Aerosol and Air Quality Research, 10: 38–42, 2010

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2009.06.0043

Explosion Characteristics of Aluminum Nanopowders

Hong-Chun Wu[1*], Hsin-Jung Ou[1], Hsiao-Chi Hsiao[1], Tung-Sheng Shih[1,2]

[1] *Institute of Occupational Safety and Health, Council of Labor Affairs, Executive Yuan, No. 99, Lane 407, Hengke Rd., Sijhih City, Taipei County 22143, Taiwan (R.O.C.)*
[2] *Department of Public Health, China Medical University, Taichung, Taiwan, No.91, Hsueh-Shih Rd., Taichung City 40402, Taiwan (R.O.C.)*

ABSTRACT

In 2005, an investigation conducted on three nanoscale attrition millers in Taiwan revealed that all three had undergone metal nanopowder explosions in the past. This research was aimed at determining the relationships between the particle diameter of an aluminum nanopowder and its maximum explosion pressure (P_{max}), maximum rate of pressure rise ($(dP/dt)_{max}$), minimum explosion concentration (MEC), and minimum ignition energy (MIE) by 20 liter apparatus and 1.2-L Hartmann apparatus. The results revealed that 35-nm aluminum powder has a P_{max} of 7.3 bar and deflagaration index (K_{St}) of 349 bar·m/s, in 100-nm aluminum powder, P_{max} of 12.5 bar and K_{St} of 296 bar·m/s and 40-µm aluminum powder, P_{max} of 5.9 bar and K_{St} of 77 bar·m/s. The value of $(dP/dt)_{max}$ for the 35-nm aluminum powder is 4.5 times that for the 40-µm aluminum powder. The 35-nm, 100-nm, and 40-µm powders have MEC values of 40, 50, and 35 g/m^3, respectively. The 35-nm and 100-nm powders both have MIEs less than 1 mJ, while the 40-µm powder has an MIE of 59.7 mJ.

Keywords: Nanopower; Attrition milling; Dust explosion.

INTRODUCTION

Mechanical attrition milling is still the main technique used in the mass production of nanopowders in Taiwan. It is not only a relatively low-cost process but is also easily scaled up for mass production. As a result, mechanical attrition milling has better controllable parameters and can be used to mill the powder particles down to 30 nm in diameter. The principle of the nano-powder grinder is to use high speed air to make the powder collide mutually. It causes the powder turns a nanometer scale from micron scale. All factory happen dust explosion when raw material containing Al feed to nano-powder grinder in Taiwan.

The risk of dust explosion is represented by minimum explosible concentration, maximum explosion pressure, maximum rate of pressure rise, limiting oxygen concentration, ignition temperature. The diameter of particle is very important factor for evaluating the risk of dust explosion. Except the diameter of particle, the factors of explosion characteristics include turbulence, initial pressure, oxygen concentration (Cashdollar, 1997).

The dust explosion research is most limited to micro scale. For example, Research on explosibility at high initial pressures of combustle dusts (Lázaro and Torrent, 2000), explosion temperatures and pressures of metals and other elemental dust clouds. (Cashdollar and Zlochower, 2007), flame propagation during dust explosion (Dobashi and Senda, 2006). The explosion characteristics of micro-aluminum is shown as following. The minimum explosive concentration were about 170 g/m^3 (0–8 µm), 180 g/m^3 (8–20 µm), 200 g/m^3 (20–37 µm), 240 g/m^3 (over than 37 µm). The minimum ignition energy were 8 mJ (0–8 µm), 6 mJ (8–20 µm), 14 mJ (20–37 µm), 48 mJ (over than 37 µm) (Nifuku *et al.*, 2007). The minimum ignition energy of nano-Ti, Fe are less than 1mJ (Wu *et al.*, 2009), That meaning of nano-Ti, Fe are very sensitivity for dust explosion.

All factory happen dust explosion when Al is from mirco to nano-scale in nano-powder grinder. It make facility destroy and fatality. Base on the effect of particle diameter for explosion characteristics, the risk of nano-aluminum were researched.

MATERIALS AND METHODS

Experiment Chemicals and Equipments

The specifications of the aluminum powders used in this study are listed in Table 1. The SEM image of aluminum powders is shown in Fig. 1. Accord Table 1, we can see the smaller the particle size, the large the surface area.

