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Research Article

Effects of Moisture Content on the Minimum Explosible Concentration of Aluminum Powder and the Related Mechanism

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Aluminum powder has been widely applied to various industries. However, its high activity and high burn rate can cause serious explosion risks. Many factors affecting the explosion of aluminum powder have been determined, yet moisture content has not been included. In the present work, the minimum explosible concentrations of aluminum powders with different moisture contents were measured with a 20-liter explosion test apparatus using the explosion accident in Kunshan, China, as a study case. The experimental results suggest that the minimum explosible concentration of aluminum powder dramatically increases with the increase of its moisture content first and the increasing trend becomes slower as the moisture content further increased. The oxidation time has no significant effects on the minimum explosible concentration of aluminum power in 8 hours at room temperature. Further investigation suggests that the moisture lowers the explosion risk of aluminum powder by altering its surface oxide film, ignition, and combustion process. The low contents of moisture in the range of 0%-8% increase the minimum explosible concentration of aluminum powder by inhibiting the reaction kinetics and particle agglomeration, while high contents of moistures in the range of 8%-20% affect the minimum explosible concentration by the endothermic effect and oxygen dilution effect.

1. Introduction

The industrial dust explosions in agriculture, pharmaceutical, and metal processing are an important research topic in safety management [1–3]. Statistical analyses suggest that 19% of explosion accidents, mostly aluminum powder explosions, are caused by metal oxidation [4]. Micron and nanoaluminum powders are widely used in various industries [5, 6]. However, their high activities and high burn rates can result in fatal and devastating explosion accidents without appropriate protections [7, 8]. Li et al. [9] systemically analyzed the aluminum powder explosion accident in Kunshan on August 2, 2014. The accident caused shocking damages with 75 deaths, 185 injures, and the direct economic loss of 3.51 billion Yuan. The accident has not only raised the public awareness of the risks of aluminum powder explosion but also promoted the study of aluminum powder explosions under special circumstances.

Aluminum powder explosion consists of complex chemical reactions. Studies have been focused on the effects of particle properties [10] and external factors [11] on the reaction. For example, Sundaram et al. [12] found that the freshly prepared aluminum powder was extremely active and could undergo spontaneous oxidation reactions in any oxidizing environment. As the reaction proceeded, the oxidation produced an oxide film on the particle surface, which passivated the aluminum particles. Risha et al. [13] and Trunov et al. [14] further confirmed that the aluminum passivation in air was attributed to the formation of a 2-4 nm layer of amorphous oxide (Al_2O_3) on the particle surface that blocked the contact between aluminum and oxygen. Friedman and Maček [15] studied the ignition of micron aluminum powder and found that melting the oxide layer on aluminum particles at 2350 K was required for the ignition. The aluminum core was then exposed to oxygen via the channels formed in the molten oxide shell due to the surface tension. Baudry et al.

[16] investigated the effects of oxide content on the oxidation behavior of aluminum powder and found that the energy required for the ignition of aluminum powder increased with the increase of its oxide content. The E50 ignition energy of aluminum powder was doubled as the oxide content increased from 0.46 wt% to 6.3 wt%. Unfortunately, to the best of our knowledge, the effects of moisture content on the explosive properties of aluminum powder have been rarely reported [15].

Moisture is widely used as a special inert medium to suppress the explosions of nonmetallic particles [17, 18]. However, the properties of metal dusts, such as aluminum powder, are significantly different, and thus the effects of moisture content on their explosions are also different. In the aluminum powder processing plants, both of the wet polishing process and the wet dust removal involve the prevention of aluminum powder explosion with water. However, the quantitative description and mechanism of the explosion prevention still remain unclear. Surprisingly, most standard protocols and procedures for dust explosion tests exclude the effects of moisture content. The tests of same explosion parameter require significantly different moisture contents in different standard measurement systems. For example, the American Society for Testing Materials [19, 20] requires the moisture content of the to-be tested dust less than 5% for the explosion parameter measurement, while that in China [21, 22] is less than 10%. The European Committee for Standardization has no specific requirement of moisture content, except for a written record [23–25]. Understanding the effects of moisture on the lower limit of aluminum powder explosion would facilitate the explosion risk control of aluminum powder using moisture spray in aluminum powder polishing processes. In the present work, the effects of moisture content on the minimum explosible concentration of aluminum powder were experimentally studied, and the related mechanism was proposed. Our work provides an important scientific guidance for the safety management of aluminum powder processing and polishing.

2. Materials

2.1. Aluminum Powder Analysis. The micron spherical aluminum powder used in the present work was supplied by Henan Yuanyang Powder Technology Co., Ltd. (Xinxiang, Henan, China). The particle sizes of aluminum powder D10, D50, D90, and D100 were measured to be 11.990 μm, 18.685 μm, 27.268 μm, and 43.551 μm, respectively, using a Hydro 2000MU laser particle size analyzer. Figure 1 shows the particle size distribution of the aluminum powder. The content of active aluminum, iron, copper, silicon, and water in the aluminum powder were measured by the corresponding standard methods (Table 1).

