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- Improve hazard communication programs so that the hazards of combustible dust are clearly identified and communicated to the employees. In particular: Ensure that the most current codes of practice are in use and that employees receive training on the revised/updated information.

5.5 Means of Preventing and Mitigating Dust Explosions in the Process Industries

5.6.1 Overview

Table 5–2 gives an overview of the various means that are presently known and in use. They can be divided in two main groups, namely means for preventing explosions and means for their mitigation. The preventive means can again be split in the two categories prevention of ignition sources and prevention of explosive/combustible clouds. Quite often one has to accept the occurrence of explosive dust clouds inside process equipment as an inherent feature of the process. One central issue is then whether only preventing ignition sources can give sufficient safety, or whether it is also necessary to employ additional means of explosion mitigation. The general answer is that preventing ignition sources is not sufficient. In the following sections the various means listed in Table 5–2 will be discussed separately.

Table 5–2 Overview of Means for Preventing and Mitigating Dust Explosions in the Process Industries

<table>
<tr><th colspan="2">Prevention</th><th rowspan="2">Mitigation</th></tr>
<tr><th>Preventing explosive dust clouds</th><th>Preventing ignition sources</th></tr>
<tr><td rowspan="2">Inerting by N_2, CO_2 and rare gases</td><td rowspan="2">Smoldering combustion in dust, dust flames</td><td>Reduce expl. cloud size</td></tr>
<tr><td rowspan="2">Partial inerting</td></tr>
<tr><td rowspan="2">Intrinsic inerting</td><td rowspan="2">Other types of open flames (e.g. hot work)</td></tr>
<tr><td>Isolation (sectioning)</td></tr>
<tr><td>Inerting by adding inert dust</td><td>Hot surfaces</td><td>Venting</td></tr>
<tr><td>Dust concentration outside explosive range</td><td>Electric sparks and arcs, electrostatic discharges</td><td>Pressure resistant construction</td></tr>
<tr><td></td><td>Heat from mechanical impact (metal sparks and hot spots)</td><td>Automatic suppression</td></tr>
<tr><td></td><td></td><td>Good housekeeping (dust removal/cleaning)</td></tr>
</table>

5.6.2 Preventing Explosive Dust Clouds

5.6.2.1 Inerting by Adding Inert Gas to the Air

For any type of combustible dust, and a given type of inert gas added to the air, there is a limiting oxygen content below which the dust cloud is unable to propagate a self-sustained flame. By keeping the oxygen content below this limit throughout the process system, dust explosions are effectively excluded. As the oxygen content in the gas is gradually reduced from that of air, the ignitability and explosivity of the dust cloud is also gradually reduced, until ultimately flame propagation becomes impossible.

Four types of inert gases are in common use for this purpose:

- nitrogen
- carbon dioxide
- water vapor
- rare gases

In some cases the special protective method called "*intrinsic inerting*" can be a good solution. This method implies that the required quantity of inert gas is produced in the plant itself, e.g. by controlled combustion in a hot-gas generator and recirculation of the gas. Such hot-gases mainly consist of nitrogen, carbon dioxide and water vapor. The residual concentration of oxygen is kept at a sufficiently low level to ensure inert conditions. However, normally such combustion gases are not clean enough for being used in connection with food and feed materials, phamarceuticals etc. In the past also *halogenated hydrocarbons* (halons) were used for inerting. However, due to the environmental problems caused by these substances, they are no longer used for protecting against explosions and fires. The choice of inert gas depends on several considerations, such as availability and cost, possible contaminating effects on products, and effectiveness. In the case of dusts of light metals, such as aluminum and magnesium, exothermic reactions with CO_2 and also in some situations with N_2 are known, and the use of rare gases may have to be considered in certain cases.

The design of gas inerting systems depends on whether the process is continuous or of the batch type, the strength of the process equipment and type and source of inert gas. Two main principles are used for establishing the desired atmosphere in the process:

- pressure variation method
- flushing method

The pressure variation method operates either above or below atmospheric pressure. In the former case, the process equipment, initially filled with air at atmospheric pressure, is pressurized to a given overpressure by inert gas. When good mixing of air and inert gas has been obtained, the process equipment is vented to the atmosphere and the cycle repeated until a sufficiently low oxygen content has been reached. The alternative is to first evacuate the process equipment to a certain under-pressure, and fill up with inert gas to atmospheric pressure, mix, and repeat the cycle the required number of times.

The flushing method is used if the process equipment has not been designed for the significant pressure increase or vacuum demanded by the pressure variation method. There are two extreme cases of the flushing method, viz. the replacement method (plug flow) and the through-mixing method (stirred tank). In order to maintain plug flow, the flow velocity of inert gas into the system must be low (< 1 m/s) and the geometry must be favorable for avoiding mixing. In practice this is very difficult to achieve, and the stirred tank method, using high gas velocities and turbulent mixing, is normally employed. It is essential that the instantaneous through-mixing is complete over the entire volume, otherwise pockets of unacceptably high, oxygen concentrations may form.

5.6.2.2 Dust Concentration outside Explosive Range

In principle one could avoid dust explosions by running the process in such a way that explosive dust concentrations were avoided. In practice, however, this is difficult in most cases, because the dust concentration inside process equipment in normal operation often varies in unpredictable and uncontrollable ways. On the other hand, keeping the powder/dust in the settled state by avoiding generation of dust clouds should be attempted whenever possible. Good process design can significantly reduce the regions in which explosive dust concentrations occur, as well as the frequencies of their occurrence. One example is the use of mass flow silos instead of the traditional funnel flow type.

Nevertheless there are some special situations where it may be possible to actively keep the dust concentration below the lower explosive limit. One such situation is in dust extraction ducts, another is in cabinets for electrostatic powder coating, and a third is spray dryers. One essential condition for control of dust concentration is that the concentration can be adequately measured. In-situ methods based on light attenuation or backscattering of light have been found most suitable. The use of dust control in dust extraction systems is more likely to be successful in cases where a small dust fraction is to be removed from a coarse main product, e.g. grain dust from grain, or plastic dust from pellets. By monitoring dust concentrations and controlling air flows the desired low level of dust concentration can be maintained. However, if the air velocities are too low to prevent dust deposition on the internal walls of the ducting over time, dust explosions may nevertheless be able to propagate through the ducts.

