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Dust explosion research. State-of-the-art and outstanding problems

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Abstract

Increased knowledge creates a justified request for a steadily more differentiated approach to design of preventive and mitigative measures against dust explosions in industry. In this process, cross-fertilisation between fundamental research and applied research and development is beneficial. Central research topics include formation of, ignition of and flame propagation in dust clouds, blast waves from exploding dust clouds, and test methods. Due to the complexity of the various problem areas, comprehensive theories are scarce. However, computer simulation models, carefully calibrated against experiments, may become useful tools in the future. Expert systems should be welcomed, but adequate Quality Assurance is essential.

1. Introduction

The present paper relates to the dust explosion hazard in the process industries. Dust explosions in mines is outside the scope of the paper.

The total amount of existing knowledge on industrial dust explosions, their origin, propagation, prevention and mitigation, is vast. And yet, further information is continually being generated through on-going research in a large number of countries. Not long ago the present author had the opportunity to review some of the knowledge accumulated up to about 1990 [1]. About 900 references were covered, but they almost exclusively originate from English/American and German literature. There is little doubt that a lot more interesting and useful information can be retrieved by screening the large amount of research reported in other languages than English and German. Perhaps this could be accomplished by organizing a joint international translation/edition effort.

Predicting the future has never been easy. This also applies to dust explosion research. The present paper is an attempt at systematizing some recently published work, as well as some information about on-going work that was kindly made available to the author, and to indicate some possible future trends. It seems useful to take a dual view. The first focuses on the fundamental aspects, whereas the second considers knowledge related directly to practical prevention and mitigation of explosions in the process industry.

Whenever reference to existing knowledge is made in the present paper without mentioning any specific source, the appropriate references can in most cases be found in the book mentioned above [1].

2. Fundamental and applied dust explosion research. A thematic framework

2.1 Fundamental research

The fundamental aspects of dust explosion research may be grouped under the four main headlines shown in Table 1.

2.2 Applied research and development

The practical aspects of dust explosion research and development may be systematized as shown in Table 2. The fundamental and the applied aspects of dust explosion research, i.e. Tables 1 and 2, are intimately related. This is because fundamental knowledge is essential for proper understanding of the practical aspects. Experience has shown that sometimes development of good practical solutions can be hampered by not drawing upon available fundamental knowledge. In recent years the appreciation of the benefits that can be harvested from cross-fertilization between fundamental and applied research has been increasing.

3. Status and outstanding problems in fundamental research related to dust explosions

3.1 Dust cloud formation processes

The status in this field up to 1989/90 is covered in Chapter 3 of ref. [1]. This is an important and sometimes overlooked aspect of dust explosions. It is well established experimentally that the initial state of a cloud of a given dust in a given gas (dust concentration, degree of dispersion into individual particles, dynamic state) has a strong influence on both the ease with which the dust cloud ignites and the rate at which it burns.

As soon as a significant blast wave has been generated by the primary dust flame, this blast may generate secondary explosible clouds ahead of the flame from dust deposits and layers there. Lebecki et al. [2] investigated such processes in a 100 m long gallery of cross-section 3 m^2. In order to establish an improved understanding of these processes, further experimental and theoretical studies of the influence of blast waves or dust clouds and dust layers/deposits need to be conducted. Work on this problem has also been performed by Ural [3], Gelfand and Tsyganov [4], and others. Gelfand and

TABLE 1

Fundamental aspects of 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*). • Entrainment of particles from dust deposits by turbulent gas flows.	• General ignition theory. Ignition of single particles and clouds. • Ignition by: – Smouldering combustion in dust layers/deposits. – Hot surfaces. – Flying burning metal particles. – Electric discharges. – Hot gas jets. – Shock waves. – Focused light-beam hot spots.	• Single-particle ignition and combustion in a flame front. • Laminar and turbulent flames in dust clouds. Mechanisms of heat transfer (conduction, convection, radiation).	• Blast wave properties as a function of properties of burning dust clouds. • Effects of blast waves on humans and mechanical structures.
• Transport of dust particles in turbulent gas flows.	• Influences of dust cloud properties on ignition sensitivity (composition, size and shape of particles, turbulence, dust concentration, gas phase composition).	• Limit conditions for flame propagation through dust clouds (particle properties, dust concentration, oxygen concentration, geometry).	• Ability of blast waves to transform dust layers into dust clouds.
• Measurement and characterization of state of turbulence of dust clouds.		• Flame acceleration processes in dust clouds. Influence of concentration gradients, and initial and explosion-generated turbulence. • Detonation of dust clouds.	

