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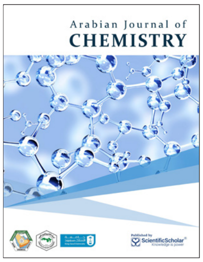

Original Article

Study on the influence of coal dust particle size on the structure and propagation characteristics of explosion flame in Hartmann tube

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ABSTRACT

Coal dust explosions in coal mines can result in numerous casualties and substantial property damage. This study investigates the flame propagation characteristics of coal dust explosions in a Hartmann tube through theoretical analysis and experimentation. The flame propagation characteristics during coal dust explosions with varying particle sizes were investigated using high-speed cameras and schlieren cameras to simultaneously capture the temporal and spatial development of flames from two perspectives: tube position and outlet. The results indicate that particle size significantly affects flame propagation. Flames produced from burning small particles of coal dust are densely packed and compact, while flames from larger particles exhibit more irregular shapes, suggesting that a more intense reaction leads to brighter light radiation on the flame surface. These morphological variations correspond to distinct combustion regions and mechanisms. In addition, during the formation of coal dust clouds, turbulence-induced phenomena create vacancies within the flames as they propagate. This results in coal dust adhering to and agglomerating on the tube wall, leading to an absence of flames near both sides of the wall. Furthermore, increasing coal dust particle size contributes to a thicker preheating zone for flames. Specifically, for particles smaller than 53 μm, this thickness measures approximately 5 mm. Clustered flames with irregular fronts characterize the combustion behavior within micron-sized coal dust particles. A comprehensive understanding of these variations in particle size, along with the spatial evolution characteristics of flames, is essential for developing effective prevention and control measures against coal dust explosions from a theoretical perspective.

1. Introduction

Coal dust is a major contributor to explosion accidents, and 80% of gas explosion accidents have coal dust involved. In recent years, coal dust and gas accidents have become one of the key issues that the country attaches great importance to. Once an explosion occurs, it often causes significant casualties and property damage [1-3]. Coal dust explosions make the safety situation of coal mines still deplorable [4]. Therefore, macro- and micro-level experimental studies on the factors influencing coal dust explosions are of great practical significance for realizing explosion prevention measures and energy control.

To effectively prevent coal dust explosion accidents, numerous scholars from both domestic and international backgrounds have conducted in-depth research on the influencing factors of coal dust explosions. These factors include coal dust concentration [5,6], volatile content [7], particle size of the coal dust [8,9], minimum ignition energy [10], explosion limit [11], and maximum explosion pressure. Wang *et al.* [12] found that an increase in ignition delay time leads to an initial increase and subsequent decrease in the rate of pressure rise and the maximum explosion pressure value. Azam S and Mishra D P [13] have shown that the decrease in coal dust particle size and the increase of rock dust particle size lead to an increase in the proportion of rock powder during the inerting of coal dust explosion. Li *et al.* [14-16] revealed the influence of ignition delay time and particle size of coal dust cloud explosion on flame height in the Hartmann tube. Jing et al. [17] studied how various concentrations of coal dust affect methane flames, and adding coal dust will prolong the total combustion time and cause the flame to oscillate. Gao *et al.* [18] conducted an experimental study on coal dust explosion in Hartmann tube and obtained the flame propagation characteristics of coal dust explosion with different concentrations. Zhao *et al.* [19] and Guo *et al.* [20] studied the change of lignite flame under different ignition energy and different combustion tube lengths. Liu *et al.* [21,22] used experimental methods to study and found that coal dust with higher volatile content has a more significant ignition tendency. Nie *et al.* [23-25] analyzed the research progress of the mechanism of coal dust explosion at the macro- and micro-levels. Jia *et al.* [26] concluded that when the mass concentration of coal dust remained constant, the pressure generated by the explosion showed a trend of continuous decrease with the increase of particle size. Liu et al. [27,28] obtained the influence of coal dust particle size and ignition delay time on the flame propagation process of lignite coal dust by analyzing the height and velocity of flame propagation. Ban *et al.* [29] found that with the increase in ignition energy, the combustion speed of coal dust is accelerated, and the deflagration reaction is more intense. Li *et al.* [16] further found that the higher the pre-oxidation state of coal, the smaller the maximum value of flame radius and velocity.

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Pre-oxidation has a significant effect on the change of flame shape and flame brightness. Li [30] investigated the propagation characteristics of coal dust cloud flames through experiments and numerical simulations. Zhao *et al.* [31] focused on the effects of coal dust concentration, oxygen concentration, and coal dust particle size on flame propagation velocity. Cao *et al.* [32] observed that under varying initial turbulence intensities, first accelerates and then decelerates, showing an inverted U-shaped parabolic shape. Liu [33] explored the different effects of coal dust particle size, coal dust particle size, ignition energy, and ignition delay time on flame propagation.

With the extensive and in-depth research on dust explosion mechanism and disaster evolution process, flame propagation process and flame microstructure have attracted the attention of scholars. Ou-Sup Han *et al.* [34] found the double-flame structure of the flame front of the lycopodium dust cloud in a vertical tube. Proust [35] concluded that the heat conduction of the flame during the flame propagation mainly depends on the radiation heat transfer. Sun [36] revealed that the flame propagation in polymethyl methacrylate (PMMA) microparticle cloud is divided into unburned zone, main reaction zone, and yellow luminescence zones. Wang [37] and Ding [38] obtained the flame microstructure of zirconium powder clouds and the combustion reaction. Peng *et al.* [39] showed that the change in flame propagation velocity has experienced two stages: exponential acceleration and linear acceleration. Zhang *et al.* [40] used a 1.2 L Hartmann tube to study the flame propagation behavior of corn starch at different concentrations. Wang *et al.* [41] studied the flame propagation behavior and microstructure of Ti powder explosion under different particle sizes. The results show that the particle size has a significant effect on the flame propagation behavior in dust explosions.