The explosion chamber was connected to a KSEP 310 auxiliary unit controller and a KSEP 332 signal detection

[*] Corresponding author. Tel.: +886-2-22607600 ext. 227;
Fax: +886-2-26607732
E-mail address: hong@mail.iosh.gov.tw

and controller, as shown in Fig. 2. Within the system, the KSEP 310 had connections to pressurized air and the vacuum pump to control the air intake and discharge; it also had connections to the KSEP 332 to open and close the air valve and to activate the chemical igniter.

The KSEP 332, however, was connected to a computer to transmit the control signals to the KSEP 310, and was connected directly to the pressure gauge on a Siwek 20 L chamber for collecting the detected pressure signals. This system induces a dust cloud explosion through the detonation of the chemical ignition composition; and during the experiment, the change in the air pressure inside the chamber with time can be determined through the pressure gauge.

A 1.2-L modified Hartmann tube (MIKE 3, Kühner AG, Switzerland) was used in this experiment to induce a dust cloud explosion through high-voltage electric sparks. The device offers seven electric spark ignition energies of 1, 3, 10, 30, 100, 300, and 1000 mJ (Cesana and Siwek, 2003). The delay time is 120 msec. An illustration of its exterior is shown in Fig. 3. During the experiments, visual inspection was required to judge whether the dust cloud had been ignited by the electric spark.

Experiment Method

In this experiment, four dust explosion characteristics were measured—the maximum explosion pressure (P_{max}), maximum rate of pressure rise ($(dP/dt)_{max}$), minimum explosion concentration (MEC), and minimum ignition energy (MIE)—for aluminum powders with three different particle sizes: Al-35 nm, Al-100 nm, and Al-45 µm. Furthermore, the incipient temperature and pressure of this experiment were 30°C and 1 atm, respectively.

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, and the chemical ignition energy was 5 kJ. 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).

Maximum explosion pressure (P_{max}) is maximum value of P_m determined by tests over a wide range of fuel concentrations. Maximum rate of pressure rise ($(dP/dt)_{max}$) is at nominal fuel concentration. It is defined as the maximum slope of a tangent through the point of inflexion in the rising portion of the pressure vs. time curve. The minimum explosion concentration (MEC) test determines the smallest concentration of material in air that can give rise to flame propagation upon ignition when in the form of a dust cloud. The test involves dispersing powder or dust samples in a vessel and attempting to ignite the resulting dust cloud with an energetic ignition source. Trials are repeated for decreasing sample sizes until the MEC is determined. Minimum ignition energy (MIE) is understood to mean the lowest energy value of a high-voltage capacitor discharge required to ignite the most ignitable dust/air mixture.

Table 1. Aluminum Powder Specifications.

Subject Code	Al-35 nm	Al-100 nm	Al-40 µm
Particle Diameter Range	10–50 nm	20–120 nm	10–50µm
Average Diameter	35 nm	100 nm	40 µm
Surface Area by BET	52.51 m^2/g	19.21 m^2/g	5.31 m^2/g
Geometry	Sphere	Sphere	Sphere
Supplier	Yong-Zhen Technomaterial Co., Ltd.	Titanex Corp.	Gredmann Well-Being Enterprise Co., Ltd.

Note: Measured by SEM and provided by supplier. The particle diameter is a projected figure calculated by a SEM (scanning electron microscope) with a confidence interval of 99%, based on a sample containing 100 particles.

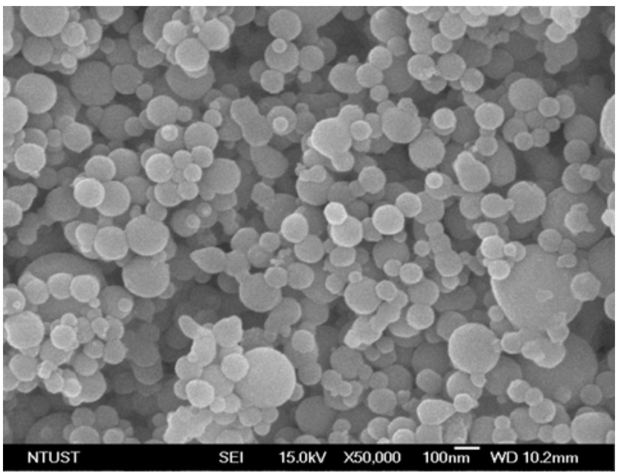

Fig. 1. The SEM of the 35 nm Al powder.

