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

by

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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 pipe-line system containing an explosion pipe-line and pressure relief pipe-line. Flame propagation behavior and overpressure dynamics of gas explosion and gas coal dust explosion were analyzed. Flame propagation behavior of gas explosion and gascoal 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 pipe-line. When the flame rushes out of the PVC membrane and enters the pressure relief pipe-line, flame front velocity decreases slightly. The flame front velocity increases rapidly in the pressure relief pipe-line. With growing gas concentration, the peak overpressure in the explosion pipe-line rises at first, then decrease, and the peak overpressure in the pressure relief pipe-line keeps rising. Peak overpressures are obtained at gas concentrations of 9 vol.% and 13 vol.%, respectively. When gas concentrations are 7 vol.% and 9 vol.% in the reaction, the peak overpressures in the pressure relief pipe-line during gas explosion and gascoal dust explosion are all lower than those in the explosion pipe-line. When gas concentrations are 11 vol.% and 13 vol.% in the reaction, the peak overpressures in the pressure relief pipe-line during the two types of explosions are higher than those in the explosion pipe-line.

Key words: partial premixing, gas explosion, gas-coal dust explosion, overpressure dynamics, flame propagation behavior

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.

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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 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 pipe-line 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 pipe-lines 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 pipe-line, 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 pipe-line.

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 and Zhang [20] proposed a numerical model for simulating the explosion process of dust in a closed pipe-line and provided the result. Song and Zhang [20] found that local gas explosion can trigger a two-phase explosion after adding deposited coal dust. Houim and Oran [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

4064

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 pipe-line system (contains explosion pipe-line and pressure relief pipe-line) to explore the overpressure dynamics and flame evolution during the gas explosion and gas-coal dust explosion.

Experimental system and scheme

Test system

Figure 1 shows a schematic of the experimental device. The test system was composed of an explosion pipe-line, a pressure relief pipe-line, 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 pipe-line and the flame pressure relief pipe-line separately appeared as transparent polymethyl methacrylate (PMMA) pipe-lines with the dimensions of 120 mm \times 120 mm \times 500 mm and 120 mm \times 120 mm \times 1000 mm, with the compressive strength of 2 MPa. The end of the explosion pipe-line was sealed by applying PVC membrane, and the sealed explosion pipe-line was tightly connected to the pipe-line by employing a rubber blanket. A slight overpressure in the explosion pipe-line 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 pipe-line, 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 pipe-line, 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 pipe-line and the middle of the pressure relief pipe-line, respectively. The high



Figure 1. Experimental system diagram

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 fps.



of the coal sample

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 pipe-line and pressure relief pipeline using the vertical pressure relief pipe-line 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 tab. 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 pipe-line. 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 pipe-line only for all conditions. Three practical experiments were conducted on each working condition.

Table 1.	Summary	of coal	analysis data	
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	Proximate	e analysis [%	6]	Ultimate analysis [%]				HHV [MJkg ⁻¹]	
A	М	VM	FC	С	Н	0	N	S	20.68
10.02	1.04	20.78	68.16	81.21	5.05	5.62	1.31	0.51	29.08

The experimental steps are:

- The coal dust was evenly spread over the bottom of a powder storage container in advance.
- The end of the explosion pipe-line was sealed by applying PVC membrane, and the sealed explosion pipe-line was tightly connected to the pipe-line 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 pipe-line from the gas entry at the lower end of the explosion pipe-line and flowed out from the exhaust vent at the upper end of the explosion pipe-line.
- To guarantee that the air in the explosion pipe-line was emitted entirely and ensure the mixture in the explosion pipe-line was homogenous, the premixed gas with a volume not less than four times the pipe-line's volume was injected into the explosion pipe-line 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 seconds 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].

Results and discussion

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 pipe-line. At 0-10 ms, almost no flame appears in the pipe-line, 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 pipe-line space, which is not affected by the existence of the side wall of the pipe-line. 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 pipe-line, 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 pipe-line. 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 pipe-line. 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 pipe-line, and the right end is stretched too fast.



Figure 3. Flame propagation process [ms]; (a) gas explosion and (b) gas-coal dust explosion

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/m³ coal dust. Gas coal dust explosion flame bright and discrete flame found in the combustion zone [3, 8],

Liu, C., et al.: Research on Deflagration Behavior of Gas and Gas-Coal ... THERMAL SCIENCE: Year 2023, Vol. 27, No. 5B, pp. 4063-4075

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 pipe-line, and the pointed-finger flame is found in the pressure relief pipe-line. The coal dust was added into the explosion pipe-line, 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 pipe-line more. The reason is that flame propagation is gradually accelerate dto realize the peak as coal particles are constantly volatilized under oxygen-rich conditions and release combustible gas.





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.

