PAPER • OPEN ACCESS

Mechanisms, Severity and Ignitability Factors, Explosibility Testing Method, Explosion Severity Characteristics, and Damage Control for Dust Explosion: A Concise Review

To cite this article: Dheyaa Ashour Khudhur *et al* 2021 *J. Phys.: Conf. Ser.* **1892** 012023

View the article online for updates and enhancements.

Mechanisms, Severity and Ignitability Factors, Explosibility Testing Method, Explosion Severity Characteristics, and Damage Control for Dust Explosion: A Concise Review

Dheyaa Ashour Khudhur[1*], Mohamad Wijayanuddin Ali[1,2], Tuan Amran Tuan Abdullah[1,2].

[1] School of Chemical and Energy Engineering, Faculty of Engineering,
Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.
[2] Centre of Hydrogen Energy, Institute of Future Energy, Universiti
Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.

Email: diaaashoor2@gmail.com

Abstract - The explosion of dust particles poses significant risks to the health and safety of humans working in process industries such as mining, energy, and manufacturing. A dust explosion is the rapid deflagration of particles in a large volume of air or gaseous oxidants. Since industrial dust explosions can occur in any plant equipment or environment, it is crucial to identify, examine and highlight the highly probable sources and risk areas for dust cloud formation and ignition along with damage control measures. Therefore, the paper presents a concise review of the various combustion classifications of dust along with the mechanisms of dust explosion, ignitability factors, and severity characteristics, explosibility testing methods, and damage control measures. Dust is broadly classified according to its explosive value, which indicates that its moisture, particle size, dust concentration, oxidant concentration, and turbulence are crucial to a dust explosion. Furthermore, the dust explosion mechanism reveals that dust particles undergo explosion when confined and or mixed oxidants, ignition sources or heat as described in the "explosive pentagon" concept. To address the risks posed by dust explosions, reduce ignitions and the severity of these hazards, numerous testing methods have been proposed or developed. The most notable characteristics of explosion severity are the maximum explosion overpressure (Pmax), maximum rate of pressure rise (dp/dt) max, dust deflagration index (Kst), and minimum explosibility concentration (MEC). Likewise, the measures for containing, isolating, suppressing, and venting the effects of dust explosion were also highlighted in detail. In conclusion, the review highlighted the role of the particles and dust clouds and the need to identify and highlight the sources of dust explosion that pose risks to human health and safety in the industry.

Keywords: Dust Explosion; Ignitability; Explosibility; Explosion Severity; Damage Control.

1. Introduction

The term dust is described as any finely divided solid materials or substances that have a diameter of below 420 μm. Dust can also be defined as particles that originate from numerous sources including the air, soil, wind or processes such as explosions. The term explosion is a thermochemical process in which flammable materials undergo rapid combustion; thereby generating suspended particles in the air [1]. Therefore, dust

explosion can be defined as the rapid combustion of particles suspended in a large volume of air or other gaseous oxidants [2]. It is also considered as the deflagration of materials or substances in an unreacted medium at rates below the speed of sound [3]. Typically, dust explosions in the industry occur in plant equipment such as mills, dryers, mixers, classifiers, conveyors, storage bins and hoppers [4], which pose significant risks to human health, safety, and the environment. In addition, dust explosions pose severe hazards to processes in industries such as mining, energy, and manufacturing among others [5]. Hence, extensive research and technological developments have been performed on the nature, severity, mechanisms, and damage control for dust explosion. Numerous methods have also been proposed to predict the process, parameters (such as dust particle size and turbulence), and consequences of dust explosions.

The characteristics of dust particles are determined through various standards such as British Standards Association (BS EN 14034-3, 2006), ASTM Standard E1226 (ASTM, 2010b), Japanese Industrial Standards (JIS) [6]. The IEC (International Electrotechnical Commission) standard method implemented through the Hartmann cylindrical tube 1.2 L and other explosion chamber devices are also widely used in dust particle characterisation [7]. The Hartmann tube and other devices such as the 20 L aspheric or 1 m^3 vessel using suitable capacitor-discharge devices have been successfully used to determine the minimum ignition energy (MIE) [8, 9]. As the ignition source is stronger than the chamber volume, the possibility of explosion is high, which results in an overestimation of the maximum overpressure and deflagration index (Kst) [1].

The different methods for determining dust explosion characteristics also contribute to different values of the same type of dust and equipment. Likewise, numerical simulation models have been designed to mitigate or prevent dust explosions for practical applications[10]. Hence, the physics and chemistry of cloud generation and combustion of dust requires detailed theoretical and experimental studies to prevent inconsistencies in the reliability of data. However, the relationship between the laboratory test conditions and actual industrial conditions is not always straightforward, although laboratory testing can provide quantitative data on various hazards associated with dust explosions [11].

