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Research Article

Study on Influence of Cavity and Water Mist on Flame Propagation of Gas Explosion in a Pipeline

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For studying the influence of the cavity and water mist on the flame propagation of gas explosion, a rectangular steel cavity of size of length 80 cm × width 50 cm × height 20 cm was designed. The influence of the cavity and it with water mist on explosion flame propagation in a large circular gas explosion system with a length of 34 m was studied. The change of gas explosion flame in the pipeline was analyzed. The results showed that the intensity and flame propagation velocity increase after the explosion flame passes through the straight pipeline, and the attenuation rates are 4.93% and -2.48%, respectively. After the explosion flame passes through a rectangular cavity of length 80 cm × width 50 cm × height 20 cm, its intensity and propagation speed are inhibited, and the attenuation rates are 66.58% and 45.26%, respectively. After the explosion flame passes through the rectangular cavity of the size of length 80 cm × width 50 cm × height 20 cm with water mist, the intensity and propagation speed are inhibited much more, and the attenuation rates are 85.09% and 65.85%, respectively. The influence of the cavity with water mist on flame attenuation of gas explosion is better than that of the cavity alone. Based on theoretical analysis, it is concluded that the inhibition influence of the cavity on explosion flame propagation is mainly due to repeated reflection of flame in the cavity, which results in the attenuation of its energy. The inhibition influence of water mist is mainly due to its heat absorption by vaporization.

1. Introduction

The gas explosion accident is one of the most destructive accidents in coal mine production in China. Although the safety level of China's coal mining production has been greatly improved in recent years, gas explosion accidents still happen from time to time [1, 2].

The mechanism of gas explosion, its suppression, and mitigation have been studied by many scholars. Yu et al. [3] implemented a comparative experimental research on the explosion flame propagation characteristics of CH_4-air mixture with different volume fractions, by using the self-built small-scale experimental platform. The results indicated that when the methane volume fraction is 9.5%, the wave pressure and explosion flame propagation velocity are the highest. Yu et al., Wen et al., and Yu et al. [4–7] studied the effect of obstacles on the propagation characteristics of gas explosion. Cao et al., Song and Zhang, and Yu et al. [8–14] researched the influence of water mist particle size, spray volume, water mist zone length, and additives on the inhibition influence of water mist in gas explosion suppression by experiments. The results showed that when the particle size of ultrafine water mist is within 10 μm to 15 μm, the inhibition effect of explosion intensity and the methane-air mixture explosion flame propagation velocity is the best. When the concentration of superfine water mist is below 1.5 kg/m^3, its inhibition effect on gas explosion overpressure is not obvious. The water mist reduces the flame temperature largely by absorbing the heat of combustion and rapidly evaporating. Shao et al. [15] found in the experiments that the inhibition effect of a vacuum cavity on gas explosion is related to the volume of the cavity. When the actual volume of the vacuum cavity is larger than the critical volume, it has the inhibition effect on the explosion; otherwise, it enhances explosion propagation to some extent. Wang et al. and Su et al. [16, 17] have concluded through experimental research that ethylene and hydrogen can increase the maximum explosion pressure, laminar combustion rate, and maximum pressure rise rate of methane-air mixture, while it shortens the combustion time. Li et al. and Yan et al. [18, 19] designed rectangular steel cavities with different aspect ratios and installed them in a 36 m long large-scale round pipeline of gas explosion test system. The experiment results showed that the cavity has an inhibition effect on the gas explosion propagation, and the effect of explosion inhibition is related to the volume of the cavities, their aspect ratios, etc. The relationship between the methane explosion peak overpressure attenuation factor y and the aspect ratio x of the cavity is as the following: $y = -1.149 \exp(x/10.089) + 2.405$. When the attenuation factor of peak overpressure is 1, the value of the aspect ratio is the critical. When the aspect ratio of the cavity is not more than 1, the cavity has an inhibition effect on the explosion wave overpressure, and the best aspect ratio for inhibition effect is 1/10. When the aspect ratio of the cavity is greater than 1, it enhances the explosion wave overpressure, and the cavity with an aspect ratio of 5/2 has the most enhancing effect on the explosion wave overpressure. Li et al. [20] studied the effects of hydraulic pressure on mechanical behavior, pore size distribution, and permeability.