The active aluminum content was measured by the gas volumetric method in GB3169.1-82. Water content was determined by the weight loss on drying method according to GB3169.3-82. Fe content was measured by the phenanthroline spectrophotometry method according to GB/T6987.4-2001. Si content was determined by the molybdenum blue spectrophotometry method according to GB6987.6-2001. Cu content was detected by oxalyl dihydrazide spectrophotometry method according to GB/T6987.2-2001.

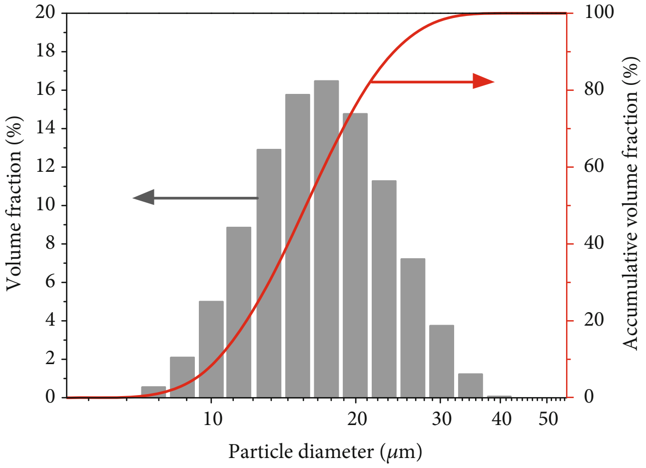


FIGURE 1: Particle size distribution of micron aluminum powder.

TABLE 1: Chemical composition of aluminum powder.

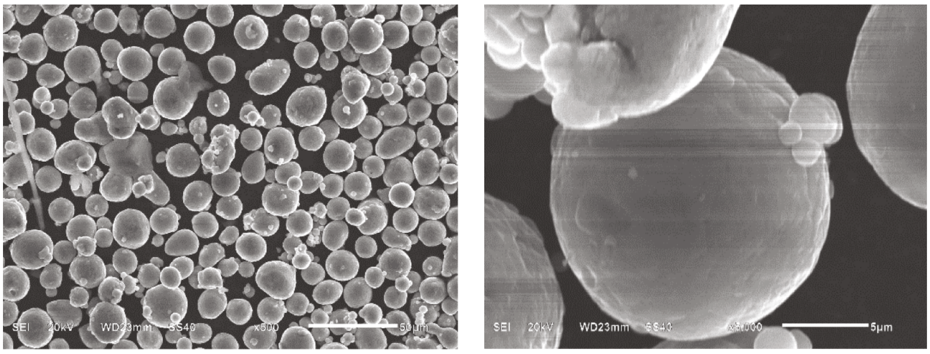
Active aluminum content (%)	Impurity content (%)			
	Cu	Fe	Si	H_2O
99.79	0.0011	0.1015	0.0417	0.02

The morphology of the aluminum powder was imaged using a JSM-6510LV high-low vacuum scanning electron microscope (SEM). The SEM image shown in Figure 2(a) suggests that the aluminum powder consists of well-dispersed spherical microparticles with smooth surfaces. The high-resolution SEM image shown in Figure 2(b) reveals tiny folds, microcracks, and small particles, possibly alumina particles, on the particle surfaces [26].

2.2. Preparation of Aluminum Powder Samples. The aluminum power (3 kg) was rapidly dried in vacuum at 50°C for 2 h to avoid the influences of oxidation, oxygen, humidity, etc. on its properties [11]. The dried aluminum powder was divided into two equal portions, immediately sealed in sealed bags, and labeled as sample a and sample b.

2.2.1. Treatment of Sample a. Sample a (1.5 kg) was divided into ten equal portions and, respectively, mixed with certain amounts of water to achieve the moisture contents of 0%, 3%, 5%, 8%, 10%, 13%, 15%, 18%, 20%, and 21% which were denoted as $a_{1\text{-}10}$. The moisture content refers to the weight percentage of water in the total weight of the water-aluminum powder mixture. To ensure the uniform distribution of moisture in the aluminum powder, the aluminum powder was repeatedly stirred in different directions and then stored in a vacuum bag. Table 2 lists the compositions of each sample and Figure 3 shows the photos of representative aluminum powder samples with different moisture contents.

The samples with low moisture contents in the range of 2-6% exhibit obvious agglomeration behaviors and the particle sizes of resultant aggregates varied significantly. The



(a) (b)

Figure 2: SEM images of aluminum powder.

Table 2: Compositions of aluminum powder samples with different moisture contents prepared from sample a.