TABLE 2

Means for preventing and mitigating/controlling dust explosions in the process industries

Prevention		Mitigation/Control
Preventing ignition sources	Preventing explosible dust cloud	
• Self-heating in dust deposits.	• Inerting by inert gas.	• Explosion-pressure-resistant process equipment.
• Open flames.	• Inerting by inert dust.	• Isolation.
• Hot surfaces.	• Keeping dust concentration outside explosible range.	• Partial inerting by inert gas.
• Burning metal particles.		• Explosion venting.
• Electrical discharges.		• Explosion suppression.
		• Preventing secondary explosions (good housekeeping for preventing dust layer formation).

Tsyganov [4] also showed that the presence of dust layers on solid surfaces exposed to blast waves, changed the blast wave characteristics as compared with the characteristics in the case of dust-free surfaces.

Increased emphasis should be put on investigating the connection between the parameters of dust cloud generation processes and the structures of the resulting dust clouds. The structures of the clouds produced must be defined in terms of distribution of dust concentration, quality of dust dispersion (de-agglomeration), turbulence level and global velocities. In order to guide fundamental research in this area in the direction of maximum practical relevance, information about dust cloud structures that are typical in industrial operation is required.

3.2 Dust cloud ignition processes

In the context of accidental dust cloud ignition, the ignition processes indicated in the first column of Table 2 are central. Although much insight has already been gained, many significant problems remain unsolved.

Ignition is a broad field of research. The concept of thermal run-away is a common basis for understanding and describing ignition processes. However, it does not seem realistic for the time being to foresee the development of one single unified theory, usable in practice, which covers all types of ignition sources. It is rather expected that separate theories, in terms of dynamic computer models, will be developed for various categories of ignition sources, such as hot surfaces and electric sparks.

Klemens [5] reported ongoing research on initiation of combustion/smouldering in dust layers by thermal radiation, whereas Hensel and John [6] provided further insight into the important relationship between the conditions required for initiating smouldering combustion of a dust layer on a hot plate, and the layer thickness. An informative overview of the state-of-the-art in this field was given by Crowhurst [7].

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. However, it has been known for some time that minimum ignition temperatures of dust clouds vary significantly with scale, and this has recently been confirmed by Wolanski [8]. Further experimental and theoretical work is needed in this area.

Ignition of dust clouds by small burning metal particles (impact sparks, metal sparks) generated by mechanical impact, is a very complex problem. A comprehensive, practically useful theory does not seem to be within sight.

Ignition of dust clouds by electric/electrostatic discharges is another very complex topic. Theories have been developed for ignition of dust clouds by electric sparks between two metal electrodes, which is the simplest case, but even such theories are only rough approximations.

With respect to the ever more complex one-electrode discharge types (corona, brush, propagating brush), valuable experimental insight has been gained during the last years, but so far no attempt at developing dust cloud ignition theories seems to have been made. Glor [9] gave an informative overview of the present status on theory and experimentation. Some of this work, on possible incendiary discharges from powders poured into a heap, was presented by Glor and Maurer [10]. The question of whether incendiary lightning type discharges can occur in dust clouds is still to be answered. Glor [11] is also continuing his work on whether occurrence of incendiary brush discharges can occur in dust clouds.

Initiation of dust explosions by shock waves has been studied by several workers, and valuable insight has been gained. An informative analysis of shock wave ignition of dust clouds was given by Wolanski [12] and research at University of Michigan, USA is reported by Kauffman et al. [13].

