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Experimental research on flame propagation characteristics of coal dust combustion

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Abstract: The presence of coal dust explosions in coal mining are significant safety hazards. This study mainly explores the flame propagation of coal dust combustion so as to provide a theoretical basis for the prevention and control of coal dust explosions. In the experiment, a dust cloud ignition device was used to experimentally explore the influence of the coal dust concentration on the flame propagation of the coal dust, and high-speed photography was used to record the coal dust flame propagation process. The results show that the flame propagates vertically along the wall of the vertical glass tube, emits a bright yellow light during the propagation process, and forms a mushroom cloud-shaped flame at the upper end of the vertical glass tube. When the concentration of coal dust is 250 g/m^3, its burning time is much less than those of 500 g/m^3 and 750 g/m^3. When the concentrations are 250 g/m^3, 500 g/m^3 and 750 g/m^3, respectively, the corresponding maximum propagation velocities of the flame front reach 1.51 m/s, 2.00 m/s and 1.61 m/s at 100 ms, 353 ms and 310 ms, respectively. The time for the flame front velocity to reach the maximum and the maximum velocity of flame propagation first increase and then decrease with the rising of concentration.

Key words: coal dust; flame propagation; coal dust concentration; flame front velocity

0 Introduction

Coal dust explosion is one of the major threats to the safety of coal mine production and people's lives and property. China is a major coal country, and coal dust explosion accidents have occurred frequently, which is a wake-up call for people. Coal dust explosion is often accompanied by the rapid spread of flames and shock waves. The spread range of coal dust explosion determines the severity of mine accidents[1]. Therefore, it is particularly important to study the propagation law of flame and shock waves in the coal dust explosion.

Researchers have done a lot of investigations on shock wave propagation law of coal dust explosion. Tan et al.[2] studied the relationship between the explosion characteristics of coal dust and particle size through a 20 L ball. Their research shows that the maximum explosion pressure of nano coal dust is greater than micrometers, and the time required to reach the maximum explosion pressure for nano coal dust is less than micrometers. Zhang et al.[3] analysed the effect of container size on hydrogen explosions and found that the explosion pressure of hydrogen increases with the increase of tube length. Guo et al.[4] found that the gas explosion involving low-concentration coal dust is mainly affected by the volatile content of coal dust and gas concentration. Qi et al.[5] found that the addition of gas has a obvious impact on the maximum explosion pressure and explosion index of coal dust with low volatile content. The addition of gas can significantly reduce the explosion low limit of coal dust, which is affected by the volatile content of coal dust. The lower the

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volatile content of coal dust, the greater the reduction. Xu et al. [6] simulated the process of gas-coal dust explosion by Fluent software. The results show that the smaller the particle size of coal dust, the more fully exposed to oxygen, the stronger the chemical reaction, the greater the maximum pressure and pressure rise rate during the gas-coal dust explosion.

Researchers also did a lot of research on the law of flame propagation in coal dust explosion. Ban et al. [7] found that the increase of ignition energy can accelerate the combustion rate of coal dust, and make coal dust deflagration more violently. Compared with high volatile coal dust, the explosion of low volatile coal dust is more significantly affected by ignition energy. Wang et al. [8] found that the higher the coal grade, the higher the MIT and MIE values of the coal, and the less likely to be ignited. Because the volatile content and pyrolysis characteristics of coal samples of diverse grades are different. Mogi et al. [9] found that the flame front turbulence accelerates the flame propagation. Ma et al. [10] studied the main reason for the decrease of flame propagation speed is the loss of volatile content in coal dust. Li et al. [11] studied the transient evolution of particle temperature when a methane/coal dust mixture with a certain concentration explodes using a three-dimensional model. It found that the interaction of gas particles, the heat absorption of gas products and the heat conduction of gas flame make the maximum temperature of coal dust cloud fluctuate. Jing et al. [12] studied the flame propagation velocity through a semi-closed pipeline and found that the gas-coal dust flame propagation velocity decreases in the order of lignite, bituminous coal, and anthracite. This is because lignite has a higher volatile content, which increases the flame intensity of the mixture, thereby increasing the flame propagation velocity.