Although the influence of coal dust particle size on the explosion process has been investigated, the depth of research into how this particle size affects flame structure and propagation characteristics remains inadequate. There has not been a comprehensive and in-depth analysis of the structural difference of the flame during coal dust combustion, the density of flame distribution, the regular change of shape, the intensity of combustion reflected by color, and the change law of the thickness of the preheating zone and the flame clusters during the flame propagation. In particular, there is a lack of research on the influence of coal dust particle size on flame structure and propagation characteristics from the two perspectives of tube and tube outlet position.

Based on the experimental device of dust explosion characteristics, this study used a high-speed camera and schlieren to record synchronously from two different angles of the tube and tube outlet. The mechanism of particle size on the combustion characteristics of coal dust is deeply explored, and the flame propagation law of coal dust under different particle size conditions is analyzed. It provides more comprehensive theoretical support for the study of combustion characteristics of multiphase composite systems so as to effectively reduce the incidence of explosion accidents in coal mining and enhance the theoretical guiding significance for the prevention and control of coal dust explosions.

2. Materials and Methods

2.1. Experiment device

The propagation characteristics of coal dust flame were studied using a HY16428T Dust explosion characteristic test device. The design of the dust explosion experimental device follows the national standard GB/T 16428-1996 “minimum ignition energy measurement method of a dust cloud,” as shown in Figure 1. This device consists of a vertical combustion glass tube, an ignition system, a high-pressure dust dispersion system, an intake system, a high-speed camera, a synchronous control system, and a data acquisition system. The vertical combustion tube has a diameter of 80 mm, a wall thickness of 5 mm, a height of 310 mm, a container volume of 1.2 L, and an opening at the top. The ignition system is located 100 mm above the bottom of the combustion tube, and the ignition is realized by electrode discharge. The ignition energy is 7.5 J. The coal dust obtained by standard sieve screening is evenly placed at the bottom of the tube, and a high-pressure powder injection with a pressure of 250 kPa is set to disperse the coal dust so that the coal dust forms a uniform coal dust cloud with an initial concentration of 500 g/m³ in the combustion tube. The high-speed camera is synchronized with the data acquisition. After the acquisition is successful, the data is further transmitted to the computer for storage. The experimental arrangement is shown in Figure 1.

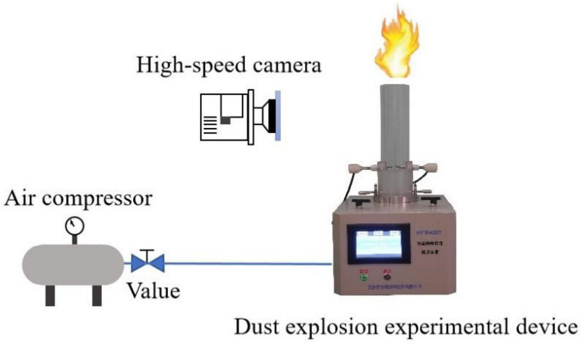

Figure 1. Experimental device layout of dust explosion characteristics. Source: Drawn by Zemiao Yang.

In order to further study the influence of coal dust particle size on the explosion flame, the Schlieren instrument was used to observe the flame synchronization at the position of the Hartmann tube outlet. It is necessary to accurately arrange these components according to the optical path system diagram to ensure that they are in the predetermined position. The positioning of the components should strictly follow the calibration dimensions to ensure the accuracy and stability of the optical path. The specific arrangement can be referred to in schematic Figure 2, which shows in detail the relative position and arrangement requirements of each component so that the schlieren can achieve efficient and accurate optical measurement and recording functions.

The core part of the schlieren is a spherical mirror with a focal length of 400 mm. The two mirrors are mounted off-axis to form a Z-shaped layout. The knife edge will cut the beam part at the focus. After Schlieren imaging on the camera or screen, the schlieren image is clearly obtained. The schlieren adopts a spherical reflection light path layout, and its structure is shown in Figure 3. This layout provides a reliable experimental basis for the study of flame propagation characteristics of coal dust explosion.

2.2. Experimental materials

To study the influence of coal dust particle size on flame propagation characteristics, coal samples were prepared according to the relevant provisions of national standard GB/T 16428. A standard sieve screened the coal dust. Three standard sieves with nominal diameters of 100 mesh, 200 mesh, and 300 mesh were selected. After screening, three samples of coal dust particles with different particle sizes were obtained. The particle size distribution ranges were as follows: 75 μm-150 μm (100 mesh), 53 μm-75 μm (200 mesh), and less than 53 μm (300 mesh). After the screening, the coal dust samples with different particle sizes

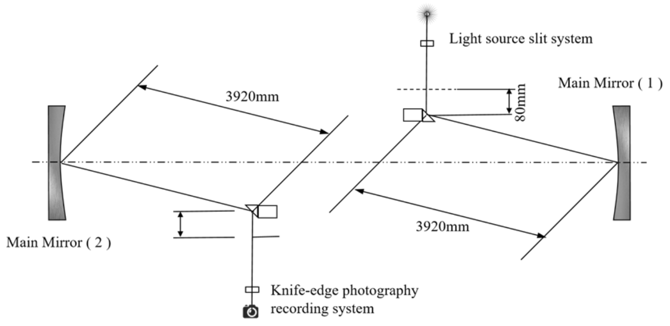

Figure 2. Optical path system diagram. Source: Drawn by Zemiao Yang.

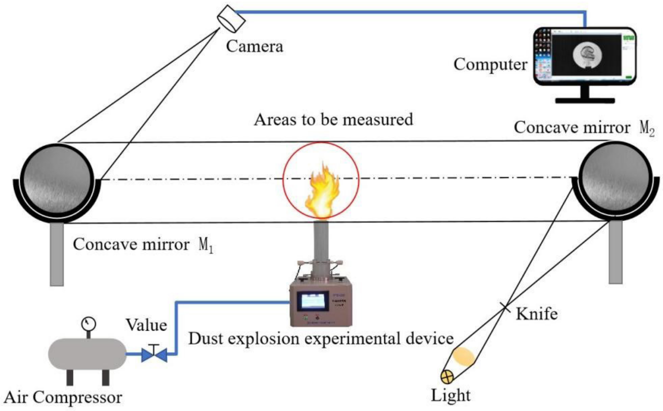

Figure 3. Diagram of experimental device (HY16428T Dust explosion characteristic test device). Source: Drawn by Zemiao Yang.

