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Research Article

Explosion Flame and Pressure Characteristics of Nonstick Coal Dust and the Inhibition of Explosion Suppressants

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Nonstick coal is widely distributed in the world and is an important resource for human beings. The explosion characteristics and explosion suppression of nonstick coal dust are increasingly concerning. In this paper, the flame and pressure characteristics of a nonstick coal dust explosion are studied, and the suppression effect of SiO_2, KCl, and $NH_4H_2PO_4$ on the explosion is analyzed. It is concluded that the maximum propagation distance of a nonstick coal dust explosion flame is 0.59 m, the maximum pressure is 0.63 MPa, and the maximum pressure rise rate is 40.79 MPa/s. The explosion suppression effect of SiO_2 is worse than that of KCl, but the inhibition effect of $NH_4H_2PO_4$ is the best among the three kinds of explosion suppressants. When the mass percentage of $NH_4H_2PO_4$ dust mixed with coal dust is 70%, the coal dust explosion is completely suppressed. It absorbs a certain amount of heat to promote the chemical reaction, which plays a certain role in controlling the explosion process, and its explosion suppression mechanism includes both physical and chemical explosion suppression.

1. Introduction

In most countries in the world, coal is still one of the main energy sources. Different coal formation conditions will lead to different metamorphic degrees. Among different types of coal, lignite has the lowest degree of metamorphism, anthracite has the highest degree of metamorphism, and bituminous coal has the middle degree of metamorphism. The coal dust particles produced by coal mining not only have an important impact on the health of miners [1, 2] but also have a great hidden danger to the safety of the working environment because the coal dust particles have the possibility of exploding after forming a suspended state [3–6], which is extremely harmful. Generally speaking, the explosion risks of different types of coal dust are different. In addition, due to the complexity of operating conditions, the explosion intensity of coal dust particles with different metamorphic degrees also varies greatly [7–9].

At present, the explosion flame and pressure are usually used to characterize the explosion intensity. Among them, the explosion pressure is very destructive, which can destroy the working environment and cause great harm to operators. The temperature of the explosion flame is extremely high, which has a destructive effect on the working environment [10–12]. Relevant research shows that coal dust explosions and gas explosions have certain similarities and differences. The same thing is that the essence of a coal dust explosion and a gas explosion is a chemical reaction of rapid combustion, and both will generate a lot of heat [13–16]. The difference is that the chemical reaction rate of a coal dust explosion is faster, the released energy is greater, and the destruction is stronger; in a gas explosion, there is no solid phase involved in the reaction [17–24]. Therefore, research on the propagation process of coal dust explosions has always been a hot and difficult point in explosive mechanics. The research on the mechanism of coal dust explosions will be limited by the experimental conditions. Therefore, with the development of computational fluid dynamics, the use of computers to carry out the numerical simulation of the coal dust explosion process has gradually attracted the attention of scholars. With the improvement of the mathematical model of coal dust explosion characteristics, the accuracy of simulation results is gradually improving, and this method is gradually being recognized by scholars [25–28].

While studying the propagation characteristics of coal dust explosions, scholars have also carried out research on the prevention and control of coal dust explosions. At present, in the field of industrial safety, explosion venting, explosion isolation, explosion resistance, and explosion suppression have gradually become the research focus [29, 30]. The most commonly used explosion prevention and control method in coal dust is explosion suppression. The specific method is to spread the explosion suppressant on the coal mine roadway for a fixed period of time. The practice shows that this method is not only economical but can also achieve an obvious explosion suppression effect without wasting a lot of manpower and material resources [31]. The current problem is that different types of explosion suppressants have different suppression effects, and the metamorphic degree of coal in different regions has also changed greatly. Therefore, the explosion suppression of coal dust with different metamorphic degrees needs to be carried out one by one, and some regular and referential research results can be obtained from them. According to previous research results, there is still a certain gap in this area.

