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Research on the Inhibition Effect of NaCl on the Explosion of Mg−Al Alloy Powder

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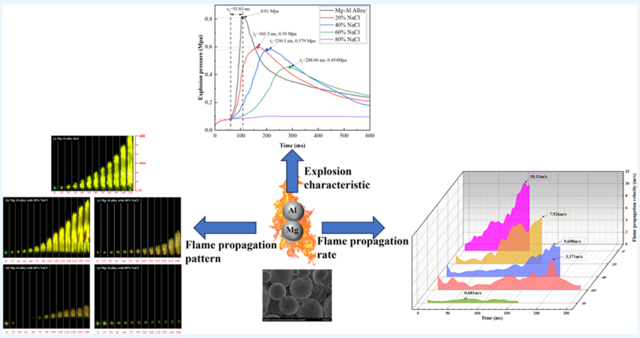
ABSTRACT: A study was conducted on the explosion overpressure and flame propagation law of magnesium−aluminum (Mg−Al) alloy powder, and the suppression mechanism of sodium chloride (NaCl) on the explosion of magnesium−aluminum alloy powder was explored. Adding NaCl powder can effectively reduce the explosion pressure, flame front position, and flame propagation speed. The higher the amount of NaCl powder added, the lower the explosion pressure of magnesium−aluminum alloy powder, the slower the flame propagation speed, and the lower the flame brightness. NaCl adsorbed on Mg−Al alloy powder isolated heat transfer and played a cooling role. The Cl$^-$ produced by NaCl decomposition will react with the free radicals H$^+$ and OH$^-$ in the reaction system, which will reduce the concentration of H$^+$ and OH$^-$ in the combustion process and hinder the propagation and expansion of the flame. The research results provide theoretical guidance for the explosion prevention of Mg−Al alloy powder and the preparation of a physical−chemical compound explosion suppressor in the later stage.



1. INTRODUCTION

As an important branch of metal materials, metal powder materials are widely used in metallurgy, catalysis, thermal spraying, electronic communication, home appliances, the automobile industry, and other industrial fields.[1] As the most common aluminum alloy, Mg−Al alloy has the advantages of high strength, low density, good heat dissipation, etc. and is widely used in electronics, automobiles, aerospace, and other fields.[2] Due to the explosive properties of aluminum−magnesium alloy powder, the explosion-proof safety of aluminum−magnesium alloy powder needs further study.[3]

There are many studies on the explosion of simple metal powder by domestic and foreign scholars.[4−6] Millogo et al.[7] determined the particle temperature and flame temperature of Al powder and Al alloy powder by infrared thermometry and spectroscopy. Wang et al.[8] tested the ignition sensitivity and explosion characteristics of metal powders by using a 20 L spherical explosion system and a dust cloud ignition temperature test system and studied the explosion characteristics with particle size, ignition energy, and dust concentration as variables. Boilard et al.[9] measured and compared the explosion parameters of micro- and nanotitanium powders. The experimental results indicate that the explosiveness of micrometer-scale titanium powder is far inferior to that of nanometer-scale titanium powder. Miao et al.[10] studied the ignition probability of various metal powders under the inertion action of $CaCO_3$ powder and found that $CaCO_3$ has an inhibitory effect on all metal powders, and the ignition success rate is reduced. Wang et al.[11,12] investigated the explosion characteristics of Al−Mg alloy particles with different particle sizes and concentrations, while using modified $Mg(OH)_2$ as an explosion suppressant. The results indicate that the flame propagation speed is inversely proportional to the particle size, and the smaller the particle size is, the higher the explosion risk. Dust explosion is more harmful, and the technology of dust explosion suppression needs more attention.