Figure 4. The experimental procedures include crushing, grind, screening, getting coal dust, drying, and preparing for the experiment. Source: Drawn by Zemiao Yang.

were evenly placed in the iron plate to ensure the uniformity of the sample distribution for subsequent drying treatment. In the drying process, the temperature of the drying oven was set to 50°C, and the drying time was strictly controlled to 6 h. After the coal sample is dried, the coal sample is taken out from the drying box and cooled to room temperature. After the coal sample is cooled to room temperature, it is divided into a sealed bag marked with name and particle size information, and the sealed coal sample is placed in a drying dish for storage. The preparation process of the test sample is shown in Figure 4.

To analyze the surface morphology of coal dust in more detail, a Hitachi Regulus 8100 scanning electron microscope (SEM) was employed to examine coal dust particles sized at 300 mesh (less than 53 μm). Figure 5 shows that coal dust exhibits irregular aggregation, suggesting inherent specific aggregation properties. Coal dust particles have irregular shapes with distinct edges and corners, intricate surface structures, and numerous micropores and fissures dispersed throughout. The particle size distribution of coal dust particles observed through SEM primarily falls below 53 μm, consistent with the particle size determined through standard sieve screening.

Table 1. Industrial analysis of coal samples.

	Proximate analysis W_{ad} /%			
Sample	**M_{ad}**	**A_{ad}**	**V_{daf}**	**FC_{ad}**
Coal samples	3.93	3.03	33.29	59.75

M_{ad}: Moisture content; A_{ad}: Ash content; V_{ad}: Volatile content; FC_{ad}: Fixed carbon content.

The coal dust selected for the test strictly adheres to the standard of GBT212-2008 “Coal Industry Analysis Method.” Moisture, ash, and volatile contents in the coal samples were measured and calculated. The results of industrial analysis of coal samples are shown in Table 1.

3. Results and Discussion

3.1. Flame propagation morphology under different coal dust particle sizes

Generally, after the coal dust encounters a heat source within the explosion concentration range, the flame instantly spreads throughout the mixed coal dust space. Due to the extremely fast chemical reaction of coal dust combustion, there is a significant heat release phenomenon, forming a high temperature and pressure, resulting in a coal dust explosion with strong destructive power. Coal dust combustion is a complex multi-scale process involving physico-chemical processes such as gas-solid two-phase flow, devolatilization of pulverized coal, coking coal combustion, turbulent gas-phase combustion, and radiative heat exchange.

As shown in Figure 6, a high-speed camera is used to record three-flame propagation processes with coal dust concentration of 500 g/m^3 and coal dust particle size of 75 μm–150 μm, 53 μm–75 μm, and less than 53 μm.

For coal dust particles with a size range of 75 μm–150 μm, the larger size results in a thin and uneven flame front after combustion, leading to slower flame propagation. The flame appears darker in color due to the larger particle size of coal dust. In addition, larger particles require more energy and time for complete ignition, resulting in an unstable and irregular flame propagation pattern. Burning large-sized coal dust results in a relatively small release of combustion products with minimal smoke around the flame. The majority of energy is released through flames and thermal radiation.

When the particle size of coal dust ranges from 53 μm to 75 μm, the explosion of medium-sized coal dust exhibits transitional characteristics as it forms a flame. The shape of the flame formed by medium-sized coal dust particles is more varied and intricate compared to that formed by larger particles. It exhibits a combination of small and large flames. The color of the flame appears more vibrant, and there is a greater release of combustion products. Although the height of the flame is relatively high, its distribution is less dense compared to that observed with smaller particle sizes.

When the particle size of coal dust falls below 53 μm, it typically results in a compact and concentrated flame shape during combustion.

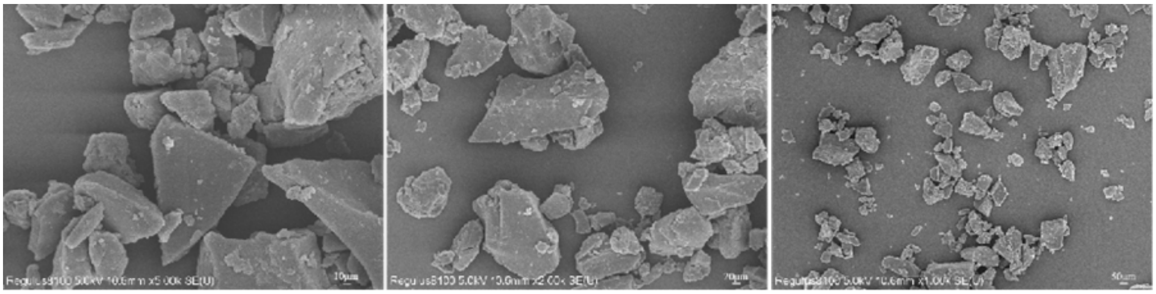

Figure 5. Scanning electron microscopy of the coal particle.

