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Research on Explosion Pressure Characteristics of Long Flame Coal Dust and the Inhibition Effect of Different Explosion Suppressants

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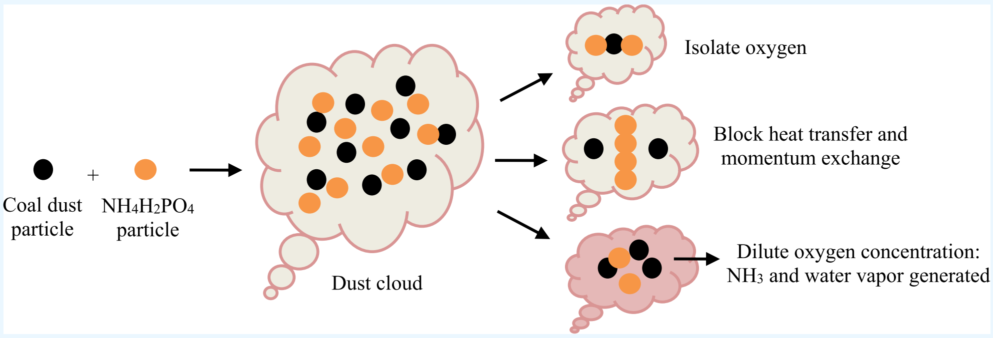

ABSTRACT: To discuss the inhibition of long flame coal dust explosion pressure, $NaHCO_3$, $KHCO_3$, and $NH_4H_2PO_4$ are selected as explosion suppression dust for explosion pressure tests under different conditions. The results show that when 25−38 and 38−45 μm coal dust are mixed in 1:1 ratio, the maximum explosion pressure is the largest, the maximum pressure is 0.79 MPa, and the maximum pressure rise rate is 74.89 MPa·s^{-1}. The suppression dusts have good inhibition effect on explosion, the order of inhibition is $NaHCO_3$, $KHCO_3$, and $NH_4H_2PO_4$ from the smallest to the largest. With the reduction of particle size of $NH_4H_2PO_4$, its inhibition effect on explosion pressure is increasing, because more $NH_4H_2PO_4$ particles move around coal dust particles, blocking the heat transfer and kinetic energy exchange. The above three suppression dust and their suppression methods can provide important data for dust prevention and control and have certain reference significance for carrying out explosion suppression work.

1. INTRODUCTION

Today, coal is still the main energy source for human production and life. In the process of mining and using coal resources, coal dust explosion accidents occur from time to time, which causes serious casualties and huge economic losses to coal mining enterprises.[1] To control the occurrence of dust and gas explosion accidents, scholars have proposed many methods. These prevention and control methods have played a positive role to a certain extent, but they have not been able to play a decisive role from the root.[2,3] The main reason for this problem is that the metamorphic degree of coal is very complex, which mainly reflects the evolution process of coal in the crust. Therefore, the explosion power of coal dust with less metamorphism is relatively large. The lignite with the least metamorphism has always been of interest for researchers of explosion mechanics, and there are many research studies on this topic.[4,5] However, although the explosion risk of lignite is relatively high, it does not mean that coal dust of other metamorphic degrees will not cause explosion accidents. Because there are many kinds of coal, their corresponding explosion suppression characteristics are also different,[6,7] so it is useful to reveal the explosion characteristics and explosion suppression characteristics.

The basis of studying the suppression of dust explosion is to master the characteristics of dust explosion. From the essence of coal dust explosion, the explosion process mainly belongs to multi-phase flow field combustion, in which the gas phase combustion is mainly the methane and ethane, which is very similar to the process of combustible gas.[8−15] Different from gas combustion, the coal dust explosion process also includes solid combustion, mainly the combustion of coke particles.[16−18] Many scholars have focused on solid phase combustion, including the influence of particle size, particle concentration, particle aggregation degree, and other factors on the explosion flame and explosion pressure.[19−21] These research results are helpful to understand the mechanics of dust explosion. In recent years, the discussion on particle explosion focuses on the numerical simulation of propagation

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process using theoretical model and numerical model. The solution process of the numerical model of gas and dust explosion mainly depends on the development of computational fluid theory. The fluid space is divided into many units, and the approximate solution of the numerical model is obtained through continuous iterative calculation. This is a method that saves manpower and material resources and it can avoid the potential danger of large explosion experiments. The information of explosion flow field can be obtained through iterative calculation, but how to effectively improve the accuracy of simulation is still a difficult point to be solved.

However, it is not enough to get the characteristics of an explosion process. The purpose of this study is to take effective measures to reduce accident frequency. In general, the related technologies have been paid more and more attention. At present, the most widely accepted method in coal mines is to use rock powder regularly in the working space.[22,23] The main component of rock powder is calcium carbonate, which can play a certain role in suppressing explosion.[24−26] The advantages of calcium carbonate are that it is easy to purchase, cheap, and economical. However, it cannot completely suppress all coal dust explosions, which is also an important disadvantage of using calcium carbonate to suppress explosions. In view of this, scholars are constantly looking for different types of explosion suppressants in order to obtain affordable and effective explosion suppressants.[27,28] The inhibitory effects of different explosion suppressants on organic dust explosions have also been widely studied. It is found that the heat absorbed by $NH_4H_2PO_4$ after decomposition is about 6.5 times that of $NaHCO_3$ after decomposition, and overall, both $NH_4H_2PO_4$ and $NaHCO_3$ have a significant inhibitory effect on organic dust explosions.[29−31] At the same time, because the explosion characteristics are very prone to change, it is necessary to continuously carry out targeted research, so as to provide valuable experience for comprehensive control of related accidents.

To sum up, at present, the research on the use of explosion suppressants is a hot issue in powder technology, and the research on the suppression of coal dust explosion is of great significance to promote the safety production of coal mines. In previous research, the authors got the ignition characteristics of dust and flame characteristics and also discussed the propagation process of toxic gas products in the explosion flow field.[32−36] However, the research on the suppression is still insufficient. Previous scholars' research mainly focused on the explosion suppression of lignite dust.[37−39] Therefore, this paper selected long flame coal as the research object to analyze the suppression effect of different explosion suppressants on its explosion pressure. Long flame coal has a higher degree of metamorphism than lignite and is also the least metamorphosed bituminous coal. It has a long flame when burning, so it is called long flame coal. In addition, on the basis of obtaining the maximum explosion power of long flame coal, this paper selects $NaHCO_3$, $KHCO_3$, and $NH_4H_2PO_4$ as explosion suppressants, discusses the suppression effect of explosion pressure of long flame coal under different explosion suppression conditions, analyzes the effect of suppressants under the conditions of single particle size and different particle size dispersions, and further analyzes the explosion suppression effect of long flame coal under the conditions of different explosion suppressants. The results obtained are important to understand the inhibition of $NaHCO_3$, $KHCO_3$, and $NH_4H_2PO_4$ on long flame coal under different explosion suppression conditions.

