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Experimental investigation and modelling of aluminum dusts explosions in the 20 L sphere

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ABSTRACT

An experimental investigation was carried out on the influences of dust concentration, particle size distribution and humidity on aluminum dust explosion. Tests were mainly conducted thanks to a 20 L explosion sphere. The effect of humidity was studied by storing the aluminum particles at constant relative humidity until the sorption equilibrium or by introducing water vapour in the explosion vessel. The tested particles sizes ranged from a volume median diameter of 7 to 42 μm and the dust concentrations were up to 3000 g m^{-3}.

Among other results, the strong influence of the particle size was pointed out, especially when the Sauter mean diameter is considered. These results stressed the predominance of the specific surface area on the mass median particle diameter.

The effect of water on aluminum dust explosion was decoupled: on the one hand, when water adsorption occurs, hydrogen generation leads to an increase of the explosion severity; on the other hand, when the explosion of dried aluminum powder occurs in a humid atmosphere, the inhibiting effect of humidity is put forward.

A model based on mass and heat balances, assuming a shrinking core model with chemical reaction limitation, leads to a satisfactory representation of the pressure evolution during the dust explosion.

1. Introduction

The Institution of Chemical Engineers (IchemE) reports that a dust explosion takes place every day in Europe (Laurent, 2003). About 19% of these dusts explosions are due to metal oxidation (CCPS, 2005) and aluminum accounts for most of these events. In fact, aluminum is a very reactive metal and its oxidation can occur both in thermite reactions, when aluminum is oxidized by other metal oxides, and in dust explosions, when aluminum dusts are suspended in air simultaneously with an ignition source. Because of their severity, aluminum dust explosions are often mentioned in accident reports as “fatal” or “devastating”. For instance, Eckhoff (2003) described two aluminum dust explosions, one in a slurry explosive factory at Gullaug, Norway, in 1973 and another one in a atomized aluminum powder production plant at Anglesey, UK, in 1983. Similarly, the Chemical Safety and Hazard Investigation Board provides a detailed report on the dust explosion which occurred in 2003 in an aluminum casting plant in Huntington (USA) (CSB, 2005). The same year in France, such an accident occurred in a bag filters unit in Saint Vincent de Tyrosse due to electrostatic discharges. From these examples, it should be noticed that various kind of aluminum could be involved in such a phenomenon: flakes, granules and atomized particles, which could be encountered during manufacturing steps or metal parts grinding or surface finishing (Ebadat & Prugh, 2007; May & Berard, 1987).

Safe handling of aluminum powder, considered as one of the most explosive metal dusts, first requires a complete risk analysis of the plant, which provides adequate prevention and protection means and involves the risk awareness of the employees. Thus, the risk evaluation step requires the knowledge of fire and explosion hazard data. Many studies were carried out on metal dusts (Amyotte, Soundararajan, & Pegg, 2003; Matsuda, Yashima, Nifuku, & Enomoto, 2001; Soundararajan, Amyotte, & Pegg, 1996; Sun, Dobashi, & Hirano, 2003) and aluminum dusts explosibility data could be found in various articles mostly focused on the determination of explosion sensitivity parameters (minimum ignition energy and temperature and minimum explosible concentration) and explosion severity characteristics (maximum explosion pressure and maximum rate of pressure rise) (Cashdollar, 1994, 2000; Jacobson, Cooper, & Nagy, 1965; Zhihua & Baochun, 2005). However, few studies include a parametric study showing the effects of particle-size distribution and concentration on the explosive characteristics of aluminum and, above all, the influence of humidity is often hardly mentioned.

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Therefore, the approach taken in this work is to control accurately both particles properties and experimental conditions in order to highlight the influence of concentration, particle-size distribution and ambient humidity on aluminum dusts explosion severity. Impact of both water activity and ambient humidity on explosion characteristics has been checked.

2. Experimental setups and methods

2.1. Aluminum samples characteristics

Aluminum powders were provided by Goodfellow with 99% purity and specific maximum particle sizes. The particle-size distribution was determined by using a laser diffraction analyzer (Mastersizer, Malvern Instrument). The samples were characterized by the d_{10}, d_{50} and d_{90} quantiles of the volumetric distribution; the d_x diameter, being defined as the size at which x% of the particles are smaller. The Sauter mean diameter $d_{3,2}$, defined as the diameter of a sphere having the same volume to surface area ratio as the particle, is also indicated in Table 1. This parameter is similar to BET diameter for spherical particles. In this work, four different particle-size distributions were determined (Fig. 1).

The granulometric properties of the powders are given in Table 1. It should be noticed that the settling velocities u_s were calculated for each characteristic quantile of the particle-size distributions thanks to Stokes ($0.0001 < Re < 1$) and Van Allen's laws ($1 < Re < 1000$) corrected by Richardson–Zaki's equations for a swarm of spherical particles settling in air. The velocities u_s range from 4.10^{-4} to 0.4 m s^{-1}: even if the settling velocity of particles of 109 µm diameter is slightly greater than 0.25 m s^{-1}, our samples could be considered as dusts and handled as well (INRS, 2003). This assertion is obviously consistent with the less restrictive definition of a combustible dust provided by NFPA 654 as "any finely divided solid material that is 420 µm or smaller in diameter" (NFPA, 2006). The knowledge of the settling velocities is of great interest in order to check the homogeneity of the explosive dust cloud during explosion/dispersion tests.

