RESEARCH ON DEFLAGRATION BEHAVIOR OF GAS AND GAS-COAL DUST IN A VERTICAL PRESSURE RELIEF PIPELINE SYSTEM

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Gas explosion and gas-coal dust explosion are serious disasters in coal mine production. To further study the hazards of gas explosion and gas and coal dust explosion under different conditions, experiments were done in this paper in a pipeline system containing an explosion pipeline and pressure relief pipeline. Flame propagation behavior and overpressure dynamics of gas explosion and gas coal dust explosion were analyzed. Flame propagation behavior of gas explosion and gas-coal dust explosion are divided into three stages: spherical flame, round-finger flame, and pointed-finger flame. Flame front position increases with time showing a class exponential growth trend. Flame front velocity has been increasing in the explosion pipeline. When the flame rushes out of the PVC membrane and enters the pressure relief pipeline, flame front velocity decreases slightly. The flame front velocity increases rapidly in the pressure relief pipeline. With growing gas concentration, the peak overpressure in the explosion pipeline rises at first, then decrease, and the peak overpressure in the pressure relief pipeline keeps rising. Peak overpressures are obtained at gas concentrations of 9vol% and 13vol%, respectively. When gas concentrations are 7vol% and 9vol% in the reaction, the peak overpressures in the pressure relief pipeline during gas explosion and gas-coal dust explosion are all lower than those in the explosion pipeline. When gas concentrations are 11vol% and 13vol% in the reaction, the peak overpressures in the pressure relief pipeline during the two types of explosions are higher than those in the explosion pipeline.

Keywords: *partial premixing, gas explosion, gas-coal dust explosion, overpressure dynamics, flame propagation behavior*

1. Introduction

The coal mining process is accident-prone, resulting in considerable casualties and property damage. Among the many types of coal mine accidents, the hazards caused by gas explosion and gas-coal dust explosion are very serious [1]. Therefore, how to avoid gas explosion and gas-coal dust explosion, and reduce the loss caused by the explosion accident, has become an important issue in coal mine production.

Clarifying the explosion mechanism, influencing factors, flame propagation behavior, and overpressure dynamics of gas explosion and gas-dust explosion can provide an important basis for coal mine safety production. Gao *et al*. [2] revealed the effect of characteristics (including thermal characteristics and particle size distribution) of particles on the flame propagation mechanism during dust explosion by combining high-speed photography and microphotography. Wang *et al*. [3] analyzed the coal dust before and after an explosion by applying a scanning electron microscope (SEM) to discuss the disparities of ignition sensitivity and explosion severity of coal dust at different levels and reveal the causes. Kundu. *et al*. [4,5] explored the explosion characteristics of methane-air and methane-coal dust mixture gas in a spherical pipeline vessel. Ajrash *et al*. [6,7] investigated the effects of changes in coal dust concentration and methane concentration in a large-scale detonation tube on the explosion pressure and flame propagation speed. The research result indicated that the addition of coal dust remarkably improves the explosive power of methane. However, different coal dust concentrations will lead to contrasting influence degrees on the result. Liu *et al*. [8] found that coal dust can accelerate the flame propagation speed of methane mixture. By exploring the explosion characteristics of premixed methane-air in bifurcated pipelines with three different angles, Zhu *et al*. [9] found that bifurcation leads to strong counter flow and turbulent flow and strengthens the explosion of premixed methane-air in the pipeline, thus reaching a higher maximum flame speed. Li *et al*. [10] investigated the influence of lignite, two types of bituminous coal and anthracite, on the combustion performances of methane-air mixture by employing an experimental device-horizontal pipeline.

Different studies have analyzed the characteristics of gas and coal dust explosions under different initial conditions in standard spherical test vessels of 20 L. By applying a standard spherical test vessel of 20 L, Liu *et al*. [11] explored the explosion characteristics of large particles of bituminous coal and found that coal with large particles requires higher dust concentration and ignition energy relative to coal with small particles. Similarly, in a spherical explosion vessel of 20 L, Man *et al*. [12] prepared coal dust and stone dust samples by applying a sieving method to explore the influence of particle size on the explosiveness and inserting effect of coal dust. By employing a standard spherical test vessel of 20 L, Li *et al*. [13,14] further investigated the particle size of coal dust and found that coal with fine particles greatly affects the deflagration of dust cloud. The higher the content of volatile substances is, the more serious the explosion. Zhao *et al*. [15]surveyed the minimum explosion concentration of coal dust below the lower explosion limit and with minor combustible gas in a spherical explosion chamber of 20 L. Ma *et al*. [16] found that the reduction of volatiles in coal dust due to low-temperature oxidation inhibits the flame propagation of methane-air/coal powder mixture. Wang *et al*. [17] experimentally and numerically explored the influence of ignition delay time on the explosion severity of coal dust-air mixture.

