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Dust Explosion Quantitative Risk Management for Nontraditional Dusts

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The current paper describes an approach for dust explosion quantitative risk management of the following nontraditional particulate fuel systems: (i) nanomaterials having particles with dimensions between 1 and 100 nm, (ii) flocculent (fibrous) materials characterized by a length-to-diameter ratio rather than a particle diameter, and (iii) hybrid mixtures consisting of a combustible dust and a flammable gas (or a combustible dust wetted with a flammable solvent). Experimental results are considered as input to a quantitative risk management framework so as to provide a comprehensive procedure to analyze, assess and control the likelihood and consequences of explosions of nontraditional dusts. Using concepts drawn from previous studies, the framework consists of three main components: (i) a new combined safety management protocol, (ii) use of the CFD (computational fluid dynamics) software DESC (Dust Explosion Simulation Code) and FTA (Fault Tree Analysis) to determine explosion consequences and likelihood, respectively, and (iii) application of the hierarchy of controls (inherent, engineered and procedural safety) to achieve residual risk reduction.

1. Introduction

Dust explosion risk reduction has been the subject of intensive research for several decades. There remains, however, a strong need for continued research on dust explosions – especially for dusts that may be termed nontraditional when compared with the more common and often-tested micron-size, spherical particles comprising a single-fuel powder (Worsfold et al., 2012). The specific fuel/air systems studied here fall in three nontraditional categories as follows: (i) micron- and nano-size titanium powders, (ii) flocculent polyamide 6.6 and polyester, and (iii) hybrid mixtures of lactose and microcrystalline cellulose dusts admixed with methanol, ethanol and isopropanol solvents. Relevant industrial applications are the handling of metallic nano-powders, fabric and textile processing, and pharmaceutical manufacturing, respectively.
A generalized Quantitative Risk Management Framework (QRMF) for dust explosions has been modified in the current work to integrate the above three nontraditional categories of dust explosions. The modifications were developed through a synthesis of experimental findings and a comprehensive literature review. Use of the QRMF for the three nontraditional fuel/air systems is proceeding in parallel, with each system being considered from the key perspectives of hazard characterization, risk (consequence and likelihood) assessment, and residual risk control (along with other aspects of the quantitative risk management sequence). Here we present a summary of hazard characterization findings and residual risk control measures for the nanomaterials, flocculent materials and hybrid mixtures being studied, along with a representative look at consequence assessment for flocculent materials and likelihood assessment for nanomaterials.

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2. Quantitative risk management

2.1 Fundamentals and framework

Quantitative Risk Management (QRM) has gained extensive recognition as a powerful tool to identify and assess significant sources of risk and measure the effectiveness of different risk controls. Shell (1995) views this technique as a systematic approach to identify hazards and potentially hazardous events, and to estimate the likelihood and consequences of hazards to people, property, process and the environment. The generalized framework shown in Figure 1 (Abuswer et al., 2012) has been adapted to the three aforementioned nontraditional categories of particulate fuel/air systems (with modifications especially in the stages of risk assessment and consideration of risk control measures).

