INVESTIGATION OF THE SUPPRESSION EFFECT OF INERT DUST ON THE PRESSURE CHARACTERISTICS OF GAS COAL DUST EXPLOSION

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The suppression effect of inert powder on gas-induced suspension coal dust explosions was investigated using a semi-closed pipeline experimental platform. The shock wave overpressure propagation characteristics of gas explosions with different concentrations of mixed dust (calcium carbonate and coal dust) were measured and analyzed. The suppression mechanism of inert powder on the explosion process was also discussed. The results indicate that when the coal dust concentration is 200g/m³, the peak overpressure of the explosion decreases gradually with increasing inert powder concentration, and the peak overpressure ratio in the pipeline shows a decreasing-increasing trend; the acceleration of the explosion pressure reduces with increasing mixed dust concentration, and when high concentration of mixed dust is involved in the explosion, the acceleration of the explosion pressure is lower than that when only coal dust is involved; The inhibitory effect of calcium carbonate on dust explosion increased linearly with its concentration when the ratio of inert dust to coal dust was 1:2.; Inert powder mainly suppresses the explosive power by physical heat absorption and reducing heat exchange efficiency. The experimental results established the theoretical basis for inert dust suppressing coal dust participation in explosions, and have reference significance for formulating mine explosion suppression measures.

Keywords: gas coal dust explosion; inert dust; explosion pressure

Introduction

Explosion accidents pose a serious threat to industrial safety production. For China, coal is a traditional energy source that is indispensable in daily life [1]. As coal mining depth and intensity increase, gas disasters become more severe [2]. Coal dust suspended in the coal mine tunnel can trigger gas explosions under favorable conditions, endangering human life and property [3]. Hence, explosion suppression and mitigation technology is essential for gas and coal dust prevention.

Many studies have been carried out on explosion suppression technology in recent years. Some methods involve modifying the explosion space to reduce the damage and suppress the blast, such as adding porous materials [4, 5], laying metal nets [6, 7], installing cavities [8, 9], etc. Another important research direction is using fine water mist to inhibit the propagation of explosion flames. Feng Xiao et al. [10] demonstrated that ultra-fine water mist could markedly lower the pressure of gas-coal dust mixed explosions and delay their pressure rise process. Yu Minggao et al. [11] performed experiments on fine water mist suppression of gas explosions on a small-scale platform. The results indicated that fine water mist enhanced gas explosions when the gas concentration was high or the spray flux was insufficient. Moreover, Yu Minggao et al. [12, 13] investigated the suppression effects of N_2-fine water mist and carbon dioxide-ultra-fine water mist on gas explosions. The experiment revealed that prolonging the spray time significantly reduced the peak flame speed, peak explosion overpressure and average pressure rise rate of the explosions under the same gas concentration. Jiang Haipeng et al. [14] used dimethyl methylphosphonate (DM) as an additive for ultra-fine water mist. The composite ultra-fine water mist could notably slow down the flame speed of gas-coal dust explosions.

Gas explosion suppression technology suppresses the explosive power by reducing the concentration of combustible gas and absorbing the reaction heat energy. Zhao Peng et al. [15] and Sun Chaolun et al. [16] compared the suppression effects of nitrogen and carbon dioxide on the pressure and flame characteristics of explosions. The experimental results show that carbon dioxide has a better suppression effect on explosions than nitrogen. Powder suppression technology has become one of the important suppression technologies due to its obvious advantages of low material cost and simple use method over other explosion suppression technologies [17]. Wang Yandong [18], Lu Kunlun et al. [19] and Zhang Yansong et al. [20] studied the suppression effect of sodium bicarbonate ($NaHCO_3$) on jet flames and coal dust explosions. The experimental results show that $NaHCO_3$ reduces the temperature and radiation fraction of jet flames, and reduces the maximum explosion pressure of coal dust. Ammonium polyphosphate (APP) as a conventional flame retardant, its effect has aroused scholars' interest. Zhao Qi et al. [21, 22] conducted a deflagration experiment of methane/coal powder/ABC powder in a vertical combustion tube. The research shows that ABC powder with a mass fraction of 30% can effectively suppress methane/coal dust deflagration. Zhao Qi et al. [23], Ding Chao et al. [24] and Wang Liancong et al. [25] combined nitrogen (N_2) with ammonium polyphosphate (APP). The research shows that there is a relatively definite critical amount of ultra-fine ABC powder required for suppressing explosions, too little powder will promote flame propagation, too much powder will not further enhance the suppression effect of explosions. At the same time, kaolin powder [26] and diatomite [27] can also be used as suppressants, which have a certain suppression effect on gas-coal dust explosions.

