Process Safety and Environmental Protection 100 (2016) 108–116

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.elsevier.com/locate/psep

Domino effect analysis of dust explosions using Bayesian networks

Zhi Yuan[a], *Nima Khakzad*[b], *Faisal Khan*[a,*], *Paul Amyotte*[c]

[a] *Safety and Risk Engineering Group (SREG), Faculty of Engineering & Applied Science, Memorial University of Newfoundland, St. John's, NL, Canada A1B 3X5*
[b] *Safety and Security Science Group, Delft University of Technology, Delft, The Netherlands*
[c] *Department of Process Engineering & Applied Science, Dalhousie University, Halifax, NS, Canada B3J 2X4*

ARTICLE INFO

Article history:
Received 12 July 2015
Received in revised form 2 January 2016
Accepted 5 January 2016
Available online 13 January 2016

Keywords:
Dust explosion
Domino effect
Escalation probability
Bayesian network
Process industries

ABSTRACT

In most dust explosion accidents, a series of explosions consisting of a primary (dust) explosion and one or more subsequent secondary dust explosion(s) has been reported. Such chain of dust explosions can be referred to as a dust explosion domino effect (DEDE). DEDEs are capable of causing severe onsite and offsite damages to human, assets, and the environment, thus requiring a detailed understanding of the causes, consequences, probabilities, and escalation mechanisms thereof to prevent and mitigate the potential damages. In this research, we have developed a methodology for the probability estimation of DEDEs based on Bayesian network. The application and efficacy of the methodology have been demonstrated via a real-world case study. The results illustrate that the developed methodology can effectively portend the propagation of DEDEs while calculating the respective probabilities.

1. Introduction

A domino effect is a chain of accidents in which a primary accident triggers secondary accidents, the total consequences of which are much more severe than that of the primary accident in terms of human and asset losses (Reniers and Cozzani, 2013). In process plants, due to the presence of many major hazardous installations (MHIs) containing large inventories of flammable and explosive substances usually under high-pressure-high-temperature conditions, a primary accident is likely to escalate to a domino effect. A variety of safety measures such as internal safety distances has been proposed to reduce the likelihood of domino effects (NFPA, 2012); however, in many cases, the implementation of such safety measures would be difficult due to restrictions such as limited available land or operational considerations.

Among domino effects, the work devoted to dust explosion domino effects (DEDEs) has been limited due to either complex escalation mechanisms or complicated interdependencies. Combustible dust is widely involved in process industries in form of production raw materials (e.g., cotton in textile mills and intermediate products such as synthetic resin powders in plastic product manufacturers) or by-products (e.g., aluminum dust in casting forges). Combustible dust can be exploded if suspended in a confined space and ignited. Characteristics of dust explosions in metal industry (Ebadat and Prugh, 2007; CSB, 2011), wool industry (Piccinini, 2008), coal mining (Wang and Li, 2001), and cork industry (Pilão et al., 2006) have been investigated by researchers.

The mechanism of dust explosions has been studied in detail in previous work (Eckhoff, 2003; Eckhoff, 2009; Amyotte et al., 2005; Cashdollar and Zlochower, 2007; Di Benedetto et al., 2010); applications of preventive and mitigating safety measures have also been investigated in some work (Amyotte et al., 2009,2010; Myers, 2008; Holbrow, 2013; Liu et al., 2013). Recently, quantitative risk analysis (QRA) methods have been applied to estimate the risk of dust explosions (van dertVoort et al., 2007; Yuan et al., 2013; Yuan et al., 2015c; Khakzad et al.,

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[*] *Corresponding author*. Tel.: +1 709 864 8939; fax: +1 709 864 4042.
E-mail address: fikhan@mun.ca (F. Khan).

http://dx.doi.org/10.1016/j.psep.2016.01.005
0957-5820/

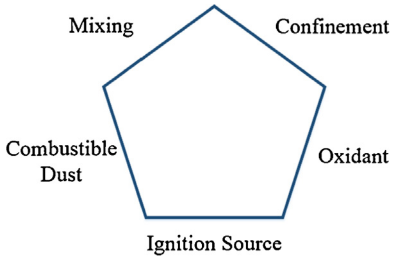

Fig. 1 – Necessary elements of dust explosion (Kauffman, 1982).

2012). Nevertheless, the attempts made to model and assess the risk of DEDEs have been very few (van dertVoort et al., 2007). Bayesian network (BN) has successfully been employed to model domino effects triggered by fires and explosions (not dust explosions) (Khakzad et al., 2013a, 2014; Khakzad, 2015). However, the application of BN to risk analysis of DEDE, to the best of our knowledge, has been lacking. The present study aims to develop a methodology using BN for modeling the propagation of DEDEs and estimating their probabilities.