2. EXPERIMENTAL SECTION

2.1. Experimental Device. The main parameter tested in this paper is the explosion pressure. The experimental device used is a sealed spherical device with a volume of 20 L. The structure of the device is shown in Figure 1. For the process of testing the pressure, the Chinese "GB/T 16426" is the one mainly referred to. In this standard document, the testing principle and method of explosion pressure are introduced in detail. The experimental process of this paper is completely based on this document. According to the structure diagram of the explosive device, the process of explosion mainly includes dust injection, dust cloud ignition, and explosion pressure data collection. After the experiment, the curve of explosion pressure changes with time can be obtained by using a computer. Two methods can be used to analyze whether the coal dust is explosive. The first method is to check whether there is flame generated after ignition through the observation window. If there is obvious flame, it indicates that the explosion has occurred. The second method is to check the curve of pressure change with time.

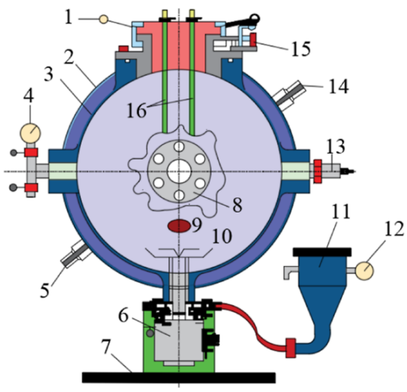

Figure 1. Structure diagram of explosive device. (1) sealing cap; (2) outer side of mezzanine; (3) inside of mezzanine; (4) vacuum gauge; (5) outlet of water; (6) mechanical two-way valve; (7) base; (8) observation window; (9) vacuum hole; (10) dispersion valve; (11) storage tank; (12) pressure gauge;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

The experimental principle of using this device to test the pressure is to spray dust to form a suspended state and disperse into the explosion space, because one of the main conditions of explosion is the formation of dust cloud, and the deposited coal dust will not explode, even under high temperature conditions, only combustion will occur. After the formation of the suspended dust cloud, the ignition device releases ignition energy to ignite the cloud in a very short time.

As shown in Table 1, the volume of the tank limits the maximum mass of the coal dust sample. The spraying pressure of dust is 2 MPa, which can blow the dust sample to the inside

Table 1. Experimental Parameters of Dust Explosion Device

volume of the dust tank (L)	volume of explosion chamber (L)	dust injection pressure (MPa)	ignition delay time (s)	ignition energy (kJ)
0.6	20	2	0.1	10

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of the explosion space to form a suspended cloud, providing conditions for explosion. However, the cloud is not ignited immediately, the ignition delay time is about 0.1 s. During the extremely short time of delayed ignition, most of the suspended particles will migrate to the area near the ignition head, and some of the suspended coal dust particles will sink slightly, which is the basic condition for explosion. When the basic conditions for explosion are met, chemical ignition heads are used for ignition. The number of ignition heads is two, therefore, the ignition energy of the two ignition heads is 10 kJ, which can ignite most of the dust. The setting of the above experimental parameters is the premise to ensure the explosion.

The pressure data can be transmitted to the computer using the data transmission system, and the computer will automatically generate an explosion pressure curve. From the test curve, we can not only analyze the change trend of pressure with time but also obtain two important explosion parameters, namely the maximum pressure and the maximum rate of pressure rise, which can be abbreviated as P_{max} and $(dP/dt)_{max}$ respectively. P_{max} reflects the maximum intensity of the explosion as a whole. The greater the P_{max}, the greater the overall damage. The $(dP/dt)_{max}$ refers to the maximum value of the pressure rise rate during the explosion process. The time corresponding to the $(dP/dt)_{max}$ is usually before the formation of the P_{max}. Therefore, the pressure rise rate will increase rapidly in a very short time before the formation of the P_{max} until it reaches the maximum value. The $(dP/dt)_{max}$ reflects the size of pressure change in unit time. The greater the $(dP/dt)_{max}$, the greater the rate of pressure rise in unit time, and the greater the destructive effect of explosion in unit time. Therefore, the above description shows that in an explosion experiment, P_{max} and $(dP/dt)_{max}$ are two important parameters, both of which can indicate the severity of the explosion.

2.2. Experimental Sample.

2.2.1. Long Flame Coal Dust. The coal resources in the world are widely distributed, lignite is the least metamorphosed, anthracite is the most metamorphosed, while bituminous coal contains many different types of coal, such as long flame coal, which is also the least metamorphosed among bituminous coal. At present, the total amount of long flame coal accounts for 12.52% of the world's proven coal resources, while in China, the total amount of long flame coal accounts for 21.59%. Therefore, the distribution of long flame coal accounts for a certain proportion in both China and the world. It is for this reason that this paper selects the long flame coal produced in Daliuta Coal Mine, Shaanxi Province, China, as the test object and analyzes the inhibition of explosion suppressants on explosion. The dust sample is shown in Figure 2. However, in the previous studies, lignite was the main sample, and the research on long flame coal dust has not been fully carried out, but the suppression of dust with different metamorphic degrees are different, so this is the main purpose of this study, and also one of the innovation points of this study. The research results will provide a basis for the comparison of the suppression characteristics of coal dust explosion with different metamorphic degrees.

Figure 2. Long flame coal dust sample.

There are usually two methods to obtain coal samples. One is to purchase standard coal samples from coal mining enterprises. The second method to obtain coal samples is to collect large coal samples from coal mines. In this paper, the second method is used. The sampling process strictly refers to the "GB 482 Coal Seam Sampling Method", while the sample preparation process strictly refers to "GB 474 Coal Sample Preparation Method". As seen in Figure 2, during sample preparation, the sample is placed on the sieve tray, on which there is a screen mesh, and on which there are screen holes. The size of particles screened will vary with the number of screen holes per unit area.

In Table 2, the corresponding relationship between the mesh number and particle size under Chinese standards is given. It is seen that the larger the mesh number of the screen, the more mesh number per unit area, and the smaller the particle size. For example, the maximum particle size screened by 200 mesh sieve is 75 μm, the maximum particle size screened by 500 mesh sieve is 25 μm. It should be noted that although the particle size of the sample screened by the sieve tray is limited by the maximum value, not all the particles screened by the sieve tray are the same, in fact, from a microscopic perspective, the shape of each particle is different, so there is a range for all the particles screened by this method, and the size of all the particles screened by the sieve tray is within this range, for example, the size of the dust screened by the 200 mesh and 250 mesh sieve tray is 58−75 μm. This is because coal dust with particle size less than 58 μm will be further screened out in 250 mesh sieve tray. Long flame coal dust samples with different particles can be got by the above methods, which is very helpful for studying the influence of particle dispersion on P_{max} and $(dP/dt)_{max}$.

Table 2. Relationship between Mesh Number of Screen and Dust Particle Size

mesh number of screen (mesh)	maximum particle size screened (μm)	minimum particle size screened (μm)	size range of sieved particles (μm)
200 and 250	75	58	58−75
250 and 300	58	48	48−58
300 and 400	48	38	38−48
400 and 500	38	25	25−38
500	25	>0	0−25

The experimental samples are obtained by sieving the long flame coal dust with a sieve tray. First, the 200 mesh sieve tray is used for sieving, and the size of the dust obtained should be all less than 75 μm in theory. In order to verify this, the particle size of the screened coal dust samples was analyzed, and the dust particle distribution image shown in Figure 3 was obtained. It can be found that the irregular shape of the particles can be clearly seen in the observation field of vision. As this is the coal sample obtained after screening with a 200 mesh sieve tray, the particle size should all be <75 μm. Figure 4 shows the distribution of the size of long flame coal dust. The number distribution of dust size presents a normal distribution.

