DUST EXPLOSIONS

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Abstract

In the past few years, much research has been conducted which has helped to reduce the number of dust explosions in industry. Still, on average, the country experiences at least one incident per week. In general, dust explosions can occur in any industry that handles, produces or has as a byproduct some combustible dust. Of all powders handled in industry, more than 70% can form explosive clouds. The sugar industry is no exception. Although the majority of the catastrophic incidents have occurred in other industries, the recent sugar dust explosion at Mhlume Sugar Mill has shown that sugar dust does present a hazard. To help bring about awareness, it is necessary to consider the nature of dust explosions, the factors affecting explosions, the common sources of ignition, preventive and protective measures that can be taken and the basics of risk assessment.

Introduction

Although the frequency of dust explosions in the sugar industry has not been as great as that in other industries, the threat of such an occurrence still exists. Consequently, special attention needs to be paid to the design, layout, installation, operation, maintenance and general housekeeping of equipment and buildings involved with sugar production. Through these means the likelihood of an explosion will be reduced.

What is a dust explosion?

Any airborne solid material that can burn in air can cause a dust explosion, the basic and general chemical reaction of which is:

$$fuel + oxygen \rightarrow oxides + heat$$

Normally in a solid sample the heat formed is easily absorbed by the solid. In a powder or dust, however, the surface area on which oxidation occurs is very large and the volume of the particle very small. In addition to this, oxygen gains easier access to the whole mass when it is in powder form. Consequently, these oxidation reactions, which are exothermic, release a large amount of energy in a short period of time resulting in a dramatic increase in temperature, which supports the burning of adjacent particles. In general, dust explosions are propagated by the combustion of particles with surrounding gas and are particularly hazardous because of the speed with which they develop and the impracticability of improvising protection during incidents.

Explosions can be classified as either physical or chemical in nature. Since sugar dust undergoes combustion during an explosion, it forms a chemical explosion. This category can be further subdivided into different types of explosions known as deflagration and detonation. Deflagration is the most common type of explosion occurring under industrial conditions and it is characterised by a flame speed that is less than the velocity of sound in the gaseous products of combustion. Detonation, on the other hand, is characterised by a flame speed equal to the velocity of sound in the gaseous products and is accompanied by a shockwave. It has not been established whether a true stable detonation can occur in a dust explosion in industrial plant. For this reason, when considering protection against dust explosions it is reasonable to assume that deflagrations occur. This has proved to be satisfactory, which is fortunate since deflagrations are much simpler to deal with.

In order for a dust explosion to occur, an ignition source of sufficient energy is required to ignite the dust. The initial source of an explosion is called the primary explosion and usually takes place in enclosed areas or within equipment. If rapid combustion occurs, the temperature and pressure may increase to the point at which the enclosure ruptures. Once this explosion has resulted in the failure of the enclosure, pressure waves or compression waves (arising from expansion or pressure effects) travelling ahead of the flames in the case of deflagrations, including the vibration of structures, are capable of dislodging and lifting settled dust elsewhere in the plant. These new dust clouds have the ability to transport the oncoming flames which can lead to other explosions anywhere in the plant and are called secondary explosions. It is these secondary explosions that cause the greatest damage. The primary explosion is often limited to a small scale incident in a limited area but this then forms a high-energy ignition source for dust in other areas or for dust clouds raised by the initial explosion. Interconnected silos are an example where a primary explosion in one silo has led to secondary explosions in the other silos purely as a result of the design and layout. From this it is clear that, in the case of deflagrations, the compression wave provides a warning signal ahead of the flame front that expansion or pressure effects are occurring. Explosion vents or pressure detectors can then operate during the early stages of the explosion and steps can be taken to prevent the maximum theoretical explosion pressure from developing. This is not the case in a detonation, where the flame accompanies the shockwave and hence no advance warning signal is received by an explosion vent or pressure detector. Figure 1 illustrates the variation of pres-

