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Pressure and Flame Propagation Characteristics of Suspended Coal Dust Explosions Induced by Gas Explosions

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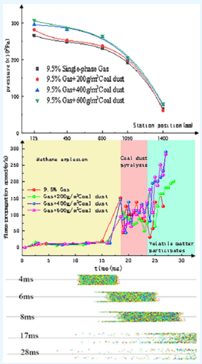
ABSTRACT: In order to explore the pressure and flame propagation characteristics of gas−coal dust composite explosions, a semiclosed pipeline explosion test platform was built. The shock wave overpressure and explosion flame propagation law of different concentrations of suspended coal dust participating in gas explosions were studied in depth through experiments, and the coal dust motion law was simulated and analyzed based on Fluent software. The experimental results show that the peak pressure of gas−coal dust composite explosion is significantly higher than that of single-phase gas explosion, and the pressure peak increase ratio at the pipeline outlet is the highest; as the suspended coal dust concentration increases, the pressure rise rate at point 3 gradually decreases. Under the condition of 600 g/m^3 coal dust participating in the explosion, the explosion pressure increase speed reduction ratio is 25.65%, the pressure wave secondary peak decreases, and the fluctuation frequency increases. When the explosion flame front passes through the suspended coal dust area, the flame shape changes from 'v' shape to 'finger' shape and propagates forward. The gas−coal dust composite explosion flame propagation speed shows a secondary acceleration phenomenon, after the flame front passes through the coal dust suspension area. As the coal dust concentration increases, the explosion core area moves away from the flame front. The coal dust cloud moves to the right, showing a concave rectangle; the larger the coal dust concentration, the smaller the moving speed. The experimental results and analysis provide an experimental basis for further exploring the mechanism and dynamic mechanism of gas−coal dust coupling explosion.



1. INTRODUCTION

China is a large coal consumption country. With the increasing mining depth and mining intensity, coal mine accidents happen frequently. Gas explosion accidents are some of the most serious accidents in coal mines. Gas explosion accidents involving coal dust often cause more serious casualties and property losses.[1−3] Coal dust in the mine is suspended due to ventilation turbulence, mining crushing, shock wave lifting, coal dust, and gas outburst. Coal dust is easily involved in the explosion process in gas explosion accidents, resulting in increased explosion power. Compared with pure gas explosion, the reaction mechanism of combined gas and coal dust explosion is more complex, and an in-depth study of its characteristics and propagation rules is of great significance to ensure the safety of coal mine production and reduce disaster losses.

In recent years, domestic and foreign scholars have done a lot of research on the explosion characteristics of gas and coal dust from ignition energy, coal dust concentration, volatile content, and other parameters. Runzhi[4] and Wu et al.[5] found that adding gas to coal dust could significantly reduce the minimum ignition energy and lower explosive limit of coal dust cloud. Zhu,[6] Weiand Wen,[7] Wang et al.,[8] and Zhao et al.[9] obtained the explosion intensity of different concentrations of gas and coal dust by experimental or simulated methods. Zhou et al.,[10] Zhang et al.,[11] and Sha et al.[12] conducted experimental research on the effects of different coal dust types on the explosion of gas and coal dust, and the research showed that the explosion pressure, explosion temperature, pressure boost rate, and explosion flame propagation speed of gas and coal dust mixture were closely related to the volatile content of coal dust. Jiang et al.[13] analyzed that when the characteristic time of turbulence disturbance is smaller than that of chemical reaction, the gas/coal dust explosion particles will increase with the increase of turbulence intensity. Yang et al.[14] showed that explosion overpressure increases with the increase of blocking ratio. Cao et al.[15] tested the change in gas explosion pressure in a 66 m pipeline. Li et al.[16] conducted an experimental study of a mixture of gas and coal dust explosion in a 20 L ball, where the overpressure and pressure increase rate of mixed gas and coal dust increase gradually with the increase of initial pressure.

In the study of coal dust participating in gas explosion propagation, the influence of coal dust mass, particle size, and volatile content on explosion characteristics was mainly analyzed. Pei et al.[17] studied and analyzed the flame

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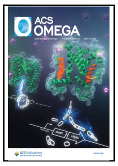

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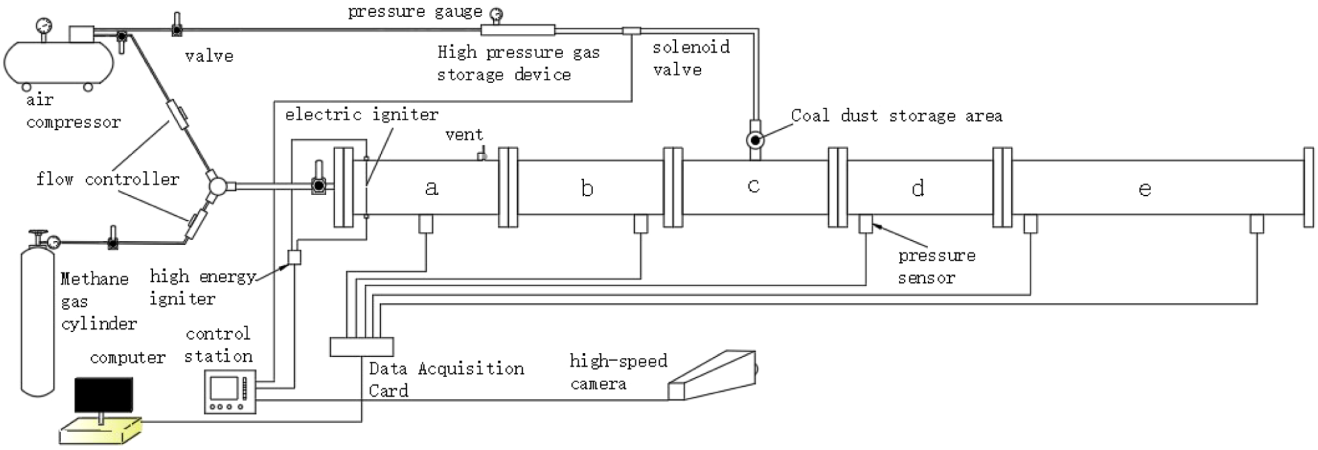