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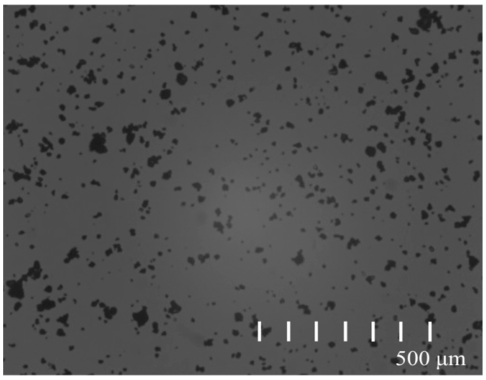

Figure 3. Dust distribution of long flame coal.

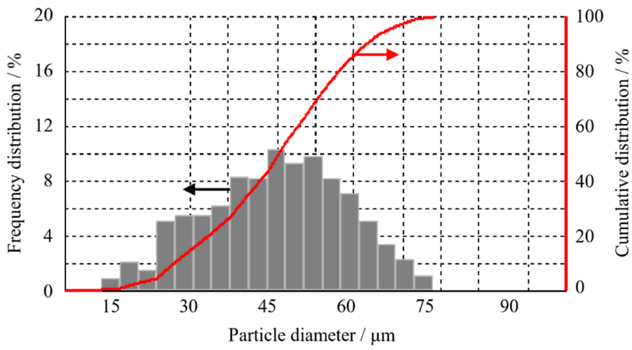

Figure 4. Particle distribution.

The smallest observed coal dust particle size is about 15 μm. Smaller coal dust particles may not be included because they are not observed in the observation field of vision. It may also be that the coal dust with smaller particles is adsorbed with other coal dust, and there may be no smaller coal dust in the sample. The maximum observed coal dust particle size is 75 μm, which is in line with the size requirements of the screen hole, because particles larger than 75 μm cannot be screened out by a 200 mesh sieve tray. The above analysis is the complete process of screening coal samples with 200 mesh sieve tray. According to this process, 250 mesh, 300 mesh, 400 mesh, and 500 mesh sieve trays can still be used for further screening, so as to obtain coal dust with different particle sizes, which can prepare for the explosion experiment in the following text.

In addition to preparing coal dust samples, it is also necessary to understand the basic composition of long flame coal samples. Long flame coal is formed by ancient plant remains buried under the stratum or through very complex change in the crust. It is mainly containing carbon, in addition to a small amount of hydrogen, nitrogen, oxygen, and other elements. In order to obtain the composition of the coal sample, the industrial analyzer is used to test the moisture, ash, volatile matter, and fixed carbon of the coal sample. At the same time, the element analyzer is used to test the proportion of different elements in the coal sample. In Table 3, the carbon element content of long flame coal dust sample is 62.75%, which is the most important element in the coal sample. Oxygen is also an important component element in long flame coal, accounting for 28.26%. It exists in organic and inorganic states. Inorganic oxygen mainly exists in water and silicate. Hydrogen is an important element in long flame coal, accounting for 4.48%. In addition to organic hydrogen, there is also a small amount of inorganic hydrogen in the minerals of long flame coal, which mainly exists in the crystal water of minerals. In Table 3, it shows the proximate analysis result. The determination principle of volatile matter is as follows. When the long flame coal is heated at 1120 K for 7 min under the condition of air isolation, the organic matter and some minerals in the coal will be decomposed into carbon monoxide, methane, and other combustible gases and overflow. The volatile of long flame coal is the overflow minus the water in the coal. The volatile of long flame coal is 37.29%, indicating that it has a strong explosion potential. The test results in Table 3 provide a data basis for comparing the composition and explosion intensity of long flame coal and other coal dust.

Table 3. Proximate Analysis and Ultimate Analysis Results of Long Flame Coal Dust Sample[a]

proximate result (%)				ultimate result (%)			
M	A	V	FC	C	H	O	N
8.30	7.24	37.29	47.17	62.75	4.48	28.26	4.51

[a]M: moisture; A: ash; V: volatile; FC: fixed carbon.

2.2.2. Explosion Suppressant Dust Samples. In the suppression of coal mine dust explosion, the use of explosion suppression dust is a very common and practical way, which can effectively control the probability of coal dust explosion accidents, thereby reducing casualties and ensuring life safety. At present, in the field of coal mine dust explosion suppression, calcium carbonate is the most widely used explosion suppression dust. Practice has proved that regular spreading of calcium carbonate dust in coal mine tunnels can indeed play a certain role in preventing explosion accidents. However, since the 21st century, whether in China or other countries in the world, there will still be some reports of coal dust explosion accidents. In these explosion accidents, statistics show that in some accidents, even if the method of using explosion suppression dust to control the explosion is adopted, the explosion still occurs. The above facts prove that although calcium carbonate dust can reduce the frequency of explosion, it still cannot completely prevent the occurrence of explosion. That is to say, the suppression of calcium carbonate dust is not ideal, especially in some complex and special coal mine environments, the explosion suppression effect may be worse. Therefore, in this paper, three kinds of new suppression dust are selected for research, to explore the effect of different suppression dust on the pressure and provide theoretical reference for comparing the suppression effect of different suppression dust.

In Figure 5, the selected three types of explosion suppression dust are $NaHCO_3$, $KHCO_3$, and $NH_4H_2PO_4$. Therefore, mixing them into long flame coal dust samples to study the explosion suppression effect will also play a significant role. The reason for selecting these three types of dust as explosion suppressants is mainly because they are the main components of fire extinguishing agents in the industrial fire protection field. The properties of three types of suppression dust are in Table 4. Under normal temperature, the suppression dust is a white crystal powder. Among the three types of explosion suppression dust, in the order of molecular weight from large to small, it is $NH_4H_2PO_4$, $KHCO_3$, and $NaHCO_3$. According to the order of dust density from large to small, it is $NaHCO_3$, $KHCO_3$, and $NH_4H_2PO_4$. The comparison shows that the density of $NaHCO_3$ and $KHCO_3$ is very close, according to the molecular structure in Figure 5, this is because the molecular

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Figure 5. Explosion suppression dust samples: (a) $NaHCO_3$, (b) $KHCO_3$, and (c) $NH_4H_2PO_4$.

Table 4. Properties of Selected Three Types of Suppression Dust

chemical formula	molecular weight	density (g/cm^3)	physical property
$NaHCO_3$	84.01	2.20	white inorganic powder, soluble in water
$KHCO_3$	100.119	2.17	
$NH_4H_2PO_4$	115.026	1.02	

structure of $NaHCO_3$ and $KHCO_3$ is very similar, the different elements are mainly connected by carbon. While the molecular weight of $NH_4H_2PO_4$ is large and the density is small, this is because the elements that make up $NH_4H_2PO_4$ are mainly connected by phosphorus, and each molecule contains four oxygen atoms and six hydrogen atoms.