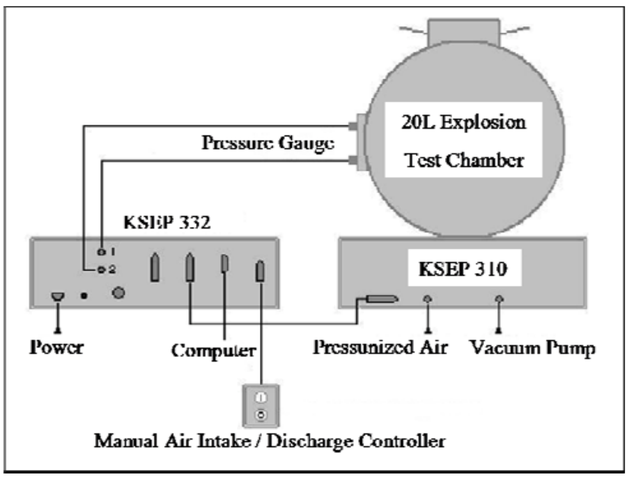

Fig. 2. 20-l-apparatus (Cesana and Siwek, 2003).

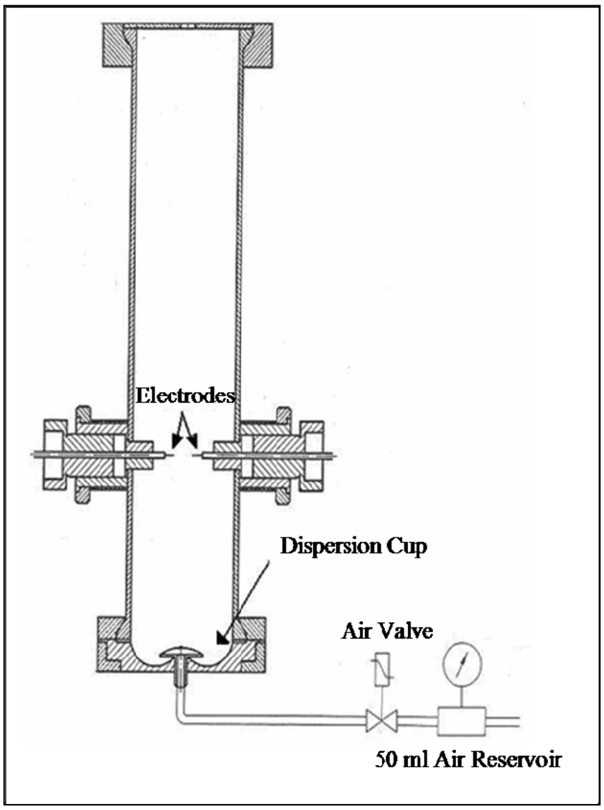

Fig. 3. 1.2-L Hartmann tube (Cesana and Siwek, 2003).

Due to the variation in $(dP/dt)_{max}$ with the volume of the experiment chamber, the deflagration index (K_{St}) is used internationally as a standard and is defined as

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

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

The experiments in this research were conducted according to the BS EN 13821 experiment standard (British Standards Institution, 2006), according to which, a given quantity of powder dust is concluded as being combustible at a specific ignition energy if at least one successful combustion trial exists in ten experimental trials of the same powder quantity and ignition energy, the MIE is the value between the maximum no ignition energy (NIE) and the minimum energy for powder ignition (IE). In 2003, Cesana and Siwek (2003) introduced Eq. (2), through the use of a statistical model to calculate the MIE from experiment results.

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

where N stands for the number of different particle diameters tested at an ignition energy value of IE (BS EN 13821 requires that N should be no smaller than 5), and N_I stands for the number of powder subjects ignited successfully at IE.

RESULTS AND DISCUSSION

Maximum Explosion Pressure (P_{max}) and Maximum Rate of Pressure Rise ($(dP/dt)_{max}$)

The results of the dust explosion experiments for the three aluminum powders are listed in Table 2. For Al-35 nm, P_{max} is 7.3 bar at dust concentrations between 1300 and 1800 g/m^3, and $(dP/dt)_{max}$ is 1286 bar/s at a dust concentration of 1800 g/m^3. For Al-100 nm, P_{max} is 12.5 bar at dust concentrations between 1500 and 2000 g/m^3, while $(dP/dt)_{max}$ is 1090 bar/s at a dust concentration of 2000 g/m^3. As for Al-40 µm, P_{max} is 5.9 bar at a dust concentration of 1250 g/m^3, while $(dP/dt)_{max}$ is 282 bar/s at a dust concentration of approximately 1750 g/m^3. These three aluminum powders have their respective P_{max} and $(dP/dt)_{max}$ in different dust concentration ranges.