Kumar *et al.* [12] showed a good agreement in determining the maximum explosive overpressure of coal dust and corn starch in a 10.3 m^3 cylindrical vessel compared with the smaller vessel. Büschgens and Pikhard [13] reported that the characteristic explosion values for icing sugar particles are below 0.063 mm in diameter with maximum explosion pressure of 9 bar, severity index of 140 bar m/s, and lower explosion limit of 60 g/m^3. Other factors that influence the characteristic explosion values are the physical properties such as particle size and concentration of the dust. Furthermore, the authors revealed that the maximum particle size of icing sugar that can cause an explosion is 0.4 mm at 15 kg/m^3 concentration. To initiate an explosion, the concentration of sugar must be at least 750 g/m^3 at a particle size of 0.4 mm or 60 g/m^3 at a particle size of 0.063 mm. If the particle size of the icing sugar bulk density is 0.8 g/cm^3, a dust layer that is greater than 0.075 mm could be critical. As the concentration of the dust increases, the effect of particle size on the dust explosion process will diminish [13].

Therefore, this paper seeks to provide a concise overview of the classifications and categories of dust based on the various combustion classes that exist in the literature. The mechanisms of dust explosion comprising the dust cloud formation and ignition processes will also be highlighted in detail. Furthermore, the various factors that impact on the severity and ignitability of dust explosion are presented. The paper will also identify, examine, and highlight the various testing methods in the literature used to test the explosibility of dust particles during the explosion at the laboratory or small scale setups. Lastly, the paper presents the various defining characteristics of explosion severity, along with the measures devised by the industry and academia to control the real and potentially damaging effects of dust explosion.

2. Classification of Dust

Dust can be classified in numerous ways based on its explosive value. According to Vijayaraghavan [14], all explosive dust is flammable but not all combustible dust is explosive. There are very explosive powders such as gun powder and dynamite that are easily burned without oxygen [15]. However, materials like anthracite and graphite have a high calorific value of heat combustion, these do not explode easily. According to the classification of the HM Factory Inspectorate of the United Kingdom (UK) Department

of Employment [16], group A is classified as dust that propagates flame when ignited in the test device. Meanwhile, Group B is used for dust that does not propagate flames in the test device. These are suitable for dust that approaches or is near atmospheric temperature (25 °C) at the ignition time [16]. Dust that is ignitable but not explosive may detonate when combined with fuel-based dust. For example, fly ash may explode when spiked with pulverised coal or petroleum coke [17]. Dust can also be categorised into the following combustion classes (CC) as shown in Table 1.

Table 1. Classification of dust base on combustion class [18].

Combustion Class	Description
CC1	No ignition; no self-sustaining combustion
CC2	Short-time ignition and fast extinction; local combustion duration is short.
CC3	Local combustion or glowing without spreading; Continuous local combustion but no propagation.
CC4	Glowing flame spread; spread smouldering combustion
CC5	Spread fire; spread open flames
CC6	Explosible burning; explosive combustion.

The classification is based on the measured ignitability and combustibility of the dust layer along with the behaviour of the dust pile. However, the classification is limited when subjected to a gas flame or hot platinum wire [18, 19]. The classification of dust based on combustion grade is more advantageous as it does not depend on temperature because different specks of dust have different minimum ignition temperatures.

3. Mechanism of Dust Explosion

The inertial forces in dust clouds can produce fuel concentration gradients unlike in the case of premixed gases [20]. Fundamentally, dust explosions can occur when dust particles/layers are distributed in the air such that the concentration of dust falls inside the explosive range. Typically, the requirement for a dust explosion is described based on the "explosive pentagon". The concept submits that dust explosion occurs due to the confinement and mixture of combustible dust, oxidants, ignition sources or heat [21]. Although confinement is a prerequisite for dust explosion, the pressure generated from a rapid reaction in the cloud of dust is greater than the pressure dissipated at the cloud boundary. Hence, a highly damaging explosion will take place in open-air [22]. In practice, the swift oxidation of fuel-based dust particles through either deflagration or detonation causes a significant increase in temperature and pressure. Deflagration is defined as a combustion event in which the resultant flame spreads slowly compared to the speed of sound. Conversely, during the detonation process, the flame is propagated faster (flame speeds as high as 1200 m/sec) than the speed of sound. The standard explosion-proof systems can contain deflagration events without explosion because the system maintains fast response times [23]. Therefore, the assessment of hazards in industries that are susceptible to dust explosions requires identifying major events. Zhi [24] identified some significant events, besides the five primary pentagon factors, that indirectly result in the explosion of dust. These typically depend on a variety of factors including the design, operational, and management deficiencies. For example, dust accumulation could be due to inefficient ventilation systems resulting from sub-factors such as equipment failure [25]. Poor housekeeping can also cause dust to accumulate in the system. However, in some process industries such as silos, dust accumulation is considered a normal operating condition. Therefore, hazards should be determined based on the characteristics of individual processes.

