Experimental Investigation on Micro- and Nano-PMMA Dust Explosion Venting

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1 Introduction

Nano-particles are currently being produced and used in a number of consumer products ranging from cosmetics, sunscreens, toothpastes, pharmaceuticals and clothing, to electronics, plastics and tires. As a consequence, “nano-safety” has emerged as a new field requiring concern. As the core aspect of “nano-safety”, dust explosion is a phenomenon that a flame is propagating in combustible nano-particle cloud dispersed in the air. The explosion severity of nano-particles is commonly enormous comparing with the micro-particles. Wu [1] measured the minimum ignition energy of micro- and nano-Ti and Fe particles. It was found that nano-particles exhibited very higher potential inflammation and explosion risks. Boilard [2], Mittal [3] and Eckhoff [4] concluded that the explosion severity rose notably with powders of particle sizes down to the 1-0.1 μm range.

Explosion venting is a protective measure that prevents unacceptably high explosion pressures by ensuring that most of the explosions takes place in a safe, open area and not inside a building or dust handling enclosure. The larger specific surface area and the stronger attraction forces, including the van der Waals' forces, the electrostatic forces and the inter-particle forces due to liquids, of nano-particles would result in the significantly different venting characteristics comparing with those of micro-particles. Till now, the current level of physical understanding of nano-dust explosion venting is still in a rudimentary state. In this study, vented flame configurations and pressure characteristics of micro- and nano-PMMA particles were examined simultaneously in the standard 20 L spherical dust explosion venting apparatus to reveal their differences.

2 Experiment

2.1 Experimental apparatus

The standard 20 L spherical dust explosion venting apparatus illustrated in Figure 1 consisted of the explosion unit, flame and pressure venting unit, dust dispersion unit, automatic control unit, data acquisition and record unit, and high-speed photography unit. The 20L spherical explosion chamber was designed according to ASTM E1226. Additionally, an open vent with DN100 was designed along the venting axis. Aluminum foil was attached as the explosion venting membrane. The orifice flange with three different venting diameters (15 mm, 28 mm and 40 mm) was bolted on the vent. A fast act valve was mounted at the bottom of the vessel, which was driven by the compressed air of 15 bar dispersion pressure. For ignition energy, a chemical igniter with 0.5 kJ was used for dust clouds to

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prevent overdriving effects [5]. The ignition delay time was 60 ms. Pressure-time history was recorded by pressure transducer with 5 kHz installed at the back of 20 L chamber. The operational atmospheric pressure was 1.01 bar and the environmental temperature was 20℃. High speed camera (Photron, SA4) with 1000 fps were used to capture the vented flame configurations.

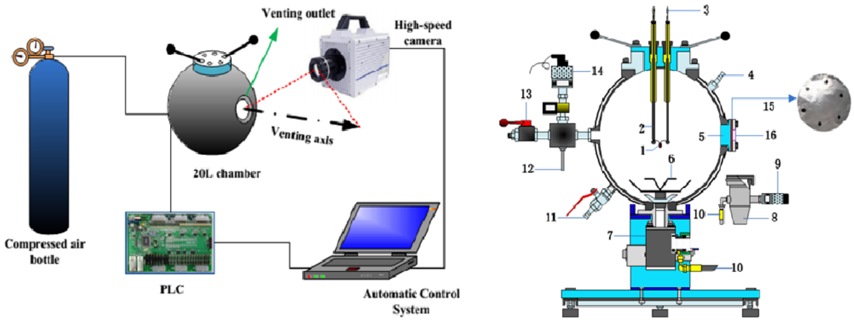

Figure 1. The standard 20 L spherical dust explosion venting apparatus: 1-chemical igniter, 2-electrode, 3-ignition leads, 4-water inlet, 5-vent (sealed), 6-rebound nozzle, 7-valve for gas and powder, 8-dust chamber, 9-pressure sensor, 10-pressure line, 11-water outlet, 12-vacuumize line, 13-exhaust valve, 14-pressure sensor, 15-Al foils, 16-orifice flange.

