Study on Dust Explosion Characteristics and Flame Propagation of Nano-Sized Aluminum Powders

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ABSTRACT

This study is mainly to explore the dust explosion characteristics and flame propagation of nano-sized aluminum (Al) powder. First of all, three kinds of Al powders with average particle sizes of 35, 75 and 100 nm were examined by scanning electron microscopy (SEM) and X-ray diffraction (XRD) to confirm the particle size and purity. An environment operation box was used to avoid the oxidation of nano-sized Al powder samples during the weighing process. Afterward, the 20-L explosion sphere apparatus was used to determine the dust explosion characteristics, including the maximum explosion pressure (P_{max}), maximum rate of pressure rise [$(dP/dt)_{max}$], minimum explosion concentration (MEC) and deflagration index (K_{St}), and the modified Hartmann tube was used to evaluate the minimum ignition energy (MIE) and flame propagation velocity (FPV). The experimental results indicated that the maximum P_{max}, $(dP/dt)_{max}$ and K_{St} values increased with decreasing average particle size of nano-sized Al powder, and the MEC and MIE values increased with increasing average particle size of nano-sized Al powder. In addition, the maximum flame propagation velocity (FPV) of nano-sized Al powder increased with decreasing particle size, and decreased with increasing ignition energy used. According to the dust explosion class, these three nano-sized Al powders were classified as Class 3, which means that they have very strong explosive power.

Keywords: nano-sized aluminum powder, dust explosion characteristics, flame propagation

奈米級鋁粉粉塵爆炸特性及火焰傳播之研究

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摘　要

本研究旨在探討奈米級鋁粉的粉塵爆炸及火焰傳播特性，首先藉由掃描式電子顯微鏡確認平均粒徑分別為 35、75 和 100 nm 三種尺寸的奈米鋁粉；實驗使用 20 公升爆炸鋼球量測粉塵爆炸特性，包括最大爆炸壓力(Pmax)、最大升壓速率[(dP/dt)max]、最小爆炸濃度(MEC)及爆燃指數(KSt)，並使用改良的 Hartmann 管評估最小點火能量(MIE)和火焰傳播速度(FPV)。實驗結果顯示 Pmax、(dP/dt)max 和 KSt 與鋁粉粒徑成反比，而 MEC 和 MIE 則與鋁粉粒徑成正比。此外，鋁粉最 FPV 值隨著粒徑減小而增加，並隨著所使用點火能量增加而減小。根據粉塵爆炸等級分類，這三種奈米級鋁粉被歸類為第 3 級，顯示它們具有很強的爆炸特性。

關鍵詞：奈米級鋁粉，粉塵爆炸特性，火焰傳播

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I. INTRODUCTION

The dust explosion is the rapid combustion of fine particles suspended in the air within an enclosed location. Some basic conditions must exist simultaneously for a combustible dust explosion to occur: a combustible dust, dispersed in air, a concentration above the flammable limit, the presence of a sufficiently energetic ignition source, and confinement of dust cloud [1]. If one of these conditions is missing, a dust explosion will not occur. Combustible dust is any fine material that has the ability to catch fire and explode when mixed with air, which usually comes from solid organic materials (such as sugar, flour, grain, wood dust, etc.), metal and non-metal inorganic materials. In the process industries dealing with combustible powder, dust explosion is a serious hazard, which can lead to death, injury and property damage. Catastrophic accidents related to dust explosions are reported every year. According to the data collected in the accident database and reported in the 2019 Combustible Dust Accident Report, between the years of 2016 and 2019, there were 133 accidents involving dust explosions in the United States, resulting in 12 worker deaths and 122 injuries [2].Therefore, it is necessary to check any dust-generating activities to confirm whether there is a risk of dust explosion.

Energetic metal particles possess desirable combustion characteristics, such as high combustion heat and fast energy release rate, and therefore have been introduced in explosives, propellants and pyrotechnic compositions to improve their performance [3]. Nano-sized metal particles have recently attracted considerable attention due to their unique and favorable physicochemical properties, as compared with micron-sized metal particles [4-5]. It is known that nano-sized aluminum (Al) powder is the most widely used energetic metal material due to its high reactivity. It is common in the processing factories of various Al products and has a great danger of dust explosion [6-8]. Nano-sized Al powder has caused many dust explosion accidents in recent years due to its increased use and the insufficient awareness of its specific hazards [9-13]. Dust explosions can occur in any process that involves handling of powdered material, such as milling, drying, processing, transport and storage. The dust explosion process of nano-sized Al particles involves a complex chemical reaction, which is classified in the kinetically controlled combustion regime, unlike the reaction of micro-sized Al particles which is controlled by diffusion [14-17]. Therefore, the surrounding pressure plays an important role. This is because the increase of pressure will enhance the heterogeneous surface reaction by inhibiting the gas phase reaction, thereby reducing the burning time and increasing the flame temperature [18]. In addition, the ambient temperature also has a great influence on the burning time of the particles. The increase in ambient temperature leads to the reduction in the burning time and the increase in the pyrometry temperature, which indicates that the condensed phase remains above the ambient temperature [19].