Spreading inert rock dust on the ground is the main method to suppress gas-coal dust explosions [28]. LIU Tian-Qi [29] compared the suppression effects of three inert dusts on the maximum pressure and flame propagation distance of coal dust explosions, and found that $NH_4H_2PO_4$ had the best suppression effect, followed by NaCl and $CaCO_3$. Wang Xinqun et al. [30] tested the suppression effects of four powder suppressants on gas explosions, and showed that the explosion suppression effects were in the following order: ultra-fine ABC powder, ultra-fine SiO_2 powder, ordinary ABC, and ultra-fine $Mg(OH)_2$. Ding Haoqing et al. [31] conducted experimental studies on the explosion suppression characteristics of nano-SiO_2 powder with different mass concentrations and particle sizes, and showed that the optimal mass concentration was about 0.10 g/L; under the same mass concentration conditions, the powder with a particle size of 30 nm had a better explosion suppression effect than those with 15 nm and 50 nm. Haiyan Wang et al. [32] carried out explosion experiments with different concentrations of coal dust and gas, and found that coal dust had a suppression effect when the methane volume fraction was 6.5%. Guo Chaowei et al. [33] compared the explosion suppression effects of fly ash (FA) and modified fly ash (MFA) on gas explosions, and the experimental results showed that FA had a better explosion suppression effect than MFA. Liu Wei et al.

[34] verified that rock dust had a good suppression effect on coal dust secondary explosions and flames. Le Wang et al. [35] performed an explosion reaction of methane-air premixed gas under the action of expanded aluminium (EA), and showed that increasing EA reduced the peak pressure of 9.5% methane-air explosions by 79.3%, and increased the residual methane content by 270%. Zhao Qi et al. [36] conducted an experimental study on nitrogen mixed with fly ash to block gas explosions in a vertical pipe, and showed that as the fly ash concentration and inert zone width increased, the maximum height, bottom velocity and temperature of the methane/coal dust deflagration flame decreased significantly, and the inert zone increased the attenuation amplitude of the flame speed. Wang Xiang et al. [37] established a mathematical model of inert powder suppression of coal dust explosions, and compared it with the experimental results of a 20 L spherical explosion vessel, and found that when the inert suppressant addition amount increased to 50% (wt%), the explosion was completely suppressed.

Previous studies have mainly investigated the influence of inert dust on explosion in closed pipes or 20 L spheres, but the research on the suppression effect of inert dust on the pressure propagation of gas/coal dust explosion is scarce. In this paper, to study the suppression law of inert dust on the suspended coal dust participating in gas explosion, a rectangular horizontal explosion experimental system was established, and calcium carbonate was selected as the inert dust. The effects of inert dust on the explosion pressure evolution process were analyzed.

Experimental apparatus and procedure

Experimental apparatus and materials

The experimental system consists of a semi-closed pipe for gas-coal dust explosion, a pressure acquisition device, an ignition device, a dust spraying device, and other components. The pipe is a semi-closed rectangular acrylic pipe designed by ourselves, consisting of five sections with a total length of 1500 mm. The cross-sectional dimensions of the pipe are 80 mm × 80 mm, and it could withstand a pressure of 2 MPa. The left end of the pipe is closed. The high-energy igniter outputs a voltage of 6 kV, and the ignition electrode is arranged at a distance of 50 mm from the left end. Gas is provided by a gas cylinder, air is provided by an air compressor, and two gas flow controllers are used to control the gas ratio and flow rate. Pressure data is collected using a USB-1608FS data acquisition card and five MD-HF high-frequency pressure sensors. The data acquisition card has a sampling frequency of 100 kS/s, and the pressure sensor has a detection range of -0.1~0.1 MPa. The high-pressure gas storage device has a gas storage pressure range of 0-3 MPa. Coal dust was subjected to coal dust industrial analysis, and the mass fractions of various components are shown in Table 1. The coal dust particles were sieved, and the particle size was mainly distributed in 4-62.4 um. The particle size of the inert dust calcium carbonate was 44 um.