For the study of gas explosion suppression and its disaster reduction, the small-scale test platforms have been mostly used, but the large-scale test platforms are not much applied. In order to further research the influence of a cavity with water mist on the flame propagation of gas explosion in a large-scale experimental pipeline system, in the paper, theoretical analysis and experimental research were used.

2. Theoretical Analysis of Influence on Gas Explosion Propagation Process

2.1. The Propagation Mechanism of Gas Explosion. The propagation mechanism of gas explosion is the feedback mechanism of the precursor shock wave created by the explosion flame to the heating and compression of the unburned premixed gas. In the process of premixed combustion of a substance, the reaction zone separates the glowing combustion products from the unburned premixed combustibles, as shown in Figure 1 [21]. From the results of combustion, it can be seen that T_0 and C_{A0} of the premixed combustible gas are transformed into T_f and C_{Af} of the reaction products after combustion, and they are separated by combustion wave in space.

According to the combustion theory of premixed flame, the turbulent premixed flame velocity S_T is expressed as the ratio of the volume flow q_v of the combustible premixed gas flowing through the flame to the apparent area A_f of the turbulent flame, as shown in:

$$S_T = \frac{q_v}{A_f}. \tag{1}$$

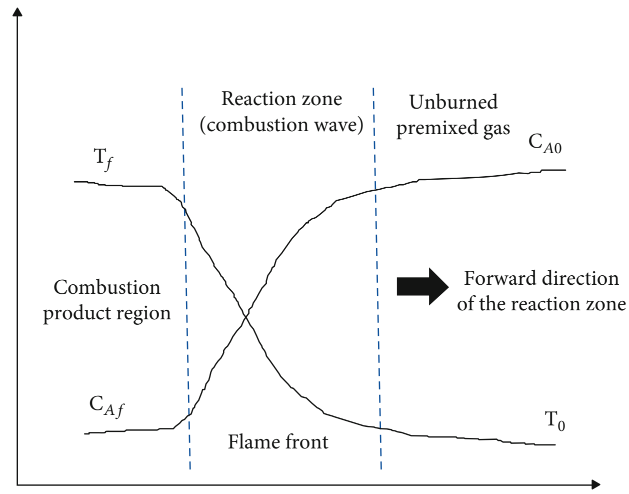


Figure 1: Combustion wave propagation process.

The main reaction of premixed gas/air explosion is shown in the following equation:

$$CH_4 + 2\left(O_2 + \frac{79}{21}N_2\right) = CO_2 + 2H_2O + 7.52N_2. \tag{2}$$

The above chemical reaction formula only expresses the final result of gas explosion. Many studies show that gas explosion is a very intricate chain reaction. When premixed CH_4/air absorbs a certain amount of heat, the molecular chain breaks and turns into free radicals. Then, the free radicals become the reaction activation center. Under the right conditions, the free radicals will continue to decompose, and as the number of free radicals increases, the reaction will become faster and faster, resulting in an explosion.

2.2. Theoretical Analysis of the Effect of Cavity on Flame Propagation of Gas Explosion. It is assumed that the mixture of CH_4 and air is uniform, and relatively static after, the mixture was prepared in the experimental pipeline system. The flame will spread to the two ends, and the periphery of the round pipeline with the ignition source as the detonation center after the mixture is ignited. At this point, the wall of the pipeline will interfere with the flame propagation, and the laminar flame will become turbulent propagation, which will lead to the distortion of the flame front and increase the flame burning speed. After the flame enters the cavity, part of the flame comes out from the cavity to form a primary flame, and the other part of the flame is stirred and mixed in the cavity to form a secondary flame. When the flame passes through the cavity, because of the influence of the cavity disturbance, the primary flame intensity attenuates and the secondary flame intensity increases. However, with the increase of the cavity length, the magnitude of the secondary flame increase decreases, and the time interval of the secondary flame also increases, and the overall attenuation of the flame front is positively correlated with the length of the cavity. Yan et al. [22] studied the mechanism of gas explosion suppression by the cavity by simulating the propagation process of gas explosion shock wave and flame in cavity. According to the method described in reference [22], the mode of the gas explosion flame premixing in the cavity is shown in Figure 2.