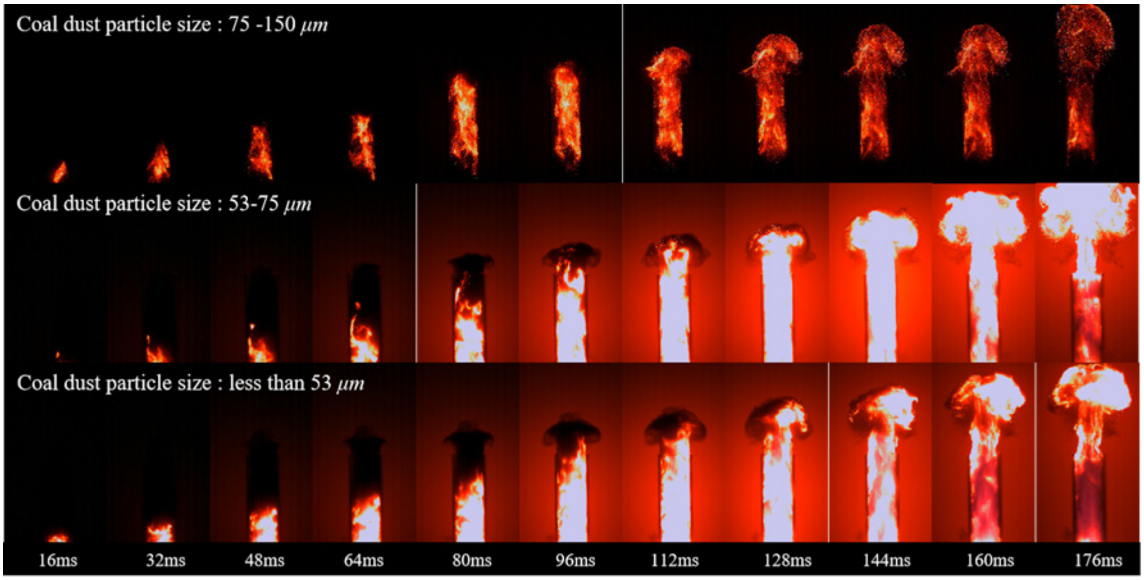

Figure 6. Flame propagation process diagram of coal dust explosion with different particle sizes, coal dust concentration of 500 g/m^3.

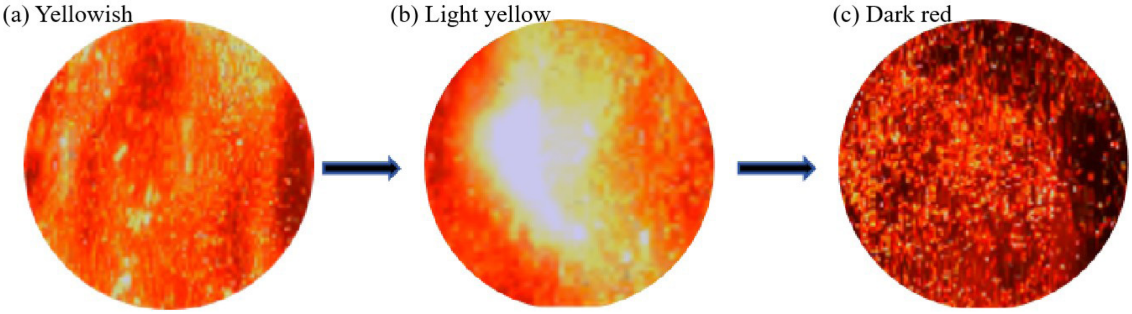
(a) Yellowish
(b) Light yellow
(c) Dark red

Figure 7. Changes in flame color (a) yellowish (b) light yellow (c) dark red.

This occurs due to an increased number of coal dust particles per unit volume along with their larger surface area facilitating rapid reactions with oxygen leading to substantial production of combustion products. The resulting flame from smaller particle sizes tends to have a lighter color, appearing as white or yellow while maintaining higher temperatures. During the combustion process, the energy release is intensive, so the flame continues to burn for a relatively long time. The flame propagation pattern is smoother and more continuous, and the flame front is clearer. A large amount of smoke is formed around the flame. The coal dust particles are small, and the combustion products released during the combustion process are more, so the smoke formed is also dense.

In summary, when small-sized coal dust particles are burned, the resulting flame is densely distributed and small in size. The flame propagation pattern appears smooth and continuous, with minimal combustion products and a bright flame color. On the other hand, when large-sized coal dust particles are burned, the resulting flame appears sparse and uneven. The shape of the flame becomes irregular and unstable while its color darkens during combustion.

During the combustion of coal dust, optical radiation is emitted in the visible light band as a form of energy release. The relationship between optical radiation color and combustion rate can be studied by analyzing the flame propagation process diagram of coal dust at different stages while keeping the concentration and particle size constant.

In the ignition stage, as depicted in Figure 7(a), the flame front propagates at a slow speed, resulting in a pale yellow-colored flame. In the flame acceleration stage, due to constraints imposed by the tube on combustion products, the flame propagates exclusively upward along the combustion tube. The expansion of these products further enhances flame acceleration. Consequently, this accelerated rate of flame propagation results in an increased heat release per unit of time. This phenomenon further boosts gas expansion within the tube and ultimately leads to maximum flame propagation characterized by a bright yellow coloration, as depicted in Figure 7(b). During the flame diffusion stage represented by Figure 7(c), there is relatively less heat released from coal dust cloud combustion compared to energy generated through flame propagation. Consequently, there is a gradual reduction and eventual extinguishing of flames' velocity during this phase, leading to a change in color from bright yellow to dark red.

In conclusion, there is a correlation between the light radiation emitted from the flame surface and the combustion rate to some extent. The high temperatures produced during coal dust combustion and byproducts within the flame result in the emission of light radiation. The burning rate of coal dust has a direct impact on both heat and energy release rates within the flame, consequently influencing its brightness and light radiation intensity. With an increase in coal dust combustion rate, there is a corresponding rise in high-temperature zones within the flame, leading to heightened flame brightness and increased light radiation intensity. Conversely, a decrease in combustion rate yields opposite effects.

3.2. Development process of coal dust cloud combustion

Spark ignition creates a high-temperature zone with ample energy. Suspended coal dust particles in the vicinity absorb heat and undergo pyrolysis, resulting in the volatilization of combustible mixed gases. Combustion reactions between coal dust and combustible mixed gases result in the formation of a spherical flame surface. The flame rapidly spreads and progresses towards the tube wall. Due to turbulence and shear forces, the front of the coal dust flame becomes irregular, while its brightness diminishes and it scatters. This intensifies flame

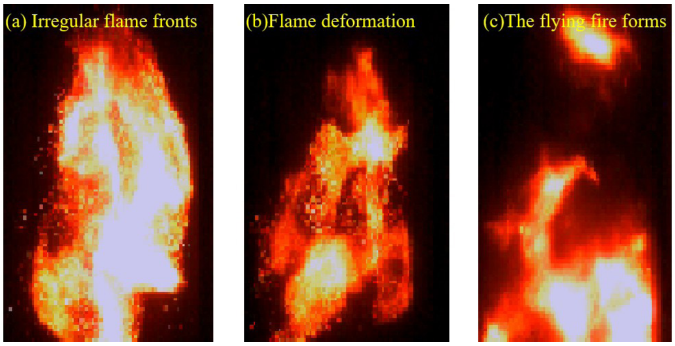

Figure 8. Irregular flame shape under turbulent shear force.
(a) Irregular flame fronts (b) Flame deformation (c) The flying fire forms.

