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The effect of particle size polydispersity on the explosibility characteristics of aluminum dust

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ABSTRACT

This paper reports experimental results elucidating the effect of particle size polydispersity (σ_D) on the explosion severity of aluminum dust. Five mixtures with a median diameter (D_{50}) of 15 μm and σ_D values of 0.95, 1.17, 1.48, 1.87, and 2.51, were systematically prepared by mixing original aluminum samples having narrow size distributions. The explosion severity of each sample was determined in a 36 L dust explosion vessel by measuring the maximum pressure (P_{max}), the maximum rate of pressure rise ($(dP/dt)_{max}$), and the deflagration index (K_{St}). Interestingly, we found that values of P_{max} and K_{St} revealed an increase in explosion severity as σ_D increases, where the latter presented a more dramatic effect due to the contribution of fine particles on the combustion kinetics. The effect of dust concentration on the explosion propagation was analyzed comparing the time span to reach $(dP/dt)_{max}$, (τ), during a dust explosion. τ was obtained from the experimental pressure traces of the original samples and their mixtures. The values of P_{max} and K_{St} were plotted as a function of the median diameter (D_{50}) and the volume- ($D_{4,3}$) and surface- ($D_{3,2}$) weighted mean diameter. We observed that $D_{3,2}$ provided a better description of the average sample size and D_{50} is inadequately related to the real hazard potential of aluminum dust. Therefore, we suggest that the explosion hazard characterization of these types of materials should be reported in terms of $D_{3,2}$ and σ_D.

1. Introduction

Dust explosions represent a serious industrial problem. They can occur if dust particles are well dispersed within a confined space in the presence of an ignition source. The severity of these explosions can be characterized from experimental parameters such as the maximum explosion pressure (P_{max}) and the deflagration index (K_{St}). K_{St} is calculated from the maximum rate of pressure rise ($(dP/dt)_{max}$) and the vessel volume ($K_{St} = (dP/dt)_{max} \cdot V^{1/3}$) [1]. These parameters are utilized to predict the consequences of a dust explosion for a given scenario and usually reported along with the median diameter (D_{50}). A dust explosion is a surface-area dependent process, where the dust explosibility increases as the particle diameter decreases (i.e., surface area increments) [1,2]. Here, we demonstrate that dust explosion hazards can be affected not only by the mean diameter but also by the size polydispersity (σ_D). σ_D is a measure of the width of the particle size distribution (*PSD*) and is not frequently reported along with the mean diameter [3,4]. σ_D can affect K_{St} values [5], and significant uncertainties can be found during the extrapolation of K_{St} values for a given dust with varying σ_D.

Many natural and industrial dusts present a wide particle size distribution (high σ_D). However, most of the experimental and theoretical combustion studies are carried out with samples of low σ_D. In addition, it is difficult to compare experimental data from different researchers when the results are reported in relation to different definitions of average particle size. In order to understand the effect of σ_D on dust explosion hazards, we restricted our analysis to aluminum dust samples.

Aluminum dust has several important production methods and applications [6]. For instance, aluminum dust can be used to improve the optical properties of pigments [7,8], increase the fire rates of chromium (Cr) production [6], and enhance the combustion and reactivity in propellants [9,10]. Aluminum dust undergoes an exothermic reaction in the presence of air ($4Al + 3\,(O_2 + (79/21)\,N_2) \rightarrow 2Al_2O_3 + (79/7)\,N_2$). This material, having a low σ_D, has been used to study several combustion parameters, such as burning velocity [11,12], ignition temperature [12], combustion [9,13], and ignition time [14]. Given that aluminum dust has been involved in devastating explosion accidents [1,15–17], several investigations have been conducted to analyze the effect of particle size on explosion hazard parameters such as P_{max} and K_{St} [17–19]. These combustion parameters are very sensitive to the variation of particle size [20–24]. Huang et al. [25] reported that the aluminum dust laminar flame speed is affected by the fine particle

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concentration within the mixture. Therefore, for a dust at a given particle diameter, the values of P_{max} and K_{St} will be affected by a systematic variation of the small and large particle size fraction contained in the mixture (i.e., different σ_D).

Our work here explores the effect of aluminum dust size polydispersity on the dust hazard parameters such as P_{max} and K_{St}. Aluminum samples of similar D_{50} but varying σ_D were prepared by mixing commercially available samples of different D_{50} and narrow size distributions. The original samples and their mixtures were tested in a 36 L dust explosion vessel. The time span to reach the maximum rate of pressure rise (τ) was calculated from the pressure time curves obtained in the 36 L vessel. τ values give insights of the effect of D_{50}, σ_D and dust concentration on the velocity of the flame propagation of the tested samples. The results obtained in this research demonstrate the importance of σ_D on aluminum dust explosion hazard characterization.

2. Methodology

2.1. Determination of P_{max}, K_{St}, and τ of aluminum dust samples

The dust explosion equipment used in this work utilizes a 36 L semi-spherical stainless steel vessel, which was designed based on the ASTM standard E-1226-05 [26]. This equipment has been carefully calibrated to produce comparable results to the ones obtained with the 20 L and 1 m^3 standard equipment [27]. In a typical experiment, a dust sample is loaded into a dust container. Later, the 36 L vessel is sealed, evacuated, and the air reservoir is pressurized. A fast acting valve is opened for 50 ms to release air from the reservoir and disperse the sample inside the vessel through a rebound nozzle. The dispersion process increases the vessel pressure to one bar absolute. After a delay time of 25 ms, two 5 kJ igniters are activated and the resulting explosion pressure trace is recorded. A customized LabView™ program controls the equipment and processes the experimental data. Fig. 1 shows a typical pressure (barg) profile as a function of time (ms) during a dust explosion test, where $(dP/dt)_{ex}$, P_{ex}, and τ are obtained for a specific dust concentration. P_{ex} is corrected into P_m to account the cooling effects of the vessel walls and the pressure effects caused by the igniters [26]. $(dP/dt)_{ex}$ is multiplied by the cubic root of the vessel volume to obtain $(dP/dt)_{ex}V^{1/3}$. P_{max} and K_{St} are the maximum values of P_m and $(dP/dt)_{ex}V^{1/3}$ at varying dust concentrations. The *optimum concentration* corresponds to the concentration where P_{max} and K_{St} values are found.