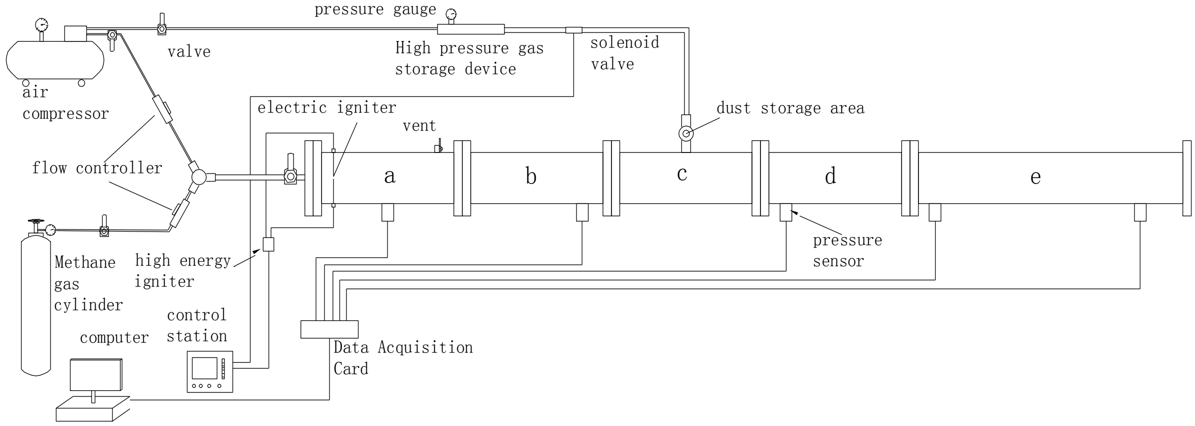

Fig. 1. Diagram of explosion experiment system

Table1. Industrial analysis of coal dust samples

Coal dust component	Mass fraction（%）
Ash content	13.1
Moisture content	1.25
Volatile matter	27.34
Fixed carbon	58.31

Experimental design

The main purpose of this experiment is to use the experimental system to collect the relevant parameters of overpressure during the explosion propagation process under different conditions of suspended coal dust/calcium carbonate participating in gas explosion, and to study the suppression effect of different mass concentrations of calcium carbonate on the explosion propagation process. The calcium carbonate concentrations set in this experiment are 100 g/m^3, 200 g/m^3, and 300 g/m^3, respectively, and the coal dust concentrations are 200 g/m^3, 400 g/m^3, and 600 g/m^3, respectively. The experimental conditions are shown in Table 2. The gas filled in the high-pressure gas storage device is air. After multiple tests, the coal dust is suspended in zone C when the gas pressure is 0.2 MPa. In order to grasp the parameter changes of the explosion shock wave overpressure in the pipe, we preset five measurement points and use pressure sensors to collect pressure data. The layout of the sensors is shown in Figure 2. The distances of the five measurement points from the left end of the pipe are 125 mm, 450 mm, 800 mm, 1050 mm, and 1400 mm, respectively.