Dust entrainment and formation of explosive dust clouds by the air blast from a primary dust explosion, may also occur in mixers, conveyors, etc. containing fine dust present as layers/deposits. This means that explosion control by controlling the concentration of suspended dust is only feasible for preventing primary explosion initiation, not for preventing secondary explosions.

5.6.2.3 Adding Inert Dust

This principle is used in coal mines, by providing sufficient quantities of stone dust either as a layer on the mine gallery floor, or on shelves, etc. The blast that will always precede the flame in a dust explosion will then entrain the stone dust and coal dust simultaneously and form a mixture that is non-combustible in air, and the flame, when arriving, will become quenched. In other industries than mining, adding inert dust is seldom applicable due to contamination and other problems.

5.6.3 Preventing Ignition Sources

5.6.3.1 Introduction

A question asked frequently is whether preventing ignition sources can be relied upon as the only means of protection against dust explosions. The general consensus is that this is not possible. Relying on preventing ignition sources only is definitely inadequate if the minimum electric spark ignition energy of the dust is in the region of vapors and gases, i.e. < 10 mJ. However, for dusts of very high MIEs it may be argued that several types of process plants could be satisfactorily protected against dust explosions solely by eliminating ignition sources.

According to Scholl (1989) one may distinguish between two categories of ignition sources. Organizational ignition sources, which can be prevented by enforcing adequate working routines, include:

- smoking
- open flames
- open light (bulbs)
- welding (gas/electric)
- cutting (gas/rotating disc)
- grinding

Operational ignition sources arise within the process itself and include:

- open flames
- hot surfaces
- smoldering nests
- exothermic decomposition
- heat from mechanical impact between solid bodies (metal sparks/ hot-spots)
- electric sparks/arcs, electrostatic discharges

5.6.3.2 Preventing Self-Heating, Smoldering and Burning in Dust Deposits

The risk of self-heating in powder/dust deposits depends on the inherent properties of the material. Therefore, possible disposition to self-heat should be known for any combustible material before admitting it to storage silos or other part of an industrial plant where conditions could favor self-heating and further temperature rise to smoldering and burning.

Possible means of preventing self-heating and self-ignition in powders with a disposition to self-heat include:

- control of temperature, moisture content and other relevant powder/dust properties before admitting powder/dust to e.g. storage silos.
- adjustment of powder/dust properties to acceptable levels by cooling, drying etc. before storage, whenever required
- ensuring that hot solid bodies do not become embedded in the powder/dust mass
- continuous monitoring of temperature in powder mass at several points by thermometer chains
- rolling of bulk material from one silo to another, or within the same silo, whenever onset of self-heating is detected, or as a routine after certain periods of storage, depending on the powder/dust type
- inerting of bulk material in silo by suitable inert gas, e.g. nitrogen
- monitoring of possible development of gaseous decomposition/oxidation products, e.g. CO and methane, for early detection of self-heating

Means for preventing and controling self-heating/self-igniting and means for extinction of smoldering combustion inside large dust deposits e.g. in silos is discussed in Chapter 4.

Some synthetic organic chemicals, in particular cyclic compounds, can decompose exothermally and become ignited by a hot surface, a smoldering nest, frictional heat or other ignition source. Such decomposition does not require oxygen, and therefore inerting has no effect. Adiabatic exothermal decomposition of bulk powder at constant volume can, due to the very high powder concentration, generate much higher pressures than a dust explosion in air. Zwahlen (1989) suggested the following alternative safety measures:

- Process the hazardous powder in the wet state, as a slurry or suspension.
- If wet processing is impossible, avoid processes involving moving mechanical parts in contact with the powder that can give rise to ignition.
- Keep the processed batches of the powder as small as feasible.
- Keep strict control to prevent foreign bodies from entering the process.
- Detectors for observing early temperature and pressure rise, and sprinkler systems must be provided.
- Use of additives that suppress the decomposition tendency may be helpful in some cases.

5.6.3.3 Preventing Ignition by Open Flames/Hot Gases

- Most potential ignition sources of the open flame type can be avoided by enforcing adequate organizational procedures and routines. This in particular applies to prohibition of smoking and other use of lighters and matches, and to enforcement of strict rules for performing hot work. Hot work must not be carried out unless the entire area that can come in contact with the heat generated by the hot work, indirectly as well as directly, is free of dust, and hazardous connections through which this heat may transmit to other areas, have been blocked. It is important to note that hot work also includes disc-cutting and grinding operations. Gas cutting torches are particularly hazardous because they work with excess oxygen. This gives rise to ignition and primary explosion development where explosions in air would be unlikely (see Section 5.4.5). Factory inspectorates in most industrialized countries have issued detailed regulations for hot work in factories containing combustible powders or dusts.

In certain situations in the process industry, hot gaseous reaction products may entrain combustible dust and initiate dust explosions. Each such case has to be investigated separately and the required set of precautions tailored to serve the purpose in question.

5.6.3.4 Preventing Ignition by Hot Surfaces

Hot surfaces may occur in industrial plants both intentionally and unintentionally. The first category includes external surfaces of hot process equipment, heaters, dryers, steam pipes and electrical equipment. The equipment where hot surfaces may be generated unintentionally include engines, blowers and fans, mechanical conveyors, mills, mixers, bearings, and unprotected light bulbs. A further category of hot surfaces arises from hot work. During grinding and disc-cutting, glowing hot surfaces are often generated, in addition to the luminous spark showers typical of these operations. A hot surface may ignite an explosive dust cloud directly, or via ignition of a dust layer that subsequently ignites the dust cloud. Parts of glowing or burning dust layers may loosen and be conveyed to other parts of the process where they may initiate explosions.

