Study on the Effect of KHCO$_3$ Particle Size and Powder Spraying Pressure on the Methane Explosion Suppression Characteristics of Pipe Networks

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ABSTRACT: To achieve the best explosion suppression effect of an active powder spraying system, the KHCO$_3$ powder suppression test for a 9.5% methane−air premixed methane explosion was studied based on an independent test platform consisting of a pipe network. The suppression effect of KHCO$_3$ powder particle size and powder spraying pressure on the methane explosion shock wave pressure, flame wave velocity, and flame wave temperature were studied, and the explosion suppression mechanism was analyzed. The results indicated that both the particle size of the KHCO$_3$ powder and powder spraying pressure had a significant effect on the explosion inhibition. When the spraying pressure was in the range of 0.1−0.2 MPa, the increase in KHCO$_3$ powder spraying pressure on the effect of explosion suppression was significantly enhanced, and when the powder spraying pressure exceeded 0.2 MPa, the explosion suppression effect did not obviously increase. With a reduction in the KHCO$_3$ powder particle size, the effect of explosion suppression significantly improved, and when the KHCO$_3$ powder particle size was reduced to 50−75 μm, we observed the best shock wave pressure, flame wave velocity, and flame wave temperature suppression effect.

1. INTRODUCTION

Methane explosions are one of the main disasters in coal mining and can very easily cause mass death and injuries, as well as seriously threaten the safety of underground operators.$^{1,2}$ The use of an active powder spray explosion suppression system to quickly spray an explosion suppressant after an explosion can weaken the intensity of methane explosions, reducing the loss of life after methane explosion accidents.$^{3,4}$

Experts and scholars worldwide have conducted active powder spraying explosion suppression system research and have focused mainly on powder explosion suppressants, such as SiO$_2$, NH$_4$H$_2$PO$_4$, NaHCO$_3$, Al(OH)$_3$, KHCO$_3$, urea, ferrocene, diatomaceous earth, and montmorillonite, which contain sodium or potassium salts compounds that exhibit good inhibitory effects.$^{5−8}$ KHCO$_3$, one of the most common fire extinguishing agents in recent years, is inexpensive, has an environmentally friendly decomposition product after heating, has superior fire extinguishing properties, has chemical stability, and is not susceptible to chemical reactions with other organic or inorganic substances.$^{9−11}$ Thus, it has been studied by scholars worldwide as a representative explosion inhibitor. KHCO$_3$ has often been used to inhibit nano PMMA dust, aluminum powder, and industrial dust explosions. Studies have shown that the smaller the particle size of KHCO$_3$ powder, and the higher the powder concentration, the stronger the explosion inhibition effect.$^{12−15}$ Meanwhile, numerous scholars have found that powder inhibitor KHCO$_3$ can significantly inhibit methane/air explosions. For example, Babushok et al.$^{16}$ studied the combustion rate and temperature suppression effect of premixed CH$_4$/air flame with the addition of KHCO$_3$, and the reduction in the combustion rate was attributed to the thermal effect of the added additives, reducing the concentration of free radicals. Yu et al.$^{17}$ tested the effect of a catalytic composite powder explosive suppressant on a methane explosion producing a maximum explosion pressure, maximum pressure rise rate, and other related characteristic parameters, using a standard 20 L spherical explosive device. The results showed that the addition of ferrocene significantly improved the agglomeration phenomenon of the traditional fire suppressant KHCO$_3$, improving its pyrolysis performance. Wang et al.$^{18}$ tested the effect of inert gases on the methane explosion suppression performance of a KHCO$_3$ cold aerosol

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using a 5 L explosion piping system. The experimental results showed that N₂ and CO₂ significantly enhanced the inhibition performance of the KHCO₃ cold aerosol against the 9.5% methane/air premixed gas explosion. Liang et al. studied the fire extinguishing abilities of typical dry powders, such as ultrafine KHCO₃, ultrafine KH₂PO₄, and ultrafine ammonium phosphate ABC, for extinguishing methane fires, and the results showed that the order of fire extinguishing ability followed ultrafine KHCO₃ > ultrafine ammonium phosphate ABC dry powder > ultrafine KH₂PO₄. In addition, Wang et al. studied the effect of KHCO₃/red-mud composite powders with a core–shell structure on methane explosion pressure parameters in a 20 L spherical explosive device, and the results showed that the core–shell KHCO₃/red mud composite powder had a better explosion suppression effect. Thus, the effectiveness of KHCO₃ has been confirmed in earlier studies.

