

Research Article

Dust Explosion Characteristics of Agglomerated 35 nm and 100 nm Aluminum Particles

Hong-Chun Wu,¹ Hsin-Jung Ou,¹ Deng-Jr Peng,¹ Hsiao-Chi Hsiao,¹
Chung-Yun Gau,¹ and Tung-Sheng Shih^{1,2}

¹Institute for Occupational Safety and Health, Council of Labor Affairs, Executive Yuan, No. 99, Lane 407,
Hengke Road, Sijhih City, Taipei County 22143, Taiwan

²Department of Public Health, China Medical University, Taichung, No. 91, Hsueh-Shih Road, Taichung City 40402, Taiwan

Correspondence should be addressed to Hong-Chun Wu, hong@mail.iosh.gov.tw

Received 9 November 2009; Revised 3 March 2010; Accepted 2 June 2010

Academic Editor: Mostafa Barigou

Copyright © 2010 Hong-Chun Wu et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In the experiment, nanoparticles of 35 nm Al and 100 nm Al powders, respectively, formed particles with average sizes of 161 nm and 167 nm in agglomeration. The characteristics of dust cloud explosions with the two powder sizes, 35 nm and 100 nm, revealed considerable differences, as shown here: $(dp/dt)_{\max-35\text{ nm}} = 1254\text{ bar/s}$, $(dp/dt)_{\max-100\text{ nm}} = 1105\text{ bar/s}$; $P_{\max-35\text{ nm}} = 7.5\text{ bar}$, $P_{\max-100\text{ nm}} = 12.3\text{ bar}$, and $\text{MEC}_{-35\text{ nm}} = 40\text{ g/m}^3$, $\text{MEC}_{-100\text{ nm}} = 50\text{ g/m}^3$. The reason of $P_{\max-35\text{ nm}}$ value is smaller than $P_{\max-100\text{ nm}}$ may be due to agglomeration. From an analysis of the explosive residue, the study found that nanoparticles of 35 nm Al powder became filamentous strands after an explosion, where most of 100 nm Al nanoparticles maintained a spherical structure. This may be because the initial melting temperature of 35 nm Al is 435.71°C, while that for 100 nm Al is 523.58°C, higher by 87.87°C. This study discovered that explosive property between the 35 nm Al and 100 nm Al powders after agglomeration were different.

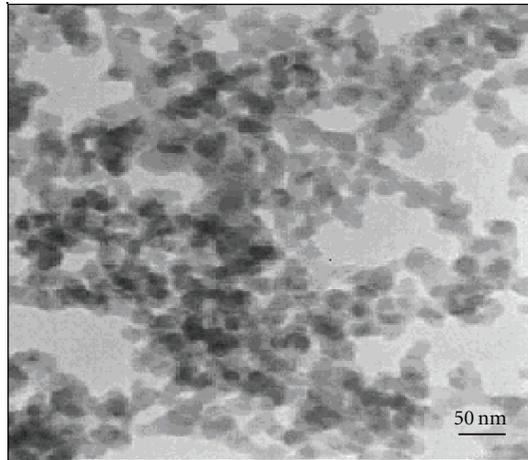
1. Introduction

When the diameter of a particle approaches the nanoscale, the van der Waals force increases. The sound, light, electrical, magnetic, and thermal properties of the particle change. When the agglomeration of particles changes them from the nano- to the microscale, certain nanoscale properties change. For example, if Fe_3O_4 particles aggregate to form 30–180 nm clusters, the color changes from black to yellow or blue, while the magnetic force increases. There is no optical effect when a Fe_3O_4 cluster is more than 180 nm [1].

