EXPERIMENTAL STUDY OF THE EFFECT OF COAL DUST ON THE FLAME DYNAMICS OF PARTIALLY PREMIXED GAS-COAL DUST EXPLOSION IN A VERTICAL PRESSURE RELIEF PIPE-LINE

by

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To further study the gas-coal dust explosion hazards under complex conditions. Experiments were conducted in pipe-line systems containing explosive pipe-line and pressure relief pipe-line. The effect of coal dust concentration and particle size on the flame dynamics of gas-coal dust explosion was investigated. The flame structure in the explosion pipe-line is divided into two-stages: spherical and round-finger. In the pressure relief pipe-line, the flame structure e varies at working conditions. Flame front position increases with time, showing a class exponential growth trend. The flame front velocity increases in the explosion pipe-line, has a short drop during the entry into the pressure relief pipe-line, and then increases. With the increase of coal dust concentration, flame propagation time has been increasing in the pipe-line system and the explosion pipe-line, with the shortest time at 25 g/m³. Flame propagation time first increases and then decreases in the pressure relief pipe-line, the shortest time at 50 g/m³. The maximum flame front velocity first increases and then decreases. The maximum flame front velocity is maximized at 50 g/m³. With the increase of coal dust particle size, flame propagation time has been increasing in the pipe-line system, and in the explosion pipe-line, flame propagation times have been decreasing in the pressure relief pipe-line. The maximum flame front velocity first increases, then decrease, and increases again. The maximum flame front velocity is minimal at 45 μm.

Key words: *partial premixing, gas-coal dust explosion, coal dust particle size, coal dust concentration; flame dynamics*

Introduction

Coal is the basic energy source and an important industrial raw material in China, and the coal-based energy system has supported the rapid development of the national economy; however, gas and coal dust explosions are major disasters in coal mines, causing property losses and casualties [1]. In the mining industry, the flame dynamics of gas-coal dust explosion include complex physical processes and chemical reactions. Therefore, it is significant to study the flame acceleration characteristics of gas and coal dust explosion prevent gas and coal dust explosion accidents.

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Xie *et al*. [2] investigated the interaction of entrained coal dust particles in lean methane-air premixed flames. They found that coal dust particle size influenced flame propagation velocity. Smaller coal dust particles contributed to faster flame propagation, intensifying the explosion. Li *et al*. [3] conducted experimental research to study the effects of particle size and size dispersion on coal dust explosibility. Smaller and more uniformly dispersed coal dust particles intensify dust-air mixtures' explosiveness. Therefore, controlling particle size and dispersion is vital in preventing severe explosions. Ajrash *et al*. [4] conducted experiments in a large-scale cylindrical explosion chamber using methane-coal dust hybrid fuel. Their findings further emphasized the role of gas concentration in explosion properties, showing that elevated gas concentrations led to higher pressure wave velocities and flame front velocities. This underscores the need for strict control of gas concentrations in industrial environments to mitigate explosion risks. The study by Bai *et al*. [5] revealed the structure of the coal dust explosion flame, indicating that the propagation velocity of the flame increases gradually as the explosion proceeds, which is related to the particle size of the coal dust particles. Li *et al*. [6] conducted an experimental study on the explosion severity of coal dust deflagration with six mass concentrations in four kinds of methane-air environments for the first time, and carried out SEM observation, theoretical analysis and qualitative discussion of the particles after the explosion, and initially proposed a methane/morphological classification and formation rules of particulate residues in coal dust mixtures. Gao *et al*. [7] delved into the effects of particle characteristics on flame propagation behavior during organic dust explosions in a half-closed chamber. Their study emphasizes that particle characteristics, including size and shape, play a pivotal role in explosion dynamics. Yuzuriha *et al*. [8] studied the effects of particle size distributions on flame propagation through dust clouds. Their findings underscored that coal dust particle size distribution could influence flame propagation behaviour, further emphasizing the need to control particle sizes in industrial settings. Xiao *et al*. [9] conducted a hydrogen/methane premixed combustion experiment to study the effect of quadrilateral, cylindrical and triangular obstacles on the overpressure flame propagation behavior. Wang *et al*. [10] investigated the effect of initial turbulence on the explosion behavior of stoichiometric methane-ethylene-air mixtures in confined spaces. Their Study revealed that turbulence intensifies the explosion, emphasizing the correlation between gas concentration and severity.

