premixed gas explosion flame is quenched or penetrated under the corrugated fire-retardant core. When $\phi = 0.8$ and 1.0, the methane premixed gas without hydrogen mixing can be quenched by the corrugated flame-retardant core, but after mixing with hydrogen, the premixed gas explosion flame penetrates it, and then, the flame achieves secondary acceleration, deflagration occurs, and the flame flow state transitions, changing from laminar flow to turbulent flow. When $\phi = 1.2$, the hydrogen/methane premixed gas with different hydrogen volume fractions can be quenched by the corrugated fire-retardant core.

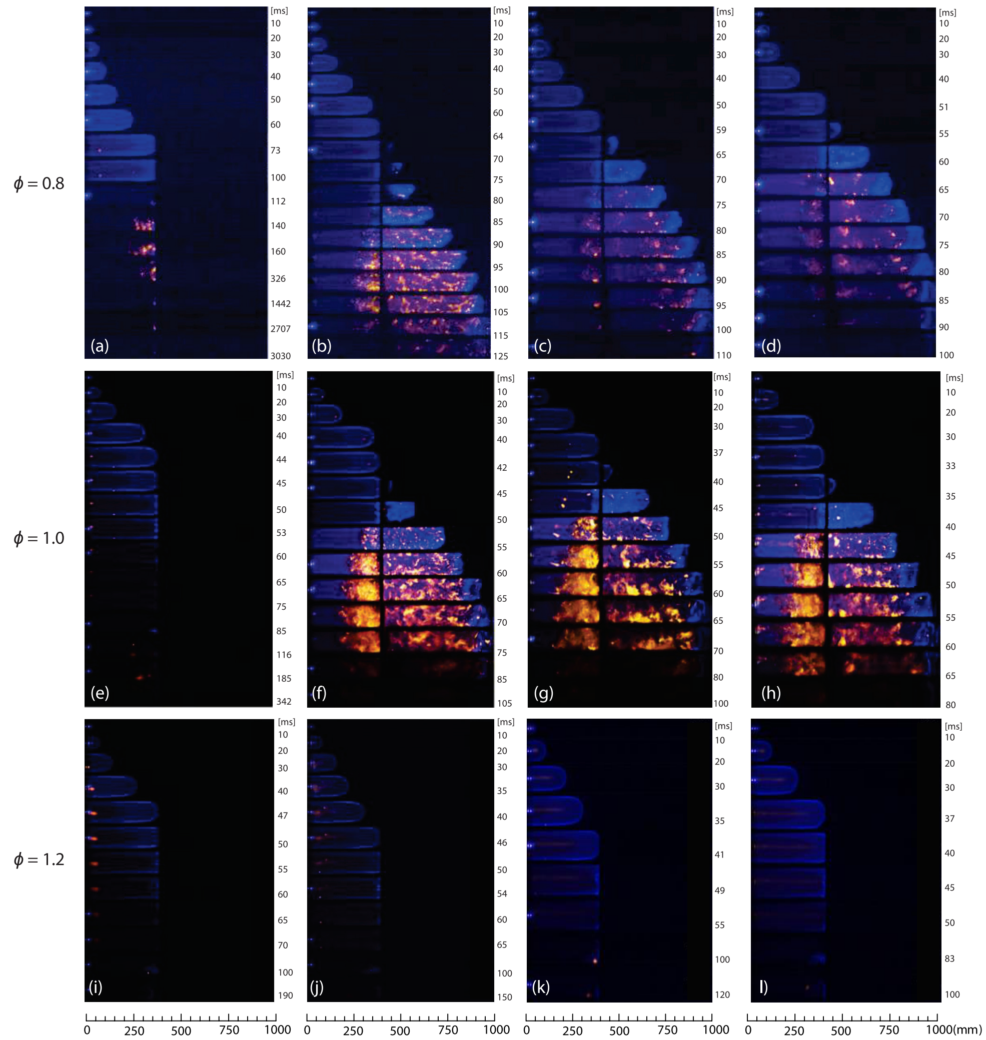
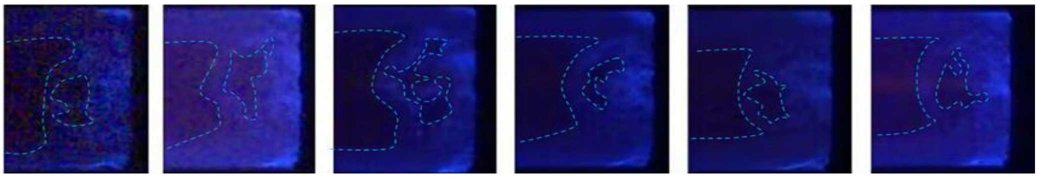