In addition, experts have made relevant research on coal explosion from a microscopic point based on the previous studies. Linet al. [13] reported that in the process of coal dust explosion, the hydroxyl structure of 3 800 cm^{-1}—3 000 cm^{-1}, the aliphatic structure of 3 000 cm^{-1} — 2 800 cm^{-1}, the oxygen-containing functional group of 1 800 cm^{-1}—1 000 cm^{-1}, and the aromatic structure of 900 cm^{-1} — 700 cm^{-1} are consumed in large quantities. Oxygen-containing functional groups are the most abundant chemical structure in raw coal and the most consumed in explosive reactions. Li et al. [14] concluded that aliphatic C—H and oxygen-containing substances may be the key factors by analyzing the residue after the explosion. Chen[15] pointed out that with the increase of coal grades, KBr-FTIR spectra show that the aromaticity and condensation of aromatic rings incesase, while aliphatic chain length and the 'C' factor (ratio of C=O at ~1 710 cm^{-1} versus (C=O +C=C)) decrease.

In this paper, the flame propagation law in the coal dust explosion under different conditions was studied, and the influence of coal dust concentration on its flame propagation law is discussed.

1 Experimental

1.1 Experimental setup

The experiment was completed with a dust cloud ignition device, and the vertical burning glass tube was the main body of the experiment. In addition, it was composed of dust ignition system, dispersion system, synchronization control system, and high-speed camera system. The connection diagram of each device is shown in Fig. 1. Coal dust particle size directly determines whether an explosion can occur in the experiment. To ensure the success rate of the experiment, the 200 mesh coal dust, and the concentration of 250 g/m^3, 500 g/m^3 and 750 g/m^3 are selected. The length of the vertical glass tubes used in the experiment is 300 mm. The spark discharge is used to achieve ignition. The ignition electrode enters into the tube from both sides of the vertical glass tube, which is located in the lower part of the tube. The energy of the spark can be adjusted by controlling the capacitor. High-speed photography was used to capture the flame propagation process in the vertical glass tube.

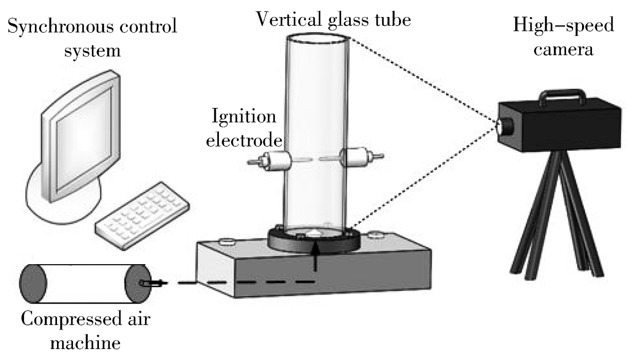


Fig. 1 Schematic diagram of experimental setup

1.2 Experimental procedures

Firstly, we connected and tested variousequipment to ensure the normal operation of the device. A certain amount of coal dust particles was weighed by an electronic balance, and was evenly placed under the spray nozzle. Then, we started the air compressor, and set the relevant instructions in different controllers so that the high-speed camera, data acquisition instrument and high-voltage ignition system work according to the set value. The experiment process was recorded using a high-speed photography system. After that, we cleaned up the combustion products in the vertical tube and repeated the experiment until after the experiments were all over.