Cao *et al.* [11] used different burner lengths in a semi-enclosed vertical combustion tube to reveal the flame propagation behavior during a coal dust explosion using numerical simulations. The result indicated that the supreme flame propagation velocity rose gradually with the tube length increasing. Chen *et al.* [12] studied the flame propagation and transient motion of dust during a dust cloud explosion by numerical simulation. Song *et al.* [13] simulated a coal dust explosion caused by a gas explosion. Cloney *et al.* [14-16] used a CFD model based on assumed Lewis number to explore the influence of the combustion of discrete coal dust particles on the flame structure and combustion velocity. The combustion velocity and flame structure of coal dust and a mixture of coal dust and methane were studied using computational fluid dynamics. Li *et al.* [17] conducted a numerical study on the dynamics of a premixed flame in a closed tube, and the results showed that the wall boundary conditions have an important impact on the generation and amplification of pressure waves and flame dynamics. Li *et al.* [18] used FLUENT to implement a 3-D numerical model to study the transient temperature evolution of coal dust cloud deflagration in a methane-oxygen atmosphere, and obtain information on heat and mass transfer and coupling interactions in gas/dust mixed explosions. Nguyen *et al.* [19] studied the effect of obstacle shape, turbulence model and spark location on flame propagation and turbulence in methane explosions. Liu and Zhou [20] proposed a particle kinetic energy-particle model using four-way coupling to reveal the interaction mechanism of gas-particle, particle-gas, and particle-particle collisions. Numerically predict the evolution of particle vortices, particle coherence structures, and particle dynamics. The predicted results agree well with the experimental measurements. Zheng *et al.* [21] performed large eddy simulations using a thickening flame model for methane explosions to quantitatively and qualitatively reproduce the experimental data. All stages of the tulip-shaped flame are repeated in 2-D and 3-D by large eddy simulation. Bisio *et al.* [22] proposed an analytical model to assess and quantify the impact of potential deflagration events. The completeness of the design methodology is illustrated with case studies, and the analytical models are validated by comparing their predictions with detailed CFD and FE simulations.

In previous studies, some progress has been made in the research on gas and coal dust explosions, but the explosion situation under different conditions needs to be revealed more comprehensively. Previous studies have focused on gas and coal dust explosion in closed pipe-lines, 20 L explosive containers, or fully premixed in semi-closed pipe-lines, and less on gas and coal dust explosion in locally premixed in semi-closed pipe-lines. Underground coal mine gas and coal dust mixing occur more in tunnel localization, so designing local premixing experimental scenarios is particularly important. In this paper, experiments were conducted in a customized semi-closed vertical pressure relief pipe-line system. The effects of pulverized coal concentration and coal dust particle size on gas-coal dust explosion flame propagation dynamics in the explosion pipe-line and pressure relief pipe-line are studied in the local premixing case. Flame is an important parameter of gas and coal dust explosion, characterizing the strength of the explosion. Flame propagation distance, propagation form, duration and propagation velocity will greatly impact the explosion power and damage effect. The research results provide a theoretical basis for further revealing the flame propagation characteristics of gas-coal dust explosion, which can help prevent accidents.