2.2 Experimental material

PMMA particles used in this study were provided by Soken Chemical & Engineering Co., Ltd of Japan. SEM was utilized to observe the static microstructures and measure the particle diameters of PMMA particles by tens of thousands times amplification. It was found from Figure 2 that all of PMMA particles were regularly spherical. 30 μm PMMA particles were homogeneously distributed, whereas 100 nm PMMA particles exhibited serious agglomeration effects due to the considerable intermolecular forces. Additionally, the optimum dust concentration, C_{ex}, at which the maximum explosion severity was obtained, was 250 g/m^3 in confined 20 L explosion chamber [6].

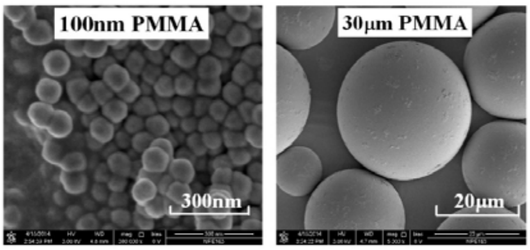

Figure 2. SEM images of 100 nm and 30 μm PMMA particles.

Table 1: Explosion severity in confined 20 L explosion chamber with the dust concentration of 250 g/m^3

Dust	Particle size	P_{max} (bar)	$(dp/dt)_{max}$ (bar/s)	K_{st} (bar·m/s)	C_{ex} (g/m^3)
PMMA	30 μm	6.31	300	81.35	250
	100 nm	8.21	1005	272.78	

3 Vented Flame Configurations

After ignition, the flame began to propagate in the enclosure and the pressure increased simultaneously. When the pressure in the enclosure reached the rupture pressure of Al foil, the blast waves would be ejected through the vent with the burned and unburned PMMA particles. Vented flame configurations of 100 nm and 30 μm PMMA particles with different venting diameters are shown in Figure 3. For 30 μm PMMA particles, the boundary of burned fields almost kept the same width with the vent, emitted yellow light, and ignited the unburned particles. It was also found that the vented flames turned into constant pressure combustion after the explosion pressure venting. On the contrary, for 100 nm PMMA particles, the venting of burned flames began earlier and were not the narrow tapered but changed from the burned bright field to high under-expanded jet flow. Mach disk resulted from series of expansion and compression waves was observed close to vent. Gradually, the vented flames degraded into the continuous plume structures. The length, width and light intensity of vented flame were more obvious. Those differences resulted from the extremely fast pyrolyzation and chemical reaction of nano-particles. In addition, with increasing the venting diameters or reducing the activation pressure, the ending of the vented flames evolution was earlier and more unburned dust would be ejected, which facilitated the propagation of the initial vented flame. The length and width of the vented flames were extended, even forming the fire ball or the second explosions.