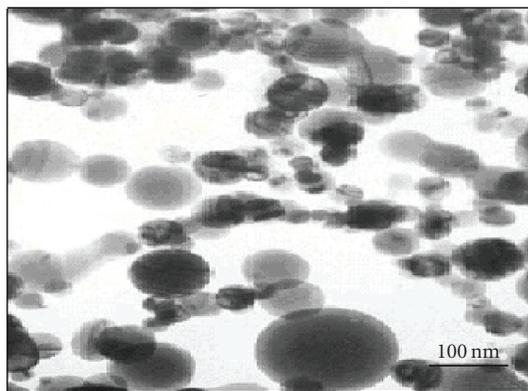
Agglomeration is related to the isoelectric point and pH value of the nanoparticles in a solution. Zhang et al. [2] pointed out that the isoelectric point of ZnO powder in water is 9.2. When initially purchased, ZnO powder is nanometer grade, but once it is transformed into an emulsion, the ZnO nanoparticles coalesce with other particles to form larger diameter particles that are no longer nanometer grade. When the pH is in the range of 7–11, ZnO powders only carry

small positive or negative charges. After the addition of a cationic dispersant of polyethyleneimine (PEI), the ZnO powder generates a large number of positive charges when it is dissolved in water to make it effectively disperse [3]. Niu et al. [4] applied polyacrylamide, which clings to the surface of the nanoparticles, to keep the SiO_2 nanoparticles uniformly dispersed in water with good stability.

The various interparticle forces give rise agglomeration of powders. The main forces have Van der Waals force, electrostatic forces, and interparticle force due to liquids (Eckhoff [5]). Bryant [6] studied the degree of agglomeration of fine boron carbide particle, dispersed as cloud in gas. He generated the cloud by blowing dust through a narrow nozzle and measured the mean effective agglomerated size as function of injection pressure. This phenomenon was investigated in greater detail by Yamamoto and Suganuma [7], their finding are significant to both the actual industrial dust explosion hazard and design of experimental methods to assess ignitability and explosibility of cloud of cohesive dusts.



(a)



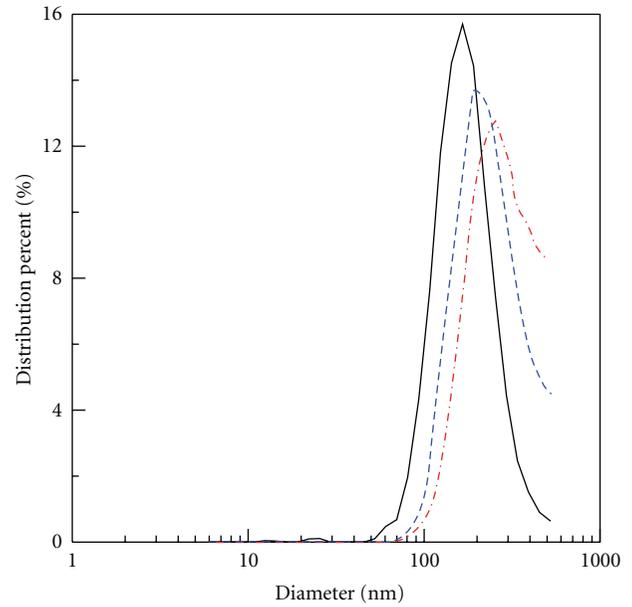
(b)

FIGURE 1: The image of primary particle Al powder (measured with TEM) (a) 35 nm (b) 100 nm.

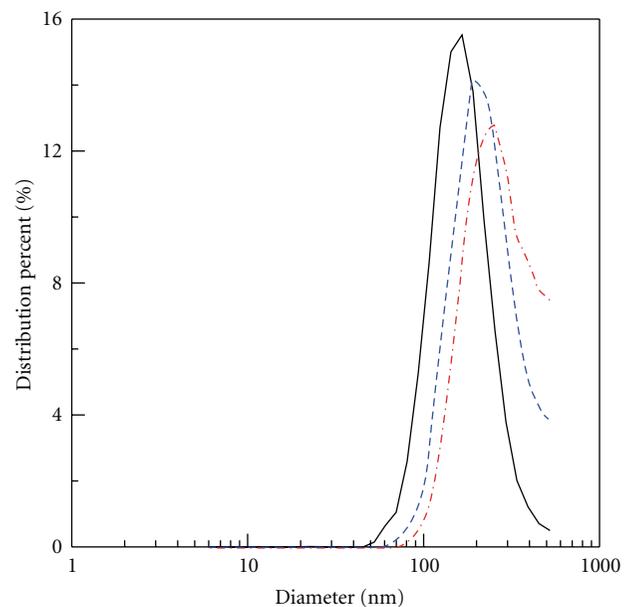
Agglomeration may occur when nanoaluminum comes in contact with moisture in the air. This research investigated the explosive characteristics of nanoaluminum, which formed aggregates with nearly equal diameters from particles with different original diameters.