In addition to the physical properties, their chemical properties, especially their thermodynamic properties, are the key to the effect of suppression. From the perspective of industrial cost, the cost of $NaHCO_3$ and $KHCO_3$ is relatively low, while the cost of $NH_4H_2PO_4$ is relatively high. As the main components of fire extinguishing agent, $NaHCO_3$ and $KHCO_3$ have certain fire extinguishing function. The fire extinguishing efficiency of $KHCO_3$ is about twice that of $NaHCO_3$, which indicates that $KHCO_3$ has greater control effect on combustion after being heated. In addition, the fire extinguishing efficiency of $NH_4H_2PO_4$ is higher than that of $KHCO_3$, which is mainly related to their thermal decomposition process and the products. It is seen from Table 4 that after heating to a certain temperature, the three types of explosion suppression dust will undergo decomposition reaction. The decomposition reaction process is endothermic, so it is helpful to control the combustion and explosion process. In addition, the generated products include solid, liquid, and gas. The solid products can cover the explosive substances, thus isolating the oxygen. The liquid products can play the role of evaporation and heat absorption, thus reducing the temperature. The gas products can play the role of diluting the concentration of substances, thus reducing the concentration of combustible substances. From the above analysis, it can be seen that three different types of explosion suppression dust are powder with good fire extinguishing effect and will also have obvious effect on suppressing the explosion pressure of long flame coal dust. Therefore, in this paper, the method of mixing the suppression dust with long flame coal dust is adopted to study the effect of the pressure of long flame coal dust under different conditions.

3. RESULTS AND DISCUSSION

3.1. Explosion Pressure of Long Flame Coal Dust under Different Conditions.

3.1.1. Explosion Pressure of Long Flame Coal Dust under Single Particle Size Condition. First of all, the pressure of long flame coal dust with different schemes is tested to find the explosion condition with the largest explosion intensity. The specific explosion pressure test scheme is as follows. The mass of coal dust in each experiment is 10 g, and each explosion experiment is repeated three times, and the final test results are taken as the average of three times, which can reduce the error caused by the experiment. Because the long flame coal dust have different particle sizes, the explosion pressure of coal dust is tested, the results are shown in Table 5. In this part, the explosion test conditions mainly include two kinds, the first is single particle size condition, and the second is mixed particle size condition. The single particle size condition means that the particle size used in each explosion test is within a specific range, such as 0−25 or 58−75 μm, and there is no mixed particle size. The mixed particle size condition refers to that in each explosion experiment, dust with different particle size are mixed together according to a certain mass percentage, so that the samples obtained are samples with mixed size. The impact of particle dispersion on explosion pressure can be obtained from the explosion experiment of mixed particle size coal dust.

Table 5. Test Results of Pressure of Long Flame Coal Dust under Different Conditions

test condition	particle size (μm)	P_{max} (MPa)	$(dP/dt)_{max}$ (MPa·s^{-1})
single particle size	0−25 (100%)	0.54	51.88
	25−38 (100%)	0.69	64.70
	38−45 (100%)	0.75	70.94
	45−58 (100%)	0.68	63.27
	58−75 (100%)	0.61	56.81
mixed particle size	0−25 (20%), 25−38 (20%), 38−45 (20%), 45−58 (20%), 58−75 (20%)	0.62	59.02
	25−38 (25%), 38−45 (25%), 45−58 (25%), 58−75 (25%)	0.65	61.73
	25−38 (33.3%), 38−45 (33.3%), 45−58 (33.3%)	0.70	66.14
	25−38 (87.5%), 38−45 (12.5%)	0.71	67.23
	25−38 (75%), 38−45 (25%)	0.72	68.92
	25−38 (62.5%), 38−45 (37.5%)	0.74	70.11
	25−38 (50%), 38−45 (50%)	0.79	74.89
	25−38 (37.5%), 38−45 (62.5%)	0.77	72.06
	25−38 (25%), 38−45 (75%)	0.76	71.93
	25−38 (12.5%), 38−45 (87.5%)	0.75	69.95

According to the analysis of the pressure of long flame coal dust under the condition of single particle size in Table 5, when the particle size is 38−45 μm, the P_{max} and $(dP/dt)_{max}$ of

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the explosion is the maximum, respectively, 0.75 MPa and 70.94 MPa·s^{-1}. In order to observe more intuitively, the pressure data under the condition of single particle size is plotted as Figure 6. This shows that the pressure is greatly affected by the particle size. On the one hand, when the particle size is less than 38−45 μm, the heat release rate between the long flame coal dust particles is very high, but the process of heat release is too short, so the explosion pressure is not the maximum at this time. On the other hand, when the particle size is greater than 38−45 μm, the energy transfer rate between long flame coal dust particles is limited, because the release of heat takes a longer time, so the explosion pressure is still not the maximum. To sum up, only when the particle size is 38−45 μm, the best balance is formed between the heat release rate and the heat release time between the dust particles, which maximizes the release of explosion energy, so the explosion pressure obtained is also the largest.

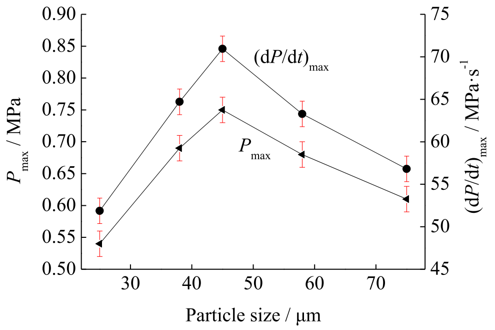

Figure 6. Pressure of long flame coal dust under single particle size condition.

3.1.2. Pressure of Long Flame Coal Dust under Mixed Particle Size Condition. In addition to using single particle size coal dust for pressure test, to explore the effect of different particle size dispersion on pressure, the authors tested the explosion pressure characteristics under different particle size dispersion conditions. As shown in Table 5, coal samples with different sizes are mixed according to a certain mass percentage to obtain coal samples with mixed particle sizes. First, five coal dust with different size ranges are mixed in the same proportion, it means that 10 g of coal samples with different size ranges are selected, respectively, and finally 10 g is mixed together. Under this condition, the P_{max} and $(dP/dt)_{max}$ of dust explosion are 0.62 MPa and 59.02 MPa·s^{-1}. The explosion intensity under this condition is less than that under the single particle size of 38−45 μm. The analysis shows that this is because the explosion intensity with single particle size 38−45 μm is the largest under the condition of single particle size. Reducing the dust within this size range will greatly weaken the intensity, but the explosion intensity under this condition is still greater than that under the condition of single particle size 0−25 and 58−75 μm.

Next, some coal dust particles with particle size that may weaken the explosion strength are removed from the coal samples in turn. Because the pressure of coal dust within the range of 0−25 μm particle size is relatively small, the coal samples within the range of 0−25 μm particle size are first removed, and the remaining four particle size coal samples are still mixed according to their respective 25% mass percentage, and the P_{max} and $(dP/dt)_{max}$ are 0.65 MPa and 61.73 MPa·s^{-1}, respectively, the maximum pressure of this explosion is 0.1 MPa less than that of the single particle size of 38−45 μm, and its strength still does not exceed that of a single particle size of 38−45 μm. Therefore, continue to remove the 58−75 μm particle size dust from the coal sample, and the P_{max} and $(dP/dt)_{max}$ obtained are 0.70 MPa and 66.14 MPa·s^{-1}. Although the explosion intensity is still less than the explosion intensity of the single particle size of 38−45 μm, it is found by continuously adjusting the particle size composition and dispersion of dust particles that under the condition of mixed particle size, increasing the mass of dust in the range of 38−45 μm can promote the increase of explosion intensity.

