RESEARCH ON THE PROPAGATION OF PRESSURE AND CO GAS OF METHANE AND COAL DUST COUPLED EXPLOSION

by

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A methane and coal dust explosion system was constructed to investigate the propagation of pressure and CO gas after methane and coal dust coupling explosion. The influence of coal dust concentration on the propagation of pressure and CO gas were analyzed by coupling explosion experiments of 5% methane with coal dust (0, 100 g/m³, 200 g/m³, 300 g/m³, 400 g/m³, and 500 g/m³), 7% methane with coal dust (0, 50 g/m³, 100 g/m³, 150 g/m³, and 200 g/m³), and 9% methane with coal dust (0, 50 g/m³, 100 g/m³, 150 g/m³, and 200 g/m³). The experimental results show that when 5% or 7% methane explodes with coal dust in the explosion chamber, the pressure first increases and then decreases with the increase of coal dust concentration. When the methane concentration is 9%, the pressure decreases with the increase of coal dust concentration. In the propagation pipe, the explosion pressure and CO gas concentration decrease with the increase of distance. When the methane concentration and distance are constant, the higher the coal dust concentration is, the higher the pressure and CO gas concentration is.

Key words: *methane, coal dust, coupled explosion, pressure, CO gas*

Introduction

According to the statistics, in China, coal production is not less than 40% of the total output of the world, and coal consumption exceeds 50% of the total consumption of the world [1]. However, approximately 90% coal dust from Chinese coal mines is potentially explosive [2]. In the coal production process, there are always some accidents causing casualties [3]. Among these accidents, methane and coal dust coupling explosion accident which plays an important roles need to be prevented urgently. The increasing interest in methane and coal coupling explosion prevention has heightened the need for the research on the characteristics of methane and coal dust coupling explosion.

The maximum pressure, p_{max}, the maximum pressure rising rate, dp/dt_{max}, the explosion limit range and flame temperature are essential parameters to study the explosive characteristics of methane and coal dust. Methane coal dust explosion is a complex gas-solid two-phase deflagration process, in which methane and coal dust react with each other [4, 5]. Through conducting gas and coal dust explosion experiments with different gas equivalent ratios in a standard 20 L spherical explosion system, Qi *et al.* [6] found that the maximum explosion pressure increases linearly with the increase of the gas equivalent ratio in coal dust and gas mixture. Song *et al.* [7] studied influential factors of hybrid methane-coal dust explosions by using 20 L

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spherical explosion vessel and indicated that the maximum explosion pressure concentrations of coal dust and methane are 200 g/m^3 and 5 vol.% in the atmospheric pressure. Researchers discovered that the explosion of hybrid mixtures occurs when both dust and gas concentrations are lower than the minimum explosion concentration of the single substances [8-10]. Deng *et al.* [11] conducted methane-air-coal dust explosion in an XKWB-1 sealed explosion system. They found that when 500 g/m^3 coal dust and methane explode, the maximum explosion pressure is linearly related to methane concentration and volatile content of coal dust, decreased with an increase in methane concentration, and increased with volatile content of coal dust.

Many experimental studies have reported that gas explosion can induce the explosion of deposited dust [12-14]. The maximum overpressure and flame acceleration mechanism of methane-coal mixed explosion in a horizontally straight pipe is investigated by Song *et al.* [15], Jiang *et al.* [16], and Jiang *et al.* [17]. After the methane-coal dust mixed explosions, two peak values appeared in the overpressure and flame waveform and the second peak with higher overpressure is generated due to the participation of coal dust in the explosion [18]. Using a pipe with a length of 60 cm and a cross-section of 10 cm × 10 cm, Li *et al.* [19] concluded that the maximum explosion overpressure and maximum rate of overpressure rise increase with the increasing of the initial pressures and coal dust concentration. Guo *et al.* [20] performed a gas explosion experiment with low concentration coal dust by using the self-developed experimental system and determined that low concentration coal dust raises the gas explosion pressure and flame propagation speed. Through explosion experiment of methane with 700 g/m^3 coal dust in a vertical shock tube, Pinaev *et al.* [21] identified that coal dust has a weaker effect on the parameters of combustion and detonation waves than methane in hybrid systems.