The commonly used gas/dust explosion suppression methods currently include ultrafine water mist,[13] inert gas,[14] solid powder,[15] and gas−solid two-phase explosion suppressants,[16,17] which have different effects on different types of combustion explosions. Especially some inert gases and ultrafine water mist can undergo chemical reactions with particles such as magnesium and aluminum.[18] Solid powders are mainly divided into physical and chemical explosion suppressors.[19] Physical explosion suppressors achieve the purpose of cooling by absorbing heat and isolating and blocking heat, so as to inhibit explosion.[20] Chemical inhibitors

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achieve cooling through endothermic decomposition, while precipitating free radicals that can block the chain reaction, thus limiting the development of the explosion.[21,22] At present, scholars at home and abroad have conducted research on powder explosion suppressors.[23−25] Jiang et al.[26−28] conducted experiments on the suppression of aluminum powder explosion by $NaHCO_3$ and $NH_4H_2PO_4$, measured the flame propagation pattern with a high-speed camera, and measured the flame temperature with a thermocouple. The mechanism of flame suppression is further studied Zhang et al.[29] Reference 27 studied the inhibition effect of expellable graphite (EGs) on Al powder explosion in dew. Due to the inhibition effect of EGs, the flame structure becomes more discrete and irregular and the propagation speed decreases to different degrees. At the same time, the optimal inhibitory concentration of each EGs was determined. Bu et al.[6] studied the effect of alumina on MIE and P_{max} of aluminum powder explosion and analyzed the effect of the particle size of the explosion suppressant on the explosive strength of Al powder.

Since there is little research on inhibiting dust explosion of Mg−Al alloy, this study chooses Mg−Al alloy as the research object. This team has previously studied the inhibition mechanism of $NaHCO_3$ on magnesium−aluminum alloy,[30] but $NaHCO_3$ is an active explosion suppressant and the decomposition temperature is low, so it is only suitable for early explosion suppression. As a typical chemical explosion suppressant, NaCl is the main raw material for the production of the Class D fire extinguishing agent and can exert a good effect in extinguishing aluminum, magnesium, sodium, and other metal fires. NaCl as an explosion suppressor itself is noncombustible, has no secondary explosion risk, is friendly to the environment, does not damage human health, is noncorrosive, and does not easily damage the instrument. Therefore, in this paper, NaCl is selected as the explosion suppressant to carry out the dedetonation inhibition experiment on Mg−Al alloy powder and study its inhibition mechanism.

2. EXPERIMENTAL SECTION

2.1. Experimental Materials. The main components of the Mg−Al powder are shown in Table 1. The particle size distribution diagram and scanning electron microscopy (SEM) image of Mg−Al alloy powder are shown in Figure 1, and its D_{50} is 24.369 μm. The D_{50} of NaCl powder was 55.314 μm.

Table 1. Main Composition of Mg−Al Alloy

component	Mg	Al	Si	Cu	others
mass percentage	49.685%	49.03%	0.461%	0.139%	<0.7%

2.2. Experimental Device and Methods. As shown in Figure 2, a 20 L spherical explosion system was used to test the explosive characteristics of the powder. 5g of Mg−Al alloy powder was used in the blank test. In the explosion suppression experiment, NaCl increased at an interval of 20 wt %. The ignition head used in the experiment is composed of barium nitrate, zirconium powder, and barium peroxide in a ratio of 3:4:3.[31] Its energy is 4 kJ. The 20 L spherical tank is vacuumed to −0.06 MPa, and the pressure of the gas reservoir is 2 MPa. Explosion was triggered after 60 ms ignition delay (GB/T 16425 and EN 14034). Each test was repeated five times, and the average value of explosion parameters is taken.

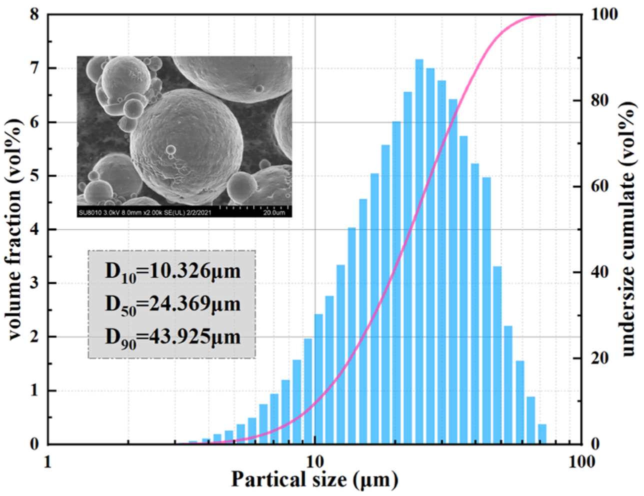
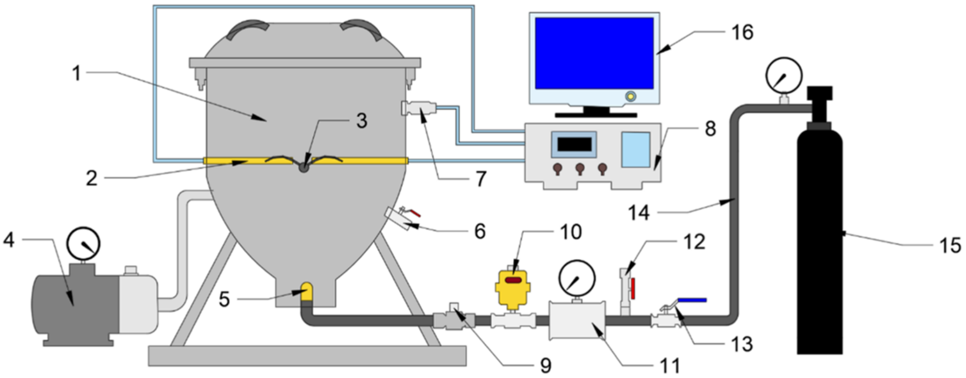