Therefore, the author continued to pick out 45−58 μm particles in the sample, and only retained the samples with the particle size range of 25−38 and 38−45 μm, and mixed them when the mass percentage of the two particle sizes is 50%, respectively, and the P_{max} and $(dP/dt)_{max}$ are 0.79 MPa and 74.89 MPa·s^{-1}, which exceeded the explosion intensity of the single particle size of 38−45 μm. It shows that the explosion intensity with different particle sizes mixed according to a certain mass percentage may be greater than that of a single particle size. Therefore, to find the best mixing ratio of the two particle ranges of 25−38 and 38−45 μm, the authors further carried out the explosion intensity study of different mass percentage mixing while mixing coal dust with these two particle sizes, and the results are shown in Figure 7.

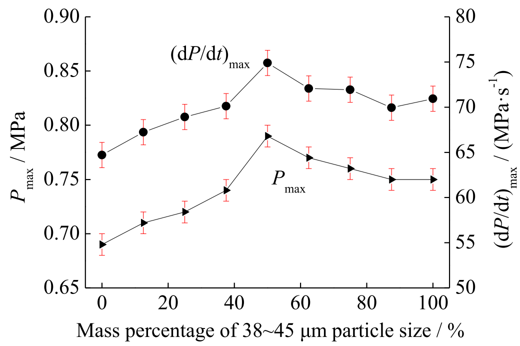

Figure 7. Explosion pressure under mixed conditions of 25−38 and 38−45 μm particle sizes with different mass percentages.

In Figure 7, the abscissa represents the mass percentage of dust with particle size of 38−45 μm on the premise of mixing 25−38 and 38−45 μm. The first conclusion drawn from this experimental result is that when the mass percentage of dust with particle size of 25−38 and 38−45 μm are both 50%, the explosion intensity of long flame coal dust with mixed particle size is the largest, and the P_{max} and $(dP/dt)_{max}$ are 0.79 MPa and 74.89 MPa·s^{-1}. This shows that the explosion intensity of long flame dust with size of 25−38 and 38−45 μm is greater than that of dust with single size of 38−45 μm after mixing them with 50% mass percentage, respectively. This result shows that in the process of explosion, there is a turbulence effect between coal dust particles of mixed particle size, which greatly increases the turbulence of dust particles in the explosion space. Meanwhile, because the dispersity of dust under mixed size condition is greater than that under single particle size condition, it also promotes the balance between the release rate of energy and the propagation time of kinetic energy in the explosion process. Thus, the explosion intensity reached the maximum.

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The second conclusion that can be drawn from Figure 7 is that under the premise of mixing dust with particle size of 25−38 and 38−45 μm, mix the dust of two particle sizes with the mass percentage of 50/50, 37.5/62.5, and 25/75% respectively, the explosion intensity of these three mixing schemes is greater than that of the dust with single size of 38−45 μm. On the one hand, this shows that coal dust with particle size of 38−45 μm plays a great role in increasing the explosion intensity, the explosion intensity of coal dust in this particle size range is indeed the largest. On the other hand, it also reveals that coal dust with particle size of 25−38 μm can increase the coal dust explosion intensity of mixed particle size. It is because the mixture of coal dust with particle size of 25−38 and 38−45 μm reaches an optimal ratio of 50/50% that the explosion intensity of coal dust of mixed particle size exceeds the explosion intensity of coal dust of single particle size. The acquisition of pressure data under the mixed particle size condition provides a good basis for the subsequent study of the effect of suppression dust on the long flame coal explosion. The subsequent study of explosion suppression will be carried out based on the 50% of 25−38 μm and 50% of 38−45 μm particle size mixing conditions, because the P_{max} and $(dP/dt)_{max}$ are the largest, and the effect of suppression study will also be the most obvious.

3.2. Inhibition of Explosion Suppressants with Different Particle Sizes on Explosion Pressure.

3.2.1. Influence of Mass Percentage of Suppression Dust on Explosion Pressure. In this part, it mainly discusses the effect of suppression dust $NaHCO_3$, $KHCO_3$, and $NH_4H_2PO_4$ on the pressure of long flame coal dust, including the influence of the particle size of the explosion suppression dust on the suppression effect. In Section 3.1, the maximum explosion pressure of long flame coal dust has been obtained. Specifically, after mixing dust of 25−38 and 38−45 μm in the proportion of 50/50% by mass, the maximum explosion intensity is obtained, and the corresponding P_{max} and $(dP/dt)_{max}$ are 0.79 MPa and 74.89 MPa·s^{-1}. The reasons for selecting $NaHCO_3$, $KHCO_3$, and $NH_4H_2PO_4$ as the explosion suppression dust studied in this paper, and the properties of these three types of suppression dust have been described in Section 2.2.2, and will not be repeated here. First, the particle size of the selected suppression dust is 58−75 μm, and the suppression data are in Table 6, where p represents the ratio of the mass of suppression dust to the sum of coal dust and explosion suppression dust mass.

Table 6. Inhibition of $NaHCO_3$, $KHCO_3$, and $NH_4H_2PO_4$ on Long Flame Coal Dust Explosion Pressure[a]

p (%)	$NaHCO_3$		$KHCO_3$		$NH_4H_2PO_4$	
	P_{max} (MPa)	$(dP/dt)_{max}$ (MPa·s^{-1})	P_{max} (MPa)	$(dP/dt)_{max}$ (MPa·s^{-1})	P_{max} (MPa)	$(dP/dt)_{max}$ (MPa·s^{-1})
0	0.79	74.89	0.79	74.89	0.79	74.89
10	0.75	70.51	0.73	68.40	0.70	62.41
20	0.67	64.99	0.61	62.31	0.57	54.38
30	0.62	59.37	0.55	54.71	0.52	46.79
40	0.55	50.76	0.50	45.32	0.44	38.32
50	0.49	43.95	0.42	36.69	0.35	27.08
60	0.41	34.10	0.34	31.70	0.17	15.80
70	0.32	27.66	0.29	23.92		

[a]p: mass percentage of suppression dust.

In order to more intuitively analyze the explosion suppression, Figures 8 and 9 are drawn. When the particle size of the suppression dust is 58−75 μm, with the increase of the mass percentage of the suppression dust mixed into the coal, the P_{max} and $(dP/dt)_{max}$ continue to decrease, indicating that the suppression dust have obvious inhibition effect on the pressure of the long flame coal. The method of combining qualitative analysis and quantitative analysis is used to discuss the suppression effect. The effect of $NaHCO_3$ on the pressure of long flame coal is worse than that of $KHCO_3$, and that of $KHCO_3$ dust is worse than that of $NH_4H_2PO_4$. The dust with the best suppression effect is $NH_4H_2PO_4$.

