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Experimental determination of explosion characteristics for aluminum powder derived from technological processes

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Abstract. Flammable gases or vapors - air mixtures generally tend to occupy the entire available volume being quasi stable systems. In contrast, the suspension of dust in air is a heterogenous unstable system, wherein the dust solid particles are deposited in time, depending on their weight. The explosive behavior which is represented by a mixture of air and flammable substances is influenced by many factors of which the most important parameters are the chemical composition and concentration of flammable and explosive mixture with air. In particular, for the combustible powders, additional factors are intervening, related to the physico-chemical properties of combustible solids, the shape and size of dust particles, as well as the environmental conditions under which dust exist in suspension. For this work were performed experimental determination of the explosion and combustible parameters specific for aluminum powder derived from technological processes, as waste, being analyzed both influence of particle size and contribution of inert substances.

Key Words: explosion, aluminium powder, inert, particle size.

Introduction. A dust explosion is the rapid combustion of a dust cloud. In a confined or nearly confined space, the explosion is characterized by relatively rapid development of pressure with flame propagation and the evolution of large quantities of heat and reaction products. The required oxygen for this combustion is mostly supplied by the combustion air. The condition necessary for a dust explosion is a simultaneous presence of dust cloud of proper concentration in air that will support combustion and a suitable ignition source. The term dust is used if the maximum particle size of the solid mixture is below 500 µm (Vijayaraghavan 2004).

A dust explosion is initiated by the rapid combustion of flammable particulates suspended in air. Any solid material that can burn in air will do so with a violence and speed that increases with the degree of sub-division of the material (Abbasi & Abbasi 2007). Higher the degree of sub-division (in other words smaller the particle size) more rapid and explosive the burning, till a limiting stage is reached when particles too fine in size tend to lump together. If the ignited dust cloud is unconfined, it would only cause a flash fire. But if the ignited dust cloud is confined, even partially, the heat of combustion may result in rapid development of pressure, with flame propagation across the dust cloud and the evolution of large quantities of heat and reaction products. The furious pace of these events results in an explosion. Besides the particle size, the violence of such an explosion depends on the rate of energy release due to combustion relative to the degree of confinement and heat losses. In exceptional situations a destructive explosion can occur even in an unconfined dust cloud if the reactions caused by combustion are so fast that pressure builds up in the dust cloud faster than it can be dissipated at the edge of the cloud (Abbasi & Abbasi 2007).

The oxygen required for combustion is mostly supplied by air. The condition necessary for a dust explosion is a simultaneous presence of:

- a combustible dust;
- oxidant (typically atmospheric oxygen);
- the dust is suspended in the air at a sufficiently high concentration;
- ignition source, situation which can be illustrated by the diagram in Figure 1.

In some traditional analyses of dust explosions, confinement is considered to be a fifth requirement; this is not an essential condition, but can greatly aggravate the physical damage that results.

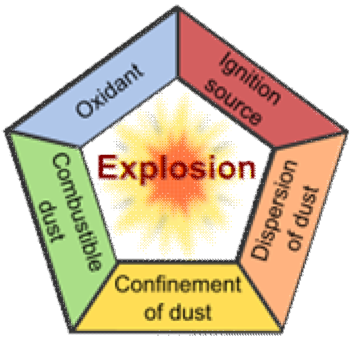

Figure 1. Diagram for dust explosion (Farahani 2012).

In case of dusts made up of volatile substances, the explosion may occur in three steps which may follow each other in very quick succession-devolatization (where volatiles are let off by the particle or the particles are vaporized), gas phase mixing of fuel (released by dusts) and oxidant (usually air), and gas phase combustion.

Many combustible dusts if dispersed as a cloud in air and ignited, will allow a flame to propagate through the cloud in a manner similar to (though not identical to) the propagation of flames in premixed fuel–oxidant gases (Proust 2006). Such dusts include common foodstuffs like sugar flour, cocoa, synthetic materials such as plastics, chemicals and pharmaceuticals, metals such as aluminum and magnesium, and traditional fuels such as coal and wood. Generally, dust explosion involves oxide formation: fuel + oxygen → oxide + heat.

