Effects of particle size and agglomeration on flame propagation behavior in dust clouds

Ichinose K.*, Mogi T., Dobashi R.

Graduate School of Engineering, The University of Tokyo, Bunkyo-ku, Tokyo, Japan
**Corresponding author's email: k_ichinose@chemsys.t.u-tokyo.ac.jp*

ABSTRACT

Dust explosion occurs when ignition energy is given to a flammable particle clouds dispersed in air. During dust explosion, high speed flame propagation occurs and pressure rises significantly. Since the specific surface area increases as the particle size decreases, the risk of dust explosion increases. However, when the particle size is further decreases to several tens micro meters, agglomeration occurs easily, and dispersion condition changes. In order to appropriately evaluate the risk of dust explosion of fine particles, it is necessary to study the relationship between flame propagation behavior and particle characteristics, such as size and agglomeration. The purpose of this study is to investigate the effects of particle size and agglomeration on flame propagation behavior in dust clouds. The flame propagation behavior was examined changing the particle size of PMMA particles and the effect of particle agglomeration was investigated. On this account, PMMA particles with a very narrow particle size distribution were used. As a result, the minimum explosible concentration increased as the particle size decreased. On the other hand, the flame propagation velocity increased as the particle size decreased. In this way, the minimum explosible concentration and flame propagation velocity showed the opposite tendency to the particle size. It is considered that the inter-particle distance will be important for the minimum explosible concentration, meanwhile the specific surface area will be important for the flame propagation velocity. The severity of the explosion can be serious for the smaller particles, despite the minimum explosible concentration is large and the occurrence probability is low.

KEYWORDS: Dust explosion, particle size, agglomeration, flame propagation.

INTRODUCTION

Dust explosion occurs when ignition energy is given to a flammable particle clouds dispersed in air. During dust explosion, high speed flame propagation occurs and pressure rises significantly. The risk of accidental dust explosion can be evaluated by the combination of probability of the accident and severity of consequence (loss) by the accident. Dust explosion is a complex phenomenon that flame propagates in the heterogeneous medium, where particles undergo heating, vaporization, pyrolysis, mixing with oxidizer, ignition, burning, and flame extinction. As powder materials are miniaturized recently, the risk of dust explosion is expected to further increase. Since the specific surface area increases as the particle size decreases, the reactivity of the particle clouds might increase [1]. As a result, the ignitability becomes higher and the pressure increases more rapidly. Therefore, the risk of dust explosion increases [2]. However, when the particle size is further decreases to several tens micro meters, agglomeration occurs easily, and dispersion condition changes. In order to appropriately evaluate the risk of dust explosion of fine particles, it is necessary to study the relationship between flame propagation behavior and particle characteristics, such as size and agglomeration.

A previous study reported flame propagation through dust cloud of 1-octadecanol particles was

Proceedings of the Ninth International Seminar on Fire and Explosion Hazards (ISFEH9), pp. 411-417
Edited by Snegirev A., Liu N.A., Tamanini F., Bradley D., Molkov V., and Chaumeix N.
Published by St. Petersburg Polytechnic University Press
ISBN: 978-5-7422-6496-5 DOI: 10.18720/spbpu/2/k19-66

mainly supported by combustion of smaller particles [3]. It was suggested that the explosion hazard characterization was effected by surface median diameter [4]. It was proved that dust particle size had the greatest influence on the propagation and inhibition of dust explosions [5]. It was deduced that flame propagation behavior varied according to the particle size distribution even if Sauter mean diameter was same [6]. It was indicated that the situation of agglomerates could have significant influence on explosion characteristics [7]. It was reported as the particle diameter of aluminum powders decreased from the micron to the nano range, the flame propagation velocity was found to increase [8]. Also it was reported as the particle diameter of magnesium powders decreased in the micron range, the risk of dust explosion increased significantly. On the other hand, in the nano range, the risk of dust explosion decreased as the particle diameter decreased [9].

