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AN OVERVIEW OF EXPLOSION SEVERITY ON DUST EXPLOSION

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Abstract. In spite of extensive research and development to prevent and mitigate dust explosions in the process industries, this phenomenon continues to represent a constant hazard to industries including manufacturing, using and handling of combustible dust material. Lack of fundamental methods in predicting the explosion severity characteristics and real dust cloud structure are recognized as a major obstacle in predicting the course and consequences of dust explosion in practice. This present paper discusses the influent factors affecting the explosion severity of the dust clouds in order to promote the advanced development for dust explosion. In addition, the impact of inerting on dust properties by using nitrogen or carbon dioxide to a level which the dust cloud can no longer propagate a self-sustained flame would also be explored.

Keywords: Dust explosion protection and mitigation; explosion severity; inerting

1.0 INTRODUCTION

A large number of accidental dust explosions have happened and found in literature since 1785 [1], leading to a significant problem of injuries, fatalities, destruction of equipment and property loss. Dust explosion may still occur in various industries handling miscellaneous organic and inorganic powders and dust. Those industries include wood and paper products, grain and foodstuffs, metal and metal products, power generation, coal mining and textile manufacturing. Dust explosion usually occur in various unit operations include mills, grinders, dryers, and other modes of transportation [1]. According to Abbasi and Abbasi [2], the record of dust explosion incidents shows that on average, one dust explosion could happen in each industrialized country everyday. Unfortunately,

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there is almost zero material whether in printed or soft copies in developing countries despite of ample information available on dust explosions. One of the most expensive and destructive accidents in the history of United State of America had happened on February 1, 1999. The catastrophic incident which killed six workers and injured fourteen others was reported to be caused by secondary explosion involving coal dust. The loss at over US one billion destroyed the powerhouse building and the facilities. Department of Safety and Health reported that in November 2010, an explosion involving aluminium dust have occurred at a motorcycle rim manufactured factory. Ten workers were injured and two of them were in severe condition [31]. Over past years, there have been many numerical/correlation models and developed systems towards prevention and mitigation of dust explosion in processing industries [8]. Nevertheless, the fundamental knowledge is still essential for proper understanding of dust explosion hazard as there is an inevitable conflict between the correlation and the complex nature of the process itself in practice. Dust explosion will occur when a flammable cloud, formed by the mixing of dust and air in the right proportion in a confined space is ignited and a rapid combustion of the fuel takes place, with the propagation of the flame across the cloud [1]. The flammability /explosibility limits need to be determined for the coals dust as the explosion will occur when the concentration of the dust falls within the explosible range. Even though no coal mining industry is commercialized in Malaysia, there is a risk of having coal dust explosion due to transportation, storage and uses of coal in power generation industry, cement industry and other manufacturing industry that use coal as fuel or raw material of their products. Coal dusts are commonly difficult to ignite and have low explosibility however it can pose a danger hazard when exploded [6]. Thus, it is crucial to know the physical characteristics and dust behavior in order to apply an effective protection and safety systems available to prevent and mitigate the dust explosion in industries and this paper will provide fundamental information on the influence of the explosion severity characteristics and inerting towards dust explosion protection and mitigation.