Some scholars have conducted numerical simulations of gas and dust explosions. Cao *et al*. [18] evaluated the explosion severity and performed numerical simulations by utilizing the FLUENT program to reveal the explosion mechanism of coal dust. Wang *et al.* [19] established a mathematical model for inhibiting coal dust explosion by gas generated from the pyrolysis of inert coal particles by conducting kinetic analysis on volatiles and the heat-transfer mechanism of gas generated within confined space. Song *et al*. [20] proposed a numerical model for simulating the explosion process of dust in a closed pipeline and provided the result. Song found that local gas explosion can trigger a two-phase explosion after adding deposited coal dust. Houim *et al.* [21,22] simulated the structures and flame speeds during explosion of coal dust in a loose dust bed with the volume fraction of 1% and a dense dust bed with the volume fraction of 47% by applying a high-order compressible numerical method of fluid dynamics and a multi-phase model for particles based on Eulerian dynamic theory.

In previous research, the experiments on gas explosion and gas-coal dust explosion are generally carried out in closed Hartmann explosive devices and 20 L spherical explosive devices, which significantly differs from the actual condition of underground coal mines. There are few types of research on gas partial premixed explosion and the interaction between gas and coal dust partial premixed explosion in a semi-closed space, especially on the effect on the explosion zone and propagation zone. The partial premixed experiment was conducted in a self-built semi-closed vertical pipeline system (contains explosion pipeline and pressure relief pipeline) to explore the overpressure dynamics and flame evolution during the gas explosion and gas-coal dust explosion.

2. Experimental system and scheme

2.1. Test system

Figure 1 shows a schematic of the experimental device. The test system was composed of an explosion pipeline, a pressure relief pipeline, a gas supply system, a dust supply system, an ignition system, a test and data acquisition system, and a high-speed photography and image acquisition system. The explosion pipeline and the flame pressure relief pipeline separately appeared as transparent polymethyl methacrylate (PMMA) pipelines with the dimensions of 120 mm × 120 mm × 500 mm and 120 mm × 120 mm × 1000 mm, with the compressive strength of 2 MPa. The end of the explosion pipeline was sealed by applying PVC membrane, and the sealed explosion pipeline was tightly connected to the pipeline by employing a rubber blanket. A slight overpressure in the explosion pipeline can cause the PVC membrane to rupture. The effect of the membrane is negligible on flame propagation [23]. The dust supply system was located at the bottom of the explosion pipeline, which comprised a compressor reservoir air tank, a high-pressure nozzle, and a powder storage container. The ignition system consisted of a HEI19 high thermal energy igniter and an ignition electrode, which was 75 mm away from the bottom of the explosion pipeline, with an ignition voltage of 6 kV. The data acquisition system was composed of MD-HF high-frequency dynamic pressure sensors, a USB-1608FS data acquisition card, and a synchronizing controller. The acquisition frequency of the pressure sensors was 15 kHz. The pressure sensors are arranged at the bottom of the explosion pipeline and the middle of the pressure relief pipeline, respectively. The high-speed photography and image acquisition system consisted of a High-Speed Star 4G camera, an image controller, and a high-speed computer, in which the shooting speed of the high-speed camera can be up to 2000 frames per second.

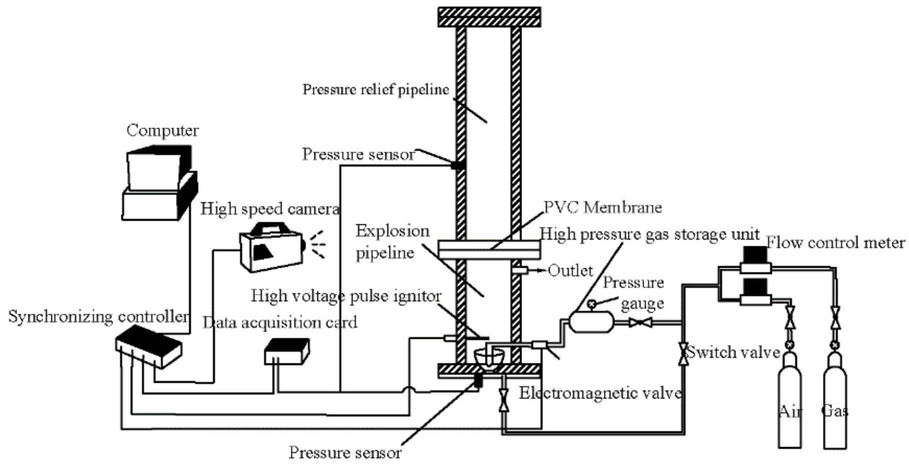


Figure 1. Experimental system diagram

2.2. Experimental scheme

The primary purpose of this experiment is to investigate the flame propagation behavior and overpressure dynamics of gas explosion and gas-coal dust explosion in the explosion pipeline and pressure relief pipeline using the vertical pressure relief pipeline experimental system. The coal dust used in the experiments was prepared from bituminous coal from the tenth mine of China Pingmei Shenma Group, and the summary of coal analysis data are shown in Table 1. After performing the crushing and screening process through a 150-mesh sieve, the particle size distribution of the coal sample is shown in Fig. 2. The coal samples with a mass concentration of 50 g/m³ were prepared according to the volume of the explosion pipeline. Four gas concentrations were designed for gas explosion and gas-coal dust explosion, 7 vol%, 9 vol%, 11 vol%, and 13 vol%, respectively. The fuel was premixed in the explosion pipeline only for all conditions. Three practical experiments were conducted on each working condition.