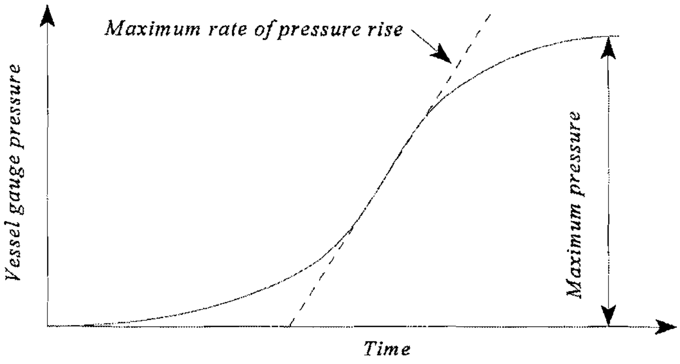

Figure 1. Pressure changes during a dust explosion.

sure with time when a dust is ignited in a test apparatus.

The most important information obtained from the graph is the maximum rate of pressure rise, which defines the speed with which venting or other protection must operate, and the maximum pressure, which defines the strength required to withstand the explosion. Added to this, the pressure developed during an explosion is directly proportional to the initial pressure in the vessel. For example, if the pressure in a vessel is increased from atmospheric pressure (1 bar) to 1,5 bars, both the maximum pressure and rate of pressure rise will also be increased by a factor of 1,5. This has important implications during the design of protective measures because if two vessels (or more) are joined together and an explosion occurs in the first one, the pressure pulse will reach the second vessel ahead of the flame front. The second vessel therefore ignites at elevated pressure and consequently higher pressures and rates of pressure rise are produced.

Where the dust is settled in layers, deposits or heaps and where the dust is not disturbed, a dust fire rather than an explosion occurs. Such fires can spread rapidly to other materials, plant or buildings. There may also be an explosion risk if the burning dust becomes airborne by a violent disturbance. For these reasons, dust fires should be dealt with carefully since, under certain circumstances, they give little indication of their presence and may be difficult to detect.

Conditions and factors affecting dust explosions

There are several conditions that are required for a dust explosion to occur. These include the following:

- A combustible material is required, the chemical composition of which will determine the rate at which oxygen is consumed and the violence of the explosion. These can be classified as follows
  - natural organic materials, including food and agricultural products
  - synthetic organic materials like plastics, pesticides and organic pigments
  - coal
  - metals, including aluminium, magnesium, zinc and iron.
- The drier the dust, the more violent the explosion. In general, dusts with moisture contents greater than 30% will not initiate dust explosions since particles of dust agglomerate and reduce the surface area for combustion. In addition to this, the evaporation of moisture can take up some of the heat of reaction which will prevent the rapid combustion required for a dust explosion to take place.
- For every combustible dust there is a minimum concentration (or lower explosive limit) that is required to support an explosion. Lower explosion limits for dusts range between 5 and 500 g/m^3, depending on the type of dust. As a general rule, particles of dust smaller than 500 µm can contribute to a dust explosion and the smaller the particles the more violent the explosion will be.
- The dust is required to be suspended or airborne.
- Sufficient oxygen is required for burning to take place, although the presence of certain functional groups will also influence the violence of the explosion. These include COOH, OH, NH_2 and NO_2. A hazardous situation can also develop when flammable gases are mixed with the dust and this is called a hybrid mixture.
- An ignition source of sufficient energy (greater than the minimum ignition energy) is required to initiate the explosion. These may include flames, hot surfaces, spontaneous heating, welding and cutting, friction heating and impact sparks, electricity, electrostatic discharges and smouldering or burning process material. In general, the higher the ambient temperature and/or the higher the turbulence, the lower the energy required to ignite the dust.
- Confinement. In general the more confined a dust is the more severe the explosion will be. Rapid heating results in a pressure build-up which can be released by the catastrophic failure of equipment. Equipment that has been prone to explosions includes bucket elevators, silos, hoppers, bag houses, cyclones, blenders and mixers, and pneumatic transport systems.