Experimental

Experimental system

The test system, fig. 1, consists of an explosion pipe-line, a pressure relief pipe-line, a gas distribution system, a dust-raising system, an ignition system, a test and data acquisition system, and a high speed camera for image acquisition. The pipes were transparent polymethylmethacrylate (PMMA) pipes with dimensions of 120 × 120 × 500 mm and 120 × 120 × 1000 mm, respectively, and a compressive strength of 2 MPa. The dust supply system was located at the bottom of the explosion pipe and consisted of a compressor tank, high pressure nozzles, and a powder storage container. The ignition system consists of a HEI19 high thermal energy igniter and ignition electrode, located 75 mm from the bottom of the explosion pipe and has an ignition voltage of 6 kV. The high speed photography and image acquisition system consists of a high speed Star 4G camera, an image controller and a high speed computer, among which the high speed camera can shoot at 2000 frames per second [23].

Experimental conditions and procedure

In this paper, the effect of coal dust concentration and particle size on the flame dynamics of gas and coal dust explosion using a vertical pressure relief pipe-line was studied in the explosion pipe-line and the pressure relief pipe-line. The coal dust used in this experiment came from bituminous coal of the No.10 coal mine of China Pingmei Shen-

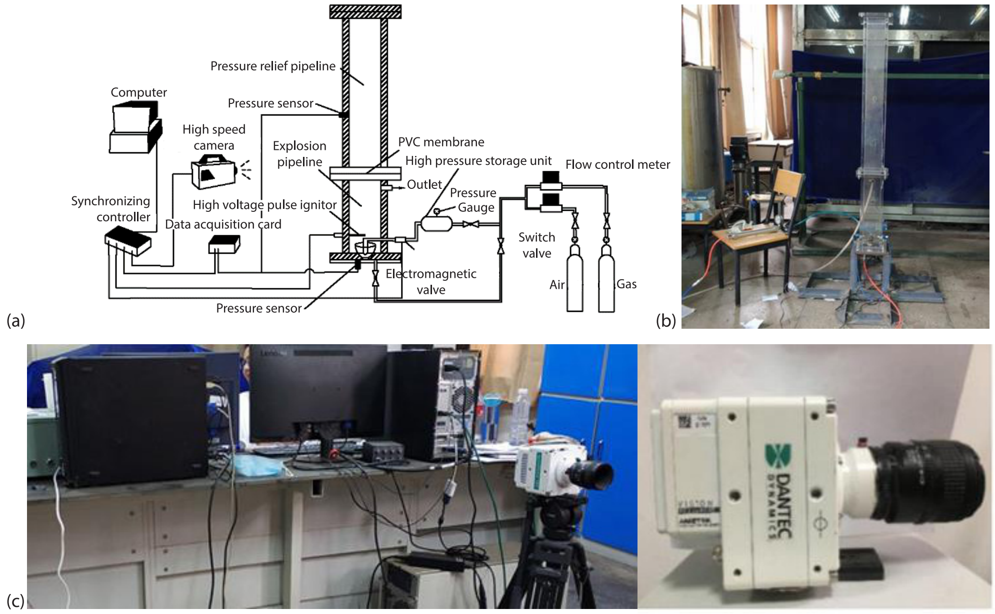

Figure. 1 Experimental apparatus; (a) schematic, (b) on-site experimental image, and (c) high speed camera and data acquisition system

ma Group, which was prepared by crushing and grinding, and the analytical data of the coal dust are summarized in tab. 1. Four coal samples with median diameters of 150 μm, 106 μm, 75 μm, and 45 μm were prepared by crushing and sieving bituminous coals using 100 mesh, 150 mesh, 200 mesh, and 300 mesh sieves. Before experiments, coal dust was dried in an electric oven at 60 °C for more than 24 hours. According to the volume of the explosion pipe-line, four kinds of coal samples with mass concentrations of 25 g/m³, 50 g/m³, 100 g/m³, and 200 g/m³ at a particle size of 75 μm were prepared. Four coal samples with coal dust particle sizes of 150 μm, 106 μm, 75 μm, and 45 μm at a concentration of 50 g/m³ were prepared. Explosion experiments with coal dust of various concentrations and