The related researches on the dust explosion of nano-sized Al particles mainly focuses on the effects of particle properties and external factors on the reaction, such as particle size and shape, dust concentration, pressure, temperature, and oxygen concentration, etc. [20-22]. Li et al. [21] found that the maximum explosion pressure (P_{max}) and maximum rate of pressure rise [$(dP/dt)_{max}$] mainly depended on the dust concentration. With the increasing of dust concentration, the P_{max} increased gradually to the maximum when the dust concentrations below 1000 g/m^3 and then the P_{max} decreased especially for the dust concentrations higher about 1250 g/m^3. At the same time, the trend of $(dP/dt)_{max}$ with the change of dust concentration was also similar. However, the change in particle size did not seem to have a significant effect on the dust explosion characteristics. The experimental results reported by Wu et al. [22] showed that the maximum P_{max}, $(dP/dt)_{max}$ and deflagration index (K_{St}) of 35 nm Al powder were 7.3 bar, 1286 bar/s and 349 bar m/s, respectively, and those of 100 nm Al powder were 12.5 bar, 1090 bar/s and 296 bar m/s, respectively. In addition, many dust explosion accidents involving flame propagation and secondary explosions have also been reported in the literature [23-25]. However, the details of the flame propagation of nano-sized Al powder are still unclear. Therefore, this is a topic worth exploring for reducing dust explosion accidents.

In this study, the dust explosion characteristics and flame propagation of three nano-sized Al powders with different particle sizes were measured by using experimental methods. First of all, the environment operation box was used to avoid the oxidation of nano-sized Al powder samples during the weighing process. The morphology and size were observed by scanning electron microscopy (SEM) and the purity was identified by X-ray diffraction (XRD). Afterward, the 20-L explosion sphere apparatus was used to determine the dust explosion characteristics, including the maximum explosion pressure (P_{max}), maximum rate of pressure rise [$(dP/dt)_{max}$], minimum explosion concentration (MEC) and deflagration index (K_{St}), and the modified Hartmann tube was used to evaluate the minimum ignition energy (MIE) and flame propagation velocity (FPV). Finally, these experimental results were used to analyzed the dust explosion hazard of nano-sized Al powder.

II. EXPERIMENTAL

2.1 Materials

Three kinds of nano-sized aluminum (Al) powders with average particle sizes of 35, 75 and 100 nm and purity of 99.9% were used to explore their dust explosion characteristics and flame propagation velocity, which were obtained from Yong-Zhen Technomaterial Co., Ltd. in Taiwan.

2.2 Equipment and Experimental Procedure

An environment operation box manufactured by Yong-Hsin Co., Ltd. in Taiwan was used to avoid the oxidation of nano-sized Al powder samples during the weighing process, as shown in Figure 1. It was assembled from acrylic plates with a thickness of 1 cm, the size was $80\times55\times50$ cm^3, and can be operated in an inert gas or vacuum environment. In addition, scanning electron microscopy (SEM, Hitachi S-3000H) was used to observe the morphology and size of nano-sized Al powder samples, and X-ray diffraction (XRD, Bruker D2 Phaser) was used to identify the purity of nano-sized Al powder samples.

Fig. 1. Photo of environment operation box

The 20-L explosion sphere apparatus (20-L-Apparatus) manufactured by Kühner AG in Switzerland was used to determine the dust explosion characteristics of three nano-sized Al powders with different particle sizes, including the maximum explosion pressure (P_{max}), maximum rate of pressure rise [$(dP/dt)_{max}$], minimum explosion concentration (MEC) and deflagration index (K_{St}), as shown in Figure 2. It consists of a hollow sphere made of stainless steel with an internal volume of 20 liters, a dust storage container connected with the chamber through a dust outlet valve, a pair of electrodes holding two pyrotechnic igniters of 5 kJ at the sphere center, and two piezoelectric pressure transducers to record the explosion development. In addition, the explosion chamber is surrounded by a jacket with flowing cooling water to keep the chamber wall temperature constant in each test [26]. The experimental procedure steps under the American Society for Testing and Materials (ASTM) E1226 test method [27] are the following. First, a certain amount of nano-sized Al powder sample was placed in the dust container. The explosion chamber was vacuumed to 0.4 bar, and then an automatic test sequence was initiated to pressurize the dust container to 20 bar. Nano-sized Al powder sample was dispersed into the explosion chamber from the dust container through the fast-actuating valve and the rebound nozzle. The rebound nozzle ensured an even distribution of dust within the explosion chamber. The control system activated the igniters located in the center of the explosion sphere with an ignition delay time of 60 ms after the dust was dispersed. P_{max} and $(dP/dt)_{max}$ were measured by two piezoelectric pressure transducers. The severity of dust explosions is usually expressed by the deflagration index (K_{St}), which is defined as

$$K_{St}=(dP/dt)_{max}V^{1/3} \quad (1)$$

where V represents the chamber volume (m^3) of the experimental apparatus.