2. Experimental Chemicals and Equipment

2.1. Chemicals. The specifications for the aluminum powder used in the study are shown in Table 1. The primary diameter is a projected figure calculated by a transmission electron microscopy (TEM) with a confidence interval of 99%, based on a sample containing 100 particles. The image is shown as (Figure 1). Since both the 35 nm and 100 nm Al nanoparticle powders demonstrated the agglomeration phenomenon, the particle size measurements obtained by the mode 3090 engine exhaust particle sizer (EEPS) were significantly bigger than the data originally provided by the material supplier (Figure 2).



(a)



(b)

FIGURE 2: Particle size distribution Al powder (a) 35 nm (b) 100 nm (measured with EEPS 3090).

2.2. Instrument

2.2.1. Particle Size Distribution Analyzer. The particle size distribution analyzer used in this study was a model EEPS 3090 made by the U.S. manufacturer TSI, and was used to measure the sizes of particles suspended in the air. EEPS 3090 has the ability to measure the dynamic behavior of particle emissions that occur during transient test cycles.

TABLE 1: The specifications for the aluminum powders.

Chemical code	Al-35 nm	Al-100 nm
True density	2.7 g/cm ³	2.7 g/cm ³
Bulk density	0.09 g/cm ³	0.14 g/cm ³
Packing degree	0.033	0.052
Diameter range	20~50 nm ^a	90~110 nm ^a
Average diameter	35 nm ^a	100 nm ^a
Shape	spherical structure ^a	spherical structure ^a
Agglomeration diameter	161 nm ^b	167 nm ^b

Note: ^aThe particle diameter is a projected figure calculated by a TEM (transmission electron microscope) with a confidence interval of 99%, based on a sample containing 100 particles.

^bThe aggregate diameter is based on an analysis by the EEPS 3090. The sampling tube was directly plugged into the 20-l-apparatus. The test was performed in accordance with the standard 20-l-apparatus test procedure. The aluminum powders came from dust container by high pressure air (20 barg) to the steel sphere (-06 barg).

TABLE 2: The characteristics of aluminum powder in a dust cloud explosion.

Chemical code	P_{\max} (bar)	$(dP/dt)_{\max}$ (bar/sec)	K_{St} (bar·m/s)	MEC (g/m ³)
Al-35 nm	7.3	1286	349	40
Al-100 nm	12.5	1090	296	50

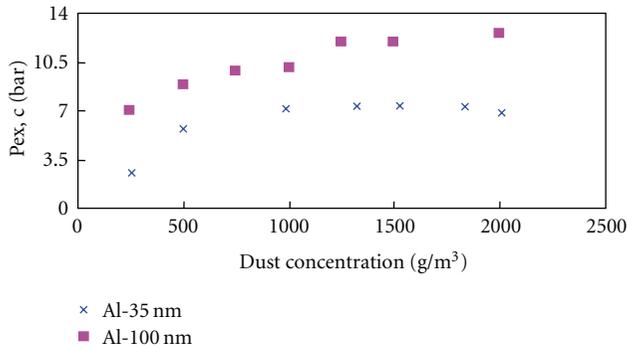
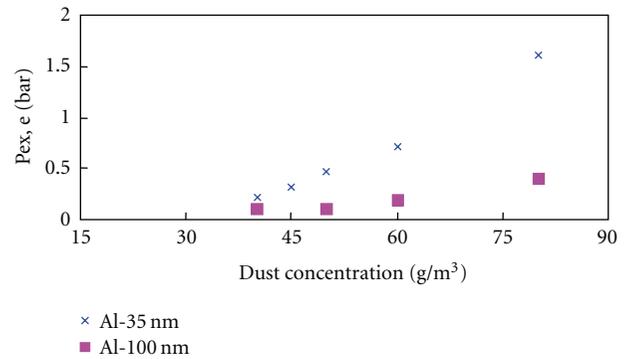
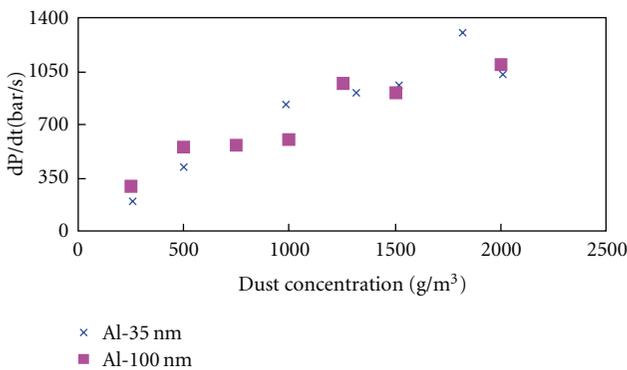
FIGURE 3: The P_{\max} for 35 nm Al (×) and 100 nm Al (■) powders.