Existing studies have mainly focused on the comparison between the inhibitor type and the synergistic effect of different phase state explosion suppressants on methane explosion suppression experiments in closed containers such as spherical explosion tanks, and fewer studies have investigated the effect of KHCO₃ powder particle size and spray pressure on gas explosion suppression characteristics in pipe networks.

In this work, we used KHCO₃ as a powder explosion suppressant, and N₂ was used as the gas driving the KHCO₃ powder in the pipe network to study the effects of KHCO₃ particle size and powder pressure on the suppression of methane explosion shock wave pressure, flame propagation speed, and flame wave temperature, specifically by changing the KHCO₃ powder particle size and powder pressure. This study provided a more efficient active powder spray explosion suppression system design, which served as the basis for the test.

2. EXPERIMENTAL DESIGN

2.1. Experimental System. As shown in Figure 1, the size of the experimental pipe network was 8100 × 5500 mm. The experimental system consisted of an experimental pipe network, gas distribution system, dynamic data acquisition system, powder injection system, and ignition system. The dynamic data acquisition system included a QSY8124 type pressure sensor, a NANMAC type transient temperature sensor, a CKG100 type light sensing high-precision flame sensor, and a TST6300 dynamic data acquisition instrument. The response times of the pressure sensor, temperature sensor, and flame sensor were 100 μs, 10 ms, and 1 ms, respectively, and the accuracy of the data acquisition device was 0.2% FS with a continuous acquisition frequency of 10 kHz/CH. The powder spraying system used a gas storage cylinder to provide the N₂ driving gas, and a gas pump was used to control the powder spraying pressure. The ignition system included a DX-GDH high-energy igniter, high-energy spark plug, high-voltage and high-temperature resistant cable, power cable, and external trigger device. The ignition control box was connected to the external trigger line, where the spark plug was placed in the front of the explosion chamber, the ignition voltage was 2200 V, and single energy storage was 30 J. Assuming that the distance between two flame sensors was L, the flame front passed through the two adjacent sensors at different moments, t₂ and t₁, and these values were recorded. Then, the flame front velocity was calculated by the following formula:

\[ v = \frac{L}{t_2 - t_1} \]  

2.2. Experimental Conditions. To study the effects of KHCO₃ spray pressure and powder particle size on the methane explosion suppression effect of the KHCO₃ powder,
spray pressures of 0.1, 0.15, 0.2, and 0.25 MPa were selected, the powder mass was set to a constant value of 20 g, and the powder particle sizes were 50−75, 75−100, 100−125, and 125−150 μm, respectively, in the 9.5% methane−air premixed gas explosion suppression test study. The particle size distribution of the KHCO₃ powder is shown in Figure 2.

2.3. Experimental Process. The various components were connected to the piping system using female threads, and silicone gaskets were installed at the connections between each component and its corresponding pipe to improve the airtightness of the unit. Before each test, the KHCO₃ powder with a mass of 20 g was evenly placed in the bottom of the pipe, as shown in Figure 1, and PTFE was used to separate the explosion chamber and the pipeline. This was followed by evacuation of the explosion chamber with 9.5% volume fraction of methane experimental gas, with the pipeline containing atmospheric air, and gas distribution was completed at the same time while the inlet hole and explosion vent were

Figure 2. KHCO₃ powder particle size distribution.

Figure 3. Peak overpressures for each branch with different powder spraying pressures and different KHCO₃ powder particle sizes.
closed. The system was allowed to stand for 30 s, and then the gas pump was opened, allowing the gas storage tank to drive the gas N\textsubscript{2} rapid spray, and the KHCO\textsubscript{3} powder in the pipe was blown up. After 600 ms of standstill, the switch for the external trigger device was powered on, to ensure that the igniter and the data acquisition system started to work synchronously. Then, the trigger button was pressed on the external trigger device, triggering the ignition after the signal light on the device was on. After the experiment, the exhaust gas in the pipeline was discharged, gas washing was carried out in the pipeline, and the next test was awaited after completion.