Figure 3. Flame propagation diagram of the explosion of methane premixed gas with different hydrogen volume fractions at different equivalence ratios; (a, e, i) $\varphi = 0\%$, $\phi = 0.8$, (b, t, j) $\varphi = 10\%$, $\phi = 0.8$, (c, g, k) $\varphi = 20\%$, $\phi = 0.8$, and (d, h, l) $\varphi = 30\%$, $\phi = 0.8$

It can be seen in fig. 3 that only two classical kinetic development stages, spherical and finger-shaped flame, can be observed at the front of flame development, it inhibits the further development of subsequent flames for the position of corrugated fire-retardant core is closer to the front of the pipe. Figures 3(a), 3(c), 3(i), 3(j), 3(k), and 3(l) shows the quenching of the premixed gas explosion flame under the action of the corrugated fire-retardant core respectively. When the flame contacted the corrugated fire-retardant core, it was quickly blocked, and the flame front sunken inward, forming a reverse spherical cell-like flame, as shown in fig. 4. The average duration of diffusion combustion is longer when the front wall of the corrugated fire-retardant core reverse diffusion combustion phenomenon occurs.



ϕ = 0.8 (0%) ϕ = 1.0 (0%) ϕ = 1.2 (0%) ϕ = 1.2 (10%) ϕ = 1.2 (20%) ϕ = 1.2 (30%)

Figure 4. Reverse spherical cell flame

Figure 5 shows the extinguishing principle of hydrogen/methane premixed gas explosion flame under the action of corrugated fire-retardant core, the reason for quenching phenomenon is based on two aspects of chain reaction theory and vessel wall effect. The combustion of hydrogen/methane premixed gas mainly produces -H, -O, -OH, -HCO, $-CH_3$, $-CH_2O$, and other free radical groups according to the chain reaction theory, when the flame propagates to the corrugated fire-retardant core, the flame is divided into small streams, the expansion wave is absorbed and reflected by the corrugated fire-retardant core, forming a reverse sparse wave, while the collision area and the probability between free radicals and wall increases. This result in the destruction of free radicals in the narrow channel and then the interruption of the chain reaction. In addition, the gas explosion propagation mechanism is mainly affected by the heat transfer effect, due to the better thermal conductivity of metal wall is, the corrugated fire-retardant core enlarges the interface between flame and wall, while the flame arrived, energy dissipation, which leads to the combustion reaction rate and free radical generation rate reduced, and ultimately the chain reaction cannot be sustained, eventually the flame is extinguished. The reason is that the amplitude of the flame transfer function increases, the heat release fluctuation due to hydrogen mixing becomes larger when $\phi = 0.8$ and $\phi = 1.0$, finally, the overall flame instability increases. When $\phi = 1.2$, hydrogen mixing causes the amplitude of the flame transfer function to decrease and then increase, the overall flame stability is stronger [19]. Moreover, when φ is less than 50%, the hydrogen/methane premixed gas combustion reaction is mainly dominated by methane [20]. As the ignition energy of hydrogen is lower than methane, hydrogen reacts in preference to oxygen, leading to an inadequate combustion reaction of the subsequent methane-dominated hydrogen/methane mixture. Therefore, the content of O_2 involved in the chain reaction decreases, the chain of hydrogen/methane reaction initiates the generation of free radicals, and the O_2 content continues to decrease as the fuel continues to increase in hydrogen content. Thus, the higher of hydrogen concentration leads to more invalid collision in the chain reaction, the increase of combustion reaction rate is smaller under the coupling effect of the broken chain in the vessel wall, which is reflected in the flame propagation speed at φ = 0%, 10%, 20%, and 30%, the trend of flame is similar, and there is little difference in peak velocity.