2.3. Theoretical Analysis of the Influence of Water Mist on Gas Explosion Propagation. Lentati and Chelliah [23] found through research that the water mist mainly inhibits explosion through physical effect, and its influence through chemical effect is less than 10%. Therefore, in the paper, only its related physical effects were analyzed. The main physical effects of the water mist include heat absorption by vaporization and energy absorption, which mainly effect on the explosion flame. According to the calculation, when the size of the droplet d is less than 200 microns, the spray speed V is less than 30 m/s, the mass concentration Q of water mist is less than 899 g/m^3, and the rate of absorption of flame energy by the droplets is far less than the order of magnitude of the latent heat of vaporization and the sensible heat absorption rate. So the suppression effect of water mist on the flame is mainly based on its heat absorption.

3. Experimental Study

The influence of the cavity and it with water mist on the flame propagation of gas explosion was studied by monitoring the parameters of the explosion flame in the gas explosion experiment system.

3.1. Experimental System. A large-scale gas explosion experiment system with a 34 m-long pipeline is shown in Figure 3. The experiment system consists of five parts: explosion experiment pipeline subsystem, ignition subsystem, gas distribution subsystem, data acquisition and storage subsystem, and explosion suppression subsystem. In the study, the large-scale experimental pipeline system consists of 34 m long circular pipeline and separately installed in it a straight pipe with the length of 50 cm and the diameter of 20 cm, a rectangular steel cavity of length 80 cm × width 50 cm × height 20 cm, or a rectangular steel cavity with length 80 cm × width 50 cm × height 20 cm. The experimental conditions are shown in Table 1. The purpose is to find the influence of the cavity alone or the cavity with water mist on the propagation of gas explosion to provide a reference for studying the suppression of the methane-air mixture explosion.

(1) Explosion experiment pipeline subsystem is made of steel round pipes with a thickness of 0.01 m, diameter of 0.2 m, and compressive strength of 20 MPa, which are connected by flanges and bolts and nuts. The air tightness is guaranteed by rubber gasket between the flange plates. (2) The ignition subsystem is composed of power supply, wire, ignition electrode, and electric fuse. The ignition electrode is installed on the flange plate of the end side of the experiment pipeline system, and the electric fuse is used for ignition. (3) The gas distribution subsystem is composed of methane bottle, connecting pipe, vacuum pump, circulating pump, digital vacuum pressure gauge, and so on. The concentration of methane used in the experiment is not less than 99.9%. (4) The data acquisition and storage subsystem

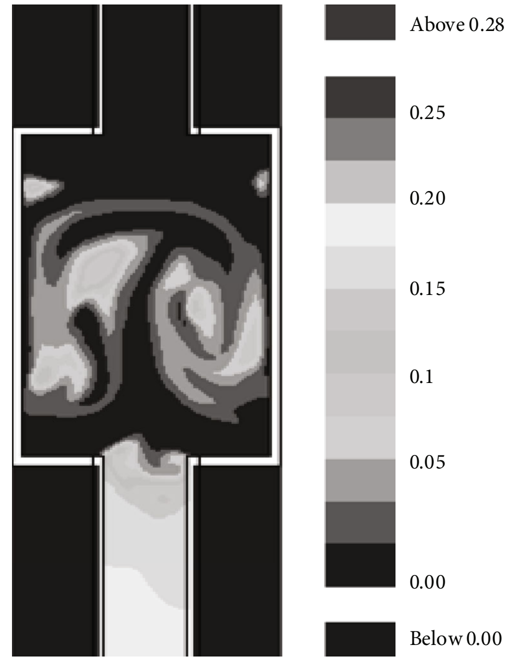


Figure 2: The simulation diagram of secondary flame formation in gas explosion in cavity.