2.0 DUST EXPLOSION MECHANISM

In dust cloud, opposite to premixed gases, inertial forces can produce fuel concentration gradients [9]. Fundamentally, dust explosion will occur when the dust particles/layers is dispersed in the air to the extent that the dust concentration drops into the explosive range. The requirement for dust explosion is well known as “the explosion pentagon” consists of combustible dust, oxidant, ignition source or heat, confinement and mixing [4]. Even though confinement is one of the condition for dust explosion to occur, a destructive explosion may even possible to occur in open air if the reaction is so fast which the pressure builds up in the dust cloud faster than it is released at the boundary of the cloud. The rapid oxidation of the fuel dust leads to a rapid increase in temperature and pressure. This explosion may be a deflagration or a detonation. Deflagration is the combustion event where the flame propagation is slower than a speed of sound while detonation is the combustion event that the flame propagation is faster than a speed of sound, up to the flame speed of ~ 1200 m/s. Standard explosion protection systems often deals on deflagration events but not the detonation due to the quick respond time for the system to sustain. Dust explosion will always initiated with primary explosion and usually occur inside process vessels such as cyclones, hoppers, filters and bucket elevators. The blast from the primary dust explosion can generate the secondary explosion ahead of the flame by entraining dust deposits and layers [8]. A 1mm layer of dust of 500kg/m^3 on the floor can generate a cloud with average concentration of 100 g/m^3 if distributed evenly in a 5-meter high room [1]. This phenomenon of entrainment of dust layers in long tubes by the blast wave heading a dust explosion propagating along the tube have been extensively researched by Kauffman *et al.* [14] and Austin *et al.* [3].

2.1 Explosion Severity Characteristics

Before determining the severity of the combustible dust, explosion classification test is done to evaluate with ease on which dust/powders will explode or not when scattered as a cloud [1,7]. The dust explosibility can be classified under K_{st} value, which will be discussed further below. The index of explosibility is defined as the ignition sensitivity multiplied by explosion severity, which measured by the maximum pressure, P_{max} produced and the rate at which it rose i.e. dP/dt. Table 1 gives the example on how K_{st} is classified by dust explosion class, St. St is classified by three classes as follows: St1 (Kst = 0-200), St2 (Kst = 201-300) and St3 (Kst = > 300). The apparatus which are widely used over the world for the testing of dust explosion characteristics are Hartmann 1.2 litre vertical tube, Siwek 20 L spherical chamber, Pittsburgh Research Laboratory (PRL) 20 litre nearly spherical chamber as well as the 1m^3 spherical chamber, Fike 1m^3 and ISO 1m^3 [1,13]. Figure 1 illustrates the work done by Cashdollar [3] on the pressure-time profiles of the carbonaceous and metal dusts at constant concentration of 600g/m^3 in 20-L chamber.

Table 1 Explosion characteristics of combustible dusts (M < 63μm) [18]

Type of dust	P_{max}(bar)	K_{st}(bar-m/s)	Dust explosion class, St
Polyethylene	8.8	131	1
Coal	8.2	135	1
Aluminum	12.5	650	3
Wood dust	9.4	208	2
Corn starch	10.3	202	2

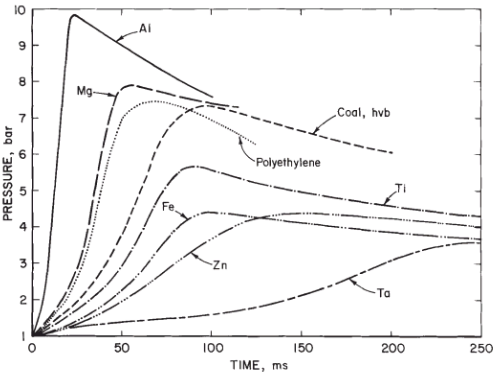


Figure 1 Pressure-time profile of the carbonaceous and metal dusts [3]

From the result, it can be seen that aluminium has the highest reactivity, which falls under Kst3, giving value of 9.8 bar overpressures compared to 3.5 bar for tantalum. The reactivity of these dusts is dependent on chemical and physical characteristics of the dust which aluminium was found to be the finest particles among all. The pressure obtained by high volatile bituminous (hvb) coal is ~ 7.5 bar, giving the coal to be classified under St1, similar to polyethylene but lower rate of pressure rise.

2.2.1 Maximum Explosion Overpressure (P_{max})

The meaning of P_{max} is the difference between pressure at the time of ignition at normal pressure and pressure at the highest point in the pressure at the highest point in the pressure time record resulting from a dust explosion [20]. P_{max} is obtained from the highest corrected value of explosion overpressure over a wide range of fuel concentration [5]. Continillo *et al.* [6] performed series of experimental tests on eight different coals to observe their P_{max} at ambient conditions. The particle size for each type of coals was 53 μm. The graph of explosion overpressures versus dust concentration is presented in Fig. 2. The test was performed in Siwek 20 L spherical chamber. Explosion overpressures will increase as the dust concentration increase. The value at the highest point of explosion overpressure is called P_{max} while the concentration at that point is the 'optimum dust concentration. At minimum value of dust concentration where the pressure is first observed is called minimum explosibility concentration or lean flammable limit.