2.2. Aluminum sample preparation and size characterization

In order to understand the effect of σ_D at a fixed D_{50} during a dust explosion, we systematically combined aluminum samples with the following mean diameters: 2, 5, 9, 15, 20, 25, and 30 μm. The combined samples were prepared by adding each component in a jar filled to about 2/3 capacity and manually blending each sample for 30 min using a *Figure 8-track* to ensure self-mixed samples. The blending process was conducted under inert conditions in a glove box. Original samples and the resulting mixtures were stored under nitrogen atmosphere to prevent aluminum oxidation.

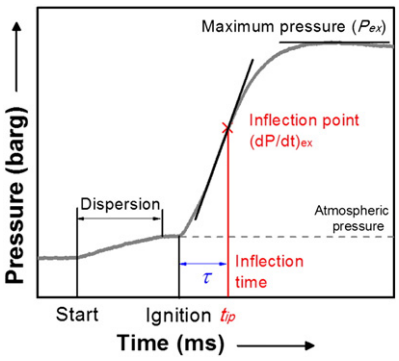

Fig. 1. Typical pressure profile during a dust explosion test.

The qualitative characterization of the alumina (Al_2O_3) content in the samples was conducted using X- ray diffraction (XRD) before and after the blending process (see ESI Fig. S1[1] and text). A quantitative estimation of the alumina content was obtained using the density of aluminum (1500–1700 kg/m^3) and the amorphous alumina (3050 kg/m^3 [28,29]). According to Trunov et al., [30], the natural oxidation in nano and microsized aluminum dust is around 2.5 nm. Thus, the Al_2O_3 content of the original samples is expected to vary from 1.5 to 0.1 wt.% for particles between 2 and 30 μm, respectively.

The particle size distribution of the original samples was determined using a Mastersizer 3000 analyzer (Malvern Inc, Worcestershire, UK) and an LS 13 320 Coulter multi-wavelength laser diffraction particle size analyzer (Beckman Coulter, Inc. Brea, CA). The laser diffraction measurement was performed in wet-mode using water as the suspension medium. Micro 90® manufactured by International Products Corporation was used as a surfactant. Aluminum *PSD* results from both instruments were in very good agreement. The measurements provide the size distribution on a volume (or mass) basis and the statistical diameters, D_{10}, D_{50}, and D_{90}. D_{xx} refer to the particle size for which xx% of the particles by weight are finer. Table 1 summarizes the particle size characterization of these samples. Table 2 shows the corresponding mass fractions of the original aluminum samples used to prepare each of the five blends having similar D_{50} and varying σ_D.

The particle size polydispersity (σ_D) characterized by the span of the size distribution is calculated using the following expression:

$$\sigma_D = (D_{90}-D_{10})/D_{50} \quad (1)$$

The *PSD* of the resulting mixtures was calculated by adding the initial size distributions in accordance to their contributions or mass fractions. The aluminum dust density is the same in all samples. The calculated size distributions shown in Fig. 2 were also verified experimentally with the Beckman Coulter analyzer described above. The calculated and experimentally measured *PSD* presented excellent agreement.

Micrographs of aluminum mixtures were obtained using scanning electron microscopy (SEM-JEOL JSM-7500 F). Fig. 3 shows the SEM images of the resulting mixtures. As observed from the micrographs, polydispersity increases from Blend 1 to Blend 5. Blend 1 ($\sigma_D = 0.95$) presents the highest homogeneity in particle size, while Blend 5 ($\sigma_D = 2.51$) is the most heterogeneous in particle size.

3. Results and discussion

3.1. Effect of D_{50} on P_{max} and K_{St} values of aluminum dust samples at low σ_D

In order to analyze the effect of D_{50} on P_m and $(dP/dt)_{ex}V^{1/3}$ at a relatively low polydispersity, the original samples listed in Table 1 were tested using the 36 L dust explosion vessel. Fig. 4 shows the experimental explosion hazard parameters of the original samples as a function of aluminum dust concentration. The experiments conducted using nominal dust concentrations of 125, 250, 500, 750, 1000, and 1500 g/m^3 were repeated and the standard deviation is shown by the error bars. The maximum values at P_m and $(dP/dt)_{ex}V^{1/3}$ curves were conducted three times. The P_{max} and K_{St} values obtained at the optimum concentrations can be found in Table 3. In general, finer particles ($D_{50} = 2$ μm) produced a higher P_m and $(dP/dt)_{ex}V^{1/3}$. In agreement with Dufaud et al., [24,31], P_{max} and K_{St} values monotonically increase as D_{50} reduces. Interestingly, the optimum concentrations, where P_{max} and K_{St} values are found, decreased as D_{50} decreases. A rapid rupture of the oxide layer in small particles might contribute to such a high explosion

[1] Electronic supplementary information (ESI).