Sample	Weight (g)		Moisture content (%)	Sample	Weight (g)		Moisture content (%)
	Aluminum	H_2O			Aluminum	H_2O	
a_1	100.01	0	0	a_6	100.01	14.94	13
a_2	100.03	3.14	3	a_7	100.07	17.63	15
a_3	100.05	5.37	5	a_8	100.04	22.03	18
a_4	100.07	8.71	8	a_9	100.07	25.01	20
a_5	100.03	11.19	10	a_{10}	100.02	26.54	21

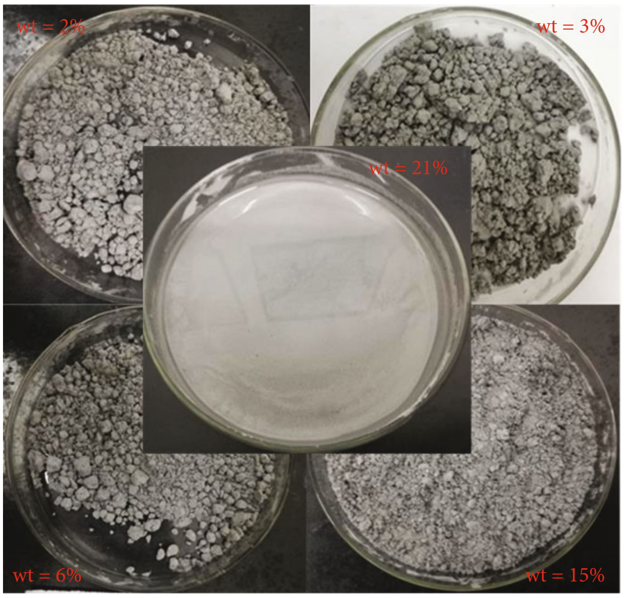


Figure 3: Photos of representative aluminum powder samples with different moisture contents.

particle sizes become more uniform as the moisture content increased to 15%. Increasing the moisture content to 21% results in a solid-liquid phase separation with no agglomeration observed. The water-aluminum powder mixture become heterogonous, yet explosive. However, no test for the minimum explosible concentration was conducted.

2.2.2. Treatments of Sample b. Sample b (1.5 kg) was divided into four portions of equal weights, added with water dropwise, homogenized using a spatula, and dried at 50°C for 2 h in an oven. One of the subsamples was divided into three equal portions (100 g) that were added with water to achieve the moisture contents of 0%, 5%, and 15%, respectively, and denoted as b_1, b_2, and b_3. The other three dried subsamples were dropwise added with 7.5 mL water, and homogenized and dried at 40°C for 4 h, 6 h, and 8 h, respectively. Similarly, each subsample was divided into three equal portions and mixed with water to achieve the moisture contents of 0%, 5%, and 15%, respectively, which were denoted as b_4-b_{12} as shown in Table 3.

3. Equipment and Experimental Procedure

3.1. Experimental Setup. The explosion parameters of aluminum powder are closely related to the experimental equipment, experimental conditions, etc. [11]. In the present work, aluminum dust explosion experiments were conducted with a standard 20-liter stainless steel spherical vessel (Figure 4) according to the international standard ISO6184-1. Firstly, the explosion chamber was partially vacuumed to 0.06 MPa and the dispersing air pressure was set to 2 MPa. When the solenoid valve between the dust storage container and the test chamber opened automatically, the air and coal dust were dispersed into the explosion chamber. The chemical igniter was energized upon the 60 ms delay. The aluminum powder was chemically ignited with an ignitor located in the center of the vessel. Data were collected with the pressure sensors on the explosion vessel wall in the range of 0-1.0 MPa at 1000 HZ. The explosion was controlled with a jet ignition relay controller connected to a computer. The

Table 3: Compositions of samples prepared with sample b.

Sample	Quality (g)		Moisture content (%)	Oxidation time (h)	Sample	Quality (g)		Moisture content (%)	Oxidation time (h)
	Aluminum	H_2O				Aluminum	H_2O		
b_1	1000.4	0	0	2	b_7	100.00	0	0	6
b_2	100.07	5.34	5	2	b_8	100.00	5.31	5	6
b_3	100.04	17.63	15	2	b_9	100.07	17.61	15	6
b_4	100.01	0	0	4	b_{10}	100.09	0	0	8
b_5	100.05	5.38	5	4	b_{11}	100.05	5.31	5	8
b_6	100.05	17.61	15	4	b_{12}	100.02	17.60	15	8