3.1. Dust Cloud Formation Processes

According to Du *et al.* [26], explosions occur as a result of the swift evolution of heat and gaseous oxides when fuels undergo chemical reactions with oxygen. Dust with a 1 mm layer and density of 500 kg/m^3 on the floor can generate a cloud with an average concentration of 100 g/m^3 if distributed evenly in a room of 5 m in height [1]. The explosion is triggered during a primary explosion that typically happens in process vessels such as cyclones, hoppers, filters and bucket elevators. According to Eckhoff [10], the primary explosion of dust can generate a secondary explosion before the flame by entrainment of the deposits and layers of dust in a separate vessel. The occurrence of an entrapped dust layer in a long tube caused the propagation of dust explosion along a tube that could be attributed to the explosion in the second vessel. This could be experimentally deduced depending on the type of ventilation in the second vessel. Other notable factors include the severity of the primary explosion, pipe diameter, and any blockages in the connecting pipe [27]. However, the cracking of the primary explosion in the containment system may cause the dust layer to disperse into the air resulting in a secondary explosion. In some cases, depending on the thickness of the dust layer and the area occupied by the dust layer, the severity of the secondary explosion may be greater than the initial explosion [28].

3.2. Ignition Processes

The ignition of combustible dust clouds can only occur in the presence of a flame source or adequate heat. Typically, the ignition is triggered in various ways from low energy to high energy ignition sources [29]. However, the ignition source differs in energy, power, and temperature. Due to the exothermic reaction, potential dust may explode by self-heating. In selected cases, the layer or deposited dust generates high temperatures, which result in internal combustion. In addition, the porous structure of the dust layer permits the permeation of oxygen in the particle surface, which reduces the thermal conductivity of the layer [30]. Contaminants such as oil, water or wood present in combustible dust mixtures may also contribute to self-heating. The storage of dust in large quantities at high initial temperatures may also cause combustible dust explosions because of the high surface area and sufficient air circulation [1, 28]. The slow heating of dust deposits is called a smouldering nest. Previous studies have shown that even if the temperature is much higher than the minimum ignition temperature (MIT) of the dust cloud, the smouldering nest does not ignite most of the combustible dust. However, it is capable of igniting sulphur clouds at temperatures of 700-800 °C [19]. A powerful trigger for ignition creates an open flame due to welding, cutting flames or smoking. The excess oxygen it provides may result in the sensitivity and severity of the explosive properties and is likely to occur in primary explosions [11]. Explosions could arise from thermal processes such as welding and cutting, along with hot surfaces such as lamps, steam pipes, heaters. Other sources include unintentional hot surfaces created by equipment moving parts such as engines, blowers, mills, and bearings. Hot surfaces are also believed to increase the temperature of the dust layer due to the thermal insulation, which increases the explosive strength of the dust cloud. Other dust explosion triggers are electrical and static sparks, lightning and shock waves [28].

4. Factors Affecting Ignitibility and Severity of Dust Explosion

4.1. Particle Size

The particle size of dust has a significant influence on the explosiveness of dust. As the particle size of dust decreases, there is an increase in the explosiveness [31]. Cashdollar [23] revealed that smaller particles are more easily dispersed, have longer airborne times, and more susceptible to combustion. Smaller dust particles require lower energy and will reduce the minimum concentration and the minimum temperature of ignition. This is because smaller particles have a larger surface area per mass [32]. Bartknecht and Zwahlen [2] reported that mixing a speck of coarse non-explosive polyethene dust with 5% fine explosive polyethene dust caused the mixture to explode. For very fine particles, the minimum explosive concentration (MEC) is independent of size. However, for larger sizes (> 100 μm), the MEC increases with particle size until it is not easily ignited. The small particle size significantly affects the maximum explosive overpressure Pmax and the maximum rate of pressure rise (dp/dt) max. However, as the particle size

increases, the optimal concentration of Pmax increases significantly [33]. Extremely fine and reactive dust can reach an overpressure of 26 bar, which could alter the quasi-detonative combustion transition [34]. When the process of devolatilization does not regulate the explosion rate, additional decreases in the particle size of most organic substances will no longer enhance the combustion rate [4]. Typically, small-sized particles yield high explosion pressure due to the large surface area and will contact with oxygen to produce an explosion with increasing particle size where the maximum pressure will reduce gradually. In addition, Kst is not a value inherent to the substance because it varies based on the shape of the test instrument, ignition energy, time delays, and dispersion system that affect the turbulence degree. The conditional constant KSt is mainly determined by the chemical nature of the dust and its reaction surface area, by keeping these boundaries.

