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Dust Explosions in the Process Industries:Research in the Twenty-first Century

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Accidental dust explosions pose a threat to personnel and property in industries that produce, process, handle or transport combustible dusts. Over the last decade, the international research community has made significant progress towards improved understanding of the dust explosion phenomenon. This has resulted in improved standards and best practice guidelines for safe operation, as well as increased awareness of the inherent limitations in test procedures and methods for extrapolating results from laboratory experiments to industrial scales. Of particular importance is the development in the field of numerical modelling of dust explosions, and the accompanying need for reliable validation data from large-scale experiments. The purpose of the paper is to review the development and trends in dust explosion research in the twenty-first century, with particular emphasis on numerical modelling of flame propagation in dust clouds and the application of advanced models for risk assessment and risk management in the process industries.

1. Introduction

Dust explosions entail rapid flame propagation through clouds of combustible dust particles, or ‘premixed combustion with non-premixed substructures’ (Williams, 1986). The fuel can be any finely divided solid material, capable of reacting rapidly and exothermically with a gaseous oxidizer (usually air). The characteristic size of the fuel particle sizes is typically in the range 1-100 micrometres. The explosion pentagon extends the classical fire triangle to fuel-air explosions, including dust explosions: dust explosions pose a hazard whenever combustible solid material is present in the form of fine powder, there is a possibility of dispersing a sufficient mass of the material in air to form an explosive dust cloud within a relatively confined and/or congested volume, and there is an ignition source present. The mechanism behind the flame acceleration process in dust explosions is essentially the same as for gas explosions: expansion of combustion products introduces flow, which generates turbulence – enhanced heat and mass transfer in the turbulent flow results in higher rate of combustion, which creates more expansion, which creates more turbulence, etc. Dust explosions may escalate through the mechanisms of dust lifting ahead of the flame front and pressure piling in complex confined geometries. The material presented here is an extract from an extensive literature study performed in connection with the preparation of the fourth edition of the book 'Dust Explosions in the Process Industries' (Eckhoff, 2003). Since other aspects of the dust explosion hazard have been reviewed elsewhere (Eckhoff, 2005; Eckhoff, 2009; Eckhoff, 2012), the primary focus here will be on experimental and numerical investigations of flame propagation in dust clouds for the purpose of estimating the consequences of accidental dust explosions in the process industries.

2. Case histories

Dust explosions continue to cause severe losses in the process industries, and detailed reports from accident investigations represents a valuable source of information for safety engineers. The U.S. Chemical Safety and Hazard Investigation Board (CSB) has published detailed reports on several accidents, including three fatal dust explosions that all occurred in 2003 (Blair, 2007) and the disaster at the Imperial Sugar manufacturing facility in Georgia where 14 worker lost their lives (Vorderbrueggen, 2011). The 'Robert W. Schoeff Agricultural Dust Explosions Research Collection' at Kansas State University (KSU, 2015) represents a

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valuable source of information for agricultural dust explosions in the US. Yan & Yu (2012) summarized case histories from dust explosions during the past 30 years in China, and Zheng et al. (2009) analyzed 106 dust explosion accidents in Chinese coal mines during the period 1949-2007.

3. Dust clouds

A dust cloud is a mechanical suspension, i.e. a system of fine particles dispersed by agitation, and not by the molecular motion in the surrounding medium (colloidal suspension). For most systems encountered in practice, this implies that the flow is inherently turbulent. Furthermore, the dynamics of the turbulent structures create local concentration gradients. Most dust samples have a relatively wide particle size distribution, and particles of different size react differently to variations in the flow field. Results from both laboratory- and large-scale experiments suggest that the dispersibility of the dust has significant influence on the explosion hazard (Siwek et al., 2004; van Wingerden et al. 2009; Klippel et al., 2013ab; Eckhoff, 2015). Knowledge about the actual dust concentration in silos or other process vessels during filling is important for risk assessments (Wypych et al., 2005; Klippel et al., 2014; Rani et al., 2015). Flame propagation fueled by dust lifting from layers represents a particular hazard in industry. Several researchers have investigated this phenomenon, both experimentally (Klemens et al., 2006; Chowdhury et al., 2015) and numerically (Zydak & Klemens, 2007; Houim & Oran, 2015ab). Taveau (2012) reviewed the hazard associated with secondary dust explosions.

4. Flame propagation

4.1 Detailed experimental studies

The combustion mechanism for individual particles represents a convenient way of classifying dust flames (Rockwell & Rangwala, 2013). For materials such as carbon and refractory metals, combustion entails strictly heterogeneous reactions on the surface of the particles, so-called Nusselt flames (Goroshin et al., 1996; Goroshin et al. 2011; Tang et al. 2009, 2011). However, most organic materials produce vapour prior to gas-phase combustion, or so-called volatile flames. The structure of volatile flames varies significantly, depending on processes such as pyrolysis, evaporation, heat and mass transfer, chemical reactions, etc. (Dobashi et al., 2006; Gao et al., 2012, 2015). For most organic solid materials, external heating of the fuel particles results in thermal degradation and liberation of volatiles through pyrolysis – the volatiles then burn in the surrounding atmosphere. This implies that the chemical species actually taking part in the combustion reactions may differ significantly from the overall composition of the fuel. Most combustible dust clouds encountered in industry are not monodisperse, and the particle size distribution has significant effect on the explosion violence (Castellanos et al., 2014). Constant pressure experiments in balloons may reveal new insights on combustion mechanisms in dust clouds (Skjold et al. 2013; Julien et al., 2014).