Therefore, based on the above analysis, this paper will take nonstick coal as the research object, use SiO_2, KCl, and $NH_4H_2PO_4$ as the explosion suppressants, and use the explosion flame and pressure to characterize the explosion intensity to study the inhibition of three kinds of explosion suppressants on the explosion intensity of nonstick coal dust. In the previous research, the author obtained the ignition characteristics of the coal dust cloud and the propagation process of the explosion flame, as well as obtained the flame characteristics of the coal dust explosion space and the concentration distribution of gas products generated by the numerical method [32–36]. In this paper, the author will further discuss the suppression effect of SiO_2, KCl, and $NH_4H_2PO_4$ on the flame and pressure of a nonstick coal dust explosion. The research results will have important reference values for the suppression of dust explosions.

2. Experimental Device and Coal Dust Sample

2.1. Experimental Device. In the experimental device part, two experimental devices are mainly used in this research, which are used to test the flame and pressure of a coal dust explosion, respectively. The experimental device for testing the explosion flame is a horizontal glass tube coal dust explosion device, and the experimental device for testing the explosion pressure is a spherical space coal dust explosion device.

2.1.1. Experimental Device of Coal Dust Explosion Flame. The physical and structural drawings of the experimental device for the coal dust explosion flame test are shown in the literature [35]. The device mainly includes a glass tube system, a dust spraying system, an ignition system, a high-speed camera system, a data acquisition system, and a tube purging system. The glass tube is open at both ends. The tube is 1.4 m long, and the inner diameter of the section is 0.08 m. High-speed cameras can be used to collect flame length data at different times. After a certain amount of coal dust is contained in the coal sample tube, the microair compressor will form high-pressure air, which will bring the coal dust in the coal sample tube into the glass tube to form a suspended cloud cluster, which will explode near the high-temperature platinum wire, which is 0.2 m away from the coal sample tube. The maximum length of the explosion flame can be expressed in l_{max}.

2.1.2. Experimental Device of Coal Dust Explosion Pressure. The characteristic of coal dust explosion pressure is an important parameter to characterize the explosion intensity of coal dust. The explosion pressure characteristics of coal dust mainly include two parameters: the maximum explosion pressure P_{max} and the maximum pressure rise rate $(dP/dt)_{max}$, which are highly variable and have research value due to the influence of experimental conditions, explosion conditions, and other factors. With reference to the relevant standard document "GB/T 16426-1996 Method for Determining the Maximum Explosion Pressure and Explosion Index of Dust Clouds," the internationally used coal dust explosion pressure characteristic testing device is adopted in this paper, as shown in Figure 1. The device is mainly composed of a dust spraying system, an ignition system, a data transmission system, and a water circulation cooling system. After the experiment, relevant explosion pressure parameters can be obtained. The volume of the device is 20 L, and it has a double stainless-steel structure. Figure 1 is reproduced from Tian-Qi Liu*, Xuan Zhao, Wei-Ye Tian, Rui-Heng Jia, Ning Wang, and Zhi-Xin Cai, et.al., 2022.

Before ignition, put the dust sample in the dust storage tank; the amount of the coal sample can be weighed well before the experiment. Different coal sample quality corresponds to different concentrations of a coal dust cloud in the explosion space. Therefore, the amount of coal sample has a great impact on the explosion pressure. After the coal sample enters the explosion space, the ignition system will release 10 kJ of energy, which is enough to ignite the coal dust cloud sample. You can observe whether there is flame through the glass window to judge whether the explosion occurs and estimate the explosion intensity. After the explosion, the data transmission system will transmit the explosion pressure data to the computer. By reading the explosion pressure curve, we can easily get the maximum pressure and the maximum pressure rise rate of the coal dust explosion. The water circulation system of the device can be used after each experiment to quickly reduce the temperature of the explosion space and save time for the next explosion experiment.