3.3 Flame propagation processes in dust clouds

Some central topics are:

- Ignition and combustion of single particles in a dust cloud
- Laminar flames
- Flame acceleration mechanisms
- Turbulent flames
- Detonation

Understanding the flame propagation processes in dust clouds is the key to understanding how dust explosions develop in terms of pressure as a function of time. A recent review was given by Lee et al. [14].

Both laminar and turbulent combustion in dust clouds have been studied experimentally and theoretically by many workers. Examples of recent research are given in the papers by Seshadri et al. [15] on the structure of laminar dust flames, and by Rzal and Veyssiere [16] on basic aspects of turbulent dust flames. Proust [17] reports on interesting continued work on both laminar and turbulent dust flames in France, and Van Wingerden [18] reports on forthcoming similar basic work in Norway.

Further work is needed on the relationship between the dynamic state of a dust cloud and its combustion rate. The induction time for ignition may be a useful parameter, describing the fundamental, global chemistry. However, Ural [19] emphasized the fact that different induction times are observed with incident and reflected shock waves, due to different ignition mechanisms. An alternative approach is to consider the laminar burning velocity as the fundamental parameter, as suggested by Bradley et al. [20]. Empirical relationships between turbulent burning velocity and turbulence intensity are then established, using the laminar burning velocity as a normalizing parameter. As pointed out by Van Wingerden [18], numerical "flame libraries" can then be formulated and used for closing the loop expansion-flow-turbulence-combustion in numerical dust explosion simulation codes. Understanding flame acceleration due to flame distortion and turbulence produced by the propagating explosion itself is central for understanding both dust and gas explosions. Proust [21] gave an informative review of the state-of-the-art on propagation of dust explosions in pipelines in relation to gas explosion propagation in pipelines. The influence of turbulence on dust explosion propagation was also discussed by Tamanini and Ural [22].

Much work has been, and is currently being done, on turbulent combustion of sprays and mists [23], which may be worth while considering in the present context.

Finally the singular phenomenon of dust cloud detonation should be mentioned. It is now generally accepted that this can occur, but further work is needed in order to establish adequate understanding of the deflagration-to-detonation-transition process (DDT). An excellent review of the state-of-the art and outstanding problems in dust cloud detonation research was given by Kauffman et al. [13].

3.4 Blast waves generated by burning dust clouds

The case of interest in practice is blast waves from explosions in partly confined geometries (e.g. deliberately vented, or bursting process equipment and work rooms). The strength and shape of blast waves from dust explosions depend on the way in which the dust clouds burn. For example, Wirkner-Bott et al. [24] conducted a fairly detailed study of the nature of the "secondary explosion", i.e. the explosion of unburnt dust cloud outside the vent opening. Central variables influencing blast wave generation, in addition to type of dust cloud and geometry of system, comprise the dynamic state of the dust cloud at the moment of ignition, ignition point in relation to vent, the vent size, and the vent cover opening pressure. Wingerden [25] gave an informative overview of pressure and flame effects in the direct surroundings of installations protected by dust explosion venting.

Some basic studies of shock wave emission from burning dust clouds were performed by Gelfand et al. [26]. More work, experimental as well as theoretical, is needed in this area. A useful condensed introduction to the complex field of properties and effects of blast waves from explosions was given by Harmanny [27]. The effect of a given blast wave on humans, buildings and process equipment is an other important area where more research is needed. Valuable reviews are given by Mercx [28] and L'Abbé [29].

4. Status and outstanding problems in preventing and mitigating/controlling dust explosions in practice

4.1 Generation and states of industrial dust clouds

Little quantitative knowledge of practical value has been generated. It is known, however, that the dynamic state of a dust cloud dramatically influences both its ignition sensitivity and its combustion rate. Experimental investigation of typical industrial processes of dust cloud generation, and the resulting states of the clouds, in various types of process equipment and modes of operation, should be encouraged.

4.2 Preventing ignition sources

See the first column of Table 2. A considerable amount of fundamental knowledge is available, as discussed in Section 3.2. Time is ripe for accepting that the concept of ignition comprises a range of very complex processes. Simple parameters such as a minimum ignition energy or temperature are not true constants for a given dust, but vary significantly with the geometry and other properties of the ignition source, as well as with the state of the dust cloud. In the future this must be accounted for in practice.