3. RESULTS AND DISCUSSION

3.1. Effect on Shock Wave Overpressure. Figure 3 shows the peak overpressure of methane explosion at each monitoring point with different spraying pressures and different KHCO\textsubscript{3} powder particle sizes. As shown in the figure, when the powder particle size was constant, different KHCO\textsubscript{3} powder spraying pressures had a significant effect on the peak overpressure. When the spraying pressure was 0.1 MPa, the highest peak overpressure values were 412, 289, 188, and 127 kPa at the monitoring points with particle sizes of 125\textendash150, 100\textendash125, 75\textendash100, and 50\textendash75 μm, respectively. When the spraying pressure increased to 0.15 MPa, the highest peak overpressure values were 384, 263, 159, and 116 kPa at the monitoring points with particle sizes of 125\textendash150, 100\textendash125, 75\textendash100, and 50\textendash75 μm, respectively. When the particle spraying pressure was increased to 0.2 MPa, the highest peak overpressure values at the four particle size monitoring points were 352, 234, 136, and 108 kPa. When the powder spraying pressure was 0.25 MPa, the highest values of overpressure peak at the four particle size monitoring points were 351.5, 233.6, 135.8, and 107.9 kPa, respectively. Comparatively, we found that within a certain range, increasing the powder spraying pressure helped to reduce the peak overpressure at each monitoring point, and when the powder spraying pressure increased to 0.2 MPa, the peak overpressure was suppressed to a maximum extent, and a continuous increase in the powder spraying pressure to suppress the explosion overpressure had no significant effect. Thus, we observed the best effect of suppressing the explosion overpressure when the spray powder pressure was 0.2 MPa.

When the powder spraying pressure was constant, different KHCO\textsubscript{3} powder particle sizes had a large impact on the peak overpressure. With a particle size of 125\textendash150 μm, the highest values of peak overpressure at each monitoring point of 0.1, 0.15, 0.2, and 0.25 MPa were 412, 384, 352, and 351.5 kPa, respectively. With a particle size of 100\textendash125 μm, the highest values of the peak overpressure at each monitoring point for the four spray powder pressures were 289, 263, 234, and 233.6 kPa. The highest values of the peak overpressure at each monitoring point for the four spray powder pressures were 188, 159, 136, and 135.8 kPa at particle sizes of 75\textendash100 μm. At a particle size of 50\textendash75 μm, the highest values of peak overpressure at each monitoring point for the four spray powder pressures were 127, 116, 108, and 107.9 kPa, respectively. Comparatively, we found that the smaller the particle size of the KHCO\textsubscript{3} powder, the lower the peak overpressure at the monitoring point, and the better the effect of blast suppression. Thus, at each monitoring point, a particle...
3.2. Effect on Flame Wave Velocity. Figure 4 shows the peak methane explosion flame wave velocity of each branch pipe with different powder spraying pressures and different KHCO$_3$ powder particle sizes. As shown in the figure, when the powder particle size was constant, different KHCO$_3$ powder spraying pressures had a significant effect on the peak flame wave velocity. We obtained the highest peak flame wave velocity values of 7.5, 5.7, 4.4, and 2.6 m/s for each branch with particle sizes of 125–150, 100–125, 75–100, and 50–75 μm, respectively, at a powder spraying pressure of 0.1 MPa. When the powder spraying pressure increased to 0.15 MPa, the highest peak flame wave velocity values were 5.6, 5.2, 3.8, and 2.1 m/s for each branch in the four particle sizes, respectively. By continuously increasing the powder spraying pressure to 0.2 MPa, we obtained the highest peak flame wave velocity values of 5.7, 5.2, 3.9, and 3.89 m/s for each branch among the four particle sizes at a particle size of 100–125 μm, respectively. In addition, the highest peak flame wave velocity values of 4.4, 3.8, 3.2, and 3.19 m/s were obtained for each branch among the four particle sizes at a particle size of 75–100 μm, respectively. Thus, we found that within a certain range, increasing the spray powder pressure would significantly reduce the flame wave speed peak, and when the spray powder pressure increased to 0.25 MPa, the peak flame wave speed almost no longer decreased, indicating that by increasing the spray powder pressure to 0.2 MPa, the speed peak was suppressed to the maximum extent, and continued increases in the spray powder pressure to suppress the flame wave speed showed no significant effect. Thus, we obtained the best flame wave speed inhibition effect when the spray powder pressure was 0.2 MPa.

