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Full Length Article

Combustion behaviors and flame microstructures of micro- and nano-titanium dust explosions

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HIGHLIGHTS

- 50 nm titanium dust flame was characterized by discrete single burning particles.
- 35 μm titanium dust flame was marked by clusters of glowing burning particles.
- Micro explosion occurred more seriously in nano-titanium dust flame propagation.
- Oxidation reaction occurred on the liquid phase surface.
- 50 nm titanium combustion products contained TiO (Ti^{2+}) and TiN (Ti^{3+}).

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ABSTRACT

Particle size has significant effect on flame propagation behaviors in dust explosions. In this study, the flame propagation behaviors and microstructures in micro- and nano-titanium dust explosions were observed and compared. Results showed that flame propagation mechanisms in 50 nm and 35 μm titanium dust clouds were quite different. 50 nm titanium dust flame was characterized by discrete single glowing burning particles with smooth spherical flame front. While 35 μm titanium dust flame was marked by clusters of glowing burning particles with irregular flame front. 50 nm titanium flame velocity was fluctuated more violent and the average flame propagation velocity was faster than that of 35 μm titanium flame. In addition, micro explosion phenomenon occurred significantly in the burning process of 50 nm titanium particles. SEM photos showed that 50 nm titanium particles were approximately spherical shape with observably agglomerations before ignition. However, the combustion products exhibited complicated structures combined the spherical titanium oxides with considerable larger diameters and irregularly spliced smaller titanium oxides. 35 μm titanium particles were in irregular shape before ignition, but in spherical shape after combustion. These results indicated that oxidation reaction occurred on the liquid surface of 35 μm and 50 nm titanium particles. From X-ray photoelectron spectroscopy, it was revealed that the dominant oxidation states of 35 μm titanium combustion products was TiO_2 (Ti^{4+}), and to a much lesser extent of Ti_2O_3 (Ti^{3+}). However, 50 nm titanium combustion products contained 61% TiO_2 (Ti^{4+}), 18% Ti_2O_3 (Ti^{3+}), 8% TiO (Ti^{2+}) and 13% TiN (Ti^{3+}).

1. Introduction

Accidental dust explosions happened frequently in the industrial processes in which combustion particles are handled cause great financial losses and people injury. As a metal elements, titanium with a low density, good strength, excellent corrosion resistance and high heat of reaction is widely used in the industry of spaceflight, spray, metallurgy, fireworks and so on. To take appropriate preventing measures against titanium dust explosion accidents, especially for the ultrafine particles, the explosion characteristics and flame propagation mechanisms through combustible titanium particle clouds must be revealed. Till now most studies are focused on the explosion likelihood (Minimum Explosible Concentration (*MEC*), Minimum Ignition Energy (*MIE*) and Minimum Ignition Temperature (*MIT*)) and explosion severity (Maximum Explosion Pressure (P_{max}), Maximum Rate of Pressure-rise ($(dP/dt)_{max}$), and Deflagration Index (K_{St})) of dust

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explosions. As to the explosion likelihood, Boilard and Wu et al. [1,2] studied the explosibility of micro- and nano-size titanium powders and found that the likelihood of an explosion increases significantly as the particle size decreases into the nano range. The same conclusions were obtained for magnesium powders [3] and aluminum powders [4–6], indicating higher potential inflammation and explosion risks for the use of nano powders. As to explosion severity, research results were controversial. Mittal [3] indicated that the explosion severity significantly increased as particle size decreased from 125 μm to 1 μm, attained the maximum for 400 nm and decreased with further decrease of particle size to nano-range 200–30 nm as it was affected by agglomeration of nano-particles. Vignesa [5] found that the explosion severity decreased for diameters lower than 1 μm. Li and Jiang [6] revealed that the maximum rates of pressure rise of nano-size powder explosions were great higher than that of micro size aluminum powders, and particle size had no significant influence on the maximum explosion pressure and pressure rise rate under the nanosize ranges. While Bouillard [4] observed that the 200 nm aluminum particles exploded more violently than the 100 nm aluminum particles. Other opinion of Boilard [1] thought that micron-size explosion severity could not be compared with that for nano-titanium due to pre-ignition of the nanopowder in the 20-L chamber. The differences between explosion characteristics are attributed to the different flame propagation mechanisms of micro- and nano-dust explosions. However, the recent studies on flame propagation behaviors are mostly focused on the micro scale particles. Sun et al. [7–9] studied the behaviors of particles across upward and downward flame propagating through micro-iron particle clouds and found that for relatively large (agglomerated) particles the number density of iron particles changed with the distance from the leading edge of the combustion zone. And the structure of flames propagating through micro-aluminum particles clouds and combustion processes of the particles were examined to understand the fundamental behaviors of metal dust explosions. Dobashi and Ju et al. [10,11] found that micro-stearic flame structure was determined by mass density of smaller particles. Gao [12] pointed out that in the micron scale as the particle size of long-chain monobasic alcohol decreased, reaction kinetics controlled the flame propagation processes in dust explosions. Huang et al. [13] pointed out that as the aluminum particle diameter decreases from micro to nano range, the combustion transits from a diffusion-controlled to a kinetically controlled mode. Shafirovich [14] suggested that oxygen diffusion in the gas phase played a major role in the combustion mechanism of 100 μm or larger titanium particles in air, while kinetics become more important for smaller sizes. However, compared with the understanding of micron-dust explosions, the current level of physical understanding of the flame propagation mechanisms in nano-dust explosions is still in a rudimentary state. Considering the agglomeration effect exited in nano dust [15], what the flame propagation behavior of nano-dust cloud should be? In this study, micro- and nano-titanium dust explosion experiments in open-space were conducted to reveal the combustion behaviors and flame microstructures.