Li *et al.* [22] analyzed the influence of coal dust concentration on gas products after explosion. Results demonstrated the combustible component (CH_4, C_2H_2, C_2H_4, C_2H_6, and C_3H_8) is almost undetectable under poor dust concentration conditions and it increased sharply under dust-rich conditions. In the experiment of explosion under conditions with different air-fuel ratios, Lin *et al.* [23] suggested that the volume fraction of flammable gas in residual gases of methane-coal dust/air mixture explosions is higher than that of methane-air mixtures. Nie *et al.* [24] investigated the characteristics of gas and solid products of coal dust explosion in a 20 L spherical explosion vessel. They discovered that the main gas components after coal dust explosion are O_2, N_2, CO_2, CO, CH_4, and at higher coal dust concentrations, the concentrations of CO increases because of the pyrolysis and incomplete combustion of coal dust. Liu *et al.* [25, 26] also carried out explosion experiments in a 20 L spherical explosion vessel and showed that with increases in the coal dust concentration, CO concentration increases and the concentrations of CO_2 rises at first and then declines.

It is evident that much research has been performed regarding methane and coal dust explosion pressure and residues. However, only a few studies have focused on the influence of methane and coal dust concentration on pressure propagation, especially in terms of propagation characteristics of toxic gas produced by explosion. Therefore, a self-built methane coal dust coupled explosion system with a dust spray device in this study was used to give insights into the propagation of pressure and toxic gas. Investigation on the topic may have important significance to reduce the consequences of accidents and improve the safety of coal mine.

Experimental preparation

Experimental device

The methane coal dust coupled explosion pipe-line system is composed of five subsystems: gas distribution system, dust spray system, ignition system, propagation pipe-line and data acquisition system, as shown in fig. 1. The gas distribution system consists of a methane cylinder, an air compressor and two flow meters. The solenoid valve and coal dust bin constitute the dust spray system. The ignition system is made of a high energy igniter, two ignition rods and wires. The ignition voltage is 6 kV. The propagation pipe-line system consists of plexiglass pipe-line with a total length of 2 m and a cross-section of 80 mm × 80 mm. The propagation pipe-line system includes 1.6 L closed explosion cavity and 11.2 L semi-closed propagation pipe. The data acquisition system includes a computer, pressure sensors (MD-HF, Shanghai Mingkong Sensing Technology Co., Ltd.), and a data acquisition card (785188-01, NI 9220 Spring, Shanghai NI Co., Ltd.). The measuring range of pressure sensor is 0~0.1 MPa. Its response frequency is 20 KHz, its response time is 0.05 ms. The concentration of toxic and harmful gases is detected by rapid gas detection reagents, with ranges of 0~500 ppm, 0~1000 ppm, and 0~5000 ppm.

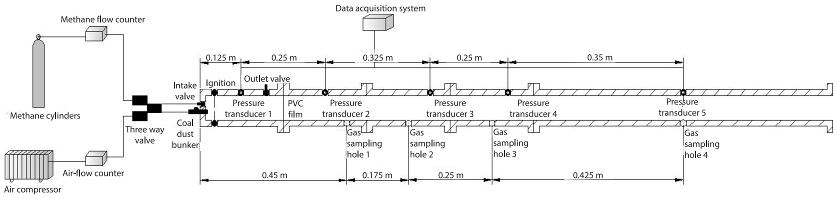

Figure 1. Schematic diagram of explosive pipe-line system

Test point arrangement

The purity of methane used in the experiment is 99.99%. The coal dust particle size is about 75 μm, and the proximate analysis of coal dust is shown in tab. 1. The experiment consisted of three different concentrations of methane coupled with coal dust to explode, mainly including: 5% methane and coal dust with concentrations of 0, 100 g/m^3, 200 g/m^3, 300 g/m^3, 400 g/m^3, and 500 g/m^3, respectively, the 7% methane and coal dust with concentrations of 0, 50 g/m^3, 100 g/m^3, 150 g/m^3, and 200 g/m^3, respectively, and the 9% methane and coal dust with concentrations of 0, 50 g/m^3, 100 g/m^3, 150 g/m^3, and 200 g/m^3, respectively. The experimental environment temperature is about 25 °C, and the environment humidity is about 50%. The semi-closed pipe with a total length of 2 m and a cross-section of 80 mm × 80 mm is made of 20 mm thick plexiglass. A PVC film is installed 0.25 m away from the closed end to form a 1.6 L airtight explosion cavity. The initial explosion pressure of the explosion cavity is a standard atmospheric pressure. The pressure sensors are, respectively 0.125 m, 0.375 m, 0.7 m, 0.95 m, and 1.3 m away from the explosion source. The gas sampling holes are, respectively 0.45 m, 0.625 m, 0.875 m, and 1.3 m away from the explosion source.