The images in figs. 5(a) and 5(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 pipe-line: 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 tabs. 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 5. Flame front position history in experimental conditions; (a) gas explosion and (b) gas-coal dust explosion

4068

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

Experimental condition	Fitting function	R^2
7 vol.% gas	$y = 2.8748 \exp(0.107x) + 92.8256$	0.99867
9 vol.% gas	$y = 5.4225 \exp(0.1041x + 75.3605)$	0.99611
11 vol.% gas	$y = 2.77538\exp(0.1281x + 95.7045)$	0.99945
13 vol.% gas	$y = 10.4241 \exp(0.1111x) + 76.8965$	0.99775

Experimental condition	Fitting function	R^2
7 vol.% gas and coal dust	$y = 0.21558 \exp(0.2392x + 123.92715)$	0.999
9 vol.% gas and coal dust	$y = 9.37484 \exp(0.12724x) + 15.45537$	0.99799
11 vol.% gas and coal dust	$y = 2.86151 \exp(0.4242x + 97.21629)$	0.99178
13 vol.% gas and coal dust	$y = 12.89895 \exp(0.09134x) + 64.61009$	0.99352

Figure 6(a) displays the durations of flame fronts reaching the top of the pipe-line 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 pipe-line 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 promote flame development. Some studies have shown that for 13 vol.% concentration, the diffusion effect, on the one hand, the explosion pipe-line concentration, will be reduced. On the other hand, the pressure relief pipe-line 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 13 vol.% and 7 vol.%, respectively. As experimental fuel is premixed in the explosion pipe-line, the pressure relief pipe is open, and oxygen is not restricted in the pressure relief pipe-line. Compared with gas concentrations of 7 vol.% and 9 vol.%, the fuel is rich under gas concentrations of 11 vol.% and 13 vol.%, therefore, the gas that is not entirely reacted continued to be reacted in the pressure relief pipe-line to accelerate the flame propagation. Thus, the explosion flame first reached the top of the pipe-line when 13 vol.% 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 higher when the explosion pipe-line. In the pipe-line system, the flame duration is higher when the excess premixed fuel of the explosion pipe-line continues to react inside the pressure relief pipe-line, accelerating the flame propagation.

As figs. 7(a) and 7(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



Figure 7. Flame front velocity history in experimental conditions; (a) gas explosion and (b) gas-coal dust explosion



through three-stages in all cases. In Stage 1, the flame accelerates in the explosion pipe-line. 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 pipe-line, flame front velocity decreases slightly. This is because when the flame first enters the pressure relief pipe-line, 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 pipe-line. In confined pipe-lines, some studies have found that gas coal dust explosions decelerate at the end of the pipe-line [30, 31]. But fuel limitations can affect flame front velocity at the end of the pipe-line [6, 7]. The flame keeps accelerating in the pressure relief pipe-line, and

due to the opening of the pressure relief pipe-line, the unburned fuel at the flame front continues to react in the pressure relief pipe-line, 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.

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



Figure 10. Explosion pressure history curves of coal dust with gas in different concentrations; (a) explosion pipe-line and (b) pressure relief pipe-line

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 pipe-line. The analysis shows that when the flame rushes out of the open end, a large amount of high temperature gas leaves the pipe-line, which will also induce expansion waves. As a result, the flame front interacts with sound waves to cause pressure oscillations [32].

Figure 11 separately shows the change of the peak overpressure in the explosion pipeline and the pressure relief pipe-line 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 pipe-line. The peak overpressure at different gas concentrations constantly increases in the pressure relief pipe-line. When gas concentrations are 7 vol.% and 9 vol.% in the reaction, the peak overpressures in the pressure relief pipe-line during the gas explosion and gas-coal dust explosion are all lower than those in the explosion pipe-line. When gas concentrations are 11 vol.% and 13.vol.% in the reaction, the peak overpressures in the pressure relief pipe-line during the two types of explosions are higher than those in the explosion pipe-line. In confined pipe-lines, 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 pipe-line opening with local premixing of the fuel [30, 35].



Figure 11. The peak overpressure in experimental conditions; (a) as explosion and (b) gas-coal dust explosion

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

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

Conclusions

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

- The spherical flame and round-finger flame are found in the explosion pipe-line, and the pointed-finger flame is found in the pressure relief pipe-line. 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 13 vol.%, gas explosion, and gas-coal dust explosion are 44 ms and 36.7 ms, 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 pipe-line. This proves that the excess premixed fuel from the explosion pipe-line continues to react in the pressure relief pipe-line and the flame front velocity keeps increasing in the pressure relief pipe-line.
- Flame evolution of gas explosion and gas-coal dust explosion has undergone three-stages. Flame front velocity keeps increasing in the explosion pipe-line. The flame front velocity decreases slightly when it enters the pressure relief pipe-line. Then, flame front velocity increases rapidly in the pressure relief pipe-line. The maximum flame front velocity in the gas concentration of 13 vol.%, gas explosion, and gas-coal dust explosion are 230 m/s and 280 m/s, respectively.
- With growing gas concentration, the peak overpressure in the explosion pipe-line rise at first, then decreases, and the peak overpressure in the pressure relief pipe-line keeps rising. Peak overpressures are obtained at gas concentrations of 9 vol.% and 13 vol.%, respectively. When gas concentrations are 7 vol.% and 9 vol.% in the reaction, the peak overpressures in the pressure relief pipe-line during gas explosion and gas-coal dust explosion are all lower than those in the explosion pipe-line. When gas concentrations are 11 vol.% and 13 vol.% in the reaction, the peak overpressures in the pressure relief pipe-line during the two types of explosions are higher than those in the explosion pipe-line.

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