Table 1. Proximate analysis of the coal dust sample used

Coal dust	A_{ad}	M_{ad}	V_{ad}	FC_{ad}
Percentage [%]	10.02	1.04	20.78	68.16

Table 2. Experimental conditions

Number	Gas	Coal dust concentration [gm⁻³]	Coal dust particle Size [μm]
Test 1	9 vol.%	25	75
Test 2		50	
Test 3		100	
Test 4		200	
Test 5		50	45
Test 6			75
Test 7			106
Test 8			150

particle size gradients with 9 vol.% gas in a pipe-line system, as shown in tab. 2. During the experiment, three experiments were carried out at each working condition, and the photos taken by the high speed camera were used for calculations and analyses. The flame images are extracted and calculated by programming the MATLAB software. The program can obtain each working condition's flame front position and velocity history [23].

Results and discussion

Flame structure evolution

Figure 2 shows the flame propagation sequential images at different coal dust concentrations when the particle size is 75 μm. Figure 3 shows the flame propagation sequential images at different coal dust particle sizes when the concentration is 75 μm. In the pipe-line system, after the flame touches the pipe-line wall, a certain degree of atomization appears at the flame front under all working conditions. The atomization is due to the pulverized coal particles' thermal decomposition at the flame's front end and the volatile matter's precipitation [24].

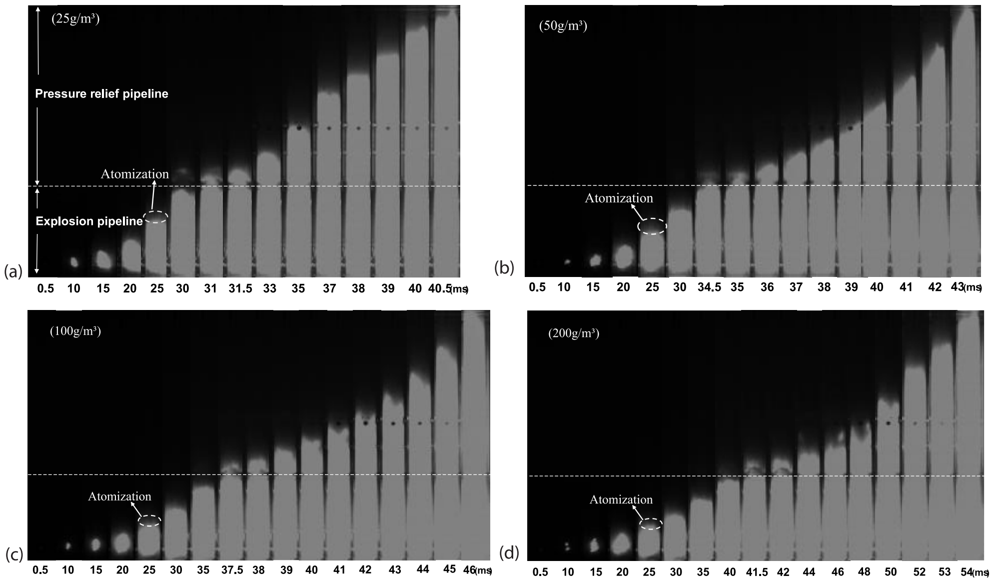

Figure 2. Flame evolution images under different concentration conditions when 75 μm

In the explosion pipe-line, all working conditions flame structural changes are similar and is divided into two-stages: spherical flame and round-finger flame. For example, in fig. 2(c), at the initial stage of flame development, the flame expands freely and is not influenced by the pipe-line sidewall. At 20 ms, the flame is spherical in shape. As the flame develops, the flame touches the pipe wall, is stretched after being constrained, and is round-fingered at 20-30 ms.