When the spray powder pressure was constant, changing the KHCO$_3$ powder particle size had a greater effect on the peak flame wave velocity. We obtained the highest peak flame wave velocity values of 7.5, 5.6, 4.2, and 4.18 m/s for each branch at a particle size of 125–150 μm for powder spray pressure values of 0.1, 0.15, 0.2, and 0.25 MPa, respectively. We also obtained the highest peak flame wave velocity values of 5.7, 5.2, 3.9, and 3.89 m/s for each branch among the four particle sizes at a particle size of 100–125 μm, respectively. In addition, the highest peak flame wave velocity values of 4.4, 3.8, 3.2, and 3.19 m/s were obtained for each branch among the four particle sizes at a particle size of 75–100 μm, respectively, and the highest peak flame wave velocity values were 2.6, 2.1, 1.7, and 1.69 m/s for each branch among the four particle sizes at a particle size of 50–75 μm, respectively. Thus, the smaller the particle size of the KHCO$_3$ powder, the lower the peak flame wave velocity for each branch, and the better the flame wave velocity suppression effect. We found that a particle size of 50–75 μm had the lowest peak flame wave velocity for each branch and the best flame wave velocity suppression effect.

3.3. Effect on Flame Wave Temperature. Figure 5 shows the peak flame wave temperature at each monitoring point for the different powder spraying pressures and different KHCO$_3$ powder particle sizes.

Figure 5. Peak flame wave temperatures at each monitoring point for the different powder spraying pressures and different KHCO$_3$ powder particle sizes.
point for the different powder spraying pressures and different KHCO$_3$ powder particle sizes. As shown in the figure, when the powder particle size was constant, changing the KHCO$_3$ powder spraying pressure had a greater effect on the peak flame wave temperature. At a spray powder pressure of 0.1 MPa, the particle sizes of 125–150, 100–125, 75–100, and 50–75 μm for the highest values of each branch flame wave temperature peak were 458, 367, 289, and 232 K. In addition, the highest peak flame wave temperature values of 419, 336, 262, and 207 K for each obtained branch among the four particle sizes at a powder spraying pressure of 0.15 MPa, respectively, and the highest peak flame wave temperature values of 383, 297, 234, and 185 K were obtained for each branch among the four particle sizes at a powder spraying pressure of 0.2 MPa, respectively. At a spray powder pressure of 0.25 MPa, the highest peak flame wave temperature values were 382.9, 296.9, 234, and 184.9 K for each branch among the four particle sizes at a powder spraying pressure of 0.2 MPa, respectively. At a spray powder pressure of 0.25 MPa, the highest peak flame wave temperature values were 382.9, 296.9, 234, and 184.9 K for each branch among the four particle sizes. Comparatively, we found that within a certain range, the greater the spray powder pressure, the lower the peak flame wave temperature. When the spray powder pressure increased to 0.25 MPa, the peak flame wave temperature almost no longer decreased, indicating that at a spray powder pressure of 0.2 MPa, the temperature peak was suppressed to the maximum extent, and continued increases in the spray powder pressure to suppress the flame wave temperature showed no significant effect. Thus, the best flame wave temperature suppression effect was observed when the spray powder pressure was 0.2 MPa.