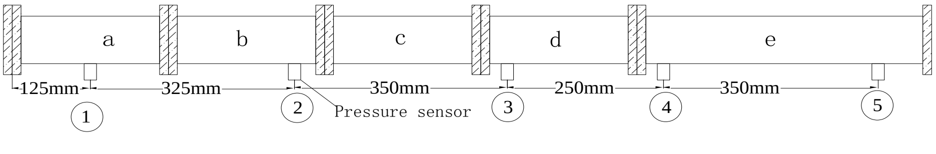

Fig. 2. Sensor layout

Before ignition, the a and b sections of the pipe were separated by a PVC film., and the mixed dust was filled in the dust placement area. The exhaust port of region A was opened, and the air flow controller was used to control the ratio of air and gas inflow. In order to discharge the original gas in region A, four times the volume of the mixed gas was introduced, then the Intake and the exhaust port were closed. At this time, the pressure in the pipe was equal to the ambient pressure, and the high-pressure gas storage device was filled with air to a specified pressure. The pressure acquisition system was first turned on, and the multithreaded control device started the high-speed camera at 50 ms, opened the solenoid valve after 10 ms, and sprayed coal dust and calcium carbonate powder into region C. After 20 ms, the high-energy igniter was activated, and the gas was ignited by an electric spark, and the explosion reaction began. After the explosion ended, the pipe was cleaned, the data was sorted, and the experiment was completed. The experimental groups are shown in Table 2. At least three experiments were performed for each condition, and the maximum explosion pressure and pressure rise rate were averaged. The pressure curve closest to the average data were selected.

Table 2 Grouping of test conditions

Serial number	Experimental condition	Serial number	Experimental condition
1	9.5% Gas	5	9.5%Gas+100g/m^3Calcium carbonate+200g/m^3Coal dust
2	9.5%Gas +200g/m^3Coal dust	6	9.5%Gas+200g/m^3Calcium carbonate+200g/m^3Coal dust
3	9.5%Gas+400g/m^3Coal dust	7	9.5%Gas+300g/m^3Calcium carbonate+200g/m^3Coal dust
4	9.5%Gas+600g/m^3Coal dust	8	9.5%Gas+200g/m^3Calcium carbonate+400g/m^3Coal dust
		9	9.5%Gas+300g/m^3Calcium carbonate+600g/m^3Coal dust

Results and analysis

Maximum pressure distribution and pressure rise rate

The effects of different concentrations of calcium carbonate on the peak explosion pressure at each measurement point were investigated under the condition of 200 g/m^3 suspended coal dust participating in 9.5% gas explosion. The results are shown in Fig 3.

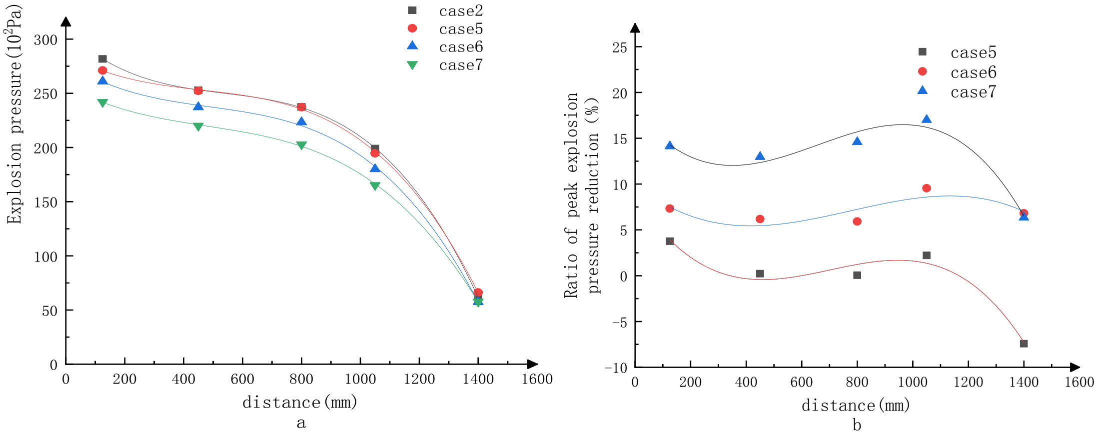

Fig. 3. Peak explosion pressure and pressure reduction ratio at different measurement points

It can be observed from the figure that the peak explosion pressure gradually decreases with the increase of the distance between the measurement point and the ignition position. The pipe is open at the right end for pressure relief, and the pressure peak value at the 4th and 5th measurement points decreases rapidly. When the calcium carbonate concentration is 100 g/m^3, the inert dust has a small inhibitory effect on the explosion propagation process, and the maximum inhibition ratio is 3.76%. With the increase of calcium carbonate concentration, the inert dust has a gradually increasing inhibitory effect on gas-coal dust explosion. When the calcium carbonate concentration is 300 g/m³, the peak pressure at 800 mm decreases by 17%. After adding calcium carbonate, the ratio of peak explosion pressure reduction in the pipe decreases first and then increases with the increase of distance. The maximum ratio of peak pressure reduction is near the 4th measurement point under the conditions of calcium carbonate concentration of 200 g/m³ and 300 g/m³.