4.2. Dust Concentration

The dust in the air mixture is required to be within a definite range of concentration for a dust explosion to occur. At concentrations below the minimum levels, the heat released by the combustion of particles near the ignition source is inadequate to stimulate the ignition of particles. Consequently, flame propagation does not occur [35]. When the concentration is above the minimum level, flame propagation is favoured and the flame speed increases at higher the concentration of the dust. As the flame speed increases, the time to devolatilization declines and a lesser percentage of the volatile material is progressively accomplished [36]. On the whole, it is problematic to accomplish the maximum concentration of dust due to the uneven concentration in the whole vessel. Hence, a substantial quantity of carbon monoxide (CO) is formed at high concentrations and dust tends to agglomerate, which inhibits the dispersion of dust clouds [12]. Westran *et al.* [37] reported, at higher concentration of sugar dust, the maximum overpressure and higher rates of pressure even out as the levels of oxygen are consumed in the chamber. Many methods and equipment have been developed to achieve minimum explosive concentrations. Conversely, significant data exists from numerous researchers based on the following factors namely; dust cloud formation methods, cloud uniformity, and equipment [6]. The physical structure and chemical properties of dust significantly affect the explosiveness and ignition sensitivity. Therefore, suitable methods for proper sampling and obtaining chemical properties of dust are needed to accurately assess real industrial hazards [11]. Eckhoff [4] reported that the concentrations of organic dust required to trigger explosions as shown in Figure 1. Based on Figure 1 range from a minimum concentration required to trigger the explosion of organic dust is from 100 g/m^3 to a few kg/m^3. Conversely, the outlined range of concentration is affected by other factors including particles size, moisture content and mass fraction of the inert material. Moreover, the different value obtained to estimated minimum value to trigger dust explosion due to change the method used, the ignition energy and the size of the explosion device [4].
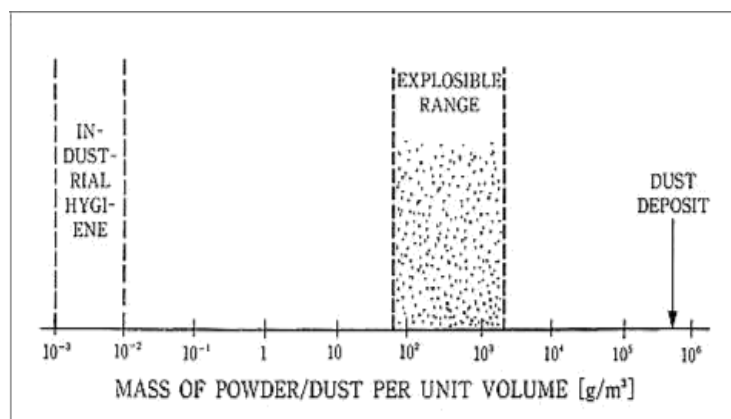

Figure 1. Range of explosive dust concentrations in air at normal temperature and pressure for natural organic dust [4].

4.3. Presence of Moisture

Typically, the explosibility of materials decreases at higher content of moisture. Hence, the occurrence of moisture in dust may reduce the strength and ignition sensitivity of the dust cloud [38]. Mintz [39] performed an explosion test on dried and undried corn starch at particle sizes from 120 μm to 150 μm. It was found that the dried sample became explosive and the undried sample could not be exploded for very fine dust, which confirms that moisture content is an important influence. The high moisture content of the dust significantly reduces the ignition sensitivity of the dust [40]. The influence of moisture on the minimum ignition energy is very significant especially in Tapioca as shown in Figure 2 [40]
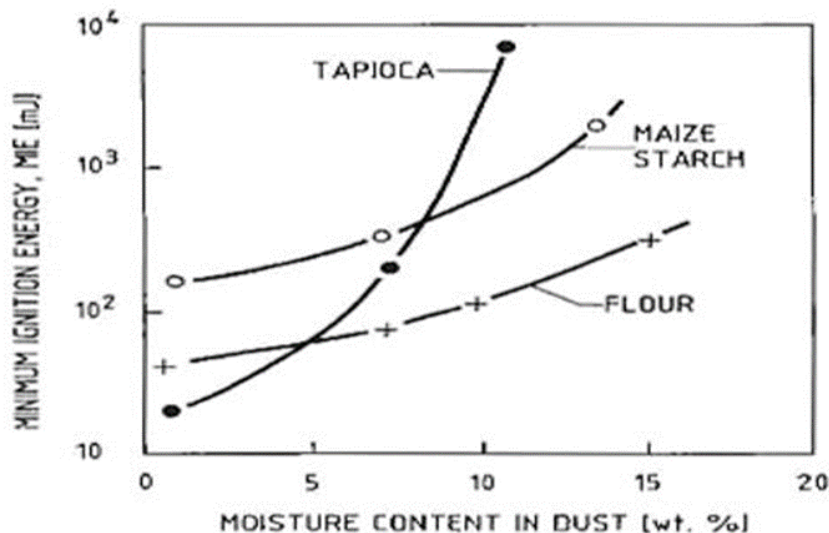