2.2. Experimental Coal Dust Samples

2.2.1. Nonstick Coal Dust Sample. In this paper, nonstick coal is selected as the research object. The nonstick coal sample is from Shaanxi Shenmu Energy Group of China, which is generally used as power coal or civil fuel.

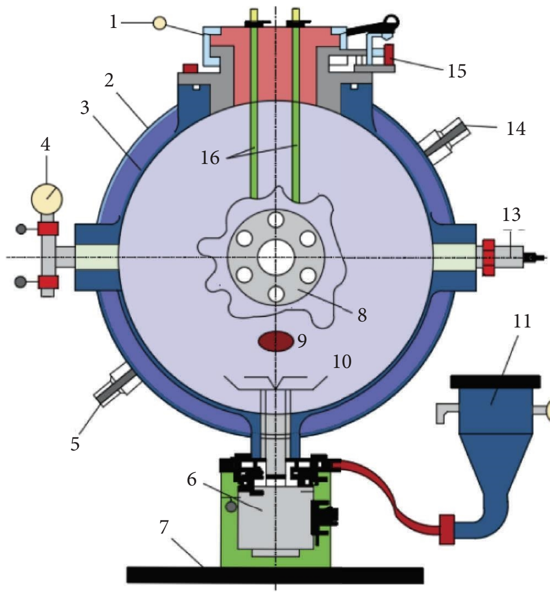

Figure 1: Structure diagram of explosion-pressure testing equipment. (1) sealing cap; (2) outer side of mezzanine; (3) inside of mezzanine; (4) vacuum gauge; (5) outlet of water; (6) mechanical two-way valve; (7) base; (8) observation window; (9) vacuum hole; (10) dispersion valve; (11) storage tank; (12) pressure gauge; (13) pressure sensor; (14) inlet of water; (15) limit switch; (16) ignition rod.

Nonstick coal is a kind of bituminous coal that has been oxidized to a certain extent from low metamorphism to medium metamorphism at the initial stage of coal formation. The coal sample in the tray is shown in Figure 2. The main components of the coal sample are shown in Table 1. It can be seen that the volatile content of the coal sample is 35.41%, which indicates that the coal sample has a significant explosion risk. The fixed carbon content of a coal sample is 51.29%, which is the main solid component involved in the combustion and explosion processes of coal dust and also an important source of energy release. According to the results of the ultimate analysis, it can be found that the carbon content of the coal sample is the largest, followed by oxygen.

In order to master the particle size distribution of coal dust particles, a shape analyzer was used to analyze the particle size of coal dust particles. The results are shown in Figure 3, where the abscissa represents the particle size and the ordinate represents the frequency distribution rate and cumulative distribution rate of particles, respectively. After the preparation of the coal dust sample, the size of the coal dust particles is relatively uniform, and the particle size reaches the micrometer level. Generally, the dust from coal dust explosions in coal mines is mainly composed of particles of micron size. The distribution map of the particle size presents a normal distribution, and the median of the particle size is about 65 μm. The abovementioned results show that the preparation of the coal dust sample completely meets the requirements of the coal dust explosion experiment.

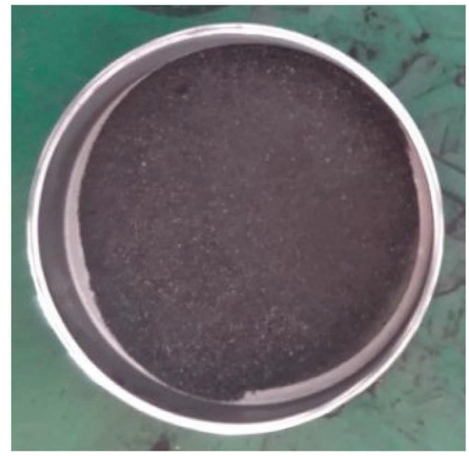

Figure 2: Nonstick coal dust sample.

Table 1: Main components of a nonstick coal dust sample.