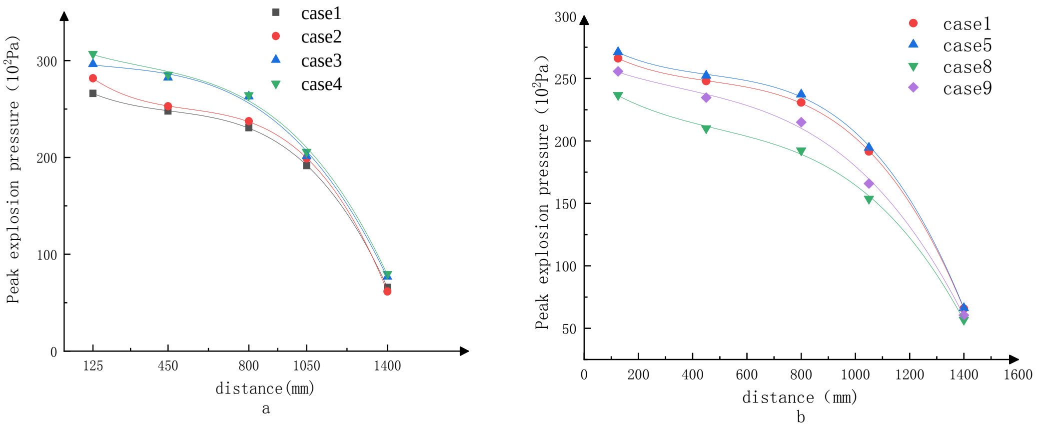

Fig. 4. Peak explosion pressure under different working conditions

The peak pressure curves of different mass concentrations of coal dust and calcium carbonate dust participating in gas explosion are shown in Figure 4. As can be seen from Figure 4(a), the peak pressure of the mixed explosion gradually increases with the increase of coal dust concentration. When 600 g/m³ and 400 g/m³ of suspended coal dust participate in gas explosion, the peak pressure and the variation trend of the measuring point are similar. The explosion pressure of fuel increases and then decreases with the increase of equivalent ratio [38,39] ,It is analyzed that coal dust has both promotion and inhibition effects on gas explosion. When excessive coal dust participates in the explosion, the heat absorption and combustion efficiency of coal dust slow down the reaction speed of coal dust participating in the explosion, resulting in a smaller peak pressure. Under the explosion conditions of case 8 and case 9, both coal dust and inert dust have inhibitory effects on the explosion, and the peak pressure is lower than that of pure gas explosion. It can be seen from the figure that the peak pressure of 400 g/m³ coal dust and 200 g/m³ inert dust is the smallest, which may be due to the fact that when the coal dust concentration is 600 g/m³, the heat absorption efficiency of 50% inert dust is lower than the heat release efficiency of coal dust combustion. In three-dimensional space, inert dust cannot effectively block high-concentration coal dust and high-temperature combustion products from heat exchange, resulting in a higher peak pressure of case 9 than case 8.

The increase ratio of peak pressure compared with pure gas explosion under various conditions is shown in Figure 5. The peak pressure of mixed dust participating in gas explosion is affected by both coal dust and inert dust. After excluding the effect of coal dust on the peak pressure of gas explosion, Figure 5(d) shows the inhibitory effect of inert dust. The inhibitory effect of inert dust on explosion mainly depends on heat absorption from the system and hindering heat exchange of coal dust. As shown in the figure, when the mass ratio of inert dust to coal dust is 1:2, the inhibitory effect of inert dust at each measuring point increases linearly with the increase of mixed dust concentration. The explosion pressure at 1400mm is influenced by the venting relief, and the inhibitory effect gradually enhances with the decrease of the distance from the opening. The slope of the inhibitory effect is concentrated in 0.04677-0.05775, indicating that the inhibitory effect of inert dust is mainly physical heat absorption.