In addition, the flame produces a reverse spherical cell flame, and its duration of a longer diffusion combustion reasons are as follows. On the one hand, on account of hydrogen/

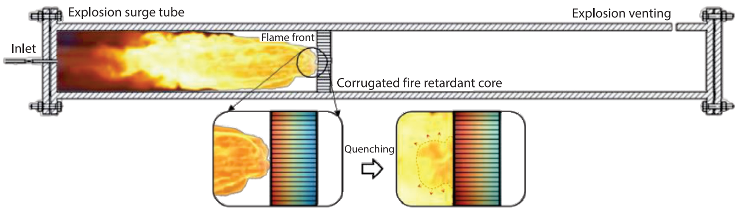


Figure 5. Flame quenching mechanism

methane premixed gas explosion generated compression waves under the action of corrugated fire-retardant core in upstream, it drives the flame front to the downstream combustible gas propagation, due to the corrugated fire-retardant core, the upstream gas is consumed resulting in upstream pressure reduction, therefore, the resulting pressure difference leads to the downstream unburned combustible gas flowing upstream to be ignited, and under the joint action of the sparse wave, a reverse spherical cell-like flame is formed in the flame spreading from inside to outside. On the other hand, the corrugated fire-retardant core has a special flame-arresting unit structure, the orderly arrangement between its corrugations, and the flow of combustible gas resistance is small, downstream unburned combustible gas under the joint effect of the pressure differential, it flows upstream through the flame-arresting unit slit, continuous supply of small flow of combustible gas to the upstream burned region, and thus the reverse flame time is longer.

Figures 3(b), 3(c), 3(d), 3(f), 3(g), and 3(h) is the situation when $\phi = 0.8$ and $\phi = 1.0$ hydrogen/methane premixed gas explosion flame penetrates corrugated fire-retardant core, respectively. It can be observed that the premixed gas explosion flame penetrates corrugated fire-retardant core, the flame front can still maintain the original flame shape forward for a while owing to the flame-arresting unit structure. When $\phi = 0.8$, the average flame duration is about 3 ms, when $\phi = 1.0$, it lasts about 2 ms, and then the flame is unstable, a transition occurs, forming a deflagration flame, the transition zone is shown in fig. 6. When $\phi = 0.8$ with $\varphi = 10\%$, 20%, and 30%, the time of premixed gas explosion flame contacts corrugated fire-retardant core front is 64 ms, 59 ms, and 51 ms respectively, but when $\phi = 1.0$, it changes to 42 ms, 37 ms, and 33 ms, respectively. The explosion flame reached the front of corrugated fire-retardant core was only 2 ms lower after mixing with 10% of hydrogen compared the time without hydrogen mixing, but it penetrated it, for the high diffusivity of hydrogen promoted the efficiency of the