The experimental steps are as follows: The coal dust was evenly spread over the bottom of a powder storage container in advance. The end of the explosion pipeline was sealed by applying PVC membrane, and the sealed explosion pipeline was tightly connected to the pipeline by employing a rubber blanket. The gas concentration was set by separately controlling methane flows with a purity of 99.99% and air using preset mass flowmeters. The premixed methane and air were injected into the explosion pipeline from the gas entry at the lower end of the explosion pipeline and flowed out from the exhaust vent at the upper end of the explosion pipeline. To guarantee that the air in the explosion pipeline was emitted entirely and ensure the mixture in the explosion pipeline was homogenous, the premixed gas with a volume not less than four times the pipeline's volume was injected into the explosion pipeline before the experiment [24]. After completing the air inflation, the inlet valve and vent valve were synchronously closed. The mixture in the duct was settled for 30 s before ignition, reducing the influence of initial turbulence generated due to gas supply.

The compressor storage tank is then filled with a gas-air mixture consistent with the experimental concentration used to disperse the coal dust. The dispersion pressure of 0.3 MPa and the delay time of 150 ms was determined after pre-experiments. This minimized the effect of turbulence [25]. The impact of coal dust particle settling was not considered in this study. The coal dust settling time is a higher order of magnitude than the explosion time [26].

Table 1. Summary of coal analysis data

Proximate analysis [%]				Ultimate analysis [%]					HHV [MJ • kg^{-1}]
A	M	VM	FC	C	H	O	N	S	29.68
10.02	1.04	20.78	68.16	81.21	5.05	5.62	1.31	0.51	

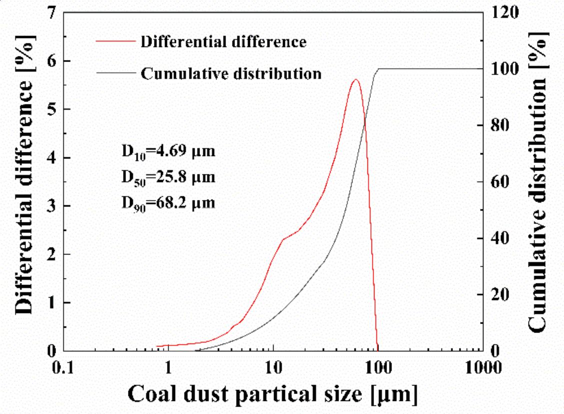


Figure 2. Particle size distribution of the coal sample

3. Results and discussion

3.1. Flame propagation behavior

One working condition each in gas explosion and gas-coal dust explosion is selected as an example to analyze the flame propagation behavior. As shown in Fig. 3(a), the gas explosion with a concentration of 9 vol% is taken as an example to analyze the process of flame development. The flame is divided into three stages: spherical flame, round-finger flame, and pointed-finger flame. Tulip flames were found in the fully premixed piping system [27] and the confined piping system [28]. However, tulip flames were not found in this experiment, probably due to the absence of reverse depression of the flame leading edge in the partially premixed pressure relief duct system. The spherical flames and round-finger flames are found in the explosion pipeline. At 0-10 ms, almost no flame appears in the pipeline, which indicates that the flame develops very slowly in the early period after ignition. At 10-20 ms, the flame develops into a spherical flame, which is the result of the free expansion and development of the flame in the pipeline space, which is not affected by the existence of the side wall of the pipeline. At 20-45 ms, the flame develops into a round-fingered flame, and the main feature is that the flame front is arc-shaped. This is because, in the explosion pipeline, the flame skirt velocity after the flame touches the tube wall is smaller than that of the flame front. After 45 ms, the flame burst out of the PVC film and developed in the pressure relief pipeline. At this time, the flame is a finger-shaped flame. This is because the unburned reactants come into contact with a large amount of air and react violently in the pressure relief pipeline. At this time, the flame wave continues to avoid reflection, and the flame front velocity of the tube wall is greater than the overall flame front velocity, which stretches the flame front. It is worth noting that after 49 ms, the flame collapsed and folded on the left tube wall. This is because the flame skirt velocity at both ends of the tube wall is inconsistent in the pressure relief pipeline, and the right end is stretched too fast.

