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Current status and expected future trends in dust explosion research

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Abstract

In spite of extensive research and development for more than 100 years to prevent and mitigate dust explosions in the process industries, this hazard continues to threaten industries that manufacture, use and/or handle powders and dusts of combustible materials. Lack of methods for predicting real dust cloud structures and flame propagation processes has been a major obstacle to prediction of course and consequences of dust explosions in practice. However, work at developing comprehensive numerical simulation models for solving these problems is now on its way. This requires detailed experimental and theoretical studies of the physics and chemistry of dust cloud generation and combustion. The present paper discusses how this kind of work will promote the development of means for prevention and mitigation of dust explosions in practice. However, progress in other areas will also be discussed, e.g. ignition prevention. The importance of using inherently safe process design, building on knowledge in powder science and technology, and of systematic education/training of personnel, is also emphasized.

Keywords: Dust explosions; Dust explosion prevention; Dust explosion mitigation; Dust explosion research

1. Introduction

The dust explosion hazard continues to represent a constant threat to process industries that manufacture, use and/or handle powders and dusts of combustible materials. However, substantial advances have been made through extensive research and development world-wide for more than 100 years. Table 1 gives an overview of the most important methods currently used for preventing and mitigating dust explosions in the process industries.

In dust explosion prevention and mitigation, as in many other challenges encountered by the process industries, there is an inevitable conflict between the short-term needs of the users of knowledge and technology, and the long-term strive for the 'perfect' solution. Industry will always need practicable solutions that can be implemented more or less immediately. It cannot wait for the ideal solutions that may become available in some distant future. However, industrial pragmatism must not, on the other hand, block the constant strive for better solutions based on improved basic understanding of the phenomena involved.

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In the present paper an attempt will be made at illustrating how research on relevant fundamental phenomena can promote further development of the practical means for preventing and mitigating dust explosions in industry listed in Table 1. The paper is essentially based on the comprehensive review of the state-of-the art in dust explosion research given in Chapter 9 of Eckhoff (2003), comprising about 600 references to works published from 1990 to 2003. In the present condensed summary, only a limited selection of these references is included.

2. The role of fundamental knowledge in assessing and controlling dust explosion hazards in practice.

Over the last 20 years there has been a gradual shift in approach in dust explosion prevention and mitigation, from simple dogmatic design methods, towards more sophisticated ones opening up for increased flexibility and tailoring. However, fundamental knowledge is essential for proper understanding of the practical aspects. In recent years the appreciation of the benefits that can be harvested from cross-fertilization between fundamental research and applied research and development has been increasing. Advanced numerical models will play an increasingly important role in solving

Table 1
Means of preventing and mitigating dust explosions. A schematic overview

Prevention		Mitigation
Preventing ignition sources	Preventing explosive dust cloud	
Smouldering combustion in dust, dust fires	Inerting of dust cloud by N_2, CO_2 and rare gases	Explosion-pressure resistant construction
Other types of open flames (e.g. hot work)	Intrinsic inerting of dust cloud by combustion gases	Explosion isolation (sectioning)
Hot surfaces (electrically, thermically or mechanically heated)	Inerting of dust cloud by adding inert dust	Explosion venting
Heat from mechanical impact (metal sparks and hot-spots)	Keeping dust conc. outside explosive range	Automatic explosion suppression
Electric sparks and arcs. Electrostatic discharges		Partial inerting of dust cloud by inert gas
		Good housekeeping (dust removal/cleaning)

practical design problems. The development of such models requires detailed experimental and theoretical studies of the relevant physical and chemical aspects. Table 2 summarizes some fundamental research topics that are essential for further development of preventive and mitigatory methods, indicated in Table 1. However, before addressing the specific methods, research on two common basic problems, must be addressed, viz. dust cloud generation, and flame propagation in dust clouds.

3. Generation of explosive dust clouds in the process industries

3.1. A historical perspective

Nearly 130 years ago professor Weber, one of the pioneers of dust explosion research, stressed the importance of accounting for dust cohesion and dust dispersibility. In his excellent paper on the ignitability and explosibility of wheat flour Weber (1878)