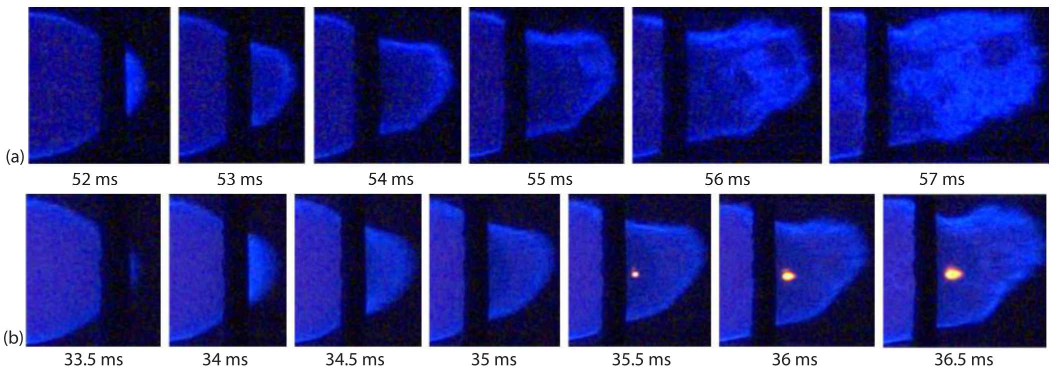


Figure 6. Flame transition zone; (a) when the equivalence ratio is 0.8 (φ = 30%) and (b) when the equivalence ratio is 1.0 (φ = 30%)

combustion reaction, and the reaction was more violent, which led to the increase of flame propagation speed and flame propagation distance, thus, it makes the corrugated fire-retardant core failure.

Combined with the Phantom V710L camera software, the propagation speed of hydrogen/methane premixed gas explosion flame at different equivalent ratios were calculated as shown in fig. 7.

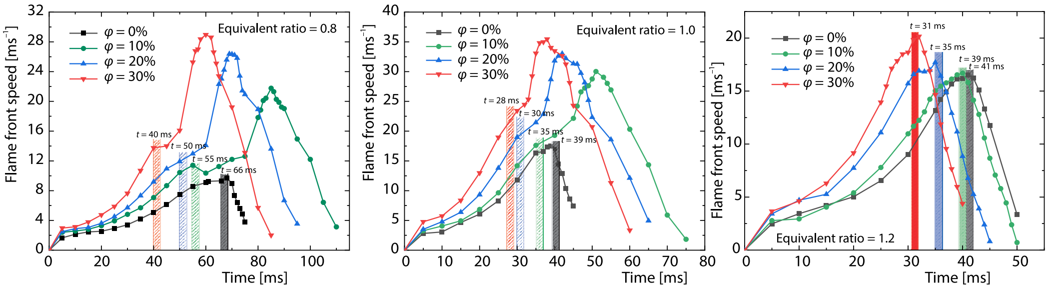


Figure 7. Premixed gas explosion flame propagation speed; (a) equivalent ratio = 0.8, (b) equivalent ratio = 1.0, and (c) equivalent ratio = 1.2

When ϕ = 0.8, the maximum flame front speed of methane premixed gas explosion flame is 9.73 m/s, the chemical reaction speed increases due to the chemical property of hydrogen after adding hydrogen. At the same time, the laminar flame transforms into a turbulent flame after passing through the corrugated fire-retardant core, and its speed reaches the maximum rapidly. The maximum velocities of the flame when φ = 10%, 20%, and 30% is 21.77 m/s, 26.37 m/s, and 28.96 m/s, respectively, and the velocity increases is 123.74%, 171.09%, and 197.69%, respectively, compared without hydrogen mixing. The velocity rise rate of premixed gas with different volume fractions decreased due to the effect of corrugated fire-retardant core according to the flame velocity image, and the acceleration slowed down at 66 ms, 55 ms, 50 ms, and 40 ms, respectively, the velocity trend started to decrease while the flame arrived corrugated fire-retardant core, but then the flame passed through it. When ϕ= 1.0, the trend of flame propagation velocity at different hydrogen volume fractions is similar to ϕ = 0.8, and the maximum velocity of the flame front is 17.48 m/s, 30.02 m/s, 33.01 m/s and 35.46 m/s, respectively, which is 71.74%, 88.89%, and 102.87% higher without hydrogen mixing condition. The maximum speed of the corresponding flame front at different hydrogen volume fractions increased by 79.65%, 37.90%, 25.18%, and 22.43%, respectively, compared with ϕ = 0.8, and the flame rise rate decreased at 39 ms, 35 ms, 30 ms, and 28 ms, respectively. Under the condition of the same equivalent ratio, the premixed gas with 10% hydrogen volume fraction has little effect on the velocity of the flame, the increase of the velocity is obvious compared with that when hydrogen is not mixed and change a little compared with the hydrogen premixed gas flame. When ϕ = 1.2, the trend of flame propagation velocity was different from ϕ = 0.8 and ϕ = 1.0, hydrogen/methane premixed gas explosion flame with different volume fractions of hydrogen was quenched. The peak velocity of the flame is similar when unmixed or mixed with different volume fractions of hydrogen. The flame velocity is 16.50 m/s, 16.69 m/s, 17.70 m/s, and 20.16 m/s respectively, and it increased by 1.12%, 5.63%, and 20.28 % respectively, which increased a little compared with methane premixed gas flame.