Proximate analysis (%)				Ultimate analysis (%)			
M	*A*	*V*	*FC*	*C*	*H*	*O*	*N*
5.98	7.32	35.41	51.29	75.82	3.36	15.69	5.13

M, moisture; *A*, ash; *V*, volatile; *FC*, fixed carbon.

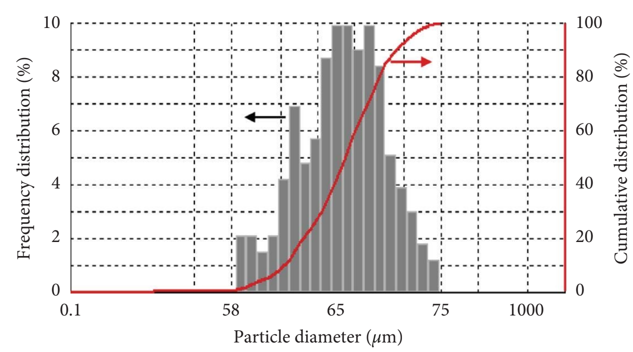

Figure 3: Particle size distribution of a coal dust sample.

2.2.2. Explosion Suppressant Dust. In this study, three kinds of explosion suppressant dust are selected, namely SiO_2, KCl, and $NH_4H_2PO_4$, as shown in Figure 4. Their explosion suppression effect on nonstick coal explosions will be verified by relevant experiments. The reason for choosing these three kinds of explosion suppressant dust is that they are all explosion suppressants that can inhibit coal dust explosions to a certain extent, but their explosion suppression effects and suppression mechanisms are different. Therefore, the suppression effect of explosion suppressants on coal dust explosion flame and pressure can be studied by mixing explosion suppressants with coal dust.

Silicon dioxide is an inorganic compound with the chemical formula SiO_2. Silicon atoms and oxygen atoms form crystalline silicon dioxide by long-term orderly arrangement, and amorphous silicon dioxide by short-term orderly or long-term disordered arrangement. Its melting point is 1996 K, which is so high that it will not participate in the explosion reaction and will not have any chemical


(a) (b) (c)

Figure 4: Inert dust samples: (a) SiO_2, (b) KCl, and (c) $NH_4H_2PO_4$.

change during the coal dust explosion. Potassium chloride is an inorganic compound with the chemical formula KCl. It has the appearance of salt and is odorless and salty. It is a white crystalline small-particle powder. Ammonium dihydrogen phosphate, also known as monoammonium phosphate, is an inorganic compound with the chemical formula $NH_4H_2PO_4$. It is a white crystalline powder, which is also the main component of a fire-extinguishing agent.

3. Results and Discussion

3.1. Explosion Flame Characteristics of Nonstick Coal Dust. First, the coal dust explosion flame test device was used to obtain the flame propagation distance at different times after the explosion, and the results are shown in Table 2 and Figure 5. In order to ensure the accuracy of the experimental results and reduce the error of the test data, each data in Table 2 is the average value calculated after ten experiments. It can be seen that after the explosion of nonstick coal dust, the flame propagation distance increases continuously within 0.375 s, and the maximum value reaches 0.59 m. After 0.375 s, the flame propagation distance starts to decrease gradually. At 0.875 s, the flame propagation distance is only 0.14 m. At this time, the flame is very close to extinction. Finally, at 1 s, the flame completely disappeared, and the explosion reaction was completely ended. Therefore, in this experiment on the explosion flame characteristics of nonstick coal dust, the maximum distance of flame propagation obtained is 0.59 m, that is, $l_{max} = 0.59$ m. This result will be an important basis for later research on the effects of explosion suppressants.

Table 2: Flame propagation distance at different times after the explosion.

t (s)	0	0.125	0.250	0.375	0.500	0.625	0.750	0.875	1
l (m)	0	0.39	0.51	0.59	0.53	0.41	0.29	0.14	0

t, time after explosion; l, flame propagation distance.