1.3 Experimental samples and conditions

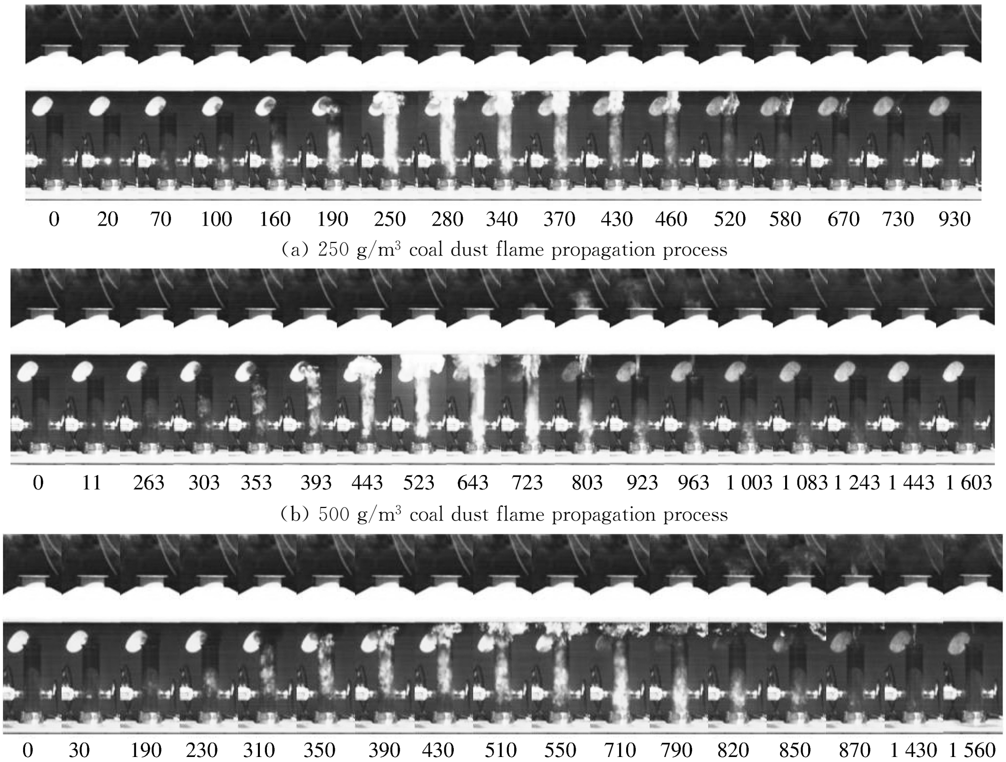
To study the influence of coal dust size on flame propagation characteristics, coal samples were pulverized under nitrogen protection, and coal dust with a particle size of 45 μm was screened out and then dried in a drying oven at a constant temperature of 50 ℃ for 6 h. The vertical glass combustion tube of the experiment is 300 mm high and 68 mm in diameter. Its volume is 1.2 L, and the maximum pressure it can bear is 0.8 MPa. The distance between the pneumatic ignition electrodes is about 10 mm, which ensures that the electric charge breaks through the air to form an electric spark.

The experimental parameters were set as follows: ignition load, no load; ignition trigger mode, moving electrode trigger; setting voltage, 8 000 V; ignition delay time: 90 ms; Inflation pressure, 0.07 MPa; high-speed camera shooting speed, 1 000 frames/s; temperature of laboratory, 20 ℃; and the electric spark ignition ignition energy, 8 J.

2 Experimental results and analysis

2.1 Flame propagation process of coal dust combustion

Fig. 2 shows the flame propagation processes of coal dust combustion with different concentrations under the condition that the ignition energy is 8 J and the length of the vertical glass tube is 300 mm.



(a) 250 g/m^3 coal dust flame propagation process

(b) 500 g/m^3 coal dust flame propagation process

(c) 750 g/m^3 coal dust flame propagation process

Fig. 2 Flame propagation processes of coal dust with different concentrations

Taking Fig. 2(a) as an example, it can be seen that the electric spark produces a bright yellowish spark at 20 ms, then the spark ignites the surrounding coal dust cloud at 20 ms—250 ms, thus the flame begins to spread in the tube, and then emits a brighter yellowish light in the vertical tube. As time goes by, the flame continues to spread, and a typical mushroom cloud-like flame is formed at the upper end of the vertical tube after 250 ms. The mushroom cloud disappears after 370 ms, and then the light of the flame begins to darken, and finally extinguishes at 930 ms. The burning time is relatively short.

In Figs. 2(a), (b) and (c), there are mushroom cloud-like flames, but in Figs. 2(a) and (b), the center of the mushroom cloud flame appears obviously white, and the white luminous area is surrounded by yellow flames. The white flame represents the full combustion of the coal dust, and the temperature is higher than the yellow area.

2.2 Relationship between flame front height, flame propagation velocity and dust concentration

The flame height during flame propagation means the distance from the flame front to the ignition position (measured until the flame front reaches the maximum height). The experimental results are shown in Figs. 3—8.

When the coal dust cloud concentration is 250 g/m^3, the flame propagates vertically upwards along the tube wall. Within 0—100 ms, the flame propagation velocity increases rapidly, and reaches the maximum of 1.51 m/s at 100 ms. The flame propagation velocity gradually decreases within 100 ms—400 ms, and after 400 ms, the flame propagation velocity begins to level off. At 580 ms, the flame front height reaches the maximum value of 535 mm.