Table 1. Proximate analysis of coal dust

Composition	Volatile matter, V_{ad}	Moisture, M_{ad}	Ash, A_{ad}	Fixed carbon, F_{cad}
Proportion [%]	26.45	1.05	12.84	59.66

Experimental procedure

- A certain mass of coal dust is added to the coal dust bin, and then the intake valve and outlet valve connected to the explosion cavity are opened.
- The PVC film is installed. The flow meters are adjusted. The explosion cavity is filled with a certain concentration of methane-air mixture through the gas circulation method, and the explosion cavity is at a standard atmospheric pressure.

- The intake valve and outlet valve of the explosion chamber are closed. After opening the solenoid valve, the high pressure gas passes through the coal dust bin, and the gas carries the coal dust into the explosion cavity, forming a certain concentration of coal dust.
- After a short delay of 60 ms, the electric ignition system ignites. At the same time, the data acquisition system starts to collect data. The pressure sensor data at different locations is recorded.
- Poisonous and harmful gas is collected after the explosion. The concentration of toxic and harmful gas at different locations is measured and recorded.
- In order to reduce the experimental error, each group of experiments is carried out three times. The average is taken as the final result.

Results and analysis

Characteristics of explosion pressure in the explosion chamber

The variation of methane and coal dust explosion pressure at pressure Sensors 1 and 2 were analyzed. The results are shown in figs. 2-4. It is found through experiments that the concentration of methane and coal dust has a very important effect on the explosion pressure. At the pressure transducer 1 in the explosion chamber, when the methane concentration is 5% and 7%, the pressure increases at first and then decreases with the increase of coal dust concentration, while when the methane concentration is 9%, the pressure decreases with the increase of coal dust concentration. It can be seen from fig. 2 that in the explosion chamber, the explosion pressure of 5% methane and 300 g/m^3 coal dust is the largest, reaching 44.89 mbar. Figure 3 shows that in the explosion chamber, the explosion pressure of 7% methane and 100 g/m^3 coal dust is the largest, about 83.55 mbar. Figure 4 shows that in the explosion chamber, as the concentration of coal dust increases from 0 to 200 g/m^3, the explosion pressure of 9% methane and coal dust drops from 253.21 mbar to 214.86 mbar. When the coupled explosion of methane and coal dust in the explosion chamber with a limited volume reaches the maximum pressure, the concentration of coal dust decreases with the increase of methane concentration.

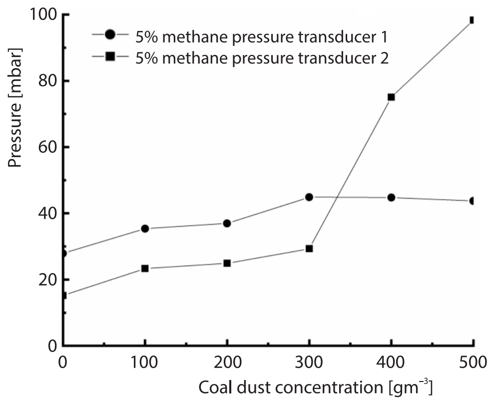

Figure 2. Pressure of 5% methane and different concentration coal dust explosion at pressure transducer 1 and 2

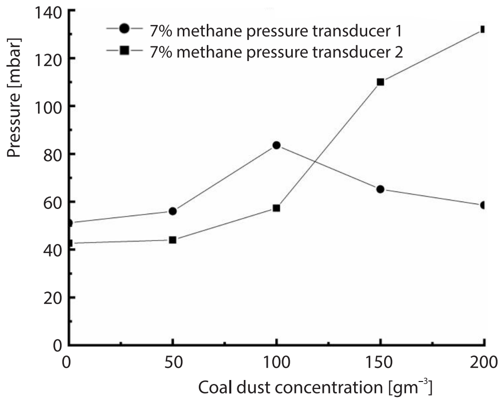

Figure 3. Pressure of 7% methane and different concentration coal dust explosion at pressure transducer 1 and 2