Table 2
Fundamental aspects addressed in dust explosion research

Dust cloud formation processes	Dust cloud ignition processes	Flame propagation processes in dust clouds	Blast waves generated by burning dust clouds
Inter-particle forces in dust deposits (cohesion)	Ignition of single particles and clouds	Microscopic aspects (Single-particle ignition) and combustion in hot oxidizer gas	Blast wave properties as a function of properties of burning dust clouds
Entrainment of particles from dust deposits by shock waves passing across the deposit surface	Ignition by smouldering combustion in dust layers/deposits	Laminar and turbulent flames in dust clouds	Effects of blast waves on humans and mechanical structures
	Ignition by hot surfaces		
Entrainment of particles from dust deposits by turbulent gas flows	Ignition by flying burning metal particles	Mechanisms of heat transfer (conduction, convection, radiation)	Ability of blast waves from dust explosions to transform dust layers into explosive dust clouds (coupled to first column of table)
	Ignition by electric sparks and arcs		
Transport of dust particles in turbulent gas flows	Ignition by electrostatic discharges	Limit conditions for flame propagation in dust clouds (particle properties, dust conc., oxygen conc., geometry).	
	Ignition by hot gas jets		
	Ignition by shock waves		
Measurement and characterization of turbulence in dust clouds	Ignition by hot-spots from focused light beams	Acceleration of flames in dust clouds by turbulence mechanisms	
Measurement and characterization of spatial distribution of particles in dust clouds	Influences on dust cloud ignition sensitivity of cloud properties (composition, size, shape of particles, dust concentration, composition, turbulence, temperature and pressure of gas phase)	Detonation phenomena in dust clouds	

emphasized that the cohesion of the flour, which is caused by inter-particle adhesion, has a strong influence on the ability of the flour to disperse into explosive dust clouds. Weber suggested that two large dust explosion disasters, one in Szczecin (Stettin) and one in München, were mainly due to the high dispersibility of the flours. He also demonstrated, using simple but convincing laboratory experiments, that the dispersibility, or dust-ability, of wheat flour increased as its moisture content decreased. A global definition of dust dispersibility is given in Eckhoff (2003), Chapter 3.

3.2. The 'state' of a dust cloud

The characterization of the 'state' of a dust cloud is far more complicated than characterizing the 'state' of a premixed quiescent gas mixture. For a quiescent gas the thermodynamic state is completely defined by the chemical composition, the pressure and the temperature. For a dust cloud, however, the stable state of equilibrium will be complete separation, with all the particles settled out at the bottom of the system. Therefore, in the context of dust explosions, the relevant 'state' will always be dynamic. In various industrial environments, as well as in experiments with dust clouds (disregarding sophisticated 'microgravity' experiments), gravity and other inertia forces act on the dust particles, giving rise to a complex dynamic picture. In the ideal static dust cloud, all the particles would be located in fixed positions, either ordered or at random. The closest approximation to the ideal dust cloud that can be encountered in practice is probably a cloud in which the particles are settling in quiescent gas under the influence of gravity alone.

3.3. Generation of primary dust clouds inside process equipment

In order for an explosive dust cloud to be formed from a layer/deposit, the layer/deposit must be exposed to a process that disperses the particles in the air to the extent that the dust concentration drops into the explosive range. Most often such dispersion generating explosive clouds takes place intentionally inside process equipment, e.g. by handling and transportation in various process equipment (in mills, dryers, mixers, bucket elevators and other conveyors, silos, filters, cyclones, connecting ducts etc.). It seems reasonable to expect that comprehensive numerical models will be developed for predicting the dust cloud structures (spatial distributions of effective particle size, dust concentration, turbulence and global flow) that will be generated in various practical situations in industry. Knowing this initial cloud structure is essential because it has a major impact both on the ignition sensitivity of the cloud and the course of development of the primary explosion. Therefore, adequate information about the initial dust cloud structure is also essential for realistic modelling of dust explosions in process plant. However, the development of adequate numerical models is only in its infancy, and little information of practical use has been traced. The works of Hauert, Vogl, and Radandt (1994); Kosinski et al. (2001) constitute valuable initial contributions. However, more experimental and theoretical work is needed in this area. In order to guide fundamental research in this area in the direction of maximum practical relevance, further information about dust cloud structures that are typical in industrial operation is required. This not only means the cloud structures in normal plant operation, but perhaps even more importantly the structures existing during abnormal transient phases, including plant start-up and close-down. The occurrence of dust explosions may sometimes seem more likely during such periods than under normal steady-state conditions.

3.4. Generation of secondary dust clouds inside and/or outside process equipment by blast waves from primary dust explosion

The blast wave from a primary dust explosion can generate secondary explosive clouds ahead of the flame by entraining dust deposits and layers there. Lebecki, Sliz, Dyduch, and Wolanski (1990) investigated such processes experimentally in a 100 m long gallery of cross-section 3 m^2. Kauffman, Sichel, and Wolanski (1992) and Austin et al. (1993) summarized their extensive research on entrainment of dust layers in long tubes by the blast wave heading a dust explosion propagating along the tube. Boiko and Poplavski (1996) studied the effect of the dust concentration in a dust cloud behind a shock wave, on the acceleration of the cloud. Data from this kind of work are essential in the development of comprehensive dust explosion codes. Klemens, Kosinski, and Oleszczak (2002a,b) presented a mathematical model for simulating the process of entrainment of dust particles from a dust layer, by the gas flow behind a shock or a rarefaction wave passing across the layer. Fedorov and Gosteev (2002) and Fedorov and Fedorova (2002) presented mathematical models describing the initial stage of the entrainment of single dust particles from a dust layer by a gas flow passing across the layer, and numerical simulations of the entrainment of dust particles from a near-wall dust layer by a shock wave propagating across the layer.