When the spray powder pressure was constant, changing the KHCO$_3$ powder particle size had a greater effect on the peak flame wave temperature. The highest peak flame wave temperature values for each monitoring point at a particle size of 125–150 μm with powder spray pressures of 0.1, 0.15, 0.2, and 0.25 MPa were 485, 419, 383, and 382.9 K, respectively. In addition, we obtained the highest peak flame wave temperature values at each monitoring point of 367, 336, 297, and 296.9 K for a particle size of 100–125 μm, respectively, with powder spraying pressures of 0.1, 0.15, 0.2, and 0.25 MPa. When the particle size was 75–100 μm, the highest peak flame wave temperature values at each monitoring point of 0.15, 0.2, and 0.25 MPa were 289, 262, 234, and 234 K, respectively. When the particle size was 50–75 μm, the highest peak flame wave temperature values at each monitoring point of 232, 207, 185, and 184.9 K for spray powder pressures of 0.1, 0.15, 0.2, and 0.25 MPa, respectively. We found that the smaller the particle size of the KHCO$_3$ powder, the lower the peak flame wave temperature at each monitoring point, and the better the flame wave temperature suppression effect. Thus, the best flame wave temperature suppression effect was observed when the particle size was 50–75 μm.

3.4. Discussion. From the above tests, we found that changing the spraying pressure of the KHCO$_3$ powder had a significant effect on the methane explosion suppression characteristics of KHCO$_3$ when the particle size of the KHCO$_3$ powder was constant. We observed that when the powder spraying pressure was 0.1 MPa, the overpressure peak, flame wave velocity peak, and flame wave temperature peak were relatively high. One possible reason for this was that the powder blew up in the pipeline and was suspended in a short period of time, while the low powder spraying pressure powder did not completely blow up and make flame contact, resulting in a relatively large explosion intensity. When the powder spraying pressure increased to 0.15 MPa, the inhibition effect improved compared to the spraying pressure of 0.1 MPa, indicating that the dispersion of the powder was improved, the increase in the suspension time in the pipe and flame contact.
area increased, and the explosion intensity was relatively weakened. When the powder spraying pressure increased to 0.2 MPa, the gas explosion overpressure peak, flame wave velocity peak, and flame wave temperature peak decreased. However, when the spray powder pressure was increased again to 0.25 MPa, the overpressure peak, flame wave velocity peak, and flame wave temperature peak no longer fell, indicating that at a spray powder pressure of 0.2 MPa, the powder was diffused to most of the region and was uniformly distributed in the pipeline. As a result, the gas explosion was suppressed to the maximum extent, and in this situation, a continued increase in spray powder pressure had no significant incremental effect on explosion suppression.

Similarly, when the KHCO₃ powder spraying pressure was constant, changes in the powder particle size had a significant effect on the methane explosion suppression characteristics of KHCO₃. The thermal characterization results of KHCO₃ for the four particle sizes 50−75, 75−100, 100−125, and 125−150 μm are shown in Figure 6, indicating that the four KHCO₃ particle sizes had only one weight loss phase and only one heat absorption peak during the entire process. According to the TG curves, we found that the temperatures at which weight loss of KHCO₃ started at 50−75, 75−100, 100−125, and 125−150 μm were 113, 130, 142, and 149 °C, respectively, and the temperatures at which the weight loss ended were 186, 196, 204, and 216 °C, respectively. It indicated that at the smaller the particle size of KHCO₃, the pyrolysis of KHCO₃ can rapidly occur and complete the thermal decomposition process at a lower temperature, and an efficient endothermic cooling effect can be produced at the low-temperature stage. At the same time, small size particles could be completely gasified more easily and fully exert their inhibition effect. However, the inhibitory effect of the large particles was limited by their slow gasification rate.22,23 According to the surface effect, as the particle size of KHCO₃ decreased, the specific surface area increased significantly, and the chemical activity was stronger, making it easier to interact with the explosion flame, resulting in a chemical inhibition effect.24 Thus, the smaller particle size of KHCO₃ could better inhibit the explosion effect.

4. EXPLOSION SUPPRESSION MECHANISM

According to the above content, the explosion suppression process of KHCO₃ included physical inhibition and chemical inhibition.