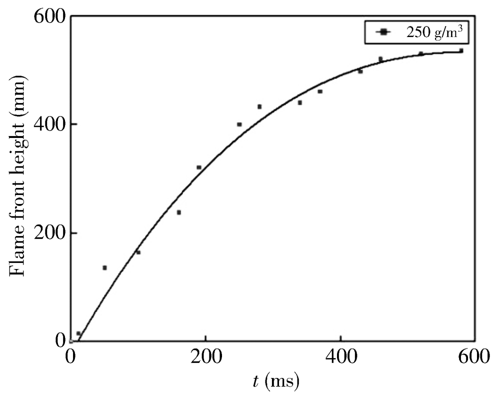


Fig. 3 Flame front height (250 g/m^3)

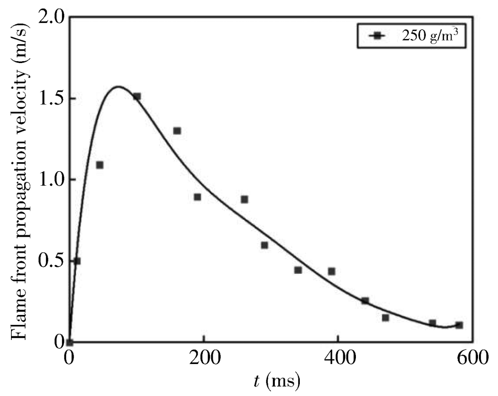


Fig. 4 Flame front propagation velocity (250 g/m^3)

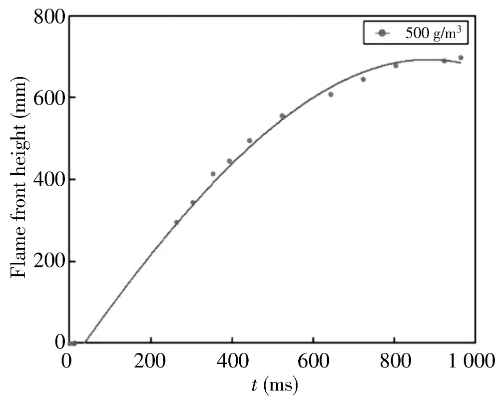


Fig. 5 Flame front height (500 g/m^3)

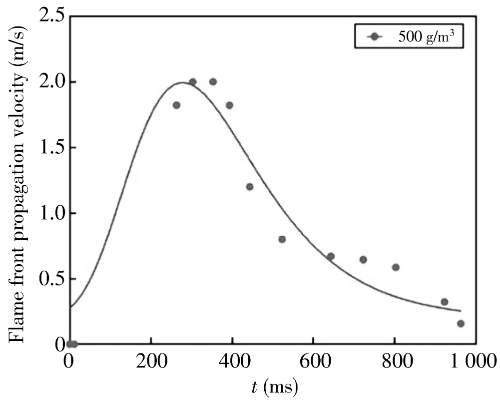


Fig. 6 Flame front propagation velocity (500 g/m^3)

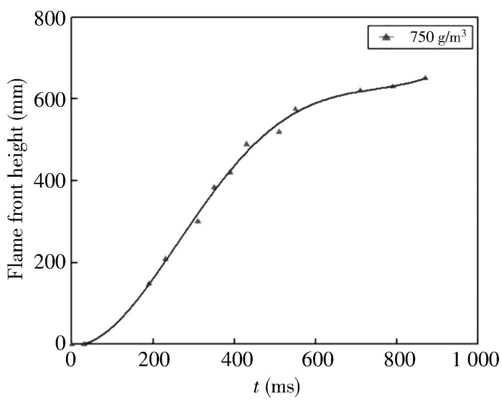


Fig. 7 Flame front height (750 g/m^3)

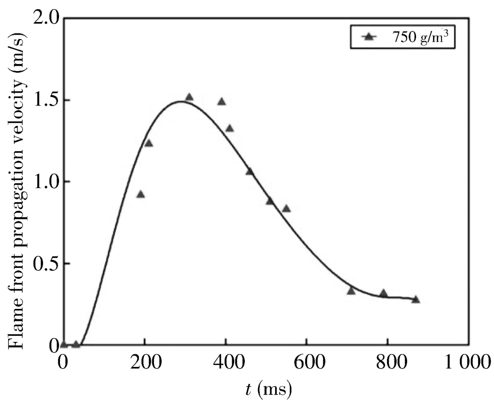


Fig. 8 Flame front propagation velocity (750 g/m^3)

When the concentration of coal dust cloud is 500 g/m^3, the upward flame propagation velocity increases rapidly within 0—353 ms and reaches the maximum of 2. 00 m/s at 353 ms. The flame propagation velocity gradually decreases in 393 ms—723 ms, and after 723 ms, the flame propagation velocity begins to level off. At 963 ms, the flame front height reaches the maximum of 698 mm.