3.5. Dust dispersibility tests

Various test methods have been proposed for evaluating the ease with which dust clouds can be produced from deposits and layers of powders/dusts (Breum, 1999; Dahmann & Möcklinghoff, 2000; Eckhoff, 2003, Chapter 7; Jong, Hoffmann, & Finkers, 1999; Tamanini & Ural, 1992).

4. Flame propagation in dust clouds

4.1. General

An important difference between dust clouds and premixed gases is that in dust clouds inertial forces can produce fuel concentration gradients (displacement of particles in relation to gas phase). Furthermore, thermal radiation may contribute significantly to the heat transfer from the flame to the unburnt cloud, depending on the type of particle material (e.g. light metals). More work is needed to explore the role of thermal radiation in the development and course of dust explosions.

Lee, Zhang, and Knystautas (1992) showed that theoretical equilibrium properties of dust cloud combustion (constant-pressure adiabatic flame temperatures, and maximum constant-volume explosion pressures) calculated by standard computer codes are in good agreement with experimental data obtained by various workers. Wolanski (1990) reviewed the problems involved in determining flame structures, laminar or quasi-laminar burning velocities, lower flammability limits, and conditions required for flame acceleration and transition to detonation in dust clouds. The influences of added inert particles were also considered. Much research work has been done on various aspects of combustion of liquid sprays and mists (Eckhoff, 1991), which is in part also relevant even in the context of dust explosions.

4.2. Laminar flames in dust clouds

It has often been assumed that the laminar burning velocity of a given dust cloud is a basic combustion property of the cloud, which is closely related also to the burning velocities at various levels of turbulence, and hence to the flame propagation through that type of cloud at large. Numerous experimental studies have been performed of quasi-laminar upwards flame propagation in vertical tubes with the top closed and the bottom open. Often a ‘true laminar’ burning velocity was calculated by multiplying the observed upwards flame speed by the ratio of the cross-section of the tube to the approximately constant observed surface area of the hemispherical/parabolic flame front. However, this method contains a logical inconsistency, in that the observed constant shape of the flame front is incompatible with assuming a constant laminar burning velocity perpendicularly to any point of the flame surface.

Valuable work on laminar dust flames in stabilized burners was carried out in the past, e.g. by Smoot and co-workers (see Eckhoff, 2003, p. 273). An excellent recent contribution to improved understanding of the nature of laminar dust flames was given by Dahoe, Hanjalic, and Scarlett (2002). They used a burner apparatus to produce stable cornstarch flames in air, and the laminar burning velocity was measured via laser Doppler anemometry (LDA). It was found that the laminar burning velocity varied with flame shape, and this was accounted for by introducing the ‘Markstein length’ of a dust/air flame. This parameter is specific for any given dust cloud. It has a magnitude of the order of the laminar flame thickness of that specific dust cloud, and serves as a measure of the sensitivity of the laminar burning velocity to changes in the flame shape. Dahoe et al. emphasized that neither the theoretical derivation nor the experimental determination of the Markstein length is trivial, and that much remains to be learnt about its precise dependence on the chemical and physical properties of the specific combustible mixture being investigated. This work also suggests that time seems ripe for reconsidering earlier work to determine laminar burning velocities of dust clouds in vertical tube experiments, because buoyancy and flame stretch probably contributed significantly to formation of the upwards moving flame front. The conclusion seems to be that a satisfactory method for experimental determination of laminar burning velocities of dust clouds remains to be developed.

4.3. Turbulent flame propagation in dust clouds

Access to adequate sub-models of flame propagation in turbulent dust clouds is essential when developing comprehensive numerical codes for dust explosion propagation. Understanding flame acceleration, due to flame distortion and turbulence produced by the propagating explosion itself, is central for understanding both dust and gas explosions in practice. Extensive experimental research programmes have been conducted to resolve basic flame acceleration mechanisms in gas explosions in obstructed geometries. Central contributors are Moen, Lee, Hjertager, Fuhre, and Eckhoff (1982); Hjertager, Fuhre, and Bjoerkhaug (1988); Bakke and Wingerden (1992).

The fundamental studies of Rzal-Rebière and Veyssière (1994) provide significant insight in possible differences between turbulent combustion of premixed gases and dust clouds. They investigated the interaction of a laminar maize starch/air flame with an obstacle, viz. a sphere, a disk or an annulus. With the annulus, flame-quenching phenomena were observed, which were attributed to centrifugal separation of dust particles and air in the turbulent eddies. This is a very important observation, indicating that the burning rate of a dust cloud may not necessarily respond to turbulence in the same way as the burning rate of a premixed gas. Further work towards improved understanding of the relation between the dynamic state of a dust cloud and its combustion rate is needed. By employing the experimental facilities used in previous extensive gas explosion experiments, e.g. in the experiments by Moen et al. (1982), and repeating these experiments using dust clouds instead of premixed gas, valuable insight could be gained. Systematic comparison of results would yield an overview of similarities and discrepancies, which would help to focus basic research efforts on important areas where dust cloud combustion may differ significantly from combustion of premixed gases.