is composed of sensors, computer, high-speed data acquisition units, transmitters, and so on. The flame sensors $F1$, $F2$, $F3$, and $F4$ are CKG100 flame sensors, which are located at 11.200 m from the explosion ignition electrode (30 cm from the entrance of the cavity), 11.250 m from the explosion ignition electrode (25 cm from the entrance of the steel cavity), $(11.700 + X)$ m from the explosion ignition electrode (20 cm from the exit of the steel cavity), and $(11.750 + X)$ m from the ignition electrode (0.250 m from the exit of the steel cavity), respectively, where X is the length of the cavity, and the unit is converted to meters. The acquisition software is DAP7.30 transient signal test and analysis software developed by Chengdu Tester Company. (5) The explosion suppression subsystem is composed of a rectangular steel cavity of the size of 0.8 m × 0.5 m × 0.2 m or the cavity with water mist. The experiment site is shown in Figure 4.

3.2. The Experiment Process. Set up the large-scale gas explosion experiment system as shown in Figure 3. Install the polyethylene diaphragm and the flame sensors $F1$, $F2$, $F3$, and $F4$. The experiment was conducted as follows:

(1) *Check the Air Tightness of the Experiment System.* The ignition electrode was sealed, the experiment system was pumped to -20PV by vacuum pump, and then waited 5-10 min to observe the negative pressure of the experiment system, if there is no change, it shows that the air-tightness of the experiment system is good and the experiment begins

(2) *Install the Ignition Electrode.* Wrap the front end of the ignition electrode around a few fuse so that the two electrodes form a path. Place the fuse-mounted ignition electrode in the position shown in Figure 3

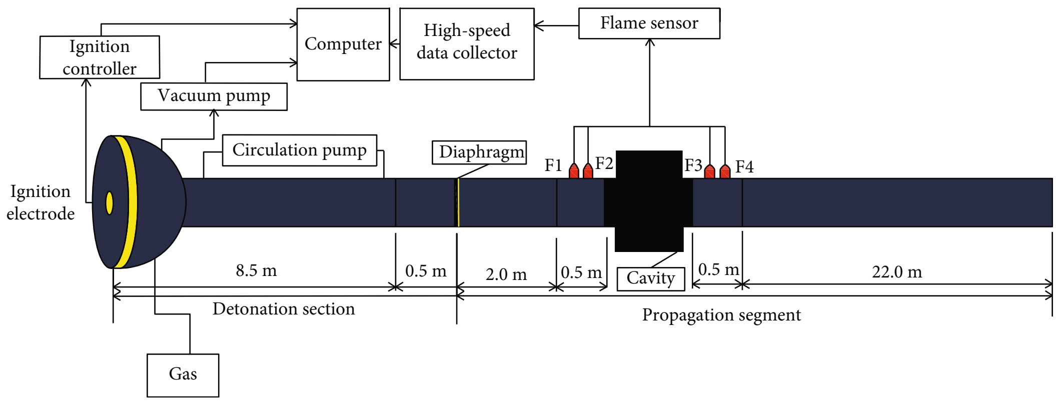


Figure 3: The schematic diagram of gas explosion experiment system.

Table 1: The working conditions in the experiments.

Working condition number	Experimental condition setting
1	A straight pipe with a diameter of 20 cm (straight pipe)
2	Installed a cavity with a length, width, and height of 80 cm × 50 cm × 20 cm
3	Attached with a cavity with a length, width, and height of 80 cm × 50 cm × 20 cm with water mist

Figure 4: The experiment site.

(3) *Gas Distribution*. Dalton partial pressure method was used for gas distribution. First, a vacuum pump was used to vacuum the experimental system to make the system pressure reach −20 PV (the maximum negative pressure of the polyethylene membrane used in the experiment was measured as -25 PV). Then, the experimental system is filled with methane gas with a concentration greater than 99.9%, and stop filling methane gas when the system pressure rises to -10 PV. Open the valve to allow air to enter the experiment system and close the valve when the pressure in the system rises to 0 PV, and a mixture of gas with a methane concentration of 10% was prepared (according to theoretical analysis, the gas concentration of 9.5% is the concentration of the maximum explosion intensity under the experimental conditions) [6]. Because the experiment precision is accurate to 1%, so the concentration of CH_4 in the gas mixture was prepared as 10%