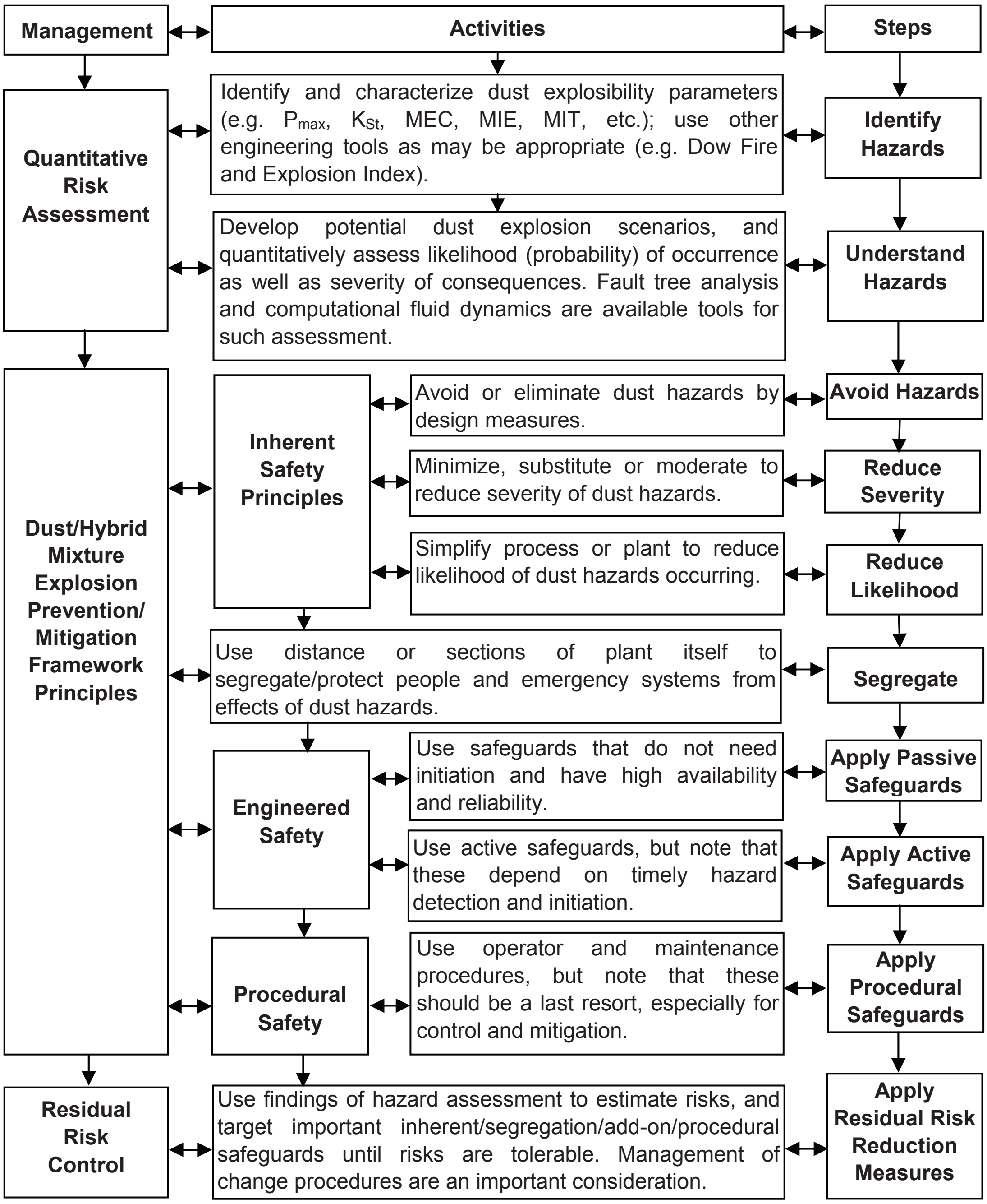

Figure 1: Generalized risk management framework for dust explosions

2.2 Hazard characterization

Hazard characterization has been undertaken as a first step to identify and evaluate the nature, magnitude and probability of risks associated with the nontraditional dusts and their anticipated application in handling, weighing, blending, spraying, machining, sanding, drilling, cleaning, etc. Various explosibility parameters, including maximum explosion pressure (P_{max}), size-normalized maximum rate of pressure rise (K_{St}), minimum explosible concentration (MEC), minimum ignition energy (MIE), and minimum ignition temperature (MIT), have been determined using standardized equipment and standardized test methods. The first two of these parameters (P_{max} and K_{St}) are related to explosion severity while the latter three (MEC, MIE and MIT) provide information on explosion likelihood.

2.2.1 Nanomaterials

A large specific surface area, the possibility of particle agglomeration, and enhanced surface reactivity are some distinct properties of nanomaterials that need to be considered in hazard characterization. It is well-known for micron-size dusts that as particle size decreases, both explosion severity and explosion likelihood increase; the situation is not as straightforward for nanomaterials. In the titanium explosibility tests conducted here (Boilard et al., 2012), it was determined that micron-size explosion severity could not be directly compared with that for nano-titanium due to pre-ignition of the nano-dust in the explosion chamber (i.e., with no external ignition source present). The likelihood of explosion occurrence was observed to increase significantly with a particle size decrease from the micron- to the nano- range as evidenced during MIE and MIT testing (Boilard et al., 2012). Potential exposure of workers and the environment, and potential release during production, handling and processing of nanomaterials, must therefore be emphasized in conducting risk studies. Pre- or self-ignition and lack of explosion inerting are experimental findings that must be accounted for in hazard/risk characterization of titanium nano-dust explosions.