When all the above conditions are simultaneously met, the conditions are right for an explosion. Should one of the conditions not be met, the explosion will not occur.

Sources of ignition

Welding, cutting and flames

In most countries, the majority of accidents are still attributed to heat generated by flames, welding torches or cutting tools, where these operations generate greater energy than is required to ignite airborne or settled dusts. Since dust layers can be ignited at temperatures of between 100 and 200°C, in addition to removing deposits of dust from the surrounding area and all surfaces that may become hot during any hot work, the inner surfaces of equipment or machinery should also be inspected and cleaned. This is to prevent residual dusts from overheating and to prevent the formation of smouldering layers, which can initiate explosions even days later. Smoking, although a small source of ignition, and flames, which are produced by process equipment during normal operation, also add to the risk. The prevention of fires and explosions caused by the abovementioned energy sources can be achieved by strictly enforcing safe working procedures and the carrying out of effective housekeeping.

Spontaneous heating

Spontaneous heating or combustion can occur if materials are stored in bulk or if layers of dust are left undisturbed for an extended period of time and where there is an exothermic reaction that produces heat faster than it can escape. Since the rate of reaction, and hence heat generation, increases with temperature, a runaway situation may be attained which may lead to the ignition of the material as soon as the auto-ignition temperature is reached. Further disruption of the layers may then cause a dust explosion. In this instance, oxidation is the most common type of reaction. The action of micro-organisms can also lead to increases in temperature, and since they require moisture, damp products, such as bagasse, stored in bulk are particularly susceptible. Although these organisms do not often survive at temperatures much greater than 70°C, the heat of reaction may be sufficient to initiate other chemical reactions, such as oxidation, which may lead to ignition. The activity of micro-organisms is greatly reduced when the moisture content is between 40 and 25%, below which microbiological activity ceases (Dixon 1988). It also appears that oxygen diffusion may be an important limiting factor in spontaneous combustion in stockpiles. However, this does not eliminate charring and smouldering and, once the bagasse is exposed to ambient conditions, flaming combustion may proceed rapidly. To reduce stockpile temperatures, water is not very effective. This is because it is difficult to penetrate the stockpile and large quantities would be required. Added to this, an increase in bagasse moisture would support microbiological activity and ultimately lead to the reheating of the stockpile.

Hot surfaces

In the case of dust layers, which tend to burn or smoulder rather than explode, hot surfaces provide a source of ignition. However, if the layers are disturbed and become airborne, the concentration may exceed the lower explosion limit and result in an explosion. In general, the thicker the layer and/or the higher the ambient temperature, the lower the minimum ignition temperature will be. Initial airborne dust that is at a concentration that exceeds the lower explosion limit may also ignite if it comes into direct contact with a surface that has a temperature greater than the minimum ignition temperature.

Hot surfaces are found on process vessels, including dryers, boilers and furnaces, space heating equipment, mechanical and electrical machinery (including bearings and slipping belts), and lights. In such instances it may be necessary to insulate components, provide a dust-free enclosure or ensure regular cleaning.

Electrical, electrostatic and frictional sparks

An electrical spark is created when an electrical circuit carrying an electric current is broken or where there is a small gap in the circuit. In such situations the current may be able to flow across the gap and form a transient arc. A short spark of only a few millijoules is sufficient to ignite many dust clouds, layers and also other flammable materials which may later ignite a dust cloud. Electrical equipment, such as switches, contactors, relays and motors (with commutators), may give off sparks in normal operation. Therefore, such machinery should be protected by being made completely dust-tight or by being kept away from any area where dust may accumulate.