Figure 1. Diagram of the explosion experiment system.

propagation velocity and shape of sedimentary coal dust explosion induced by different impact strengths, and believed that shock wave intensity and flame front temperature were the causes of composite flame acceleration. Shi et al.[18] made a theoretical calculation on the dynamic process of gas explosion in suspended coal dust, and the explosion shock wave was mainly affected by the concentration and particle size of coal particles. Wang et al.[19] conducted a test of coal dust explosion induced by gas explosion in large roadway, and Yu et al.[20] conducted an experimental study of coal dust explosion induced by gas explosion, and analyzed that the explosion pressure increased first and then decreased with the increase of coal dust mass, and decreased with the increase of coal dust particle size. Wang et al.[21] found that deposition of aluminum powder can significantly increase flame propagation speed and explosion overpressure. Hou et al.[22] found that when sedimentary coal dust with different metamorphic degrees participated in the explosion, the peak overpressure and flame propagation speed of composite explosion were positively correlated with the volatile content of coal dust. Chuanjie,[23] Liu et al.,[24] and Li[25] carried out numerical simulation of dust cloud participating in explosion induced by shock waves, and analyzed the motion state of coal dust being swept by shock waves.

Researchers have focused on the mixed explosion characteristics of gas and coal dust and mostly used 20 L spheres to conduct premixed experiments of gas and coal dust. There have been relatively few studies on the propagation characteristics of gas—coal dust explosions in pipelines, as well as insufficient research on the pressure and flame propagation laws of gas explosions that entrain suspended coal dust. In view of this, this experiment used a self-built experimental platform, simulated the process of gas explosion inducing suspended coal dust participation with the help of Fluent flow field simulation platform, and studied the propagation characteristics of shock wave pressure and flame change law of suspended coal dust with different mass concentrations participating in gas explosion.

2. MATERIALS AND METHODS

2.1. Experimental System. The experimental system is composed of pipeline system, ignition system, gas distribution system, pressure data acquisition system, and picture acquisition system. Each system is coordinated and controlled by a multithreaded control device according to a preset time: first turn on the pressure data acquisition system, press the console start switch, the high-speed camera is started after 50 ms, the solenoid valve is opened after 10 ms, and the high-energy igniter starts to work after 20 ms. The experimental pipeline material is made of acrylic plate with a compressive strength of 2 MPa. The pipeline section is 80 × 80 mm^2 with a closed left end and an outlet on the right end, and the pipeline area a is isolated from other areas by a PVC film with a thickness of 0.01 mm. The output voltage of the high energy igniter is 6 kV, and the ignition electrode is arranged 50 mm away from the closed end of the pipeline. The gas distribution system is composed of a gas cylinder, air compressor, high-pressure gas storage device, and gas flow controller. The pressure data acquisition system uses a USB-1608FS data acquisition card, which can monitor up to 16 signals, and the acquisition frequency can reach up to 100 kS/s. The monitoring range of MD-HF high-frequency pressure sensor is −0.1 to 0.1 MPa. The test system diagram is shown in Figure 1.

During the experiment, the test equipment was installed as shown in Figure 1, and a certain amount of coal dust was placed in the coal dust filling part (as shown in Figure 1, the coal dust filling device was located 625 mm away from the left end of the pipeline). The air compressor and gas cylinder were opened to allow air into the high-pressure gas storage device. At the same time, a certain proportion of the gas—air mixture was injected into the area of pipeline a through two gas flow controllers, and in order to discharge the air in area a, the gas—air mixture was four times the volume of the explosion chamber. During this time, the initial pressure in area a was identical to the standard atmospheric pressure, and the right end of the pipeline was opened. After the high-pressure gas storage device was started, the pressure in the pipeline was at atmospheric pressure. Following aeration, the vent and switch valve were closed, ready to spray coal dust and ignition. The picture acquisition system was opened, the synchronization controller was activated, and the dust spray system, data acquisition system, and ignition system began and ended in a preset chronological order. After the explosion, the data were collated and saved, completing the test.

2.2. Test Scheme Design. The main purpose of the experiment is to use the gas explosion experimental system to test the shock wave overpressure and flame-related parameters of single-phase gas explosion and composite gas—coal dust explosion under different mass suspended coal dust conditions and study the propagation and change of shock wave overpressure and flame. The sprayed coal dust was suspended in the pipeline c area. In this experiment, three groups of coal dust mass concentrations were designed, which were 200, 400, and 600 g/m^3, respectively, to study the change law of shock wave pressure and flame of composite explosion with different mass suspended coal dust. The study shows that the gas concentration has an effect on gas−coal dust composite explosion. Under the closed condition, the single-phase gas explosion with 9.5% has the greatest power and can effectively ignite the suspended coal dust. Choosing 9.5% gas concentration is convenient to analyze the difference of the explosion effect. The coal dust was sieved, and the particle size was mainly distributed between 4 and 62.4 μm. In order to grasp the change of explosion shock wave pressure in the pipeline, we set up five measuring points, collected pressure data by using high-frequency sensors, and arranged the sensors as shown in Figure 2. The distances between the five measuring points and the left end of the pipeline were 125, 450, 800, 1050, and 1400 mm, respectively.