The hot surface temperature various apparatuses can, if covered by a dust layer, be significantly higher than it would normally be without dust, due to thermal insulation by the dust. This both increases the ignition hazard and may cause failure of equipment due to increased working temperature. The measures taken to prevent ignition by hot surfaces must cover both layer and cloud ignition. The measures include:

- removal of all combustible dust before performing hot work
- prevention/removal of dust accumulations on hot surfaces (electrical apparatuses etc.)
- isolation or shielding of hot surfaces
- use of electrical apparatus approved for use in the presence of the combustible dust of concern
- use of equipment with minimal risk of overheating
- inspection and maintenance procedures that minimize the risk of overheating

5.6.3.5 Preventing Ignition of Dust Clouds by Smoldering Nests

Infrared radiation detection and subsequent extinction of smoldering nests and their fragments during pneumatic transport in dust extraction ducts, has proven to be an effective means of preventing fire and explosions in downstream equipment, for example dust filters. Normally the transport velocity in the duct is known, and this allows effective extinction by precise injection of a small amount of extinguishing agent at a convenient distance just when the smoldering/burning nest or fragment passes the nozzles. Water is the most commonly used extinguishing agent, and it is applied as a fine mist. Such systems are mostly used in the wood industries, but also to some extent in the food and feed and some other industries.

5.6.3.6 Preventing Ignition by Heat from Accidental Mechanical Impacts

Mechanical impacts produce two different kinds of potential ignition sources, viz. small flying burning fragments of solid material and a pair of hot-spots where the impacting bodies touch. Sometimes, e.g. in rotating machinery, impacts may occur repeatedly at the same points on one or both of the impacting bodies, and this may give rise to hot-spots of appreciable size and temperature. The hazardous source of ignition will then be a hot surface.

With regard to single accidental impacts, research has revealed that in general the ignition hazard associated with single accidental impacts is smaller than often believed in the past. This in particular applies to dusts of natural organic materials such as grain and feedstuffs, when being exposed to accidental sparking from impacts between steel hand tools like spades or scrapers, and other steel objects or concrete. In such cases the ignition hazard is probably non-existent.

However, if more sophisticated metals are involved, such as titanium or some aluminum alloys, energetic spark showers can be generated. In the presence of rust, luminous, incendiary thermite flashes can result. Thermite flashes may also result if a rusty steel surface covered with aluminum paint or a thin smear of aluminum, is struck with a steel hammer or another hard object. However, impact of ordinary soft unalloyed aluminum on rust seldom results in thermite flashes, but just in a smear of aluminum on the rust. For a given combination of impacting materials, the incendivity of the resulting sparks or flash depend on the sliding velocity and contact pressure between the colliding bodies.

Although the risk of initiation of dust explosions by accidental single impacts is probably smaller than believed by many in the past, there are special combinations of impacting materials where the ignition hazard is real. It would in any case seem to be good engineering practice to:

- Remove foreign objects from the process stream as early as possible.
- Avoid construction and tool materials that can give incendiary metal sparks or thermite flashes (titanium, magnesium, aluminum etc.).
- Inspect process and remove cause of impact immediately in a safe way whenever special noise signals indicating accidental impact(s) in process stream are observed.

5.6.3.7 Electric Sparks and Arcs: Electrostatic Discharges

The various types of electric sparks and arcs and electrostatic discharges are described in Section 2.2.6 and Section 5.3.6. Sparks or arcs due to breakage of live circuits can occur when fuses blow, in rotating electric machinery and when live leads are accidentally broken. The main rule for minimizing the risk of dust explosions due to such sparks and arcs is to:

- Obey regulations for electrical installations and apparatuses in areas containing combustible dust. (see Chapter 7)

The electrostatic hazard is more complex and it has not always been straightforward to specify clearly defined design guidelines. However, Glor (1988), who has contributed substantially to developing a unified approach, recommends the following measures:

- Use conductive materials or materials of low dielectric strength, including coatings, (breakdown voltage across dielectric layer or wall < 4 kV) for all plant items that may accumulate very high charge densities (pneumatic transport pipes, dust deflector plates, and walls of large containers that may become charged due to ionization during gravitational compaction of powders). This prevents propagating brush discharges.
- Earth all conductive parts of equipment that may become charged. This prevents capacitive spark discharges from equipment.
- Earth personnel if powders of minimum ignition energies (MIE) < 100 mJ are handled. This prevents capacitive spark discharges from humans.
- Earth electrically conductive powders (metals etc.) by using earthed conductive equipment without non-conductive coatings. This prevents capacitive discharges from conductive powder.

- If highly insulating material (resistivity of powder in bulk > 10^{10} Ωm) in the form of coarse particles (particle diameter > 1 mm) is accumulated in large volumes in silos, containers, hoppers, etc., electrostatic discharges from the material in bulk may occur. These discharges can be hazardous when a fine combustible dust fraction of minimum ignition energy < 10–100 mJ is present simultaneously. So far, no reliable measure is known to avoid this type of discharge in all cases, but an earthed metallic rod introduced into the bulk powder will most probably drain away the charges safely. It is, however, not yet clear whether this measure will always be successful. Therefore the use of explosion venting, suppression or inerting should be considered under these circumstances.
- If highly insulating, fine powders (resistivity of powder in bulk > 10^{10} Ωm) with a minimum ignition energy < 10 mJ as determined with a low-inductance capacitive discharge circuit, is accumulated in large volumes in silos, containers, hoppers, etc., measures of explosion protection should be considered. There is no experimental evidence that fine powders without any coarse particles will generate discharges from powder heaps, but several explosions have been reported with such powders in situations where all possible ignition sources, other than electrostatics have been effectively eliminated.

If combustible powders are handled or processed in the presence of a flammable gas or vapor (hybrid mixtures), the use of electrically conductive and earthed equipment is absolutely essential. Insulating coatings on earthed metallic surfaces may be tolerated provided that the thickness is less than 2 mm, the breakdown voltage less than 4 kV at locations where high surface charge densities have to be expected, and conductive powder cannot become isolated from earth by the coating. If the powder is non-conducting (resistivity of the powder in bulk > 10^6 Ωm), measures of explosion prevention (e.g. inert gas blanketing) are strongly recommended. If the resistivity of the powder in bulk is less than 10^6 Ωm, brush discharges, which would be incendiary for flammable gases or vapors, can also be excluded.