But metal dusts can also react with nitrogen or carbon dioxide to generate heat for explosion.

The interdependence of the various parameters which influence the explosion pressure is described by the equation of state for ideal gases:

$$P = nRT/V$$

where P is the pressure, V the volume, R the universal gas constant, n the number of moles of gas and T is the temperature. Other factors being equal, the increase of T due to the heat developed in the burning dust cloud has the deciding influence on the explosion pressure. It follows that higher the heat of combustion of a given dust per mole of O_2 consumed, greater is the likely severity of an explosion.

Table 1 presents the heat of combustion of a few commonly encountered dusts (Eckhoff 2003).

Table 1

Heat of combustion of some common dust

Material	*Oxidation products*	*Heat of combustiuon (kJ/mol O_2)*
Calcium	CaO	1270
Magnesium	MgO	1240
Aluminum	Al_2O_3	1100
Silicon	SiO_2	830
Chromium	Cr_2O_3	750
Zinc	ZnO	700
Iron	Fe_2O_3	530
Copper	CuO	300
Sulphur	SO_2	300

It reveals that metals form highly hazardous dusts from this viewpoint (Eckhoff 2003). Explosion hazard always exists whenever dusts are produced, stored or processed and where situations can occur when these materials are present as a mixture in air (Abbasi

& Abbasi 2007). The mixture is deemed "explosible" if combustible dusts are present in such quantities in air that an explosion can occur on ignition.

Dust deposits in a technological area can be accumulated in such quantities that the whirling can form mixtures with air at concentrations of hundreds of g/m^3, far surpassing the minimum explosive concentration.

Among the metals powders, aluminum powder is known to be the most reactive.

Aluminum dust*.* The explosive properties of aluminum dust are in the literature, including the National Fire Protection Association (NFPA) fire prevention standards. In NFPA 68 (2002), aluminum is ranked among the most explosive of metal dusts. Preliminary data collected by the U.S. Chemical Safety and Hazard Investigation Board (CSB) indicate that nearly one fourth of all dust explosions in the United States in the last 25 years involved metal dusts, and that aluminum accounted for the majority of these events. Metals account for about 19% of dust explosions worldwide. This data indicates that metal dusts are particularly hazardous and all appropriate precautions need to be taken to prevent dust explosions.

Dust explosivity is typically expressed using the deflagration constant, K_{ST}:

$$(dp/dt)_{\max} \cdot V^{1/3} = const. = K_{st} = K_{\max},$$

where $(dp/dt)_{max}$ is the maximum measured rate of pressure rise and V is the container volume.

This constant is determined experimentally by measuring how fast the pressure rises when dust of a known concentration is ignited in a container of a specific volume (20 liters). The higher the K_{ST}, the more severe a dust explosion can be. Three "dust hazard classes" indicate relative explosiveness.

For comparison, Table 2 shows K_{ST} values for a few known explosive dusts. Pure aluminum has a high K_{ST} and is rated as a Class ST-3 dust (CSB 2005).

Table 2

Comparative explosivities of dusts

Dust type	*Avg. particule size*	*K_{ST} (bar-meter/sec)*	*Dust hazard class*
Pure aluminium powder	29	415	ST-3
Coal dust	< 10-38	55-108	ST-1
Wheat flour	57	87	ST-1
Wood dust	43	102	ST-2

The Institution of Chemical Engineers (IchemE) reports that a dust explosion takes place every day in Europe. About 19% of these dusts explosions are due to metal oxidation and aluminum accounts foremost of these events (Dufaud et al 2010).

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.

Another dust explosion occurred at the Daido Kako Enka Firework manufacturing factory, Moriya, Japan, in June 1992 and the presumed cause of this accident was the ignition of powdery mixture of potassium chlorate and aluminum by friction-induced sparks during a mixing operation (Dufaud et al 2010).

A Mg–Al alloy exploded in a bag filter dust-collecting device at a manufacturing plant of electronic devices from Tokyo, Japan in October 2000 (Vijayaraghavan 2004).

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 kinds 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 (Dufaud et al 2010).