FIGURE 5: MEC test measurements for 35 nm Al (×) and 100 nm Al (■) powders.

FIGURE 4: $(dP/dt)_{\max}$ test results for 35 nm Al (×) and 100 nm Al (■) powders.

Data is collected from all electrometers at rate of 10 times per second. This model reports 16 channels per decade of size, for a total of 32 channels between 5.6 and 560 nm.

The sampling tube was directly plugged into the 20-l-apparatus. The test was performed in accordance with the standard 20-l-apparatus test procedure. The aluminum powders came from dust container by high pressure air (20 barg) to the steel sphere (-06 barg).

2.2.2. The 20-l-Apparatus. A 20-l-apparatus was used for the explosion test. This apparatus was manufactured by Kühner AG of Switzerland. The temperature was set at 25°C. This instrument was used to measure three dust explosion characteristics: the maximum explosion pressure (P_{\max}), maximum rate of pressure rise ($(dP/dt)_{\max}$), and minimum explosion concentration (MEC). The chemical ignition energy was 10 kJ for the experiments of P_{\max} , and 2 kJ for MEC.

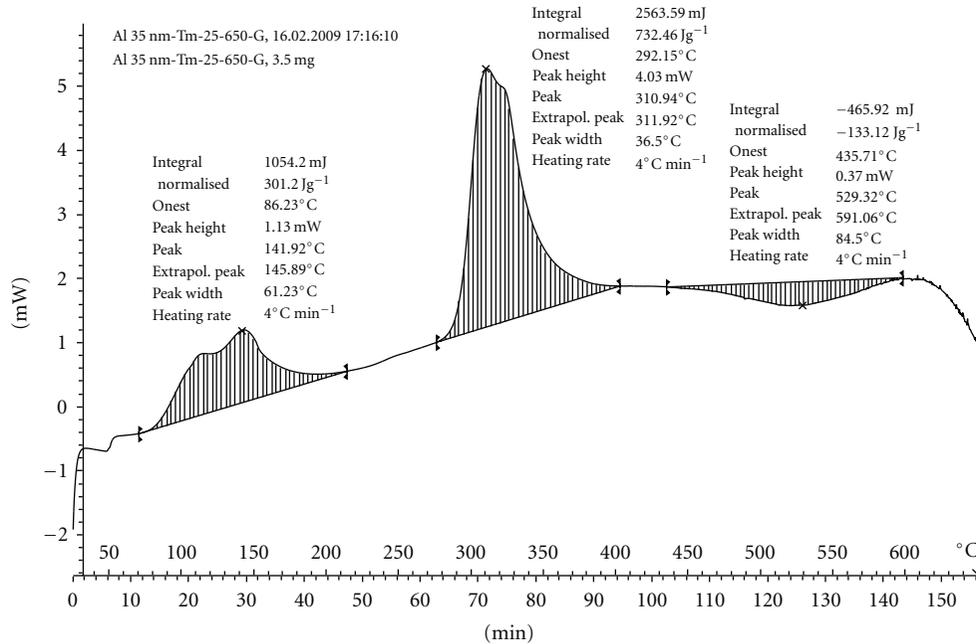


FIGURE 6: Thermal spectrum of 35 nm Al.