An electrostatic spark occurs when there is no external voltage source but a charge, created for example by friction, accumulates on an isolated conductor. The accumulated charge may raise the potential to several kilovolts even though the total charge stored is not high. A spark occurs when the voltage rises to a level sufficient to break down the air in the spark gap. The various electrostatic discharge types include spark, corona, brush, cone and propagating brush discharges. In general, the best way of dissipating static charge is to ground the item in question. The basic requirement laid down in international regulations is for a leakage path to ground to be less than 1 MΩ, which will generally be achieved with metallic plant but not with powders and non-metallic items. Items that are affected by static charge include fluidised bed drier bags, dust filter bags, storage bins, fluidised bed driers, large industrial storage bags, conveyor belts and pneumatic transfer of particles in metal pipes or flexible ducts. Electrostatic sparks are generally not well understood and since this forms a new subject on its own, it is strongly suggested that the reader seeks expert advice if he/she suspects this phenomenon of being a possible source of ignition.

Mechanical sparks caused by friction or impact can under the right conditions ignite a flammable atmosphere. Very little work has been carried out on the ignition of dust atmospheres by this mechanism, and as yet there has been no success in igniting a dust cloud in the laboratory by an impact spark unless a chemical reaction such as a thermite reaction is present or the dust is particularly sensitive to ignition. (A thermite reaction results when light metals such as aluminium come into contact with rust to produce an exothermic reaction.) However, a number of industrial explosions have been attributed to impact sparks and so should be considered. Impact sparks may be caused by tramp metal in process streams, overloading of grinding plant, conveyors or other mechanical equipment, misalignment of plant causing moving parts to come into contact or from the use of power tools, shovels and hammers.

Explosion prevention and protective measures

Although many steps can be taken to eliminate sources of ignition and to reduce the formation of dust clouds, it is not always possible to guarantee that all dust ignition sources have been eliminated and that an explosion will not occur. For this reason, the following safety measures are used in industry today. Since factors of safety are often incorporated into designs, it is not required to have the exact values of ignition parameters in order to design or install a prevention or protection system.

Preventive measures

The methods used focus on the prevention of explosive mixtures and ignition sources.

Inerting

Inerting involves reducing the oxygen concentration in the equipment to a level that does not exceed the limiting oxygen concentration. Below this level oxidation cannot proceed rapidly enough to sustain the progress of an explosion. Often nitrogen, carbon dioxide or flue gas is used. The disadvantage of the inerting technique is that the plant has to be sealed (closed-loop design) or semi-sealed in order to prevent the loss of inerting gas. Monitoring devices for the gas concentrations need to be installed and possible toxicity or suffocation of operatives has to be guarded against. Generally, inerting is the most expensive solution, but where ignitions are frequent and cannot be reduced it may be more economical in the long term to eliminate explosions completely by inerting rather than have the expense of frequent activation of a suppression system or the disruption and loss of time and product in a vented explosion. Ultimately, the inerting system should be 100% reliable because if it fails, an explosion can occur.

Operation under vacuum

Explosions can also be eliminated or the severity reduced if a vacuum is created in the equipment that is to be protected. The advantage is that, should explosions occur, the maximum explosion pressure is greatly reduced and, generally, a vacuum of less than 50 mbar will prevent explosions.

Protective measures

Protective measures allow the explosion to progress, but in such a way as to eliminate danger or damage to persons or plant. The following measures should always be used in conjunction with plant isolation in order to prevent the propagation of explosions to other interconnected plant since the severities of such explosions increase dramatically. Isolation would include the use of explosion-proof rotary valves, ventex valves, flame traps and barriers, relief stacks or explosion diverters, or quick-acting slide valves. To activate the isolation mechanisms CO detection (since CO is a byproduct of combustion), infrared detection of sparks or smouldering pockets, or temperature/pressure transducers would have to be installed.