The purpose of this study is to investigate the effects of particle size and agglomeration on flame propagation behavior in dust clouds. In this study, poly methyl methacrylate (PMMA) spherical particles were used to examine the minimum explosible concentration (MEC) as an index of probability of the explosion, and the flame propagation velocity (V_f) as an index of explosion severity. The flame propagation behavior was examined changing the particle size of PMMA particles from 10 µm to 100 µm and the effect of particle agglomeration was investigated. On this account, PMMA particles with a very narrow particle size distribution were used.

EXPERIMENTS

PMMA Particles

The PMMA particles used in this experiment exhibited a very narrow particle size distribution and were of spherical shape to realize systematic examinations on particle size effects. There was not agglomeration in the state of powder. The particle median diameters are listed in Table 1. The image and the measured size distribution of 48.5 µm PMMA particles are shown in Figs. 1 and 2.

Table 1. Diameters of PMMA particles

No.	Particle diameter (µm)
1	9.1
2	20.5
3	34.1
4	40.0
5	48.5
6	107.4

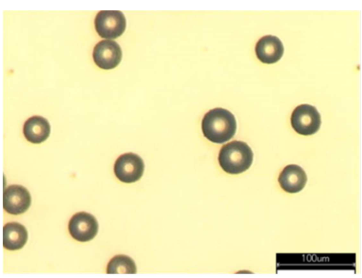

Fig. 1. The image of 48.5 µm PMMA particles.

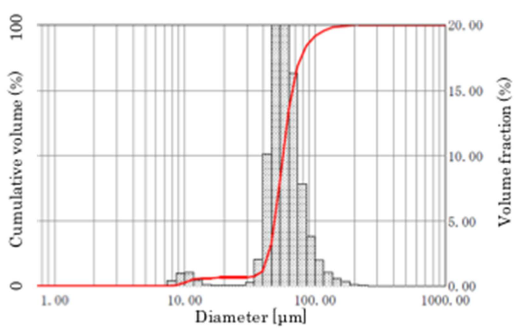

Fig. 2. Measured size distribution of 48.5 µm PMMA particles.

Experimental apparatus

The experimental apparatus for measuring the minimum explosible concentration (MEC) is the Hartmann tube which is composed of a cylindrical explosion tube with a volume of 0.0012 m^3, an air piping, and spark electrodes (Fig. 3). PMMA particles were placed at the bottom of the explosion tube and dispersed by compressed air of 0.06 MPa to form the dust cloud. 200 ms later, the 15 kV neon transformer was discharged and the spark was drawn between two tungsten electrodes to ignite the dust cloud at the center of the explosion tube. In this condition, the dispersed particle layer came close to uniform and stable state. The spark gap was set at 2 mm. The flame propagation behavior was observed by a video camera.

The experimental apparatus for measuring the flame propagation velocity (V_f) is the open-space flame propagation observation apparatus which is composed of a cylindrical explosion tube with a volume of 0.0013 m^3, an air piping, and spark electrodes (Fig. 4). A mesh was attached at the top of the duct, which prevented particles from going out easily. PMMA particles were placed at the bottom of the explosion tube and dispersed by compressed air of 0.09 MPa to form the dust cloud. 500 ms later, the 15 kV neon transformer was discharged and the spark was drawn between two iron electrodes to ignite the dust cloud. In this condition, the dispersed particle layer also came close to uniform and stable state in this apparatus. 200 ms before the dust cloud was ignited, the stoppers of the solenoids were removed, and the middle part of the tube was moved down to make the ignition point open space. The ignition and fall duration was controlled by the pulse generator (Quantum Composer Sapphire 9200 Series). The flame propagation behavior at the open space without the effect of tube surface was observed by a high-speed camera (Photron FASTCAM SA2).

The dispersed particles were collected and their microscopic observation was made by an optical microscope (Keyence VH-5000). The particle size distribution of dispersed dust clouds was measured by a laser diffraction scattering grain size distribution measuring apparatus (Sysmex Spraytec).

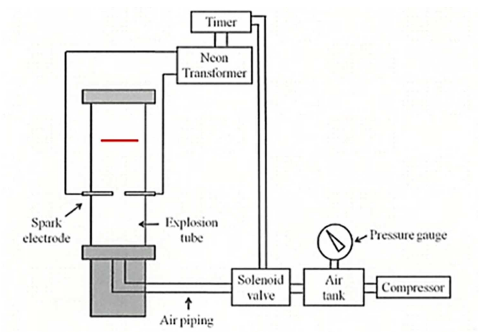

Fig. 3. Experimental apparatus for measuring MEC.