Figure 1. Particle size distribution and SEM of Mg−Al alloy powder.

The flame propagation characteristics were tested by a Hartmann experiment system, as shown in Figure 3. 1 g of Mg−Al alloy powder was used in the blank test, and the NaCl powder increases at intervals of 20 wt % until no obvious flames are generated in the glass tube (φ 70 mm × 600 mm). During the experiment, the gas reservoir was pressurized to 0.5 MPa to ensure the uniform diffusion of the dust cloud. The ignition delay is 30 ms, and a high-speed camera is used to record the flame propagation state. Test procedures refer to standard GB/T 16428-1996. Each test is copied five times. This study is based on the image edge detection algorithm in MATLAB programs to recognize and extract flame edges.[32]

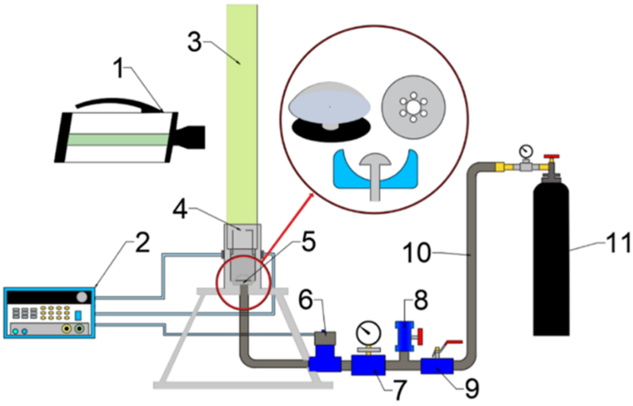
3. RESULTS AND DISCUSSION

3.1. Inhibition Effect of NaCl on Dust Explosion Intensity of the Mg−Al Alloy. The explosion characteristic curves of the Mg−Al alloy powder are shown in Figures 4 and 5. The explosion pressure of Mg−Al powder rose rapidly after 60 ms. t_1 is the time to reach the maximum pressure. In the blank test, t_1 = 55.85 ms, P_{max} = 0.81 MPa, and $(dP/dt)_{max}$ = 84.3 MP/s. When 20% NaCl powder was added, the P_{max} value decreased by 0.212 MPa (26.1%), t_1 increased to 135.5 ms, and $(dP/dt)_{max}$ = 71.5 MP/s. This is because the added sodium chloride powder increases the distance between the particles of the Mg−Al alloy powder and isolates part of the thermal radiation, so that part of the alloy particles do not participate in the reaction, thereby slowing down the speed of the explosion reaction and reducing P_{max}. When adding 40 wt % NaCl powder, P_{max} = 0.58 MPa, a decrease of 28.3%. Compared with the addition of 20 wt % NaCl powder, the decrease was almost unchanged. However, with t_1 = 290.5 ms, $(dP/dt)_{max}$ = 57.21 MPa/s, there are significant changes in the arrival time and rate of the maximum explosion pressure. When adding 60 wt % NaCl powder, P_{max} and $(dP/dt)_{max}$ decreased by 43.9 and 59.5%, respectively, t_1 = 288.06 ms, and the explosion suppression effect was significantly improved. When 80 wt % NaCl is added, it is basically completely inhibited. This is because NaCl particles consume the heat of the explosion flame in the system and play a role in cooling. With the increase of NaCl concentration, more heat transfer is isolated, resulting in a lower temperature in the 20 L spherical explosion vessel and better suppression of explosion. Compared with the explosion suppression effect of $NaHCO_3$ previously studied by