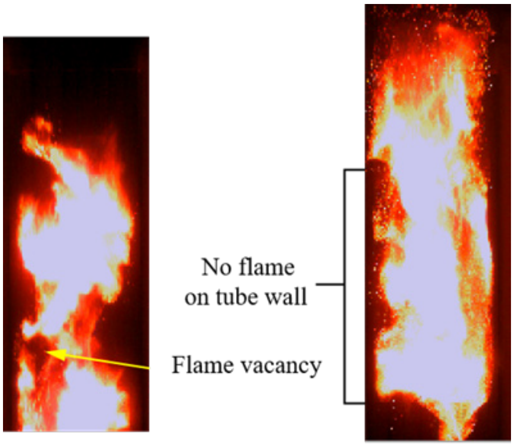

Figure 9. Combustion pattern of flame vacancy.

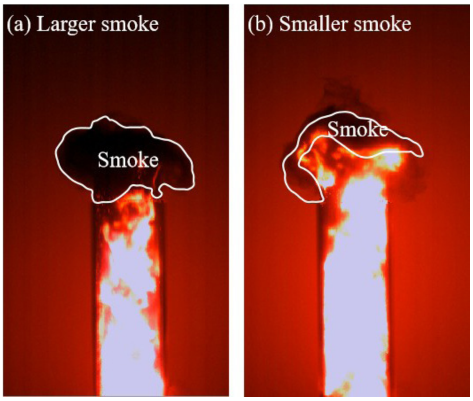

Figure 10. There are unburned particles and flame morphology of combustion products. (a) Larger smoke (b) Smaller smoke.

Figure 11. Coal dust flame propagation under high-speed camera.

distortion, causes protrusions along its edges, results in an irregular shape presentation, and gives rise to a “flying fire” appearance, as depicted in Figure 8.

As the flame continues to develop, it eventually comes into contact with the tube wall. Because of ignition at one end of a closed tube, high-temperature gas products are unable to be released promptly. As a result, coal dust fills up the confined space within the tube and starts expanding rapidly along its length. The lower part of the flame reaches the outlet of the tube, while no flames are observed on either side near its walls. The adhesion and agglomeration of coal dust near the inner wall of the tube hinder the rapid propagation of the flame, as illustrated in Figure 9. The adhesion and agglomeration of coal dust impede the spread of flames to both sides of the tube wall. In addition, this agglomeration can result in inadequate localized combustion. Flame vacancies indicate regions where stable combustion cannot be sustained, leading to incomplete burning due to insufficient oxygen and heat supply for certain fuels.

As the flame nears the tube opening, high-pressure and high-speed coal dust particles experience a rapid increase in velocity due to pressure differentials between the expanding flame flow and the vent. Within a brief timeframe, a majority of these particles fail to undergo cracking or gasification promptly, leading to their expulsion from the tube. Insufficient combustion heat leads to unheated particles, resulting in the ejection of unburned coal dust particles and combustion byproducts from the tube outlet forming smoke, as illustrated in Figure 10.

3.3. Microstructure of combustion zone

A high-speed camera was utilized to record the flame propagation process for observing the morphological characteristics of the combustion zone. Figure 11 illustrates that the front of the coal dust flame is relatively smooth and arc-shaped. Multiple coal dust particles are ignited to produce a single-ignition flame, and the peripheral coal dust is discrete after being ignited. The flame at the bottom of the tube is the brightest, indicating the ignition position of coal dust. The flame burns intensively in this area, and there is a high temperature and energy release. As the flame spreads upward, it can be found that the flame gradually becomes dispersed. In the middle and upper parts of the flame, obvious vortex structures can be observed. These vortices appear in a ring shape, revealing the turbulence effect in flame propagation.

Figure 12 depicts the enlargement and analysis of a single local image capturing the flame propagation within a coal dust cloud. Multi-colored spot flames consisting of red, yellow, and white hues are observable. The various flame colors correspond to distinct combustion regions and mechanisms. Specifically, the red flame primarily arises from gas-phase combustion, predominantly involving volatile substances. The yellow flame represents multiphase combustion with heterogeneity present. The white flame results from the combustion of solid coke material. A sufficient oxygen supply enables the burning of solid coke within coal dust, generating substantial heat and light radiation emissions. The alteration in flame color exposes the intricacy underlying its internal combustion process.

In the combustion zone, numerous discontinuous point flames of varying sizes are dispersed. While the density of light-emitting points is relatively high, they primarily exhibit small forms of illumination. Toward the perimeter of the combustion zone, there is a noticeable decrease in luminescent spot density, primarily from larger coal dust particles burning. This phenomenon suggests that within the combustion zone, smaller coal dust particles quickly heat up because of their substantial specific surface area advantage. As a result, smaller coal dust particles with smaller sizes can reach the ignition point ahead