Figure 2. Effect of moisture on minimum electric spark ignition energy of dust [40]

Eckhoff [11] showed that the increase in moisture content reduced the severity of corn starch as the moisture content increases from zero to 28%. Hence, the highest rate of pressure rise lowered by 100 (bar/s) for corn starch. However, the highest rate of pressure rise is between 100 (bar/s) and 200 (bar/s) for dry starch based on the ignition delay time. For a material with 28% moisture content, the highest pressure rise rate ranges from around 20 (bar/s) to slightly less than 100 (bar/s). Traoré *et al.* [41] studied the influence of relative humidity on the explosion parameters of icing sugar as shown in Figure 3.

As observed, the moisture content increases from near zero to 0.34%. In addition, as the maximum rate of pressure rise increases, there is a corresponding decrease as the moisture content is increased further. The initial increase in the severity of the sugar explosion could be the reason for the water reaction that converts sucrose into fructose and glucose. Furthermore, the adsorption and desorption of interfacial gases are caused by the effect of humidity, which creates an oxygen-saturated "syrup" layer on the surface of the particles and enhances the potential for spontaneous combustion. This modified surface stimulates the kinetics of the combustion of the sugar particles. However, the effect of moisture is highly dependent on the chemical properties of the particles. Typically, moisture reduces the severity of the explosion and ignition sensitivity.
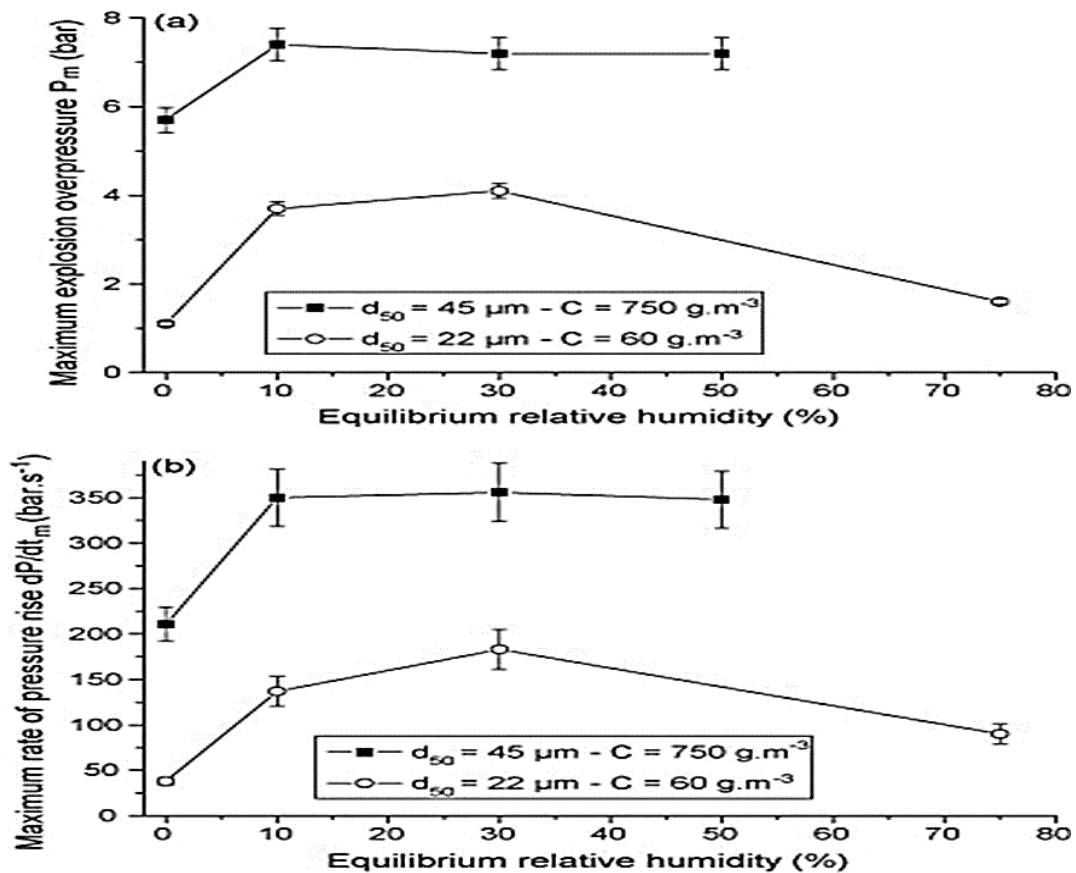
Figure 3. Influences of relative humidity on (Pmax) and (dp/dt) max of icing sugar at various dust concentrations [40]