1-20L spherical tank; 2-Ignition electrode; 3-Ignition head; 4-Vacuum pump; 5-Dust diffuser; 6-Exhaust valve; 7-Pressure sensor; 8-Explosion controller; 9-Dust chamber; 10-Solenoid valve; 11-Gasholder; 12-Exhaust valve; 13-Inlet valve; 14-High-pressure gas pipe; 15-High-pressure air cylinder; 16-Computer

Figure 2. 20 L spherical explosive device diagram.



1-High speed camera; 2-Ignition system; 3-Vertical tube; 4-Ignition electrode; 5-Dust diffuser; 6-Solenoid valve; 7-Gasholder; 8-Exhaust valve; 9-Inlet valve; 10-High-pressure gas pipe; 11-High-pressure air cylinder

Figure 3. Schematic diagram of the Hartmann instrument.

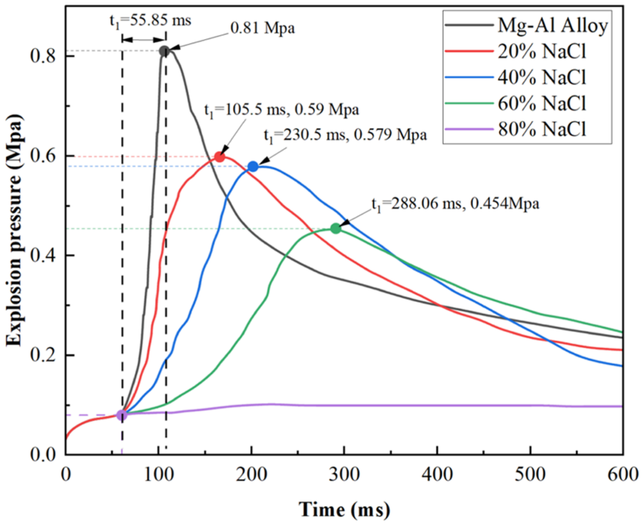


Figure 4. Explosion pressure curve.

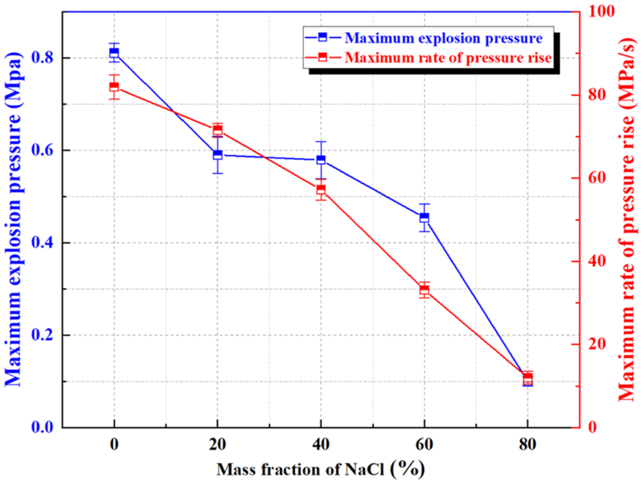


Figure 5. Maximum explosion pressure and pressure rise rate curve.

the team,[30] the explosion suppression effect of NaCl is better when the addition amount of the explosion suppression agent is less than 60%. The effect of $NaHCO_3$ on explosion suppression is better when the additive amount is more than 60%. When the amount of the suppressor added is small, NaCl acts as a coolant to absorb the heat generated by the alloy particles during the explosion process while preventing the alloy particles from pyrolysis into volatile gases. The decomposition temperature of $NaHCO_3$ is low, and $NaHCO_3$ has been basically decomposed in the early stage of explosion, which cannot effectively inhibit the explosion. When the mass fraction increases, $NaHCO_3$ in addition to endothermic decomposition will also produce a large number of Na^+ and consume the reaction system of free radicals, so as to better prevent the explosion. However, it is difficult for NaCl to decompose by heat and the explosion cannot be further inhibited by cooling alone.

