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Explosion characteristics of micron- and nano-size magnesium powders

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ABSTRACT

Explosion characteristics of micron- and nano-size magnesium powders were determined using CSIR-CBRI 20-L Sphere, Hartmann apparatus and Godbert-Greenwald furnace to study influence of particle size reduction to nano-range on these. The explosion parameters investigated are: maximum explosion pressure (P_{max}), maximum rate of pressure-rise ($(dP/dt)_{max}$), dust explosibility index (K_{St}), minimum explosible concentration (MEC), minimum ignition energy (MIE), minimum ignition temperature (MIT), limiting oxygen concentration (LOC) and effect of reduced oxygen level on explosion severity. Magnesium particle sizes are: 125, 74, 38, 22, 10 and 1 μm; and 400, 200, 150, 100, 50 and 30 nm. Experimental results indicate significant increase in explosion severity (P_{max}: 7–14 bar, K_{St}: 98–510 bar·m/s) as particle size decreases from 125 to 1 μm, it is maximum for 400 nm (P_{max}: 14.6 bar, K_{St}: 528 bar·m/s) and decreases with further decrease of particle size to nano-range 200–30 nm (P_{max}: 12.4–9.4 bar, K_{St}: 460–262 bar·m/s) as it is affected by agglomeration of nano-particles. MEC decreases from 160 to 30 g/m^3 on decreasing particle size from 125 to 1 μm, its value is 30 g/m^3 for 400 and 200 nm and 20 g/m^3 for further decrease in nano-range (150–30 nm). MIE reduces from 120 to 2 mJ on decreasing the particle size from 125 to 1 μm, its value is 1 mJ for 400, 200, 150 nm size and <1 mJ for 50 and 30 nm. Minimum ignition temperature is 600 °C for 125 μm magnesium, it varies between 570 and 450 °C for sizes 38–1 μm and 400–350 °C for size range 400–30 nm. Magnesium powders in nano-range (30–200 nm) explode less violently than micron-range powder. However, likelihood of explosion increases significantly for nano-range magnesium. LOC is 5% for magnesium size range 125–38 μm, 4% for 22–1 μm, 3% for 400 nm, 4% for 200, 150 and 100 nm, and 5% for 50 and 30 nm. Reduction in oxygen levels to 9% results in decrease in P_{max} and K_{St} by a factor of 2–3 and 4–5, respectively, for micron as well as nano-sizes. The experimental data presented will be useful for industries producing or handling similar size range micron- and nano-magnesium in order to evaluate explosibility of their magnesium powders and propose/design adequate safety measures.

1. Introduction

Magnesium is being used extensively in military as well as aeronautics, chemical and metallurgical industries. Powdered and granulated magnesium have recently undergone rapid development to be used as metal-based fuels in propellants, explosives and pyrotechnics, thermite and incendiary devices. Magnesium powder manufacturing processes include cutting, milling, emulsification, vortex milling, atomization milling, mechanical attrition milling and airflow milling producing a range from micron- to nano-size magnesium powders. There exists high potential fire and explosion risk in magnesium powder manufacturing plants and related facilities using other metalworking operations like casting, grinding, machining and welding. High purity and ultrafine powders are currently attracting more attention than in the past and an increasing range of materials including magnesium are being produced as nano-powders composed of particles in size range from about 1 to 100 nm for use in industrial and research fields. Information on explosion characteristics of magnesium powder is necessary to predict the likelihood and severity of explosions and design explosion prevention and mitigation measures. Literature studies concerning the evaluation of flammability and explosion risks of micron-sized powders do not enable to evaluate the fire and explosion risk probabilities and gravities of nano-powders. It is desirable that the explosion characteristics of nano-powders be determined using the standard apparatus and procedures already employed for assessing dust explosion hazards. Comparison with

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data for micron-scale powders of the same materials will allow knowledge of particle size effects to be extended into the nano-size range.

There exist some information on explosion characteristics – maximum explosion pressure (P_{max}), maximum rate of pressure rise ($(dP/dt)_{max}$), dust explosibility index (K_{St}), minimum explosible concentration (MEC), minimum ignition energy (MIE), minimum ignition temperature (MIT), limiting oxygen concentration (LOC) – of micron scale magnesium powders (Benson, 2012; BIA, 1997; Cashdollar & Zlochower, 2007; Eckhoff, 1991; Jacobson, Cooper, & Nagy, 1964; Kuai et al., 2011; Li, Yuan, Fu, Zhong, & Chen, 2009; Li, Yuan, Zhong, & Chen, 2008; NFPA, 2012; Nifuku et al., 2007; Roser, 1998) based on experiments using standard set-ups having same or different volumes and configurations. The literature data are summarized in Table 1. The explosion severity data in the work reported by Jacobson et al. (1964) were measured in 1.2-L Hartmann apparatus while those from others work are using either 20-L or 1 m^3 chamber. The values of various ignition and explosion parameters for micron scale magnesium powder reported by different workers are quiet different even for the closer particle size-range. For example values of explosion severity data – P_{max} and K_{St} for 30 μm magnesium are 10.8 bar and 400 bar·m/s (Roser, 1998) and those for 28 μm are 17.5 bar and 508 bar·m/s (BIA, 1997; Eckhoff, 1991). The variation of values of explosion characteristics obtained by the laboratories reflects the difficult nature of the magnesium dust samples testing in respect of uniform experimental conditions.