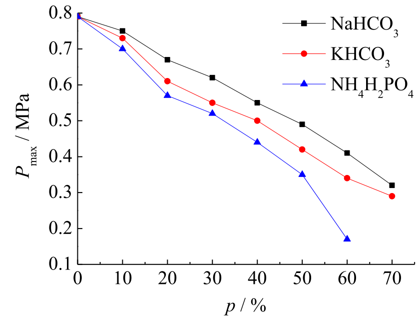

Figure 8. Inhibition of explosion suppression dust on P_{max}.

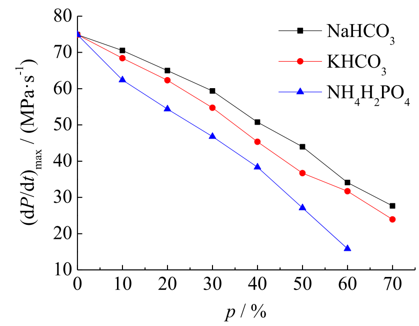

Figure 9. Inhibition of explosion suppression dust on $(dP/dt)_{max}$.

Among the three types of explosive suppressants, when the temperature reaches a certain value, the explosive suppressant undergoes a chemical reaction of thermal decomposition. When the temperature reaches 323 K, $NaHCO_3$ will rapidly decompose and undergo the following chemical reactions: $NaHCO_3 \rightarrow Na_2CO_3 + CO_2 + H_2O$, resulting in H_2O and CO_2 with good explosion suppression effects. When the temperature reaches 373 K, $KHCO_3$ will rapidly decompose and undergo the following chemical reactions: $KHCO_3 \rightarrow K_2CO_3 + CO_2 + H_2O$. Meanwhile, when the temperature reaches 463 K, $NH_4H_2PO_4$ will rapidly decompose and undergo the following chemical reactions: $NH_4H_2PO_4 \rightarrow P_2O_5 + NH_3 + H_2O$. This chemical reaction is endothermic, so it will have a certain inhibitory effect on the explosion process. At the same time, the generated products also have a good inhibitory effect on the explosion.

The study found that the greater the mass percentage of the anti-explosion dust, the better the anti-explosion effect. This is because the anti-explosion dust can reduce the ignition energy directly contacted by the coal dust, so that the pressure generated will be greatly reduced. When the mass percentage of suppression dust is 70%, the P_{max} mixed with $NaHCO_3$ and $KHCO_3$ is 0.32 and 0.29 MPa, respectively, and the $(dP/dt)_{max}$

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Table 7. Inhibition of $NH_4H_2PO_4$ on Explosion Pressure of Long Flame Coal Dust[a]

p (%)	0−25 μm		25−38 μm		38−45 μm		45−58 μm		58−75 μm	
	P_{max} (MPa)	$(dP/dt)_{max}$ (MPa/s)	P_{max} (MPa)	$(dP/dt)_{max}$ (MPa/s)	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	0.79	74.89	0.79	74.89	0.79	74.89	0.79	74.89	0.79	74.89
10	0.56	47.81	0.62	51.87	0.65	55.87	0.67	58.57	0.70	62.41
20	0.45	40.03	0.48	43.18	0.51	47.60	0.54	50.48	0.57	54.38
30	0.37	31.26	0.42	37.92	0.46	41.05	0.49	43.01	0.52	46.79
40	0.26	22.94	0.31	28.15	0.38	32.33	0.41	35.57	0.44	38.32
50	0.13	13.26	0.19	15.33	0.26	21.19	0.31	24.30	0.35	27.08
60					0.12	10.45	0.15	12.16	0.17	15.80
70										

[a] p: mass percentage of suppression dust.

mixed with $NaHCO_3$ and $KHCO_3$ is 27.66 and 23.92, respectively, indicating that under this suppression condition, the maximum pressure mixed with $NaHCO_3$ and $KHCO_3$ has decreased by 59.5 and 63.3%, respectively, so under this suppression condition, the explosion suppression effect of $NaHCO_3$ and $KHCO_3$ has been significant. However, the long flame coal mixed with $NH_4H_2PO_4$ has no longer exploded, so from the perspective of explosion suppression effect, $NH_4H_2PO_4$ has the best explosion suppression effect, and has the best potential to develop into a good explosion suppression dust in the future.

3.2.2. Inhibition of $NH_4H_2PO_4$ with Different Sizes on Explosion Pressure of Long Flame Coal Dust. The variation law of long flame coal dust pressure when the particle size of suppression dust is 58−75 μm is obtained in Section 3.2.1, it can be found that when the mass percentage of the suppression dust is 70%, only the dust mixed with $NH_4H_2PO_4$ will no longer explode. This suppression effect is unacceptable in the field of industrial safety production. So, a better explosion suppression scheme must be discussed from the perspective of particle size of suppression dust. Therefore, this section will mainly discuss the inhibition of explosion pressure of long flame coal dust by $NH_4H_2PO_4$. According to the preparation method of different particle size dust in Section 2.2.1, $NH_4H_2PO_4$ dust samples are prepared, and the $NH_4H_2PO_4$ dust samples of 0−25, 25−38, 38−45, and 45−58 μm are obtained. The suppression experiment is conducted with $NH_4H_2PO_4$ dust of different particle sizes, and the data are shown in Table 7. The curves of $NH_4H_2PO_4$ with different particle sizes on the suppression of pressure are drawn, as shown in Figures 10 and 11.

With the reduction of particle size of $NH_4H_2PO_4$ dust, its inhibition effect on the pressure increases. When the particle size of $NH_4H_2PO_4$ dust is reduced to 0−25 μm, the pressure is

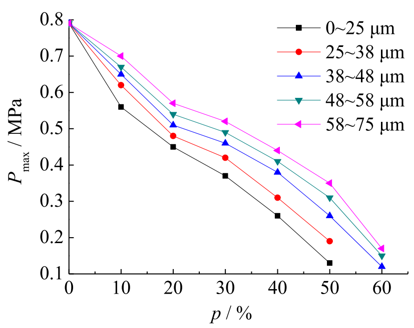

Figure 10. Inhibition effect of $NH_4H_2PO_4$ on P_{max}.

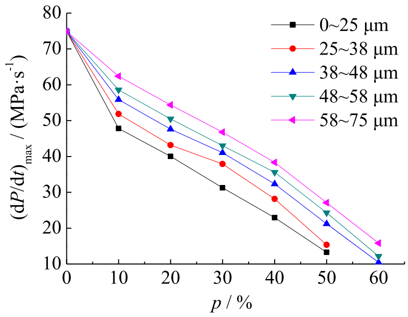

Figure 11. Inhibition effect of $NH_4H_2PO_4$ on $(dP/dt)_{max}$.

the smallest. When the mass percentage of $NH_4H_2PO_4$ dust is 50%, the P_{max} is 0.13 MPa. At this time, the intensity is very small, and almost no obvious fire can be observed in the glass window. The explosion pressure curve can only be used to determine whether the explosion has occurred. When the mass percentage of $NH_4H_2PO_4$ is 60%, the explosion can be prevented. However, when the particle size of $NH_4H_2PO_4$ is 38−45 and 45−58 μm, the explosion cannot be completely suppressed, but when the mass percentage of $NH_4H_2PO_4$ dust is 70%, the explosion cannot occur again, which further shows that reducing the size of $NH_4H_2PO_4$ can not only reduce the pressure but also reduce the mass percentage of $NH_4H_2PO_4$ dust mixed into coal dust.