2.2.2 Flocculent materials

Flocculent materials (or flock) are non-spherical and cannot be easily characterized by a singular measure such as particle diameter; these materials are better described in terms of their length-to-diameter ratio (Worsfold et al., 2012). Explosibility testing in the current work (Iarossi et al., 2012) demonstrated that fine flock (smaller dtex and shorter length) generally yield higher explosion pressures and rates of pressure rise, and are more easily ignitable by electric spark, than larger flock sizes. The parameter dtex or decitex is a unit of measure for the linear density of fibers. It is equivalent to the mass in g per 10,000 m of a single filament, and can be converted to a particle diameter. The relevance here is that industrial flocking processes often involve size reduction and further manipulation as well as the presence of energetic ignition sources.

2.2.3 Hybrid mixtures

The effects of flammable solvent admixture to a combustible dust (thus forming a hybrid mixture) depend on several factors, including the burning velocity of the solvent and the proximity of the solvent concentration to its lower flammability limit (Amyotte et al., 2010). In the current work (Amyotte et al., 2012), pre-wetting of microcrystalline cellulose (MCC) and lactose with solvent (methanol, ethanol and isopropanol) had a measurable effect on each explosibility parameter (P_{max}, K_{St}, MEC, MIE and MIT). The influence was generally an enhancement of the particular parameter (e.g., increase in K_{St}, decrease in MIE, etc.) as anticipated; the only exception was P_{max} for MCC which displayed a slight decrease with solvent admixture. Additionally, while the effect of solvent admixture to MCC was generally distinguishable for the different solvents, that was not the case for lactose. Pre-wetting of lactose with each of the three solvents resulted in similar values of P_{max}, K_{St} and MIE. Enhanced ease of ignition and severity of consequences therefore occur with solvent admixture to a given fuel dust. In the case of hybrid mixtures, explosion prevention and mitigation measures based on the dust component alone are inadequate.

2.3 Risk assessment

2.3.1 Severity of consequences

One of the available methodologies to evaluate the severity of different dust explosion scenarios is computational fluid dynamics (CFD); the most comprehensive software currently available for simulating dust explosions is DESC – Dust Explosion Simulation Code (Skjold, 2007). DESC requires physical and thermodynamic properties along with standardized (20-L) explosion test results as input data to the combustion model. At the time of writing, computational work with DESC has been initiated using the above-referenced flocculent experimental data (Iarossi et al., 2012) for polyamide 6.6 and polyester (both, dtex 1.7 and length 0.5 mm) with central ignition and a dust concentration of 500 g/m^3. The 20-L simulation results for polyamide 6.6 and polyester dust (Figures 2(a) and 2 (c), respectively) were in good agreement with the corresponding experimental results (as expected). As shown in Figures 2(b) and 2(d), the peak overpressure in a 1-m^3 chamber is similar to the 20-L case for each fuel dust, but with a longer time to attainment of P_{max}. Polyester (Figures 2(c) and 2 (d)) is seen to take less time to reach its maximum pressure than polyamide 6.6 (Figures 2(a) and 2(b)) because of the higher experimental rate of pressure rise for polyester (Iarossi et al., 2012). Work is ongoing to extend the flocculent material simulations to industrial-scale geometries, and to investigate the applicability of DESC to other nontraditional particulate fuel/air systems.