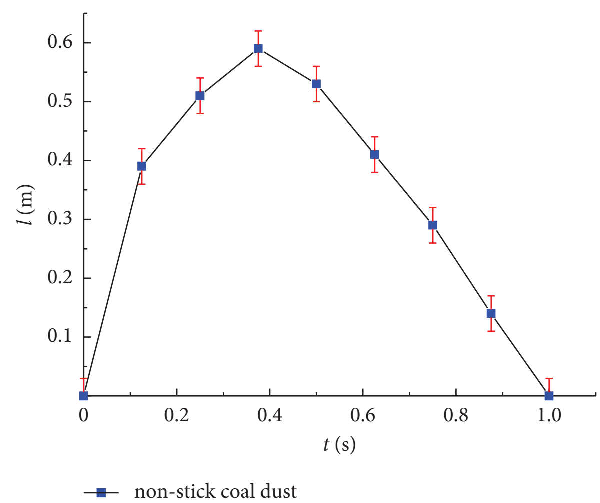

Figure 5: Flame propagation distance at different times.

3.2. Explosion Pressure Characteristics of Nonstick Coal Dust. There are two indicators reflecting the characteristics of explosion pressure, namely the maximum pressure and the maximum rate of pressure rise, which are represented by P_{max} and $(dP/dt)_{max}$, respectively. The difference between the two is that P_{max} represents the maximum pressure that can be reached during the explosion, which can directly determine the destructiveness of the explosion. $(dP/dt)_{max}$ represents the maximum rate of pressure rise at the moment of explosion, which reflects the rate of explosion. The explosion pressure characteristics of nonstick coal dust are obtained by using the coal dust explosion pressure experimental device, and the results are shown in Table 3.

The explosion data in Table 3 are the average values calculated on the basis of ten repeated experiments, which can reduce the experimental error and improve the accuracy of the results. When the coal dust is uniformly dispersed in the sphere space, the mass concentration of the coal dust cloud can reach 300 g/m^3. The particle size of the coal dust used in the experiment is 58–75 μm. The maximum explosion pressure of nonstick coal dust obtained in the experiment is 0.63 MPa, and the maximum pressure rise rate is 40.79 MPa/s. At the moment of explosion, obvious explosion flame and brightness are also seen in the observation window, indicating that under this condition, the explosion pressure has been destructive to a certain extent. These data provide an important basis for later research on the suppression effect of explosion suppressants.

Table 3: Test results of nonstick coal dust explosion pressure characteristics.

Mass concentration of coal dust cloud (g/m^3)	Particle size (μm)	Test results	
		P_{max} (MPa)	$(dP/dt)_{max}$ (MPa/s)
300	58~75	0.63	40.79

P_{max}, maximum pressure; $(dP/dt)_{max}$, maximum rate of pressure rise.

3.3. Inhibition of Explosion Suppressant on Explosion Flame of Nonstick Coal Dust. In order to study the suppression effect of explosion suppressants on the explosion flame of nonstick coal dust, three kinds of explosion suppressants, SiO_2, KCl, and $NH_4H_2PO_4$ were selected to test the explosion suppression effect by mixing the explosion suppressants with coal dust. In order to describe the amount of explosion suppression dust added, the mass percentage of explosion suppression dust mixed with coal dust is expressed as p. The particle size of explosion suppressant dust is 58–75 μm. The obtained experimental data of coal dust explosion flame suppression effect are shown in Table 4 and Figure 6. Through comparison, it can be concluded that the explosion suppression effect of SiO_2 is worse than that of KCl, but the inhibition effect of $NH_4H_2PO_4$ is the best among the three kinds of explosion suppressants because when the mass percentage of $NH_4H_2PO_4$ dust mixed with coal dust is 70%, the maximum flame propagation distance of a coal dust explosion is 0 m, which indicates that the explosion is completely suppressed by $NH_4H_2PO_4$, so that the explosion will not occur again. This result is very important for the suppression of industrial coal dust explosions.