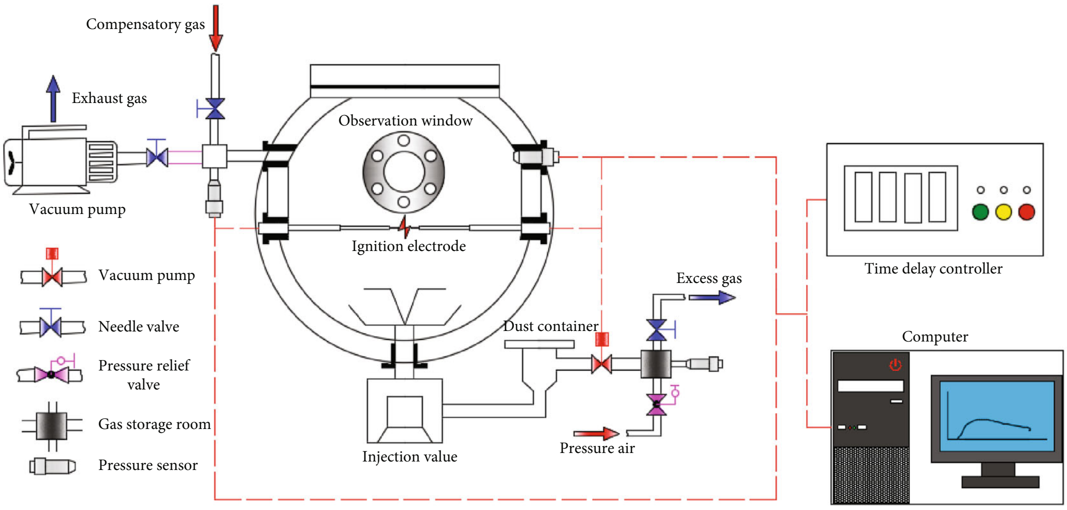


Figure 4: 20-liter spherical explosion test apparatus.

gas distribution system consisted of a high-pressure air tank and a pressure relief valve.

3.2. Standard Experiment Protocol. Experiments were carried out in compliance with the EN14034-3:2006 and GB/T16425 for the determination of the minimum explosible concentration of dust. Aluminum powder was chemically ignited using a pyrotechnic ignition device outputting a couple of 1 kJ igniters. The chemical igniter containing 40% zirconium powder, 30% barium nitrate, and 30% barium peroxide was weighted 0.48 g. To ensure the effective ignitions and reduce experimental errors, the ignition agent was weighted with an electronic balance with the precision of 0.01 g.

The minimum explosible concentration is usually measured by the dust explosion test in a certain concentration range. The reaction is considered an explosion if the maximum pressure produced by the ignition is equal to or greater than 0.15 MPa. If the explosion occurs, the dust concentration is then lowered for further explosion test until the maximum pressure produced under the same experimental conditions becomes less than 0.15 MPa for three consecutive times. The experimental minimum explosible concentration of dust ($C_{\min}$) is between the highest concentration to produce pressures less than 0.15 MPa in three consecutive tests (C_1) and the highest concentration to produce pressures equal to or greater than 0.15 MPa in three consecutive test (C_2), e.g.,

$$C_1 < C_{\min} < C_2 \tag{1}$$

For statistical purpose, we define $C_{\min} = C_2$ for the aluminum powder in the present work.

3.3. Experiment Procedure. A certain amount of aluminum powder was weighed, quickly put into the dust bin, and sealed. The explosion vessel was vacuumed to the absolute pressure of 0.06 MPa using a vacuum pump. Meanwhile, the air chamber was filled with dry air to obtain the absolute pressure of 2.0 MPa by adjusting the pressure reducing valve and the needle valve. The data acquisition was then activated. The aluminum powder was injected via the electromagnetic valve and ignited by the ignition system. The explosion pressure was recorded with the pressure sensors. After each explosion test, the explosion vessel and dust bin were thoroughly cleaned up and the ignition tip was replaced.