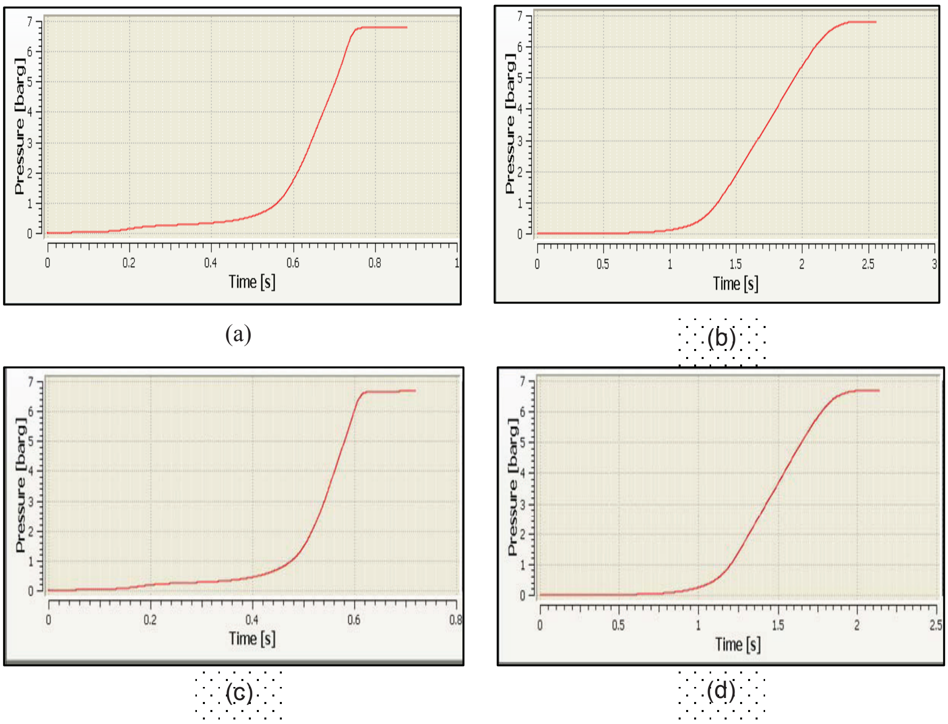

Figure 2: DESC simulation of polyamide 6.6 (dtex 1.7 and length 0.5 mm) explosions in (a) a 20-L spherical chamber and (b) a 1-m^3 spherical chamber; similarly for polyester (dtex 1.7 and length 0.5 mm) explosions in (c) a 20-L spherical chamber and (d) a 1-m^3 spherical chamber

2.3.2 Likelihood of occurrence

Fault tree analysis (FTA) is being employed to quantify the likelihood of occurrence of nontraditional dust explosions. Relex (Reliability Excellence) software has been used as the FTA tool to determine the occurrence of probable events by means of a series of logic gates. In Figure 3, an example is given of a qualitative fault-tree diagram for explosion of a nano-dust (e.g., titanium), which has been established by modifying the generalized dust explosion fault tree developed by Abuswer et al. (2012). Key features of Figure 3 include the possibilities of self-ignition, particle agglomeration and inerting inadequacies. Ongoing work includes further development of the fault-tree logic for nanomaterials, as well as modifications to the generalized dust explosion fault tree (Abuswer et al., 2012) to accommodate flocculent materials and hybrid mixtures.

2.4 Residual risk control

Within the concept of the hierarchy of risk controls (or safety measures), inherent safety is the most effective means of risk reduction and therefore sits at the top of the hierarchy – followed in order of decreasing effectiveness by passive engineered safety, active engineered safety, and finally procedural safety (Amyotte et al., 2011). In this section, illustrative examples of control measures are given for the prevention and mitigation of explosions of nontraditional dusts. A goal currently being pursued is preparation of a comprehensive, hierarchy-based compilation of such measures for nanomaterials, flocculent materials and hybrid mixtures drawing on findings from experimentation and modeling simulations as well as the process safety literature.

2.4.1 Nanomaterials

Coating of particles with a less hazardous substance is a possible approach to manage the risk of a given nanomaterial (Williams et al., 2010); this is an example of inherent safety. Surface modification, change-of-form and other approaches to alter the physical state of nanoparticles could also be acceptable safety measures in nano-risk reduction. Control of hazards at their source with containment is a possible engineering safety measure for nano-dust explosions (Williams et al., 2010). Isolation of workers, local ventilation, specially designed dust collectors, and process changes are some other engineering/ procedural controls to manage the risk of dust explosions associated with nanoparticles. Inerting with admixed solids could be applied to avoid pre-ignition and associated risks. Moreover, discharge control measures, special organizational measures, and personal protective equipment designed for nano-dusts are further important safety measures for nanomaterials.