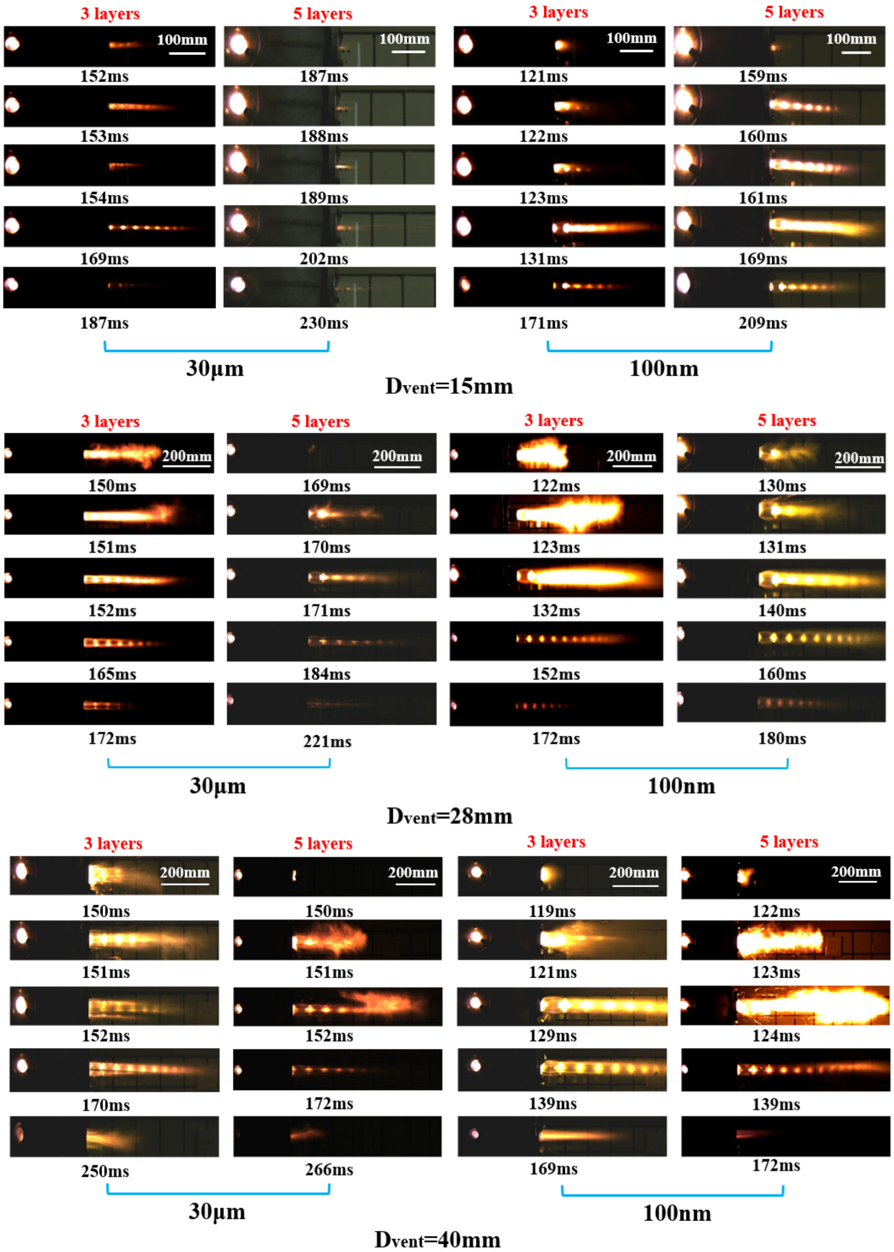

Figure 3. Vented flame configurations of 100 nm and 30 μm PMMA particles with different venting diameters.

During the venting process, the pressure near the vent inside the enclosure P_1 was higher than the atmospheric pressure outside P_a, which would lead to the under-expanded jet flow after the membranes were ruptured. The dilatation, NPR, of this flow was defined as the ratio of outlet pressure P_1 and ambient pressure P_a to divide the different under-expanded jet types.

$$NPR = \frac{P_1}{P_a} = \left[\frac{r+1}{2}\right]^{\frac{r}{(r-1)}}$$

Where r is the ratio of specific heats. Considering the deflagration of PMMA particles in the enclosure, the NPR was all greater than 1 for current experiments (NPR>1). According to the eject theory, the under-expanded jet was divided into three different types: poor under-expanded as NPR less than 2.5, medium under-expanded as NPR in the range 2.5-3.8, advanced under-expanded as NPR beyond 3.8. During the initial venting processes of 100 nm PMMA dust explosions with different venting diameters, advanced under-expanded structure of vented flame with three zones shown in Figure 4 appeared, in which the triple-shock-wave configuration with barrel shock, reflected shock wave and normal shock (Mack disk) at the plume axis would be formed. The near zone exhibited the supersonic flow and unambiguous Mack disk structure, followed by the subsonic pointed zone (transition zone) and fully developed flow (far zone). On the contrary, similar vented flame configuration was not observed in the venting processes of 30 μm PMMA dust explosions due to the weaker explosion pressure and slower burning rate in the enclosure.