In order to prevent and protect to explosion hazard are needed some mandatory minimum information regarding the safe handling and processing of solid combustible materials with fine particle size, including: knowledge of the characteristics that influence the security, control and monitoring the leaks of dust in technological processes, designing the installations to prevent migration and accumulation of dusts and not the least the implementation of a rigorous cleaning work place program.

Determination of safety characteristics is an important role in early-stage risk explosion assessment and conformity assessment phase of equipment and protective systems intended for use in potentially explosive environments (Jurca et al 2014).

It is necessary to be noticed that the explosion parameters of dusts are not physical constants, they are dependent of the techniques used for measuring, particle size, by the presence or absence of inert substances and by the reaction conditions.

The objective of the present paper is to show that, for the combustible powders, additional factors are intervening, related to the physico-chemical properties of combustible solids, the shape and size of dust particles, as well as the environmental conditions under which dust exist in suspension. For this work were performed experimental determination of the explosion and combustible parameters specific for aluminum powder derived from technological processes, as waste, being analyzed both influence of particle size and contribution of inert substances.

Material and Method

Materials. For conducting the experiments samples of aluminum powder were used, resulting from the process of grinding/polishing with abrasive brushes of some semi-finished products from aluminum contaminated with inert powder (talc, calcium oxide) and a small quantity of fibers. The experiments were performed in January–February 2014.

Particle size analysis. Particle size analysis is a set of operations that determines the particle size distribution after forming a cohesionless rock or for separating a dimensional fraction of a powder grain variety. Particle size analysis is performed by sieving for particle size greater than 0.1 mm or by sedimentation otherwise.

Particle size analysis by sieving is performed using sieves with a standardized mesh size. The sample of material is sieved sequentially through a set of sieves, and then the quantities of material retained on each sieve are weighed and by relating them to the initial sample weight are calculated the particle size fractions.

For particle size analysis six sieves with the following standard dimensions were used: 2 mm; 1 mm; 0.4 mm; 0.25 mm; 0.125 mm; 0.063 mm and 0.05 mm.

Determining the explosion parameters. The method principle is described here: determination of the explosion parameters from combustible dusts by whirling the dust sample (grain size known) inside an explosion-proof vessel type KSEP-20l (Figure 2) and the initiating of the cloud (to known values of energy ignition) under the initial conditions of temperature and pressure data (standard).

The explosion vessel is an explosion-proof enclosure, made of stainless steel with a volume of 20 dm^3. A water jacket has the role to absorbing the heat produced by the explosions. In order to perform the test, the dust is dispersed into the vessel under pressure through a quick-acting valve and a dispersing jet. The quick-acting valve is opened and closed with a pneumatic displacer. The compressed air supply valves are electrically operated. The ignition source is placed in the center of the sphere.

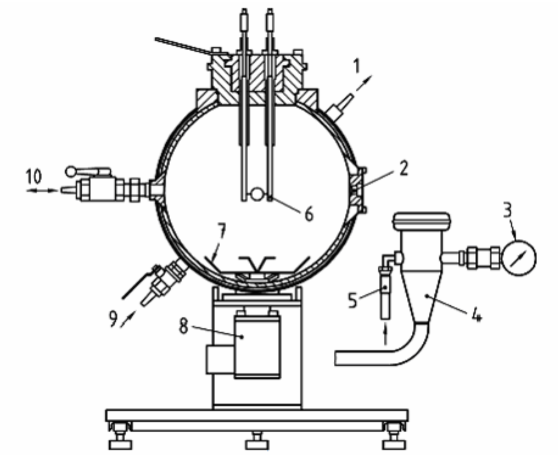

Figure 2. KSEP – 20 L: 1 - exhaust vent of water; 2 - pressure transducers; 3 - manometer; 4 - dust vessel (0.6 dm^3); 5 - inlet port of air; 6 - ignition source; 7 - jet deflectors; 8 - quick-acting valve; 9 - inlet port of water; 10 - exhaust vent (air, reaction products).