4.4. Ignition Energy

Dust requires stronger ignition energy than gas (10–100 mJ). However, the ignition energy required to initiate a dust explosion also increases with the level of turbulence especially for dust clouds [2]. The strong ignition used in smaller chambers could excessively energize dust explosions, thereby resulting in the overestimation of the overpressure and pressure rise rates [7, 42]. However, some studies have proposed 5–10 kJ energy region for assessment of minimum ignition concentration (MIC). This is because the outcomes gained at the proposed energy levels are more stable and reproducible [43, 44]. The extra energy generated by a robust igniter increases the temperature of the explosive system, which could trigger the explosion of non-explosive dust [45]. Janès *et al.* [43] compared the MIC values measured with two different explosion tubes namely; the Hartmann and MIKE 3. Typically, the MIKE 3 device provides MIE results that are equal to or below values measured with the Hartmann device. This is especially true for energy ranges between 1 and 10 mJ and above 100 mJ, which is in good agreement with Lepik *et al.* [46]. However, numerous studies have determined the ignition sensitivity or severity of the explosion of icing sugar. Ramírez *et al.* [38] reported that, although, icing sugar did not H_2O_2 indicating it is non-oxidisable and requires temperatures above 270 °C for flammable volatile substances to be emitted. However, icing sugar is prone to self-ignition according to TG and DSC analysis. The dust for icing sugar appeared to present a very high risk of self-ignition, although the low melting of the product could impede its occurrence.

4.5. Turbulence

The explosive characteristics of dust are significantly influenced by turbulence, which poses grave anxieties to researchers of dust explosion [31]. The concerns are due to the lack of a comprehensive understanding of the variables that influence the dust explosion. Turbulence is vital due to various reasons. Pre-ignition turbulence occurs in dust or air suspensions due to the critical role of cloud development. Post-ignition turbulence in unburned clouds in front of the flame, which may be due to flow dynamics produced by combustion in the presence of walls, obstacles, and other confinements such as vents. Conversely, the level of turbulence could differ from one device to the other, which is contingent on the scattering vessel volume, air pressure, and the container geometry [47]. The increased rate of combustion and the corresponding higher rate of combustion during the explosion of dust causes an increase in turbulence which also raises the maximum explosion pressure and maximum pressure rise rates. Hence, the extrapolation of explosion data is complex, which can be empirically determined on a small scale in laboratories to large apparatus by cubic relations. In general, the ignitability of dust is adversely affected by turbulence, which indicates high-energy sources of ignition are compulsory for testing the limit of flammability [48]. Abbasi and Abbasi [1] reported that a highly turbulent cloud would distribute dust evenly throughout it. When such a cloud is captured, the turbulence will produce a mill-like effect mixing the hot combustion/combustion portion of the cloud with the cold unburned portion, producing alternating three-dimensional hot combustion/combustion and cold unburned areas laminate. In short, if the latter is highly turbulent, it will quickly spread through the dust cloud thereby resulting in an explosion. Turbulence influences the rate of pressure rise far beyond the peak pressure. Conversely, when a not so turbulent cloud is burned an initial yet large amount of heat is released, which is locally concentrated due to its low heat dissipation rate. The further propagation of the generated flame in the dust cloud is completely based on the degree of dispersion of the dust. Hence, well-dispersed dust has a higher propensity to ignite [49].