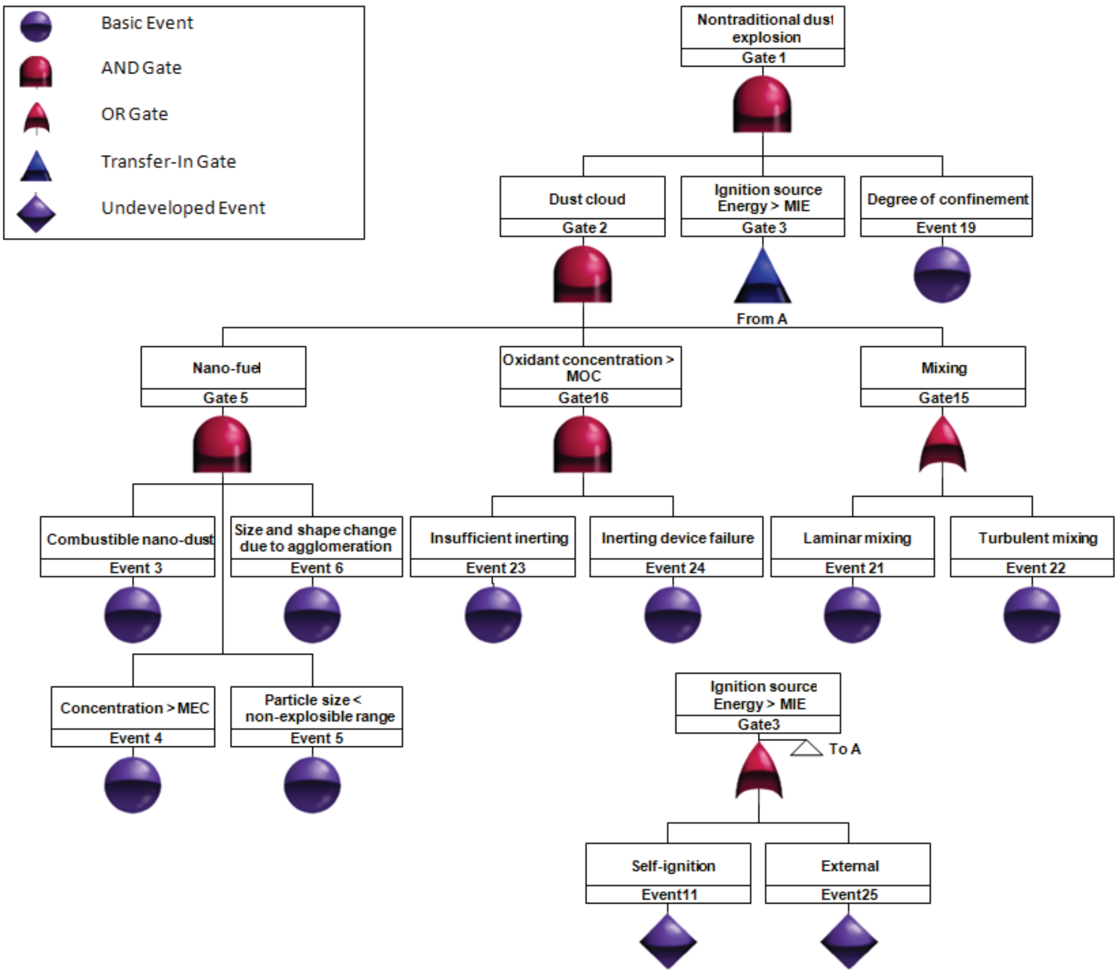

Figure 3: FTA diagram for nano-dust explosions

2.4.2 Flocculent materials

Fine flocculent materials are more hazardous and easily ignitable than larger ones. Thus, length and diameter optimization are required to control the associated risks. Another safety measure is to modify the flocking process and use a flameless venting technique as indicated by von Pidoll (2002). As flocculent materials are often manufactured using an electrostatic flocking process, the hazard of ignition from a high voltage discharge and subsequent explosion must not be ignored. Appropriate electrical equipment should be used in locations that are hazardous because of the presence of easily ignitable fibrous materials. Good housekeeping of flock in facilities that produce them is essential to avoid dust explosions.

2.4.3 Hybrid mixtures

Utilizing every precaution during and after the transfer of powders into flammable solvents is very much needed to provide a safer process for transferring powder regardless of the characteristics of the powder and solvents. Substituting a less hazardous solvent (an application of inherent safety principles) can reduce the risk in a workplace that handles combustible dusts and flammable solvents. For example, our recent experiments have demonstrated that ethanol and isopropanol may provide a safer environment than methanol as a pre-wetting medium for MCC (microcrystalline cellulose) on the basis of both likelihood of occurrence and severity of consequences (Amyotte et al., 2013). Engineering controls can also be helpful to mitigate risks associated with hybrid mixtures. These measures include installation of local ventilation hoods, enclosures around work processes (e.g., fume hoods, glove boxes, and other safety cabinets), and using closed systems to transfer solvents from storage containers to process vessels during mixing.

3. Conclusion

The concepts of a modified risk management framework presented in this paper have been established to assess and manage the risks of nontraditional dust explosions in relevant industrial applications involving metallic nano-powders, flocculent textile materials, and pharmaceutical base powders and solvents. Quantitative analysis of explosion likelihood and consequences, as well as implementation of the hierarchy of safety controls, can provide guidance and establish measures to prevent and mitigate nontraditional dust explosions. Appropriate case studies as well as validation of the abovementioned comprehensive framework have been planned for further analysis of various aspects of nontraditional dust explosions.

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