3.2. Inhibition Effect of NaCl on Flame Propagation of the Mg–Al Alloy.

3.2.1. Propagation Mode of the Deflagration Flame of the Mg–Al Alloy. Figure 6 shows the propagation image of the Mg–Al alloy powder deflagration flame. In the blank test, the electric spark released by the high-pressure ignition system ignites the Mg–Al alloy powder instantaneously, forming a weak yellow flame. When $t = 30$ ms, the pyrolysis products of magnesium–aluminum alloy begin to expand, the flame becomes brighter, and the flame front is more obvious. When $t = 70$ ms, the flame surface appears in a discrete state, which is Mg–Al alloy particles vaporized into flammable protective volatile gas, and gas thermal expansion

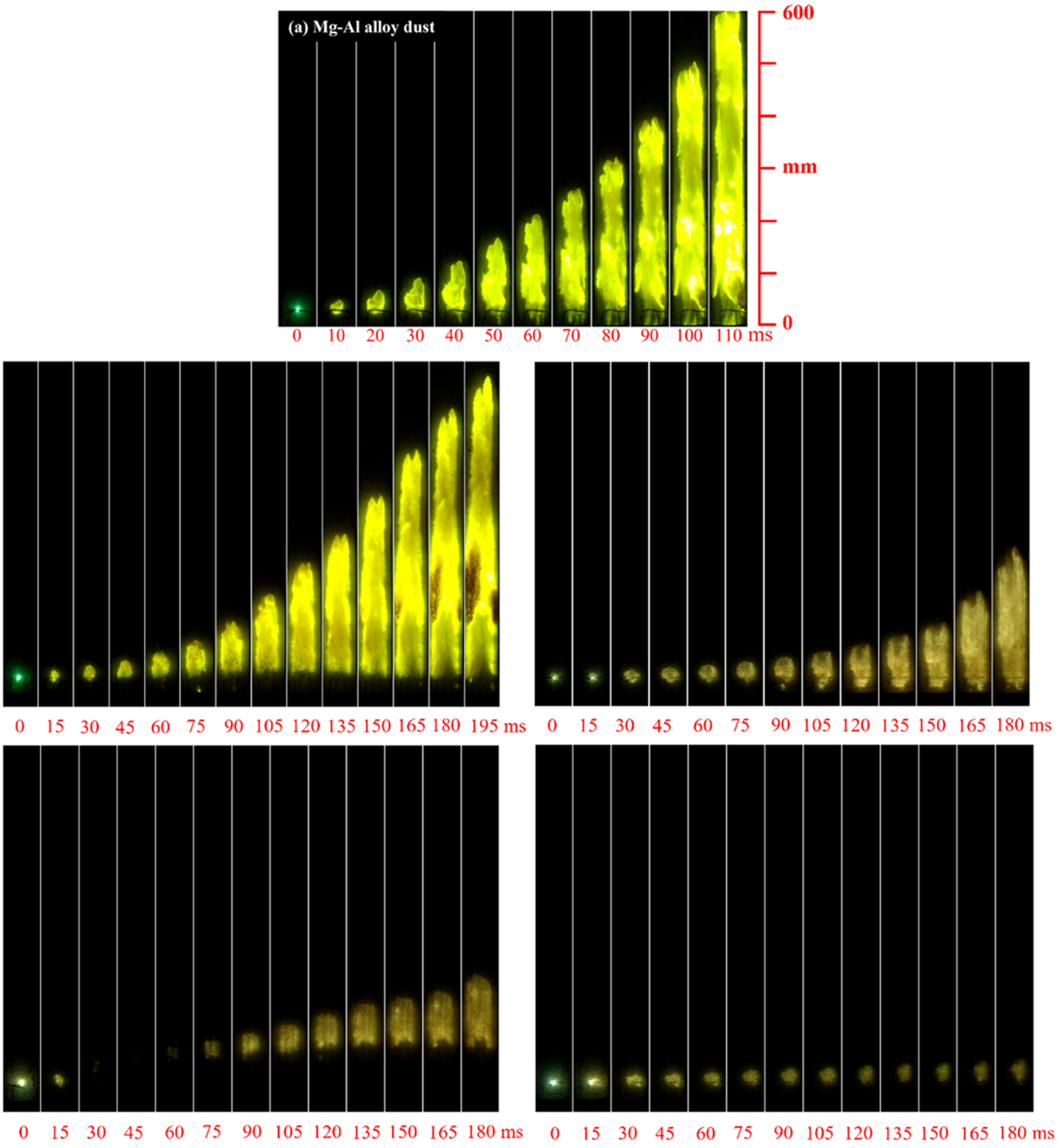


Figure 6. Deflagration flame spread.