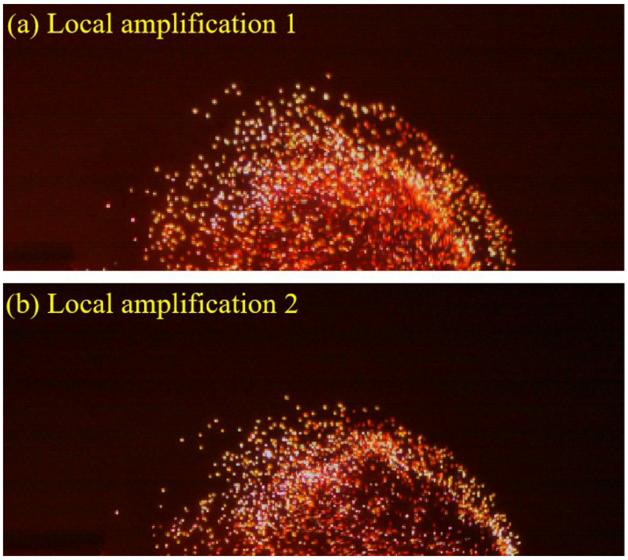

Figure 12. Coal dust flame propagation edge. (a) Local amplification 1 (b) Local amplification 2.

of larger particles, allowing for a faster completion of the combustion process. On the other hand, larger coal dust particles or agglomerates experience a delayed ignition process and a longer combustion time due to limitations in heat conduction and mass transfer. Therefore, through the local amplification analysis of the flame structure during the flame propagation of the coal dust cloud, it can be observed that the small coal dust particles in the front of the combustion zone burn first.

Figure 13 illustrates the presence of flame clusters and irregular flame fronts during the combustion process of micron-sized coal dust particles. During the flame diffusion stage, ignition and diffusion occur for small-sized coal dust particles. Once heated, these small-sized coal dust particles rapidly experience thermal desorption, releasing volatile compounds that subsequently combust with oxygen to generate localized flames. The adjacent larger-sized coal dust particles are then heated by these localized flames, leading to the formation of a diffusion flame. Small-sized coal dust particles play a crucial role in this process as they not only determine the direction of flame propagation but also regulate the entire combustion reaction through their pyrolysis process.

The clustering phenomenon exerts a substantial impact on the propagation of coal dust flames. Flame cluster formation alters the distribution of coal dust particles, influencing the advancement of the flame front and resulting in either an acceleration or deceleration of flame propagation speed. In addition, intimate contact between coal dust particles within a flame cluster intensifies heat conduction and accelerates chemical reaction rates, thereby influencing both the shape and stability of the flame. Furthermore, this clustering phenomenon results in localized high-temperature regions within the flame, thus augmenting both combustion intensity and complexity.

Complex gas flow structures exist within the flame, influenced by combustion products, resulting in the formation of vortexes and layers. The flow structure within the flame significantly impacts both the rate of combustion reactions and the diffusion of combustion products, consequently influencing the shape and stability of the flame. In addition, various oxidation and reduction reactions occur within the flame, such as those involving coal dust particles reacting with oxygen to undergo oxidation or combustion products undergoing re-oxidation. These chemical reactions take place in distinct regions within the flame, collectively facilitating coal dust combustion while generating substantial amounts of heat and energy.

3.4. Effect of coal dust cloud particle size on preheating zone structure

The experimental study aimed to investigate the characteristics of flame propagation in coal dust explosions using a combination of schlieren system and a high-speed camera for capturing and analyzing the microstructure and dynamic behavior of the flames. The schlieren technique utilizes the refraction principle of light to visualize the dynamic changes in flame shape by observing variations in density gradients within a transparent medium. As the flame resulting from a coal dust explosion traverses through a transparent medium, it causes varying degrees of light refraction across different density regions, resulting in an alternating pattern of light and dark areas in a schlieren image that provides an intuitive representation of both shape and propagation process.

The schlieren image of flame propagation in a coal dust explosion reveals three distinct zones (Figure 14): undisturbed zone, preheating zone, and combustion zone. The topmost zone represents the undisturbed area, in which the coal dust particles have not yet been ignited, and the explosion flame front has not yet reached. The physical and chemical properties of the region remain in the original state, and the temperature and density are consistent with the initial state. The region on the schlieren image shows uniform and no obvious change. The preheating zone follows the undisturbed zone, with a distinct boundary separating the two in Figure 15. This occurs because heat is radiated from the combustion zone to its surroundings, causing an increase in temperature and changes in density within the preheating zone. As a result, light passing through this region undergoes refraction, producing a distinct schlieren image.

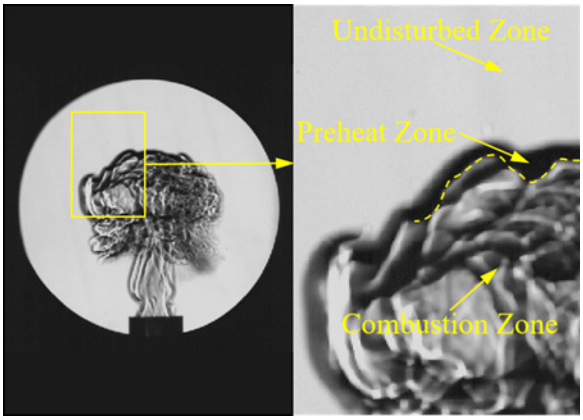

Figure 14. Flame propagation structure of micron coal dust particles. Rectangles and yellow arrows and yellow dashed lines represent local magnification.

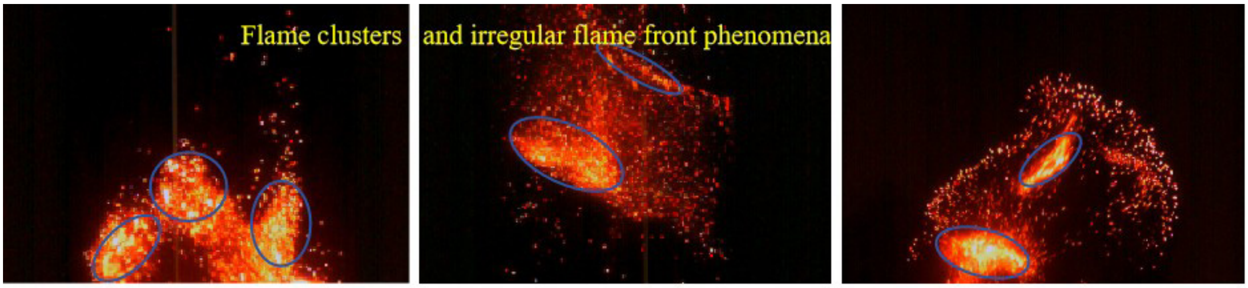

Figure 13. Particle cluster of non-uniform luminous combustion flame. Blue circle: Flame cluster and irregular flame front phenomenon.