(4) *Premixed the CH_4/Air Mixture*. The specific steps are as follows: when the gas distribution finished, open the circulating pump and circulate the CH_4/air mixture for about 15 minutes, so that the methane gas and the air are fully mixed

(5) *Spray Mist in the Cavity*. 1-2 minutes before detonation, turn on the sprayer. Close the sprayer until the explosion process is complete. The model of high pressure atomizing pump is NS-KL04750. The nozzle is 0.20 mm in diameter, and the spray volume is 0.117-0.155 L/min. The spray direction is from the upper part of the cavity to its lower part

(6) *Detonation and Data Acquisition*. The mixture was ignited by ignition device, and the ignition energy is 10 J. The experimental data were collected and saved by DAP7.30 transient signal test and analysis software, flame sensors, and computer

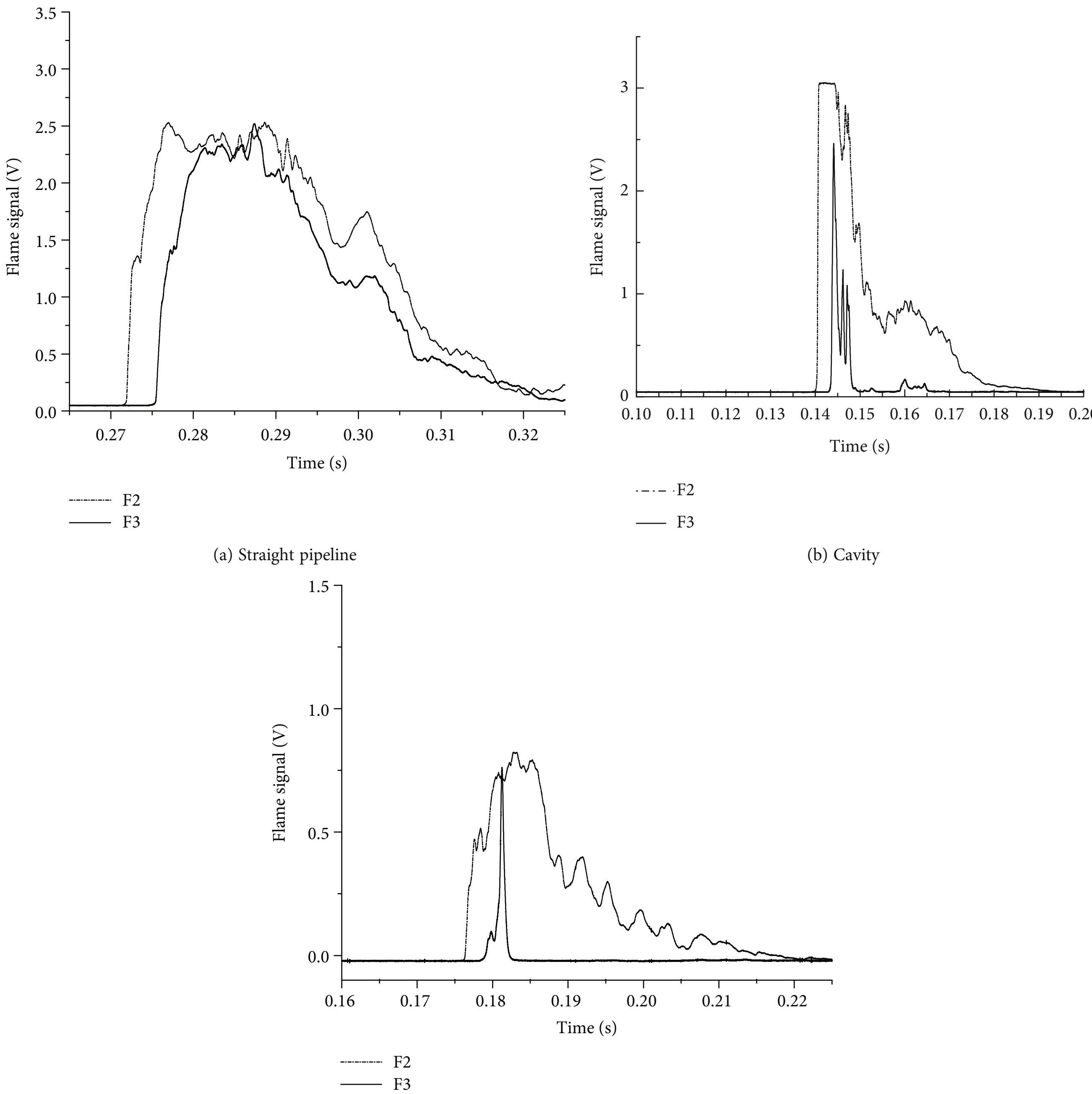
(7) At the end of the experiment, the exhaust gas in the pipeline was swept by an air compressor

