Suppression of metal dust deflagrations

Jérôme Taveau [a, *], Jim Vingerhoets [b], Jef Snoeys [b], John Going [a], Thomas Farrell [a]

[a] Fike Corporation, Industrial Protection Group, Blue Springs, USA
[b] Fike Europe, Herentals, Belgium

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ABSTRACT

Dust explosions continue to pose a serious threat to the process industries handling combustible powders. According to a review carried out by the Chemical Safety Board (CSB) in 2006, 281 dust explosions were reported between 1980 and 2005 in the USA, killing 119 workers and injuring 718. Metal dusts were involved in 20% of these incidents. Metal dust deflagrations have also been regularly reported in Europe, China and Japan.

The term "metal dusts" encompasses a large family of materials with diverse ignitability and explosibility properties. Compared to organic fuels, metal dusts such as aluminum or magnesium exhibit higher flame temperature (T_f), maximum explosion pressure (P_{max}), deflagration index (K_{St}), and flame speed (S_f), making mitigation more challenging. However, technological advances have increased the efficiency of active explosion protection systems drastically, so the mitigation of metal dust deflagrations has now become possible.

This paper provides an overview of metal dust deflagration suppression tests. Recent experiments performed in a 4.4 m³ vessel have shown that aluminum dust deflagrations can be effectively suppressed at a large scale. It further demonstrates that metal dust deflagrations can be managed safely if the hazard is well understood.

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1. Introduction

Industrial explosions have been a hazard for as long as man has been processing, storing and transporting materials. Most of the reported dust explosions have involved organic products, mainly because most of the combustible materials in commerce are organic (agriculturals, food, fuel, pharmaceuticals).

Metal dusts have been reported in a growing number of explosions in the last decades (May and Berard, 1987; Senecal, 1991; Pratt and Atherton, 1999; Matsuda and Yamaguma, 2000; Matsuda et al., 2001; Lembo et al., 2001; Eckhoff, 2003; CSB, 2005; CSB, 2006; Ebadat and Prugh, 2007; CSB, 2012; Yan and Yu, 2012; CSB, 2014) due to their increased use in the process industries (automotive, aeronautics, electronics).

Traditionally, the suppression of metal dust deflagrations has been perceived difficult to address due to the high reactivity of metal dusts. Nevertheless, technological advances described in details by Going (2009) have enabled earlier pressure detection and faster suppressant injection. This, in turn, has drastically increased the efficiency of explosion suppression systems, so the mitigation of metal dust deflagrations has now become possible.

This paper provides an overview of past (Going and Snoeys, 2002) and more recent (Taveau et al., 2013) suppression tests with metal dusts. Parameters such as explosibility characteristics (K_{St}, P_{max}), dust concentration, vessel volume, suppressant type/concentration, number and size of containers, and detector activation pressure were varied to determine their influence on suppression effectiveness.

2. Anatomy of metal dust deflagrations

Metal dusts are similar to organic dusts in that they, once ignited, undergo oxidation reactions and the combustion can propagate through a dust cloud. They differ in the nature of the products formed: while organic fuels primarily form carbon dioxide and water vapor (Equation (2)), each metal dust forms a particular metal oxide (Equation (3)):

$$Fuel + Oxygen \rightarrow Oxides + Heat \tag{1}$$

* Corresponding author.
  E-mail address: jerome.taveau@fike.com (J. Taveau).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + Heat \qquad (2)$$

$$Al + \frac{3}{4}O_2 \rightarrow \frac{1}{2}Al_2O_3 + Heat \qquad (3)$$
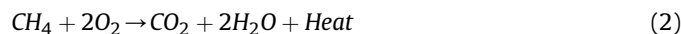
As a result, organic materials have quite similar combustion properties, whereas metal dusts exhibit more variability and extremes (Hertzberg et al., 1992; Beck et al., 1997; Eckhoff, 2003). From Table 1, three categories of metal dusts can be distinguished with low (iron, zinc), medium (silicon), and high reactivities (aluminum, magnesium).

Fig. 1 shows typical deflagration curves for titanium and aluminum in comparison with an organic material (Pittsburgh coal).

Most deflagrations involving organic fuels propagate by a heterogeneous mechanism: upon heating, the materials generate various hydrocarbon volatiles, which then undergo gas phase combustion. Metal dusts deflagrations, on the other hand, are capable of propagating by this volatilization process as well as by a surface reaction process; the combustion behavior is indeed strongly dependent on the nature of the metal: while gas phase combustion is important for aluminum and magnesium particles, solid phase reactions dominate for other metals such as iron (Taveau, 2014).

Another significant difference between organic and metal dusts is the amount of fuel that is required to reach the maximum explosion pressure P_{max} and the maximum pressure rate of rise $(dP/dt)_{max}$: while a concentration of 500 g/m^3 is typically expected for organic dusts, values of 1500 g/m^3 or more are common for metal dusts; indeed, a larger amount of metal is needed to react with one mole of oxygen. Deviation from stoichiometric conditions, on the other hand, can be explained by the incomplete combustion that occurs in a closed vessel compared to burner experiments, for example (Julien et al., 2014).