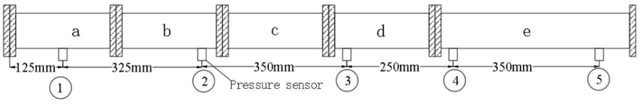


Figure 2. Schematic diagram of the measurement point location.

In the initial stage, the gas in the pipeline was air, the initial pressure was ambient, and the inside temperature was maintained at 25 °C. In the experimental process, each group of experiments was conducted more than three times to ensure the reliability of the experiment, and the arithmetic mean of three groups was taken as the valid data for each working condition experiment. The coal sample was subjected to coal dust industrial analysis, and the mass fractions of each component are shown in Table 1.

Table 1. Industrial Analysis of Coal Dust Samples

coal dust component	mass fraction (%)
ash (Aad)	13.1
moisture (Mad)	1.25
volatile matter (Vad)	27.34
fixed carbon (Fcad)	58.31

3. RESULTS

3.1. Pressure Propagation Law of Explosion Shock Wave.

Figure 3 illustrates the peak pressure distribution of suspended coal dust at different concentrations during the explosion. The figure shows that the peak pressure at each measuring point decreases with an increasing distance from the closed end. This is because the flame spreads forward, enlarging the explosion reaction space and consuming more heat energy, which reduces the pressure. The pressure relief at the pipeline outlet is the main cause for the pressure drop at measuring point 5. Compared with gas explosions, gas and coal dust composite explosions generate much higher pressures. The figure also reveals that the composite explosion pressure curves for suspended coal dust at 400 and 600 g/m^3 have similar trends, while the peak pressure for suspended coal dust at 200 g/m^3 is significantly lower. This suggests that high concentrations of suspended coal dust can effectively enhance the explosion power, but the pressure increase diminishes when the coal dust concentration reaches 600 g/m^3. This phenomenon may be due to chemical energy consumption during coal dust pyrolysis, which produces an excessive concentration of combustible gas that does not fully react in the explosion, resulting in a smaller pressure increase. Compared with pure gas explosion, suspended coal dust at 400 g/m^3 increased the peak pressure by approximately 11.37%, 13.91%, 13.98%, 5.10%, and 16.89%, at different measuring points. Interestingly, the smallest peak pressure increase occurs at measuring point 4, while the largest peak pressure occurs at measuring point 5 (the farthest from the closed end) because the oxygen at the pipe opening promotes the incomplete combustion of coal dust, accelerating the combustion process and increasing the peak pressure.

Explosion is a rapid chemical reaction process. Under different working conditions, the peak time of the explosion pressure is different. The moment when the pressure peak appeared at measurement points 2, 3, 4, 5 and measurement point 1 was compared and plotted as shown in Figure 4.

It can be seen from Figure 4 that the maximum time interval for the peak explosion pressure at the measuring point is only 0.239 ms, and the composite peak explosion pressure involving 400 and 600 g/m^3 suspended coal dust appears later at the measuring point 5 than other measuring points, which may be due to the delay in the explosion reaction due to the higher concentration of coal dust, i.e. 400 g/m^3. Under the working conditions of coal dust participating in the explosion, the

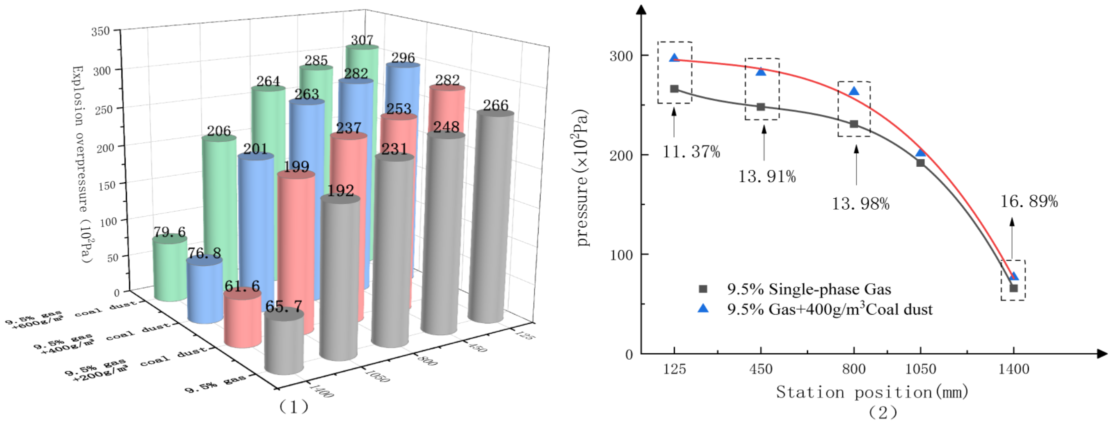


Figure 3. Peak value of the explosion pressure.

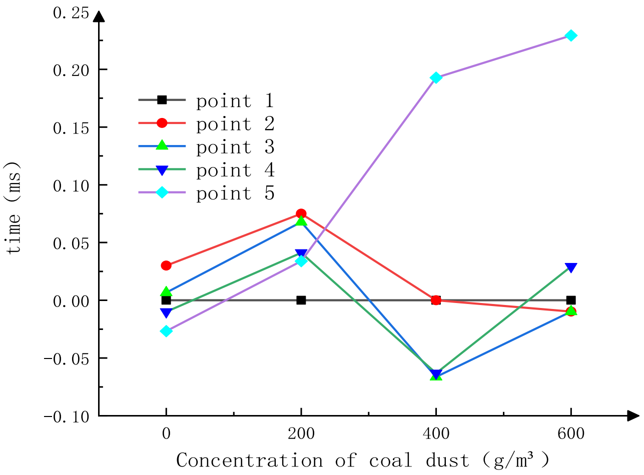


Figure 4. Occurrence time of peak pressure.

explosion peak is reached first at measuring points 3 and 4, indicating that the coal dust rapidly reacts at 800−1050 mm of the pipeline and the pressure rises rapidly. With the increase of the coal dust concentration, the most intense position of the explosion reaction gradually moved to the closed end, indicating that coal dust can quickly participate in the explosion reaction, and coal dust can absorb the kinetic energy of the flame, preventing the reaction center from moving to the pressure relief port. When the coal dust concentration is small, the explosion energy is deposited in the closed end and the maximum pressure peak appears first at measuring point 1.