Under experimental conditions 1 or 2, the experiment was implemented according to steps 1-4, 6, and 7. Under experimental conditions 3, the experiment was implemented according to steps 1-7.

3.3. The Experiment Results and Analysis. The explosion flame intensity is defined as the integral value of the flame light signal on the time coordinate axis [22]. The attenuation

Table 2: The results in the experiments.

Working condition number	The flame intensity at $F2$	The flame intensity at $F3$	The explosion flame propagation velocity from $F1$ to $F2$ (m/s)	The explosion flame propagation velocity from $F3$ to $F4$ (m/s)
1	0.07813	0.07428	570.13	584.25
2	0.05134	0.01716	575.00	314.78
3	0.04535	0.00676	573.21	195.75

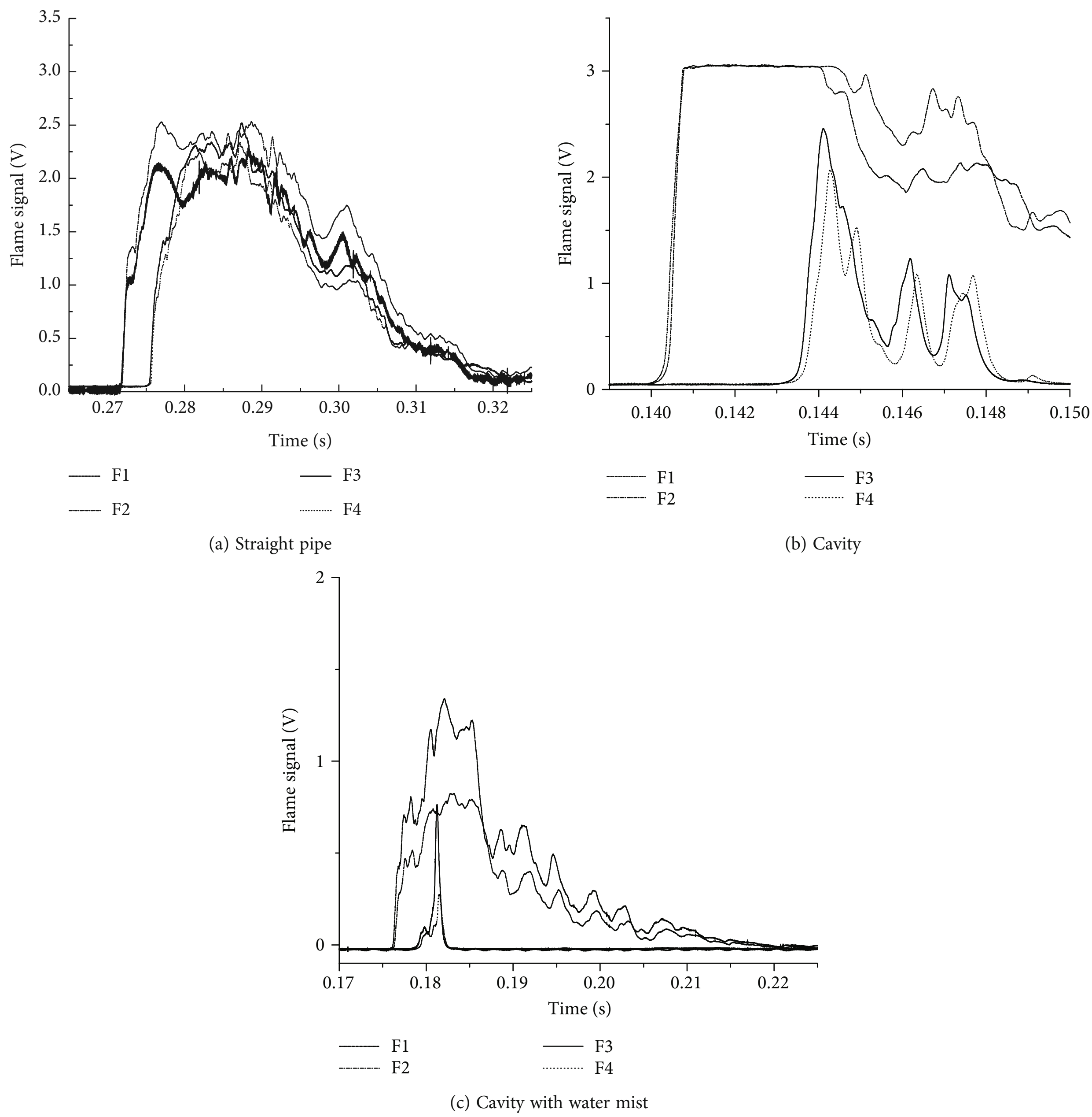


(a) Straight pipeline

(b) Cavity

(c) Cavity with water mist

Figure 5: Explosion flame intensity signal at measuring points $F1$ and $F3$ under different working conditions.



(a) Straight pipe

(b) Cavity

(c) Cavity with water mist

FIGURE 6: Explosion flame velocity signal information of measuring points $F1$, $F2$, $F3$, and $F4$ under different working conditions.

rate of the flame strength is the ratio of attenuation value ΔS of the flame intensity from $F1$ to $F2$ to the explosion flame intensity at $F1$. The flame propagation velocity is defined as the ratio of the distance S between the two flame sensors to the time interval Δt between signals received by the two sensors, that is, $V_1 = S_{F1-F2}/\Delta t$, $V_2 = S_{F3-F4}/\Delta t$, the attenuation rate of flame speed $\eta_v = (V_1 - V_2)/V_1$. The experimental results are shown in Table 2.