will produce upward buoyancy, promote the particles that are not burned in time to move upward, and promote flame propagation. However, the flammable gas distribution is not uniform, so it will cause the flame to appear discrete. At $t = 110$ ms, the flame rushes out of the Hartmann tube.

Figure 6 shows the flame propagation image after adding 20−80% NaCl powder. When 20% NaCl powder was added, the flame became significantly darker, the gap between the flame and the tube wall became larger, and it only broke out of the Hartmann tube at 195 ms. When 40% NaCl powder was added, the flame turned into light−dark yellow, and when the flame spread to 180 ms, the flame height was less than half of the pipeline and the flame became fuzzy. When 60% NaCl powder was added, the flame shape became incomplete and a fracture zone appeared, which was due to the decrease of alloy particles involved in combustion with the addition of the explosion suppressor. When 80% NaCl powder was added, the flame basically stopped spreading.

3.2.2. Propagation Velocity of the Deflagration Flame and Location of the Flame Front. Figures 7 and 8 show the position and velocity of the deflagration flame front. The addition of NaCl powder continuously reduces the flame front and propagation speed, and the flame front finally decreased to 69.64 mm, and the velocity decreased from 10.11 to 0.681 m/s. When 20% NaCl powder was added, the flame still propagated to 600 mm within 195 ms without successfully preventing flame propagation. When 40% NaCl powder was added, the flame front remained at 528.35 mm. When NaCl powder was added to 60 and 80%, the flame was significantly suppressed. At the beginning of the flame burning, the flame is spread around in a spherical state. When the flame is hindered by the tube wall, the flame begins to expand and work upward. The heat radiation and heat transfer between magnesium and aluminum alloy particles are getting stronger and stronger, and the generation of a large amount of heat also speeds up the propagation of the flame speed. With the decrease of unreacted alloy particles and the decrease of thermal expansion of Mg−Al

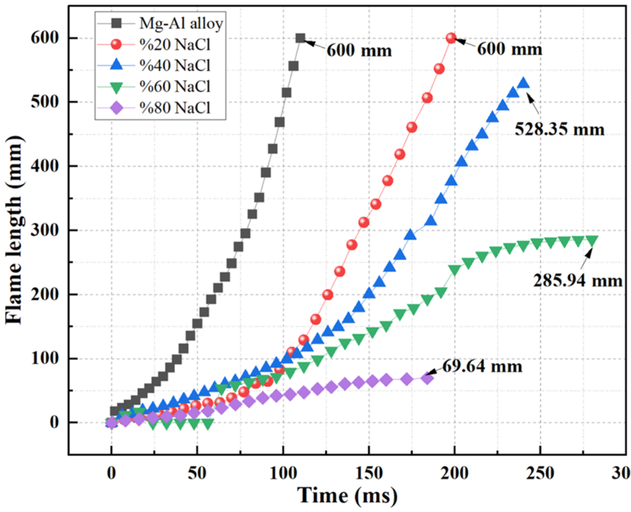


Figure 7. Mg−Al alloy deflagration flame propagation length.

particles, the propagation velocity begins to decrease. The speed curve shows a fluctuating phenomenon, which is due to insufficient heat generation by the alloy particles when the speed is high, resulting in insufficient pyrolysis time for the alloy particles at the flame front position. When the propagation speed is slow, the pyrolysis time will correspondingly increase, which will generate more heat to improve combustion and increase the propagation speed. The suppression law of NaCl on flame propagation is consistent with that of $NaHCO_3$.