From the perspective of the explosion suppression mechanism, it can be concluded that dust SiO_2 mainly plays the role of inerting in the process of participating in a coal dust explosion. Because dust SiO_2 itself does not participate in the chemical reaction of coal dust explosions, its role is mainly to control the propagation process of the explosion by blocking the heat transfer between coal dust particles so that the explosion cannot fully release energy, so the length of the generated flame becomes smaller. The explosion suppression mechanism of dust KCl is almost the same as that of dust SiO_2. The difference is that dust KCl is better at blocking the heat transfer between coal dust particles and the maximum propagation distance of the resulting explosion flame is smaller.

For the explosion suppressant $NH_4H_2PO_4$, its explosion suppression mechanism includes both physical and chemical explosion suppression. Because $NH_4H_2PO_4$ will have a chemical reaction after being heated, it first absorbs a certain amount of heat to promote the chemical reaction, which plays a certain role in controlling the coal dust explosion process. In addition, the products generated by the reaction include H_2O and P_2O_5. H_2O itself is the main component of common fire extinguishing agents, while P_2O_5 will combine with coal dust particles, further hindering the energy release and heat transfer of coal dust particles. It is precisely because of this explosion suppression mechanism of dust $NH_4H_2PO_4$ that its inhibition effect is the best among the three kinds of explosion suppressants.

Table 4: Inhibition of an explosion suppressant on the explosion flame of nonstick coal dust.

p (%)	l_{max} (m)		
	SiO_2	KCl	$NH_4H_2PO_4$
0	0.59	0.59	0.59
10	0.55	0.53	0.50
20	0.51	0.48	0.42
30	0.47	0.45	0.40
40	0.44	0.42	0.31
50	0.42	0.39	0.24
60	0.38	0.32	0.17
70	0.34	0.28	0

p, mass percentage of explosion suppression dust mixed with nonstick coal dust; l_{max}, maximum flame propagation distance.

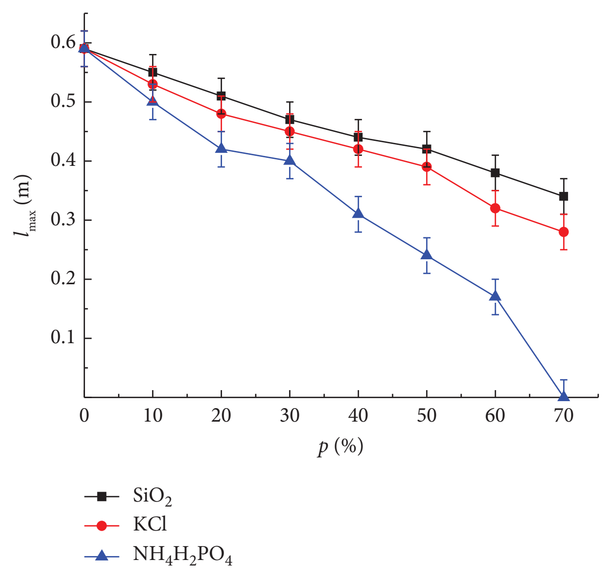

Figure 6: Inhibition of an explosion suppressant on the maximum flame propagation distance.

3.4. Inhibition of Explosion Suppressant on Explosion Pressure of Nonstick Coal Dust. The test results for coal dust explosion pressure mainly include the maximum pressure and the maximum rate of pressure rise. Therefore, in this part, the change of the maximum pressure and the maximum rate of pressure rise of a nonstick coal dust explosion under the condition of mixing explosion suppressants will be discussed. The inhibition effect of three kinds of explosion suppressants on coal dust explosion pressure is shown in Table 5. It can be seen that the inhibition effect of the explosion suppressants SiO_2 and KCl is relatively close. With the increasing mass percentage of explosion suppressant mixed in the coal dust sample, the maximum pressure and maximum pressure rise rate of an explosion are decreasing. When the mass percentage of explosion suppressant SiO_2 mixed is 80%, the maximum pressure and maximum pressure rise rate of the explosion are 0.27 MPa and 22.12 MPa/s, respectively. When the mass percentage of explosive suppressant KCl mixed is 80%, the maximum explosion pressure and the maximum pressure rise rates are 0.24 MPa and 20.46 MPa/s, respectively. At this time, no matter whether SiO_2 or KCl is used, the explosion is not completely suppressed. The inhibition effect of the explosion suppressant $NH_4H_2PO_4$ is better. When the mass percentage of explosion suppressant $NH_4H_2PO_4$ mixed is 70%, the explosion will not occur again, indicating that the coal dust explosion is completely suppressed at this time.