In the pressure relief pipe-line, the flame front structure e varies at working conditions. This is because the pressure relief pipe-line is open, the fuel-rich situation of coal dust oxidation exothermic promotion of flame development, coal dust heat absorption and decomposition and pipe-line heat dissipation effect to inhibit flame development. This combined effect leads to the different flame structures in the pressure relief pipe-line under different working conditions [25]. The flame structure shows a round-finger type in figs. 2(a) and 3(a). In figs. 2(b), 3(b), and

3(c), the flame structure shows a pointed-finger type. In figs. 2(c) and 3(d), elongated flames with flame skirts touching the sidewalls are observed. As fig. 2(d) shows, it is noteworthy that the flame front underwent severe distortion and reversal at 200 g/m³. The flame front was torn and continued to propagate forward. This may be due to the suppression of the flame by the excess coal dust and needs further study.

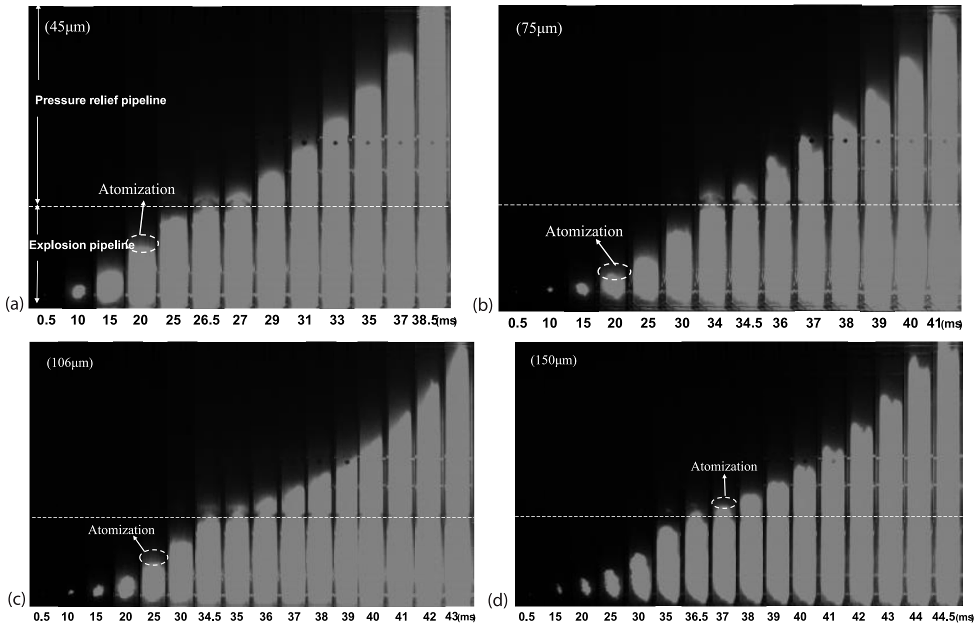

Figure 3. Flame evolution images under different particle size conditions when 50 g/m³

Flame front trajectory and velocity

Figure 4(a) shows that the flame front position history of gas-coal dust explosion at different concentrations when the coal dust particle size is 75 μm. Figure 4(b) shows that the flame front position history of gas-coal dust explosion at different particle sizes when the coal dust concentration is 50 g/m³. Flame front position increases with time in the pressure relief pipe-line system. The flame front position increases with time in the pipe-line system for all working conditions. The fit is performed with the ExpGrol function in ORIGIN software, and the fitted data are shown in tabs. 2 and 3, with a good fit and a class exponential growth of the flame cover position with time.

As shown in fig. 5(a), with the increase of coal dust concentration, flame propagation time has increased in the pipe-line system and the explosion pipe-line. Flame propagation time first increases and then decreases in the pressure relief pipe-line. In the pipe-line system and the explosion pipe-line. At a coal dust concentration of 25 g/m³, the shortest flame propagation time was 40 ms and 29.8 ms, respectively, and at a coal dust concentration of 200 g/m³ the flame propagation time increased by 34% and 26% compared to the concentration of 25 g/m³, 53.5 ms and 40 ms, respectively. When the coal dust concentration is 50 g/m³, the shortest flame propagation time is 8 ms in the pressure relief pipe-line. The flame propagation time increases by 68% when the coal dust concentration is 200 g/m³ than when the concentration is 50 g/m³, which is 13.5 ms. When the concentration is 25 g/m³, oxygen is consumed near the reaction front due to the low total fuel amount in the system. Excessive volatile substances are transported to the downstream reaction products, most of the coal dust is consumed near the reaction front, and the whole system's exothermic and endothermic reactions are balanced, promoting the flame's development. As the coal dust concentration continues to increase, the energy provided by the gas phase reaction cannot overcome the heat loss of the particles and the endothermic reaction of the excess volatiles. When the concentration was 200 g/m^3, the total heat absorption of the explosion reaction is greater than that of the heat released during the reaction. This slows the entire flame front, and it takes longer to reach the top of the pipe.