4.6. Oxygen Content of Oxidizer Gas

The ignition sensitivity and severity of the explosion of the dust cloud is diminished with decreasing oxygen content of the gas distributed within the dust [50]. The oxygen content strongly affects the process dynamics of combustion. The maximum pressure is roughly related to the content of oxygen based on thermodynamics [51]. The maximum explosion pressure drops to around 16% in proportion to the oxygen content, whereas the maximum rate of pressure rise declines even more. Hence, the content of oxygen greatly affects the dust explosion process [1, 23]. For example, an oxygen concentration greater than 21% will increase the burning rate of the fuel. However, when the concentration is below 21%, the burning rate is lowered. This is because the fuel consumes oxygen during combustion, which reduces the oxygen concentration. Consequently, the burning speed of the dust is lowered. Eventually, the burn may disappear or perchance a mild explosion will take place. The fire will continue only when the concentration of oxygen in the air is above 10% [30]. Mittal [52] performed several experiments in different dust concentration ranges as shown in Figure 4.

Based on Figure 4, the standard procedures adopted to examine the lower oxygen concentration (LOC), the first experiment was conducted at 21% oxygen to determine the most severe dust explosion. Subsequently, more tests were performed at different oxygen concentrations. In the initial experiment, the oxygen concentration was reduced by 3% and then 1%. The explosion characteristics with variable dust concentration and different oxygen levels. However maximum explosion overpressure reduced with reducing oxygen concentration.
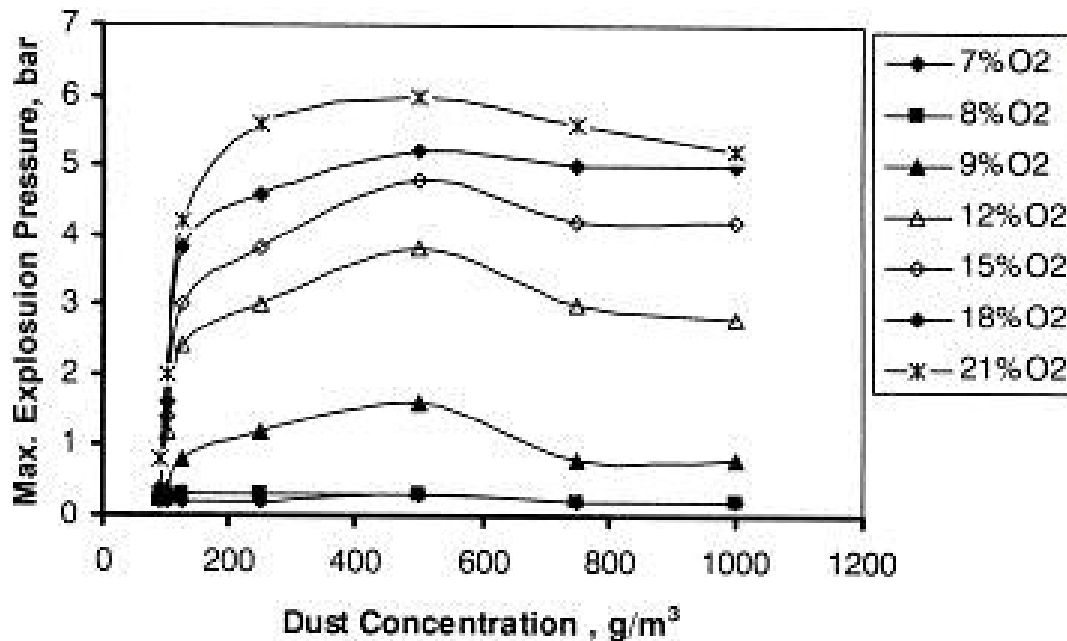
Figure 4. Maximum explosion pressure with variation in oxygen concentration [52].

4.7. Admixed Inert Dust Concentration

The addition of inert materials to highly flammable materials reduces the ignition sensitivity of combustible dust [53]. When inactive substances are mixed with combustible powders, the influence of the additive can be noted at each step of the risk assessment process. However, inert gases could reduce the oxygen content of the planet's atmosphere so that no combustion occurs. Therefore, when selecting an inert gas, the reactivity of the dust, the strength and duration of the source of ignition are critical. In general, the evolution of Pmax as a function of inert solids content is characterised by a slight decrease and a sudden drop, while the kinetic factors are more susceptible to this addition, causing a steady reduction in (dp/dt)max [44]. Addai *et al.* [53] carried out test studies on the MIE and minimum ignition temperature (MIT) using the Hartmann tube 1.2 L. The tests were performed by mixing different quantities of three inert substances (magnesium oxide, ammonium sulphate, and sand) along with six flammable fragments of dust (brown coal, corn starch, high-density polyethene, niacin, stone pine, and toner). In general, the increase in the concentration of the inert material improved the MIE and MIT up to the verge of zero ignition was accomplished. The inert gas mixture allows for a minimum ignition risk range between 60% and 80%. Ganesan *et al.* [54] reported that the regular distance of the volatile particles in the MEC, energy content, along with the hypothetical and real inert fraction of mass essential to avert the propagation of the flame in the test dust is shown in Table 2.