Figure 3(b) shows that the flame propagation process of gas-coal dust explosion is analyzed. The condition is a local premixed explosion of 9 vol% gas and 50 g/m^3 coal dust. Gas coal dust explosion flame bright and discrete flame found in the combustion zone [3,8], which is the thermal resolution of coal dust caused by the combustion of volatile components. The flame is divided into three stages: spherical flame, round-finger flame, and pointed-finger flame. The spherical and round-finger flames are found in the explosion pipeline, and the pointed-finger flame is found in the pressure relief pipeline. The coal dust was added into the explosion pipeline, then from which volatiles were released, to atomize the flame front at different degrees. The reason is that the coal-dust particles are reacted in the leading end of the flame front to accelerate the flame development. The addition of coal dust promoted flames to reach the top of the pipeline more. The reason is that flame propagation is gradually accelerated to realize the peak as coal particles are constantly volatilized under oxygen-rich conditions and release combustible gas.

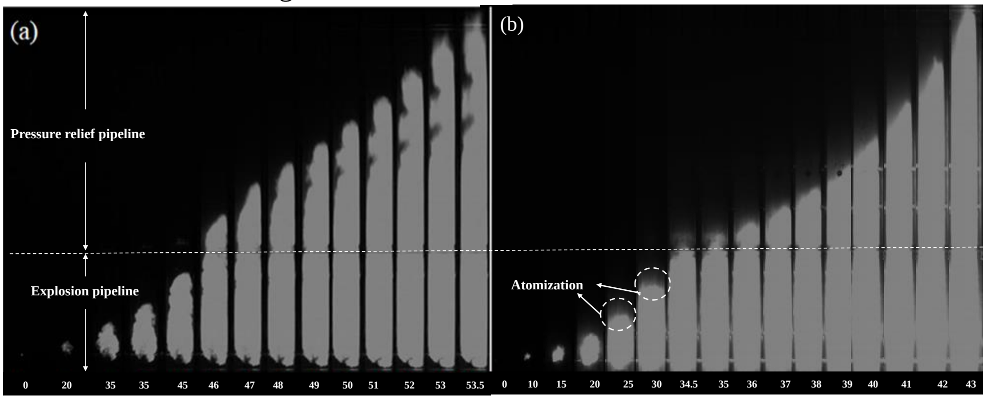


Figure 3. Flame propagation process (ms). (a) Gas explosion. (b) Gas-Coal dust explosion.

3.2. Flame front trajectory and velocity

The flame image was extracted and calculated by MATLAB software programming. The program can obtain the flame front position and flame front velocity history of each working condition.

The shimmer at the front of the flame causes image noise, which affects the accuracy of flame image extraction and calculation, and needs de-noising [28]. Figure 4 shows the image de-noising processing. The glimmer of the flame front disappears after processing, eliminating its impact on procedural calculations.

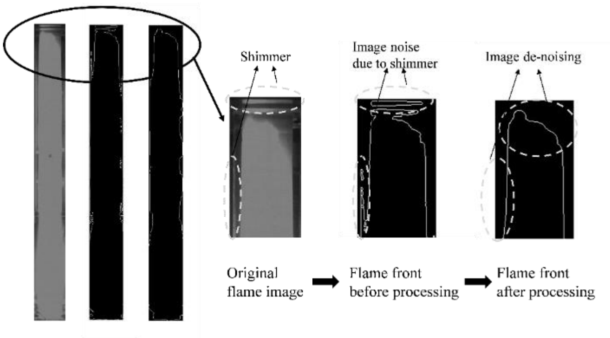


Figure 4. De-noising processing of flame image by MATLAB

The images in Figs. 5(a) and (b) show the change curves of the flame front position with time in the gas explosion with four different concentrations and the coupled explosion between four concentrations of gas and coal dust. The flame front position during the gas explosion and gas-coal dust explosion presented the exact change in the process when it reached the top of the pipeline: the displacement of the flame front constantly rose and then rapidly developed after the flame rushed out of the PVC membrane. The exponential fitting is performed using the ExpGrol function in the origin software. As shown in Tables 2 and 3, it can be seen that the fitting function exhibited a high fitting degree, which implied that the curves exponentially increased. A similar pattern was found in reference [29]. Fresh air enters the ductwork, and the flame accelerates, creating this growth pattern.