As shown in fig. 5(b), with the increase of coal dust particle size, flame propagation time has been increasing in the pipe-line system, and in the explosion pipe-line, flame propagation times have been decreasing in the pressure relief pipe-line. Take the pipe-line system as an example. The flame propagation time for a particle size of 45 μm is 13% less than that for a particle size of 150 μm, which is 38.5 ms and 43.5 ms, respectively. In the pressure relief pipe-line, the flame propagation time for a dust particle size of 45 μm increased by 42% compared to that for a particle size of 150 μm, 7.4 ms and 12.8 ms, respectively.

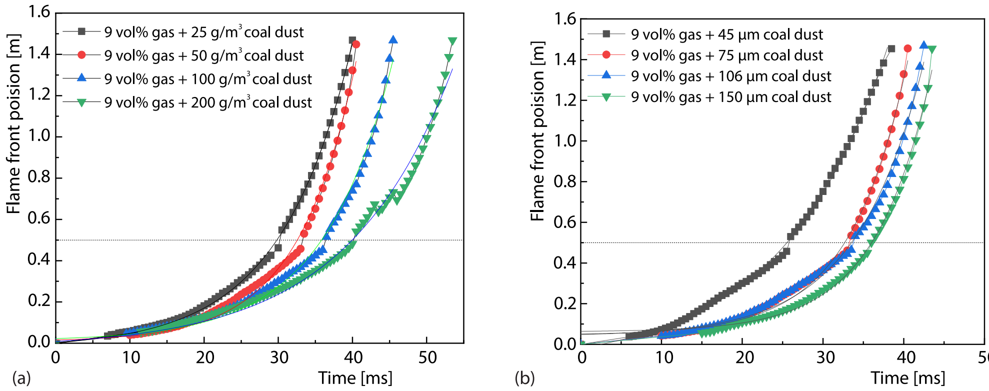

Figure 4. Flame front position history under different working conditions; (a) effect of coal dust concentrations and (b) effect of coal dust particle sizes

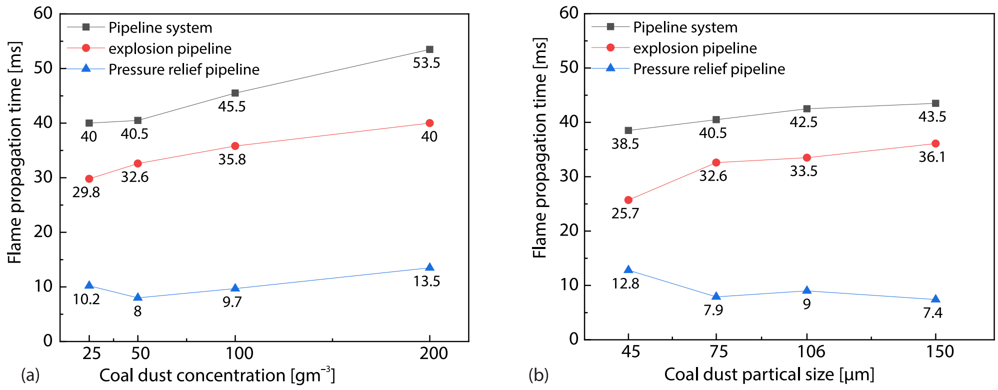

Figure 5. Flame propagation time in pipe-line system; (a) effect of coal dust concentrations and (b) effect of coal dust particle sizes