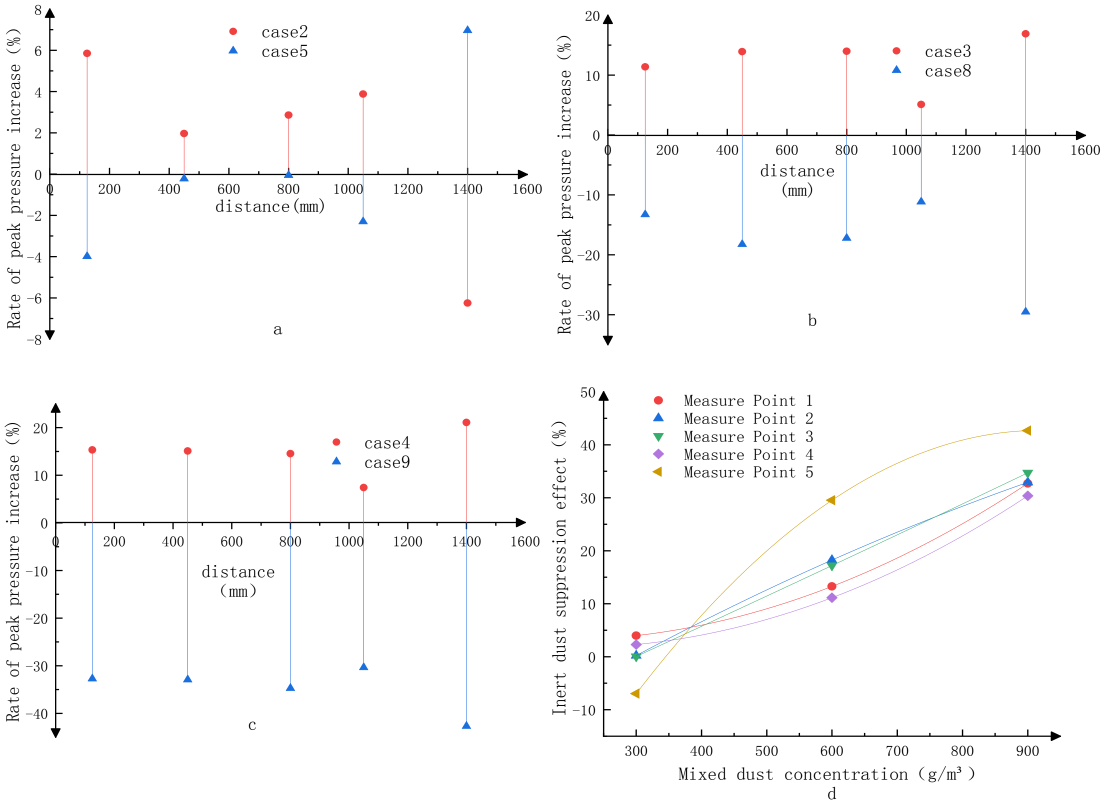

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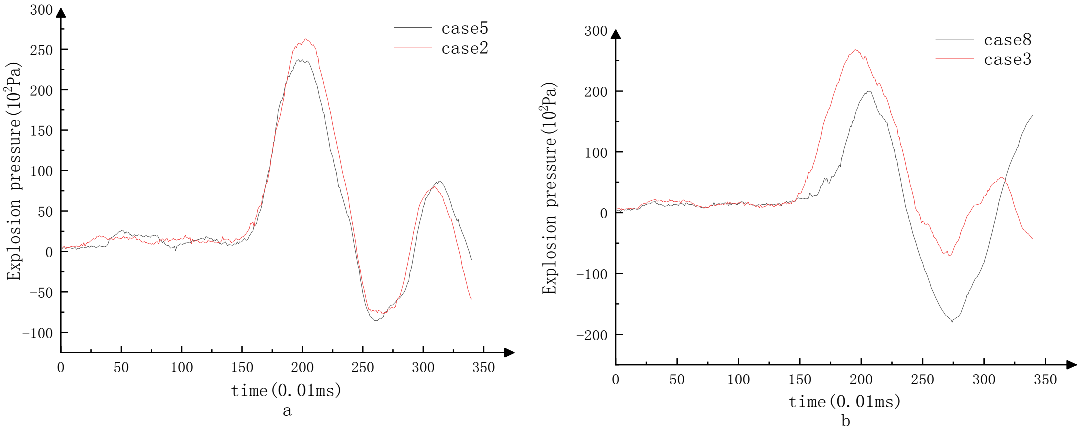
Fig 5. Pressure change ratio under different working conditions