3.3. Analysis of the Explosion Mechanism and NaCl Inhibition Mechanism of the Mg−Al Alloy.

The explosion mechanism of the Mg−Al powder is shown in Figure 9. Al and Mg are easily oxidized in air, and a layer of oxide film composed of Al_2O_3 and MgO is formed on the surface of Mg−Al alloy powder particles. After the explosive reaction begins, when the alloy particles are thermally decomposed, Al and Mg vaporize into a flammable volatile gas composed of gaseous Al and Mg. Part of the thermal expansion breaks through the oxide film on the surface of the alloy particles and then mixes with oxygen to burn, generating Al_2O_3 and MgO, releases a lot of heat, and is transferred to the surrounding Mg−Al alloy particles in the form of flame radiation and heat conduction, so that the combustion reaction continues to cycle. With each successive cycle, the combustion reaction speed gradually increases, and eventually, an explosion is formed. The other part failed to break through the oxide film after thermal expansion and was recooled into solid Al and Mg after the temperature in the explosion tank was reduced and was covered by the oxide film.

When Mg−Al alloy powder and NaCl powder are mixed and explosion occurs, NaC1 particles can absorb the heat of the reaction system and play a cooling role. The decrease of heat and the weakening of thermal radiation lead to the gradual extinguishment of the flame. At the same time, NaCl powder will be adsorbed on the surface of alloy particles, to a certain extent, prevent the precipitation of volatile gas on the surface of alloy particles, and also isolate the contact between Mg−Al powder particles and oxygen, shielding the thermal radiation and heat conduction between Mg−Al powder particles. With the increase of NaCl concentration, more heat transfer is isolated, resulting in lower temperature in the 20 L spherical explosion vessel and better suppression of explosion. NaCl will turn into a molten state when it is above 800 °C, which will decompose and produce free radical Cl^-. Because combustion is a free radical chain reaction, Cl^- generated by decomposition will react with free radicals H^+ and OH^- in the explosion process, reducing the concentration of H^+ and OH^-

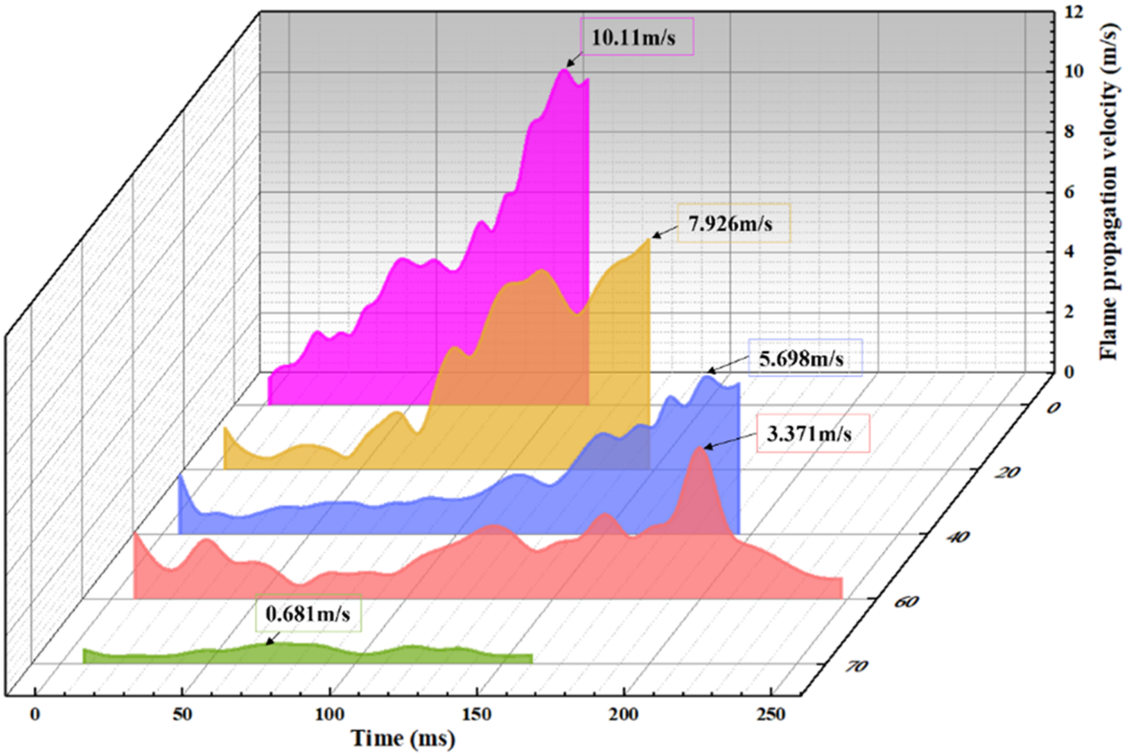


Figure 8. Mg−Al alloy deflagration flame propagation speed.

