



DETERMINATION OF FIRE AND EXPLOSION CHARACTERISTICS OF DUST

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Review article

Abstract: The aim of this paper is to approximate danger of dust clouds normally occur by determining their explosion characteristics. Nowadays, dusty environment is phenomenon in the industry. In general, about 70% of dust produced is explosive. Dust reduction in companies is the main purpose of the national and European legislative. Early identification and characterization of dust in companies may reduce the risk of explosion. It could be used to identify hazards in industrial production where an explosive dust is produced. For this purpose several standards for identification and characterization of explosion characteristics of industrial dust are being used.

Keywords: Dust clouds, explosion characteristics, dust explosion, minimum ignition energy, maximum explosion pressure.

Introduction

According to BS 2955: 1958 (BS2955 1958), materials with particle size less than 1000 μm (16 BS mesh size) are defined as ‘powders’; when particles have a diameter less than 76 μm (200 BS mesh size), they are referred to as ‘dust’. As per NFPA (NFPA, 68 2002) ‘dust’ is any finely divided solid, 420 μm or less in diameter.

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 (Eckhoff, 2003). 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 (Cashdollar, 2000).

The condition necessary for a dust explosion is a simultaneous presence of dust cloud of appropriate concentration in air that will support combustion throughout the process and a suitable ignition source. 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/devolatilization (where volatiles are let off by the particle or the particles are vapourized), 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, 2005)

Some of the natural and synthetic organic materials that can form combustible dusts include:

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- Food products (e.g., grain, cellulose, powdered milk, sugar, flour, starch, cocoa, maltodextrin);
- Pharmaceuticals (e.g., vitamins);
- Wood (e.g., wood dust, wood flour);
- Textiles (e.g., cotton dust, nylon dust);
- Plastics (e.g., phenolics, polypropylene);
- Resins (e.g., lacquer, phenol-formaldehyde);
- Biosolids (dried wastes from sewage treatment plants);
- Coal and other carbon dusts. (Geddie, 2012)

Combustible dusts can also be formed from inorganic materials and metals including:

- Aluminum;
- Iron;
- Magnesium powder;
- Manganese;
- Sulfur. (Geddie, 2012)

Materials and methods

While fire is caused when three factors - fuel, oxidant, and ignition - come together to make what has been called 'the fire triangle', a dust explosion demands two more factors: mixing (of dust and air), and confinement (of the dust cloud). The 'dust explosion pentagon' (Kauffman, 1982) is formed when these five factors occur together (Fig. 1):

- presence of combustible dust in a finely divided form;
- availability of oxidant;
- presence of an ignition source;
- some degree of confinement;
- state of mixed reactants.

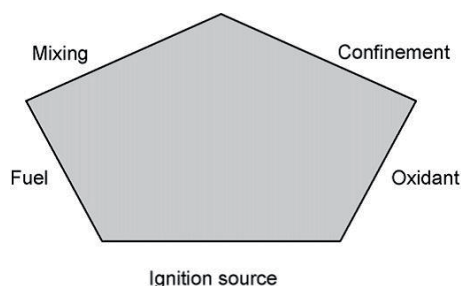


Fig. 1 The dust explosion pentagon (Kauffman, 1982)

A point to be noted here is that even partial confinement of an ignited dust cloud is sufficient to cause a highly damaging explosion. In this sense, too, dust clouds behave in a manner similar to clouds of flammable gases. (Proust, 2005)

A dust layer is deemed 'combustible' if it can be ignited with a foreign source and the local fire thus generated propagates sufficiently after the outside source is taken away (Siwek, 1996). All explosible dusts ought to be combustible, but not all combustible dusts are easily explosible. (Vijayaraghavan, 2004)

As all the initiatives on the understanding, prevention, and control of dust explosions revolve round 'dust explosibility', 'minimum explosible dust concentration', 'minimum ignition energy', and 'minimum ignition temperature' (Tab. 1), it may be relevant to dwell upon how these parameters are measured and what are the uncertainties involved in the measurements. The two apparatus most often used for dust explosibility testing have been the 'Hartmann vertical tube' and the '20 l sphere'. Of these the Hartmann tube was the first to be commonly used and a great deal of data exists which has been generated in the pre-1980 era by this apparatus (Lees, 2005). A Hartmann apparatus consists of a 1.2 l vertical tube in which dust is dispersed by an air blast. A hot wire or a spark igniter serves as ignition source (Fig. 2).