4.2 Large-scale experiments

Health and Safety Laboratory (HSL) conducted a series of dust explosions tests in a vented connected vessel system (Holbrow, 2004, 2005). The experimental program included 34 tests, with four types of dust, particularly designed for validating the computational fluid dynamics (CFD) tool DESC. The results varied significantly between repeated tests, and only test no. 13 with coal dust produced significant pressure enhancement in the secondary vessel. This represents a challenge for model validation (Skjold, 2010). Other large-scale dust explosions experiments in relatively complex geometries that may be useful for model validation include tests in bucket elevators (Holbrow et al., 2002; Roser et al., 2011), pneumatic transport systems (Vogl & Radant, 2005), and a full-scale roller mill (van Wingerden et al., 2011). Skjold et al. (2014) demonstrated the strong effect of repeated obstacles on flame acceleration in dust clouds in a 3.6-litre flame acceleration tube.

4.3 Numerical modelling

Dust Explosion Simulation Code (DESC) was a project supported by the European Commission (Skjold, 2007). The main purpose of the project was to develop a simulation tool based on computational fluid dynamics (CFD) that could predict the consequences of industrial dust explosions in complex geometries. Skjold et al. (2005, 2006) presented simulation results obtained with DESC for large-scale dust explosion experiments in silos. Skjold (2010) revisited the HSL experiments in the vented connected vessel system (Holbrow, 2004; Holbrow, 2005), and demonstrated that the results are highly sensitive to modest variations in the initial conditions. This suggests that the use of advanced modelling tools for consequence assessments should include sensitivity analysis for variables such as vent and ignition position. Tascón et al. (2011, 2015) simulated vented dust explosions with DESC and obtained good agreement with current standards for explosion venting. Castellanos et al. (2013) investigated the effect of vent ducts on vented dust explosions with DESC. Other researchers have used other CFD tools (e.g. Wawrzyniak et al., 2012; Polanczyk et al., 2013).

5. Test methods

Dust samples with a given overall chemical composition may differ widely in particle size, particle shape, and particle surface reactivity. The strong effect of material properties on the reactivity of dust clouds implies that safety parameters, such as the maximum constant volume explosion pressure and maximum rate of pressure rise must be determined through testing of representative samples in standardized equipment (Beck, 2001). From a modelling point of view, this introduces a significant complication relative to gaseous fuels. Dahoe et al. (2001abc) investigated the transient flow conditions in the 20-litre test vessel, and Dahoe et al. (2013) presented an elaborate technique for extracting combustion parameters from pressure-time histories measured in constant volume explosion vessels. Proust et al. (2007) presented results that show significant differences between the values for the size-corrected maximum rate of pressure rise values obtained in the 20-litre sphere and a 1-cubic metre vessel. Kalejaiye et al. (2010) demonstrated that the dispersion process in the standard 20-litre vessel has significant effect on the particle size distribution in the dispersed dust cloud.

6. Risk management

Risk management refers to a coordinated set of activities and methods used to direct an organization and to control the risks that can affect its ability to achieve its objectives (Aven & Vinnem, 2007). Management of operational risk should take into account previous events and near misses, safety barriers, modifications and ageing of installations, technological developments, the likelihood of natural disasters, safety training and risk awareness, etc. The purpose of risk analysis and risk assessment is to systemize knowledge and uncertainties about phenomena, processes and activities in a system, to describe and discuss the results of the analysis in order to provide a basis for evaluating what is tolerable and acceptable, and to compare different design options and risk reducing measures. Quantitative risk assessment (QRA) has proven particularly valuable for detecting deficiencies and improving safety performance in complex technical systems. However, a qualitative approach may suffice for simpler systems. There are inherent uncertainties associated with most risk assessments: the hazard identification process is rarely complete, there may be insufficient data to support precise estimates of the event frequencies, and there can be significant uncertainty associated with the estimates for the consequences of hazardous events. The main uncertainties associated with the consequences of flow-related accident scenarios, including dust explosions, relate to scaling and complexity. The solution to a given flow problem depends on the initial and boundary conditions, e.g. the initial flow field and the geometry. This poses inherent limitations to the applicability of empirical correlations for non-trivial systems. Several researchers have presented methods and frameworks for risk assessment and risk management related to industrial facilities where dust explosions represent a hazard (van der Voort et al., 2007; Weirick & Manjunath, 2009; Davis et al., 2011; Abuswer et al., 2013ab; Yuan et al., 2013, 2015ab; Hassan et al., 2014). Inherent safety is a proactive approach for risk management during process plant design and operation (Amyotte & Khan, 2002; Amyotte et al. 2003ab, 2007, 2008, 2009).

7. Conclusions

Flame propagation and pressure loads during industrial dust explosions are extremely complex phenomena, and comprehensive numerical models for predicting the consequences of dust explosions from fundamental physical and chemical principles in general are, at present, beyond reach. To this end, it is not surprising that the existing knowledge on phenomena related to flame propagation in dust clouds is somewhat fragmented. There is nevertheless steady progress in the field, and the results obtained with CFD-based engineering models during the last decade demonstrate the potential for practical applications to engineering design. It is foreseen that further development of numerical methods will result in improved representation of particle-laden flows and multiphase combustion. However, there will always be significant uncertainty associated with the initial and boundary conditions used for the simulations, so best practice will most likely entail the use of relatively conservative assumptions regarding the system.

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