As shown in Figure 12, the reason why $NH_4H_2PO_4$ dust has good explosion suppression effect is that the smaller the size of $NH_4H_2PO_4$ dust, the more evenly distributed it will be in the explosion space, and more $NH_4H_2PO_4$ dust particles will move to the middle of the particles. A part of $NH_4H_2PO_4$ dust particles will attach to the surface of the particles to isolate oxygen, and a part of $NH_4H_2PO_4$ dust particles will block the heat transfer, so the smaller the size of $NH_4H_2PO_4$, the smaller the mass percentage of $NH_4H_2PO_4$ dust required, and the better the effect of suppression. In addition, when $NH_4H_2PO_4$ dust participates in the explosive chemical reaction, it will also generate a large amount of NH_3 gas and water vapor. These two gaseous products can dilute the oxygen. Once the oxygen concentration decreases, the pressure of explosion is difficult to increase. The above research plays a critical role in guiding industrial safety protection.

In the process of industrial explosion prevention and control, the amount of explosive suppression dust that needs to be spread is too large, which will increase the difficulty of explosion-proof work. If the amount of explosive suppression dust is insufficient, it will not play an effective suppression role. To sum up, the above three suppression dust and their

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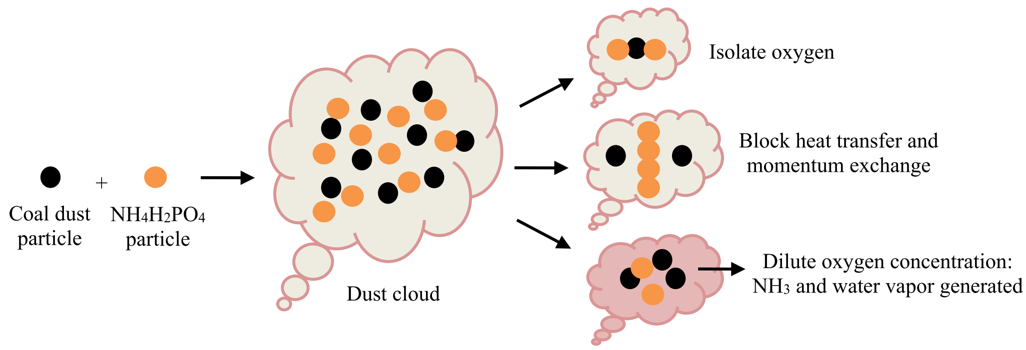

Figure 12. Inhibition mechanism of $NH_4H_2PO_4$ dust.

suppression methods can provide important data for dust prevention and control and have certain reference significance for carrying out explosion suppression work.

4. CONCLUSIONS

By studying the explosion pressure of long flame coal dust under the condition of single particle size and mixed particle size, it is found that the explosion pressure is the largest when the particle size is 38−45 μm. By mixing coal dust with different particle sizes in different proportions, it is noted that when 25−38 and 38−45 μm coal dust are mixed in 1:1 ratio, the maximum pressure is the largest. These data are larger than the explosion pressure of a single particle size, which indicates that the dust dispersion can affect the movement of particles.

On the premise that $NaHCO_3$, $KHCO_3$, and $NH_4H_2PO_4$ are mixed into long flame coal dust, it is found that with the increase of the mass percentage of the suppression dust, the pressure of the long flame coal dust continues to decrease, indicating that the three types of suppression dust have good inhibition effect on the pressure. In contrast, $NH_4H_2PO_4$ has the most obvious explosion suppression effect, followed by $KHCO_3$, and the worst is $NaHCO_3$.

The dust with the best suppression effect is $NH_4H_2PO_4$, with the reduction of the size of $NH_4H_2PO_4$, its inhibition effect on the explosion pressure is increasing. When the $NH_4H_2PO_4$ is 0−25 μm and its mass percentage mixed into the coal dust is 50%, the maximum pressure is only 0.13 MPa, which is because the smaller the size of $NH_4H_2PO_4$, the more $NH_4H_2PO_4$ particles move to the middle of the coal particles, so that the heat transfer and kinetic energy exchange can be blocked.

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Eckhoff, R. K. Current status and expected future trends in dust explosion research. *J. Loss Prev. Process Ind.* **2005**, *18*, 225−237.

(2) Joseph, G. Combustible dusts: a serious industrial hazard. *J. Hazard. Mater.* **2007**, *142*, 589−591.

(3) Niu, Y.; Zhang, L.; Shi, B. Experimental study on the explosion-propagation law of coal dust with different moisture contents induced by methane explosion. *Powder Technol.* **2020**, *361*, 507−511.

(4) Wang, Y.; et al. Influences of coal dust components on the explosibility of hybrid mixtures of methane and coal dust. *J. Loss Prev. Process Ind.* **2020**, *67*, 104222.

(5) Lin, S.; Liu, Z. T.; Qian, J. F.; Li, X. L. Comparison on the explosivity of coal dust and of its explosion solid residues to assess the severity of re-explosion. *Fuel* **2019**, *251*, 438−446.

(6) Amyotte, P. R.; Eckhoff, R. K. Dust explosion causation, prevention and mitigation: an overview. *J. Chem. Health Saf.* **2010**, *17*, 15−28.

(7) Cao, W. G.; Cao, W.; Peng, Y.; Qiu, S.; Miao, N.; Pan, F. Experimental study on the combustion sensitivity parameters and pre-combusted changes in functional groups of lignite coal dust. *Powder Technol.* **2015**, *283*, 512−518.

(8) Yan, X. Q.; Yu, J. L. Dust explosion venting of small vessels at the elevated static activation overpressure. *Powder Technol.* **2014**, *261*, 250−256.

(9) Cheng, Y. F.; Su, J.; Liu, R.; Zan, W. T.; Zhang, B. B.; Hu, F. F.; Zhang, Q. W. Influential factors on the explosibility of unpremixed hydrogen/magnesium dust. *Int. J. Hydrogen Energy* **2020**, *45*, 34185−34192.

(10) Cheng, Y. F.; Wu, H. B.; Liu, R.; Yao, Y. L.; Su, J.; Wang, W. T.; Shu, C. M. Combustion behaviors and explosibility of suspended metal hydride TiH_2 dust. *Int. J. Hydrogen Energy* **2020**, *45*, 12216−12224.

(11) Cheng, Y. F.; Song, S. X.; Ma, H. H.; Su, J.; Han, T. F.; Shen, Z. W.; Meng, X. R. Hybrid H_2/Ti dust explosion hazards during the production of metal hydride TiH_2 in a closed vessel. *Int. J. Hydrogen Energy* **2019**, *44*, 11145−11152.