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

Experimental condition	Fitting function	R^2
25 g/m³ coal dust	$y = 9.46795\exp0.10196x + 0.00336$	0.99896
50 g/m³ coal dust	$y = 7.95421\exp0.12799x + 0.00569$	0.99363
100 g/m³ coal dust	$y = 0.01074\exp0.106479x + 0.005$	0.99343
200 g/m³ coal dust	$y = 0.03154\exp0.07026x + 0.008$	0.99057

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

Experimental condition	Fitting function	R^2
45 µm coal dust	y = 0.08569exp0.07643x + 0.007	0.99897
75 µm coal dust	$y = 0.00476\exp0.13942x + 0.00682$	0.9953
106 µm coal dust	$y = 0.00827\exp0.11987x + 0.008$	0.99394
150 µm coal dust	$y = 0.00245\exp0.14405x + 0.00673$	0.99566

Figure 6(a) shows that the flame front velocity history of gas-coal dust explosion at different concentrations when the coal dust particle size is 75 µm. Figure 6(b) shows that the flame front velocity history of gas-coal dust explosion at different particle sizes when the coal dust concentration is 50 g/m³. In all working conditions, flame front velocity accelerates in the explosion pipe-line, has a short drop during the entry into the pressure relief pipe-line, and then accelerates in the pressure relief pipe-line. In the explosion pipe-line, the flame in the explosion pipe-line due to oxygen limitation, the explosion response is slower. In the pressure relief pipe-line, the pulverized coal particles in the atomization zone in front of the flame continue to propagate with the flame, and the unburned pulverized coal particles continue to absorb heat from the surroundings for pyrolysis, resulting in a temporary decrease in flame velocity [4]. Subsequently, due to the restriction of the pipe wall, the inflow of air into the pressure relief pipe-line, and the presence of a large amount of unburned gas, the coal dust particles continued to burn, and the flame front continued to accelerate [26].

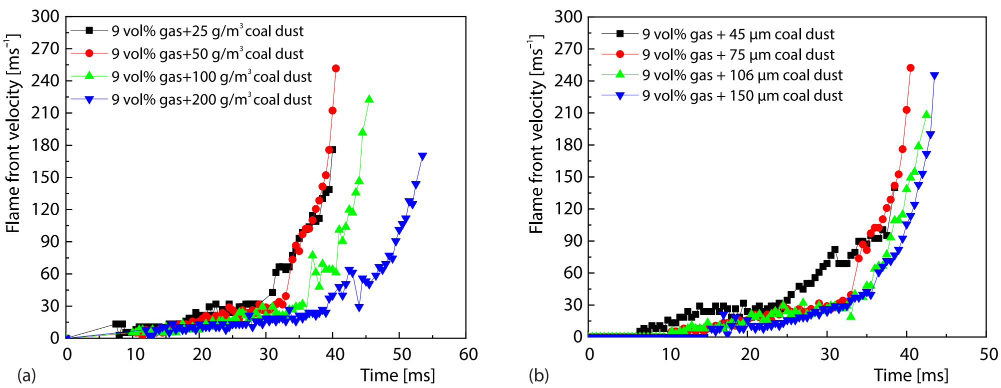

Figure 6. Flame front velocity history under different working conditions; (a) effect of coal dust concentrations and (b) effect of coal dust particle sizes

Figure 7(a) shows that with the increase of coal dust concentration, the maximum flame front velocity first increases and then decreases. The maximum flame front velocity is maximized at the 50 g/m³ concentration. The maximum flame front velocities are 175.8 m/s, 251.6 m/s, 222.4 m/s, and 170.3 m/s, respectively. When the coal dust concentration is low, the volatile substances in the coal dust are at the front of the flame, and the excess volatile substances enter the downstream reaction products. The surface reaction rate of coal and oxygen is related to the surface particle diffusion, and the diffusion of oxygen to the particle surface is related to the mass fraction of the particles near the oxygen. As the particles move downstream, they consume more oxygen, which continuously slows the surface reaction rate. As the dust concentration increases, more rapidly reacting volatiles appear at the flame front than the slower-burning carbon. This increases the burning rate with increasing dust concentration and an increase in the flame front velocity. When the coal dust concentration continued to increase, the heat loss of particles and excess volatiles exceeded the energy provided by surface reaction and gas reaction, and the combustion flame velocity decreased with the dust concentration.