From Eq. (1), the K_{St} values for Al-35 nm, Al-100 nm, and Al-40 µm are 349, 296, and 77 bar·m/s, respectively. According to the explosion class categorization from Table 3, Al-35 nm falls into class 3, which means that it has an extremely large explosive power. Al-100 nm is in class 2, which indicates a strong explosive power, while Al-40 µm is in class 1, with a weak or medium explosive power. Thus, the smaller the particle diameter, the larger the values of P_{max} and K_{St}. These results are consistent with the experiment results of Bartknecht (1989) and Cashdollar (1996).

Minimum Explosion Concentration (MEC)

The $P_{ex,e}$ values at different dust concentrations for the three different aluminum powders are plotted in Fig. 4., the MEC values are 40, 50, and 35 g/m^3, respectively. From a microscopic viewpoint, the MECs of these three aluminum powders are apparently different. Taking only two—Al-35 nm and Al-100 nm—into consideration, the MEC decreases with the particle size, which agrees with the results of Amyotte (1993) and Cashdollar (1996). After consulting other reported experimental results, the relation between the aluminum particle diameter and MEC is plotted in Fig. 5. We can see that when the particle diameter is less than 50 µm, the MEC remains in the range of 50 g/m^3 plus or minus 15 g/m^3, and for diameters of 52 µm and 71 µm, the MECs rises to values of 125 g/m^3 and 250 g/m^3, respectively. Therefore, for aluminum powder, the critical diameter is around 50 µm.

Minimum Ignition Energy (MIE)

The experimental results for different powder quantities and ignition energies for the three kinds of aluminum powders, Al-35 nm, Al-100 nm, and Al-40 µm are shown in Fig. 6. In Fig. 6, a solid dot indicates successful ignition of that specific quantity of powder at that ignition energy, and a hollow dot stands for no ignition at that quantity and ignition energy. The MIEs of Al-35 nm and Al-100 nm are both under 1 mJ, while the MIE of Al-40 µm is between 30 and 300 mJ. The Al-40 µm powder, for example, has an IE of 100 mJ and an NIE of 30 mJ; with N equal to 6 and N_I equal to 3, MIE can then be obtained through calculation as being 59.7 mJ.

Table 2. Aluminum Powder Explosion Characteristics.

Subject Code	P_{max}(bar)	$(dP/dt)_{max}$(bar/s)	K_{St}(bar·m/s)	*MEC*(g/m^3)	*MIE*(mJ)
Al-35 nm	7.3	1286	349	40	< 1
Al-100 nm	12.5	1090	296	50	< 1
Al-40 μm	5.9	282	77	35	59.7

Table 3. Dust Explosion Class.

Class	K_{St} (bar·m/s)	Explosion Characteristics
0	$K_{St} = 0$	No Explosion
1	$0 < K_{St} \leq 200$	Weak or Medium-Scale Explosion
2	$200 < K_{St} \leq 300$	Large-Scale Explosion
3	$K_{St} > 300$	Extremely Large Scale Explosion

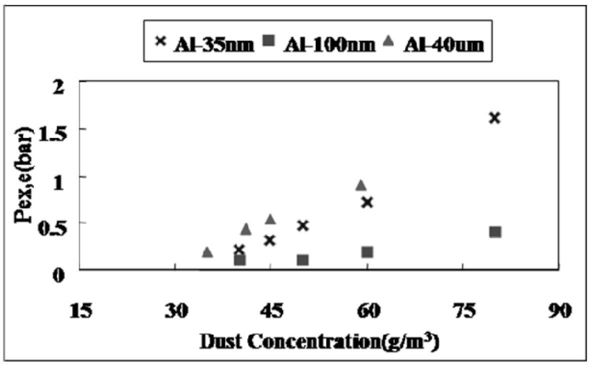

Fig. 4. MEC measurement.

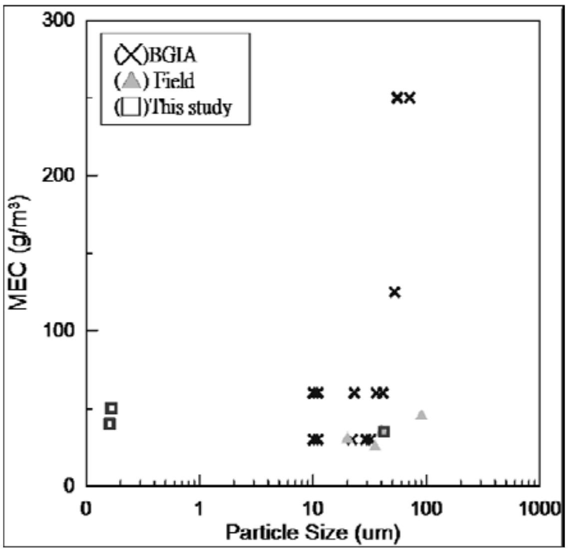

Fig. 5. Relationship between particle size and MEC.

