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Comparative study of explosion processes controlled by homogeneous and heterogeneous combustion mechanisms

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The dust explosion behaviors induced by two different combustion mechanisms (homogeneous and heterogeneous mechanisms) were comparatively investigated, based on the experiments under different dust concentrations, particle sizes and initial pressures in Siwek 20-L chamber. Based on the thermogravimetric analysis (TGA), sweet potato dust and magnesium dust were selected as the representative dusts with homogeneous and heterogeneous combustion mechanisms, respectively. Experiments find that these two dusts have different behaviors in the explosion kinetics due to different combustion mechanisms. For sweet potato dust, the explosion pressure p_{max}, the pressure rise rate $(dp/dt)_{max}$ and the combustion fraction η exhibit similar variation trends as dust concentration increases and they all reach to the maximum values at the worst-case concentration; while for magnesium dust, the variation of $(dp/dt)_{max}$ is somewhat different from that of p_{max}, that is, the $(dp/dt)_{max}$ will achieve the maximum at the concentration higher than the worst-case and keep stabilized with further increase of dust concentration. As the particle size decreases, the $(dp/dt)_{max}$ for sweet potato dust will increasingly rise and gradually approach to a stabilized value, but for magnesium dust, the increase of $(dp/dt)_{max}$ becomes pronounced only in the range of smaller particle sizes. To account the effect of initial pressure on p_{max} under different combustion mechanisms, a dimensionless pressure P_R was introduced to denote the relative intensity of explosion. It is found that, for sweet potato dust, the increased initial pressure will promote the explosion process (or with high P_R) for the dust cloud with high concentration due to the augmented oxygen concentration, but for the dust cloud with low concentration, the increased initial pressure will suppress the explosion process due to the increased resistance in devolatilization. For magnesium dust, the rise of initial pressure will generally promote the explosion process even for the dust cloud with low concentration; however, in the case of small particle size, the promotion of increased initial pressure to the explosion process is not so pronounced.

1. Introduction

Dust explosion is a complex phenomenon in the sense that it involves simultaneous momentum, energy, and mass transport in a reactive multi-phase system. The most common dust explosion occurs in underground coal mines. In coal mine tunnel, coal dust explosion is usually caused by gas explosion. Moving at the speed of sound, pressure wave resulting from gas explosion lifts the deposited coal dust in the air. Then gas flame reaches the coal dust causing a dust explosion which is more severe than the first one (Bidabadi, Dizaji, Dizaji, & Ghahsareh, 2014; Bidabadi, Mostafavi, Dizaji, & Dizaji, 2013). A series of studies shows that the initiation and subsequent explosion processes are governed by numerous factors, such as dust concentration (Calle, Klaba, Thomas, Perrin, & Dufaud, 2005; Cashdollar & Zlochower, 2007; Denkevits & Dorofeev, 2006; Goroshin, Fomenko, & Lee, 1996; Klippel, Schmidt, Muecke, & Krause, 2014), particle size (Benedetto, Russo, Amyotte, & Marchand, 2010; Castellanos et al., 2014; Gao, Mogi, Sun, Yu, & Dobashi, 2013; Huang, Risha, Yang, & Yetter, 2009; Soundararajan, Amyotte, & Pegg, 1996), oxidant concentration (Cashdollar, 1996; Mittal, 2013; Wilen, Rautalin, Garcia-Torrent, & Conde-Lazaro, 1998), ignition energy (Cashdollar, 2000; Eckhoff, 2005; Kuai et al., 2013), initial pressure (Lazaro & Torrent, 2000; Pilao, Ramalho, & Pinho, 2004; Torrent, Lazaro, Wilen, & Rautalin, 1998), moisture content (Dufaud, Traore, Perrin, Chazelet, & Thomas, 2010; Traore, Dufaud, Perrin, Chazelet, & Thomas, 2009; Yuan et al., 2012),

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turbulence (Benedetto, Garcia-Agreda, Russo, & Sanchirico, 2012; Pu, Jia, Wang, & Skjold, 2007; Scheid, Geibler, & Krause, 2006) and uniformity of dust cloud (Benedetto, Russo, Sanchirico, & Sarli, 2013; Sarli, Russo, Sanchirico, & Benedetto, 2014). For explosion mitigation and prevention in process industries that manufacture, use and/or handle powders and dusts of combustible materials, an accurate knowledge of dust explosion hazard is quite essential.

As mentioned by Eckhoff (2003) and Kuai et al. (2013), it is well-accepted that dust explosions undergo two alternative combustion mechanisms (i.e. the homogeneous and heterogeneous mechanism). However, the current substantial researches mainly focus on the determination of explosion parameters and the influences of factors involved. Few studies include a systematic investigation distinguishing the difference between two mechanisms. As a result, the interpretation of explosion behaviors will be disagreed to some extent, especially of the explosion kinetics.

In general, the combustion of coal and carbonaceous dust belongs to homogeneous mechanism and mainly occurs in the three consecutive processes pyrolysis/devolatilization, gas phase mixing and gas phase combustion; while the metals mainly feature the surface heterogeneous oxidation, as they are melt and burn as discrete entities. The overall combustion rate, which depends on the slowest step of explosion processes, will be certainly affected by the combustion mechanisms as well as the factors involved. Thus, for a thorough understanding of the explosion processes, the mechanisms of dust explosion should be taken into account.