Significant differences between combustion of premixed gases and dust clouds also exist on the microscopic scale. For example, the basic microscopic turbulence mechanisms that promote the combustion process must be identified. The results of Mitgau (1996) and Mitgau, Wagner, and Klemens (1997) indicate that more efficient replacement of gaseous reaction products by fresh air round each particle may be a strong basic turbulent combustion enhancement mechanism.

4.4. Comprehensive mathematical models of turbulent flame propagation in dust clouds

Kjäldman (1992), being one of the pioneers in this field, summarized his early work on applying computational fluid dynamics (CFD) to turbulent dust explosion propagation. Subsequent contributions were made by Bielert and Sichel (2001); Korobeinikov, Semenov, Klemens, Wolanski, and Kosinski (2002); Kosinski, Klemens, and Wolanski (2002); Rose, Roth, and Frolov (1999); Smirnov, Nikitin, and Legros (2000); Wörsdörfer, Sippel, Fuisting, and Kneer (2001); Zhong, Teodorczyk, Deng, and Dang (2002). In developing a comprehensive numerical code for dust explosion simulation, corresponding existing codes for gas explosion simulation constitute a logical starting point. The comprehensive FLACS code originally developed by Hjertager et al. (1988) is currently being used as a basis for developing the corresponding dust explosion code DESC. Arntzen, Salvesen, Nordhaug, Storvik, and Hansen (2003); Hansen, Skjold, and Arntzen (2004), and Wingerden, Arntzen, and Kosinski (2001) presented dust explosion simulations using preliminary versions of the DESC code. Very recently Skjold, Arntzen, Hansen, Storvik, and Eckhoff (2004) presented results from simulation of dust explosions in a large silo of 236 m^3, performed in Norway about 20 years ago, using an improved version of the same code. Skjold et al. (2004a) presented further DESC simulations of explosions in other process equipment. It seems clear that this type of comprehensive numerical computer simulation codes will become the future tool for predicting of the course of dust explosion scenarios encountered in the process industries, including process units interconnected by ducts and conveyor lines. However, development of, and confidence in, any such comprehensive computer code have to be built on extensive validation against full-scale dust explosion experiments, covering a wide range of dusts, initial dust clouds states, and geometrical configurations.

5. Preventing explosive dust clouds

5.1. Inherently safe process design

Most often one tries to fight the dust explosion hazard by adding preventive and mitigatory measures to an existing process. However, the technical measures adopted are often expensive, and safety procedures may fail. Inherent safety is an alternative approach implying that the process itself be designed in such a way that no explosion hazard exists. Kletz (1999), the 'father' of the inherently-safe-process design concept, outlined its basic philosophy and recommended the use of it whenever feasible. In the context of preventing and mitigating dust explosions inherently safe process design could include use of production, treatment, transportation and storage operations where dust cloud generation is kept at a minimum. One example is use of mass flow silos and hoppers instead of the frequently used funnel flow types. Eckhoff (1997) emphasized the importance of knowing powder science and technology when striving for inherently safe process design in industries having a dust explosion hazard. Amyotte and Khan (2002) proposed a framework for directing the concept of inherently safe process design specifically towards reducing the dust explosion hazard in industry. Hopefully, such initiatives will promote further work in this important area.

5.2. Inerting by adding inert gas

Inert dust clouds can be generated by mixing the air with an inert gas such as nitrogen or carbon dioxide to a level at which the dust cloud can no longer propagate a self-sustained flame. Some further insight has been gained over the last few years. For example, in contrast to what had been found earlier for coal dust, Wilen (1998) measured an increase of the limiting oxygen concentration (LOC) for inerting bio-mass dust clouds, with increasing initial pressure in the range 5–18 bar. Schwenzfeuer, Glor, and Gitzi (2001) found that LOC for ignition of dust clouds by electrostatic discharges, or metal sparks from mechanical impact, were significantly higher than the conservative limit determined in standard tests, using a very strong pyrotechnical ignition source.

Whilst a reduction of the oxygen content in the atmosphere can prevent dust explosions, it may introduce a suffocation risk. However, research has shown that adding a few vol.% of CO_2 to the gas mixture reduces the critical oxygen threshold for suffocation considerably. An inert gas mixture utilizing this effect was described by Dansk Fire Eater A/S (1992).