Explosion resistant design or containment

Equipment can be built strong enough to withstand the forces of the explosion (7 to 10 bars) and to eliminate any external damage. All the individual units and connections between units have to be of the same strength and special attention should be paid to the points where the dust enters and exits the plant. These areas are often the weakest and it should be ensured that there is never direct access from the interior to the exterior of the plant. If the plant or vessel is designed according to the pressure vessel regulations, the unit is called explosion pressure resistant. If deformations are acceptable it is called explosion pressure shock resistant. These design methods are not often used due to the high capital cost of manufacturing and installing the equipment, and thus are generally limited to small plant. With toxic or valuable materials, however, this method of explosion protection may be appropriate.

Suppression

Explosion suppression is used based on the assumption that explosions are likely to be of the deflagration type and hence there is some time available to take action. The initial stages of the explosion are detected (by optical or pressure transducers) and initiate the release of an extinguishing substance, such as liquid, mist or non-explosive powder, to blanket the system in order to prevent the explosion from developing further. The development of a suppressed and an unsuppressed explosion is illustrated in Figure 2.

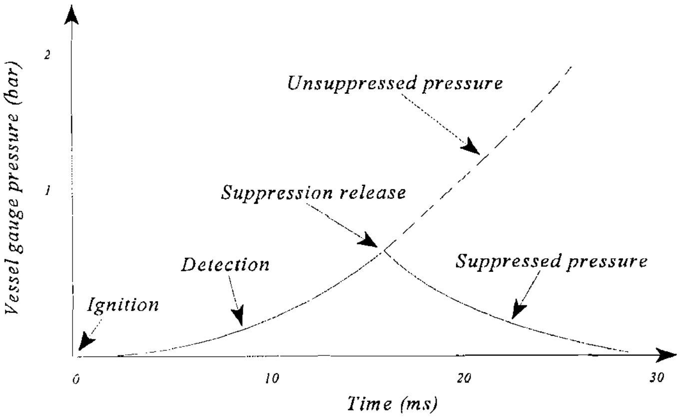

Figure 2. Suppressed and unsuppressed dust explosions.

The most common types of suppressants are the halons (halogenated hydrocarbons), such as chlorobromomethane (halon 1011), ammonium phosphate (tropolar) or sodium bicarbonate powder, and water which is also used in some circumstances. These suppressants are stored in containers such as hemispherical suppressors, which operate rapidly but have a limited range, or high-rate discharge (HRD) suppressors, which are used in larger installations where greater throw is required. Detection pressures should be chosen such that the system will not be activated during normal operating process pressures, particularly on starting up and shutting down. In addition to this, explosion flame speeds are such that the reaction time of the suppression mechanism should be less than 10 ms for this system to work effectively. In general, explosion suppression is often selected over other protective measures if, for instance, there is insufficient space available on the equipment for the required vent area, or if equipment cannot be vented in a safe direction and is located too far from the outside of the building, or if toxic or dangerous materials are being processed.

Venting

This is the most commonly used system where a bursting disk or a trap door is placed in a suitable position so that at a predetermined pressure (vent opening pressure) the vent is opened. In this way the explosion byproducts of combustion can escape rapidly, resulting in a lower maximum explosion pressure, below the design strength, without causing damage to the equipment. Adequate anchoring of the structure is required to withstand the resultant reaction forces, and venting should always be ducted to the exterior of any building in an unobstructed and safe manner. Since ducts reduce the venting efficiency, larger vent areas may have to be installed in order to compensate. Therefore, ducts should be as short as possible, free from bends and other restrictions to flow, and be kept clean from dust during normal operation. It should also be borne in mind that the volume of flame exiting from vents can be large, especially when large quantities of unburnt dust are discharged and, on contact with the air outside the plant, are ignited by the explosion flame. This system should only be considered if the byproducts of the explosion are not toxic to the environment. Figure 3 illustrates the development of pressure during an explosion for a vessel with and without explosion venting.