Kleinschmidt [30] reported that the GreCon system for extinction of "sparks" in terms of flying burning metal particles or organic material, is being developed further with respect to optimizing system performance.

4.3 Preventing explosible dust clouds

Reference is made to the second column of Table 2. Inerting of dust clouds by adding inert gas such as nitrogen or carbon dioxide, implies that the volume percentage of oxygen in the atmosphere is reduced to a level at which the dust cloud no longer can propagate a selfsustained flame. A fair amount of data for maximum permissible oxygen content in the atmosphere for inerting exists. However, there is room for improving the test methods by which such data are obtained. Furthermore, most data are for atmospheric pressure and normal temperature. Data for other conditions, in particular for elevated temperatures and pressures, are sometimes required, and adequate test methods should be developed. Glor [11] reported work on the determination of maximum permissible O_2-contents for inerting clouds of coal dusts at elevated temperatures and pressures.

Whilst reducing the oxygen content in the atmosphere prevents dust explosions, it can introduce a suffocation hazard. However, recent research has shown that adding a few vol.% CO_2 to the gas mixture reduces the critical oxygen threshold for suffocation considerably. An inert gas mixture (INERGEN) utilizing this effect is now being marketed by Dansk Fire Eater A/S [31]. Further work to identify gas mixtures that keep the dust cloud inert without presenting a suffocation hazard, should be welcomed.

Inerting by adding non-combustible dust is not generally applicable, because the inert dust will in most cases cause unacceptable contamination. However, there are cases where the dust/powder processed is already a mixture of combustible and non-combustible dusts, and where control of the composition ensures that dust clouds are non-flammable. It is then essential to avoid segregation of combustible and non-combustible components, throughout the process.

Keeping the dust concentration below the minimum explosible concentration is a third means of maintaining dust clouds non-explosible. There are, however, at least two problem areas requiring further research and development. First, more work is needed to establish test procedures for the determination of the minimum explosible concentration that is relevant in industrial situations. Secondly, more research is needed to establish the minimum mass of dust deposit per unit of surface area that is required for maintaining a self-sustained explosive combustion along the surface. A thin dust layer on a floor may be dispersed into a shallow, dense dust cloud close to the floor, through which the flame can sweep. The conditions required for producing this kind of self-sustained shallow sweeping flames need to be investigated further.

4.4 Mitigating and controlling measures

Attention is drawn to the third column of Table 2. The use of *explosion-pressure-resistant process equipment* is limited because of high equipment costs. Current experimental methods allow sufficiently accurate prediction of maximum explosion pressures in simple vessels with point source ignition. However, if complex dynamic pressure development, e.g. with pressure piling, is to be expected, such test data are of limited value. There is also room for further improvement in the design of the process equipment itself, with respect to minimizing its heaviness. The German concept of pressure-shock-resistant design should be further developed. Crowhurst [32] gave a useful overview of the state-of-the-art on design of process equipment to withstand a given overpressure caused by a fully confined or vented explosion.

The objective of *explosion isolation* is to prevent dust explosions from spreading from the primary explosion location to other process units, workrooms etc. Various passive and active techniques have been developed and are being used, but there is room for further improvement. If adequate performance can be achieved, passive techniques are clearly more attractive than active ones. Basic understanding of flame propagation and pressure build-up in coupled geometries ("interconnected vessels") is important for the prediction of the performance of various active and passive isolation equipment. Valuable large-scale experimental work in this area was reported by Lunn [33]. Zellweger [34] reports on further improvement of passive and active isolation valves of the VENTEX type. Closing times (from sensing of the explosion to valve is closed) down to 12 ms are now being obtained for active valves. A simplified VENTEX valve, operating in one direction only, has also been developed. Passive explosion interrupters based on venting at a bend have been in use for some time. However, there is room for further exploration of the potential of this attractive, simple principle of explosion isolation. A new development was described by Alfert and Fuhre [35]. Glor [11] reports on ongoing work on performance of explosion barriers in ducting connecting to vessels with venting or automatic explosion suppression.