The oxidation properties of aluminum powders also depend on the particle shape and on the surface roughness. Scanning electron microscope (SEM) was performed on aluminum samples (Fig. 2). The particles shapes are rather ellipsoidal than spherical, but their surface is quite smooth.

It should also been noticed that aluminum particles are naturally coated with a protective layer of a few nanometres of alumina. In order to study the mechanisms of aluminum oxidation, the melting T_m and boiling points T_b of aluminum and alumina are quoted: $T_{m,Al} = 933$ K; $T_{b,Al} = 2792$ K; $T_{m,\ Al_2O_3} = 2328$ K; $T_{m,\ Al_2O_3} = 3253$ K.

2.2. The sample preparation

The aluminum samples were systematically dried at 50 °C under vacuum during 2 h before handling. Two methods were used to demonstrate the influence of relative humidity on aluminum dust explosions: i) the dry dust was dispersed in a humidity controlled atmosphere in the explosion vessel, or ii) the dust sample was stored in a controlled workstation (glovebox) at constant relative humidity during a sufficient period of time allowing the equilibrium to be reached. To reduce relative humidity, a nitrogen flow or silica crystals can be used to dry the powder.

Table 1
Granulometric properties of aluminum powders.

Samples	d_{10} (µm)	d_{50} (µm)	d_{90} (µm)	$d_{3,2}$ (µm)
Sample A	3	7	13	3
Sample B	5	11	21	9
Sample C	12	27	52	21
Sample D	13	42	109	27

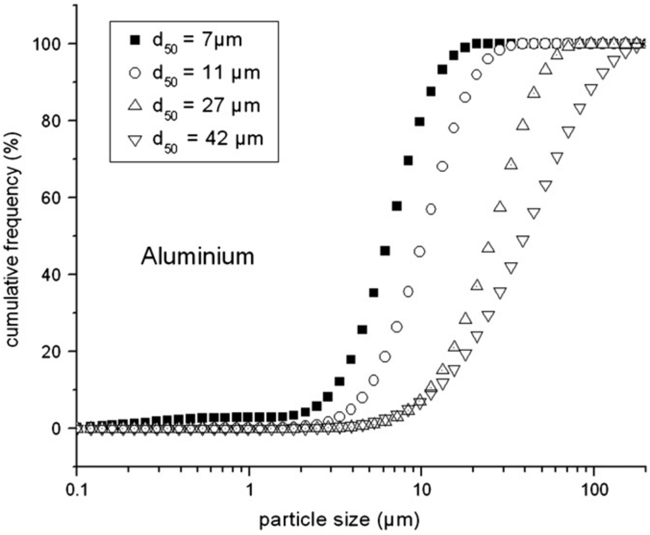

Fig. 1. Cumulative curves of aluminum particles.

The sorption kinetics linking the relative humidity at which the samples are exposed, and the moisture content in the powder, was characterized by using an electromagnetic suspension microbalance represented in Fig. 3 (Sartorius 4201) (El Brihi, Jaubert, Barth, & Perrin, 2002). The time to equilibrium was also determined by this mean.

In a typical experiment, vacuum is obtained by pumping, and then the water vapour source is connected with the sorption chamber. The weight of the sample is monitored as a function of time. The sorption experiments were carried out under atmospheric pressure and the sample weight was measured over a large range of vapour pressures. The relation between the water activity and the water content in the powder is called the adsorption isotherm of aluminum (Fig. 4). Water activity represents the ratio between the vapour pressure of water in the sample to the vapour pressure of distilled water under the same conditions.

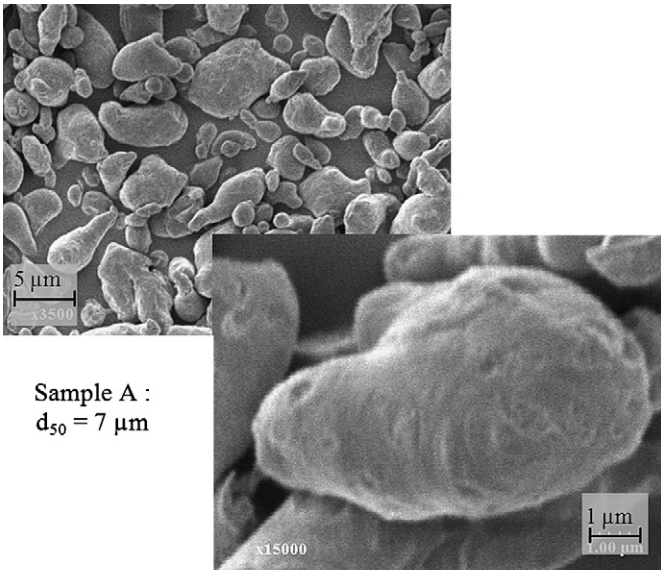

Fig. 2. SEM observations of aluminum particles.