In order to determine the explosion parameters was used SR EN 14034+A1:2011, Determination of explosion characteristics of dust clouds:

- Part 1: Determination of the maximum pressure p_{max} of the dust suspension;
- Part 2: Determination of the maximum rate of pressure rise (dp/dt)max of a dust clouds;
- Part 3: Determination of the lower explosion limit at the dust clouds - LEL.

Lower explosion limit is the minimum concentration of the combustible dust which mixed with air can cause an explosion. The maximum explosion pressure, p_{max}, is the highest pressure which occurs during the explosion of a mixture of powder in a closed vessel. The maximum rate of pressure rise $(dp/dt)_{max}$ is the maximum value of the pressure increase per unit time during the explosions. The maximum explosion pressure, the maximum rate of pressure rise and the specific constant of the dust - Kst (the index of the explosion) are explosion parameters based on which it performed the correlation with protection and prevention measures.

The specific constant of the dust K_{st} (the index of the explosion) is the independent characteristics of the volume who is calculated using the cubic equation:

$$(dp/dt)_{\max} \cdot V^{1/3} = const. = K_{st} = K_{\max}$$

For the spherical vessel of 20 l it applies the following equation:

$$K_{max}=K_{st}= 0,271 \cdot (dp/dt)_{\max} \qquad [bar.m/s]$$

Initial conditions for testing:

- particle size distribution for the tested samples: under 63 µm;
- the system used for the dust dispersion is the dispersing jet type;
- characteristics of the test device:
  - method for spark generating – chemical igniters – 5kJ,
  - explosion device type KSEP – 20 L,
  - initial temperature inside the vessel: 20°C,
  - initial pressure inside the vessel– atmospheric pressure.

Initially for aluminum dust samples were performed preliminary laboratory tests for dust sample classification (combustible/incombustible) – qualitative pretesting on the behavior to explosive mixture of dust/air.

For this purpose, was used a modified Hartmann glass tube with a volume of 1.2 liters (Figure 3).

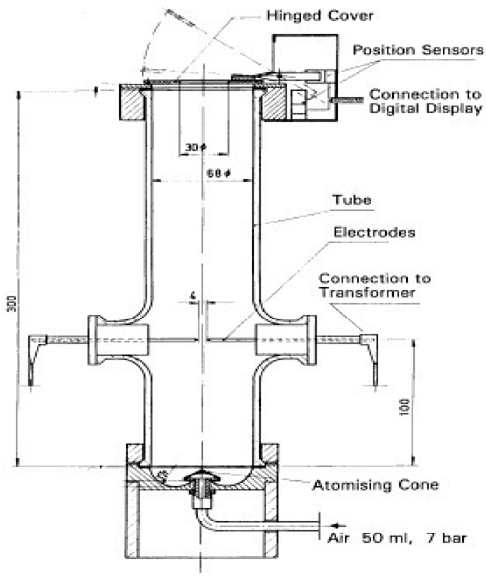

Figure 3. Hartmann tube.

The dust dispersion system at the base of the tube is the mushroom type which around the sample is spread free. For the dispersion a blast of compressed air at 7 bar is used. The dust is dispersed into the cylinder glass where it is ignited by a continuous electric arc between two electrodes. The bursting behavior of the mixture is recorded through a module consisting of an electronic device type active valve installed in the top of the glass tube interconnected with a device which displays the explosion index.

Results and Discussion

Particle size analysis. Results of particle size analysis are listed in Table 3.

Table 3

Particle size analysis results

Sample	*Particle size (mm)*					
	0.05–0.063	*0.063- 0.125*	*0.125–0.25*	*0.250–0.4*	*0.4–1*	*> 2*
Sample 1	47.10%	14.16%	13.51%	3.32%	4.60%	17.30%
Sample 2	22.7%	9.84%	35.86%	18.01%	7.4%	6.18%

Sample no. 1 represents the aluminum dust deposited on the ventilation installation. The main fraction of 47% consisted of aluminum dust with particle size under 0.063 mm which was unpurified with fine particles from the polishing material. It was also identified a fraction of 17% above 2 mm, which consisted of textile fibers resulted in the polishing process as seen in the Figure 4.

Figure 4. Textile fibers from sample no. 1.