When the coal dust cloud concentration is 750 g/m^3, the upward flame propagation velocity increases rapidly within 0—310 ms and reaches the maximum of 1. 61 m/s at 310 ms. The flame propagation velocity gradually decreases in 310 ms—710 ms, and after 710 ms, the flame propagation velocity begins to level off. At 870 ms, the flame front height reaches the maximum value of 671 mm.

Test results of coal dust explosion flame at different concentrations are shown in Table 1. When the concentration values are 250 g/m^3, 500 g/m^3 and 750 g/m^3, the maximum propagation velocities of the flame front reach 1. 51 m/s, 2. 00 m/s and 1. 61 m/s at 100 ms, 353 ms and 310 ms, respectively. The time for the flame to reach the maximum velocity increases first and then decreases with the improvement of concentration and the maximum velocity of flame propagation also presents the same law.

Table 1 Test results of coal dust explosion flame with different concentrations

C (g/m^3)	250	500	750
t (ms)	100	353	310
v (m/s)	1. 51	2. 00	1. 61

Note: "t" means the time required for the maximum propagation velocity of the flame front; "v" means the maximum propagation velocity of the flame front.

The main reasons for this law are as follows: At a lower concentration of coal dust, the combustion of dust particles generates a certain amount of energy, but there is less dust in a unit volume and oxygen-enriched combustion is formed so that the burning time of lower concentration coal dust is shorter and the time reaching the maximum velocity is also shorter. The increase of the coal dust concentration adds the number of effective combustion particles in a unit volume, and the amount of heat released and the heat release rate also increase, thereby the maximum flame propagation velocity increases. However, the increase in the total dust mass greatly prolongs the dust combustion time, so the time for the flame front to reach the maximum velocity also increases.

The higher concentration of coal dust results in too much unignited coal dust in a unit volume. Unburned coal dust particles will be used as heat capacity to absorb combustion heat and reduce the combustion efficiency of coal dust. In addition, in turbulent motion, the combustion rate of particles and the propagation rate of flame are directly proportional to the intensity of the flow field. Taking 500 g/m^3 as the standard, reducing the concentration is equivalent to increasing the turbulence intensity, so the time required to reach the maximum flame propagation velocity is reduced at 250 g/m^3; increasing the concentration is equivalent to reducing the turbulence intensity, so the flame front the maximum propagation velocity of the front is significantly reduced at 750 g/m^3.

3 Conclusions

An experimental study on coal dust combustion process in a vertical glass tube is carried out, and the influence of the concentration of coal dust cloud on the flame propagation of coal dust cloud is concluded.

1) After the coal dust cloud is ignited by the ignition electrode, the flame propagates vertically along the wall of the vertical glass tube. The flame emits a bright yellow light during the propagation and forms a mushroom cloud-shaped flame at the upper end of the vertical glass tube.

2) When the concentration of coal dust cloud is 250 g/m^3, its burning time is much less than those of 500 g/m^3 and 750 g/m^3.

3) When the concentration values are 250 g/m^3, 500 g/m^3 and 750 g/m^3, the propagation velocities of the flame front reach the maximum values of 1. 51 m/s, 2. 00 m/s and 1. 61 m/s at 100 ms, 353 ms and 310 ms, respectively. The time for the flame front to reach the maximum velocity and the maximum velocity of flame propagation first increase and then decrease with the increase of concentration.

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煤粉云火焰传播特性实验研究

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摘　要: 煤矿开采中存在煤粉爆炸的重大安全隐患，本实验主要研究煤粉云的火焰传播，为预防和控制煤粉爆炸事故提供理论依据。实验采用粉尘云点火装置对煤粉在燃烧玻璃管中进行试验，通过改变煤粉云浓度探讨其对煤粉云火焰传播过程的影响，并利用高速摄影记录煤粉火焰传播过程。结果表明，点火电极在点燃煤粉云后，火焰沿着玻璃直管管壁竖直传播，火焰在传播过程中发出明亮的黄光并在玻璃直管上端端口形成蘑菇云状的火焰。当煤粉云的浓度为 250 g/m^3 时，其燃烧时间远远小于浓度为 500 g/m^3 和 750 g/m^3 时的燃烧时间。当浓度分别为 250 g/m^3、500 g/m^3 和 750 g/m^3 时，其火焰前锋阵面最大传播速度分别在 100 ms、353 ms 和 310 ms 时达到相应的最大值 1.51 m/s、2.00 m/s 和 1.61 m/s。火焰前锋阵面达到最大速度的时间和火焰传播的最大速度随浓度的增加先增大后减小。

关键词: 煤粉; 火焰传播; 煤粉浓度; 火焰传播速度

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