Figure 7(b) shows that with the increase of coal dust particle size, the maximum flame front velocity first increases, then decreases, and increases again. The maximum flame front velocities are 140 m/s, 252.3 m/s, 208 m/s, and 245.7 m/s, respectively. The maximum flame front velocity is minimal at 45 μm. This is because the coal dust has a small particle size, the coal dust has a shorter heating time, and the volatile is more likely to overflow. Smaller coal dust particles absorb more heat than larger coal dust particles. Cloney *et al.* [14] also found a similar phenomenon in the explosion condition of coal dust with a high concentration of coal dust.

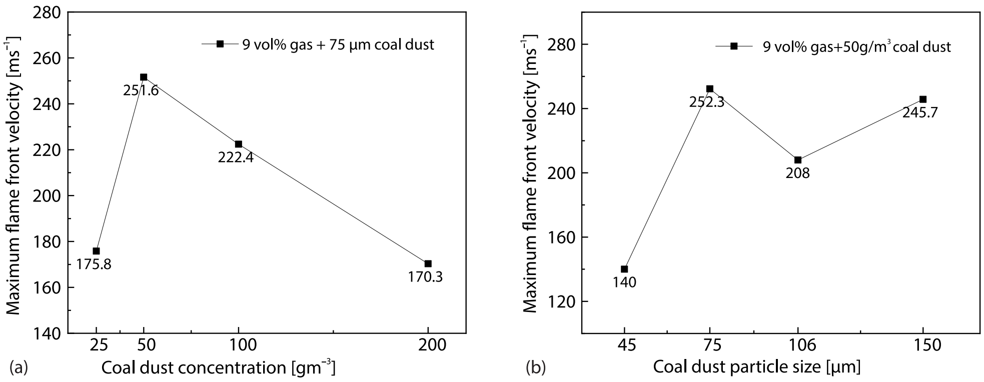

Figure 7. Maximum flame front velocity under different working conditions; (a) effect of coal dust concentrations and (b) effect of coal dust particle sizes

Conclusions

The conclusions are as follows.

- A certain degree of atomization appears at the flame front under all working conditions in the pipe-line system. In the explosion pipe-line, all working conditions flame structural changes are similar and divided into two-stages: spherical and round-finger flame. In the pressure relief pipe-line, the flame front structure e varies at working conditions.
- Flame front position increases with time, showing a class exponential growth trend for all working conditions. With the increase in coal dust concentration, flame propagation time in the pipe-line system and the explosion pipe-line increases, and the shortest flame propagation time is 40 ms and 29.8 ms when the coal dust concentration is 25 g/m³. Flame propagation time first increases and then decreases in the pressure relief pipe-line, and the shortest flame propagation time is 8 ms when the coal dust concentration is 50 g/m³. With the increase in coal dust particle size, flame propagation time in the pipe-line system and the explosion pipe-line increases, flame propagation times in the pressure relief pipe-line decreases.

- All working conditions, flame front velocity accelerates in the explosion pipe-line, has a short drop during the entry into the pressure relief pipe-line, and accelerates in the pressure relief pipe-line. With the increase of coal dust concentration, the maximum flame front velocity first increases and then decreases. The maximum flame front velocity is maximized at the 50 g/m³ concentration. With the increase of coal dust particle size, the maximum flame front velocity first increases, then decreases, and increases again. The maximum flame front velocity is minimal at 45 μm.

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