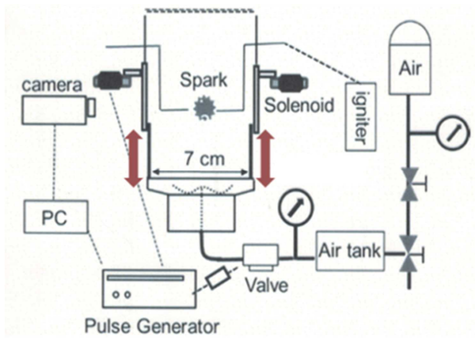

Fig. 4. Experimental apparatus for measuring V_f.

Minimum explosible concentration (MEC)

MEC is the lower flammable limit of flammable dust concentration, which is an index of probability of occurrence of the explosion. The experiments were conducted in accordance to Japanese Industrial Standard Z 8818 [10]. Five measurements were conducted at each concentration, and explosion was confirmed when even once the flame propagated 10 cm above the ignition point as shown in the Fig. 5. In other words, when dust cloud of certain concentration did not ignite in five serial tests, the dust cloud was determined to non-explosible at the concentration. It was confirmed by the video camera whether uniform dust cloud was generated and the flame propagated above the explosion line. The experiments was carried out at all particle diameters, and MEC was measured for each particle diameter (9.1, 20.5, 34.1, 40.0, 48.5, 107.4 μm).

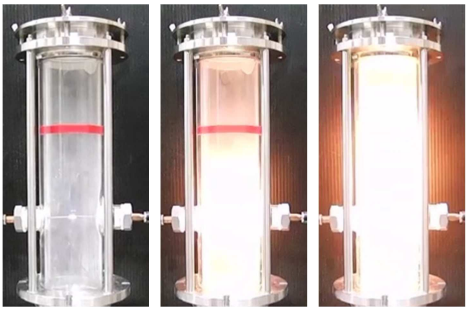

Fig. 5. Flame propagation in the Hartmann tube.

Flame propagation velocity (V_f)

V_f is the average flame propagation velocity, which is an index of severity of the explosion. In this experiment, V_f was obtained as the inclination by linearly approximating the relationship between the flame radius (R_f) and time. R_f was obtained by measuring the half distance between the flame front in the horizontal direction every 1 ms. Measurements were conducted with changing the dust concentration of PMMA particles (155, 230, 385, 575 g/m^3), and the experiments was carried out at all particle diameters, and V_f was measured for each particle diameter (9.1, 20.5, 34.1, 40.0, 48.5, 107.4 µm). Flame propagation in 34.1 µm PMMA dust cloud (385 g/m^3) is shown in Fig. 6, and the relationship between R_f and time is shown in Fig. 7. In Fig. 7, it is shown that R_f is increasing linearly with time after the first stage.

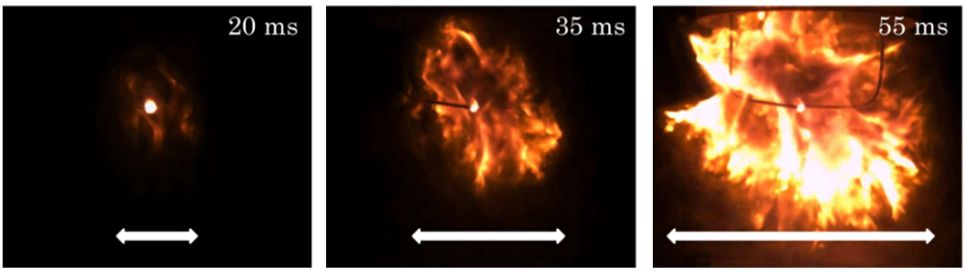

Fig. 6. Flame propagation in 34.1 µm PMMA dust cloud (385 g/m^3).