3.2. Measurement Point Pressure Fluctuation Analysis.

Measuring point 3 is located in pipeline area d, on the right side of the coal dust suspension area c. Figure 5 shows the pressure waveform diagram of the composite explosion of suspended coal dust and gas at measuring point 3.

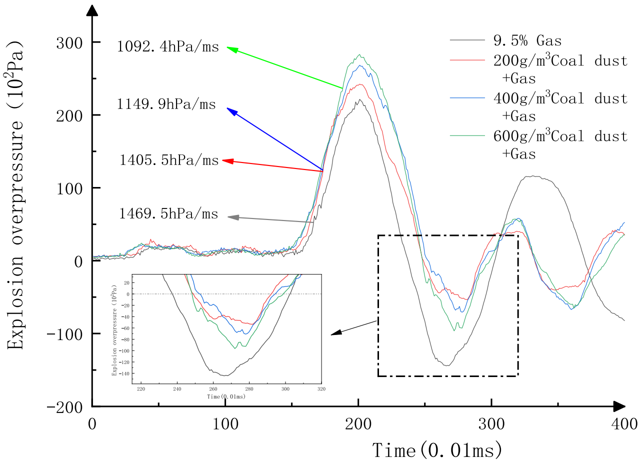
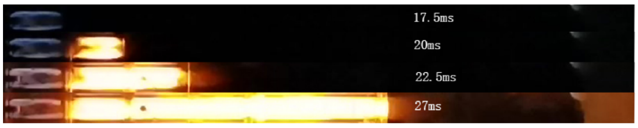


Figure 5. Pressure variation at measuring point 3.

As shown in Figure 5, it can be seen that the pressure at measurement point 3 quickly reached the maximum value at the first peak, and as the coal dust concentration increased, the peak pressure increased, the pressure acceleration gradually decreased, and then quickly decreased to negative pressure. The first pressure curve did not show a second rise of the peak value in the rising process. When the suspended coal dust participated in the explosion, the second pressure fluctuation peak value was lower than the pure gas explosion pressure peak value, and the fluctuation frequency increased. This indicates that at the third measurement point, the volatile substances of the suspended coal dust participated in the reaction and the heat generated by the combustion increased the pressure peak value, while the coal dust pyrolysis absorbed the reaction heat, reduced the reaction speed, and caused the maximum pressure acceleration to decrease, with the maximum reduction ratio of 25.65%. Compared with the 20 L sphere, the semiclosed pipeline can effectively unload the explosion energy, and when the coal dust participates in the explosion reaction, it does not cause the second rise of the peak. The time scale of gas molecule combustion is obviously lower than that of coal dust particle pyrolysis, and as the flame propagates, the reaction space gradually increases, so the pressure changes with time in an oscillating manner. The gas−coal dust coupled explosion reaction intensified the energy consumption, and the remaining less combustible material participated in the reaction again, resulting in the acceleration of the fluctuation frequency and the reduction of the second fluctuation amplitude. The peak value of the pressure acceleration of pure gas explosion appears first, and as the coal dust concentration increases, the peak occurrence time of the pressure acceleration shifts backward and gradually decreases.

3.3. Propagation Law of Explosion Flame.

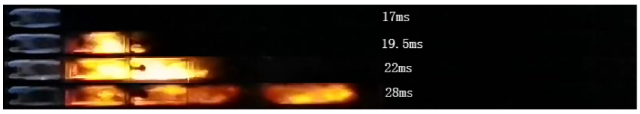
Different concentrations of suspended coal dust participate in the flame propagation process of gas explosion with a 9.5% concentration, as shown in Figure 6.



(1) The composite explosion flame shape of gas and coal dust with a concentration of 600*g* *m*

(2) The composite explosion flame shape of gas and coal dust with a concentration of 400*g* *m*

(3) The composite explosion flame shape of gas and coal dust with a concentration of 200*g* *m*



(4) Flame shape of single-phase gas explosion

Figure 6. Flame spread image of four coal dust concentrations at 9.5% methane concentration.

As observed in Figure 6, the single-phase gas explosion flame was light blue when it was in the pipe area a. The explosion flame accelerated and emitted bright flames when it encountered air after entering the propagation pipe. At 28 ms, the chemical energy was insufficient, and the flame front broke and oscillated back and forth. When the explosion flame front reached the pipe area c, it can be seen that the flame front was concave inward. Under the working condition of 600 g/m^3

suspended coal dust, the flame concavity was more obvious. When the flame propagated to 750 mm of the pipe, the flame connected from the middle, and the flame front structure was finger-like, showing dazzling firelight, and the propagation speed increased significantly. The flame rushed out of the pipe and slowed down due to the expansion wave effect. The flame diverged to all sides and finally oscillated and contracted into the pipe.

When the explosion flame front reached 500, 750, and 1500 mm, MATLAB was used to read the brightness information on the pictures at these moments, and the horizontal coordinates of the areas with the highest brightness were counted and plotted. The explosion core distribution diagram is shown in Figure 7.