Figure 6(a) displays the durations of flame fronts reaching the top of the pipeline system during gas explosion and gas-coal dust explosion. The duration of the flame front reaching the pipe orifice during the gas explosion constantly reduced with the growth of gas concentrations, which are 57.6 ms, 53.5 ms, 48.3 ms, and 44 ms, respectively. Similarly, the durations of the flame front reaching the pipe orifice during gas-coal dust explosion consistently decreased, where 51.5 ms, 43 ms, 40.2 ms, and 36.7 ms, respectively. It indicated that the duration of the flame front reaching the top of the pipeline during the gas-coal dust explosion was shorter than that during the gas explosion. The gas phase combustion caused flame propagation during the gas explosion. At the same time, the addition of coal dust led to the synchronous occurrence of gas phase combustion and combustion of char particles. The gas released from the heated coal dust was burned to form an incredibly complex chain reaction to promote flame development. Some studies have shown that for 13 vol% concentration, the diffusion effect, on the one hand, the explosion pipeline concentration, will be reduced. On the other hand, the pressure relief pipeline concentration is to a higher level so that the flame outside the original gas occupation area can continue to accelerate a certain longer distance [30].

The flame showed the most rapid and slowest overall propagation speeds of gas explosion and gas coal dust explosion when the gas concentrations were 13vol% and 7vol%, respectively. As experimental fuel is premixed in the explosion pipeline, the pressure relief pipe is open, and oxygen is not restricted in the pressure relief pipeline. Compared with gas concentrations of 7vol% and 9vol%, the fuel is rich under gas concentrations of 11vol% and 13vol%; therefore, the gas that is not entirely reacted continued to be reacted in the pressure relief pipeline to accelerate the flame propagation. Thus, the explosion flame first reached the top of the pipeline when 13vol% of gas participated in the reaction. As shown in Fig. 6(b), the flame duration is higher when the gas concentration is 13 vol% than when the gas concentration is 11 vol% in the explosion pipeline. And in the pipeline system, the flame duration is higher when the gas concentration is 13 vol% than when the gas concentration is 11 vol%. This proves that the excess premixed fuel of the explosion pipeline continues to react inside the pressure relief pipeline, accelerating the flame propagation.

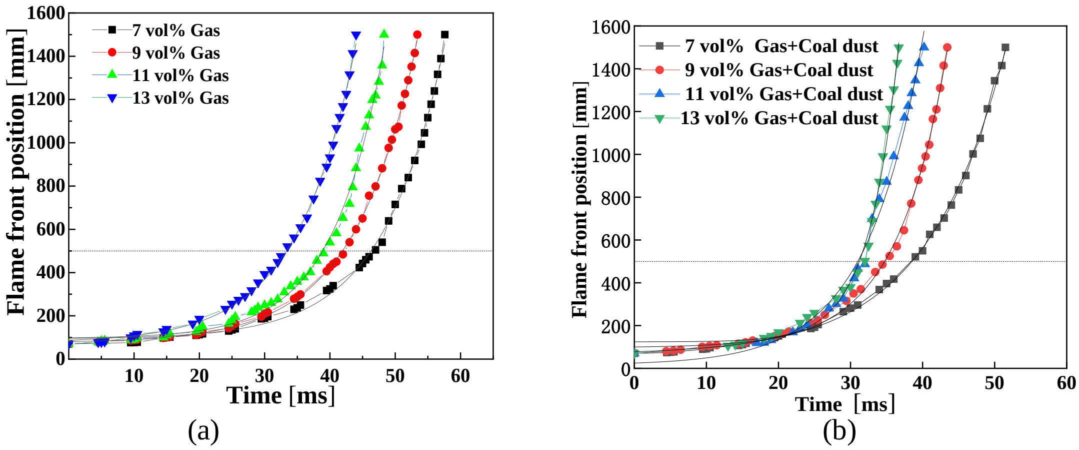


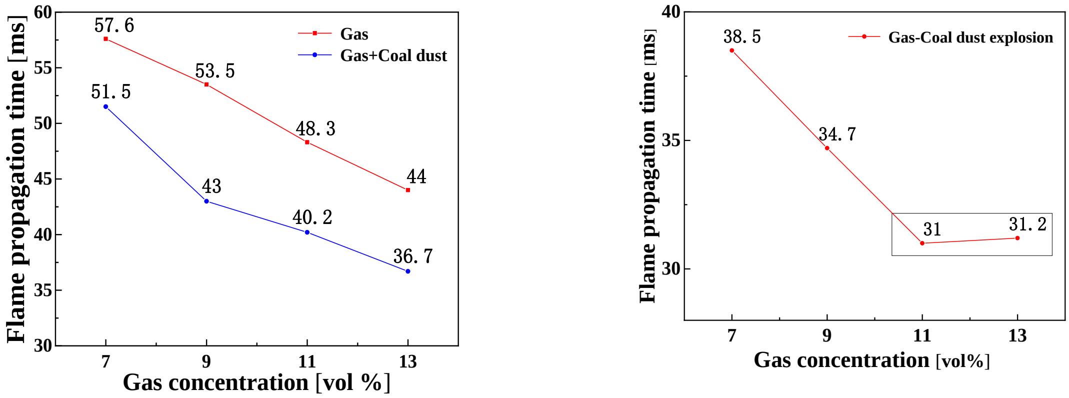
Figure 5. Flame front position history in experimental conditions: (a) gas explosion, (b) gas-coal dust explosion