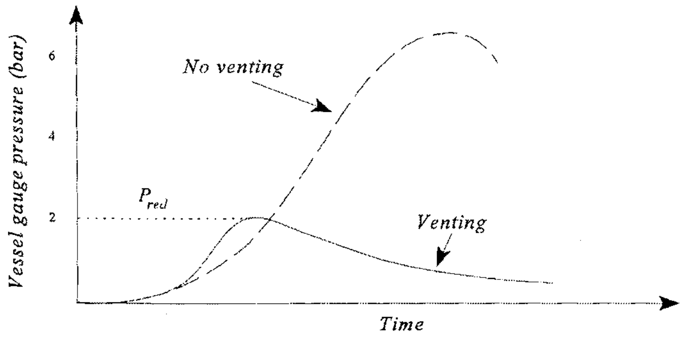

Figure 3. Pressure-time curve for a vessel with and without explosion venting.

Dust explosion parameters

Laboratory tests have been set up in various countries to determine the nature and characteristics of dusts in explosions. The results of these tests can then be used in the design of plants and to highlight the sensitivity of dusts to particular sources of ignition. Although some of the procedures differ, the tests are still useful for comparisons to be made between different dusts. Since tests are done on the laboratory scale, the results have to be scaled up and applied to industrial situations. It is here that a measure of uncertainty is introduced. Despite this uncertainty, during the design of measures to handle dust explosions it is appropriate to use the values of dust parameters which maximise explosion severity. The most important parameters are defined below.

Minimum ignition energy (MIE). The minimum ignition energy is a measure of the sensitivity of a dust-air mixture to electrical and electrostatic discharges. In general a dust which has a minimum ignition energy of less than 25 mJ should be regarded as prone to ignition by static electricity. At higher ambient temperatures and/or lower moisture the minimum ignition energy also tends to decrease and vice versa. An MIE of less than 10 mJ is very low and special precautions should be taken regarding the handling of dusts and the use of special clothing and footwear for operatives. Table 1 lists the amount of energy released by several ignition sources.

Table 1. Relationship between the minimum ignition energy of a dust and air mixture and ignition source.

Ignition source	Ignition takes place if MIE (mJ) is less than
Fires, flames, hot surfaces	1_10^{7}
Self heating, overheated bearings including above	1_10^{5}
Frictional sparks, propagating brush discharges including above	1000
Electrostatic sparks including above	100
Cone discharges including above	10
Brush discharges plus above	1

Minimum ignition temperature (MIT). The minimum ignition temperature indicates the temperature of a surface above which a dust cloud may be ignited. It can be used to assess the hazards of hot surfaces on electrical and mechanical machinery, such as motors, heated bearings, furnaces, boilers, steam and hot process pipes, slipping V-belts, and driers. At higher pressures, lower values are obtained. The smouldering temperature is the same as the minimum ignition temperature but is referred to when dealing with dust deposits or layers. The smouldering temperature of dust layers is thickness dependent. The thicker the layer, the lower the temperatures and vice versa. In practice, the smouldering temperature is less than the minimum ignition temperature for a particular dust due to the greater contact time that layers have with heated surfaces. Dust clouds, on the other hand, are usually in motion past hot surfaces. In general, the minimum ignition temperature decreases with increasing particle size and concentration.

Auto-ignition temperature (AIT). This is the temperature which a dust layer or deposit has attained or is exposed to while undergoing an exothermic reaction and which is sufficiently high for the dust to ignite. This temperature is determined by placing a specific amount of dust in a temperature controlled oven.

Limiting oxygen concentration (LOC). This is the maximum oxygen concentration below which combustion or an explosion cannot take place. In general the drier or the finer the product the lower these values will be. Depending on the type of dust, this figure varies between 2 and 15% by volume. An oxygen level of 8% can be used as a rough guide for organic dusts when inerting with nitrogen or carbon dioxide.