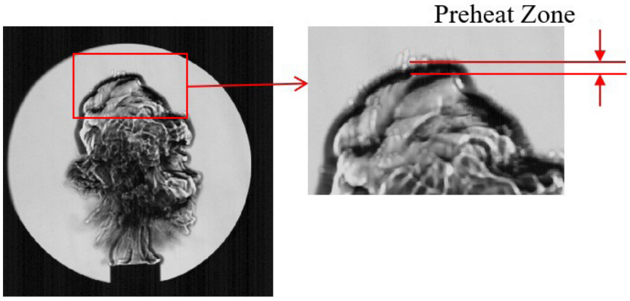

Figure 15. The schlieren image of the flame preheating zone of coal dust explosion. Red rectangles and red arrows represent the overall image on the right side of the partial zoom. Source: Drawn by Zemiao Yang.

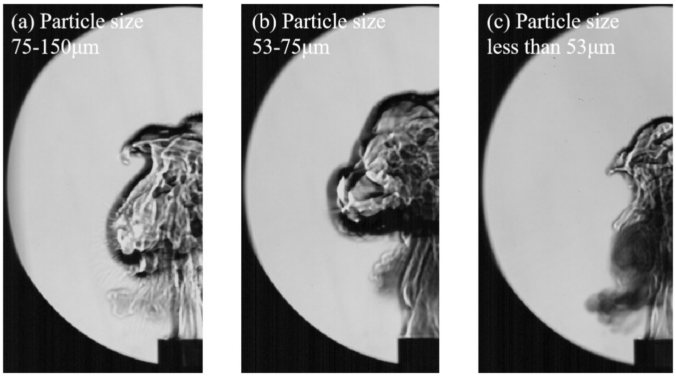

Figure 16. Schlieren picture of flame propagation under different coal dust particle sizes, concentration of 500 g/m^3. (a) Particle size 75-150 μm (b) Particle size 53-75 μm (c) Particle size less than 53 μm. Source: Drawn by Zemiao Yang.

Nevertheless, as the preheating zone has not yet reached the ignition temperature of coal dust particles, no combustion flame is present. Following the preheating zone is the combustion zone. Within this zone, the temperatures reach levels sufficient for igniting coal dust particles and initiating their burning process. The combustion zone serves as both the core and pivotal stage in flame propagation. Here, coal dust particles undergo vigorous reactions with oxygen, resulting in the emission of light energy and heat energy that manifests as a vibrant yellow flame.

Analyzing the microstructure of the preheating zone during flame propagation using schlieren photography reveals how coal dust cloud particle size affects this zone. Figure 16 presents high-speed schlieren images capturing coal dust cloud explosion flames with varying particle sizes (particle sizes less than 53 μm, 53 μm-75 μm, and 75 μm-150 μm) and a concentration of 500 g/m^3 at the same time are selected.

To further investigate how coal dust cloud particle size affects the flame preheating zone, we analyzed schlieren images captured during the flame propagation process and established a correlation between the thickness of the preheating zone and the particle size of the coal dust cloud. Figure 17 demonstrates that as coal dust particle size increases, there is a corresponding increase in preheating zone thickness.

When the coal dust particle size is less than 53 μm, smaller particles have a larger specific surface area and come into greater contact with air during combustion. This enables them to reach the ignition temperature and accelerate flame formation quickly. The rapid release of heat promotes continuous reactions between small coal dust particles and enhances flame diffusion capacity. Thus, when the preheating zone contains these easily ignitable small coal dust particles, it rapidly enters the combustion state and releases significant heat to fuel flame propagation. In addition, since these small particles can rapidly complete combustion reactions, temperatures and pressures in the preheating zone increase swiftly. This process not only accelerates combustion reaction rates but also contributes to explosive characteristics formation during combustion as a result of rapid temperature increases. As temperature and pressure increase, flame combustion releases more energy, leading to a more explosive combustion process, particularly in enclosed or partially enclosed spaces.

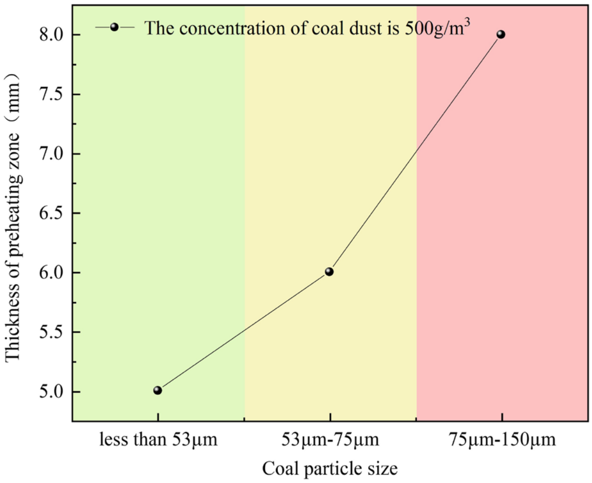

Figure 17. Relationship between particle size of coal dust cloud and preheating zone. Green represents the particle size less than 53 μm, yellow represents the particle size of 53-75 μm, and pink represents the particle size of 75-150 μm. Source: Drawn by Zemiao Yang.

For coal dust particle sizes of 75 μm-150 μm, larger particles have a greater volume and exhibit slower heating rates. Large particles take a significant amount of time in the preheating zone to reach the combustion temperature. Combustion reactions of larger particles are comparatively delayed, leading to reduced heat release and combustion product formation. Consequently, this results in a slower temperature increase within the preheating zone and slower flame formation and propagation speeds. The dimness of flames, along with their slow propagation speed and smaller area, can be attributed to coarse particles' sluggish combustion rate. Slower combustion reactions from larger particles result in comparatively gradual increases in temperature and pressure within the preheating zone. This reduction lowers both explosion risks as well as energy released during an explosion event.