Sample no. 2 is represented by the dust collected from the cyclone, where the dust was mixed with a small quantity of inert dust. It was identified also a fraction of 6.18% above 2 mm which consisted of textile fibers and inert dust, as seen in the Figure 5.

Figure 5. Size fraction greater than 2 mm corresponding to sample no. 2.

The preliminary analysis concerning the classification of dust samples (combustible/non-combustible). The preliminary analysis gives an indication regarding the explosivity of a tested dust. If the dust is explosive, it will be further tested in the 20 L explosion vessel for the determination of the explosion parameters. As it can be seen in the Table 4 both tested dust samples are combustible.

Table 4

Preliminary analysis results

Sample	*Particle size distribution (μm)*	*Value indicated by the device*	*Clasification of dust sample (combustible/non-combustible)*
Sample 1	< 63 μm	2	Combustible
Sample 2	< 63 μm	2	Combustible

Determination of the lower explosive limit, LEL. As mentioned before in the chapter 2.2, the lower explosive limit is determined in the 20 L explosion vessel, using as ignition source a chemical igniter with 5 kJ energy. The values for the two aluminum dust are listed in the Tables 5 and 6. As it can be seen from the tables, the values of lower explosive limit for sample 1 and sample 2 are 40 g/m^3 respectively 90 g/m^3.

Table 5

Lower explosion limit, LEL (g/m^3) of the tested sample 1

No.	*Dust concentration (g/m^3)*	*Measured values of the explosion overpressure, p_{ex} [bar]*	*Number of tests*
1	125	4.7	1
2	60	2.1	1
3	50	1.6	1
4	40	1.1	1
5	40	0.8	1
6	40	1.0	1

Lower explosion limit, LEL (g/m^3) of the tested sample: 40 g/m^3.

Table 6

Lower explosion limit, LEL (g/m^3) of the tested sample 2

No.	*Dust concentration (g/m^3)*	*Measured values of the explosion overpressure, p_{ex} [bar]*	*Number of tests*
1	125	2.1	1
2	100	1.5	1
3	90	1.3	1
4	90	1	1
5	90	1.3	1

Lower explosion limit, LEL (g/m^3) of the tested sample: 90 g/m^3.

Determination of maximum pressure, p_{max}. The results from the experimental determination of the maximum explosion pressure are listed in the Tables 7 and 8. In the Figure 6, one can see the difference in explosion pressure function of dust concentration for the two tested samples.

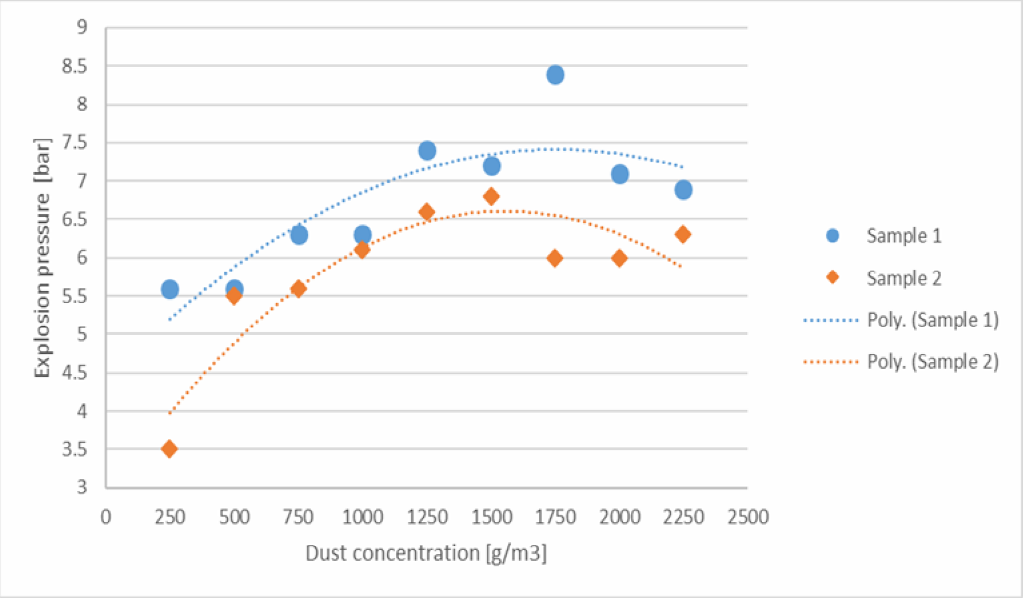

Figure 6. Explosion pressure function of dust concentration.

