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A model to assess dust explosion occurrence probability

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HIGHLIGHTS

- This paper presents a novel probabilistic model to assess impact of hazardous materials (dusts).
- Application of the model to industrial processing facilities handling dusts.
- A nomograph to facility easy application of the proposed probabilistic dust explosion prediction model.

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ABSTRACT

Dust handling poses a potential explosion hazard in many industrial facilities. The consequences of a dust explosion are often severe and similar to a gas explosion; however, its occurrence is conditional to the presence of five elements: combustible dust, ignition source, oxidant, mixing and confinement. Dust explosion researchers have conducted experiments to study the characteristics of these elements and generate data on explosibility. These experiments are often costly but the generated data has a significant scope in estimating the probability of a dust explosion occurrence. This paper attempts to use existing information (experimental data) to develop a predictive model to assess the probability of a dust explosion occurrence in a given environment. The pro-posed model considers six key parameters of a dust explosion: dust particle diameter (PD), minimum ignition energy (MIE), minimum explosible concentration (MEC), minimum ignition temperature (MIT), limiting oxygen concentration (LOC) and explosion pressure (P_{max}). A conditional probabilistic approach has been developed and embedded in the proposed model to generate a nomograph for assessing dust explosion occurrence. The generated nomograph provides a quick assessment technique to map the occurrence probability of a dust explosion for a given environment defined with the six parameters.

1. Introduction

1.1. Dust explosion

Dust explosions pose a serious hazard in dust processing facilities. According to the definition of BS2955 [1,2], particles with a diameter of less than 1000 μm are defined as powder and when particles have a diameter less than 76 μm (200BS mesh size) they are referred to as dust. As per NFPA (National Fire Protection Association), dust is any finely divided solid, 420 μm or less in diameter. Though BS:2955 [1,2] and NFPA 68 have different definitions for defining dust, Palmer [3] proposed that a particle with a diameter coarser than 1000 μm should be called dust [2]. The term dust used as per the NFPA 68 [4] definition, which is considered potentially threatening for the process industries. As the range of the explosible particle size may be larger for a specific material, the particle size distribution is considered in addition to the median particle diameter [5]. In this study, combustible dust is the primary focus. Any particular material capable of exploding when suspended in air in ignitable concentrations, regardless of size, shape or chemical composition termed combustible dust [5].

Dust explosion scenarios are not only restricted to coal mines or food industries; they may occur at a chemical process plant, in the wood and paper industry, in metal handling units, etc. Most dust handling plants are susceptible to dust explosions and thus require special safety measures and monitoring aids.

Combustible dust needs to achieve certain criteria to explode. Five factors are identified as triggers responsible for a dust explosion: particle diameter, minimum explosible concentration, minimum ignition energy, minimum ignition temperature and limiting oxygen concentration. To cause an explosion, five criteria (fuel, oxidant, ignition source, mixing and confinement) need to be fulfilled. The five identified parameters cover the five essential elements of a dust explosion. A dust explosion is a rapid

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combustion of flammable dust particles in an environment that supports the initiation of the combustion.

A dust explosion is initiated when suspended flammable particles in the air are in close proximity with a proper ignition source. If the dust cloud is unconfined and the ignition source is present, it would typically produce a flash fire. For rapid and violent combustion, confinement is a necessary element. Likewise, four other conditions are also very important for an explosion to occur. According to Kauffman [6] a dust explosion will occur when the explosion pentagon is completed. This pentagon consists of mixing, confinement, fuel, oxidant and an ignition source. When these parameters reach a sufficient threshold limit (explosible range), a dust explosion occurs [7]. In addition, an explosion may not occur if all parameters do not reach the explosible range [4].

In this study, a conceptual framework for a dust explosion prediction model is proposed which considers a process plants operating conditions and provides a quick estimate of dust explosion occurrence. For the development of the model, six basic parameters are identified that are necessary to describe dust explosion phenomena in a conditional probabilistic way. These parameters are analyzed thoroughly to understand their pattern. The parameters have a wide range of numerical values so their inherent distributions are identified. The distribution highlights the characteristics of the parameter and also imparts knowledge on the variety of the data. These distributions are used to develop the dust explosion prediction model. To assess the conditional probability, two parameters at a time have been considered to estimate the probability of explosion occurrence for a given scenario. Estimating the conditional probability for each parameter and integrating them over a range provides the total probability of dust explosion occurrence. The systematic approach provides a simple guideline, which can be used in monitoring process facility conditions. A simplified "nomograph" is introduced to make the model easier and user-friendlier.