Table 5: Inhibition of an explosion suppressant on the explosion pressure of nonstick coal dust.

p (%)	SiO_2		KCl		$NH_4H_2PO_4$	
	P_{max} (MPa)	$(dP/dt)_{max}$ (MPa/s)	P_{max} (MPa)	$(dP/dt)_{max}$ (MPa/s)	P_{max} (MPa)	$(dP/dt)_{max}$ (MPa/s)
0	0.63	40.79	0.63	40.79	0.63	40.79
10	0.57	35.67	0.56	34.82	0.52	30.43
20	0.49	32.18	0.47	31.41	0.42	26.41
30	0.43	30.20	0.41	29.95	0.36	22.68
40	0.38	28.75	0.36	27.63	0.30	18.23
50	0.34	26.49	0.32	25.33	0.25	15.14
60	0.31	24.17	0.30	23.67	0.21	13.95
70	0.29	23.06	0.26	21.93	—	—
80	0.27	22.12	0.24	20.46	—	—

p, mass percentage of explosion suppression dust mixed with nonstick coal dust.

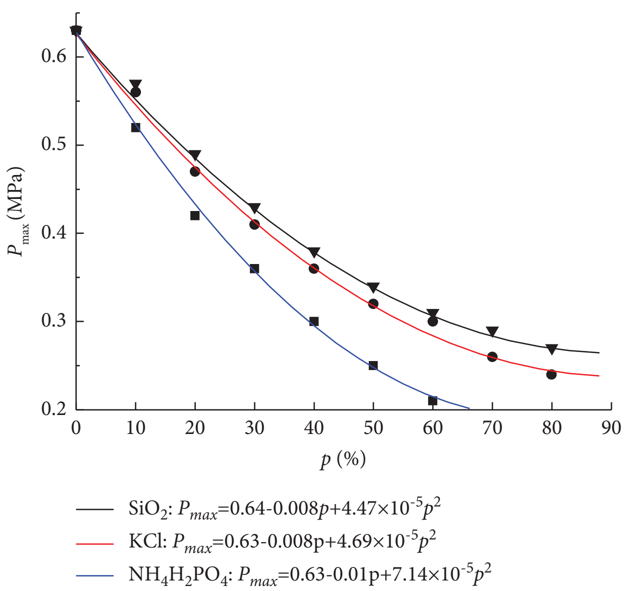

Figure 7: Inhibition effect of an explosion suppressant on maximum explosion pressure.

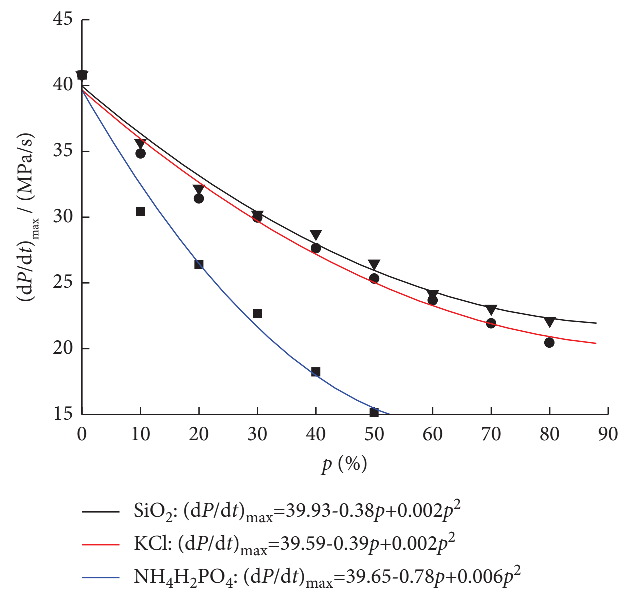

Figure 8: Inhibition effect of an explosion suppressant on maximum pressure rise rate of explosion.