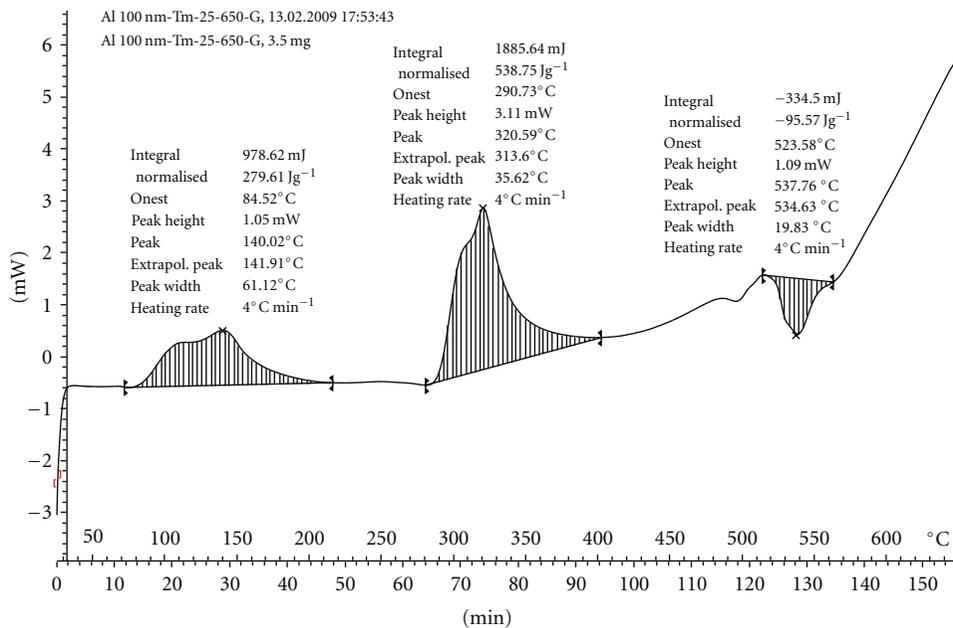


FIGURE 7: Thermal spectrum of 100 nm Al.

2.2.3. *Scanning Electron Microscope (SEM)*. A TESCAN Model 7435 was used. Samples of the explosive residue of the 35 nm and 100 nm nanoparticles were taken, which had been dispersed from the 20-l-apparatus after a dust explosion with a dust concentration of 1000 g/m³.

2.2.4. *Differential Scanning Calorimetry (DSC)*. This research used a DSC 822e analyzer (Mettler Toledo, Langacher, Switzerland) to obtain a thermal curve with differential

scanning calorimetry (DSC). The heating rate was set to 4°C/min, and the scanning temperature ranged from 25°C to 650°C for the characteristic analysis of the nanoaluminum.

3. Results and Discussion

3.1. *The Particle Size after Agglomeration*. The nanoparticles of 35 nm Al and 100 nm Al powders, respectively, formed particles with average sizes of 161.3 nm and 167.5 nm in