5.3. Keeping the dust concentration below LEL

In principle, keeping the concentration of dust in the cloud below the minimum explosive limit (LEL), is a means of maintaining dust clouds non-explosive.

However, the method has limited applicability in practice. Mittal (1993) discussed various mathematical models for calculating minimum explosive concentrations of dust clouds.

6. Preventing ignition sources

6.1. Smouldering layers, deposits and nests

A practical question that has been asked is whether metal particle sparks from single accidental impacts can initiate combustion in dust layers/deposits. Hesby (2000) found that the number of sparks from single accidental impacts of steel objects is all too low to be able to cause ignition of the layers of organic dusts studied.

Krause and Hensel (1996) presented a numerical method by which non-steady temperature fields in dust deposits can be computed. This enables numerical analysis of a number of practical cases of self-heating/self ignition that cannot be analyzed using the classical thermal explosion theory of Frank-Kamenetzki. Krause and Schmidt (2001) studied experimentally critical thermal conditions that may lead to initiation of smouldering processes, or to further development of such processes, once initiated. Gummer and Lunn (2003) found that smouldering nests were poor ignition sources for most dust clouds, whereas, flaming nests caused ignition more readily. More work is needed to clarify both the conditions under which smouldering or flaming nests of various materials are generated in industrial plant, and the circumstances under which such nests will ignite explosive clouds of various dusts.

6.2. Hot surfaces

In the past, the minimum hot-surface temperature for ignition of a dust cloud has often been regarded as if it were a universal constant for a given cloud. Consequently, results from small-scale laboratory tests were often applied directly in design of large-scale industrial plant. However, minimum hot-surface ignition temperatures of dust clouds vary significantly with scale, as well as with the geometry of the hot surface in relation to the dust cloud. There is a need for both a more differentiated basic understanding and a more differentiated testing approach. Development of numerical models for dynamic simulation of hot-surface ignition processes encountered in practice is foreseen.

6.3. Electric/electrostatic discharges between two metal electrodes

Electric and electrostatic discharges between two metal electrodes can be generated in a number of ways, e.g. in switches, by failures in electric circuits, and by discharge of static electricity. The parameters influencing the minimum energy required for igniting a dust cloud by an electric spark include voltage and current characteristics across the spark gap, spark gap geometry and electrode material, as well as all the dust cloud parameters. The latter include particle material and particle size/shape distributions, dust moisture content, dust concentration, and the dynamic state of the dust cloud with respect to the spark gap. Minimum ignition energies (MIE) of clouds of a given dust material decreases strongly with the fineness of the dust. Eckhoff (1995) discussed the influence of dust fineness on MIE of ferro-alloys dusts. In the past dust fineness was often specified just as a mass percentage finer than an arbitrary size, e.g. 74 or 63 μm, without any specification of the distribution of particle sizes below these limits. This complicates the analysis of published experimental data, and more systematic research is needed to clarify the exact influence of particle size. In the case of metal alloys the most hazardous components may sometimes accumulate in the fine tail of the particle size distribution (e.g. Mg in MgFeSi), and special investigations are required. Lorenz and Schiebler (2001) presented the results from a comprehensive, detailed experimental and theoretical investigation of the energy transfer processes taking place during an electrostatic spark discharge. The temperature and pressure development in the spark channel during its formation and subsequent expansion were investigated. This also included cooling of the channel by thermal radiation. The dependence of the ability of a given discharged electrical energy to ignite a dust cloud on these basic physical spark characteristics was emphasized.

Recently Randeberg and Eckhoff (2004) investigated an alternative method for measuring MIEs of explosive dust clouds, which may be in better accordance with accidental electrostatic spark ignition in industrial plant. In the conventional method a special electronic system is employed for optimal synchronization of the dust cloud and the spark discharge. In the work of Randeberg and Eckhoff the transient dust cloud itself was used to initiate spark breakdown between a pair of electrodes pre-set at a high voltage somewhat below the breakdown voltage in dust-free air. Using this method, the MIEs of three dusts were determined. The results were of the same order, although somewhat higher than those obtained using the conventional method.

Up to now the lower spark energy limit for apparatuses commonly used for determining MIEs of dust clouds has been 1–3 mJ. However, recently Randeberg, Olsen, and Eckhoff (2005) presented a new test method that permits MIE determination for dust clouds, using synchronized sparks, down to the order of 0.03 mJ.

6.4. Electrostatic one-electrode discharges

With regard to the even more complex one-electrode electrostatic discharge types (corona, brush, propagating brush, etc.), valuable experimental insight has been gained during the last years. The issue of whether brush discharges can ignite dust clouds was revisited experimentally by Larsen, Hagen, Wingerden, and Eckhoff (2001), who were in fact able to ignite clouds of sulphur dust in oxygen-enriched air by true brush discharges. However, ignition in air only was never observed. Because of the very low MIE of clouds of sulphur dust in air, this indicates that ignition of even the most sensitive dust clouds by brush discharges in air, is unlikely.