Premixed gas explosion pressure analysis

Figure 8 is the pressure image of hydrogen/methane premixed gas explosion flame with different equivalent ratios when ϕ= 0.8, it can be seen from the image that the peak pressure of the upstream and downstream changes a little when φ = 0% due to the flame is quenched, and the maximum pressure reaches a peak of 10.24 kPa and 10.46 kPa, respectively, at 37.70 ms and 40.18 ms. The process of pressure can be divided into two stages, the prodromal blast wave region and oscillation wave area. The character of prodromal blast wave region is mainly boost and buck, and oscillation wave causes the pressure to oscillate back and forth until it reaches zero. When φ = 10%, 20%, and 30%, the upstream peak pressure is 12.52 kPa, 13.50 kPa, and 14.83 kPa reached at 30.02 ms, 31.04 ms, and 46.68 ms, respectively, and the downstream peak pressure is 29.62 kPa, 37.77 kPa, and 46.4 kPa reached at 70.24 ms, 56.56 ms, and 48.84 ms, respectively. Compared with the absence of hydrogen, the upstream explosion overpressure increased by 22.27%, 31.84%, and 44.82% after the addition of hydrogen, and the downstream explosion overpressure increased by 183.17%, 261.09%, and 343.59%, respectively. Compared to without hydrogen mixing, except the prodromal shock wave region and the oscillation wave region, the process of pressure forms a secondary reverse shock wave, which rises rapidly to peak pressure, and then the pressure begins to fall, reaching the oscillation wave region until the oscillation disappears.

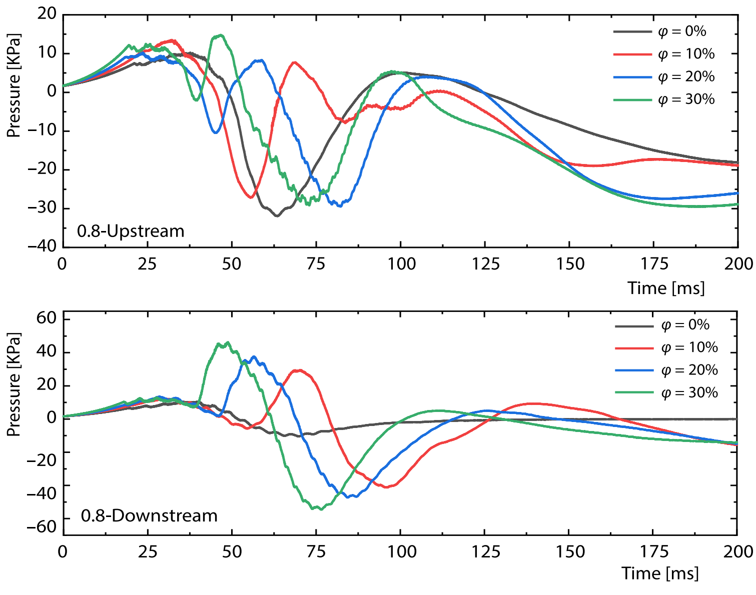


Figure 8. Pressure upstream and downstream of the explosion flame of hydrogen/methane premixed gas with different equivalence ratios