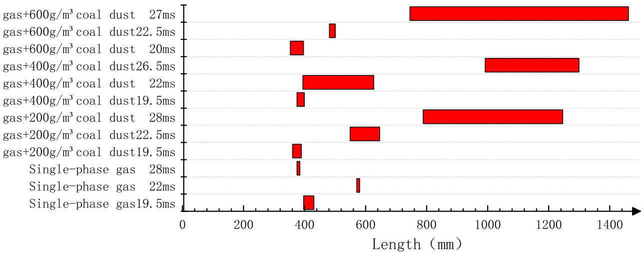


Figure 7. Distribution of the explosion core area.

A gas−coal dust explosion is a chemical explosion that releases a large amount of heat in a short period of time, produces high temperatures, and emits bright light. Therefore, the brightness can reflect the intensity of the explosion. As can be seen from Figure 7, the reaction core area was near the flame front when it reached 500 mm. When the flame front reached 750 mm, the explosion reaction core areas were 169.35 104.03, 123.39, and 249.19 mm away from the flame front. As the coal dust concentration increased, the inhibitory effect of coal dust concentration on the explosion flame became the main factor, and the position of the explosion core area gradually moved backward. When the flame reached 1500 mm, the maximum brightness of the flame of different concentrations of coal dust and gas composite explosion was the same. Compared to single-phase gas explosion, the flame brightness increased by 15.98%. The explosion core area gradually approached the flame front as the coal dust concentration increased. The core area length of 600 g/m^3 suspended coal dust participating in explosion occupied 47.74% of the pipe, while the single-phase gas explosion reaction core area was at 375−384.67 mm. The composite explosion core area with coal dust participation gradually moved forward with the flame front. Combined with Figures 4 and 6, it can be known that the pressure point with the maximum external work of explosion should appear between 22 and 28 ms.

3.4. Flame Propagation Speed Analysis.

The MATLAB software was used to obtain the brightness data of the picture and binate the grayscale of the picture, as shown in Figure 8. The length of each pixel in the picture is about 0.003086 m.

Figure 8. Grayscale image binarization.

The flame velocity is derived from the propagation distance reached by the flame front over time, and the formula is as follows:

$$v = \Delta \times (N_2 - N_1)/(t_2 - t_1) \tag{1}$$

where t_1 and t_2 are the time, Δ is the distance represented by the unit pixel, N_1 and N_2 are the horizontal coordinates of the flame front pixel in the t_1 moment and t_2 photo, respectively. The calculated speed line chart is shown in Figure 9.

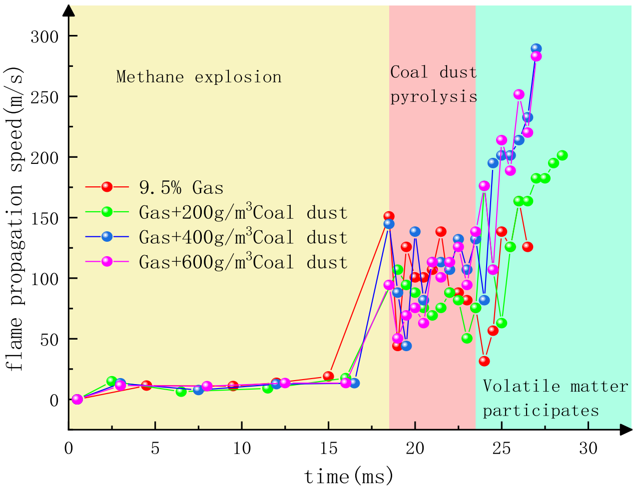


Figure 9. Flame propagation speed.

The flame front position was counted, and the flame speed under different working conditions was calculated, as shown in Figure 9. As can be seen from the figure, in the initial stage of the explosion, the flame propagation speed of different working conditions was slow, and the speed curves basically overlapped. At about 15 ms, the explosion pressure broke through the PVC film, and the air in the propagation pipe mixed with the combustible gas to accelerate the reaction speed, and the flame propagation speed increased rapidly. The pure gas explosion was limited by the pressure and the chemical energy of the combustible, and the flame propagation speed decayed in oscillation. The suspended coal dust at 400 g/m^3 had the largest flame acceleration compared to other working conditions. From 19 to 23 ms, the flame propagation speed of gas−coal dust composite explosion was relatively gentle. From 23 to 28 ms, the flame speeds of suspended coal dust at 400 and 600 g/m^3 were similar. The flame propagation speed of the gas−coal dust composite explosion showed a second acceleration phenomenon. As can be seen from Figure 6, the flame front passed through the coal dust suspension region at 23 ms. The high concentration of suspended coal dust particles hindered the flame propagation, while the explosion flame turbulence was in the development stage, resulting in a relatively gentle flame propagation speed. When the flame front approached the outlet, the combustible gas released by the coal dust pyrolysis mixed with air, causing the flame propagation speed to increase.

4. MOVEMENT RULES OF COAL DUST PARTICLES

4.1. Model Assumptions.

In this paper, finite element analysis software Fluent is used to simulate the movement of coal dust particles in the process of gas explosion igniting suspended coal dust, and the movement law of coal dust

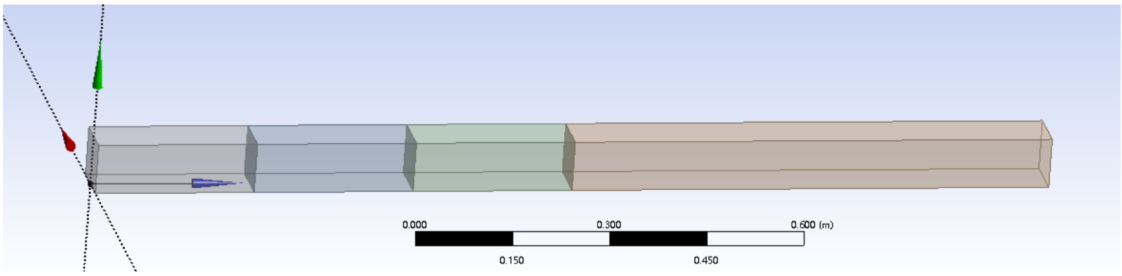


Figure 10. Fluid computational domain.

particles is analyzed. The following assumptions are made for the simulation conditions: 1. Assume that there is no heat loss on the pipe wall, and the wall thickness is ignored. 2. Suppose that there is normal temperature and atmospheric pressure in the roadway, and the oxygen content is 21%. 3. Assuming that the pulverized coal particles are spherical and have the same particle size, they will start to burn when the reaction conditions are met. 4. The process of the gas reaction is simplified, and the gas explosion reaction is defined as a single reaction and the reaction is irreversible.