However, experience has shown that even in the case of powders of resistivities in bulk < 10^6 Ωm it is very difficult in practice to exclude all kinds of effective ignition sources when flammable gases or vapors are present. In such cases large amounts of powders should only be handled and processed in closed systems blanketed with an inert gas.

Glor also emphasized that, due to increasing use of non-conducting construction parts in modern industrial plants, the chance of overlooking unearthed conducting items is high. Therefore the effort to ensure proper earthing of all conducting parts must be maintained, in particular in plants handling dusts of low MIE. Adequate earthing is maintained as long as the leak resistance to earth does not exceed $10^6\ \Omega$ for process equipment and $10^8\ \Omega$ for personnel. However, in practice, one should aim for considerably lower resistances to earth.

5.6.4 Mitigating Dust Explosions that are Initiated in Spite of Preventive Measures

5.6.4.1 Reducing Sizes of Explosive Dust Clouds by Good Process Design (Inherently Safe Design)

5.6.4.1.1 Minimize Volumes of Process Equipment

A general rule is that volumes of process equipment should not be larger than the volumes required by the process. Nevertheless one sometimes finds industrial plants with e.g. silos that are considerably larger than required by the process. This can either be due to inadequate design in the first place, or due to the plant being used for another purpose than originally designed for.

5.6.4.1.2 Minimize Volumes of Dust Clouds Generated at Transfer Points

Undesired dust clouds are practically always generated when powder/dust/pelletized material etc. is falling freely under gravity. Whenever possible, therefore, efforts should be made to design transfer points in such a way that the material is flowing smoothly in bulk, rather than being dispersed as a cloud. For example, by having an inclined chute at transfer points between chain or belt conveyors, dusting can be reduced considerably. Another example is the very smooth discharge of material from a silo on to a chain/belt conveyor, which can be obtained if the silo hopper is designed to produce mass flow rather than funnel flow.

5.6.4.2 Partial Inerting by Inert Gas

In Table 5–2 partial inerting, as opposed to complete inerting discussed in Section 5.6.2.1, has been included as a possible means of mitigating dust explosions. The concept, discussed by Eckhoff (2004), implies that a smaller fraction of inert gas than that required for complete inerting, is added to the air. In this way both the ignition sensitivity, the explosion violence and the maximum constant-volume explosion pressure will reduced, in some cases appreciably. This offers a new possibility for applying mitigatory measures such as explosion venting or automatic explosion suppression in situations where the explosion violence of the dust in air only is too severe to permit the use of such techniques. More research is needed to establish correlations between the oxygen content in the gas phase and various ignitability and explosibility parameters of various dusts.

5.6.4.3 Isolation (sectioning)

In Section 2.4.5.2, three main reasons are given for trying to prevent a gas explosion in one process unit from spreading to others via pipes and ducts. This also applies to dust explosions. Firstly, there is always a desire to limit the extent of the explosion as far as possible. Secondly, a dust flame propagating in a duct between two process units can give rise to violent flame jet ignition of the dust cloud in the second volume. The third main reason is pressure piling. The effect of pressure piling towards generation of very high transient explosion pressures is enhanced by flame jet ignition in the second chamber.

As for gases basically two categories of methods are used for obtaining explosion isolation, viz. passive methods activated by the propagating explosion itself, and active ones, which require a separate flame/pressure sensor system, which triggers a separately powered system for activating the isolation mechanism. For obvious reasons, the passive systems are generally preferable, as long as they function as intended and are otherwise suitable for the actual purpose.

Passive isolation systems include the concept of flame propagation interruption in ducts by providing a vented 180° bend system, as illustrated in Figure 5–54. This concept is used quite frequently to interrupt dust explosions in pipes and ducts.

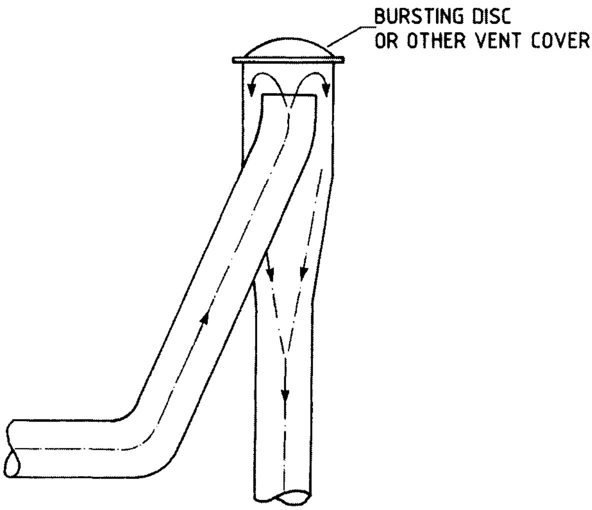

Figure 5–54 Passive device for interrupting dust explosions in pipes and ducts by combining change of flow direction and venting. Flow direction may also be opposite to that indicated by the arrows. From Eckhoff (2003).

The basic principle is that the explosion is vented at a point where the flow direction is changed by 180°. Due to the inertia of the fast flow caused by the explosion, the flow will tend to maintain its direction rather than making a 180° turn. However, the boundaries for the applicability of the principle have not been fully explored. Parameters that may influence performance include explosion properties of dusts, velocity of flame entering the device, direction of flame propagation, and direction, velocity and pressure of initial flow in duct. The use of two passive explosion interrupters of the type shown in Figure 5–54 in series in ducts between two process units, probably is a satisfactory solution in most cases. One interrupter should then be located close to each of the two process units. Screw conveyors can also be used for interrupting dust explosions. The removal of part of the screw will ensure that a plug of bulk powder/dust will always remain as a choke that will prevent transmission of a dust explosion through the screw. Specially designed rotary locks are also used for preventing explosion transfer between process units or a process unit and a duct.