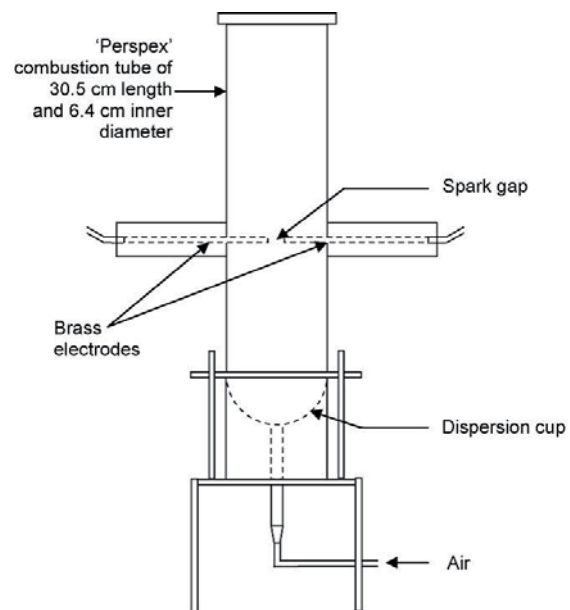


Fig. 2 Hartmann vertical tube apparatus (Abbasi, 2006)

Flame propagation is observed as a function of dust particle size, dust concentration, ignition energy, temperature, etc. Even as the Hartmann vertical tube and its variants - the horizontal tube, and the inflammatory apparatus - have been extensively utilized in the past, it has been increasingly realized that the Hartmann tube is not apt to give uniform conditions for dust dispersion and turbulence. Further, it is subject to wall effects; after the flame

goes through initial spherical expansion, it travels as two fronts up and down the tube. These conditions give a lower rate of combustion and of pressure rise than the actual; consequently the strength of the pressure rise one records with the Hartmann bomb is less than one gets from more advanced apparatus. The Hartmann tube may also yield false negatives for dusts that are difficult to ignite with a spark but are ignitable by stronger ignition sources. (Cashdollar, 2000)

The minimum explosible dust concentration and the minimum explosion energy are also determined using 20l/1m³ spheres. The experimental conditions required to obtain agreement with the 1m³ ISO vessel were specified in a standard issued by the American Society for Testing and Materials (ASTM) in 1988 (Eckhoff, 2003). The ignition source has to be the same type of 10 kJ chemical ignitor as used in the 1m³ ISO test but the ignition delay can be shorter (60 ms) because of the smaller vessel size EN 14034-3+A1:2012.

Experimental modified KV 150-M2 chamber has been used during experiment. Scheme of a chamber is shown in Figure 3. Dust clouds in this unit are carried out mechanically. The compressed air is transmitted from the tank of by fast opening of the valve to inner space of chamber. The chamber has a volume of 291 liters. The sample is located on plate and spread by compressed air. This compressed air is directed to the sample through the metal profiled sheeting. The sample is initiated by a chamber nitrocellulose initiator after the spreading of this sample. The initiator works on a resistive principle. Immediate initiation of nitrocellulose is achieved by the voltage value which is supplied to the resistance wire and results into an immediate burning and interruption of wire. Ignition energy of nitrocellulose used in initiator is 5 kJ.