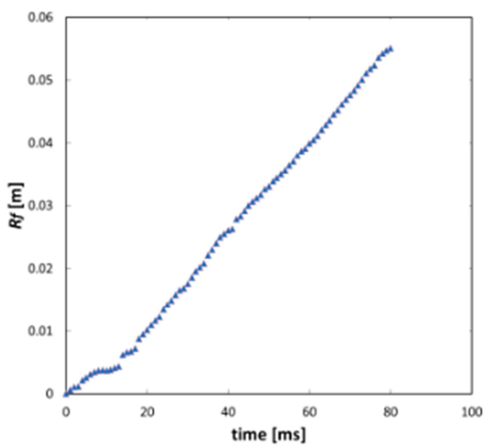

Fig. 7. Relationship between measured R_f and time in 34.1 µm PMMA dust cloud (385 g/m^3).

RESULTS AND DISCUSSIONS

Minimum explosible concentration (MEC)

The measured MEC and the particle size dependence are shown in Fig. 8. In general, MEC tends to decrease as the particle size decreases shown as a dashed line in Fig. 8, because the specific surface area increases and the reactivity of the particle clouds increases as the particle size decreases. However, in this study, MEC increased as the particle size became smaller when the particle size was less than 50 μm. This tendency is contrary to the previous trends. The possible explanation of this is the agglomerating property. When the particle size becomes smaller, the interaction between the particles becomes stronger. Therefore, the small particles gather to be large agglomerations when they collide with each other. It was observed in the photomicrograph (Fig. 9) that the agglomerations were formed by many small particles. In the particle size distribution of the dispersed particles smaller than 50 μm, many agglomerations larger than the original particle diameter were observed (Fig. 10(a) and (b)). When the particle size became larger than 50 μm, the proportion of agglomerations was small in the size distribution (Fig. 10(c) and (d)). Since the degree of agglomeration increased as the particle size decreased, the influence of agglomeration appeared strongly.

One of the key parameters of the explosion limit is the distance between the particles. The number density of the particles decreased due to the agglomeration and the inter-particle distance became larger than when the particles were individually dispersed, which might cause difficulty of continuous flame propagation. As a result, MEC increased in the region where the particle diameter was small.

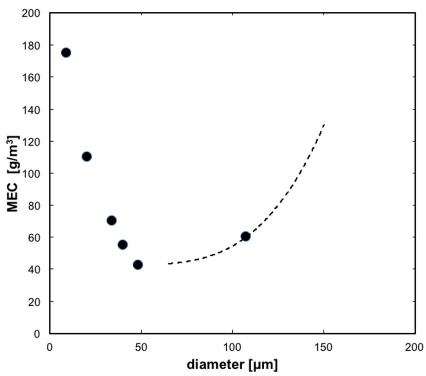

Fig. 8. Measured MEC. Dashed line shows the general trends of dust explosion that MEC decreases as the particle size decreases.

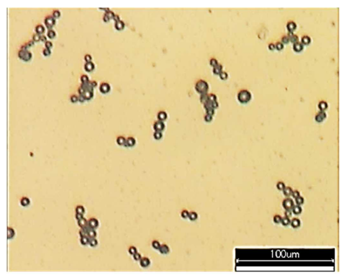

Fig. 9. Agglomerated particles formed by many PMMA particles (9.1 μm).

Flame Propagation Velocity (V_f)

The measured V_f and the particle size dependence at each concentration (155, 230, 385, 575 g/m^3) are shown in Fig. 11(a). As the dust concentration was lowered (155 g/m^3), flame propagation did not occur when the particle diameter was smaller than 40 μm, because the dust concentration was lower than the MEC. On the other hand, at the concentration which was much higher than the MEC (230, 385, 575 g/m^3), V_f increased as the particle size became smaller. This is consistent with the general trends of dust explosion. In this case, because the dust concentration is high and there are enough particles, even if agglomeration occurs and the number density of the particles decreased, the influence is slight and flame propagation occurred continuously. It is considered that the surface area of agglomerated particles is much larger than single spherical particles of the same size. As a result, the increase of specific surface area might accelerate the flame propagation.