2. Experimental

2.1. Experimental apparatus

The experimental apparatus was same with that used in our previous study [16], as shown in Fig. 1(a). The combustion system was consisted of combustion tubes, a dispersion system, a gas supplying system, an ignition system, a high-speed photography system, and a time controller system. The middle combustion tube was designed to move down at 0.2 s after dispersion to create an open combustion space so that the flame can propagated in an open field without any influence of the chamber wall. The dispersion pressure was 0.5 MPa and the dispersion process lasted 0.5 s. The discharge time for ignition was 0.03 s by using a 15 kV voltage transfer at 0.5 s after dispersion. Normal and microscopic lens (Nikkor 50 mm f/1.2 and AF Micro Nikkor 200 mm f/4D, Nikon) installed on high-speed cameras (FASTCAM SA 4 and SA 5, Photron) were synchronously used to record the flame propagation processes and flame microstructures. The experimental timing sequence was controlled by a programmable logic controller (CPM1A, OMRON). Before the combustion experiments, particles were dried and the real mass densities of titanium dust clouds were measured by a mass density measurement system shown in Fig. 1(b). The particle dispersion conditions were the same as the combustion experiments. Results of 5 times repetitive experiments proved that the mass densities of 35 μm and 50 nm titanium particles used in comparative experiments were 258.97 ± 11.58 g/m^3 and 258.46 ± 6.53 g/m^3.

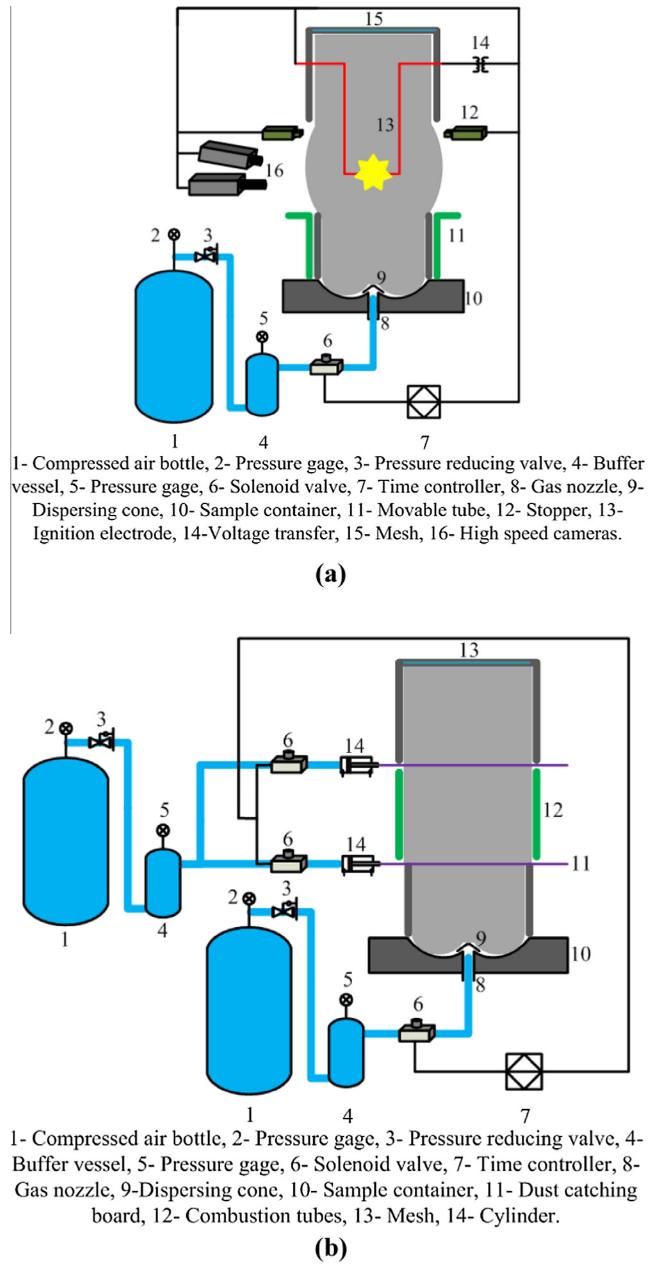

Fig. 1. Experimental apparatus and mass density measurement system.