6.5. Glowing/burning particles

Ignition of dust clouds by small burning metal particles (impact sparks, metal sparks) generated by mechanical impact is a complex process, and comprehensive, practically useful theories do not seem to be within sight. Such theories must comprise several complex sub-processes. The first is the generation and initial heating of the metal particle by the impact. The second is the ignition of the flying hot particle and the subsequent burning process. The third is the heat transfer to the dust cloud, which ultimately determines whether ignition occurs or not.

6.6. Electrical equipment

The present situation internationally concerning standards for apparatuses for use in areas containing combustible dust is confusing, as discussed by Eckhoff (2004a). Whereas, the International Electrotechnical Commission (IEC) has decided to base its development on European Union 'Atex' philosophy, the European Union Atex 94/9/EC Directive does not distinguish adequately between combustible dusts and combustible gases/vapours. In particular the Directive does not point out the vast differences between the ways in which explosive gas clouds on the one hand, and explosive dust clouds on the other, are generated and sustained in industrial practice. This has resulted in undue alignment of a series of new IEC standards for electrical apparatuses for combustible dusts with established standards for gases/vapours. The current European Union Atex 1999/92/EC Directive also lacks the required distinction between gases and dusts, which gives rise to problems with area classification.

6.7. Other ignition sources

Proust (2002) determined experimentally the minimum laser beam power required for igniting dust clouds by the heat absorbed by a solid target heated by the laser beam. The variable parameters included the laser beam diameter, the duration of the irradiation, the target material (combustible/non-combustible), and the type of dust. Initiation of dust explosions by shock waves has been studied by several workers, including Wolanski (1990); Klemens, Klammer, and Wolanski (1998).

7. Protective/mitigatory measures

7.1. Full confinement

The applicability of the concept is limited because of high equipment costs. However, the method is being used in some special cases, e.g. when the powder/dust is highly toxic, and completely reliable confinement is absolutely necessary. Current experimental methods allow sufficiently accurate prediction of maximum explosion pressures in simple vessels with point source ignition. However, there is considerable room for improvement in the design of pressure resistant process equipment, with respect to minimizing its heaviness, e.g. by using advanced 'finite element' computation methods. See also Section 7.6.

7.2. Explosion isolation

The objective of explosion isolation is to prevent dust explosions from spreading from the primary explosion site to other process units, workrooms, etc. Basic understanding of flame propagation and pressure build-up in coupled process equipment ('interconnected vessels'), as discussed in Section 4, is required for specification of performance criteria of various types of active and passive isolation equipment. Wingerden, Pedersen, Teigland, and Eckhoff (1994) reported on dust explosion experiments in a system of two vented vessels connected by a duct. Holbrow, Andrews, and Lunn (1996); Holbrow, Lunn, and Tyldesley (1999) summarized the results from extensive similar experiments in UK, and presented coherent quantitative guidance for design of interconnected process equipment, focusing on the two protection technologies explosion containment and explosion venting. Vogl and Radandt (2001, 2002) presented results from a comprehensive experimental programme in Germany on propagation of dust explosions in interconnected process systems. Various passive and active techniques for interrupting explosions in pipelines have been developed, but there is room for further improvement.

7.3. Partial inerting

This is a relatively new, promising concept for mitigating dust explosions, which deserves further attention. The idea is that, as the oxygen content in the atmosphere is reduced, there is a systematic decrease of both ignition sensitivity and combustion rate of the dust cloud. In many cases the explosion hazard may be reduced markedly by only a moderate reduction of the oxygen content. Glor and Schwenzfeuer (1999) confirmed experimentally that even modest reductions of the oxygen content, can increase the minimum ignition energies of dust clouds substantially. Devlikanov, Kuzmenko, and Poletaev (1995) found that K_{st} was a linear function of the percentage of oxygen in the gas phase (mixture of nitrogen and oxygen). Conde-Lazaro and Garcia-Torrent (2000) carried out a series of partial inerting experiments at 12 bar initial pressure, in a demonstration PFBC pulverized coal power plant. Eckhoff (2004b) called for more extensive use of partial inerting in industrial dust explosion protection.

As mentioned in Section 5.2 above, reducing the oxygen content in the atmosphere by adding nitrogen can introduce a suffocation hazard. However, research has shown that adding a few vol.% of CO_2 to the gas mixture reduces the critical oxygen threshold for suffocation considerably.

7.4. Explosion venting

This is probably the most widely used method for mitigating dust explosions. In spite of extensive research and development, dust explosion venting remains a complex and in part controversial subject. The key issue is vent area sizing, but the required basic understanding of flame propagation processes inside and outside vented enclosures is still unsatisfactory. Neither the processes by which the dust clouds are generated in industrial plant, nor the ways in which the clouds burn, are sufficiently well understood (see sections 3 and 4). However, in view of the different turbulence levels, degrees of dust dispersion, and distributions of dust concentrations encountered in industry, the need for a differentiated approach to assessment of vent area requirements is becoming generally accepted.