Active isolation methods also include various kinds of fast-response mechanical valves. The required closing time of an automatic explosion isolation valve depends on the distance between the remote pressure or flame sensor, and the valve, and on the type of dust. Often closing times as short as 50 ms, or even shorter, are required. This may be obtained by using an electrically triggered explosive charge for releasing the compressed air or nitrogen that operates the valve. The slide valve must be sufficiently strong to resist the high pressures of 5–10 bar(g) that can occur on the explosion side after valve closure (in the case of pressure piling effects and detonation, the peak pressures may be even higher than this).

Another active explosion isolation method is flame interruption by fast automatic injection of extinguishing chemicals ahead of the flame in pipes connecting process units. This is a special application of automatic explosion suppression, which will be described in Section 5.6.4.5. However, there is a possibility of the inert plug being pushed by the explosion in the pipe into the downstream process unit where its flame-stopping effect may be destroyed. Important design parameters for this type of barrier are type of dust, initial turbulence in primary explosion, duct diameter, distance from vessel where primary explosion occurs, method used for detecting onset of primary explosion, and type, quantity and rate of release of extinguishing agent.

5.6.4.4 Dust Explosion Venting

5.6.4.4.1 Main Principle

The main principle of dust explosion venting is the same as for venting of gas explosions and outlined in Section 2.4.5.6 and illustrated in Figure 2–68.

5.6.4.4.2 Sizing of Dust Explosions Vents

Several parameters have an influence on the required area for venting of dust explosions:

- enclosure volume
- length/diameter ratio of enclosure
- maximum over-pressure P_{red} that the enclosure can withstand
- static opening over-pressure P_{stat} of vent cover
- mass of vent cover
- burning rate of the dust cloud

For some time it was thought by many that the burning rate of a cloud of dust in air was a constant property of a given dust, which could be determined once and for all e.g. in the standard 1 m^3 closed vessel test (see Figure 5–18). However, a cloud in air of a given dust can burn with widely different combustion rates, depending on the dust concentration, the turbulence and the degree of dust dispersion in the actual industrial situation. This means that the required vent area also depends markedly on the specific industrial situation of dust cloud generation and flame propagation. During the last few decades, further experimental evidence in support of this fact has been produced. As a result a differentiated view on dust explosion vent sizing has gradually evolved, which has also been taken into account in the latest European Union dust explosion venting standard issued by CEN (2002a). Experimental evidence supporting a differentiated vent sizing approach is given in Chapter 6 of Eckhoff (2003). It is forseen that in the future CFD-based numerical codes will be used even for vent sizing. for simulating turbulent dust explosions in complex geometries.

5.6.4.4.3 Vent Covers

A wide range of vent cover designs are in use. One classical and simple type of vent cover is a light but rigid panel, e.g. an aluminum plate, held in position by a rubber clamping profile as used for mounting windows in cars. The profile must then remain unlocked. Other methods for keeping the vent cover in place include various types of clips. When choosing a method for securing the panel, it is important to make sure that the pressure, P_{stat}, needed to release the vent panel is small compared with the maximum tolerable explosion pressure, P_{red}. It is further important to anchor the vent panel to the enclosure to be vented, e.g. by means of a wire or a chain. Otherwise the panel may become a hazardous projectile in the event of an explosion. Finally, it is also important to make sure that rust formation or other processes do not increase the static opening pressure of the vent cover over time.

Bursting panels constitute a second type of vent covers. In the past, such panels were often "home made," and adequate data for the performance of the panels were lacking. A primary requirement is that P_{stat}, the static bursting pressure of the panel, is considerably lower than the maximum permissible explosion pressure, P_{red}. Today, high quality bursting panels are manufactured in several countries. Figure 5–55 shows one example.

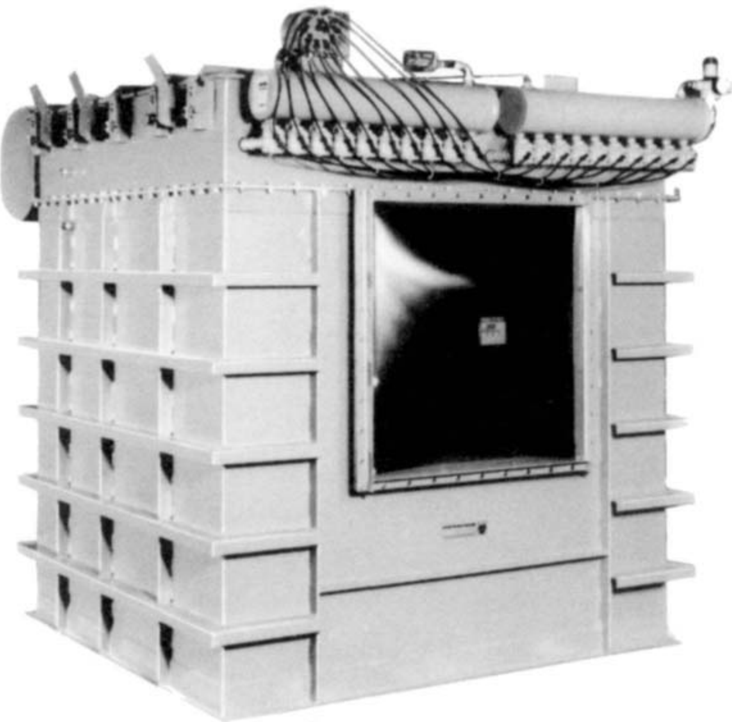

Figure 5–55 Reinforced 6 m^3 vented bag filter enclosure fitted with a modern 0.85 m^2, 3-layer bursting panel. P_{red} is 0.4 bar(g). From Eckhoff (2003).

Modern explosion vent panels burst reliably at the P_{stat} values for which they are certified, and are manufactured in a wide range of sizes and shapes, and coatings may be provided that allow permanent contact with various types of chemically aggressive atmospheres. Often a backing film of Teflon is used as an environmental protection to prevent the vent panel from contaminating the product inside the enclosure that is equipped with the vent. However, the upper working temperature limit of Teflon is about 230°C.