In order to discuss the inhibition effect of explosion suppressants on the maximum pressure and maximum pressure rise rate of a coal dust explosion from the perspective of quantitative analysis, Figures 7 and 8 are drawn, respectively. The relationship between the mass percentage of explosion suppressant mixed with coal dust and the maximum pressure and the maximum rate of pressure rise was obtained by using the method of quadratic fitting. The unitary quadratic relationship in the figure only represents the functional relationship between the mass percentage of the explosion suppressant and the explosion pressure and does not consider the dimension in the calculation process. The determination coefficients of the function relations obtained by the quadratic fitting are all greater than 0.9, indicating that the fitting effect is good, which establishes the quantitative functional relationship between the mass percentage of the explosion suppressant and the explosion pressure of coal dust.

It is clear from Figures 7 and 8 that the fitting curves of the explosion suppressants SiO_2 and KCl are very close, but the explosion suppression effect of KCl is slightly better than that of SiO_2. The explosion suppression effect of $NH_4H_2PO_4$ is the best, and its curve is obviously below the SiO_2 and KCl curves. From the perspective of the explosion suppression mechanism, it can be seen that the melting point of ammonium dihydrogen phosphate is 476 K, which is easily reached during coal dust explosions, so it will lead to rapid thermal decomposition of ammonium dihydrogen phosphate and participate in the explosion process. As the products after decomposition can slow down the heat transfer between coal dust particles and also slow down the thermal radiation rate of the explosion source, the maximum pressure generated by the explosion and the maximum rate of pressure rise will be reduced accordingly. The above research data and analysis results are of great significance for mastering the suppression effect of noncaking coal dust explosions.

4. Conclusions

In this paper, the inhibition effect of SiO_2, KCl, and $NH_4H_2PO_4$ on nonstick coal dust explosion pressure and a flame is discussed. The conclusions of this study are as follows.

The research results show that the maximum propagation distance of a nonstick coal dust explosion flame is 0.59 m, the maximum pressure is 0.63 MPa, and the maximum pressure rise rate is 40.79 MPa/s. These experimental results provide an important basis for the study of the explosion suppression effect.

By studying the suppression effect of explosion suppressants on the explosion flame of nonstick coal dust, it can be found that the explosion suppression effect of SiO_2 is worse than that of KCl, but the inhibition effect of $NH_4H_2PO_4$ is the best among the three kinds of explosion suppressants. When the mass percentage of $NH_4H_2PO_4$ dust mixed with coal dust is 70%, the maximum flame propagation distance of a coal dust explosion is 0 m, which indicates that the explosion is completely suppressed by $NH_4H_2PO_4$, mainly because its explosion suppression mechanism includes both physical and chemical explosion suppression.

By analyzing the suppression effect of explosion suppressants on the explosion pressure of nonstick coal dust, it can be concluded that when the mass percentage of explosion suppressant $NH_4H_2PO_4$ mixed is 70%, the explosion will not occur again, indicating that the coal dust explosion is completely suppressed at this time. This is mainly because the melting point of $NH_4H_2PO_4$ is 476 K, which will rapidly decompose during the explosion and hinder the heat transfer of coal dust particles and the heat radiation of the explosion source. In future work, the author will further discuss more effective explosion suppressants for coal dust explosions and consider the suppression effect of mixed explosion suppressants.

Data Availability

The experimental data used to support this study are available within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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