Table 2. Fitting function for flame front position of gas explosion

Experimental condition	Fitting function	R^2
7vol% Gas	y = 2.8748exp0.107x + 92.8256	0.99867
9vol% Gas	y = 5.4225exp0.1041x + 75.3605	0.99611
11vol% Gas	y = 2.77538exp0.1281x + 95.7046	0.99945
13vol% Gas	y = 10.4241exp0.1111x + 76.8965	0.99775

Table 3. Fitting function for flame front position of gas-coal dust explosion

Experimental condition	Fitting function	R^2
7vol% Gas and coal dust	y = 0.21558exp0.2392x + 123.92715	0.999
9vol% Gas and coal dust	y = 9.37484exp0.12724x + 15.45537	0.99799
11vol% Gas and coal dust	y = 2.86151exp0.14242x + 97.21629	0.99178
13vol% Gas and coal dust	y = 12.89895exp0.09134x + 64.61009	0.99352

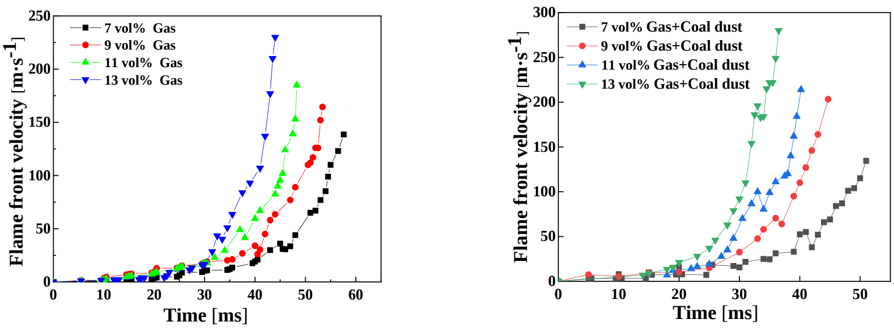


(a) (b)

Figure 6. Flame duration time: (a) In pipeline system, (b)In explosion pipeline

As Figs. 7(a) and (b) show the flame front velocity during gas explosion with different concentrations and coupled explosion between different concentrations of gas and coal dust all increase at first, then reduce for a short time and rapid rise. Flame evolution has gone through three stages in all cases. In stage 1, the flame accelerates in the explosion pipeline. The heat loss of the pipe wall is not obvious. Flame front velocity due to the expansion of combustion products, heat release, and conduction will be chemically active species pushed to the flame front, flame front velocity gradually increased, but the acceleration is slow. In stage 2, when the flame rushes out of the PVC membrane and enters the pressure relief pipeline, flame front velocity decreases slightly. This is because when the flame first enters the pressure relief pipeline, the unburned fuel at the flame front absorbs heat pyrolysis, which also causes flame front velocity to decrease in a short period. In stage 3, the flame front velocity increases rapidly in the pressure relief pipeline. In confined pipelines, some studies have found that gas coal dust explosions decelerate at the end of the pipeline [30,31]. But fuel limitations can affect flame front velocity at the end of the pipeline [6,7]. The flame keeps accelerating in the pressure relief pipeline, and due to the opening of the pressure relief pipeline, the unburned fuel at the flame front continues to react in the pressure relief pipeline, releasing a large amount of heat [29].

It can be seen from Fig. 8 that with the growth of gas concentrations, the maximum flame-front velocities constantly rise during the gas explosion, which are 138.6 m/s, 164.4 m/s, 185 m/s, and 230 m/s, respectively. The maximum flame-front velocities during gas-coal dust explosion always grow, which are 143.5 m/s, 203.3 m/s, 214.4 m/s, and 280 m/s, respectively. The addition of coal dust resulted in a significant improvement in the maximum flame front velocity.



(a) (b)

Figure 7. Flame front velocity history in experimental conditions : (a) Gas explosion, (b) Gas-Coal dust explosion