The PVC film between the explosion chamber and propagation pipe makes the explosion chamber a sealed space with limited volume. If the methane concentration is 5% or 7%, the explosion chamber is in the oxygen-rich state when the coal dust concentration is small, but the explosion chamber is in the oxygen-poor state when the coal dust concentration is large. When the methane concentration is 9%, the oxygen in the explosion chamber is in the oxygen-poor state regardless of the coal dust concentration. In the oxygen-rich state, coal dust promotes the coupled explosion of methane and coal dust, and the pressure increases with the increase of coal dust concentration. Before the explosion, coal dust is in solid particulate matter. The large amount of gas products are produced after the explosion. The rapid expansion of the gas increases the pressure. At the same time, the energy released by the oxidation reaction of coal dust is greater than the energy absorbed by the coal dust, which in turn causes the pressure in the explosion chamber to increase. In the oxygen-poor state, coal dust inhibits the methane and coal dust coupled explosion. The coal dust in the explosion cavity absorbs the energy released by the methane explosion. Due to the limited oxygen, the oxidation reaction of some coal dust is incomplete, and the energy released by the coal dust explosion is less than the absorbed energy, which in turn causes the coal dust to inhibits the explosion and the pressure decreases.

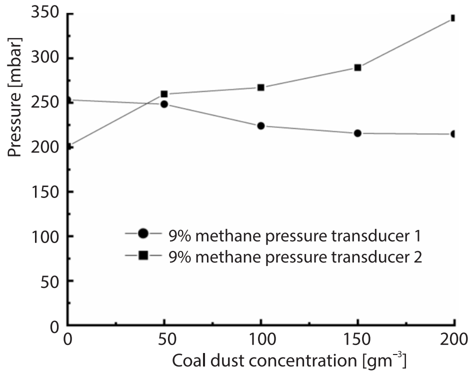

Figure 4. Pressure of 9% methane and different concentration coal dust explosion at pressure transducer 1 and 2

Comparing the pressure of pressure transducers 1 and 2, it can be seen that with the increase of coal dust concentration, the pressure of pressure transducer 1 gradually changes from greater than the pressure of pressure transducer 2 to less than the pressure of pressure transducer 2. Due to the lack of oxygen, the coal dust which has not been fully reacted in the explosion chamber continues to react with oxygen when it moves forward along the pipe. As the gas product is generated by coal dust and energy is released, the pressure continues to rise, resulting in a greater pressure of pressure transducer 2 than pressure transducer 1. The pressure measured by pressure transducer 2 increases with the increase of methane concentration and coal dust concentration.

Propagation of the explosion pressure in the propagation pipe

The pressure transducer 2-5 located in the propagation pipe are, respectively 0.375 m, 0.7 m, 0.95 m, and 1.3 m from the explosion source. In the propagation pipe, the explosion pressure propagation of methane is similar to the explosion pressure propagation of methane and coal dust coupling explosion. The explosion pressure continually decreases with the increase of distance, as shown in figs. 5-7. The pressure change of the shock wave in the propagation process is determined by the relationship between the supplementary energy of the explosive expansion and the energy consumption. When the supplementary energy of the explosion shock wave is greater than the energy consumption, the pressure gradually increases. On the contrary, the pressure decreases. In the propagation pipe, the methane and coal dust have reacted completely and will not continue to provide energy for the shock wave, resulting in a continuous drop in shock wave pressure. Moreover, heat absorption and friction on the pipe wall consume energy, which also leads to a drop in pressure.

When the concentration of methane is constant, the pressure increases as the concentration of coal dust increases. The greater the concentration of coal dust, the more coal dust will participate in the explosion. Therefore, the more energy the shock wave obtains from the explosion, resulting in greater pressure. It can be seen from fig. 5 that when 5% methane

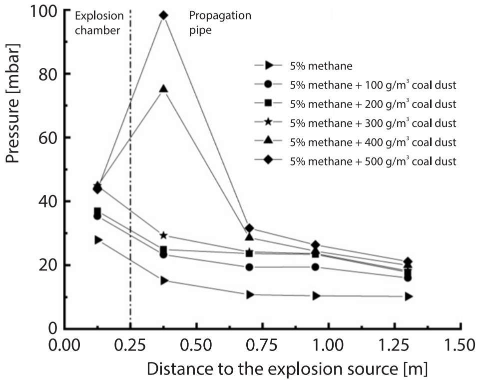

Figure 5. Explosion pressure of 5% methane and different concentrations of coal dust