In this paper, an overview of the methodology and a brief description of the proposed model are provided in Sections 2 and 3. The application of the proposed model in the industry is described in Section 4. Section 5 is devoted to discussion and Section 6 gives the conclusions, which include recommendations for future work.

1.2. Mechanism and causes

A dust explosion is a rapid and simultaneous combustion of flammable suspended particles [7]. Its strength is dependent on flame speed and the degree of confinement of the particles [8]. The outcome of the dust explosion is measured in terms of severity. In the study, the maximum explosion pressure is the indicator of the severity, as it is the most widely used indicator of the explosion scenario for a particular dust. A brief description of these six parameters is given below:

- *Particle diameter (PD)*: Dust particles have different shapes and sizes. In this study, the particle median diameter is chosen as PD and only micron-sized dusts are considered. Median diameter may be different if it is on a mass basis or a volume basis. However, for most dusts particles of interest, it is assumed that density remains constant throughout the entire particle size distribution. Thus mass basis analysis can be treated similar as volume basis. The unit of the PD is μm.
- *Minimum explosible concentration (MEC)*: If the dust particles are accumulated in a certain volume then the concentration is a major factor in an explosion. A dust cloud must maintain a minimum concentration below which it will not be able to explode. MEC is measured in g/m^3.
- *Minimum ignition energy (MIE)*: If the minimum ignition energy requirement is not met the explosion will not take place. The unit of MIE is mJ.
- *Minimum ignition temperature (MIT)*: The minimum temperature which is required to initiate the ignition process is called the minimum ignition temperature, MIT. The unit used to measure MIT is °C.
- *Limiting oxygen concentration (LOC)*: Limiting oxygen concentration is the availability of the oxidant. The LOC is measured by volume % of O_2 above which a deflagration can take place [9].
- *Maximum explosion pressure (P_{max})*: When an explosion takes place the parameter which measures the severity of the explosion is pressure. The unit of measurement for maximum explosion pressure is bar (g).

For a given dust material, P_{max} increases with a decrease in PD. Usually, MIE decreases with a decrease of PD and a decrease of PD can also lower MEC and MIT [8]. In present study, the developed model to assess the probability of dust explosion is a generic model irrespective of dust's chemical composition. The finer the particles size the lesser the requirement for MIE, which allows the dust particles to burn easily. Once they are in contact with air and fuel in a confined space, this can produce an explosion. Sometimes partial confinement can also cause an explosion which is similar to a flammable gas [10–12]. A dust explosion may follow a domino effect: a primary explosion followed by a secondary one. Most of the safety hazard mitigation processes try to eliminate the possibility of an explosion by imposing a layer of protection to prevent the simultaneous deterioration of the safety barrier. Once the secondary explosion begins it might take on a more violent form causing a great amount of loss [13].

1.3. Current status of dust explosion research

Dust explosion hazards are a continuous threat to process facilities that deal with powders or combustible materials. Research on safer plant design, safer work places and several standard safety codes is available in contemporary literature and books [8,14–17].

Amyotte et al. [15] proposed inherent safety as a proactive approach for hazard and risk mitigation during the design and operation phase. The proposed methodology discusses safer process implementation, considering inherent safety in the reduction of hazards at the very first instance in the workplace. Their conceptual framework mainly discusses minimizing, substituting, moderating and simplifying the process plant to eradicate the possibilities of hazards to improve safety and protection [16].

The framework proposed by Amyotte et al. [18] incorporates the principle of inherent safety, which is actually aimed at first reducing or completely removing the hazard, followed by addressing the frequency of occurrence and the subsequent severity component of risk.

Eckhoff [17] analyzed a comprehensive compendium of the current status and expected future of dust explosion research. He discussed various existing safety precautionary measures used or under consideration. Flame propagation reduction, preventing explosive dust clouds and ignition sources were elaborately analyzed. Moreover, explosion isolation, automatic explosion suppression and explosion venting were discussed throughout his study.

A number of safety codes are available that help to protect the industry from dust explosions. The National Fire Protection Association (NFPA) provides a number of codes (e.g. NFPA 68, 69, 650, 654) to prevent and mitigate dust explosions [7].