Tamanini and Valiulis (1996) presented an improved version of the VDI (Germany) and NFPA (USA) guidelines for sizing of dust explosion vents. The improvement was achieved by systematizing the data in the context of a simplified physical model of the vented explosion. A similar contribution was made by Ural (2001). The new CEN (2002) standard for design of dust explosion venting systems in principle opens up for a differentiated approach to vent sizing, which accounts for the variations in dust cloud structures encountered in practice in industry. In most practical cases this will result in more liberal vent area requirements than those of some previous rigorous standards. Other aspects of explosion venting studied more recently include the influence of the inertia and specific design of the vent cover on the gas dynamics of the venting process. A further dimension of complexity is added to the venting problem if the initial pressure (and/or temperature) deviates from atmospheric. Results from venting of dust explosions in air of elevated initial pressure were reported by Siwek, Glor, and Torreggiani (1992).

In dust explosion venting, maintaining the integrity of the enclosure is not the only concern. Venting implies that both blast waves and flames are emitted into the surroundings, and this may present a hazard, depending on the size of the emitted flame and the magnitude of the blast wave. Several workers, including Forcier and Zalosh (2001); Harmanny (2001); Holbrow, Hawksworth, and Tyldesley (2000), investigated various aspect of this. Various methods have been developed for eliminating hazardous effects of flames from vent openings. Li, Deng, and Liu (1994), and Emde and Penno (1996) discussed further aspects of the Q-pipe for dust and flame free venting. The influence of vent ducts on the maximum explosion pressure in the vented vessel has been studied experimentally by several workers including and Lunn (2001). Tamanini and Valiulis (2000); Ural (1993) presented a new theoretical approach for predicting the resultant reaction impulse acting on a process structure during a vented explosion.

Venting of industrial buildings requires special considerations. An overview was given by Crowhurst (1993). Höppner (1996) discussed the design of dust explosion venting arrangements for rooms/buildings of volumes > 5000 m^3, with walls that can only withstand overpressures less than 0.2 bar. In case of a dust explosion, only part of such large volumes will be filled with explosive dust cloud.

Improvement of current methods for designing dust explosion venting arrangements is badly needed. Tamanini (2002) summarized his valuable effort of correlating existing experimental dust explosion venting data by applying the classical method of dimensional analysis. It is regrettable that this important work was not included in the recent European Union guideline for design dust explosion venting arrangements, CEN (2002). However, the ultimate long-term solution for design of explosion venting arrangements will be comprehensive computer models that are capable of predicting propagation of dust explosions in the variety of complex coupled process systems encountered in the process industries. As discussed in Section 4.4, such models are now being developed at great pace and are likely to become the answer in practical design of explosion vents in a not too distant future.

7.5. Automatic explosion suppression

This active method for dust explosion mitigation is comparatively complex and expensive. It is therefore used when simpler and less expensive methods are inadequate. Although the method has been in use for several decades, significant progress has been made during the last decade. For example Moore (1996); Chatrathi and Going (1998) discussed the choice of suitable suppressant, and Tyldesley (1993) reported that super-heated water can also be an effective suppressant. Moore and Siwek (1998) summarized their extensive multi-year experimental work on suppression of dust explosions, whereas Chatrathi and Going (2000) gave an overview of current technology and philosophy for implementing automatic explosion suppression systems in practice. The influence of elevated initial temperature of the explosive dust cloud on the efficacy of an automatic explosion suppression system was studied by Brehm (1996).

The European standardization organization CEN (2001) has produced a draft standard for design of explosion suppression systems, which seems to open up for greater flexibility than the traditional, mostly very conservative approach. Hence, if the turbulence level and/or degree of homogeneity of the cloud of a given dust in the actual process situation are lower than produced by the rather conservative traditional standard VDI-method of dust cloud generation, this can be accounted for in the design of the suppression system.

Comprehensive numerical models of the complex explosion suppression process, based on computational fluid dynamics (CFD), is likely to be the future tool for design of optimal explosion suppression systems. Some initial simulation trials were reported by Siwek et al. (2004). Morgan (2000) assessed the suitability of commercially available CFD software for modelling the types of flows encountered in explosion suppression processes. Using results from his model simulations he was able to design a novel suppressant injection nozzle, which was shown to be more effective than standard nozzles currently used.