3.5. Coal dust explosion reaction mechanism

An important mechanism of coal dust explosion is thermal explosion. When coal dust particles accumulate in a certain space, and there is enough ignition source, the temperature of coal dust particles increases after absorbing heat. As the temperature increases, the volatiles in the coal dust particles begin to precipitate. The volatiles in coal dust play a key role in the explosion process. Volatile substances mainly include methane (CH_4), carbon monoxide (CO), hydrogen (H_2), and other combustible gases; after the coal dust particles are heated, firstly, the volatiles are precipitated, volatiles typically burn faster than the coal dust particles themselves, and it forms a combustible atmosphere around the coal dust particles. When the volatiles are ignited, they will burn rapidly and release heat, which in turn will promote the further combustion of coal dust particles. At the same time, it will also increase the temperature of more coal dust particles in the vicinity, thus triggering the explosion of the entire coal dust cloud.

3.5.1. Redox reaction process

The redox reaction between the surface of coal dust particles and oxygen is the core link of coal dust explosion. Coal dust is mainly composed of elements such as carbon (C) and hydrogen (H). A series of reactions will occur in the presence of oxygen (O_2). For example, carbon reacts with oxygen to form carbon dioxide ($C+O_2=CO_2$), and hydrogen reacts with oxygen to form water ($2H_2+O_2=H_2O$). At the beginning of the reaction, the active site on the surface of the coal dust particles comes into contact with the oxygen molecules and reacts. These active sites may be the defects on the surface of coal dust particles, locations where chemical bonds are not saturated. As the reaction progresses, oxygen

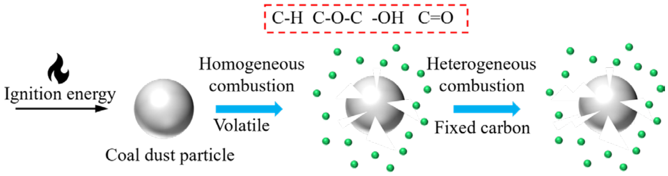

Figure 18. Coal dust explosion mechanism.

is consumed and reaction products such as carbon dioxide and water are generated. If the reaction takes place in a closed or semi-enclosed space, the accumulation of products will affect the continuation of the reaction, but in the process of coal dust explosion, due to factors such as violent turbulence, the products will be continuously diffused, so that the reaction can continue.

3.5.2. Chain reaction mechanism

There is a chain reaction in the process of coal dust explosion. When external energy, such as electric sparks and high-temperature heat sources, causes the breaking of chemical bonds in coal dust particles, some reactive free radicals are generated. When a carbon-hydrogen (C-H) bond is broken, hydrogen radicals (H·) may be produced. These free radicals have high chemical activity, and they react with surrounding oxygen, other coal dust particles, or their volatiles. Hydrogen radical reacts with oxygen to form hydroxyl radicals ($H\cdot + O_2 \rightarrow OH\cdot + O\cdot$), which in turn react with other combustible substances (such as carbon monoxide) ($OH\cdot + CO \rightarrow CO_2 + H\cdot$), thus forming a chain reaction. In this process, free radicals are constantly produced and consumed, and energy is released with each reaction. As the reaction progresses, the number of free radicals can grow exponentially, resulting in a rapidly intensified explosive reaction.

At present, the reaction mechanism of coal dust explosion needs to be further studied [29]. Under the action of an ignition source or high-temperature environment, coal dust reacts with oxygen, which involves a complex physicochemical multiphase coupling reaction process. As shown in Figure 18, when the coal dust particles are refined, the porous structure on the surface increases the contact area with oxygen [42], and the oxidation reaction occurs rapidly when it encounters a heat source. With the gradual increase in temperature, the volatile gases in the coal dust first escape, and the gas homogeneous combustion occurs [43]. The small molecular hydrocarbon gases in the volatile matter escape and cover the surface of the coal dust particles to form a gas film, which accelerates the gas-solid-liquid coupling oxidation reaction process. The number of free radicals increases, releasing a large amount of heat causing heat conduction between coal particles. During the pyrolysis process of coal dust, after the volatile in the coal dust particles escape, the coal surface evolves into coarse and loose coal coke [44], which is melted by heat and heterogeneous combustion reactions such as gas-solid and solid-solid occur [45,46], weak bonds are broken, and new bonds are formed. This paper lays a foundation for further revealing the mechanism of coal dust explosion.

4. Conclusions

In this study, a series of experiments were conducted using a Hartmann tube to investigate the flame propagation characteristics during coal dust explosions. The analysis was carried out through high-speed cameras and schlieren imaging techniques, focusing on both the tube and outlet locations. The following detailed conclusions were drawn:

(1) Small-particle coal dust combustion produces a compact, small-sized flame with smooth and continuous propagation, fewer combustion byproducts, and a bright color. The reaction rate correlates with the flame's surface light radiation. As the coal dust reaction intensifies, the light radiation from the flame surface becomes more brilliant.
(2) The turbulent flow results in coal dust explosion flame void and smoke, and the flame wall interaction results in coal dust adhesion, caking, and flame void near the wall.
(3) Clusters of flames and irregular fronts can be observed when burning micron-sized coal dust particles. Small particles dominate combustion, with different flame colors indicating distinct combustion regions.
(4) Schlieren images reveal the undisturbed, preheating, and combustion zones. A reduction in coal dust particle size results in a decrease in the thickness of the preheating zone. When the particle size of coal dust is less than 53 μm, the thickness of the preheating zone is 5 mm.

CRediT authorship contribution statement

Zemiao Yang: Investigation, Writing–Original draft preparation, Data Curation, and Validation. **Ke Gao:** Resources, Writing–Review and Editing, Supervision, Project administration, and Funding acquisition. **Yujiao Liu:** Resources and Supervision.

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.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors confirm that there was no use of AI-assisted technology for assisting in the writing of the manuscript and no images were manipulated using AI.

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