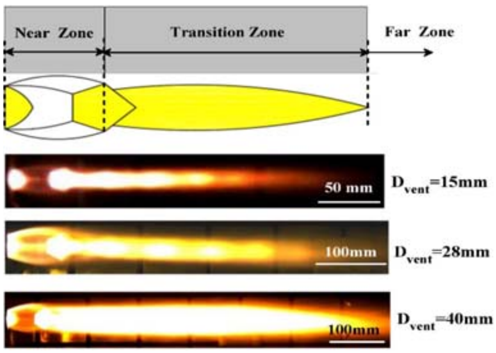

Figure 4. Advanced under-expanded vented flame configurations of 100 nm PMMA particles during the initial venting processes.

During the middle and later venting processes of 100 nm PMMA dust explosions, the advanced under-expanded jet flow was decayed into the medium and poor under-expanded flows shown in Figure 5 due to the rapid consumption of energy and momentum, in which the main burning fields were retained in the contained areas between compression waves and expansion waves. Similar vented flame configuration was observed during the whole stage of 30 μm PMMA dust explosions venting.

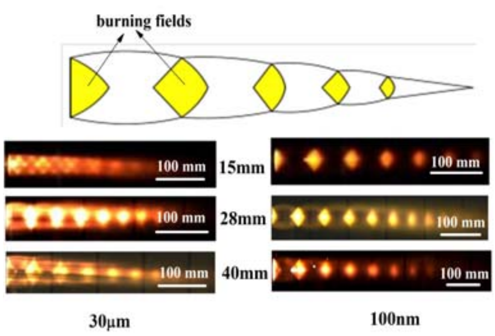

Figure 5. Vented flame configurations of 100 nm and 30 μm PMMA particles during the middle and later development of venting processes.

4 Pressure Characteristics of Dust Explosions Venting with Different Venting Diameters

Maximum overpressure developed in a vented enclosure after venting P_{red} implied the consequence of initial pressure rise and pressure venting after Al foil was ruptured. Figure 6 shows the pressure characteristics of 100 nm and 30 μm PMMA dust explosions venting with different venting diameters. It was found that the maximum overpressure of 30 μm PMMA particles reduced significantly after venting comparing with 100 nm PMMA particles. Increasing the vent diameter, the maximum pressure reduced sharply and peaked earlier because the pressure venting finished earlier. Additionally, higher activation pressure would delay the arriving time of P_{red}, which would subsequently induce the higher P_{red}. It should be noted that the pressure rise rate of 100nm PMMA particles still maintained 1005 bar/s. It surpassed the pressure relieving capacity and would resulted in the higher P_{red}.