4. Results

4.1. Effects of Moisture Content on the Minimum Explosible Concentration of Aluminum Powder. Figure 5 shows the

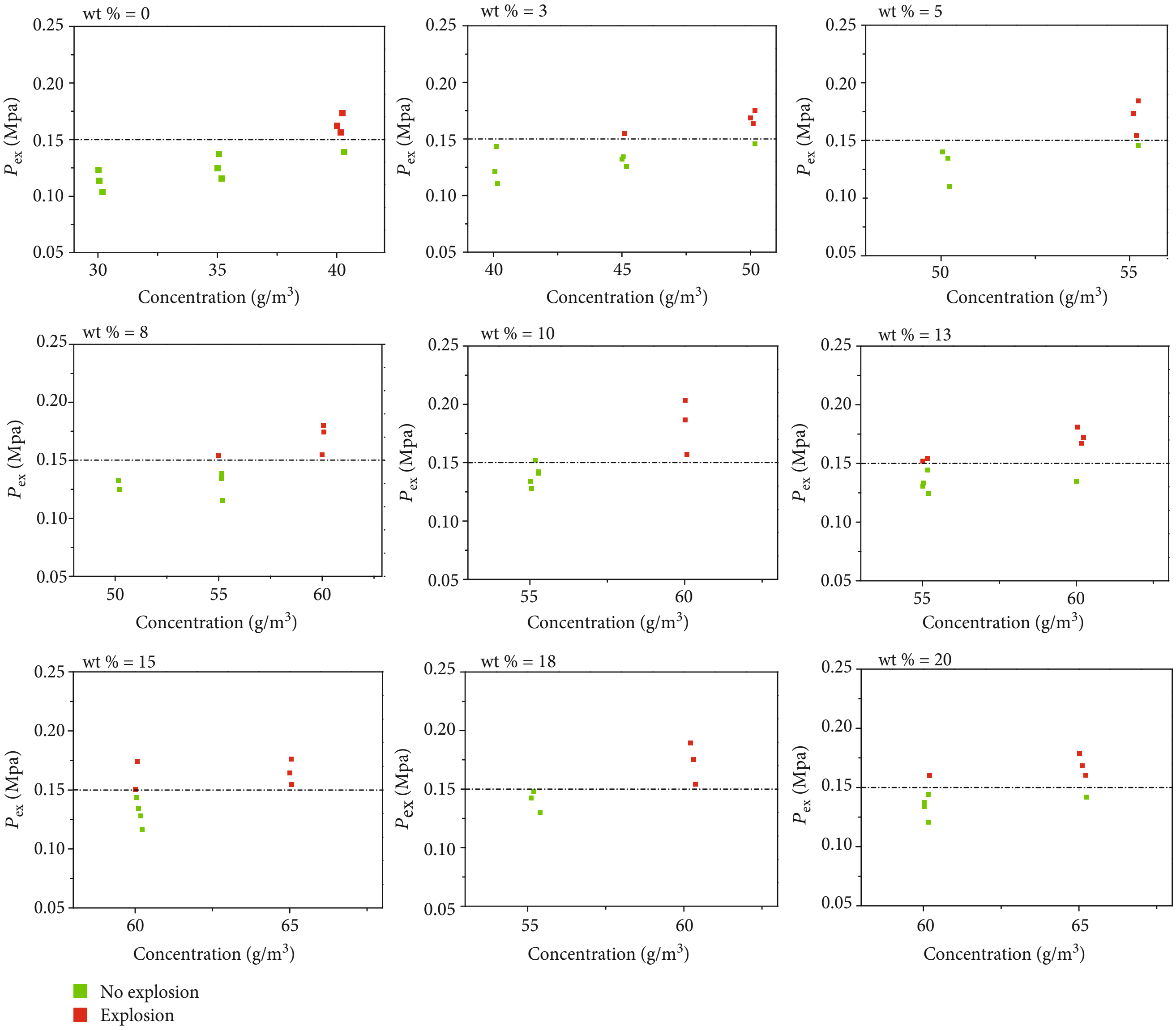


Figure 5: Maximum explosion pressures of the aluminum powders with different moisture contents.

maximum explosion pressures of the aluminum powders with different moisture contents. The maximum explosion pressure of aluminum powder with wt% = 0 and $\rho = 40$ g/m 3 exceeds 0.15 MPa in three consecutive tests. Therefore, the lower explosion limit of dry aluminum powder is determined to be 40 g/m^3. Table 4 lists the minimum explosible concentration of the aluminum powders of different moisture contents.

Table 4: Minimum explosible concentrations of aluminum powders with different moisture contents.

Sample	MEC (g/m^3)	Sample	MEC (g/m^3)	Sample	MEC (g/m^3)
a_1	40	a_4	60	a_7	65
a_2	50	a_5	60	a_8	60
a_3	55	a_6	60	a_9	65

Figure 6 shows the variation of the minimum explosible concentration of aluminum powder with moisture content. It is clear that the minimum explosible concentration rapidly increases with the increase of moisture content first, and the increasing trend becomes slower as the moisture content further increased. It is linearly increased by 50%, from 40 g/m^3 to 60 g/m^3, as the moisture content increased from 0% to 8%, and only gradually increased by 8.3%, e.g., from 60 g/m^3 to 65 g/m^3, as the moisture content further increased to 20%. It is worth noting that, even if the moisture lowers the explosion risk of aluminum powder, the aluminum powder is still explosive. In addition, compared with its effects on non-metallic dusts, such as pulverized coal [27], moisture is less effective in inhibiting the explosion of aluminum powder, which is significantly important for the explosion-proof guidance of aluminum powder processing and polishing.

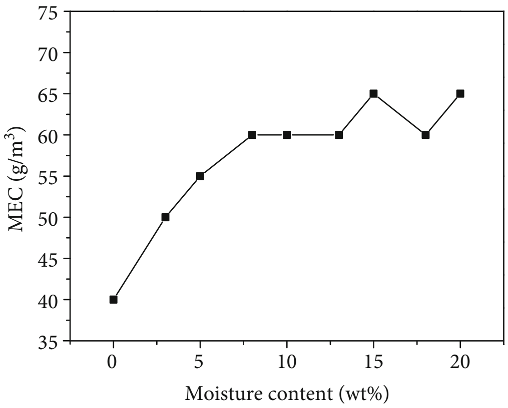


Figure 6: Variation of the minimum explosible concentration of aluminum powder with moisture content.