Table 7

Maximum value of the maximum pressure for the tested sample 1

No.	*Dust concentration [g/m^3]*	*Measured values of the explosion pressure, p_{ex} [bar]*
1	250	5.6
2	500	5.6
3	750	6.3
4	1000	6.3
5	1250	7.4
6	1500	7.2
7	1750	8.4
8	2000	7.1
9	2250	6.9
10	2500	6.3

Maximum value of the maximum pressure for the tested sample - p_{max} = 8.4 [bar].

Table 8

Maximum value of the maximum pressure for the tested sample 2

No.	*Dust concentration [g/m^3]*	*Measured values of the explosion pressure, p_{ex} [bar]*
1	250	3.5
2	500	5.5
3	750	5.6
4	1000	6.1
5	1250	6.6
6	1500	6.8
7	1750	6.0
8	2000	6.0
9	2250	6.3

Maximum value of the maximum pressure for the tested sample - p_{max} = 6.8 [bar].

As it can be seen from the Figure 6 and Tables 7 and 8, the maximum explosion pressure for the sample 2, respectively the sample treated with inert dust is slightly lower than the untreated sample.

The pressure generated in the closed vessel has a small relevance for the explosions occurred in open spaces (rooms). Windows, doors, walls succumb to pressures that are 1% of the pressure increases obtained in cells closed explosion. The maximum explosion pressure is in this case determined by the size and resistance pressure of these exhaust areas. In industrial buildings there are pressure relief systems in order to avoid damage.

Determination of the maximum rate of pressure rise $(dp/dt)_{max}$. The results from the experimental determination of the maximum rate of pressure rise are listed in the Table 9 and Table 10 and represented in Figure 7.

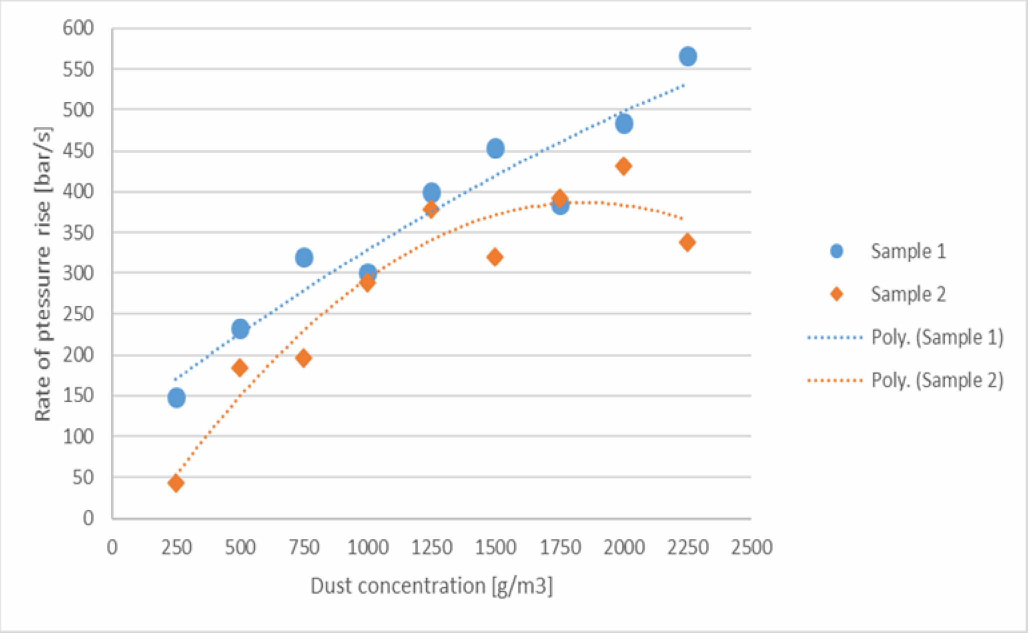

Figure 7. Rate of pressure rise function of dust concentration.