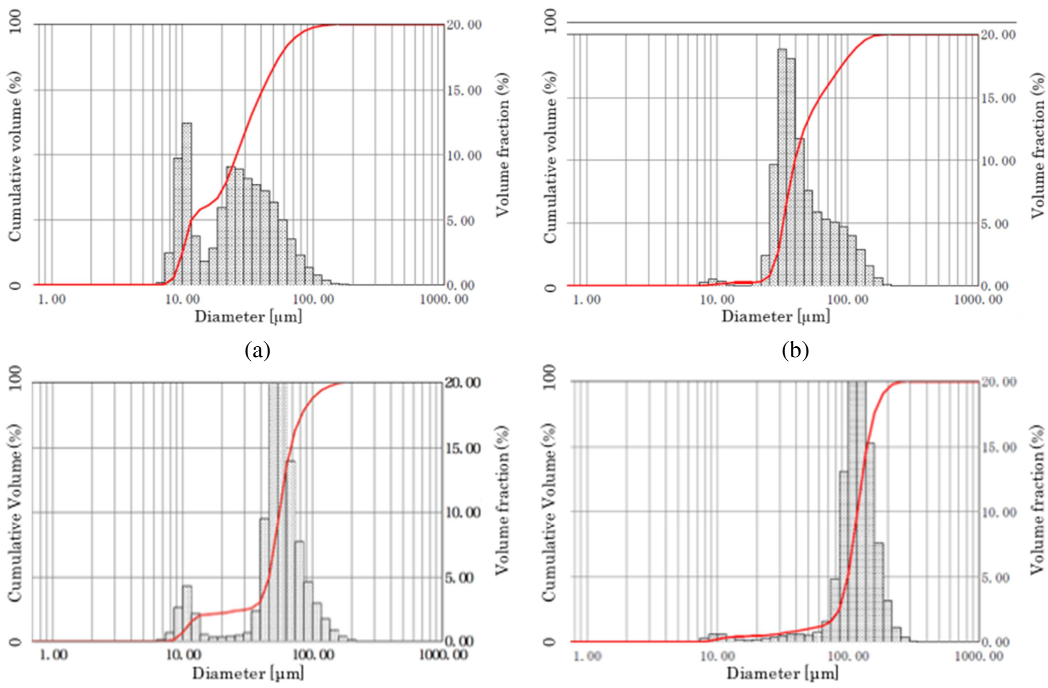

Fig. 10. Particle size distribution of the dispersed particles:
(a) 9.1 μm, (b) 34.1 μm, (c) 48.5 μm, and (d) 107.4 μm.

The measured V_f and the dust concentration dependence are shown in Fig. 11(b). Larger particles were less affected by the concentration changes, whereas as the concentration of smaller particles got close to the MEC, V_f decreased significantly. As the measurement of MEC, when the dust concentration was low, the decrease of number density and the increase of inter-particle distance due to the agglomeration might make continuous flame propagation difficult. It means V_f of small particles might be also affected by agglomeration near the MEC. Near the MEC, V_f might change significantly with the change of concentration. Therefore, V_f of smaller particles was much affected by the concentration change whereas that of larger particles was less affected.

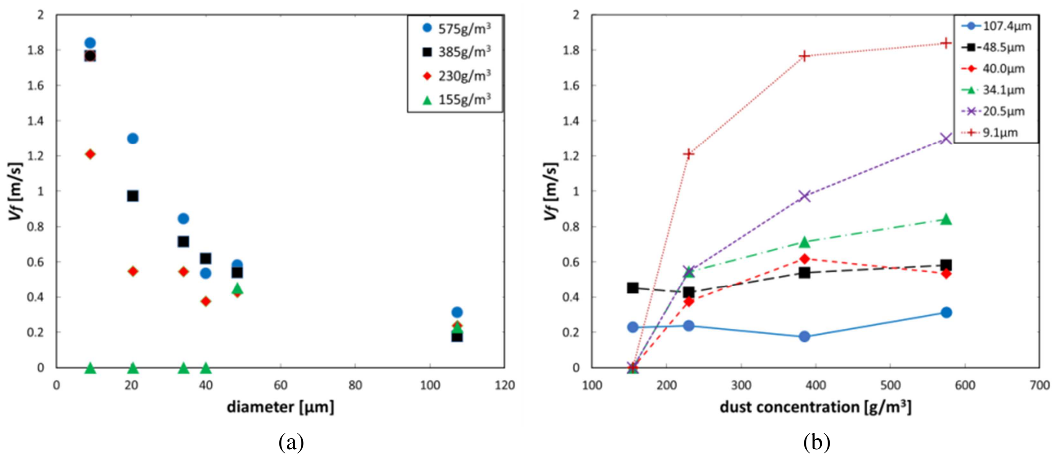

Fig. 11. Measured V_f. (a) particle size dependence; (b) dust concentration dependence. $V_f = 0$ means flame propagation did not occur.