4.2. Effects of Oxidation Time on the Minimum Explosible Concentration of Aluminum Powder. Figure 7 shows the maximum explosion pressures of aluminum powders with different moisture contents as oxidized for 2 h, 4 h, 6 h, and 8 h. Table 5 lists the corresponding minimum explosible concentrations. The minimum explosible concentration of the dry aluminum powders oxidized for 2 h, 4 h, 6 h, and 8 h is same with the value of 40 g/m^3. Increasing the moisture content to 5 wt% and 15 wt% increases their minimum explosible concentration to 55 g/m^3 and 65 g/m^3, respectively. These results suggest that moisture is the major contributor to the increased minimum explosible concentration of aluminum powder, and short oxidation time has no significant effects on its minimum explosible concentration.

5. Discussion

Moisture inhibits the explosion of aluminum powder mainly by altering the oxide film on its surface and influencing its ignition and combustion process [28–30]. Micron aluminum powder is highly chemically active due to its large specific surface area. The surface oxide film can inhibit its chemical reactions with water and oxygen. The explosion of micron aluminum powder is a very complex unsteady gas-solid two-phase reaction. Moisture can act as an antidetonant for its explosion.

5.1. Effects of Moisture on the Surface Oxide Film of Aluminum Powder. Ye et al. [31] proposed an aluminum oxidation mechanism at room temperature, by which the Al_2O_3 film could maintain the chemical stability of aluminum powder at room temperature. Briefly, the micron aluminum powder particles adsorb free oxygen as exposed to the air. The adsorbed oxygen atoms on the particle surface and aluminum are converted to O^{2-} and Al^{3+}, respectively, via electron transfer, which eventually form an Al_2O_3 layer on the particle surface under strong induced dipole/dipole. The initial oxide layer formed first on the surfaces of neutral particles by adsorption produces a pressure gradient due to the electrostatic force and causes the orientational transfer of Al^{3+} and O^{2-}. The Al_2O_3 layer continuously grows via the oxidant (proton H^+) transfer at the metal-oxide interface. The electrostatic force gradually decreases due to the steric hindrance and eventually reaches the equilibrium state. The growth of the oxide layer is then stopped (Figure 8). Zeng et al. [32] found that the average thickness of Al_2O_3 films on micron aluminum particle surfaces increased exponentially with the average particle size. For example, the thickness of the Al_2O_3 layer on 10 μm particles was found to be 17 nm, and that on the particles of 100 μm was as thick as 54.8 nm. The dense and stable Al_2O_3 layer can maintain the stability of aluminum particles because the ignition of aluminum powder requires more energy to destruct the Al_2O_3 layer.

In our experiments, a thin water film can be formed on the dense and stable Al_2O_3 film as the aluminum powder exposed to moisture, which acts as a dielectric liquid to promote the hydration of Al_2O_3. During the hydration, the Al-O-Al bond in the oxide film is broken to form Al-OH bonds with water, producing highly thermal-stable AlOOH and $Al(OH)_3$. The destruction of this hydroxide film for the ignition of aluminum powder requires higher energies. Therefore, moisture can inhibit the explosion of aluminum powder. However, the hydration of Al_2O_3 is a very slow process at low temperatures. The AlOOH and $Al(OH)_3$ film cannot be formed rapidly in a short period of time, and the inhibition effect of the hydroxide film can be suppressed by the high ignition energy (10 kJ), e.g., "overridden effect" [33]. Therefore, the oxidation time has no significant effects on the minimum explosible concentration of aluminum powder.

5.2. Inhibition Effects of Moisture on the Ignition and Combustion of Aluminum Powder. The explosibility of a dust (obtained as a product or as a byproduct) may depend on all the variables. The natural consequence is the need of a careful process control, as the control may affect the risk of explosion in a plant. Our study also highlights the importance of the proper sampling phase during the assessing process of the explosion hazard of dust, as the sampling phase may affect the fine content and, consequently, the dust properties to significant extents [34]. There are two types of dust combustion in air: homogeneous combustion, i.e., gas-phase combustion, and nonuniform combustion [35]. Howard and Essenhigh [36] found that the dust combustion was strongly affected by dust particle size and gradually evolved from nonuniform combustion to gas-phase combustion with the increase of dust particle size. Moisture can affect the ignition and combustion of aluminum powder by endothermic processes, oxygen dilution, inhibiting the reaction kinetics, and particle agglomeration [27]. The influencing factors are different for different combustion mechanisms and affect the combustion in different ways. Water has no chemical specificity and acts strictly as a thermal quenching agent. If deployed very early in an explosion, it can have certain degrees of effectiveness in diffusing an incipient explosion. However, in this process, there are also acts that promote the occurrence of aluminum powder explosion. When water adsorption occurs, the hydrogen generation leads to an augmentation of the explosion severity. In contrast, the inhibiting effect could be put forward when the effective contact time between water and aluminum is reduced to the explosion duration.