Figure 9 is the pressure image of hydrogen/methane premixed gas explosion flame with different equivalent ratios when ϕ = 1.0, the propagation of the explosion flame without hydrogen is suppressed by the corrugated flame-retardant core, therefore, the pressure trend of the premixed gas explosion is similar to ϕ = 0.8, and the time of peak pressure is significantly advanced, reaching the peak pressure of 15.93 kPa and 16.88 kPa for upstream and downstream at 24.68 ms and 27.32 ms, respectively. When φ = 10%, 20% and 30 %, the upstream peak pressure of 22.83 kPa, 31.62 kPa, and 35.74 kPa was reached at 40.94 ms, 33.64 ms, and 31.04 ms, respectively, the downstream pressure of 63.5 kPa, 71.98 kPa, and 78.18 kPa was

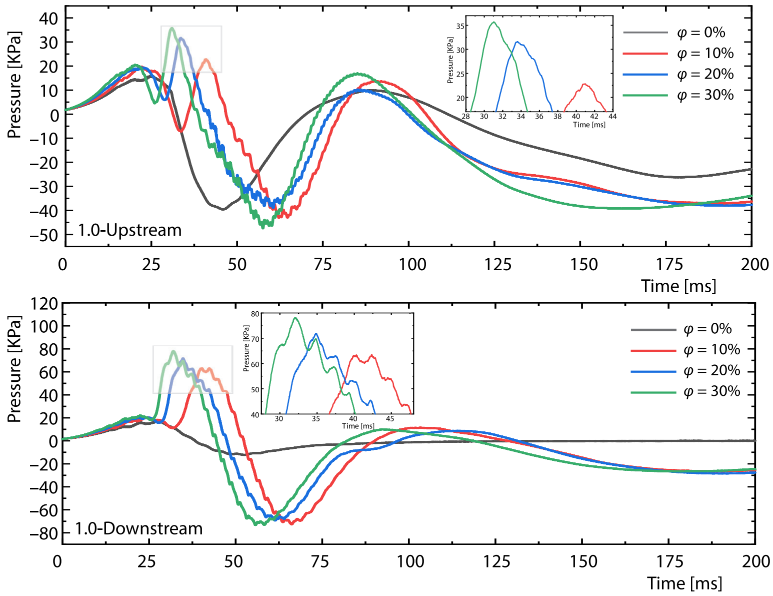


Figure 9. Pressure upstream and downstream of the explosion flame of hydrogen/methane premixed gas with different equivalence ratios when $\phi = 1.0$

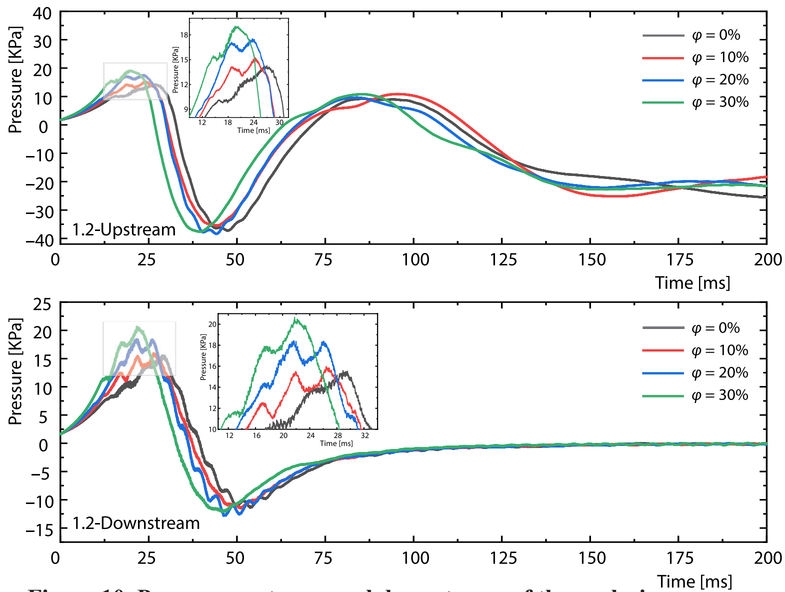


Figure 10. Pressure upstream and downstream of the explosion flame of hydrogen/methane premixed gas with different equivalence ratios when $\phi = 1.2$