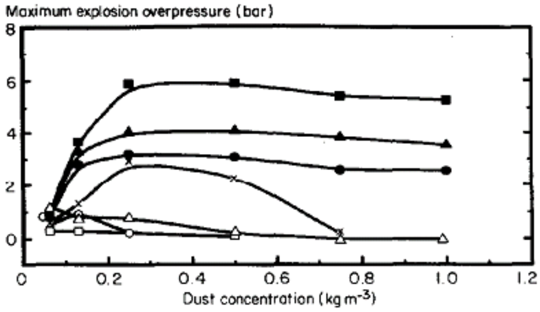
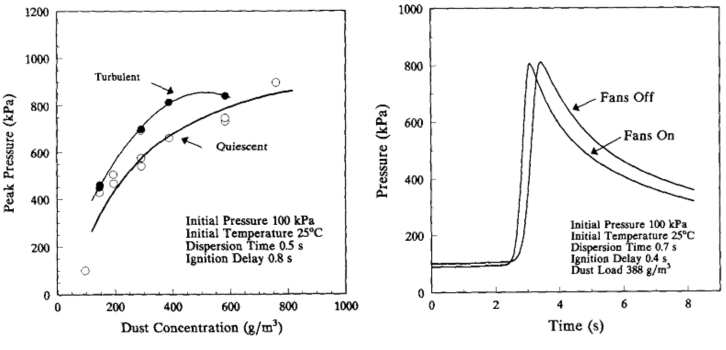


Figure 2 Maximum explosion overpressure as a function of dust concentration on coals [5]

Fig. 3 gave example for the influence of the initial condition to the overpressure of cornstarch/air mixtures at different concentration. It is clear that there is no apparent difference for the initial state of the dust cloud with and without fan-generated turbulence. This trend gave better evidence for coal dust/air mixtures as shown in Fig. 3.



(a) (b)

Figure 3 Comparison of peak pressure with and without the fan-generated turbulence for cornstarch/air mixture (a) and coal dust/air mixtures (b) [16]

2.2.2 Dust Deflagration Index (K_{st})

K_{st} is often referred to as the cubic or cube root law or simply known as the dust constant. The 'st' is derived from German word for dust; staub. The K_{st} value is derived from multiplying the maximum rates of pressure rise, $(dP/dT)_{max}$ by the cube root of the explosion chamber volume. The equation is called cube root law as shown below:

$$K_{st} = (dP/dT)_{max} \, . \, V^{1/3} \tag{1}$$

This concept is introduced for scaling the maximum rates of pressure rise to larger volumes by normalizing them [2]. The result of explosion severity may be used to design the basis for explosion protection and mitigation such as explosion relief venting and explosion suppression but it depends entirely on the validity of the cube root law [20]. According to Eckhoff [2003], cube root law is only valid in geometrically similar vessels, if the flame thickness is negligible compared to the vessel radius, and if the burning velocity as a function of pressure and temperature is identical in all volumes [1]. Kumar *et al.* [16] gave the influence of K_{st} on dust concentration of cornstarch /air mixtures for quiescent and turbulent by applying the fan for turbulence condition (refer to Fig.4). It is found that turbulent condition gave rise on K_{st} value of the dust for increased dust concentration. For example, at 600 g/m^3 of cornstarch/air mixtures, K_{st} of turbulent condition gave about 180 compared to 70 for quiescent condition. This can be said that K_{st} value is varied depending on the dynamic state of the dust cloud i.e. turbulent or quiescent and its combustion rate.