Due to its strong hydrophilicity, the micron aluminum powder exhibits sever aggregation at the moisture contents

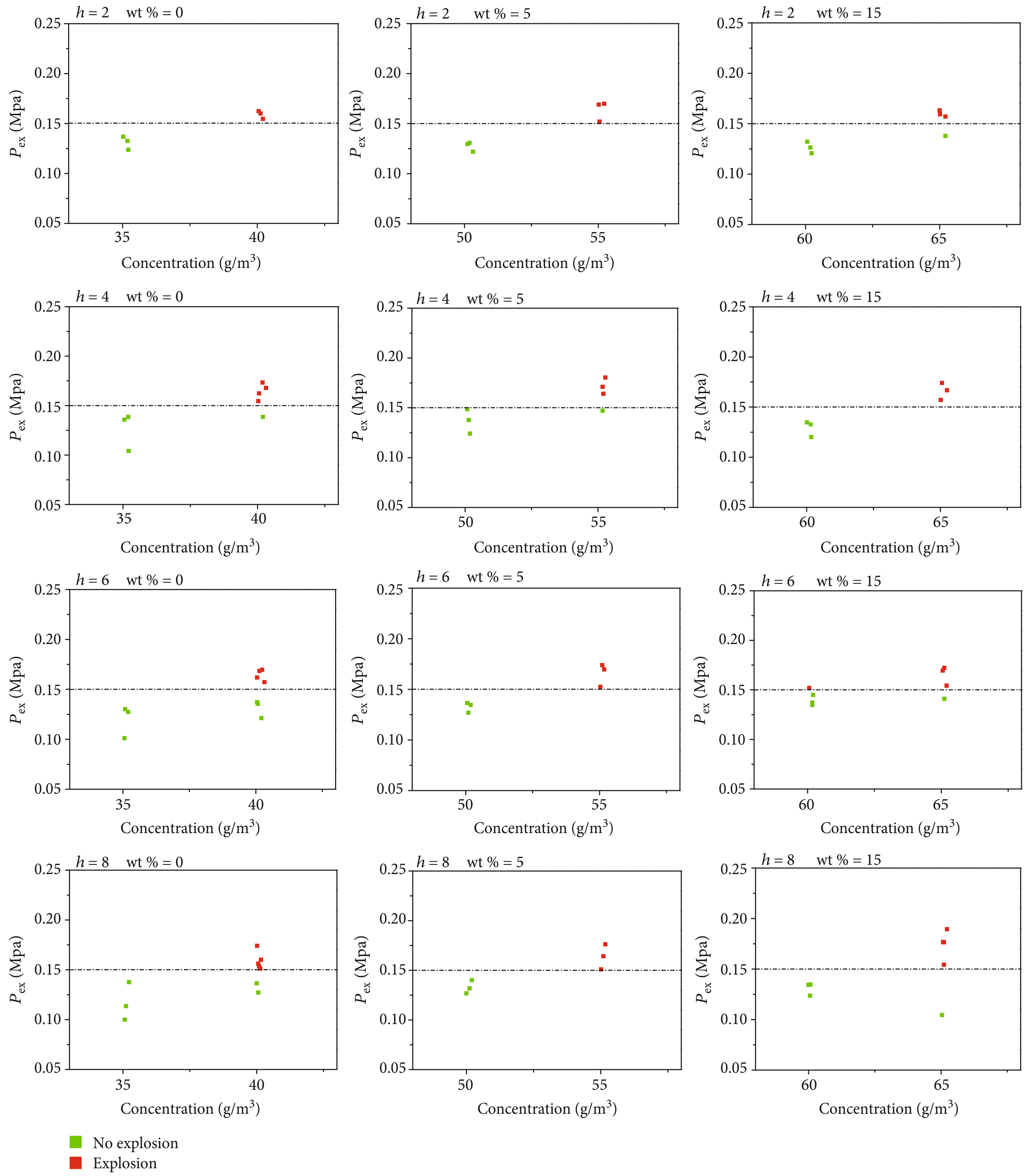


Figure 7: Maximum explosion pressures of aluminum powders with different moisture contents as oxidized for 2 h, 4 h, 6 h, and 8 h.

in the range of 0-8%, and thus undergoes nonuniform combustion. In the nonuniform combustion mechanism, combustion occurs on the particle surface, and thus the diffusion rate of oxygen to the particle surface is the key factor affecting the explosion. Water is transformed from liquid phase to gaseous phase at the ignition energy of 10 kJ. The water vapor increases the oxygen diffusion resistance and flame propagation, and thus reduces the burn rate of dust. Therefore, moisture inhibits the aluminum powder explosion by inhibiting the chemical reaction kinetics and the inhibition effect gradually decreases with the increase of moisture content. In addition, the moisture on aluminum

Table 5: Minimum explosible concentration of the aluminum powders with different moisture contents oxidized for different periods of time.