As for Al-35 nm and Al-100 nm, because of the limitations of the apparatus, the NIEs were not measurable, hence, their MIEs could not be calculated through Eq. (2). We can only conclude that their MIEs are both smaller than 1 mJ. The experimental results show that the MIEs of the nanoscale aluminum powders are smaller than those of micrometer-scale aluminum powders, which agrees with the results of Eckhoff (2003) that the smaller the particle diameter, the smaller the MIE. Based on the results of pervious research and experimental records, the relation between the aluminum particle size and the MIE is obtained and plotted in Fig. 7.

In Fig. 7, ▲ denotes the maximum ignition energy to induce a no combustion trial (NIE), and ▼ denotes the minimum ignition energy to successfully induce powder combustion (IE). The region on the left of Fig. 7 is the region of successful powder combustion, while the region on the right is the region of no powder combustion.

We can see from the graph that the smaller the particle size, the smaller the MIE, and judging by the overall trend, the MIE would become smaller than 1 mJ for aluminum particle diameters smaller than 10 μm.

Data Reliability

Except to particle diameter affects to explosion characteristics, the other factor is the turbulence (Cashdollar, 1997). Because the system is not thermodynamic equilibrium when air carry particle in the experiment of dust explosion. It make the actual pressure lower than measured pressure (Mintz, 1995). It also appear transmission data from the Siwek 20 L chamber were

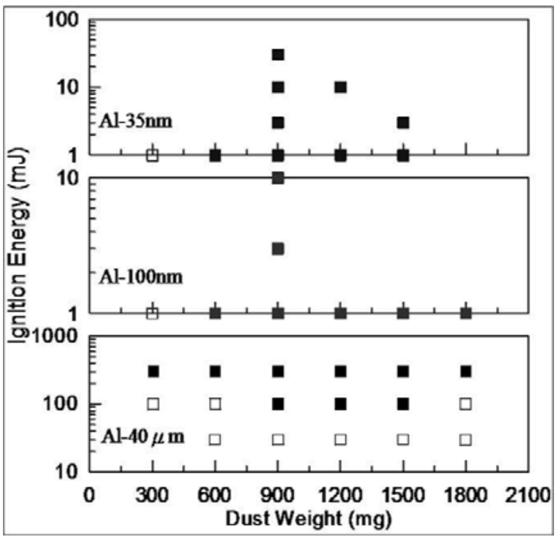

Fig. 6. MIE measurement.

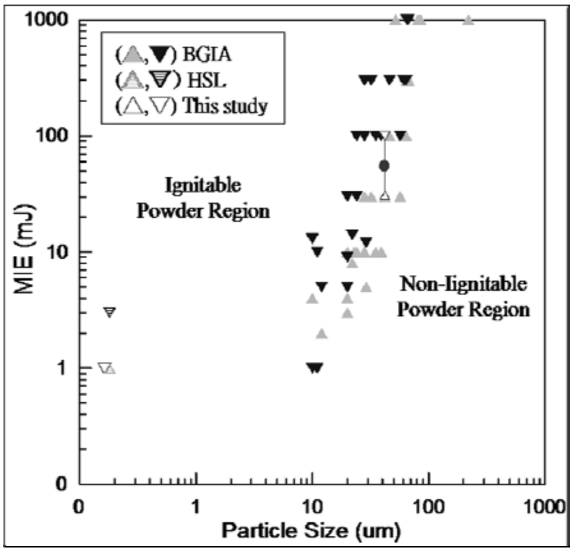

Fig. 7. Effect of particle size.

significantly lower than those of PRL and Fike chamber (Kalejaiye *et al.*, 2009). The delay time, representing the degree of the turbulence, is not follow cube root law between 20 liter and 1 m^3 vessel (Dahoe, *et al.,* 2001). Therefore, the turbulence disturbs the measurement of dust explosion seriously. The data of this research only represents the measurement by 20 liter apparatus (delay time = 60 msec), and 1.2-L modified Hartmann tube (MIKE 3, Kühner AG, Switzerland) (delay time = 120 msec).