3.3.1. The Variation of Flame Intensity of Gas Explosion under the Three Experiment Conditions. After the mixture gas exploded in the experimental device, the evolution process of the flame at measuring point $F2$ and $F3$ with time is shown in Figure 5. The influence of experiment condition 1 on flame propagation of gas explosion was presented in Figure 5(a). According to Figure 5(a), the flame intensity at $F2$ is 0.07813, and the flame intensity at $F3$ is 0.07428. The attenuation rate of flame intensity from $F2$ to $F3$ is 4.93%. Therefore, the methane explosion flame intensity is enhanced after it passes through the straight pipeline. The influence of experiment condition 2 on flame propagation of gas explosion was shown in Figure 5(b). According to Figure 5(b), the flame intensity at $F2$ and $F3$ is 0.05134 and 0.01716, respectively. The attenuation rate of explosion flame intensity from $F2$ to $F3$ is 66.58%, which indicates that the cavity has a suppression effect on the flame intensity. The influence of experimental condition 3 on flame propagation of gas explosion was presented in Figure 5(c).

According to Figure 5(c), the flame intensity at $F2$ and $F3$ is 0.04535 and 0.00676, respectively. The attenuation rate of flame intensity from $F2$ to $F3$ is 85.09%. The experiment condition 3 has a suppression influence on flame propagation. The cavity with water mist has better effect on inhibition of explosion flame propagation than the cavity alone.