Partial inerting by inert gas is a means for mitigating dust explosions, which deserves further attention. The idea is that as the oxygen content in the atmosphere is decreased, there is a gradual decrease of both ignition sensitivity and combustion rate of the dust cloud. In some cases the explosion hazard may be reduced substantially by only a moderate reduction of the oxygen content in the gas. However, more research seems necessary in this area to establish correlations between the oxygen content in the gas and various ignitability and combustion parameters.

Explosion venting remains a complex and in part controversial subject. Adequate understanding of flame propagation processes in dust clouds is essential for the design of optimal venting arrangements in practice. Useful reviews of various aspects of dust explosion venting in practice were given by Scholl [36] and Lunn [37]. The basic understanding of flame propagation processes inside and outside vented enclosures is still unsatisfactory. This implies that neither the processes by which dust clouds of given structures are generated, nor the way in which clouds of given initial structures burn, are well understood. Consequently, adequate venting theories do not exist, and one must rely on experiments. During the last few years the need for differentiating vent area requirements in view of the different turbulence levels, degrees of dust dispersion and concentration distributions of dust clouds, which occur in practice, has become widely accepted.

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 at elevated initial dust cloud pressure were reported by Siwek et al. [38]. The effect of pressure piling and turbulent flame jet ignition on vent area requirements in systems of interconnected vessels, were studied by Lunn [33].

The influence of vent ducts on the maximum explosion pressure in the vented vessel has been studied experimentally by several workers. Recently, however, Ural [39] presented a theoretical model for vented gas explosions by which he has been able to predict pressure-versus-time characteristics in the vented vessel that agrees well with corresponding experimental data. It would be interesting to see whether a similar theory could reproduce existing data for dust explosion venting via ducts.

The prediction of pressure and flame effects in the direct surroundings of installations protected by dust explosion venting was discussed by Van Wingerden [25].

Dust explosion venting remains an area in which considerably more work is required. An extensive review of existing knowledge is given by Lunn [40], whereas the German Verein deutscher Ingenieure [41] issued a new draft version of their venting guideline VDI 3673.

Automatic explosion suppression, being an active, comparatively sophisticated method of dust explosion mitigation/control, is used when simpler and less expensive methods cannot be applied. Recently Moore [42] reported that the number of suppressant bottles of a given size required for suppressing explosions of a given dust in a given vessel, was reduced by a factor of 0.2–0.3 when the dust clouds were generated by industrial pneumatic injection, rather than by the traditional VDI method used in previous experiments.

Siwek [43] described experiments where a *combination of explosion venting and automatic suppression* was adopted for mitigating/controlling dust explosions in various enclosures. Although automatic suppression has been in use for many years, there is still a need for research and development. Glor [11] and Moore [44] reported on current work on the possibility of applying this method even in the case of highly explosible organic dusts of $K_{St} > 300$ bar m/s. In the case of aluminium powders, satisfactory suppression has not yet been achieved for powders of $K_{St} > 200$ bar m/s, which means that only dust explosions in clouds of relatively coarse aluminium powders can be suppressed. The influence of the dynamic state of the dust cloud at the moment of suppressant injection, the influence of the suppressant injection on this state, and development of improved suppressants, are some of the areas where further work seems useful. Recent experiments have indicated that water can be effective as a suppressant, if injected at a temperature >180 °C.

5. Status and outstanding problems in testing of dust ignitability and explosibility

5.1 Historical background

When some of the older test methods were designed, the ambition was in fact quite modest. The original intention was just to establish some relative measures of properties of practical relevance to preventing and controlling/mitigating dust. Later some of these methods were adopted as official standards, and test data were sometimes treated as basic physical constants for a given dust to an extent far beyond the original purpose of the test. As more knowledge from systematic research became available, the lack of justification for this use of these test data was pointed out, and the arbitrary, relative nature of the various test methods was brought to light again.

The situation today is complex. It is realized that only a few of the dust parameters that are currently being used for characterizing ignition sensitivity and explosibility of dusts, can be regarded even as approximate "physical constants" for a given dust. In most cases a great number of variables are involved and a differentiated view is required. Typical examples are the minimum ignition energy and the explosion violence of dust clouds.