Fig. 2. Photo of 20-L explosion sphere apparatus

The modified Hartmann tube (MIKE 3 of Kühner AG, Switzerland) was used to determine the minimum ignition energy (MIE) of three nano-sized Al powders with different particle sizes, as shown in Figure 3. The apparatus consists of a vertical cylindrical glass tube with an internal volume of 1.2 liters and a diameter of 7 cm mounted onto a dust dispersion system, and is fitted with two electrodes. The electrodes are connected to a circuit that produces an electrical spark of known energy. On top of the glass tube, a hinged cover allows for pressure relief in the case of a dust fire or explosion in the tube. The experiments were carried out according to BS EN 13821 experiment standard (British Standards Institution, 2006). A certain amount of nano-scale Al powder sample was placed in the dispersion cup, which was blown into the tube by compressed air and passed through the ignition source. If flame propagation was observed, the energy of the electrical spark was reduced until no flame propagation was seen for 10 consecutive tests. The MIE lies between the lowest energy value (IE) at which ignition occurred and the energy (NIE) at which in at least 10 successive experiments no ignition was observed. A statistical model was developed by Cesana and Siwek [28] to calculate the MIE from experimental results, as shown below

$$\log\ \mathrm{MIE} = \log\ \mathrm{IE} - \mathrm{N_I} \times \frac{\log\ \mathrm{IE} - \log\ \mathrm{NIE}}{\mathrm{N}+1} \qquad (2)$$

where N_I is the number of runs with successful ignition at IE and N stands for the total number of tests at the energy level of NIE. At least 5 concentrations need to be investigated to calculate the probability of ignition.

Fig. 3. Photo of modified Hartmann tube

The flame propagation of three nano-sized Al powders with different particle sizes was also studied by using the modified Hartmann tube. The flame propagation process was recorded by a high-speed video camera (FASTCAM SA1.1, Photron, Japan), which is composed of processor, imager and keypad, and can shoot 3000 frames per second. In addition, the digital-image processing device was connected with the video camera by an image acquisition card and the shot video was edited by image processing software to evaluate the flame propagation velocity (FPV).

III. RESULTS AND DISCUSSION

3.1 Identification of Experimental Samples

The SEM images of Al powders with average particle sizes of 35, 75 and 100 nm are shown in Figure 4. It can be seen from Figure 4 that the three nano-sized Al powders with different particle sizes have a spherical shape and tend to agglomerate. Figure 5 shows the XRD patterns of Al powders with average particle sizes of 35, 75 and 100 nm. The diffraction peaks appear at 38.47°, 44.72°, 65.10° and 78.23° corresponding to the (111), (200), (220) and (311) planes, which matches well with the standard pattern of Al (JCPDS No. 89-4037). This result means that the nano-sized Al powder samples have a very high purity, and the content of aluminum oxide is very low.

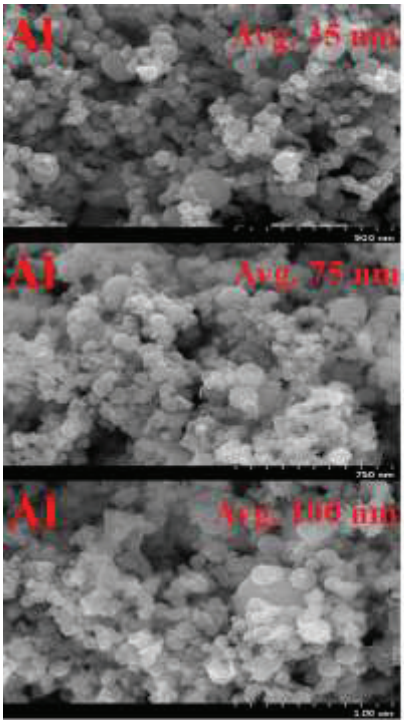

Fig. 4. SEM images of Al powders with average particle sizes of 35, 75 and 100 nm