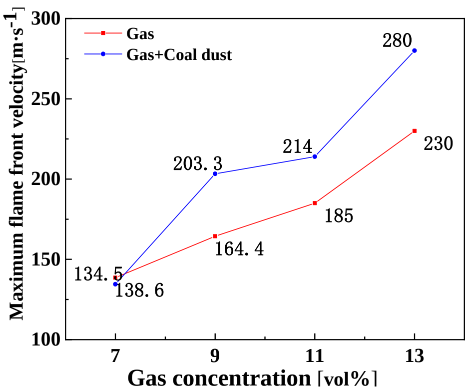
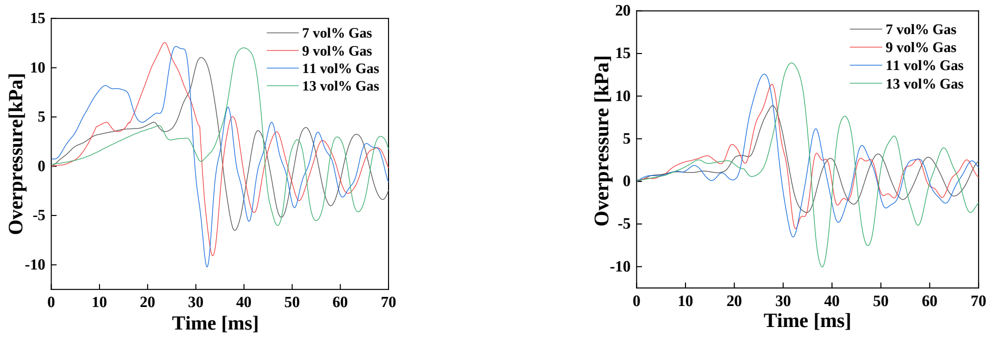


Figure 8. Maximum flame front velocity

3.3. Overpressure dynamics

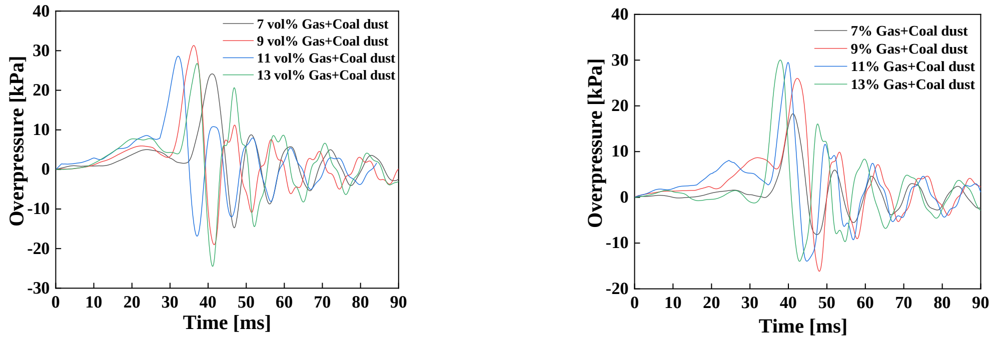
Figure 9 shows the change of explosion overpressures of gas with different concentrations. Figure 10 shows the effects of coal dust on the change of explosion overpressures of gas with different concentrations. A similar phenomenon was observed by analyzing all pressure-time processes recorded during the explosion: the overpressure rises to reach the maximum after ignition and then dramatically decreases with fluctuations.

As shown in Fig. 9, gas phase combustion exhibited a low reaction rate in the initial stage of the reaction, so the release rate of energy was low, and the overpressure was gently changed. As the reaction continued, the contact area between the flame front and the unburned gas enlarged, and the reaction rate accelerated to promote the explosion overpressure to climb the peak. As shown in Fig. 10, the explosion pressure after adding coal dust presented a similar change trend with time relative to the gas explosion. However, the peak overpressure considerably rose. The pressure reaches a peak and then oscillates, but the shock amplitude is small in this experimental pipeline. The analysis shows that when the flame rushes out of the open end, a large amount of high-temperature gas leaves the pipeline, which will also induce expansion waves. As a result, the flame front interacts with sound waves to cause pressure oscillations [32].



(a) (b)

Figure 9. Explosion pressure history curves of gas in different concentrations. (a) Explosion pipeline, (b) Pressure relief pipeline



(a) (b)

Figure 10. Explosion pressure history curves of coal dust with gas in different concentrations. (a) Explosion pipeline, (b) Pressure relief pipeline

Figure 11 separately shows the change of the peak overpressure in the explosion pipeline and the pressure relief pipeline during the gas explosion and gas-coal dust explosion. The peak overpressure at different gas concentrations rises at first and then declines in the explosion pipeline. The peak overpressure at different gas concentrations constantly increases in the pressure relief pipeline. When gas concentrations are 7vol% and 9vol% in the reaction, the peak overpressures in the pressure relief pipeline during the gas explosion and gas-coal dust explosion are all lower than those in the explosion pipeline. When gas concentrations are 11vol% and 13vol% in the reaction, the peak overpressures in the pressure relief pipeline during the two types of explosions are higher than those in the explosion pipeline. In confined pipelines, gas explosions are measured at chemical dose concentrations with maximum overpressure [33,34]. Related studies have also found that the peak overpressure does not occur at the stoichiometric concentration but at higher concentrations at the end of the pipeline opening with local premixing of the fuel [30,35].