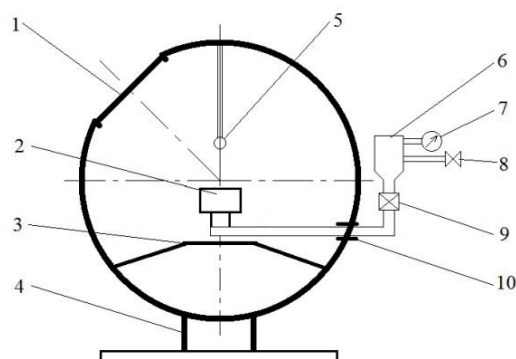


Fig. 3 Scheme of modified chamber KV 150-M2
(1 - lid, 2 - nozzle for spreading of sample, 3 - desk,
4 - base, 5 - pyrotechnical igniter, 6 - vessel,
7 - manometer, 8 - compressed air inlet valve,
9 - fast opening valve, 10 - window (Pastier, 2014)

Initiation of dust and its agitation is timed with dual digital timing relay. The relay has a fixed time interval set between opening of the fast opening valve and with connecting power to clamps of initiator. The pressure changes inside the chamber are recorded through an industrial pressure transducer with mA output and the maximum measurable overpressure value of 16 bar. The pressure transducer is powered by a stabilized DC source. Response time of the sensor is 1 ms and the current value is recorded through the datalogger.

Explosibility classification

In the UK these are used to divide dusts into two groups:

- Group A - dusts able to ignite and propagate a flame;
- Group B - dusts that do not propagate a flame.

As in all explosion testing, the sample selected for testing must be representative of the material in the plant at risk. Best practice is to ensure that the sample is as dry as the driest material in the plant and that the size distribution of the test dust is similar to the finest size fractions that are likely to occur in any part of the process. Also it is important that the classification pertains to the conditions, for example, the temperature, under which the dust will be handled. It is not sensible to conduct an explosibility assessment at room temperature when the process temperature is to be substantially higher. Some dusts, classified as Group B at room temperature, can ignite at higher temperatures. A series of tests has been devised allowing explosibility classification under increasingly severe conditions. (Barton, 2002)

Explosibility characteristics

A quantitative assessment requires further testing to measure explosion characteristics that are important to the design of explosion protection methods such as venting, suppression, and containment. These explosion characteristics are:

- The maximum explosion pressure, P_{max} . This is the highest explosion pressure developed by an enclosed dust explosion. It is measured in a standard test at the optimum dust concentration.
- The maximum rate of pressure rise, $(dP/dt)_{max}$. This is the highest rate of pressure rise generated by an enclosed dust explosion. It is measured in a standard test at the optimum dust concentration. (Barton, 2002)

The procedures for measuring these characteristics are given in an ISO standard available as ISO 6184/1: 1985. The standard test vessel for these determinations is the 1 m³ vessel, but the standard also allows the use of alternative vessels provided it can be shown that they give comparable results. The criteria for demonstrating conformity are given in the standard. CEN Technical Committee 305 is refining the ISO procedure. They will recommend use of the 1 m³ apparatus as the standard apparatus, but will also allow the use of alternatives such as the 20 litre sphere if conformity can be demonstrated, and new European Standards for the determination of P_{max} and $(dP/dt)_{max}$ will be issued. The peak value of the maximum rate of pressure rise $(dP/dt)_{max}$ is used to calculate a dust specific explosibility characteristic called the K_{st} value. The K_{st} value is given by:

$$K_{st} = (dP / dt)_{max} V^{1/3} \quad (1)$$

where $(dP/dt)_{max}$ is the peak maximum rate of pressure rise [bar.s⁻¹] and V is the total volume of the vessel [m³]. The units of K_{st} are bar.m.s⁻¹.

Tab. 1 Definition of dust explosion classes (1 m³ apparatus, 10 kJ ignition source) (Barton, 2002)

Dust explosion class	K_{st} [bar m s ⁻¹]	Characteristics
St0	0	Non-explosible
St1	$0 < K_{st} \leq 200$	Weak to moderately explosible
St2	$200 < K_{st} \leq 300$	Strongly explosible
St3	$300 < K_{st} \leq 800$	Very strongly explosible

The K_{st} value is derived only from measurements in either the 1 m³ vessel or the 20 litre sphere.

The K_{st} value can be used to classify dusts into one of several groups. Table 1 shows the classification that is generally adopted. Comparisons of results from the 1 m³ vessel and the 20 litre spherical tester generally show that:

- The values for the maximum explosion pressure, P_{max} , measured in the 20 litre sphere are slightly lower than those measured in the 1 m³ apparatus;
- The K_{st} values are equal up to about 600 bar.m.s⁻¹].