Lower explosion limit (LEL). This is the minimum airborne concentration of a dust or a powder that is required to propagate an explosion because the particles must be sufficiently close to exert some influence on each other. At this spacing of particles, the heat of reaction of one particle is able to initiate a reaction in surrounding particles.

Upper explosion limit (UEL). This is the maximum airborne concentration of a dust or a powder above which an explosion is not propagated. Due to the high density of airborne material there is insufficient oxygen to sustain reactions rapidly enough for an explosion to occur. This parameter is not easy to measure and, because there are difficulties in ensuring that dust clouds are maintained at concentrations above the upper explosion limit in industrial plants, less significance is placed on this parameter. More attention is placed on the lower explosive limit which has more practical value.

Dust explosion constant (Kst). The dust explosion constant is a standardised parameter for the maximum rate of pressure rise in a closed vessel under optimal conditions. It is an indication of the violence of the explosion and of the time available to take action against the explosion in the form of explosion venting, suppression, quick acting valves, etc. Although the maximum explosion pressure is largely independent of the size of the containing space, the maximum rate of pressure rise is volume dependent. For a given system the maximum rate of pressure rise becomes smaller as the volume of the vessel increases. The relationship obtained is known as the Cubic Law

$$K_{st} = \left(\frac{dP}{dP}\right)_{\max} x\ V^{1/3}$$

where $(dp/dt)_{max}$ is the maximum rate of pressure rise (bar/s) and V is the volume of the vessel (m^3). Tests in large enclosures show that the Cubic Law, which is known to be true for closed, unvented vessels, also applies within limits to vented vessels. Dusts can therefore be classified according to the K_{st} values as shown in Table 2. This forms the basis of the German system of powder classification and is accepted throughout Europe.

Maximum explosion pressure (P_{max}). The maximum explosion pressure and is an indication of the pressure that can be obtained in a closed test vessel in the event of an explosion. It is used to design structural measures to cope with the effects of a dust explosion by venting, suppression, explosion isolation and explosion-proof design. P_{max} is in fact largely independent of the size of the containing space.

Some values for sugar have been listed in Table 3. To cater for the differences in the figures reported by some authors, ranges of values have been given which, for all practical purposes, should be sufficient.

K_{st} below 200 implies that explosions are characteristically weak or moderate.

Risk assessment

Before installing preventive and protective measures, it is necessary to conduct a risk assessment to determine the criticality of a perceived threat, with regard to the effect that it will have on plant operation, health and safety of personnel, and the cost in relation to the benefits that will be derived from the installation. The following guide on risk assessment should be used in conjunction with any additional studies.

Are there any potentially explosive dusts or flammable liquids or gases?

It is necessary to determine which products would cause an explosion under the right conditions of concentration, particle size, moisture and confinement when they become airborne, assuming that there are sufficiently high energy ignition sources present. The explosion parameters listed above can be used to determine this. In addition, a survey should be carried out to pin-point areas or equipment which contain or are able to contain fine fractions of the product.

Are there any hybrid mixtures present?

This is particularly important since explosions of hybrid mixtures are potentially more severe than explosions of dust. Hybrid mixtures are mixtures of dust and flammable solvents, gases or vapours present in the air. These mixtures should always be assumed to be explosive.

Are there ignition sources of sufficient energy to cause dust explosions?

Areas which have abnormally high ambient temperatures, machinery or equipment with hot (uninsulated) surfaces or electrical equipment exposed to dusts should be considered. Electrostatic ignition sources are generally not well understood because their discharges are not readily seen and the phenomenon is often not well explained.

Table 2. German dust classification system.

Dust explosion class	K_{st} (bar.m/s)	Explosion violence	Example
St* 0	0	No explosion	Cement or sand
St 1	> 0 - 200	weak to moderate	Grain and sugar dust
St 2	> 200 - 300	strong	Organic pigment
St 3	> 300	very strong	Fine metallic dust

* St stands for Staub, the German word for dust.

Table 3. Sugar dust parameters for dust explosions.