reached at 42.34 ms, 34.82 ms, and 32.04 ms, respectively. The upstream pressure increased by 43.31%, 98.49%, and 124.36%, and the downstream pressure increased by 276.18%, 326.42%, and 362.15% compared with $\varphi = 0\%$. The shock wave generated by the explosion flame has a greater impact on the downstream after the corrugated fire-retardant core fails, and the negative pressure is close to the pressure peak. When $\phi = 1.0$, for the upstream pressure peak appears earlier after the corrugated fire-retardant core failure according to the pressure image, the upstream and downstream pressure peak occurrence time is similar, and the reverse pressure wave generated by the explosion flame is greater than the prodromal blast wave.

Figure 10 is the pressure image of hydrogen/methane premixed gas explosion flame with different equivalent ratios when $\phi = 1.2$, the explosion flame of hydrogen/methane premixed gas with different volume fractions is suppressed, and the trend of the pressure image is approximate when $\varphi = 0\%$, 10%, 20%, and 30%, the upstream pressure peak of 14.27 kPa, 15.28 kPa, 17.51 kPa, and 19.05 kPa reached at 27 ms, 24.18 ms, 23.62 ms, and 19.66 ms, respectively, the downstream peak pressure of 15.59 kPa, 15.98 kPa, 18.38 kPa, and 20.64 kPa reached at 28.90 ms, 26.42 ms, 26.02 ms, and 21.76 ms, respectively. Similarly, the upstream peak pressure increased by 7.08%, 22.71%, and 33.50%, respectively, and the downstream peak pressure increased by 2.50%, 17.90%, and 32.39%, respectively, compared with the time when $\varphi = 0\%$, which is a small increase. When the flame was quenched, the rising trend of the downstream pressure was smaller than the upstream pressure.

Conclusions

- Under the action of the corrugated flame-retardant core, upstream flame development and structure are unaffected, the hydrogen/methane premixed gas explosion flame is manifested as inhibiting or promoting. The flame is quenched when $\phi = 0.8$ and $\phi = 1.0$ with $\varphi = 0\%$ and when $\phi = 1.2$ with $\varphi = 0\%$, 10%, 20%, and 30%. What's more, the quenching flame appears reverse diffusion combustion phenomenon, reverse spherical flame appears. Explosion flame speed and pressure are dramatically increased after through the corrugated fire-retardant core in the rest circumstances.
- Equivalent ratio $\phi = 1.0$, the flame combustion reaction of the hydrogen/ methane mixed gas explosion is the most intense, and the total reaction time is shorter than when $\phi = 0.8$ and $\phi = 1.2$. The speed of flame propagation and explosion overpressure are significantly increased, rising rapidly to a peak after the flame has passed through the corrugated fire-retardant core. The reverse flame has a greater impact on the upstream due to the special structure of the corrugated fire-retardant core and the combined effect of the sparse wave after the explosion flame through the corrugated fire-retardant core. Given the same equivalent ratio, the premixed gas with per 10% hydrogen mixing has little effect on the velocity of the flame front, and the increase in the velocity of the flame front is obvious compared to that when $\varphi = 0\%$, and it's not much compared to the explosion flame of the hydrogen/methane premixed gas.
- When $\phi = 1.2$, the more the concentration of combustible gas increases, the more concentration of O_2 decreases. Under the coupling effect of the broken chain of the tube wall, the corrugated fire-retardant core has the most significant effect on hydrogen/methane premixed gas explosion, the flame propagation trend is basically the same, the increasing rate of flame propagation is flat, the upward trend of explosion overpressure is similar, the reverse flame combustion phenomenon is not obvious, showing a discontinuous intermittent combustion flame.

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