Sample	MEC (g/m^3)	Sample	MEC (g/m^3)	Sample	MEC (g/m^3)	Sample	MEC (g/m^3)
b_1	40	b_4	40	b_7	40	b_{10}	40
b_2	55	b_5	55	b_8	55	b_{11}	55
b_3	65	b_6	65	b_9	65	b_{12}	65

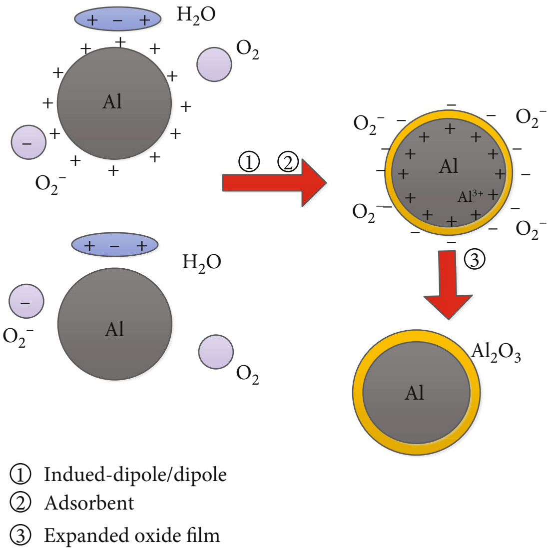


Figure 8: Oxidation mechanism of aluminum powder at room temperature.

particle surfaces can significantly reduce the effective distance between the particles, resulting in strong attractions between the particles and agglomeration tendency. The moisture in aluminum powder particle crackers can form liquid bridges between some particles, causing particle agglomeration. Therefore, the microstructure of micron aluminum powder particles also contributes to the particle agglomeration. The agglomeration weakens the particle dispersion, and thus increases the particle size of the aluminum powder. The agglomeration becomes more obvious with the increase of moisture content, and eventually becomes the main factor suppressing the combustion of aluminum powder. However, the aluminum powder particle agglomeration stops as the particle size increased to a certain value at a certain moisture content. During this process, moisture inhibits the aluminum powder combustion by the endothermic processes and oxygen dilution. As the moisture content increased to over 8%, the water film formed on the particle surface absorbs heat directly from the particle surfaces, the chemical ignition agent, the flame, and the combustion products, resulting in higher temperature. It also consumes the energy during liquid-gas phase transformation, which dominates the energy consumption. It is worth noting that the endothermic processes and oxygen dilution mainly rely on the liquid-gas phase transition of water. They inhibit the heat transfers of ignitor-aluminum powder and combusted aluminum powder-aluminum powder, and the inhibition effect is gradually weakened with the increase of moisture content. The water vapor generated during the phase transition inevitably decreases the oxygen content in the air, which in turn reduces the oxygen gradient between the environment and the combustion zone. The amount of water vapor is decreased as the moisture content increased. Therefore, the explosion inhibition effect of the endothermic processes and oxygen dilution are negatively correlated with moisture content, which also explains the explosivity of the micron aluminum powder with the moisture content of 21%.

6. Conclusion

In the present work, the effects of moisture content on the explosion of aluminum power were investigated. The results suggest that moisture can lower the explosion risk of aluminum powder. The minimum explosible concentration of aluminum powder is increases by 50%, from 40 g/m^3 to 60 g/m^3, as the moisture content increased from 0% to 8%, and increased by 8.3%, to 65 g/m^3, as the moisture content further increased to 20%. However, the oxidation of aluminum powder at 40°C for 8 h did not significantly alter the minimum explosible concentration, mainly because the hydration of Al_2O_3 was a slow process. The effects of the small amounts of AlOOH and $Al(OH)_3$ formed by the hydration can be overridden by the high ignition energy (10 kJ). Further investigation suggests that moisture inhibits the explosion of aluminum powder by altering its surface oxide film and inhibiting its ignition and combustion. In the moisture content range of 0-8%, the inhibition is attributed to the inhibited reaction kinetics and particle agglomeration and that the moisture content range of 8-20% is due to the endothermic processes and oxygen dilution effect. Increasing the moisture content to 21% caused solid-liquid phase separation, resulting in the heterogeneity of the system. However, the aluminum powder at the phase separation state is still explosive.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no competing interests.

Acknowledgments

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