Particle size has a strong effect on the hazard of metal dusts. Micrometric particles of aluminum and magnesium (Beck et al., 1997) can exhibit very high K_{St} values (up to 1100 bar.m/s for aluminum) and very low minimum ignition energies (below 1 mJ). Several authors (Boilard et al., 2013; Krietsch et al., 2014) have also reported spontaneous ignition with metallic nanoparticles.

Particle shape is also important in determining the severity of the deflagration. In a study (Moore and Cooke, 1988) sponsored by the British Material Handling Board (BMHB), aluminum powder was able to generate K_{St} values between 300 and 400 bar.m/s at optimum concentration. When in the flake form, K_{St} was 600 bar.m/s and a value as high as 1400 bar.m/s was reported.

3. Suppression of dust deflagrations

Suppression is the process of controlling deflagrations by "chemically" participating in the combustion reaction and/or by absorbing energy produced by the combustion reaction

("physical" mechanism). Suppressant agents typically used for explosion protection applications, such as sodium bicarbonate (SBC), mono-ammonium phosphate (MAP), and potassium bicarbonate (PK), are thought to provide extinction of organic flames by both physical and chemical mechanisms. It is believed that suppression of metal dust deflagrations is mainly achieved by physical mechanism.

In suppression experiments, dust fuel is discharged into a test vessel and ignited. The pressure resulting from the deflagration is detected. Upon detection, a control panel initiates the suppressant discharge. Both nitrogen and suppressant agent are rapidly discharged into the vessel and extinguish the fireball (Fig. 2). The maximum pressure reached after ignition of the fuel dust and discharge of suppressant agent into the enclosure is reported as the reduced pressure, or total suppressed pressure (TSP).

The components that make up the total suppressed pressure (Equation (4)) in any enclosure are:

1. Activation pressure (P_{act}) of the detector
2. Pressure due to injection of nitrogen (P_{N2}) from the discharge container
3. Combustion pressure (P_{comb}) associated with flame growth (after P_{act} has been reached):

$$TSP = P_{act} + P_{N_2} + P_{comb} \qquad (4)$$

4. Suppression of metal dust deflagrations: past attempts

While quite effective for organic fuels, suppression has generally been considered very difficult for metal dusts. Indeed, materials such as aluminum or magnesium exhibit higher rates of pressure rise (i.e. a faster pressure generation and less time available for the suppression system), and also higher flame temperatures (i.e. more suppressant is needed to absorb the heat generated by the combustion reaction).

In 1988, a report from the BMHB (Moore and Cooke, 1988) stated that "metal dusts explosion hazards have always been considered to be beyond the capability of explosion protection technology".

Therefore, few examples of attempts to suppress metal dust deflagrations exist in literature.

Bartknecht (1989) reported on the suppression of aluminum dust in a 1 m^3 vessel using SBC. At a low aluminum concentration, suppression was effective. However, at concentrations of and above 500 g/m^3, suppression was not successful (TSP ~ 90% of P_{max}). The failure was attributed to the low suppressant discharge velocity (only 10 m/s).

Moore and Cooke (1988) investigated metal dust deflagrations suppression in more details. Using aluminum flake (K_{St} = 321 bar.m/s, P_{max} = 10.7 bar, dust concentration of 500 g/m^3) in a 6.2 m^3 vessel with a detector activation pressure of 0.05 bar, various suppressant agents were screened. While sodium bicarbonate (Dessikarb™) and rock dust (calcium carbonate) showed some promise (TSP less than 3 bar), china clay, copper dust, talc, silicon oil, metal halide (MET L X™), and mono ammonium phosphate (Furex 770) were unsuccessful. A total suppressed pressure of 1.8 bar was achieved for a SBC concentration of 12.9 kg/m^3.

Suppression assisted by venting was also tested in a continuation of this effort. Using an 18.5 m^3 vessel, SBC at a concentration of 5.7 kg/m^3, a 0.95 m^2 vent with a P_{stat} of 0.2 bar, a P_{act} of 0.04 bar and an aluminum dust with a K_{St} = 350 bar.m/s, the reduced pressure was ~1.3 bar. For a higher K_{St} of 600 bar.m/s, however, TSP was 3.8 bar.

Table 1
Physical properties of selected metal dusts compared to carbon.

Element	T_f^a (K)	P_{max} (bar)	K_{St} (bar.m/s)	Oxidation products	ΔH_c (kJ/mole O_2)
Al	3550	13	800	Al_2O_3	1100
Mg	3100	17.5	500	MgO	1240
Si	2870	~10	~150	SiO_2	830
Fe	2250	4.5	29	Fe_2O_3	530
Zn	1860	4.4	17	ZnO	700
C	2320	5–9	50–350	CO_2, H_2O	400

[a] Adiabatic flame temperature.