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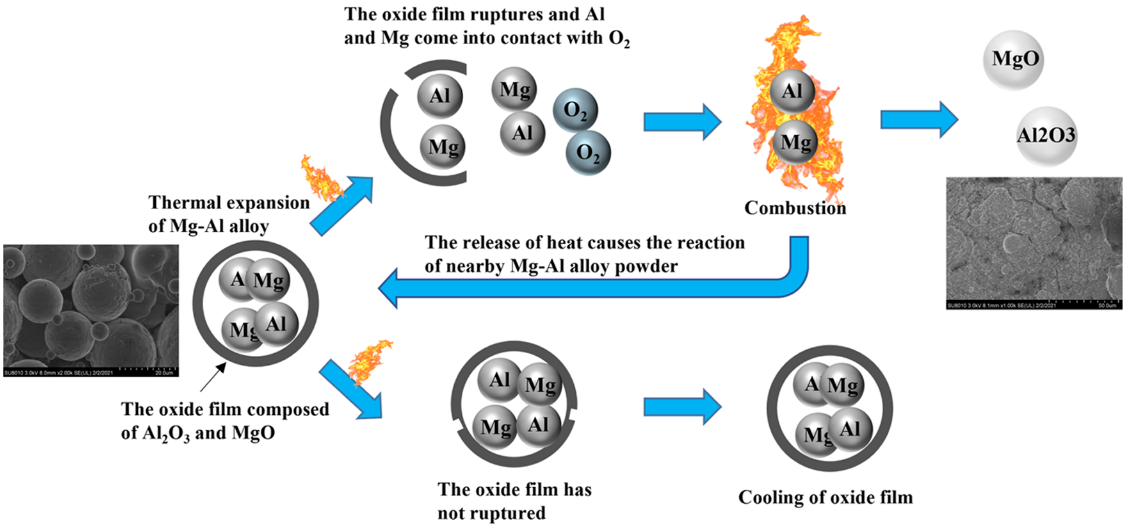

Figure 9. Explosion mechanism of the Mg−Al alloy powder.

and hindering the development of explosion. Through this study and the previous research of the team, it is found that the suppression of explosion propagation needs to be carried out from both physical and chemical perspectives to achieve the ideal effect. Therefore, the preparation of a physical−chemical compound explosion suppressor will play a better role in explosion suppression.

4. CONCLUSIONS

In this paper, the suppression performance of NaCl powder on Mg−Al alloy powder explosion was studied, and the specific suppression mechanism of NaCl powder was further explored, drawing the following conclusions:

(1) The P_{max} and $(dP/dt)_{max}$ of pure magnesium−aluminum alloy powder were 0.81 and 84.3 MPa/s, respectively. As the amount of NaCl powder added increases, the P_{max} and $(dP/dt)_{max}$ significantly decreased. When 80 wt % NaCl powder is added, they were basically completely suppressed.

(2) The maximum flame propagation speed of pure magnesium−aluminum alloy powder was 10.11 m/s, and the flame propagation state was complete and bright. With the increase of NaCl powder concentration, flame height and flame propagation speed gradually decreased, flame brightness dimmed, and the flame became discrete. When 40 wt % NaCl was added, the flame length could not reach 600 mm. When 80 wt % NaCl powder was added, the deflagration flame was basically suppressed.

(3) NaCl particles can absorb the heat of the reaction system and play a cooling role. The decomposed Cl^- can capture the free radicals produced in the explosion of Mg−Al alloy powder and reduce the concentration of free radicals. The activity of the remaining free radicals is reduced, which hinders the continued occurrence of the chain reaction, thereby reducing the reaction rate, affecting the continued propagation of the flame, and realizing the inertion of Mg−Al powder.

(4) The research conclusions can reveal the explosion risk of magnesium−aluminum alloy powder and provide the corresponding measures for disaster control. In addition, by summarizing the research conclusions, the effect of the physical−chemical compound explosion suppressor is better.

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Author Contributions

The article was written through contributions of all authors. All authors have given approval to the final version of the article.

Notes

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