3.3.2. The Variation of Flame Propagation Velocity of Gas Explosion under Three Working Conditions. After the mixture gas exploded in the experimental device, the evolution of the flame at each measuring point $F1$, $F2$, $F3$, and $F4$ is shown in Figure 6. It can be seen from Figure 6(a) that the influence of experimental condition 1 on the explosion flame propagation velocity was explored. The explosion flame propagation velocity $V1$ from $F1$ to $F2$ is 570.13 m/s, and the explosion flame propagation velocity $V2$ from $F3$ to $F4$ is 584.25 m/s. The explosion flame propagation velocity decay rate from $V1$ to $V2$ is -2.48%, so the explosion flame velocity increases after the explosion flame passes through the straight pipe. According to Figure 6(b), the influence of experimental condition 2 on the methane explosion flame propagation speed was explored. The methane explosion flame propagation speed $V1$ from $F1$ to $F2$ is 575.00 m/s, and the explosion flame propagation velocity $V2$ from $F3$ to $F4$ is 314.78 m/s. The explosion flame propagation velocity decay rate from $V1$ to $V2$ is 45.26%. Compared with a pure straight pipe, the cavity has a suppression effect on the methane explosion flame propagation velocity. According to Figure 6(c), the influence of experimental condition 3 on the methane explosion flame propagation speed was explored. The methane explosion flame propagation speed $V1$ from $F1$ to $F2$ is 573.21 m/s, and the methane explosion flame propagation speed $V2$ from $F3$ to $F4$ is 195.75 m/s. The explosion flame propagation velocity decay rate from $V1$ to $V2$ is 65.85%. Compared with the pure straight pipe, the explosion flame propagation velocity is inhibited under the experimental conditions. Compared with experimental condition 1, experimental condition 2 only has a cavity to suppress the methane explosion flame propagation speed. Compared with experimental condition 1, experimental condition of cavity combined with water mist has a stronger suppression effect on the methane explosion flame velocity, and it is better than the restraining effect of only attaching a cavity.

3.4. Analysis of Explosion Suppression by Coeffect of Cavity and Water Mist. After the explosion flame enters the cavity, it expands and dissipates. When it propagates at the outlet, part of the methane explosion flame passes out of the steel cavity, and the other part is blocked by the walls of the cavity and reflected, forming a reverse explosion flame and propagating in the opposite direction. Due to the different reflection angle, part of the reverse explosion flame enters the steel cavity inlet and passes out of the cavity after being superposed. The reverse explosion flame that cannot enter the inlet of the cavity is blocked by the walls of the cavity. The flame is reflected again and propagates toward the outlet. This process is repeated so that the flame disappears as the premixed gas is exhausted. Therefore, the flame of explosion attenuates obviously after passing through the cavity, and the functions of flameout and wave elimination are realized.

The coeffect of cavity and water mist increases the effect of flame suppression because of the reasons such as (1) when the flame enters the cavity, the temperature of the water mist is lower than that of the explosion flame, and heat transfer occurs between water mist and methane explosion flame, resulting in the temperature of the flame decrease. (2) The water mist with high density in the confined space of the cavity can cool down the temperature and isolate the oxygen, so that the enhancement of the secondary flame in the cavity is weakened and the explosion flame is suppressed. (3) As an inert droplet, water can directly interfere with the chemical reaction in the explosion reaction zone, and thus, has the effect of chemical inhibition. The suppression effect of the flame propagation velocity is better because the water mist forms a "water wall" in the cavity, which hinders the explosion flame propagation, thus, resulting in greater inhibition effect on the methane explosion flame propagation speed.

4. Conclusions

(1) The attenuation rate of the explosion flame intensity by using the cavity with the aspect ratio of 5/8 is 66.58%, and the attenuation rate of the flame propagation velocity is 45.26%. The attenuation rates by using the cavity increased by 61.65% and 47.74%, respectively, compared with those in the straight pipelines

(2) The attenuation rate of the methane explosion flame intensity under the coeffect of the cavity with the aspect ratio of 5/8 and the water mist is 85.09%, and the attenuation rate of the flame propagation velocity is 65.85%. The attenuation rates have increased by 80.16% and 68.33%, respectively, compared with those in the straight pipes. The attenuation rates increased by 18.51% and 20.59%, respectively, compared with those by using cavity alone. The suppression effect on the intensity and speed of gas explosion flame by coeffect of the cavity with the aspect ratio of 5/8 and water mist is better than by using the cavity with the aspect ratio of 5/8 alone

(3) The repression effect of the steel cavity on the explosion flame propagation is mainly due to the repeated reflection of the flame in the steel cavity, causing its energy to be attenuated. The repression effect of the water mist is mainly due to its vaporization and heat absorption

Data Availability

The data can be obtained by contacting Zhuo Yan: 37571616@qq.com.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

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