Hinged explosion doors constitute a third category of vent covers. Such doors may take a variety of different forms, depending on the equipment to be vented and other circumstances. Various kinds of calibrated locking mechanisms to ensure release at the predetermined P_{stat} have been developed. Hinged doors may be preferable if explosions are relatively frequent.

The final category of vent covers to be mentioned are the reversible ones, i.e. covers that close as soon as the pressure has been relieved. The purpose of such covers is to prevent secondary air from being sucked into the enclosure after the primary explosion has terminated, and giving rise to secondary explosions and fires. However, there is a risk of implosion that must be kept under control. The reversible vent covers include counterbalanced hinged doors and spring-loaded, axially traversing vent covers.

5.6.4.4.4 Potential Hazards Caused by Venting

Explosion venting prevents rupture of the enclosure in which the explosion takes place. However, significant hazards still remain. These include:

- ejection of strong flame jets from the vent opening
- emission of blast waves from the vent opening
- reaction forces on the equipment, induced by the venting process
- emission of solid objects (vent panels and other possible objects)
- emission of toxic combustion products

In general, flame ejection will be more hazardous the larger the vent and lower the static opening pressure of the vent cover. This is because with a large vent and a weak cover, efficient venting will start at an early stage of the combustion process inside the enclosure. Then large clouds of unburned explosive mixture will be pushed out through the vent and subsequently ignited when the flame passes through the vent. The resulting, secondary fire ball outside the vent opening can present a substantial hazard. If, on the other hand, the enclosure is strong, allowing the use of a small vent and a high P_{red}, mainly combustion products are vented, and the flame outside the vent is considerably smaller.

Reaction forces from explosion venting can significantly increase both the material damage and the extent of the explosion. Process equipment can tilt and ducts can become torn off, and secondary explosive clouds can be formed and ignited. Whenever an explosion vent is installed, it is therefore important to make an assessment of whether the equipment to be vented is able to withstand the reaction forces from explosion venting. A simple first order quasi-static consideration says that the maximum reaction force equals the maximum pressure difference between the interior of the vessel being vented and the outside atmosphere, times the vent area. Experiments have confirmed that this simplified model in fact predicts reaction forces in fairly close agreement with the forces actually measured, as long as the duration of the pressure peak is not too short. However, for very fast explosions, dynamic (impulse) considerations may be required.

5.6.4.4.5 Vent Ducts

One traditional solution to the flame jet problem is the use of vent ducts. As illustrated in Figure 5–56, this means that a duct of cross-sectional area at least equal to the vent area is mounted between the vent and a place where a strong flame jet will not present any hazard. Vent ducts will generally increase the flow resistance, and therefore also the pressure difference to the atmosphere. Consequently, adding a vent duct increases the maximum explosion pressure in the vented vessel. Furthermore, the pressure increases with increasing duct length, increasing number of sharp bends and decreasing duct diameter.

5.6.4.4.6 The Quenching Tube

In some applications where venting ducts are difficult to implement, the quenching tube, invented by Alfert and Fuhre (1989) may provide a good solution. The principle of this device is illustrated in Figure 5–57.

If a dust explosion occurs in the enclosure to be vented, and the bursting panel, which constitutes an integral part of the quenching tube assembly, bursts, the explosion is vented through the comparatively large specially designed wall of the quenching tube. The wall is designed to yield low pressure drop, but high retention efficiency for dust particles and efficient cooling of combustion gases. This means that flame ejection from the vent is effectively prevented and the blast effects significantly reduced. Furthermore, burning lumps of powder and other smaller objects that could be ejected through an open vent, are retained inside the quenching tube. However, any toxic gaseous combustion products, e. g. carbon monoxide, will escape to the atmosphere. The increase of the maximum explosion pressure in the vented enclosure due to the flow resistance through the quenching tube wall is mostly moderate, and can normally be compensated for by a moderate increase of the vent area.

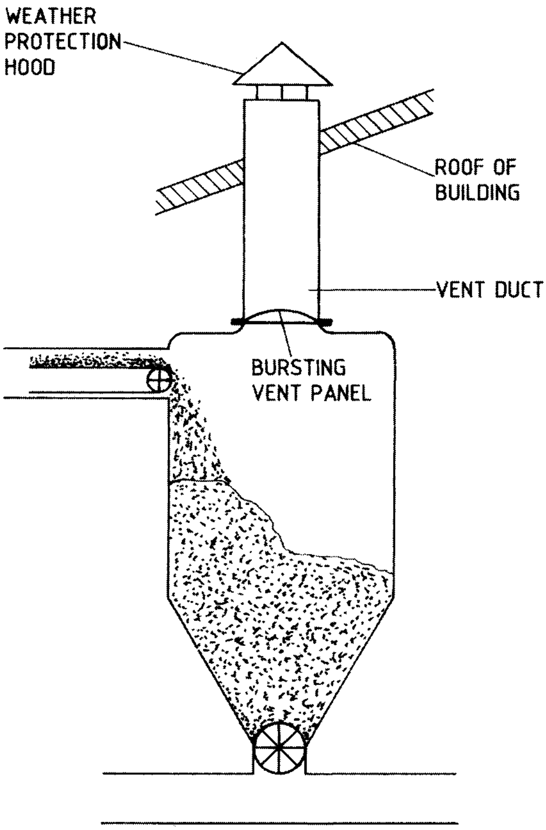

Figure 5–56 Illustration of the principle of vent ducts. From Eckhoff (2003).