The inter-particle distance will be important for the minimum explosible concentration (MEC), meanwhile the specific surface area will be important for the flame propagation velocity (V_f). It has to be understood that the severity of the explosion can be serious for the smaller particles, despite the MEC is large and the occurrence probability is low.

CONCLUSIONS

The effects of particle size on the minimum explosible concentration (MEC) and flame propagation velocity (V_f) were examined experimentally using very fine PMMA particles. When the particle size was smaller than 50 μm, MEC increased as the particle size decreased due to the agglomeration. The number density of the particles decreased and the distance between the particles became larger, which might cause difficulty of continuous flame propagation. On the other hand, V_f increased as the particle size decreased, because the influence of agglomeration on V_f was slight when the dust concentration was high and there were enough particles. However, since V_f decreased significantly near the MEC, it is considered that when the dust concentration approaches the MEC, increased inter-particle distance due to agglomeration makes continuous flame propagation difficult. In this way, MEC and V_f showed the opposite tendency to the particle size. It is considered that the inter-particle distance will be important for the MEC, meanwhile the specific surface area will be important for the V_f. The severity of the explosion can be serious for the smaller particles, despite the MEC is large and the occurrence probability is low.

ACKNOWLEDGMENTS

The authors gratefully thank Negami Chemical Industrial Co., Ltd., of Japan Ministry for providing the experimental PMMA particles.

REFERENCES

[1] R. K. Eckhoff, Dust Explosions in the Process Industries, Third ed., Gulf Publishing Co., 2003.

[2] R. Dobashi, Risk of Dust Explosions Combustible Nanomaterials, J. Phys.: Conf. Ser. 170 (2009) 012029.

[3] J.L. Chen, R. Dobashi, T. Hirano, Mechanisms of Flame Propagation through Combustible Particle Clouds, J. Loss Prevent. Proc. Ind. 9 (1996) 225-229.

[4] D. Castellanos, V.H. Carreto-Vazquez, C.V. Mashuga, R. Trottier, A.F. Mejia, M.S. Mannan, The Effect of Particle Size Polydispersity on the Explosibility Characteristics of Aluminium Dust, Powder Technol. 254 (2014) 331-337.

[5] M.L. Harris, M.J. Sapko, I.A. Zlochower, I.E. Perera, E.S. Weiss, Particle Size and Surface Area Effects on Explosibility Using a 20-L Chamber, J. Loss Prevent. Proc. Ind. 37 (2015) 33-38.

[6] Y. Yuzuriha, W. Gao, T. Mogi, R. Dobashi, Effects of Particle Size Distributions on Flame Propagation Behavior through Clouds of PMMA Particles, J. Loss Prevent. Process Industries 49 (2017) 852-858.

[7] T. Mogi, A. Sugiura, S. Usuba, M. Nifuku, T. Matsunaga, R. Dobashi, Dust Explosion Characteristics of Ultrafine Polymethylmethacrylate (PMMA) Particles, Bull. Japan Assoc. Fire Sci. Eng. 67(2) (2017) 87-92 (in Japanese).

[8] Y. Huang, G.A. Risha, V. Yang, R.A. Yetter, Effect of Particle Size on Combustion of Aluminum Particle Dust in Air, Combust. Flame 156 (2009) 5-13.

[9] M. Mittal, Explosion Characteristics of Micron- and Nano-size Magnesium Powders, J. Loss Prevent. Proc. Ind. 27 (2014) 55-64.

[10] M. Nifuku, T. Matsuda and H. Enomoto, Recent Development of Standardization of Testing Methods for Dust Explosion in Japan, J. Loss Prevent. Proc. Ind. 13 (2000) 243-251.