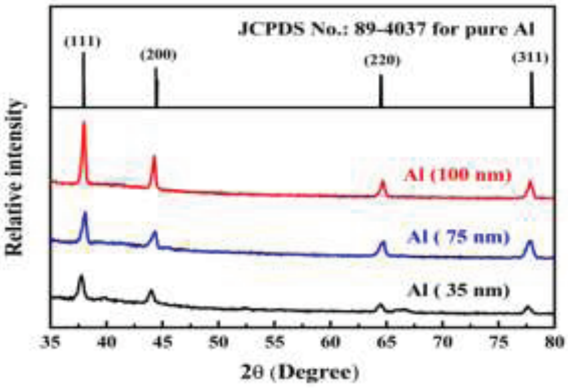

Fig. 5. XRD patterns of Al powders with average particle sizes of 35, 75 and 100 nm

3.2 Maximum Explosion Pressure (P_{max}), Maximum Rate of Pressure Rise [$(dP/dt)_{max}$] and Minimum Explosion Concentration (MEC)

The dust explosion characteristics of three nano-sized Al powders with different particle sizes were measured by 20-L-Apparatus, including the maximum explosion pressure (P_{max}), maximum rate of pressure rise [$(dP/dt)_{max}$] and minimum explosion concentration (MEC). The tested concentration was in the range of 10-750 g/m^3, including 10, 20, 30, 60, 125, 250, 500 and 750 g/m^3. The results indicate that the Al powder with an average particle size of 35 nm has a maximum P_{max} of 9.4 bar at a dust concentration of 500 g/m^3, and a maximum $(dP/dt)_{max}$ of 1617 bar/s at a dust concentration of 750 g/m^3. The maximum deflagration index (K_{St}) value calculated by equation (1) is 439 m bar/s. According to the dust explosion class in Table 1, Al powder with an average particle size of 35 nm can be classified as Class 3, which means that it has a very strong explosive power. For the Al powder with an average particle size of 75 nm, the maximum P_{max} is 8.6 bar at a dust concentration of 500 g/m^3, and the maximum $(dP/dt)_{max}$ is 1419 bar/s at a dust concentration of 750 g/m^3. Its maximum K_{St} value is 385 m bar/s and can also be classified as Class 3. For the Al powder with an average particle size of 100 nm, the maximum P_{max} and $(dP/dt)_{max}$ are 8.1 bar and 1201 bar/s at a dust concentration of 750 g/m^3, respectively. Its maximum K_{St} value is 326 m bar/s and can also be classified as Class 3. It is found that the maximum P_{max}, $(dP/dt)_{max}$ and K_{St} values increase with decreasing average particle size of nano-sized Al powder. This trend is consistent with the experimental results of Bartknecht [29] and Cashdollar [30]. In addition, the MEC values of Al powders with average particle sizes of 35, 75 and 100 nm are 20, 20, and 30 g/m^3, respectively. All the experimental results of the dust explosion characteristics for these three nano-sized Al powders are listed in Table 2. Wu et al. [22] have reported that the maximum P_{max}, maximum $(dP/dt)_{max}$, K_{St} and MEC of the Al powder with an average particle size of 35 nm are 7.3 bar, 1286 bar/s, 349 and 40 g/m^3, respectively, and these of the Al powder with an average particle size of 100 nm are 12.5 bar, 1090 bar/s, 296 and 50 g/m^3, respectively. These data indicate a lower hazard compared to the results of our experiments.

Table 1. Dust explosion class

Class	K_{st}(bar m/s)	Explosion Characteristics
0	K_{st}=0	No explosion
1	0<K_{st}≦200	Weak to moderate explosion
2	200<K_{st}≦300	Strong explosion
3	K_{st}>300	Very strong explosion

3.3 Minimum Ignition Energy (MIE) and Flame Propagation Velocity (FPV)

The minimum ignition energy (MIE) and flame propagation velocity (FPV) of three nano-sized Al powders with different particle sizes were evaluated by using modified Hartmann tube. The MIE tests used seven electric spark ignition energies of 1, 3, 10, 30, 100, 300 and 1000 mJ ,and six dust weights of 300, 600, 900, 1200, 1500 and 1800 mg. The ignition delay time was 120 ms. Figure 6 shows the MIE measurement results of Al powders with average particle sizes of 35, 75 and 100 nm. The solid square indicates successful ignition of that specific quantity of powder at that ignition energy, and the hollow square stands for no ignition at that quantity and ignition energy. The MIE values of Al powders with average particle sizes of 35, 75 and 100 nm calculated by equation (2) are 2.19, 2.19 and 2.56 mJ, respectively, which are also listed in Table 2. This is in line with expectations that the MIE of nano-sized Al powder is smaller compared with the MIE of micro-sized Al powder, and is consistent with the report of Eckhoff [31] that the smaller the particle size, the smaller the MIE.