5.2 Limits of flame propagation — A special problem of scale

Determining limits of flame propagation constitutes an important test objective. However, special care must be exercised in designing flame-propagation-limit tests. The basic problem is that near the limits self-sustained flame propagation cannot be established unless a considerable amount of energy is supplied for initiating flame propagation. Hence, if the volume of the experimental dust cloud is too small, it is difficult to assess whether observed flame propagation is truly independent of the ignition source. Some recent results by Cashdollar and Chatrathi [45] are of fundamental significance in this context. They found that clouds in air at normal ambient conditions of an anthracite coal dust of 8% volatile matter, did not show self-sustained flame propagation in a 1 m^3 test chamber, even when being exposed to a 30 kJ chemical igniter. However, in a 20 litre chamber, fully developed explosions were generated even with a 5 kJ chemical igniter. The reason for this could be that in the small chamber, due to the initial combustion and expansion of the dust cloud directly affected by the ignition source, the pressure and temperature in the unburnt cloud ahead of the flame increase significantly before flame propagation does no longer receive support from the ignition source. Consequently the self-sustained flame propagation, if any, occurs in adiabatically pre-compressed dust cloud, rather than in a cloud of normal ambient temperature and pressure.

The results of Cashdollar and Chatrathi suggest that great care must be exercised whenever comparatively small chambers, in particular closed ones, are used for any explosion limit determination (explosible/non-explosible assessment, minimum explosible dust concentration, maximum permissible oxygen concentration for inerting).

6. Computer models and expert systems

During the last years there has been an increasing interest in developing sophisticated mathematical models and expert systems for evaluation of dust explosion hazards and assessment of optimal safety design features.

This development is a natural consequence of two main factors. The first is the almost explosive development of the performance of personal computers. The second is the steadily increasing knowledge about ignition and explosion phenomena, which demands a steadily more differentiated and complex approach for solving practical design problems.

As long as this development is conducted by people who are not only experts on computers, but also on the physics and chemistry of the phenomena treated, models and expert systems should indeed be welcomed. However, there may be a possibility of the future market place being offered software that is not up to acceptable standards with respect to the physics and chemistry. As long as the interior of the code is unknown, deficiencies in the basics may not be obvious to the user.

A time may come where it could be useful and necessary to introduce the concept of *Quality Assurance* even in this context. A need may emerge for establishment of some internationally recognized body of experts that can ensure that the software offered is up to acceptable standards. Software having passed the investigation of this body could receive a certificate of approval.

7. Joint research efforts in Europe

Over the last years a steadily growing potential for organizing joint European research efforts has emerged within the EEC/EFTA/EUREKA system. This also applies to dust explosion research.

British Materials Handling Board (BMHB) in UK has played a central role in this process [46]. A number of research programmes have been started. Gibson [47] reviewed the BMHB dust explosion research projects existing by the date of his report, and some of the work on this topic being conducted or planned in Europe and USA on the whole. He summarized the areas requiring further work under the headlines:

- Combustion processes in dust clouds (experiments, theoretical models)
- Identification and control of ignition sources
- Design of methods to prevent/protect against dust explosions

These three headlines covers most of the research needs identified in the present review, apart from mechanisms of generation of the dust cloud, which are important because they set the stage for subsequent ignition and combustion.

8. Conclusion

Initiation and propagation of industrial dust explosions are, from a fundamental scientific point of view, extremely complex phenomena. Comprehensive theories for predicting ignition and combustion of dust clouds in industrial environments from fundamental physical and chemical knowledge, are so far beyond reach.

It is not surprising, therefore, that existing knowledge is to a large extent fragmented. Nevertheless the hope is that more and more fragments will, step by step, become tied together, and steadily increasing domains of coherence emerge. Powerful computers are invaluable tools in this process. However, experiments will remain indispensable for calibration of the mathematical models, because such models will remain approximate and require tuning in the foreseeable future.

It is necessary to continue the execusion of realistic industrial-scale experiments, at the same time as the more basic research and mathematical modelling should continue at full pace.

The current efforts to establish international co-operation in joint research programmes should be encouraged.

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