For nano-range particles, there have been number of dust explosion studies performed since 2002 (Benson, 2012; Boilard, Amyotte, Khan, Dastidar, & Eckhoff, 2013; Bouillard, Vignes, Dufaud, Perkin, & Thomas, 2010; Dufaud, Vignes, Henry, Perrin, & Bouillard, 2011; Eckhoff, 2011; Holbrow et al., 2010; Kwok et al., 2002; Pritchard, 2004; Vignes et al., 2009; Worsfold, Amyotte, Khan, Dastidar, & Eckhoff, 2012; Wu, Chang, & Hsiao, 2009; Wu, Ou, Hsiao, & Shih, 2010). Kwok et al. (2002) studied nano-aluminium explosion characteristics. Using 20-L Sphere, Vignes et al. (2009) investigated explosion data of carbon black, carbon nanotubes and aluminium; Wu et al. (2009, 2010) studied explosibility of aluminium, titanium and iron; and Holbrow et al. (2010) determined explosion characteristics of different nano-materials: iron, copper, silicon carbide, zinc oxide, iron oxide, zirconium oxide, zinc, multiwalled carbon nanotubes, carbon monofibres, aluminium, carbon black, etc. in specially designed 2-L explosion chamber. Boilard et al. (2013) studied explosibility of micron and nano-size titanium and Dufaud et al. (2011) studied aluminium, zinc, carbon nanotubes and carbon black. The knowledge of explosion data of nano-powders is still limited. The recent edition of NFPA 484 (NFPA, 2012) covering the unique hazards associated with metal fine dusts and powders, does not include the risks of metal dust combustibility at nano-scale.

To the author's best knowledge, there exists no data on explosion characteristics of nano-size magnesium. The reliability of standard experimental method designed for micron-size dust explosions has been questioned due to various factors influencing behaviour of nano-size dust cloud during experiments (Boilard et al., 2013; Vigens et al., 2009). In the standard 20-L sphere, powder is dispersed using compressed air. With nano-powders, their large surface to volume ratio means that many of them are spontaneously flammable on contact with air, or surface oxidation alters their properties. Hence equipment/procedure that avoids oxidation until the point of ignition is required.

The present investigation was undertaken to measure the ignition sensitivity and explosion severity parameters of magnesium powder in relation to particle size in both the micron- and nano-size ranges and compare the results to examine whether production, handling and use of magnesium nano-powders can present an

Table 1
Explosion characteristics of micron-size magnesium powder-literature data.

Reference	Mean particle size, μm	MEC, g/m^3	MIT, °C	MIE, mJ	P_{max}, bar	$(dp/dt)_{max}$, bar/s	K_{St}, bar·m/s	LOC, %
Jacobson et al. (1964)	<74		620	40	90 psig[a]	9000 psi/s[a]	–	–
Eckhoff (1991)	28	30			17.5		508	
	240	500	760		7.0		12	
BIA (1997)	240	30	–	–	17.5		508	–
	241	500	760	–	7.0	12	–	–
	400	–	n.i.u.	–	–	–	–	–
			850					
Roser (1998)	30				10.8		400	
Cashdollar and Zlochower (2007)	16	55	–	–	8.5	–	–	–
Nifuku et al. (2007)	0–20	90	513	4				<8%
	20–37	90	530	5	–	–	–	<8%
	37–45	120	550	12	–	–	–	–
	45–74	130	563	44	–	–	–	–
	74–105	270	575	82	–	–	–	–
	105–125	330	578	102	–	–	–	–
	125–149	500	585	194	–	–	–	–
	149–177	900	625	242	–	–	–	
Li et al. (2008, 2009)	6	–	480	>2	–	–		–
	47	–	520	46–54	8	150		6.8
	104	–	620	250–300	–	–		–
Benson (2012)	75	328	560	–	–	–	–	–
	–	–	–	20	–	–	–	–
	20–60	–	–	–	–	53	–	–
Kuai et al. (2011)	7.5	20	–	–	7.8	430	–	–
	22.4	25	–	–	6.6	380	–	–
	54.5	40	–	–	5.8	250	–	–
NFPA (2012)	28	–	–	–	17.5		508	
	240	500	760	–	7		12	
	<44	40	620	40	–		–	
	<44	30	600	240	–		–	
	16	55	–	–	7.5		–	

[a] Hartmann explosion tube data.