Table 9

Maximum value of the rate of pressure rise (sample 1)

No.	*Dust concentration [g/m^3]*	*Maximum rate of pressure rise $(dp/dt)_{max}$ [bar/s]*
1	250	148
2	500	232
3	750	320
4	1000	300
5	1250	400
6	1500	454
7	1750	384
8	2000	484
9	2250	567
10	2500	512

Maximum value of the rate of pressure rise - $(dp/dt)_{max}$ = 567 [bar/s]; Explosion index – the specific constant of the tested sample: $K_{max} = K_{st}$ [bar·m/s]; $K_{max} = K_{st} = 0.271 \times (dp/dt)_{max}$ = 154 bar·m/s.

Table 10

Maximum value of the rate of pressure rise (sample 2)

No.	*Dust concentration [g/m^3]*	*Maximum rate of pressure rise $(dp/dt)_{max}$ [bar/s]*
1	250	43
2	500	184
3	750	196
4	1000	288
5	1250	378
6	1500	320
7	1750	392
8	2000	432
9	2250	338

Maximum value of the rate of pressure rise - $(dp/dt)_{max}$: 432 [bar/s]; Explosion index – the specific constant of the tested sample: $K_{max} = K_{st}$ [bar·m/s]; $K_{max} = K_{st} = 0.271 \times (dp/dt)_{max}$ = 117 bar·m/s.

Experiments were performed with dried powders for dust concentrations ranging between 40 g/m^3 and 2500 g/m^3. The evolution of maximum pressures p_{max} has been represented as a function of dust concentrations.

The results obtained for the maximum rate of pressure rise for the two tested dusts reveal the fact that the inert powder is influencing the behavior of the explosion pressure in time, the value obtained for the inert sample being slightly lower than the untreated one.

After conducting the experiments above on the two samples of aluminum dust derived from a technological process of grinding aluminum products, one of the sample being treated with inert powder, can conclude that the effect of the inert powder is a beneficial one, lowering the explosion limit and the explosion severity.

The explosion parameters determined in the paper represents punctual values for two samples of dust encountered in process, there are not intrinsic values for another aluminum dust as stated before in introduction.

In order to elaborate the explosion protection measures, one should experimentally determine the content of inert dust that should be used in order to eliminate or to lower the explosion consequences.

From the results in this paper, it is however clear that when dealing with explosive dusts, especially metallic ones, the explosive danger is inherent and measure should be taken.

Conclusions. After conducting the experiments above on the two samples of aluminum dust derived from a technological process of grinding aluminum products, one of the sample being treated with inert powder, one can conclude that the effect of the inert powder is a beneficial one, lowering the explosion limit and the explosion severity.

In order to elaborate the explosion protection measures, one should experimentally determine the content of inert dust that should be used in order to eliminate or to lower the explosion consequences. From the results in this paper, it is however clear that when dealing with explosive dusts, especially metallic ones, the explosive danger is inherent and explosion protection measures should be taken.

For preventing the explosion hazard are needed some mandatory minimum information regarding the safe handling and processing of solid combustible materials with fine particle size, including: knowledge of the characteristics that influence the security, control and monitoring the leaks of dust in technological processes, designing the installations to prevent migration and accumulation of dusts and not the least the implementation of a rigorous cleaning work place program.

Determination of safety characteristics of combustible dusts plays an important role in early-stage risk explosion assessment and conformity assessment phase of equipment and protective systems intended for use in potentially explosive environments.

It is necessary to be taken into account that the explosion parameters of dusts are not physical constants, they are depending of the techniques used for measuring, particle size, by the presence or absence of inert substances and by the reaction conditions.

In order to prevent damages to health, environment and productivity, due to aluminum dusts explosions, adequate prevention and protection means should be specify considering the best available techniques, but also, and above all, the exact operating conditions.

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.

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