Table 2. Explosion characteristics of Al powders with average particle sizes of 35, 75 and 100 nm

Average particle size (nm)	Maximum P_{max} (bar)	Maximum $(dP/dt)_{max}$ (bar/s)	Maximum K_{st} (m bar/s)	Explosion class	MEC (g/m^3)	MIE (mJ)
35	9.4	1617	439	3	20	2.19
75	8.6	1419	385	3	20	2.19
100	8.1	1201	326	3	30	2.56

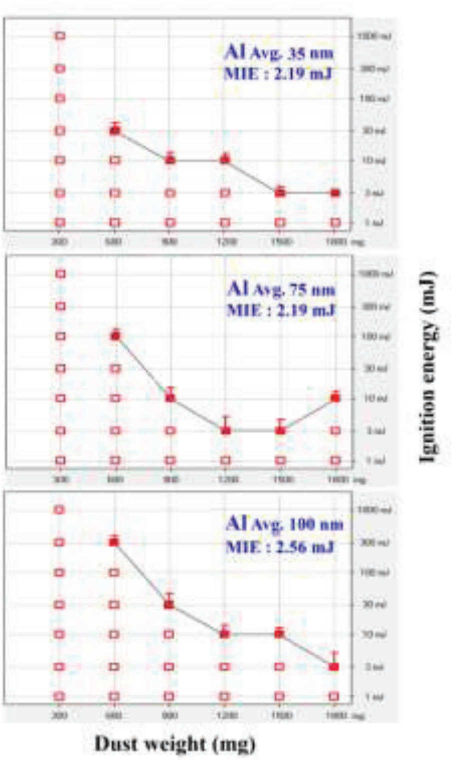

Fig. 6. MIE measurement results of Al powders with average particle sizes of 35, 75 and 100 nm

The FPV tests used two electric spark ignition energies of 30 and 100 mJ and four dust weights of 900, 1200, 1500 and 1800 mg. The ignition delay time was also 120 ms. Figure 7 displays the snapshots of flame propagation of dust explosion taken by high-speed video camera for Al powder with an average particle size of 35 nm under the conditions of different dust weights and an ignition energy of 30 mJ. The relationships between flame propagation distance and velocity versus time were measured and calculated as shown in Figure 8 and Figure 9, respectively. It is found that the Al powder with an average particle size of 35 nm has a maximum FPV of 2.27 cm/ms at a dust weight of 1200 g by using an ignition energy of 30 mJ. In addition, it is also observed from Figure 10 and Figure 11 that the 35 nm Al powder has a maximum FPV of 1.46 cm/ms at a dust weight of 1500 g by using an ignition energy of 100 mJ. It is worth noting that the maximum FPV of the 35 nm Al dust explosion with an ignition energy of 100 mJ is smaller than that of the 35 nm Al dust explosion with an ignition energy of 30 mJ.

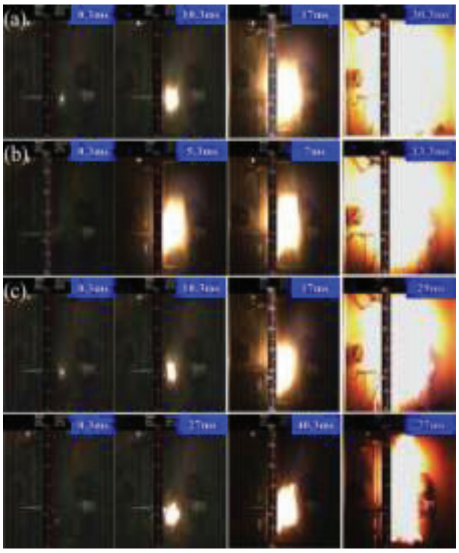

Fig. 7. Snapshots of flame propagation of dust explosion taken by high-speed video camera for Al powder with an average particle size of 35 nm [Dust weight: (a) 900, (b) 1200, (c) 1500 and (d) 1800 mg; Ignition energy: 30 mg]

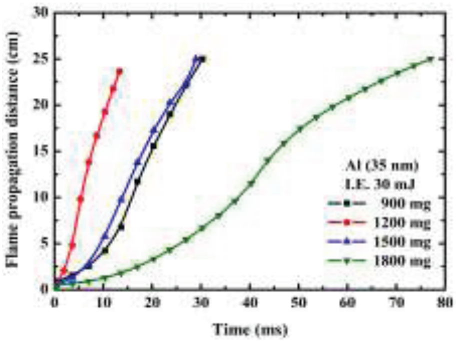

Fig. 8. Relationship between flame propagation distance versus time for dust explosion of Al powder with an average particle size of 35 nm under the conditions of different dust weight and ignition energy of 30 mJ