The measuring point 3 is located behind the mixed dust suspension zone, and the pressure change of measuring point 3 is the result of coal dust-calcium carbonate coupling effect. To analyze the pressure influence law of inert dust on the fixed point, the composite explosion pressure waveform of measuring point 3 is drawn, as shown in Figure 6.



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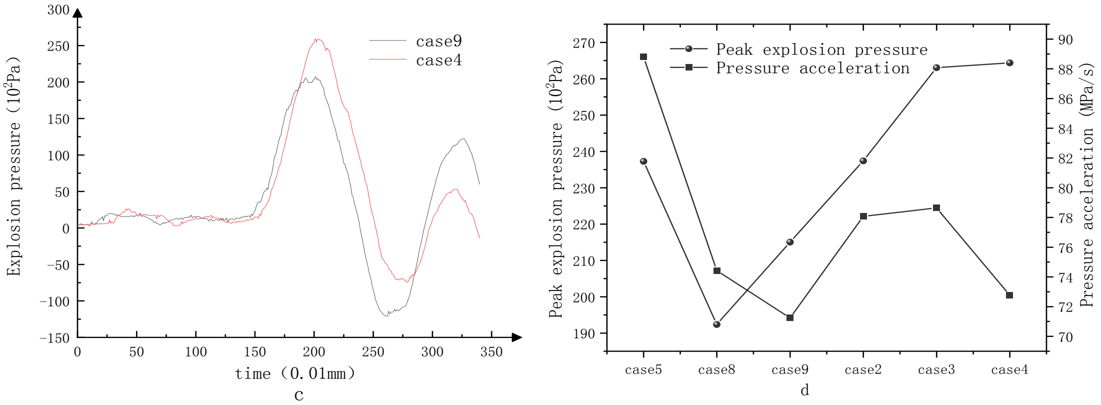

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Fig. 6. Pressure and pressure rise rate at measurement point 3

It can be seen from Fig 6 that the pressure wave at measurement point 3 rises to the maximum value first, and then the pressure drops rapidly, fluctuating with time, and the fluctuation amplitude gradually decreases. A negative pressure zone is formed by the explosion products' continuous expansion and inertial motion, which generates a typical oscillatory pressure curve of the shock wave.[40] Increasing 50wt% of inert dust, the peak pressure at measurement point 3 decreases, the fluctuation amplitude increases, and the vibration frequency increases, indicating that the inert dust delays the release of chemical energy. In previous literature, when inhibitors were added in a closed space, the pressure fluctuation showed two consecutive peaks [31], while in a semi-closed pipe, the pressure dropped rapidly to the minimum value after the first peak appeared, and then the pressure rose rapidly, indicating that the semi-closed pipe can effectively discharge the pressure and promote the oxygen and reactants to continue secondary reaction. It can be seen from Fig 6d that when coal dust participates in the explosion reaction, the explosion pressure increase rate increases first and then decreases; when inert dust participates in the explosion reaction, the explosion pressure acceleration decreases with the increase of concentration; When the mixed dust concentration is 600 g/m^3 or 900 g/m^3, the pressure acceleration decreases by 5.36% and 2.11%, respectively, compared to the coal dust explosion.

Explosion suppression mechanism of Calcium carbonate

The physical and chemical processes of coal dust participating in gas explosion are very complex, and the detailed reaction mechanism is still unclear. From a microscopic perspective, the increase of H and OH radicals is the main reason for promoting the forward chemical reaction, enhancing the explosive power and danger. [41,42] It is generally believed that coal dust participates in the explosion in two forms: homogeneous and heterogeneous reactions [43,44]. The mechanism of coal calorific value is determined by fixed carbon, volatiles and ash [45]. The mechanism of coal dust participating in gas explosion in 20L sphere is generally analyzed as follows [46-48]. Specifically, methane first reacts with oxygen in a homogeneous manner to release heat, which provides conditions for the subsequent reaction with coal dust. In the preheating stage, the gas explosion heats the coal dust particles. In the volatile release stage, a combustible mixture is formed around the coal dust particles. In the reaction stage, coal dust particles, volatiles and methane participate in the reaction together.