Figure 11 (a) shows that during the gas explosion in the pressure relief pipeline, the explosive shock waves are attenuated from the explosion pipeline to the pressure relief pipeline owing to gas being completely reacted in the explosion pipeline in the case of having 7vol% and 9vol% of gas. As a result, the peak overpressure in the pressure relief pipeline is lower than in the explosion pipeline. When the gas concentrations are 11vol% and 13vol%, gas was not wholly reacted in the explosion pipeline. Thus, the gas continued to be reacted in the pressure relief pipeline and then was superposed with the explosive shock waves from the explosion pipeline. Therefore, the peak overpressure in the pressure relief pipeline is higher than in the explosion pipeline.

Figure 11 (b) shows that during the gas-coal dust explosion on condition of gas concentrations of 7vol% and 9vol%, coal dust is pyrolyzed to release volatiles to participate in the reaction. However, the gas content flowing into the pressure relief pipeline is low, and coal dust was slowly and incompletely burned, so the reacting intensity of gas is low in the pressure relief pipeline. As a result, the peak overpressure in the pressure relief pipeline is lower than in the explosion pipeline. When gas concentrations are 11vol% and 13vol%, large amounts of gas and coal dust are not entirely reacted in the explosion pipeline. Therefore they exhibited a high reacting intensity after being contacted with oxygen in the pressure relief pipeline, which increased the peak overpressure. That is, the peak overpressure in the pressure relief pipeline is higher than in the explosion pipeline. When the volume fraction of gas was 13vol%, the content of gas that did not wholly react in the explosion pipeline was the highest, so gas more dramatically reacted in the pressure relief pipeline. Therefore, the peak overpressure is the maximum in this working condition.

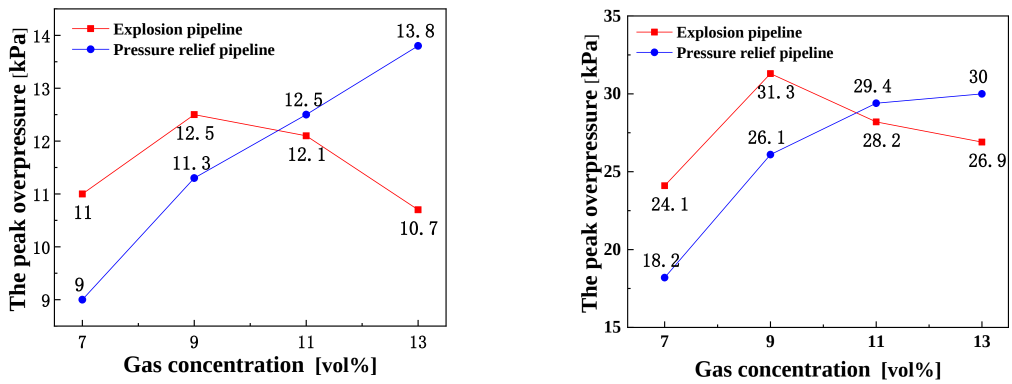


Figure 11. The peak overpressure in experimental conditions: (a) Gas explosion, (b) Gas-Coal dust explosion

4. Conclusions

In this paper, the deflagration behavior of gas explosion and gas-coal dust explosion are studied in a vertical pressure relief pipeline system. The main conclusions are drawn as follows:

(1) The spherical flame and round-finger flame are found in the explosion pipeline, and the pointed-finger flame is found in the pressure relief pipeline. Flame front position shows a class exponential growth trend with time in gas explosion and gas-coal dust explosion. The shortest flame duration in the gas concentration of 13vol%, gas explosion, and gas-coal dust explosion are 44ms and 36.7ms, respectively. The flame duration is higher for gas coal dust explosion when the gas concentration is 13 vol% than when the gas concentration is 11 vol% in the explosion pipeline. This proves that the excess premixed fuel from the explosion pipeline continues to react in the pressure relief pipeline and the flame front velocity keeps increasing in the pressure relief pipeline.

(2) Flame evolution of gas explosion and gas-coal dust explosion has undergone three stages. Flame front velocity keeps increasing in the explosion pipeline. The flame front velocity decreases slightly when it enters the pressure relief pipeline. Then, flame front velocity increases rapidly in the pressure relief pipeline. The maximum flame front velocity in the gas concentration of 13vol%, gas explosion, and gas-coal dust explosion are 230 m/s and 280 m/s, respectively.

(3) With growing gas concentration, the peak overpressure in the explosion pipeline rise at first, then decreases, and the peak overpressure in the pressure relief pipeline keeps rising. Peak overpressures are obtained at gas concentrations of 9vol% and 13vol%, respectively. When gas concentrations are 7vol% and 9vol% in the reaction, the peak overpressures in the pressure relief pipeline during gas explosion and gas-coal dust explosion are all lower than those in the explosion pipeline. When gas concentrations are 11vol% and 13vol% in the reaction, the peak overpressures in the pressure relief pipeline during the two types of explosions are higher than those in the explosion pipeline.

Acknowledgements

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