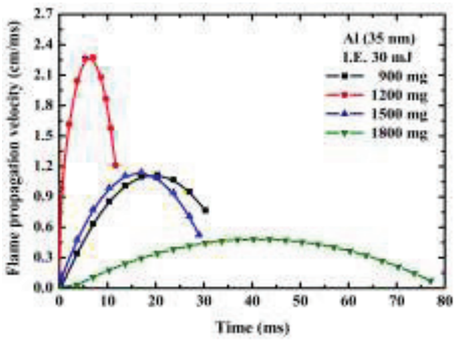

Fig. 9. Relationship between FPV versus time for dust explosion of Al powder with an average particle size of 35 nm under the conditions of different dust weight and ignition energy of 30 mJ

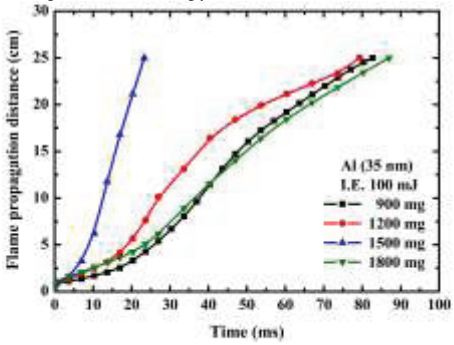

Fig. 10. Relationship between flame propagation distance versus time for dust explosion of Al powder with an average particle size of 35 nm under the conditions of different dust weight and ignition energy of 100 mJ

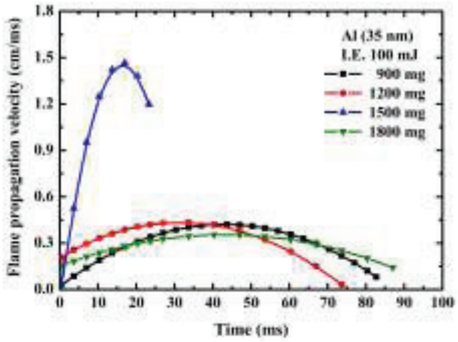

Fig. 11. Relationship between FPV versus time for dust explosion of Al powder with an average particle size of 35 nm under the conditions of different dust weight and ignition energy of 100 mJ

The snapshots of flame propagation of dust explosion for Al powder with an average particle size of 75 nm under the conditions of different dust weights and an ignition energy of 30 mJ are shown in Figure 12, and the corresponding relationships between flame propagation distance and velocity versus time are shown in Figure 13 and Figure 14, respectively. For the Al powder with an average particle size of 75 nm, the maximum FPV is 1.37 cm/ms at a dust weight of 1200 g by using an ignition energy of 30 mJ. In addition, the maximum FPV is 0.98 cm/ms at a dust weight of 1500 g by using an ignition energy of 100 mJ, as shown in Figure 15 and Figure 16. As with 35 nm Al powder, the maximum FPV of the 75 nm Al dust explosion with an ignition energy of 100 mJ is also smaller than that of the

75 nm Al dust explosion with an ignition energy of 30 mJ.

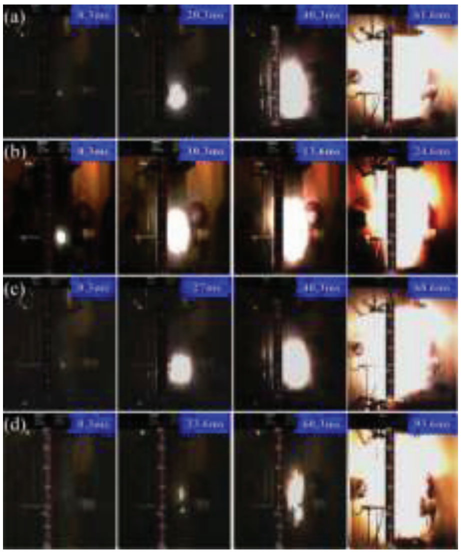

Fig. 12. Snapshots of flame propagation of dust explosion taken by high-speed video camera for Al powder with an average particle size of 75 nm [Dust weight: (a) 900, (b) 1200, (c) 1500 and (d) 1800 mg; Ignition energy: 30 mJ]

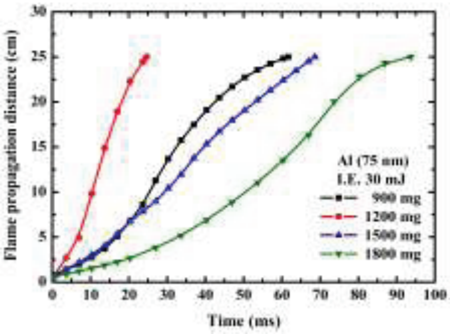

Fig. 13. Relationship between flame propagation distance versus time for dust explosion of Al powder with an average particle size of 75 nm under the conditions of different dust weight and ignition energy of 30 mJ