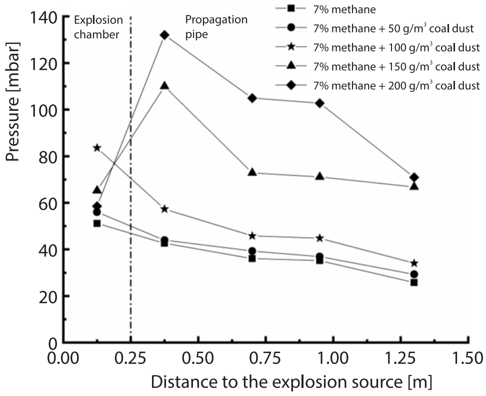

Figure 6. Explosion pressure of 7% methane and different concentrations of coal dust

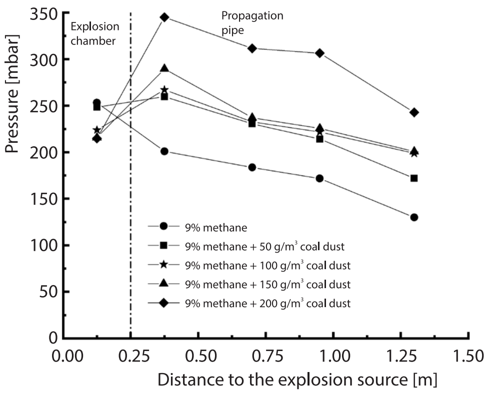

Figure 7. Explosion pressure of 9% methane and different concentrations of coal dust

is coupled with coal dust to explode, the maximum pressure in the propagation process increases from 15.21 mbar to 98.34 mbar as the concentration of coal dust increases from 0-500 g/m^3. Figure 6 shows that when 7% methane is coupled with coal dust to explode, as the coal dust concentration increases from 0-200 g/m^3, the maximum pressure in the propagation process increases from 42.62-132.01 mbar. Figure 7 shows that when 9% methane is coupled with coal dust to explode, as the concentration of coal dust increases from 0-200 g/m^3, the maximum pressure in the propagation process increases from 200.96-345.06 mbar. At 1.3 m from the explosion source, the pressure increased from 10.19-21.13 mbar when 5% methane and coal dust coupled explosion; when 7% methane and coal dust coupled explosion, the pressure increased from 25.78 mbar to 70.93 mbar and when 9% methane and coal dust coupled explosion, the pressure increased from 130.01-242.71 mbar.

By comparing the pressure difference caused by the coal dust concentration at different distances from the explosion source, it is obvious that the coal dust concentration has a greater influence on the pressure at a location closer to the explosion source. Conversely, it has less influence on the pressure farther from the explosion source. In the process of shock wave propagation, when the shock wave pressure is large, the pressure decays faster, while when the shock wave pressure is small, the pressure decays slower. Therefore, the pressure difference caused by the coal dust concentration will gradually decrease as the distance increases.

Propagation of CO gas in the propagation pipe

After the methane and coal dust coupled explosion, the gas composition is particularly complex, mainly including CO_2, CO, N_2, and O_2. Among toxic gases, CO gas has the largest concentration. This paper mainly studies the propagation of CO gas. The concentration of CO gas after methane and coal dust coupled explosion was measured, respectively at 0.45 m, 0.625 m, 0.875 m, and 1.3 m from the explosion source. It is found through experiments that the distance of CO gas propagation is much longer than the original mixing area of methane and coal dust. There is a significant entrainment effect in the propagation process of methane and coal dust explosion. The shock wave and flame can carry the gas passing through the place together during the propagation process, resulting in the combustion area being larger than the original gas distribution area, making the CO gas propagation range larger than the original methane coal dust mixture distribution area.

The concentration of CO gas produced by methane and coal dust explosion is the highest near the explosion source. As the distance from the explosion source increases, the concentration of CO gas gradually decreases, as shown in figs. 8-10. The propagation range of CO gas exceeds the flame propagation range of methane and coal dust coupled explosion, so the propagation of CO gas can be divided into two-stages: the propagation in the combustion area and the propagation in the non-combustion area. When propagating in the combustion area, a large amount of gas is generated after methane and coal dust explosion, which dilutes the concentration of CO gas. At the same time, the temperature in the combustion area is relatively high. The gas expansion causes the CO gas concentration gradually decrease. In the non-combustion area, the CO gas loses energy supply and continues to propagate forward under the action of inertia. During the propagation process, the air is continuously integrated, resulting