Considering the physical inhibition processes, the KHCO₃ powder was injected into the pipe driven by N₂, and most of the KHCO₃ powder was suspended in the upper part of the pipe under a certain spraying pressure. One of the reasons for the rapid increase in the methane explosion pressure was that the heat released by combustion in the form of thermal radiation to preheat the unburned area and suspended KHCO₃ could prevent the transfer of heat radiation from the combustion zone to the unburned zone, thus reducing the efficiency of heat transfer and reducing the explosive reaction rate.25 Figure 6 shows the thermal gravity analysis (TG) and differential scanning calorimeter (DSC) thermal analysis results of KHCO₃, indicating that there were obvious heat absorption peaks in the weight loss phase for the four particle sizes of KHCO₃, indicating that KHCO₃ could absorb the heat of the methane explosion reaction during decomposition and weaken the explosion intensity by cooling.

The KHCO₃ decomposition products contained CO₂ and H₂O. Also, CO₂ and N₂ from the storage tank could dilute the concentrations of CH₄ and O₂ when they entered the explosion area as an inert gas. According to the chemical reaction collision theory, the prerequisite for a methane explosion reaction consists of effective collision between CH₄ and O₂ molecules, while the dilution effect of the inert gas would decrease the probability of effective collision between CH₄ and O₂ molecules, increasing the difficulty of an explosion reaction.26 Second, as CO₂ and N₂ were the third body in the explosion reaction, when the high-energy radicals in the chain reaction collided with CO₂ and N₂ molecules, energy was transferred to them, resulting in a reduction in the number of high-energy radicals used in the chain reaction and a decrease in the explosion reaction rate. Finally, the explosive chain reaction required a certain amount of heat to start and maintain the reaction, and CO₂ and N₂ absorbed heat from the explosion area, making it more difficult to start the explosive chain reaction.27 In addition, H₂O absorbed heat and formed water vapor, which also reduced the O₂ concentration and weakened the methane explosion intensity by asphyxiation.

As for chemical inhibition, KHCO₃ manifested its chemical inhibition mainly by participating in the chain reactions and consuming key radicals during methane explosions. This was shown by the key steps of the methane explosion chain reaction mechanism:28
In this work, we studied the suppression effect and explosion suppression mechanism of different KHCO₃ powder particle sizes and different dusting pressures on the methane explosion shock wave pressure, flame wave velocity, and flame wave temperature in a pipe network. The main conclusions were as follows.

1. When the spraying pressure was in the range of 0.1–0.2 MPa, the effect of the increase in KHCO₃ powder spraying pressure on the explosion suppression was significantly enhanced when the spraying pressure was increased to 0.2 MPa, and the peak overpressure, peak flame wave velocity, and temperature peak were suppressed to the maximum extent. However, continuous increases in the powder spraying pressure showed no significant effect on explosion suppression.

2. The KHCO₃ powder particle size was an important factor that affected the gas explosion suppression effect; with a reduction in KHCO₃ powder particle size, the effect of explosion suppression significantly improved, and the potassium bicarbonate powder with particle size range of 50–75 μm had the best explosion suppression performance. Analysis from the perspective of thermal properties showed that the smaller the particle size of KHCO₃, the lower the temperature at which weight loss began and the lower the temperature required for the end of pyrolysis, which indicated that pyrolysis could absorb heat from the methane explosion reaction at a lower temperature, resulting in faster heat absorption and better inhibition effect.

3. The optimal parameters of the explosion suppressants obtained through the experiments were verified in the pipeline network, providing theoretical reference and support to suppress the occurrence of methane explosions and reduce accident risk in actual pipeline networks.

In future research, we plan to start with the structure of the pipe network and carefully analyze the compound effects of the changes in the pipe network structure and the type of detonation inhibitor on the detonation suppression effect.

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### Notes

The authors declare no competing financial interest.

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## REFERENCES

1. Juganda, A.; Strebinger, C.; Brune, J. F.; Bogin, G. E. Computational Fluid Dynamics Modeling of a Methane Gas Explosion in a Full-Scale. Underground Longwall Coal Mine. Mining. Metall. Explor. 2022, 39 (3), 897–916.

2. Zhang, J.; Xu, K.; Wang, Y.; Niu, B.; Li, Li; Li, C. Study on causation mechanism of extraordinary serious gas explosion accidents in coal mines. China Saf. Sci. J. 2017, 27 (1), 48–52.