(12) Zhu, C.; Gao, Z. s.; Lu, X. m.; Lin, B. q.; Guo, C.; Sun, Y. m. Experimental study on the effect of bifurcations on the flame speed of

premixed methane/air explosions in ducts. *J. Loss Prev. Process Ind.* **2017**, *49*, 545−550.
(13) Cao, W. G.; et al. Under-expansion jet flame propagation characteristics of premixed H_2/air in explosion venting. *Int. J. Hydrogen Energy* **2021**, *46*, 38913.
(14) Cao, W. G.; Zhou, Z.; Zhou, W.; Xu, S.; Xiao, Q.; Cao, W.; Jiao, F.; Zhang, Y.; Yu, S.; Xu, S. The flow field behaviours of under-expansion jet flame in premixed hydrogen/air explosion venting. *Int. J. Hydrogen Energy* **2022**, *47*, 10420−10430.
(15) Zhang, P.; Du, Y.; Zhou, Y.; Qi, S.; Wu, S.; Xu, J. Explosions of gasoline-air mixture in the tunnels containing branch configuration. *J. Loss Prev. Process Ind.* **2013**, *26*, 1279−1284.
(16) Cao, W. G.; Gao, W.; Peng, Y.; Liang, J.; Pan, F.; Xu, S. Experimental and numerical study on flame propagation behaviors in coal dust explosions. *Powder Technol.* **2014**, *266*, 456−462.
(17) Gao, W.; Mogi, T.; Sun, J. H.; Yu, J.; Dobashi, R. Effects of particle size distributions on flame propagation mechanism during octadecanol dust explosions. *Powder Technol.* **2013**, *249*, 168−174.
(18) Gao, W.; Mogi, T.; Sun, J. H.; Dobashi, R. Effects of particle thermal characteristics on flame structures during dust explosions of three long-chain monobasic alcohols in an open-space chamber. *Fuel* **2013**, *113*, 86−96.
(19) Eckhoff, R. K. Understanding dust explosions. The role of powder science and technology. *J. Loss Prev. Process Ind.* **2009**, *22*, 105−116.
(20) Houim, R. W.; Oran, E. S. Structure and flame speed of dilute and dense layered coal-dust explosions. *J. Loss Prev. Process Ind.* **2015**, *36*, 214−222.
(21) Kosinski, P.; Hoffmann, A. An investigation of the consequences of primary dust explosions in interconnected vessels. *J. Hazard. Mater.* **2006**, *137*, 752−761.
(22) Wei, X. R.; Zhang, Y.; Wu, G.; Zhang, X.; Zhang, Y.; Wang, X. Study on explosion suppression of coal dust with different particle size by shell powder and $NaHCO_3$. *Fuel* **2021**, *306*, 121709−122239.
(23) Liu, Q. M.; Hu, Y. L.; Bai, C. H.; Chen, M. Methane/coal dust/air explosions and their suppression by solid particle suppressing agents in a large-scale experimental tube. *J. Loss Prev. Process Ind.* **2013**, *26*, 310−316.
(24) Cao, W. G.; Gao, W.; Liang, J. Y.; Xu, S.; Pan, F. Flame-propagation behavior and a dynamic model for the thermal-radiation effects in coal-dust explosions. *J. Loss Prev. Process Ind.* **2014**, *29*, 65−71.
(25) Cao, W. G.; Qin, Q.; Cao, W.; Lan, Y.; Chen, T.; Xu, S.; Cao, X. Experimental and numerical studies on the explosion severities of coal dust/air mixtures in a 20-L spherical vessel. *Powder Technol.* **2017**, *310*, 17−23.
(26) Song, Y. F.; Nassim, B.; Zhang, Q. Explosion energy of methane/deposited coal dust and inert effects of rock dust. *Fuel* **2018**, *228*, 112−122.
(27) Wang, X.; Huang, X. W.; Zhang, X. Y.; Zhang, Y. S.; Zhang, Y. Q. Numerical simulation of coal dust explosion suppression by inert particles in spherical confined storage space. *Fuel* **2019**, *253*, 1342−1350.
(28) Lu, K. L.; Chen, X. K.; Zhao, T. L.; Wang, Y. Y.; Xiao, Y. The inhibiting effects of sodium carbonate on coal dust deflagration based on thermal methods. *Fuel* **2022**, *315*, 123122.
(29) Jiang, H.; Bi, M.; Peng, Q.; Gao, W. Suppression of pulverized biomass dust explosion by $NaHCO_3$ and $NH_4H_2PO_4$. *Renewable Energy* **2020**, *147*, 2046−2055.
(30) Zhao, Q.; Li, Y.; Chen, X. Fire extinguishing and explosion suppression characteristics of explosion suppression system with N_2/APP after methane/coal dust explosion. *Energy* **2022**, *257*, 124767.
(31) Zhou, J.; Li, B.; Ma, D.; Jiang, H.; Gan, B.; Bi, M.; Gao, W. Suppression of nano-polymethyl methacrylate dust explosions by ABC powder. *Process Saf. Environ. Prot.* **2019**, *122*, 144−152.
(32) Liu, T. Q.; Tian, W.; Sun, R.; Jia, R.; Cai, Z.; Wang, N. Experimental and numerical study on coal dust ignition temperature characteristics and explosion propagation characteristics in confined space. *Combust. Sci. Technol.* **2023**, *195*, 2150−2164.
(33) Liu, T. Q.; Wang, N.; Sun, R.; Cai, Z.; Tian, W.; Jia, R. Flame propagation and CO/CO_2 generation characteristics of lignite dust explosion in horizontal pipeline. *Int. J. Low-Carbon Technol.* **2021**, *16*, 1384−1390.
(34) Liu, T. Q.; Jia, R.; Sun, R.; Tian, W.; Wang, N.; Cai, Z. Research on ignition energy characteristics and explosion propagation law of coal dust cloud under different conditions. *Math. Probl. Eng.* **2021**, *2021*, 21−28.
(35) Liu, T. Q.; Cai, Z. X.; Wang, N.; Jia, R. H.; Tian, W. Y. Prediction method of coal dust explosion flame propagation characteristics based on principal component analysis and BP neural network. *Math. Probl. Eng.* **2022**, *2022*, 41−48.
(36) Liu, T. Q.; Cai, Z.; Sun, R.; Wang, N.; Jia, R.; Tian, W. Flame propagation characteristics of deposited coal dust explosion driven by airflow carrying coal dust. *J. Chem. Eng. Jpn.* **2021**, *54*, 631−637.
(37) Liang, G. Q.; Dai, H. M.; Yin, H. P.; Zhao, Q.; Chen, X. F. Inhibition characteristics of coal dust explosion at the gasification atmosphere. *Adv. Powder Technol.* **2021**, *32*, 3725−3734.
(38) Dai, H. M.; Liang, G. Q.; Yin, H. P.; Zhao, Q.; Chen, X.; He, S. Experimental investigation on the inhibition of coal dust explosion by the composite inhibitor of carbamide and zeolite. *Fuel* **2022**, *308*, 121981.
(39) Zhang, Y. S.; Wu, G. G.; Cai, L.; Zhang, J.; Wei, X. R.; Wang, X. Study on suppression of coal dust explosion by superfine $NaHCO_3$/shell powder composite suppressant. *Powder Technol.* **2021**, *394*, 35−43.

https://doi.org/10.1021/acsomega.3c03700
ACS Omega 2023, 8, 35919−35928