This paper is organized as follows: Section 2 briefly explains the characteristics of dust explosions and introduces the basis of DEDEs. In Section 3, a BN methodology is developed to model and assess the likelihood of DEDEs. The application of the methodology is demonstrated using a real-world case study in Section 4. The conclusions drawn from this work are presented in Section 5.

2. Background

2.1. *Dust explosion mechanism*

Combustible dust, oxidant, mixing (or suspension), confinement, and ignition are five essential factors for any dust explosion (Ebadat and Prugh, 2007; Eckhoff, 2003; Cashdollar and Zlochower, 2007; Abbasi and Abbasi, 2007; Amyotte and Eckhoff, 2010; Kauffman, 1982) as shown in Fig. 1 (Kauffman, 1982). When all these factors coexist, a dust explosion would happen.

A dust explosion is likely to occur when combustible dust that has been suspended in a confined space meets an adequate ignition source. Nevertheless, a dust explosion is usually influenced by other factors such as particle size, the minimum ignition temperature (MIT), and the minimum ignition energy (MIE). For a combustible dust, the diameter of dust particles should be within a respective explosible range (Eckhoff, 2003). Otherwise, dust is considered non-explosible. MIT is the temperature above which suspended combustible dust (combustible dust cloud) can be ignited. A high MIT indicates that the mixture of combustible dust and oxygen is more difficult to ignite (needs a high temperature) and thus is less likely to explode. Similarly, MIE refers to the minimum energy required to ignite combustible dust cloud. The severity of a dust explosion can be represented using the maximum explosion pressure (P_{max}) or the normalized maximum rate of pressure rise (K_{St}) (Hassan et al., 2014).

2.2. *Domino effects of dust explosions*

The schematic of DEDE propagation is shown in Fig. 2. A DEDE usually originates from a primary explosion. If the blast wave generated by the primary explosion is large enough to suspend settled dust layers and form a combustible dust cloud, a secondary dust explosion can take place given an ignition source with adequate MIT or MIE. Compared to the primary dust explosion, the secondary dust explosion(s) can cause more severe consequences due to larger quantities of combustible dust involved (Lees, 2005).

As the primary and secondary dust explosions could occur in different units of a process plant, sometimes safety barriers are difficult to implement between different hazardous units in order to block the propagation of the pressure and flames generated by the primary explosion. A typical example is the phenolic resin dust explosion at CTA Acoustics, Inc., U.S. in 2003 (CSB, 2005a). The initial (primary) dust explosion occurred at the production line 405 while the secondary dust explosion took place at the line 401, more than 25 m away from the initial explosion. Another case is the aluminum dust explosion at Hayes Lemmerz International-Huntington, Inc., US (CSB, 2005b) where a primary dust explosion in the aluminum dust collector located outside of the building propagated through ducts and caused a secondary dust explosion around furnace No. 5 in the workshop due to the absence of an explosion isolation device between the dust collector and the connected units.

For the sake of better clarification, consider a process plant in Fig. 3 where, A1, A2, and A3 represent the units susceptible to dust explosions whereas B1 and B2 are the units for which a pool fire and vapor cloud explosion (VCE), respectively, have been determined as dominant accident scenarios based on the involved processes and hazardous materials.

With a primary dust explosion in A1, several domino effects can be envisaged (Fig. 3(a)). The one shown in Fig. 3(b) is a chain of dust explosions, which is the focus of this research. In Fig. 3(b), the primary dust explosion in A1 could trigger a dust explosion in A2 which in turn could cause a dust explosion in A3 without causing credible damages to B1 or B2. Thus, the dust explosions in A2 and A3 can be considered as secondary and tertiary dust explosions, respectively. However, it is worth noting that the dust explosion in A1 could directly cause a dust explosion in A3 depending on the magnitude of the overpressure received by A3 from A1. In this case, A2 and A3 are both considered as secondary dust explosions. As another chain of accidents in Fig. 3(c), the primary dust explosion in A1 can result in a VCE in B2; the overpressure and flames caused by the VCE can then trigger simultaneous dust explosions in A2 and A3. As a result of these dust explosions, B_1 could be damaged, leading to a loss of chemical containment and a subsequent pool fire. To determine which domino effects are likely to take place, the magnitudes of the overpressures and escalation probabilities have to be calculated. This is discussed in more detail in the next section.

2.3. *Escalation probabilities*

For a primary accident to cause significant damage to a target unit, the magnitude of the physical effects – also known as escalation vectors – such as heat fluxes and explosion overpressures should be higher than some predefined threshold values. These threshold values are usually determined using experimental data and regression methods for a number of vessels (Gledhill and Lines, 1998; Contini et al., 1996; Pettitt et al., 1993; Cozzani et al., 2001,2005; Cozzani and Salzano, 2004). There are several methods to estimate the probability of damage to a target unit – known as escalation probability – among which probit functions are very popular due to their