3. Sun, C.; Zhang, Y.; Pei, B.; Wang, Y.; Meng, X.; Ji, W. Experimental study on suppression effects of inert gas/red mud two-phase inhibitors on gas explosion. China Saf. Sci. J. 2020, 30 (10), 112–118.

4. Wang, B.; Rao, Z.; Xie, Q.; Wolanski, P.; Rarata, G. Brief review on passive and active methods for explosion and detonation suppression in tubes and galleries. J. Loss Prev. Process Ind. 2017, 49 (1), 280–290.

5. Kuang, K.; Chow, W. K.; Ni, X.; Yang, D.; Zeng, W.; Liao, G. Fire suppressing performance of superfine potassium bicarbonate powder. Fire Mater. 2011, 35 (6), 353–366.
Inhibition of aluminum dust explosion by NaHCO$_3$ and inert gas.

Williams, B.; Fleming, J. W. Suppression mechanisms of alkali metal compounds. Halon Options Technical Working Conference, Albuquerque, NM, April 27–29, 1999; NIST: Gaithersburg, MD, 1999; pp 157–169.

Reding, N.; Shiflett, M. B. Characterization of Thermal Stability and Heat Absorption for Suppressant Agent/Combustible Dust Mixtures via Thermogravimetric Analysis/Differential Scanning Calorimetry. Ind. Eng. Chem. Res. 2019, 58 (11), 4674–4687.

Cao, X.; Bi, M.; Ren, J.; Chen, B. Experimental research on explosion suppression affected by ultrafine water mist containing different additives. J. Hazard. Mater. 2019, 368 (1), 613–620.

Wu, Y.; Yuan, J.; Kui, N.; Huang, W. Effect of carbonates on dust explosion pressure in closed vessel. China Saf. Sci. J. 2010, 20 (10), 92–96.

Lin, C.; Qi, Y.; Gan, X.; Feng, H.; Wang, Y.; Ji, W.; Wen, X. Investigation into the Suppression Effects of Inert Powders on the Minimum Ignition Temperature and the Minimum Ignition Energy of Polyethylene Dust. Processes 2020, 8 (3), 294.

Dai, L.; Hao, L.; Kang, W.; Xu, W.; Shi, N.; Wei, H. Inhibition of different types of inert dust on aluminum powder explosion. Chin. J. Chem. Eng. 2020, 28 (7), 1941–1949.

Zhou, J.; Jiang, H.; Zhou, Y.; Gao, W. Flame suppression of 100 nm PMMA dust explosion by KHCO$_3$ with different particle size. Process Saf. Environ. Prot. 2019, 132 (1), 303–312.

Babushok, V. I.; Linteris, G. T.; Hoorelbeke, P.; Roosendans, D.; van Wingerden, K. Flame inhibition by potassium-containing compounds. Combust. Sci. Technol. 2017, 189 (12), 2039–2055.

Yu, M.; Wang, X.; Zheng, K.; Han, S. Experimental investigation of gas explosion suppression by catalytic composite powder inhibitor. J. China Coal Soc. 2021, 46 (10), 3212–3220.

Wang, Y.; Lin, S.; Li, Z.; Li, L.; Weng, X.; Ji, W. The synergistic effect of inert gas on the methane explosion suppression performance of KHCO$_3$ cold aerosol. Coal Sci. Technol. 2021, 49 (2), 145–152.

Li, X.; Zhang, H.; Yang, C.; Zhao, J.; Bai, S.; Long, Y. Effect of water on the chain reaction characteristics of gas explosion. ACS Omega. 2021, 6 (19), 12513–12521.

Gan, B.; Li, B.; Jiang, H.; Gao, W.; Bi, M. Suppression of polymethyl methacrylate dust explosion by ultrafine water mist/additives. J. Hazard. Mater. 2018, 351 (1), 346–355.

Polli, S.; Barozzi, M.; Scotton, M. S.; Fumagalli, A.; Derudi, M.; Rota, R. A predictive model for the estimation of the deflagration index of organic dusts. Process Saf. Environ. Prot. 2019, 126 (1), 329–338.