CONCLUSIONS

The research reveal the following results.

1. The 35-nm aluminum powder has a P_{max} of 7.3 bar and deflagaration index (K_{St}) of 349 bar·m/s, in 100-nm aluminum powder, P_{max} of 12.5 bar and K_{St} of 296 bar·m/s and 40-μm aluminum powder, P_{max} of 5.9 bar and K_{St} of 77 bar·m/s. The value of $(dP/dt)_{max}$ for the 35-nm aluminum powder is 4.5 times that for the 40-μm aluminum powder.
2. The 35-nm, 100-nm, and 40-μm powders have MEC values of 40, 50, and 35 g/m^3, respectively.
3. The 35-nm and 100-nm powders both have MIEs less than 1 mJ, while the 40-μm powder has an MIE of 59.7 mJ. The smaller the particle size, the smaller the MIE, and judging by the overall trend, the MIE would become smaller than 1 mJ for aluminum particle diameters smaller than 10 μm.

According to the explosion characteristic of three aluminum powder, the production is achieved through dry milling, the possibility of dust explosion will present a serious threat for production process when aluminum material is milled down to nanoscales.

REFERENCES

Amyotte, P.R., Mintz, K.J., Pegg, M.J. and Sun, Y.H. (1993). The Ignitability of Coal Dust-Air and Methane-Coal Dust-Air Mixtures. *Fuel.* 72: 671-679.

Bartknecht, W. (1989). *Dust-Explosions, Course, Prevention, Protection.* Springer-Verlag Berlin, Heidelberg, New York.

British Standards Institution. (2006). Determination of the Lower Explosion Limit LEL of Dust Clouds. In Determination of Explosion Characteristics of Dust Clouds, BS EN 14034-3.

Cashdollar, K.L. (1996). Coal Dust Explosibility. *J. Loss Prev. Process Ind.* 9: 65-76.

Cashdollar, K.L. (1997). Overview of Dust Explosibility Characteristics. *J. Loss Prev. Process Ind.* 10: 317-324.

Cashdollar, K.L. and Zlochower, I.A. (2007). Explosion Temperatures and Pressures of Metals and Other Elemental Dust Clouds. *J. Loss Prev. Process Ind.* 20: 337-348

Cesana, Ch. and Siwek, R. (2003). MIKE 3: Minimum Ignition Energy 3.3, Kühner AG, Birsfelden, Switzerland.

Cesana, Ch. and Siwek, R. (2003). Operating Instruction 20-l-Apparatus 6.0, Kühner AG, Birsfelden, Switzerland.

Dahoe, A.E., Cant, R.S. and Scarlett, B. (2001). On the Decay of Turbulence in the 20-Liter Explosion Sphere. *Flow Turbul. Combust.* 67: 159-184.

Dobashi, R. and Senda, K. (2006). Detailed Analysis of Flame Propagation during Dust Explosions by UV Band Observations, *J. Loss Prev. Process Ind.* 19: 149-153.

Eckhoff, R.K. (2003). *Dust Explosions in the Process Industries*, 3rd ed.; Gulf Professional Publishing/Elsevier Science: Amsterdam.

K.J. Mintz (1995). Problems in Experimental Mmeasurements of Dust Explosions. *J. Hazard. Mater.* 42: 177-186

Kalejaiye, O., Amyotte, P.R. Pegg, M.J. and Cashdollar, K.L. (2009). Effectiveness of Dust Dispersion in the 20-L Siwek Chamber. *J. Loss Prev. Process Ind.* In Press.

Lázaro, E.C. and Torrent, J.G. (2000). Experimental Research on Explosibility at High Initial Pressures of Combustible Dusts. *J. Loss Prev. Process Ind.* 13: 221-228.

Nifuku, M., Koyanaka, S., Ohya, H., Barre, C., Hatori, M., Fujiwara, S., Horiguchi, S. and Soche, I. (2007). Ignitability Characteristics of Aluminium and Magnesium Dusts that Are Generated during the Shredding of Post-Consumer Wastes. 20: 322-329.

Wu, H.C., Chang, J.C. and Hsiao, H.C. (2009). Research of Minimum Ignition Energy for Nnano Titanium Powder and Nano Iron Powder. *J. Loss Prev. Process Ind.* 22: 21-24.

Received for review, June 11, 2009
Accepted, August 7, 2009