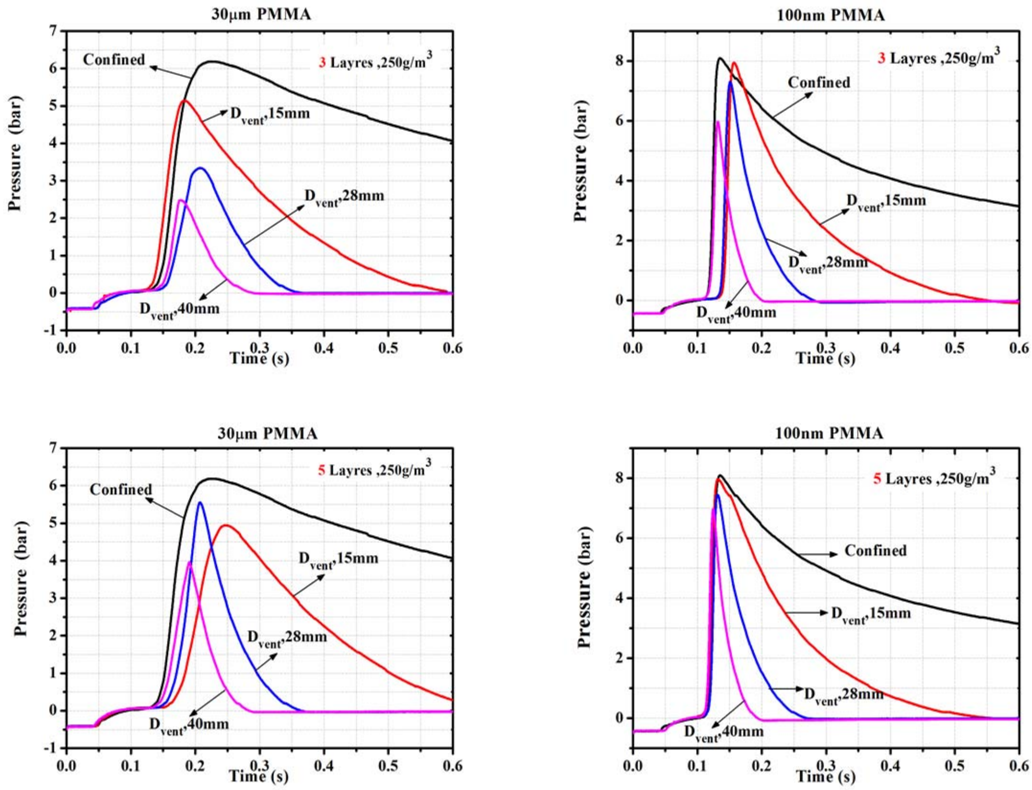

Figure 6. Pressure characteristics of 100 nm and 30 μm PMMA dust explosions venting with different venting diameters.

Figure 7 shows the maximum overpressure developed in the venting enclosure with different venting diameters. It was found that P_{red} of 30 μm PMMA particles decreased significantly with increasing the venting diameters, especially for lower activation pressure that decreased nearly by linear gradient. On the contrary, for 100 nm PMMA particles P_{red} decreased gradually with increasing the vent diameters until 28mm, after that, P_{red} dropped sharply between 28mm and 40mm, which exhibited the extremely binomial fitting (R-Squared 0.99). In other words, it would obtain the suitable efficiency for 100 nm PMMA dust explosion venting with D_{vent} larger than 28 mm in the 20 L spherical dust explosion venting apparatus. In addition, higher activation pressure would lead to the unsatisfactory explosion venting.

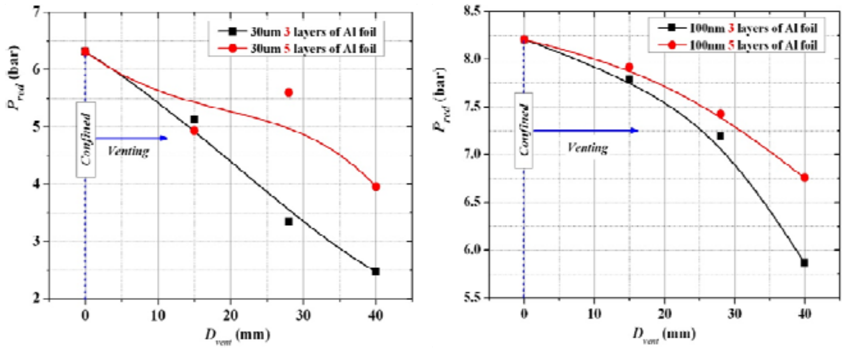

Figure 7. Maximum overpressure developed in the venting enclosure with different venting diameters.

5 Conclusions

Comparison of venting characteristics between micro- and nano-PMMA dust explosions were conducted using the standard 20 L spherical dust explosion venting apparatus. It was found that the boundary of 30 μm PMMA vented burned fields almost kept the same width with the vent, emitted yellow light, and exhibited medium and poor under-expanded structures. On the contrary, the venting of burned 100 nm PMMA flames began earlier and were not the narrow tapered flames but changed from the burned bright field to high under-expanded jet flow. In addition, maximum overpressure of 30 μm PMMA particles reduced significantly after venting comparing with 100 nm PMMA particles.

References

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