Explosion limits

Explosion limits describe the concentration range of dust/air mixtures in which explosions are possible. Usually, only the lower explosion limit (LEL) is determined. These measurements are

important if the avoidance of an explosible dust cloud forms part of the basis for safety.

For the determination of the lower explosion limit both the 1 m³ apparatus and the 20 litre sphere apparatus are commonly used. CEN Technical Committee 305 is currently preparing a standard for the test procedure. Essentially the concentration of an explosible dust is systematically reduced in a series of tests until the dust suspension can no longer be ignited. The highest dust concentration at which the dust/air mixture can no longer be ignited in the tests is specified as the LEL. (Barton, 2002)

Minimum ignition energy

The minimum ignition energy (MIE) of a dust air mixture is defined as the lowest value of electrical energy stored in a capacitor that just ignites the most ignitable dust/air mixture following the discharge of the energy across a spark gap. This measurement is important when considering the elimination of ignition sources as part of the basis of safety. A single MIE value for a substance cannot be defined with universal agreement because the value depends on the physical and chemical properties of the dust as well as the test apparatus used (for example, the electrical circuit used to generate the spark). The MIE is usually quoted as a pair of values. The lower value specifies the energy at which ignition no longer took place. The higher value specifies the energy at which the most ignitable dust/air mixture could just be ignited. In view of the dependency of the MIE on the apparatus used, the method used should be stated when values are quoted (Mike, 1994).

Minimum ignition temperature of a dust cloud

The minimum ignition temperature (MIT) of a dust cloud describes the ignition behaviour of a dust/air mixture at a hot surface. The MIT is specified as the lowest temperature at which the most ignitable dust/air mixture could just be ignited. A test method is given in IEC 61241-2-1 (1994). Measurement of the MIT is not only important when considering the elimination of ignition sources, but is also required for the specification of electrical equipment, and is a design parameter for explosion suppression. Lower values of MIT are usually determined in the BAM furnace, because, due to the nature of the apparatus, delayed ignition of the gases produced from the dust that settles on the bottom of the furnace makes a contribution. (IEC 61241-2-1 1994).

Flammability

The flammability of a dust deposit or layer specifies the ease with which the dust can be ignited by one or more ignition sources. If the dust deposit can be ignited in the test the dust is considered to be flammable. The test consists of placing a triangular shaped dust deposit with base dimensions of 2 cm wide by 4 cm long on a ceramic plate and trying to ignite it with different ignition sources - for example, a gas flame, cigarette, match, etc. Further details on the procedure are given in an ISSA (1997) publication. Details of the ignition source must be given. (Barton, 2002)

Burning behaviour

If a dust deposit is flammable, the burning behaviour is used to describe the nature of the fire in the deposit. The UN rules for the transportation of dangerous goods describe a burning rate test that is commonly used. A mould is used to make a train of dust 200 mm. long and one end is ignited with a small flame or hot wire. The speed of spread of burning through the train is measured, as is the ability of the burn to pass through a section of wetted dust. The test can be performed either at room temperature or at an elevated temperature (usually 100 °C). Burning rates are often greatly increased if the dust is ignited at an elevated temperature. A class number according to the definitions given in Table 2 then rates the burning behaviour of the dust sample. The higher the combustion class, the more effective an ignition source the burning deposit is. (Barton, 2002)

Tab. 2 Burning behaviour of dust layers (Recommendations, 1999)

Type of reaction	Class
No burning, no ignition	1
Brief burning, rapid extinction	2
Localized combustion or smouldering (no or only very minor propagation)	3
Spread of a smouldering fire or slow. flameless decomposition	4
Spread of an open fire (burning with flame development)	5
Very rapid burn through with flame development or rapid, flameless decomposition	6