5.6.4.5 Explosion-Pressure-Resistant Design

In most situations one can assume that the maximum pressure load from dust explosions is static. However, in some cases with very fast explosions, dynamic considerations may be recognized. The strength of some materials, including structural steels, is highly strain rate sensitive. This means that the stress at which plastic deformation starts, depends on the rate of loading. On the other hand, the damage to a structure also depends on how quickly the structure responds to the pressure loading. The natural period of vibration of the mechanical structure is normally used as a measure of the response time. If the duration of the pressure peak is long compared with the natural period of vibration, the loading can be considered as being

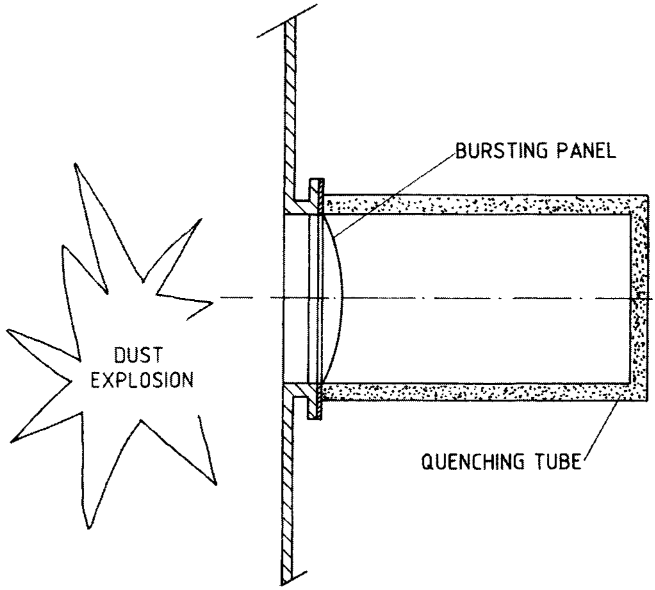

Figure 5–57 Illustration of the principle of the quenching tube for flame and dust free venting of dust explosions. From Eckhoff (2003).

essentially a static load. If, on the other hand, the pressure pulse is short compared with the response time of the structure, the damage is determined by the impulse, i.e. the time integral of pressure.

5.6.4.6 Automatic Explosion Suppression

The basic principle is described in Section 2.4.5.8. and illustrated in Figure 2–70.

Automatic suppression of dust explosions has been found to be feasible for organic dusts of maximum rate of pressure rise in the standard 1 m^3 closed ISO-vessel of up to 300 bar/s, i.e. K_{St} = 300 bar·m/s. It is somewhat unclear, however, whether the method can also be used for aluminum dusts of K_{St} in the range 300–600 bar·m/s. Moore and Cooke (1988) found that for aluminum flake of K_{St} = 320 bar·m/s it was difficult to ensure lower suppressed explosion pressures than about 2 bar(g), even under optimum conditions for suppression. In the case of dusts of natural organic materials and plastics of K_{St} up to 300 bar·m/s, the corresponding suppressed explosion pressures would typically been 0.2–0.4 bar(g). It was therefore concluded that reliable suppression of the very violent aluminum flake explosions is difficult. However, they showed that a combination of explosion suppression and venting can reduce the maximum explosion pressure to a level significantly lower than the level for venting only. An alternative approach is to reduce K_{St} by partial inerting (see Section 5.6.4.2), but then one has to rely on two active systems, which is quite expensive.

Moore and Bartknecht (1987) conducted dust explosion suppression experiments in large vessels of volumes up to 250 m^3 and were able to show that successful suppression of explosions in clouds of organic dusts is possible even in such large volumes. However, as the vessel volume increases, more suppressant and faster injection are required for successful suppression. The actual design of suppression systems depends very much on the specific design of the suppressors, and other details which vary somewhat from supplier to supplier. Therefore generally applicable quantitative design criteria are difficult to specify.

Moore and Bartknecht employed three standardized types of suppressors. The smallest type, of volume 5.4 liters, was used for vessel volumes up to 5 m^3, whereas suppressors of 20 liters were used in the vessel volume range of 5–30 m^3. The largest suppressor type of 45 liters was used for the larger process volumes. The performance of the suppression system in large process volumes was verified experimentally in vessels of up to 250 m^3, for which ten of the 45 liter suppressors were required for successful suppression of St 2 dust explosions (organic dusts). For St 1 dusts, seven such suppressors were sufficient. However, these results refer to dust clouds of very high turbulence and homogeneity, and later investigations have shown that considerably smaller total suppressor volumes are required if the dust cloud is less turbulent and less homogeneous, which is often the case in industrial practice.

Moore (1989) compared venting and suppression and showed that the two explosion protection methods are to a great extent complementary. In practice, cost effective safety is achieved by using either one of the two methods, or a combination of both.

5.6.4.6.1 Influence of Type of Suppressant (Extinguishing Agent)

Traditionally halogenated hydrocarbons (halons) were used as suppressants in automatic dust explosion suppression systems. However, long before the environmental problems caused by these chemicals became a major issue, Bartknecht (1978) showed that powder suppressants, such as $NH_4H_2PO_4$, were in general much more effective for suppressing dust explosions than halons. Therefore, powder suppressants have been used for suppressing dust explosions for many years. But powders differ in their suppressive power, and efforts have been made to identify the most effective ones. For example, addition of only 30 weight % of $NH_4H_2PO_4$ powder is required to prevent flame propagation in dust clouds in air of Pittsburgh bituminous coal, whereas with $CaCO_3$ dust (limestone) 70 weight % is needed. $NaHCO_3$ has proved to be an effective agent for suppressing some aluminum dust explosions. This material can also in some cases be used even in the food industry. It is soluble in water and can therefore be removed effectively by water only. Superheated steam (water at > 180°C) has also been used as a non-polluting suppressant.

5.6.4.7 Flexible Options for Explosion Prevention and Mitigation

Figure 5–58 and Figure 5–59, based on an analysis by Farber, illustrates how a given process plant can be protected against hazardous dust explosions by choosing quite different overall strategies. In Figure 5–58, the main strategy is explosion prevention by inerting using CO_2, whereas in the strategy adopted in Figure 5–59 explosion mitigation/control by venting and isolation plays a central role. Whenever a solution is developed for a given process plant, cost effectiveness is a major concern.

5.6.4.8 Good Housekeeping (Dust Removal/Cleaning)

5.6.4.8.1 General Outline

The main prerequisite for disastrous secondary explosions in factories is that significant quantities of combustible dust have accumulated outside the process equipment to permit development of explosive secondary dust clouds (see Section 5.2.7). Therefore, the possibility of extensive secondary explosions can be eliminated if the outside of process equipment, and shelves, beams, walls and floors of work rooms are kept free of dust.