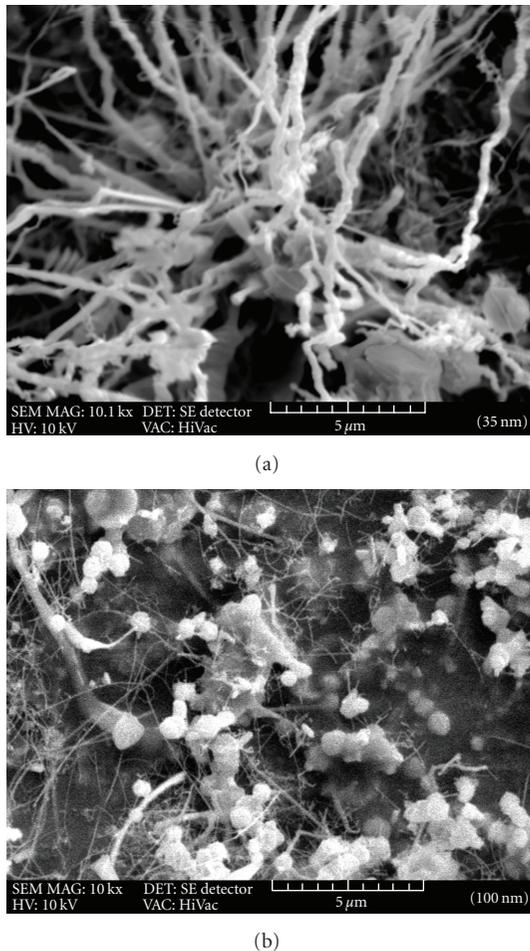


FIGURE 8: The residues of the 35 nm and 100 nm Al powders after the explosions.

agglomeration. The mean size of the agglomerates were only marginally larger than the sizes of the primary particle, which means that on average each agglomerate contains only a small number of primary particle. The reason may be the nozzle effect. The aluminum powders came from dust container by high pressure air (20 barg) to the steel sphere (-06 barg). The valve between dust container and steel sphere was like a nozzle that made agglomerate contain a small quantity of primary particle.

3.2. Maximum Explosion Pressure (P_{max}) and Maximum Rate of Pressure Rise ($(dP/dt)_{max}$). The experiment was based on 35 nm and 100 nm Al powders. Under different dust concentrations, the characteristics of dust explosions using these 2 particle sizes were demonstrated through measurements of the explosion pressure ($P_{ex,c}$) and maximum rate of pressure rise ($(dP/dt)_{max}$), as shown in Figures 3 and 4.

The test results for the 35 nm Al nanoparticles were recorded during the dust explosion. Its maximum explosion pressure (P_{max}) was 7.5 bars with a dust concentration of 1300 to 1800 g/m³, and the maximum pressure stepup rate ($(dP/dt)_{max}$) was 1254 bar/sec, with a dust concentration

of 1800 g/m³. For nanoparticles of the 100 nm Al powder, the maximum explosion pressure (P_{max}) was 12.3 bars, with a dust concentration from 1500 to 2000 g/m³, and the highest rate of pressure stepup ($(dP/dt)_{max}$) was 1105 bar/sec, with a dust concentration of 2000 g/m³. The explosive characteristics of the nanoaluminum powders are shown in Table 2.

The smaller size of microparticles could generate larger P_{max} and $(dP/dt)_{max}$ values (Bartknecht and Cashdollar [8, 9]); however, there are different tendency on P_{max} value in this study. It may result from agglomeration. In the future, this kinds of experiments need to do for identifying the property.

3.3. Minimum Explosion Concentration (MEC). This study was based on BS EN 14034-3, which states that if one of three test explosions with the same dust concentration is successfully fired with a recorded pressure ($P_{ex,e}$) larger than or equal to 0.5 bar, this confirms that the dust cloud has been ignited, where $P_{ex,e}$ is directly obtained with a pressure gauge without data correction. The $P_{ex,e}$ test results for the two powders, 35 nm Al and 100 nm Al, with different dust concentrations for the dust explosion test are charted in Figure 5. Based on BS EN 14034-3, the MEC for the two samples of different particle sizes were 40 g/m³ and 50 g/m³.

From the microperspective, the MEC results for these 2 samples showed a significant difference. Under the condition that the experiment only used 35 nm and 100 nm Al powders, the relationship between the particle size of the aluminum powder and MEC was directly proportional, with the MEC decreasing as the particle size decreased. The test results corresponded with the findings of Cashdollar and Amyotte et al. [9, 10].

3.4. The Melting Point Experiment for Nanoaluminum. Using differential scanning calorimetry, the melting points of the 35 nm Al (Figure 6) and 100 nm Al (Figure 7) were measured. The initial melt temperature of the 35 nm Al was 435.7°C, and that of the 100 nm Al was 523.5°C. This represents a difference of about 87.8°C. The melt point of the 35 nm Al was 529°C, and that of the 100 nm Al was 537.7°C.