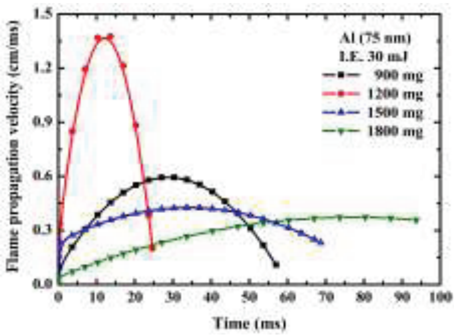

Fig. 14. Relationship between FPV versus time for dust explosion of Al powder with an average particle size of 75 nm under the conditions of different dust weight and ignition energy of 30 mJ

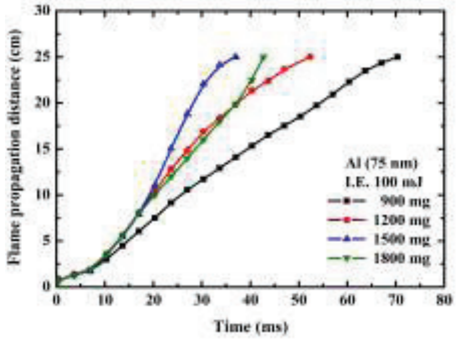

Fig. 15. Relationship between flame propagation distance versus time for dust explosion of Al powder with an average particle size of 75 nm under the conditions of different dust weight and ignition energy of 100 mJ

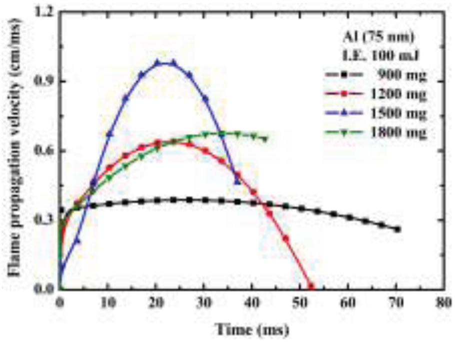

Figure 16. Relationship between FPV versus time for dust explosion of Al powder with an average particle size of 75 nm under the conditions of different dust weight and ignition energy of 100 mJ

Figure 17 displays the snapshots of flame propagation of dust explosion for Al powder with an average particle size of 100 nm under the conditions of different dust weights and an ignition energy of 30 mJ. Figure 18 and Figure 19 show the corresponding relationships between flame propagation distance and velocity versus time, respectively. It can be seen that the maximum FPV is 1.07 cm/ms at a dust weight of 1500 g. In addition, Figure 20 and Figure 21 also show the maximum FPV of 0.43 cm/ms at a dust weight of 1500 g by using an ignition energy of 100 mJ. The variation trend of maximum FPV with ignition energy is the same as that of 35 and 75 nm Al powders. The maximum FPV of these three nano-sized Al powders at the ignition energies of 30 and 100 mJ are listed in Table 3. It is also worth noting that the maximum FPV increases with decreasing average particle size of nano-sized Al powder.

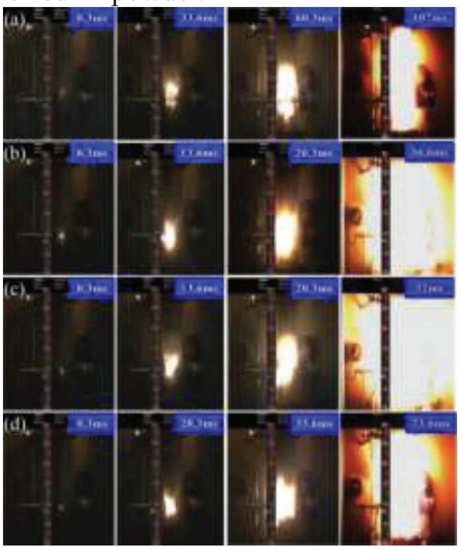

Fig. 17. Snapshots of flame propagation of dust explosion taken by high-speed video camera for Al powder with an average particle size of 100 nm [Dust weight: (a) 900, (b) 1200, (c) 1500 and (d) 1800 mg; Ignition energy: 30 mJ]

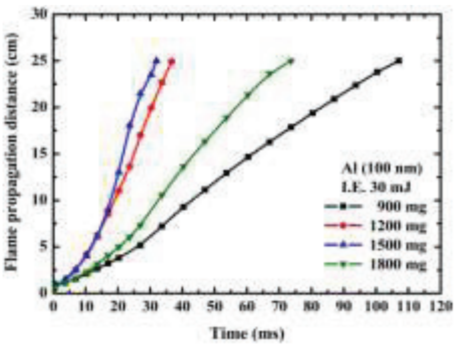

Fig. 18. Relationship between flame propagation distance versus time for dust explosion of Al powder with an average particle size of 100 nm under the conditions of different dust weight and ignition energy of 30 mJ