The Limiting Oxidant Concentration (LOC) test

The Limiting Oxidant Concentration (LOC) test determines the minimum concentration of oxygen (displaced by an inert gas such as nitrogen or carbon dioxide) capable of supporting combustion. An atmosphere having an oxygen concentration below the LOC is not capable of supporting a dust cloud explosion. The LOC test is used to study explosion prevention or severity reduction involving the use of inert gases and to set oxygen concentration alarms or interlocks in inerted vessels. LOC testing can be performed using the 20-Liter Sphere apparatus. Dust samples of various sizes are dispersed in the vessel and attempts are made to ignite the resulting dust cloud with an energetic ignition source. Trials are repeated for decreasing oxygen concentrations until the LOC is determined. The LOC of a given dust cloud is dependent on the type of inert gas that is used to replace the oxidant of the atmosphere as well as some process conditions such as temperature. Therefore, LOC testing should simulate the process conditions and be performed by using an inert gas that is representative of the inert gas used in practice (Ibadad, 2009).

Minimum ignition temperature of a dust layer

The minimum ignition temperature (MIT) of a dust layer is the lowest temperature at which a dust layer on a hot surface ignites. For a dust layer of thickness 5 mm, the MIT is often referred to as the smoulder temperature, or sometimes the glow temperature. The measurement is important to assess the need for limiting the temperatures obtained in dust handling plant. Layer ignition temperatures are almost always lower than cloud ignition temperatures. Procedures for determining the layer MIT are given in the ISSA (1997) publication and in IEC 61241-2-1 (1994). There are slight differences between the procedures, but both methods use an electrically heated circular plate (200 mm diameter) upon which a dust layer 100 mm in diameter and 5 mm thick is placed. The plate is maintained at a constant temperature for a specified period and the condition of the dust sample noted. The layer MIT is the temperature at which ignition just takes place. This temperature cannot be divorced from an induction time, defined as the time between initial heating and the onset of glowing. Caution must be exercised in using this layer MIT as a universal value for assessing the ignition risk where there is an accumulation of a dust. The geometry of the accumulation as well as the state of the accumulation can have a marked

influence on the ignition temperature. A thin layer of a dust is likely to have a higher ignition temperature than a bulk deposit of the same dust, due to the difference in heat loss. The ignition temperature will also be different if air flows over the dust layer or through the dust (for example, in a fluidized bed dryer). Material held in bulk storage for long periods can also undergo spontaneous ignition as a result of slow exothermic reactions with oxygen or biological reactions. Test methods for determining the ignition temperature more appropriate to these different situations can be found in the ISSA (1997) publication and the IChemE (1990) dryers guide (Abbott, 1990).

- An explosible dust cloud is never allowed to form.
- The atmosphere is sufficiently depleted of oxidant (normally the oxygen in air) that it cannot support combustion.
- All ignition sources capable of igniting the dust cloud are removed.

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Results

Tab. 3 Explosibility parameters for a number of dusts (Barton, 2002)

Type of dust	Min cloud ignition energy [mJ]	Cloud ignition temp. [°C]	Layer ignition temp. [°C]	Max. explosion pressure [bar(a)]	K_{st}^* [bar.m.s ⁻¹]	Minimum explosible conc. [g.m ⁻³]	Limiting O ₂ conc. volume [%]
Lignite	30	390	180	11.0	151	60	12
Aluminium	15	550	740	13.0	750	60	5
Coal	60	610	170	9.8	114	15	14
Cellulose	80	480	270	11.0	125	30	9
Cornflour	40	380	330	10.3	125	60	9
Wood	40	470	260	10.2	142	60	10
Charcoal	20	530	180	10.0	10	60	-
Wheat flour	50	380	360	9.8	70	125	11
Cotton linter	1920	560	350	8.2	24	100	-
Sugar	30	370	400	9.5	138	60	-
Sulphur	5	280	113	6.8	151	30	-
Magnesium	80	450	240	18.5	508	30	-
Zinc	9600	690	540	7.8	93	250	-

* 1 m³ vessel.

Conclusion

The task of any enterprise is to ensure prevention of explosive atmospheres. Suitable methods for determining a variety of explosion properties are discussed in this paper.

The risk of an explosion can be minimized when one of the following measures is ensured:

- A detailed study of explosion characteristics of dust as explosion limits, minimum ignition energy, minimum ignition temperature of a dust cloud, etc.

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