3.5. The Residue Analysis after the Dust Explosion. After the dust explosion, particles of the 35 nm Al powder were changed into filamentous strands. A clear pattern can be seen from these test results. On the other hand, since the 100 nm Al powder contained larger particles, most of the residue after the explosion still maintained its spherical structure, with only a small amount of filamentous strands (as shown Figure 8). The highest explosion temperature had melted 30 nm Al particle with smaller diameter and lower melting point.

4. Conclusions

The nanoparticles of 35 nm Al and 100 nm Al powders, respectively, formed particles with average sizes of 161.3 nm

and 167.5 nm in agglomeration. The dust explosion characteristics for 35 nm and 100 nm Al aggregate particles are, respectively: $(dp/dt)_{\max-35\text{ nm}} = 1254\text{ bar/s}$, $(dp/dt)_{\max-100\text{ nm}} = 1105\text{ bar/s}$; $P_{\max-35\text{ nm}} = 7.5\text{ bar}$, $P_{\max-100\text{ nm}} = 12.3\text{ bar}$; and $\text{MEC} = 40\text{ g/m}^3$, $\text{MEC} = 50\text{ g/m}^3$. The reason of $P_{\max-35\text{ nm}}$ value is smaller than $P_{\max-100\text{ nm}}$ may be due to agglomeration.

The initial melt temperature of 35 nm Al is 435.7°C, while that of 100 nm Al is 523.5°C. This is a difference of about 87.8°C. 35 nm Al powder is readily melted under extreme heat, but 100 nm particles have demonstrated that they can sustain relatively high temperatures.

A residue analysis after the dust explosions showed that particles of 35 nm Al powder were changed into filamentous strands by the explosion, but that most of the 100 nm Al particles after the explosion still had a spherical structure, with only a small amount of filamentous strands.

This study discovered that the particle sizes of 35 nm and 100 nm Al powders were comparable after agglomeration, yet their explosive characteristics were different.

References

- [1] J. Ge, Y. Hu, M. Biasini, W. P. Beyermann, and Y. Yin, "Superparamagnetic magnetite colloidal nanocrystal clusters," *Angewandte Chemie*, vol. 46, no. 23, pp. 4342–4345, 2007.
- [2] Y. Zhang, Y. Chen, P. Westerhoff, K. Hristovski, and J. C. Crittenden, "Stability of commercial metal oxide nanoparticles in water," *Water Research*, vol. 42, no. 8-9, pp. 2204–2212, 2008.
- [3] F. Tang, T. Uchikoshi, and Y. Sakka, "Electrophoretic deposition behavior of aqueous nanosized zinc oxide suspensions," *Journal of the American Ceramic Society*, vol. 85, no. 9, pp. 2161–2165, 2002.
- [4] Y. Niu, Y. Wang, E. Wang, and J. Fu, "Research on dispersion and stability of SiO₂ nanoparticles in water medium," *China Powder Science and Technology*, vol. 12, pp. 1–3, 2006.
- [5] R. K. Eckhoff, *Dust Explosion in the Process Industries*, Gulf Professional Publishing, 3rd edition, 2003.
- [6] J. T. Bryant, "Powdered fuel combustion: mechanism of particle size," *Combustion and Flame*, vol. 20, pp. 138–139, 1973.
- [7] H. Yamamoto and A. Sukanuma, "Dispersion of airborne aggregated dust by an orifice," *International Chemical Engineering*, vol. 24, no. 2, pp. 338–345, 1984.
- [8] W. Bartknecht, *Dust Explosions: Course, Prevention, and Protection*, Springer, New York, NY, USA, 1989.
- [9] K. L. Cashdollar, "Coal dust explosibility," *Journal of Loss Prevention in the Process Industries*, vol. 9, no. 1, pp. 65–76, 1996.
- [10] P. R. Amyotte, K. J. Mintz, M. J. Pegg, and Y. H. Sun, "The ignitability of coal dust-air and methane-coal dust-air mixtures," *Fuel*, vol. 72, no. 5, pp. 671–679, 1993.



Hindawi

Submit your manuscripts at
<http://www.hindawi.com>