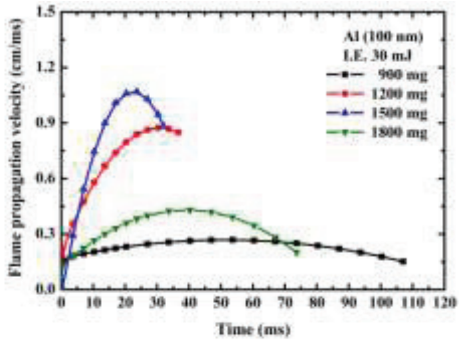

Fig. 19. Relationship between FPV versus time for dust explosion of Al powder with an average particle size of 100 nm under the conditions of different dust weight and ignition energy of 30 mJ

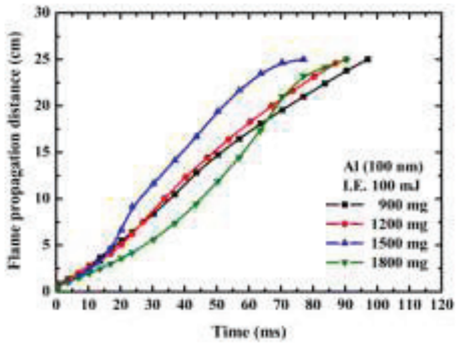

Fig. 20. Relationship between flame propagation distance versus time for dust explosion of Al powder with an average particle size of 100 nm under the conditions of different dust weight and ignition energy of 100 mJ

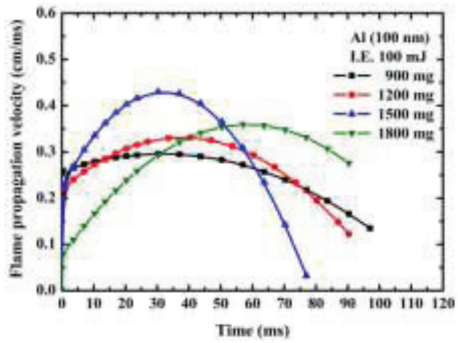

Fig. 21. Relationship between FPV versus time for dust explosion of Al powder with an average particle size of 100 nm under the conditions of different dust weight and ignition energy of 100 mJ

Table 3. Maximum FPV of dust explosion of Al powders with average particle sizes of 35, 75 and 100 nm

Average particle size (nm)	Ignition energy (mJ)	Maximum FPV (cm/ms)
35	30	2.27
	100	1.46
75	30	1.37
	100	0.98
100	30	1.07
	100	0.43

Ⅳ. CONCLUSION

In this paper, the experimental methods were used to study the dust explosion characteristics and flame propagation of Al powders with average particle sizes of 35, 75 and 100 nm. Based on the above experimental results and analyses, the following conclusions are obtained:

(1) The Al powder with an average particle size of 35 nm has a maximum P_{max} of 9.4 bar, a maximum $(dP/dt)_{max}$ of 1617 bar and a maximum K_{St} of 439 m bar/s. For the Al powder with an average particle size of 75 nm, the maximum P_{max}, $(dP/dt)_{max}$ and K_{St} are 8.6 bar, 1419 bar/s and 385 m bar/s, respectively. For the Al powder with an average particle size of 100 nm, the maximum P_{max}, $(dP/dt)_{max}$ and K_{St} are 8.1 bar, 1201 bar/s and 326 m bar/s, respectively. The maximum P_{max}, $(dP/dt)_{max}$ and K_{St} values increase with decreasing average particle size of nano-sized Al powder. According to the dust explosion class, Al powders with average particle sizes of 35, 75 and 100 nm can be classified as Class 3. In addition, the MEC values of Al powders with average particle sizes of 35, 75 and 100 nm are 20, 20, and 30 g/m^3, respectively.

(2) The MIE values of Al powders with average particle sizes of 35, 75 and 100 nm are 2.19, 2.19 and 2.56 mJ, respectively. The MIE of nano-sized Al powder is smaller compared with the MIE of micro-sized Al powder.

(3) The Al powder with an average particle size of 35 nm has a maximum FPV of 2.27 cm/ms by using an ignition energy of 30 mJ, and a maximum FPV of 1.46 cm/ms by using an ignition energy of 100 mJ. For the Al powder with an average particle size of 75 nm, the maximum FPVs by using ignition energies of 30 and 100 mJ are 1.37 and 0.98 cm/ms, respectively. For the Al powder with an average particle size of 100 nm, the maximum FPVs by using ignition energies of 30 and 100 mJ are 1.07 and 0.43 cm/ms, respectively. The maximum FPV of nano-sized Al powder increases with decreasing particle size, and decreases with increasing ignition energy used.

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