Dust type	Size	LEL	MIE	MIT	P_{max}	K_{st}
Sugar	20-30μm	15-30g/m^3	30-50mJ	330-480 °C	7,5-8,5bar	< 200

What is the probability of ignition? Will it cause a fire or dust explosion?

The probability of an explosion depends on the sensitivity of the product and the equipment and machinery used to process and handle the product. During many industrial operations, dust clouds cannot be prevented. This is typically the case in dust extraction systems, silos and bucket elevators.

What would the effects be if a dust explosion were to occur? Are the results acceptable?

The severity of the explosion can be judged from an analysis of parameters such as P_{max} and K_{st}. The maximum explosion pressure gives an indication of the strength of structures required to contain explosions. It should also be borne in mind that in the event of an explosion much damage is caused by flying debris. Structural damage caused in a specific section of the plant can also cause damage in other interconnected sections due to vibrations in common structures or foundations. For example, history has shown that although an explosion may occur in only one silo, other silos have also sustained damage because they are often connected. There are also many examples where office blocks have been placed too close to hazardous areas and have been damaged in explosions. The maximum rate of pressure rise is a measure of the time available to take action against an explosion and can also be used to estimate the explosion severity.

Areas which are more labour intensive should ideally be placed further away from high-risk areas to minimise secondary effects, although this is not always possible. In addition, an analysis of areas, plant or equipment which might be subjected to secondary dust explosions should also be identified. As a general rule, plant that may have a low probability of undergoing an explosion but which may cripple production as a result may be classed as high-risk. Isolated plant that has a high probability of exploding, but which is unlikely to injure personnel and which is not critical to the process, has a lower risk attached.

What measures are available? Which measure can be used that will achieve the desired security and at what cost? What effect will it have on the economics of the process?

The cheapest method of taking steps to reduce the risk and probability of dust explosions is to enforce strict compliance with factory rules and regulations. In particular, the items that are important are the installation and maintenance of electrical equipment, good housekeeping and the prevention of smoking and hot work in hazardous areas. However, such steps do not guarantee the elimination of all ignition sources and often additional measures should be taken.

Conclusion

The ignition of powder or dust is complicated and different laboratory test systems in various countries tend to give different results. Ignition is affected by particle size, moisture, shape, agglomeration tendency, and minor surface differences, as well as by effects of the apparatus such as volume and turbulence. Therefore, when published figures are used to design equipment, explosion parameters must be used to provide a general guide rather than precise design criteria. The explosion data selected must be that for which the maximum explosion pressure (P_{max}) and the maximum rate of pressure rise ($(dp/dt)_{max}$) are at their greatest. Although dust ignition tests cannot be treated as precise measurements in the way that gas ignition characteristics can, these do provide a useful guide to the relative behaviour of different materials. In general, it is necessary to consider very carefully the conditions that prevail in the factory to ensure that laboratory tests fairly represent the true situation and that the test sample is in the same state as the product handled, with the same particle size distribution and contaminants.

The explosive nature of sugar dust makes it a hazard and increases the risk of damage to plant and machinery, and injury to personnel. With this in mind, attention should be paid to current installations where most dust problems arise in the conveying, weighing and storage sections. Future designs of plant should be such that the minimum amount of dust is produced. Mechanical handling equipment, such as conveyors and bucket elevators, pneumatic transport and dust collection systems deserve important considerations here. Where possible, any plant or system that is at risk should be located outside buildings and in such a location that flying fragments would not be a threat. Since extraction systems are highly susceptible to dust explosions, a common network of ducts is generally not good practice. Hence, it is far safer to have dedicated extraction systems for each critical area.

Ultimately, to help prevent a dust explosion from occurring any one of the following three essential requirements should be undertaken: (i) limit the oxygen concentration to prevent rapid combustion; (ii) prevent dust from becoming airborne; (iii) eliminate ignition sources.

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