4.2. Grid Division, Mathematical Model, and Initial Conditions. A three-dimensional model of a hexahedral pipeline with a length of 1.5 m, a height of 0.08 m, and a width of 0.08 m was developed. The gas air filling area was established from the left port of the pipeline to 0.25 m, followed by the flame spreading area, and an opening at the right end. Figure 10 shows the geometric model of the pipeline, and the hexahedron region in the figure is the calculation domain of the fluid.

At $x = 0.05$ m, $y = 0$ m, $z = 0.04$ m, electric spark ignition is used, ignition energy is 12 J, area a is filled with methane air mixture, and area c is the coal dust suspension area. Geometry software was used to create 3D models, and ICEM software was used for grid division. As shown in Figure 11, the gas filling area and coal dust suspension area were finely divided into grids with an accuracy of 0.002 m, and the accuracy of the remaining areas was 0.005 m. The model is divided into 451200 regular hexahedra, the orthogonal quality of the model is 1 and the aspect ratio is 1.73309, indicating that the model is of high quality.

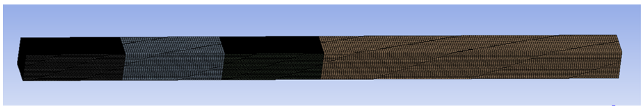
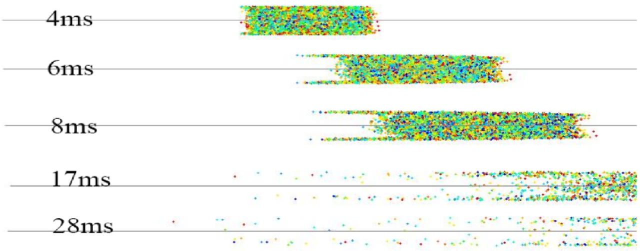


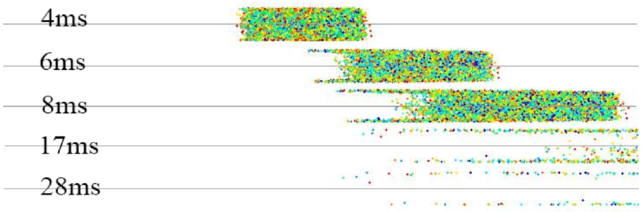
Figure 11. Model grid division.

$\kappa-\varepsilon$ turbulence model and laminar finite rate vortex dissipation model are used to describe the rate change of chemical reaction in gas explosion. The discrete phase model can simulate the particle phase in the flow field under Lagrangian coordinates and can also calculate the orbit of these particles and the heat mass transfer caused by the particles. Initial parameter settings are as follows: the initial temperature is 300 K, the initial pressure is atmospheric pressure, the ignition energy is 12 J; the initial velocity in the pipeline is 0; the open end is defined as escape; the incident particle velocity is 7 m/s; the forward injection in the z direction of z is from the bottom of the c region; the particle combustion expansion rate is 1.1; the injection duration is 0.01s; the injection end time is 20 ms away from the ignition time; the calculation time step is 0.001 s, and each step is iterated 20 times.

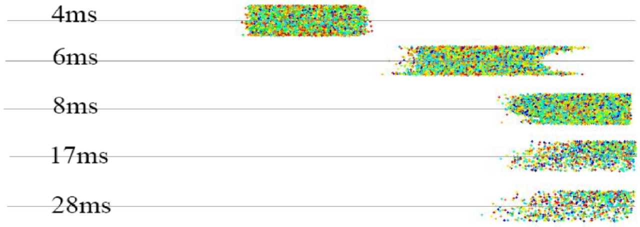
4.3. Law of Particle Motion. Different concentrations of suspended coal dust and gas were observed from the negative z axis. Particle states at 4, 6, 8, 17, and 28 ms are shown in Figure 12.



(1) Particle motion state during 600g/m³ coal dust and gas compound explosion



(2) Particle motion state during 400g/m³ coal dust and gas compound explosion



(3) Particle motion state during 200g/m³ coal dust and gas compound explosion

Figure 12. Location of coal dust particles.

From Figure 12, it can be seen that at 4−8 ms, the coal dust gradually accelerates to move to the right, and with the increase of the coal dust concentration, the coal dust movement speed gradually decreases, and the coal dust cloud with the concentration of 200 g/m^3 first escapes from the pipeline at 8 ms. On the left side of the coal dust cloud near the wall, the coal dust particles move slowly, while on the right side of the coal dust cloud near the wall, the particles move faster. From the image, the shape of the coal dust cloud is a rectangle with left and right inward depressions, indicating that the roughness of the wall and the shape of the roadway have an important effect on the movement of coal dust particles. At the 8−28 ms stage, some particles in the coal dust cloud move to the left, and the farther the particles move to the left, the higher the concentration of the coal dust cloud, similar to the flame brightness figure, with 600 g/m^3 coal dust and gas composite explosion flame having the largest core reaction zone. At 28 ms, 200 g/m^3 coal dust has the most residual coal dust particles in the pipeline, while 400 g/m^3 coal dust has the least residual coal dust.