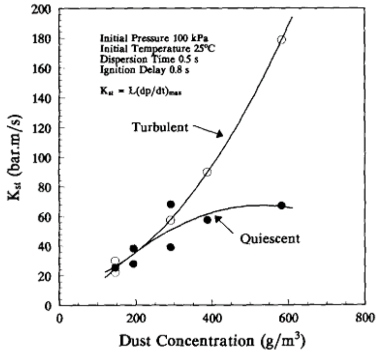


Figure 4 Comparison of Kst for cornstarch/air mixtures with and without fan generated turbulence [16]

3.0 DUST EXPLOSION PREVENTION AND MITIGATION

The most effective ways to prevent the dust explosion hazard is to avoid at least one of criteria from 'explosion pentagon', however, this method is sometimes fail as some of the criteria are needed in the practice and not feasible to be substituted with others. Inherent safe process design, initiated by Kletz [15] is the alternative for the no explosion hazard to exists. The basic philosophy and recommendation given by him includes the dust cloud generation is kept at minimum and must be handle as safe as possible in processes involve like transportation, production, storage operations and treatment [15]. However, this recommendation is not totally agreed by Nifuku *et al.* [19] that reported it is not easy to keep the dust below the minimum explosive concentration as the concentration needed in the process industries is in the high amount. However, by adopting good safety culture, appropriate training and effective housekeeping will minimize the hazard and risk of dust explosion. Further, explosion venting can be implemented for protection from dust explosion by providing a planned pathway for the fire propagation to escape as well as lower the pressure build up during the explosion. However, this method is not practical if the vented products can cause harm to people and environment. The explosion also can be isolated from spreading through vessel, ductwork or to other areas or process equipment. Suppression is expensive system to adopt but give advantage by detecting and suppressing explosion chemically from it earliest stages before an explosion becomes catastrophic [1,2,8].

3.1 Inerting by Adding Inert Gases

One of the effective and inexpensive methods of preventing explosive dust clouds is by inerting the air by adding inert gas or other substance such as rock dusting. The explosive dust cloud can be inerted by mixing the air with an inert gas such as nitrogen or carbon dioxide up to a level on which the dust cloud can no longer propagate a self-sustained flame. The use of carbon dioxide as an inert is more efficient than nitrogen for inerting carbonaceous gas [17] whereas nitrogen is more efficient inert for using on metal dusts. However, reducing the oxygen concentration in atmosphere by adding nitrogen, may pose suffocation hazard to human, but research has shown that by adding a few volume of CO_2 to the mixture may reduce the suffocation hazard as it will reduce the critical oxygen threshold [8]. Research has also confirmed that by reducing the oxygen content in atmosphere, the ignition sensitivity and combustion of the dust cloud are decreased [11]. The work found that minimum ignition energies of dust clouds increase with moderate reduction of the oxygen content [5,9]. Rock dusting has been used extensively since early centuries to prevent and inhibit a coal dust explosion in coal mining. The coal dust in mines is thermally inerted by spreading rock dust on the floor, ribs, and roof of mine passageways. However, based on experiments, the concentration of rock dust that need to be used varies by different countries and this would give conflict on the determination of the appropriate concentration to be used. Another approach is by using salt paste and salt powder to coat the coal dust to inhibit the dispersion of dust cloud [12].

4.0 CONCLUSION

Dust explosion may pose severe destruction to human, properties and environment. However, by understanding the fundamental cause and understanding on the severity explosion characteristics of the dust, the hazard and risk of dust explosion can be minimized. Overpressure and K_{st} are the crucial parameters which the higher the value of P_{max} and K_{st}, the more violent the hazard and risk of dust. These parameters also depend on other influent factors such as the dynamics state of the dust clouds, oxygen content, dust concentration and particle size. By understanding the possible hazard posed by P_{max} and K_{st} on dust clouds, the appropriate method of protection and mitigation may be applied accordingly and effectively. The inerting method using carbon dioxide and nitrogen has become a promising and economical method in industrial dust explosion protection.

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