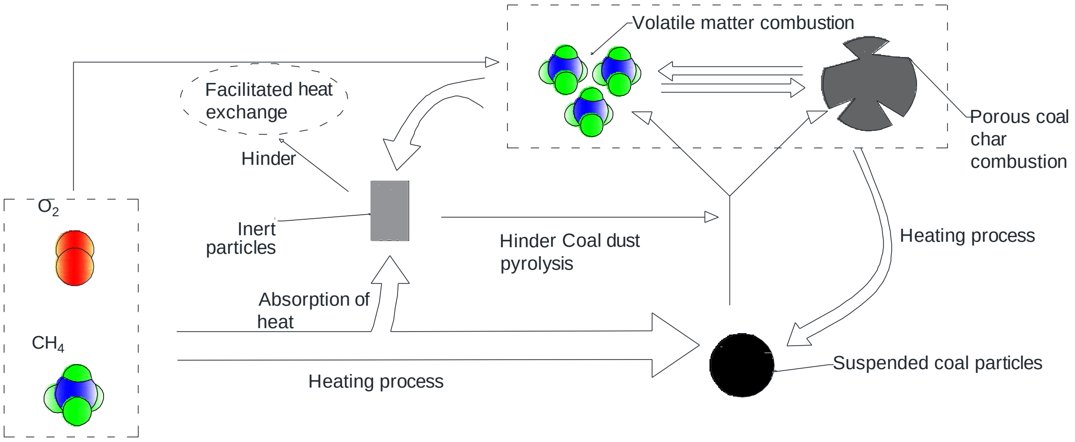

Fig. 7. Inert dust suppression mechanism

The suppression mechanism of inert dust on gas-coal dust explosion is analyzed based on the explosion pressure change. The gas explosion flame entrains air to participate in the reaction, and the flame propagation rapidly increases. The coal dust and inert particles are driven by the airflow and start to stack and move toward the flame propagation direction, while absorbing radiation energy and increasing their temperature. During the process of flame entrainment of coal dust and calcium carbonate particles, the inert particles reduce the thermal convection between coal dust and combustible gas, absorb the thermal radiation of coal dust particles, delay the release amount and rate of combustible gas from coal dust, reduce the pressure acceleration and maximum explosion pressure. Under the condition of coal dust and inert particle addition ratio of 2:1, the higher the concentration of mixed particles, the more obvious this suppression effect.

Conclusions

Based on the experimental system of inert dust suppression of gas-coal dust explosion, the experimental study on the composite explosion pressure propagation law was carried out, and the influence of different concentrations of inert dust on the explosion pressure of gas-coal dust was analyzed. The following conclusions are drawn:

- With the increase of inert dust concentration, the peak pressure reduction ratio increases. When 200g/m^3 of coal dust mixed with inert dust of different concentrations participated in the explosion, the inert dust had the best suppression effect at 64.8%-75.5% of the distance from the pipe. When the ratio of coal dust to inert dust is 2:1, the inert dust can effectively inhibit the energy release efficiency, and the inhibition effect increases linearly, the slope of the inhibitory effect is concentrated in 0.04677-0.05775.
- As the concentration of the mixed dust increases, the maximum acceleration of the explosion pressure gradually decreases, and the pressure fluctuation amplitude increases. Inert dust suppresses coal dust from participating in the explosion reaction by physical heat absorption and hindering heat exchange.

Credit author statement

Guoxun Jing: Writing- review & editing. Yue Sun: Investigation, Formal analysis, Writing - original draft, Writing- review & editing. Chuang Liu: Resources. Shaoshuai Guo: Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (No. U1904210 and No. 51774120).

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Submitted: 09.12.2023.

Revised: 31.01.2024.

Accepted: 04.02.2024.