7.6. Design of process equipment for specific internal explosion loads

This problem is always a central concern when designing explosion protection systems, whether they are for full explosion confinement (7.1), explosion venting (7.4), or automatic explosion suppression (7.5). Harmanny (1993) presented a new equation for predicting the duration of vented dust explosions in enclosures of volumes from 10 to 60 m^3. This is a useful tool for evaluating whether static pressure considerations or impulse considerations apply when predicting the response of the enclosure structure to the explosion load. Harmanny (1996, 1999) revisited the problem of assessing the structural response of a given process equipment and buildings to explosion loads. With regard to dust explosions in the process industries, he concluded that most often they are sufficiently slow for the load to be regarded as quasi static. However, there are certain cases where dynamic effects play a significant role. Comprehensive finite-element-based computer codes for determining detailed stress/strain analyses of complex structures exposed to defined static and dynamic loads have been available for some time. It is foreseen that the use of such tools in assessing the explosion strength of complex process equipment will increase in the years to come. The concept of pressure-shock-resistant design should be developed further to facilitate cost effective equipment design. Li, Chen, Deng, and Eckhoff (2002) compared elastic and plastic structural responses of a simple mechanical structure determined experimentally with predictions from using a computational finite-element approach.

7.7. Preventing secondary explosions outside process equipment

This remains a most important issue in all efforts to fight the dust explosion hazard. Adequate housekeeping is an essential means of achieving this aim. However, there are still questions to be answered concerning the level of cleanliness required. More research is needed for assessment of the maximum acceptable mass of deposited dust per unit area of surface for preventing secondary dust flame propagation under various conditions.

Cybulski, Dyduch, Lebecki, and Sliz (1993) showed that comparatively weak secondary dust explosions in short, narrow tunnels in grain elevators, can be extinguished by properly designed, actively triggered water barriers.

8. Other factors influencing the dust explosion risk

8.1. Explosion risk management

Barth (2001) emphasized the importance of companies establishing systems for explosion risk management control to ensure effective, long-lasting explosion protection of process plant. Hesener, Barth, and Dyrba (2001), with reference to the pharmaceutical industry, underlined the need for having adequate systems for explosion risk management and control even in small and medium size plants.

8.2. Cost/benefit in dust explosion prevention and mitigation

Alfert (1996) addressed the bottom-line costs of various dust explosion protection systems on the market. Janssens (2001) pointed out that the investments required to achieve proper prevention and control of the explosion hazard in a given plant are not necessarily excessive. By combining thorough knowledge of the processes to be protected, with knowledge of relevant ignition and flame propagation phenomena, and principles and technologies available for explosion control, good solutions can be obtained at an acceptable cost.

8.3. Education and training

High safety levels in the process industries cannot be established once and for all by a single all-out effort. Deterioration results if the high level once attained is not actively secured by continuous maintenance and renewal. This applies both to technology and human factors. Education and training, from short practical training courses to in-depth long-term education, play a key role in the continuous maintenance and renewal process. Universities and colleges have responded to this challenge by establishing study courses on a wide range of process safety aspects. Relevant topics include reliability and risk analysis, the physics, chemistry and technology of processes and hazards, and means of accident prevention and mitigation. Much emphasis has been put on methods of reliability and risk analysis, which are indeed very important. However, it is sometimes felt by the process industry itself that education in the ‘hard’ aspects, i.e. the physics, chemistry and technology of processes and process hazards, has been somewhat left behind. This situation presents a special challenge to universities and colleges.

9. Some perspectives for the future

(a) The approaches taken in dust explosion prevention and mitigation in the process industries will become steadily less dogmatic and more *tailored and differentiated* in the years to come. Industry will strive for steadily more *cost effective safety measures*.

(b) Increasing awareness of the benefits from using the *inherent safety* concept in design of processes for production, treatment and handling of combustible powders/dusts is anticipated. *Adequate knowledge of powder/particle technology* is a basic requirement.

(c) Tailored, cost effective safety measures will require in-depth knowledge both about actual dust cloud structures, potential ignition sources, and the flame and pressure development that follows an ignition. Therefore, substantial progress is foreseen in *mathematical modelling of dust cloud generation and flame propagation processes in dust clouds*. It is anticipated that such models will gradually replace conventional empirical equations and graphs as design tools for tailored systems for explosion isolation, explosion venting and automatic explosion suppression and for evaluating consequences of secondary dust explosions. However, extensive *experimental validation* of the numerical models is absolutely necessary. International co-operation will be required, as e.g. in the current European DESC project.

(d) The evaluation of *potential ignition sources* will also become more detailed and differentiated, in accordance with reality. Further development of mathematical models for simulation of various ignition processes (self-heating/smouldering, hot surfaces, various electrical and electrostatic sparks/discharges, metal sparks etc.) is foreseen.

(e) Increased use of *combined protective solutions*, e.g. partial inerting in combination with e.g. venting, venting combined with automatic suppression, is also foreseen.

(f) High-quality training/education, ranging from short courses of a few days to extensive university studies, will continue to be essential for minimizing the hazards in the process industries, including minimizing the risk of dust explosions.

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