In the present study, the combustion mechanisms for two typical dusts were confirmed through the thermo-gravimetric analysis. Then the dust explosion experiments were carried out systematically and, based on the experimental results, comparative analysis was performed on the explosion behaviors of two dusts with different combustion mechanisms, under different dust concentrations, particle sizes and initial pressures. Finally, the limiting factors of the explosion processes controlled by the two mechanisms have also been discussed.

2. Experimental

2.1. Apparatus and materials

Explosion experiments were conducted in a standard Siwek 20 L vessel (Siwek, 1996), according to the recommendations of European standard EN 14034 (CEN/TC305, 2004a, 2004b, 2004c), ASTM standard E1226 (ASTM, 2007) and Chinese standard GB/T16425 (MCI, 1996). The vessel, made of stainless steel, consists of the spherical explosion chamber, dispersion system, automated control system, ignition system and pressure measuring system.

Before testing, the storage canister is charged with a pre-weighed amount of dust sample, and then the vessel with ignition source installed inside is sealed with the bayonet closure and partially evacuated. The dust is dispersed by a blast of pressure air and ignited after a given delay 60 ms (CEN/TC305, 2004a, 2004b, 2004c; MCI, 1996). All tests were performed at least in three replications and the standard deviations were indicated by means of error bars for readability purpose.

In the present study, magnesium and sweet potato fine powders were employed as the representative dusts controlled by heterogeneous and homogeneous mechanisms, respectively. Their combustion mechanisms will be confirmed by thermo-gravimetric analysis, using TA Q500 analyzer. The particle size distributions and heat of combustion were listed in Table 1. The tested magnesium powder with 99% purity provided by CNPC POWDER was produced by atomization, and powder of sweet potato was prepared by milling and sieving the purchased materials. Both the samples were systematically dried in a vacuum before handling.

Table 1
Analytical data for dust samples studied.

Samples		Granulometry			Heat of combustion (kJ/g)
		d_{10} (μm)	d_{50} (μm)	d_{97} (μm)	
Sweet potato	SP-1	11.8	39.2	185.5	16.27
	SP-2	6.9	29.8	47.9	
	SP-3	6.9	18.5	40.6	
Magnesium	Mg-1	24.9	54.5	129.9	23.21
	Mg-2	12.3	22.4	88.8	
	Mg-3	4.1	7.5	23.9	

2.2. Effects of ignition energy on the pressure rise

In the present work, the dust cloud in the vessel is ignited by electrically activated pyrotechnical ignitor, which is prepared in accordance with the principle of zero-oxygen balance. The ignitor consists of zirconium, barium nitrate and barium dioxide by the weight ratio of 4:3:3, and the energy release of 1.2 g mixture is corresponding to 5 kJ. The rapidly energy release will cause a temperature rise and lead to an obviously pressure rise p_{ign}. This pressure rise, superposed to the tested explosion pressure will confuse the interpretation of dust explosion behaviors to some extent. To distinguish the p_{ign} from the tested explosion pressure in later analysis, a test to determine the pressure rise p_{ign} caused by ignition energy E_{ign} was performed under no dust loaded condition and the relationship between p_{ign} and E_{ign} was obtained, as shown in Fig. 1. Results indicate that p_{ign} is directly proportional to E_{ign}.

2.3. Calibration of initial pressure

In this study, different initial pressures p_i were achieved by varying the injection pressure p_{inj} in dust storage canister and the pre-vacuum p_{vac} in explosion vessel. Table 2 shows the different combinations between p_{inj} and p_{vac}. In order to evaluate whether the injection air velocity would affect the explosion severities, a series of tests were conducted under initial pressure of 1.0 bar (abs) through two different combinations between p_{inj} and p_{vac}, as shown in Table 2 (case 2 and case 3).

Fig. 2 shows the effects of dust dispersion methods on p_{max} and $(\mathrm{d}p/\mathrm{d}t)_{\mathrm{max}}$ for sweet potato dust (SP-2) concentrations of 250, 750 and 1250 g/m^3, using ignitors of 5 kJ. Results show that the explosion parameters are not significantly affected by modifications on the air injection pressure, which are consistent with the

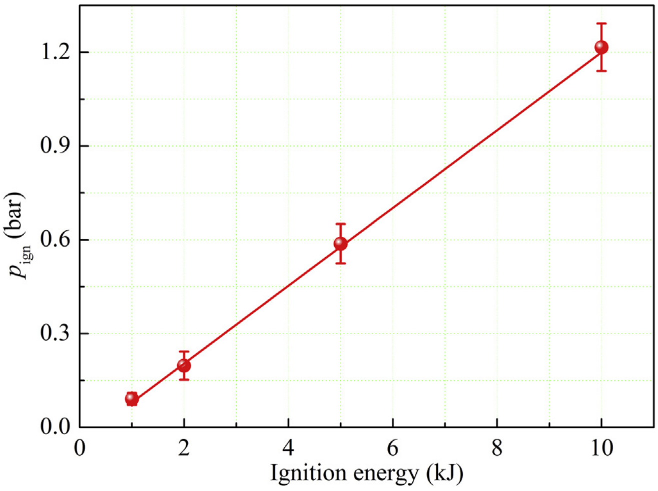

Fig. 1. Evolution of p_{ign} with ignition energy E_{ign}.