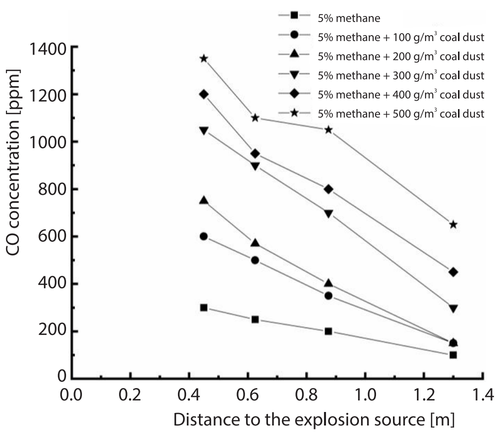

Figure 8. The CO concentration propagation of 5% methane and different concentration coal dust explosion

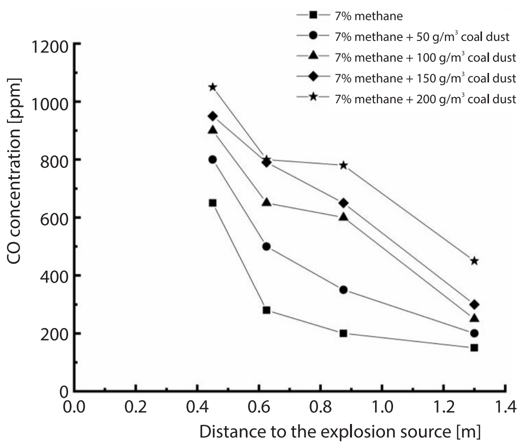

Figure 9. The CO concentration propagation of 7% methane and different concentration coal dust explosion

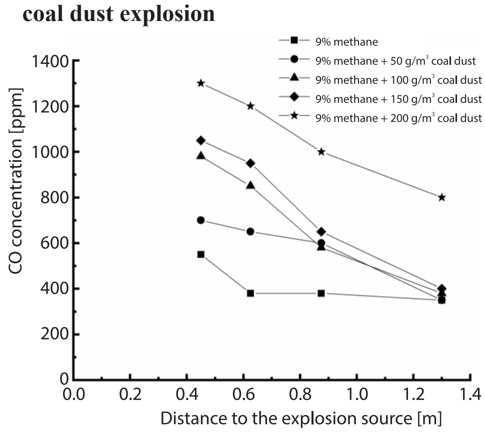

Figure 10. The CO concentration propagation of 9% methane and different concentration coal dust explosion

in the gradual concentration decrease of CO gas. On the other hand, the CO gas spontaneously propagates from a high concentration a low concentration under the action of the concentration gradient, so the CO gas concentration gradually decreases as the propagation distance increases.

As shown in figs. 8-10, the propagation distance of high concentration CO increases significantly after the explosion of methane and high concentration coal dust. The more coal dust involved in the explosion, the more energy produced by the explosion. Therefore, the energy of CO gas obtained from the explosion increases, resulting in a greater propagation distance of CO gas along the pipe-line. When the methane concentration and propagation distance are constant, the CO gas concentration increases with the increase of coal dust concentration. In addition the CO gas produced by methane explosion, CO gas is also produced by coal dust explosion. As the concentration of coal dust increases, the more CO gas is produced, the higher the concentration of CO gas is.

Conclusions

The pressure propagation and CO gas propagation are analyzed using a self-built methane and coal dust coupled explosion system. The major conclusions are summarized as follows.

- In the explosion chamber with limited volume, when 5% or 7% methane explodes with different concentrations of coal dust, the pressure increases first and then decreases with the increase of coal dust concentration. When 9% methane explodes with different concentrations of coal dust, the pressure decreases with the increase of coal dust concentration.
- In the propagation pipe-line, the coupled explosion pressure of methane and coal dust decreases with the increase of the distance from the explosion source. When the methane concentration and the distance from the explosion source are constant, the greater the concentration of coal dust, the greater the pressure.
- The propagation distance of CO gas generated by methane and coal dust coupled explosion is much longer than the original mixing area of methane and coal dust. During the propagation process, the concentration of CO gas is highest near the explosion source. As the distance from the explosion source increases, the concentration of CO gas gradually decreases. When the methane concentration and propagation distance are constant, the CO gas concentration increases with the increase of the coal dust concentration. The propagation distance of high concentration CO gas increases significantly with the increase of coal dust concentration.

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