Significant quantities of dust may accumulate accidentally outside process equipment due to discrete accidental events such as bursting of sacks

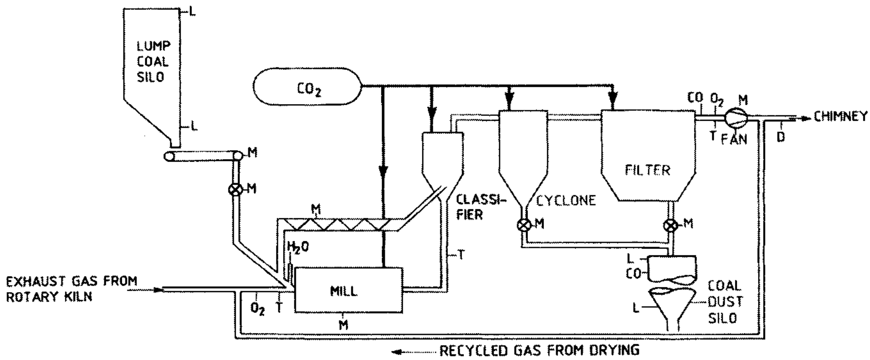

Figure 5–58 Comprehensive sensor system for monitoring, controlling and interlocking of a process for milling and drying of coal. Explosion protection based on inerting with CO_2.
CO = Carbon monoxide concentration sensors, D = Dust concentration sensor, L = Level sensors for coal and coal dust in silos, M = Movement sensors for mechanical components, O_2 = Oxygen concentration sensors, T = Temperature sensors. From Eckhoff (2003).

or bags or erratic discharge from silos or filters. In such cases it is important that the spilled dust be removed immediately. In case of large dust quantities the main bulk may be sacked by hand using spades or shovels, whereas industrial, explosion-proof vacuum cleaners should be used for the final cleaning. In the case of moderate spills, dust removal may be accomplished by vacuum cleaning only. Effective dust extraction should be provided in areas where dusting occurs as part of normal operation, e.g. at bagging machines.

Considerable quantities of dust can accumulate outside process equipment over a long time due to minor but steady leaks from process equipment. The risk of such leaks is comparatively large if the working pressure inside the process equipment is higher than ambient pressure, whereas running the process at slightly lower than ambient pressure reduces the leaks.

Process equipment should be inspected regularly for discovery and sealing of obvious accidental leak points as early as possible. However, often one has to accept a certain unavoidable level of dust leaks from process equipment. It is then important to enforce good housekeeping routines by which accumulations of combustible dust outside process

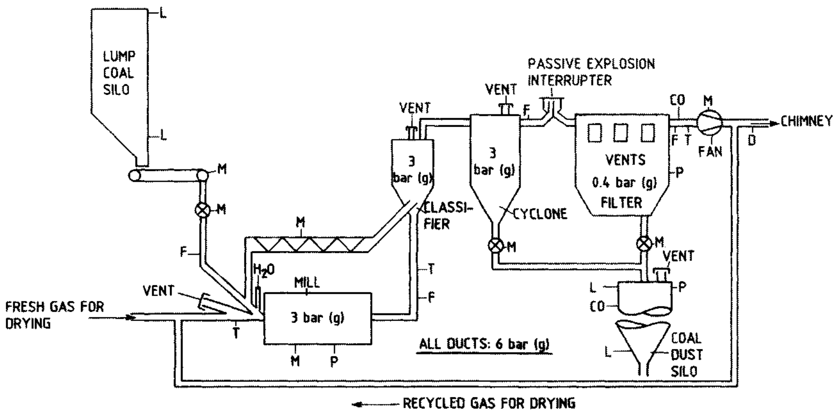

Figure 5–59 Comprehensive sensor system for monitoring, controlling and interlocking of a process for milling and drying of coal. Explosion protection based on venting and explosion shock resistant design.,
CO = Carbon monoxide concentration sensors,
D = Dust concentration sensor,
F = Flame sensor,
L = Level sensors for coal and coal dust in silos,
M = Movement sensors for mechanical components,
P = Pressure sensors
T = Temperature sensors.
From Eckhoff (2003).

equipment are removed at regular intervals, preferably by explosion-proof vacuum cleaning.

Use of compressed air for blowing spilled dust away should be prohibited. By this method dust is not removed, but only transferred to another location in the same room. Besides, dust explosions can result if the dust concentration in the cloud that is generated is in the explosive range and an ignition source exists in the same location.

5.6.4.8.2 Industrial Explosion-Proof Vacuum Cleaners

The subject was discussed by Beck and Jeske (1989) who listed the requirements to mobile type 1 vacuum cleaners recommended in F. R. Germany for removal of combustible dusts:

- The fan must be on the clean side and protected against impacts by foreign bodies.
- The electric motor and other electric components must satisfy the general requirements to such components that are to be used in areas containing combustible dusts. Motors must be protected against short-circuits and overheating.
- The exhaust from the vacuum cleaner must be guided in such a way that it does not hit dust deposits and generate dust clouds.
- All electrically conducting parts of the equipment, including hose and mouthpiece, must be earthed with a resistance to earth of less than 1 ΩM.
- Vacuum cleaner housings must be constructed of materials that are practically non-flammable. Aluminum and aluminum paints must not be used.
- A clearly visible sign saying "No suction of ignition sources" should be fitted to the housing of the vacuum cleaner.

Figure 5–60 shows an example of a large mobile vacuum cleaner for combustible dusts in industry.

Sometimes it is useful to install stationary vacuum cleaning systems rather than having mobile ones. Then a central dust collecting station with suction fan is connected to a permanent tube system with a number of plug-in points for vacuum cleaning hoses at strategic locations. Good housekeeping is essential because clean work rooms exclude the possibility of extensive secondary explosions. Cleanliness also improves the quality of the working environment in general.

Figure 5–60 Large mobile vacuum cleaner for collecting combustible/exposable dusts in industry. Both the main vessel and the connecting ducts are designed to withstand internal explosion pressures of 9 bar(g). Power requirement 45-55 kW. From Eckhoff (2003).