5. DISCUSSION

1. The physical and chemical processes of coal dust participating in gas explosion are very complex. 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.[26,27] It is generally believed that coal dust participates in the explosion in two ways: homogeneous and heterogeneous reactions.[28,29] The mechanism of coal calorific value is determined by fixed carbon, volatiles, and ash.[30] The mechanism of coal dust participating in gas explosion in 20 L sphere is generally analyzed as follows.[31−33] Specifically, methane first reacts with oxygen in a homogeneous manner to release heat, which provides conditions for subsequent reaction with coal dust. In the preheating stage, 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.

2. The combustion of coal dust and gas promotes each other and jointly increases the explosion pressure. The volatile matter released by the pyrolysis of coal dust participates in the explosion reaction, which not only promotes the rapid consumption of gas, but the increase in reaction heat causes the rapid release of volatile matter, and the pressure rises rapidly, forming a positive feedback mechanism. Gas and coal dust are rapidly consumed in the reaction process; when the coal dust concentration is too high, the lack of oxygen causes the reductant reaction process to be incomplete, releasing less energy. As the reaction center moves towards the opening, the release of pressure through the opening dissipates energy within the reaction system, diminishing the impact of coal dust concentration on the explosion pressure. The maximum explosion pressure coal dust concentration may range between 400 and 600 g/m^3, or even higher.

3. The explosion reaction pressure and the flame propagation process are greatly influenced by the shape of the container. The explosion reaction produces negative pressure, and positive pressure appears again after the negative pressure appears, which indicates that the reaction space has a great limiting effect on the explosion. Additionally, the heat generated by the reaction drives the flame to work on the noncombustion zone while maintaining the pressure of the combustion zone. When the energy of the explosion reaction is not enough to maintain the pressure in the reaction space, the reaction space begins to collapse inward, a small amount of oxidant is sucked into the contracted reaction space, and after mixing with the incompletely reacted combustible, the heat output of the reaction raises the explosion pressure again. However, the collapse speed of the explosion space is slow, the huge space disperses the heat generated by the secondary explosion, and the pressure peak drops sharply. The reaction center moves toward the opening direction, and because the pressure of the closed end cannot be released to the outside of the system, the pressure of the closed end is the maximum value.

6. CONCLUSIONS

Based on the gas and coal dust explosion experiment system, the combined explosion pressure and flame propagation law of suspended coal dust induced by gas ignition are experimentally studied, the influence of different coal dust concentrations on the combined explosion pressure and flame is analyzed, and the following conclusions are drawn:

1. With the escalation of coal dust concentration, there is a gradual augmentation in the peak value of composite explosion pressure. The coexistence of gas and coal dust synergistically accelerates the rapid onset of an explosion reaction. Within the range of 200 to 600 g/m^3 coal dust concentration, the peak explosion pressure at each measurement point progressively amplifies with increasing coal dust concentration, while exhibiting a maximum time interval between pressure peaks across different measurement points of 0.239 ms.

2. The shape of the pipe and the concentration of coal dust exert significant influences on the fluctuation of the explosion pressure. The presence of coal dust absorbs both system heat energy and flame kinetic energy, thereby decelerating the rate at which the pressure rises. As the suspended concentration of coal dust increases, there is a decrease in the amplitude of the composite explosion pressure wave along with an increase in fluctuation frequency.

3. Coal dust serves as the primary source of energy for the propagation of explosion flames. As the flame front traverses through the region containing suspended coal dust, gas consumption occurs rapidly, causing the core area of the explosion to gradually distance itself from the flame front. Within a time frame ranging from 22 to 28 ms, an extreme value is reached in terms of composite explosion reaction speed.

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Notes

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REFERENCES

(1) Chun-Li, Y.; Xiang-Chun, L. Reason and Statistical Rule of Especially Serious Gas and Coal Dust Explosion Accidents in Coal Mine. *Coal Technol.* **2015**, *34* (10), 309−311.

(2) Rong-Jun; Yi-Hui; Zi-Chao, L.; Quan-Sheng. Research progress on dynamic characteristics of coal mine gas and dust explosion. *Eng. Blasting* **2023**, *29* (1), 30−39.

(3) Wang, D.; Shao, Z.; Zhu, Y. Several scientific issues on major thermodynamic disasters in coal mines. *J. China Coal Soc.* **2021**, *46* (1), 57−64.

(4) Runzhi, L. Minimum explosive concentration of coal dust cloud in the coexistence of gas and coal dust. *Explos. Shock Waves* **2018**, *38* (4), 913−917.

(5) Wu, D.; Krietsch, A.; Schmidt, M.; Krause, U. Effect of oxygen concentration, inert gas and CH4/H2 addition on the minimum ignition energy of coal dusts. *J. Loss Prev. Process Ind.* **2022**, *77*, 104772.

(6) Zhu, Q.; Bai, C. H.. Effects of gas and coal dust concentration on overpressure of mixture explosion. *Proceedings Of 2011 Academic Annual Meeting Of China Occupational Safety And Health Association Research On Numerical Modeling*. 2011, *398*.

(7) Wei, J.; Wen, L. Q. Numerical Simulation of Gas and Coal Dust Explosive Characteristics. *J. N. Univ. China* **2015**, *2*, 208.

(8) Wang, H.; Zhang, Y.; Xu, J.; Li, J.; Fan, C.; Hu, Y. Experimental study on effect of dilute coal dust on gas explosion pressure/flame evolution process. *Powder Technol.* **2022**, *404*, 117450.

(9) Zhao, Q.; Liu, J.; Huang, C. Characteristics of coal dust deflagration under the atmosphere of methane and their inhibition by coal ash. *Fuel* **2021**, *291*, 120121.

(10) Zhou, Y.; Gan, B.; Jiang, H.; Huang, L.; Gao, W. Investigations on the flame propagation characteristics in methane and coal dust hybrid explosions. *Explos. Shock Waves* **2022**, *42*, 167.

(11) Zhang, L.; Wang, H.; Chen, C. Experimental study to assess the explosion hazard of CH4/coal dust mixtures induced by high-temperature source surface. *Process Saf. Environ. Prot.* **2021**, *154* (60), 60.

(12) Sha, D.; Li, Y.; Zhou, X.; Zhang, J.; Zhang, H.; Yu, J. Influence of Volatile Content on the Explosion Characteristics of Coal Dust. *ACS Omega* **2021**, *6*, 27150.

(13) Jiang, H.; Bi, M.; Gao, Z.; Zhang, Z.; Gao, W. Effect of turbulence intensity on flame propagation and extinction limits of methane/coal dust explosions. *Energy* **2022**, *239*, 122246.

(14) Yang, K.; Chen, K.; Ji, H.; Xing, Z.; Hao, Y.; Wu, J.; Jiang, J. Experimental study on the effect of modified attapulgite powder with different outlet blockage ratios on methane-air explosion. *Energy* **2021**, *237*, 121675.

(15) Cao, M.; Zhang, Y.; Li, R.; Chen, X.; Zhang, M.; Dong, H. Explosion and vented explosion behaviors of low-concentration gas in large-scale pipes. *Eng. Sci. Technol., Int. J.* **2023**, *42*, 101410.

(16) Li, Q.; Lin, B.; Dai, H.; Zhao, S. Explosion characteristics of H2/CH4/air and CH4/coal dust/air mixtures. *Powder Technol.* **2012**, *229*, 222.

(17) Pei, B.; Zhang, Z. Y.; Pan, R. K.; Yu, M. G.; Chen, L. W.; Wen, X. P. Flame propagation characteristics of deposited coal dust explosion induced by shock waves of different intensities. *J. China Coal Soc.* **2021**, *46*, 498.

(18) Shi, J.; Zhang, P.; Xu, Y.; et al. Effects of dilute coal char particle suspensions on propagating methane detonation wave. *Combust. Flame* **2023**, *249*, 112618.

(19) Wang, X.; Li, R. Z.; Zhang, Y. S. Experimental Study on the Propagation Laws of Gas Explosion Inducing Coal Dust Explosion. *China Saf. Sci. J.* **2009**, *19*, 73.

(20) Yu, C. J.; Tan, Y. X.; Guo, Z. C. Experiment Research on Deposited Coal Dust Explosion Occurred by Gas Explosion Shock WaveCoal Sci. Technol. *Coal Sci. Technol.* **2009**, *37* (37), 37−39.

(21) WANG, D.; JING, Q.; CHENG, Y. Influence of Dust Layers in Connecting Pipes on Explosion Propagation Characteristics of Flake Aluminum Powder in Cylindrical Interconnected Vessels. *ACS Omega* **2023**, *8*, 2197.

(22) Hou, Z.; Wang, D.; Zhu, Y. Experimental study on pressure wave-induced explosion of different types of deposited coal dust. *Process Saf. Environ. Prot.* **2023**, *172*, 825.

(23) Chuanjie, Z. *Dust Lifting Process Induced by Flow field before Shock Wave and its Multiphase Destructive Effects*, Ph. D. Thesis; China University of Mining and Technology: BeiJing, 2011.

(24) Liu, D.; Li, R. Z.; Si, R. J.; Zhang, Y. S. Pattern of gas explosion induced coal dust explosion. *J. China Coal Soc.* **2011**, *36*, 1879−1883.

(25) Li, R. Z. Numerical simulation of coal dust explosion induced by gas explosion. *Explos. Shock Waves* **2010**, *30*, 529.

(26) Zhang, Q.; Qian, X.; Li, R.; et al. Explosion characteristics and chemical kinetics of blended LPG/DME clean fuel based on pyrolysis and oxidation mechanism model. *Fuel* **2022**, *320*, 123896.

(27) Zhou, G.; Ma, Y.; Kong, Y.; Zhang, Q.; Sun, Y.; Wang, Y.; Ding, J. Study on explosion dynamics and kinetic mechanism of DME/H2 blended gas at typical fuel-lean/rich concentrations. *Case Stud. Therm. Eng.* **2022**, *40*, 102444.

(28) Li, H.; Chen, X.; Deng, J. Numerical simulation on the premix properties and explosion process of methane/coal dust mixture in a vertical pipeline under turbulent flow. *J. China Coal Soc.* **2018a**, *43*, 1769−1779.

(29) Zhang, L.; Wang, H.; Chen, C.; Wang, P.; Xu, L. Experimental study to assess the explosion hazard of CH4/coal dust mixtures induced by high-temperature source surface. *Process. Saf. Environ. Prot.* **2021**, *154*, 60−71.

(30) Parikh, J.; Channiwala, S. A.; Ghosal, G. K. A correlation for calculating HHV from proximate analysis of solid fuels. *Fuel* **2005**, *84*, 487−494.

(31) Bai, C.; Gong, G.; Liu, Q.; Chen, Y.; Niu, G. The explosion overpressure field and flame propagation of methane/air and methane/coal dust/air mixtures, Saf. *Saf. Sci.* **2011**, *49*, 1349−1354.

(32) Guo, C.; Shao, H.; Jiang, S.; Wang, Y.; Wang, K.; Wu, Z. Effect of low-concentration coal dust on gas explosion propagation law. *Powder Technol.* **2020**, *367*, 243−252.

(33) Song, S.; Cheng, Y.; Meng, X.; Ma, H.; Dai, H.; Kan, J.; Shen, Z. Hybrid CH4/coal dust explosions in a 20-L spherical vessel, Process. *Saf. Environ. Prot.* **2019**, *122*, 281−287.