Based on Table 2, the distance amongst the sugar particles at MEC (30 g/m^3) was about 450 μm calculated using the CAAQES chamber. When the distance amongst the particles is < 450 μm, deflagration takes place in the CAAQES compartment. Hence, it is assumed that an upsurge in the inert fraction of mass enhances the distance between the volatile particles, which stops the propagation of the flame. Hence, the inert fraction of mass improved up to the point the mean particle distance became larger than the mean particle distance at the MEC. An inert mass fraction whose average particle distance exceeds the average particle distance of the MEC is the theoretical inertness percentage necessary to avoid propagation of the flame.

Table 2. Hypothetical and real inert mass essential to avoid dust deflagration [54].

Dust type	MEC g/m^3	Average distance Between particle (µm)	Energy Content (J/g)	Inert mass fraction	
				Theoretical %	Actual %
Sugar	30	455	16575	64	47
Corn starch	25	700	15630	49	48
Rice flour	28	567	15765	59	50
Dust XX	52	675	15395	49	47
Rye flour	81	464	16590	43	49
Brown rice flour	72	472	16640	23	40
Wheat flour	85	564	1400	NA	NA

4.8. Degree of Dust Dispersion

Dispersion is one of the most important characteristics of dust. It is defined as the various sized proportions of dust in an entire composition [55]. The degree of dispersion is characteristically contingent on how the dust is spread and the gradation of turbulence in the cloud of dust [56]. However, the influence of the distributed particle sizes on dust clouds from any specified cohesive powder varies extensively. The agglomerated particles in the cloud of dust could seem as separate agglomerate-sized particles during burning. Therefore, the sensitivity of ignition and severity of the explosion of the clouds can be subsequently altered. The changes take place irrespective of the original particle size before coalescence arises because agglomeration reduces the quantity of particles cubic meter of dust clouds to about 109 cm^3 per second. The average effective particle size will then increase to above 100 nm [57]. The degree of dispersion and agglomeration affects combustion, since the parameters change the effective local dust concentration and effective particle size, respectively.

Hence, more evenly dispersed dust will burn more easily due to the larger surface area of finer particles that supports combustion. However, agglomerates have a smaller surface area and therefore have reduced combustion [11]. In another study, Eckhoff [58] revealed that dispersed dust may have nanoparticle powders that do not produce extreme ignition sensitivity and extreme explosive rates. However, there are two basic reasons why this is not certainly the case. First, this is due to the very strong interparticle force. Hence, it is hard to wholly convert the bulk nanoparticle powder into a dust cloud composed of well-dispersed primary particles. Second, the extremely fast coagulation process in a nanoparticle cloud of explosive mass concentration will convert the primary particles into larger agglomerates in a fraction of a second in well-dispersed clouds. Therefore, it is important to understand the effectiveness of dust dispersion in the laboratory during ignition to assess the assumption of dust cloud uniformity and its impact on the data accuracy of minimum explosion concentration MEC.

4.9. Flammable Gases

The incidence of combustible gas and sources of energetic ignition is needed to initiate a combustion reaction that risks a danger [17, 59]. The occurrence of flammable gas in the dust enhances the severity of the explosion since the MEC, MIT and MIE are reduced, which increases the maximal rate of pressure rise [60]. Therefore, the combustible gas can cause the mixture of the dust and gas to detonate at a lower concentration of dust compared to the lower limit of the explosion of the dust. This occurs when the gas concentration is lower than the normal lower explosion limit of the gas [61]. It may also cause the explosion

to become such a large particle size dust that would otherwise be non-explosive [1, 62]. By adding flammable gases, smouldering gases or solvent vapours, the explosion of dust may be influenced without increasing the combination of combustibles, which is referred to as a mixture of mixtures [63]. In the case of a mixed mixture, the maximum rate at which the explosion pressure rises become particularly higher. Hence, the MIE is lower than the MIE in the pure dust/air mixture. If the gas, steam or dust concentration is below its lower explosion limit, the mixture may be explosive [64].

5. Dust Explosibility Testing Methods

The purpose of testing for dust explosion is to reduce the explosion, prevent ignition, and reduce the severity in case of an explosion. The commonly used laboratory tests are categorised into two groups namely; severity of the explosion and the explosion sensitivity parameters. The tests are used to examine the likelihood of explosion severity characteristics and consequences [65]. Before determining the severity of the combustible dust, an explosion classification test is performed to determine if the dust/powder will explode as a cloud spread or not when scattered as a cloud [1, 65]. The dust explosion can be classified using the Kst value. Table 6 presents an example of how dust explosion class, St, classifies Kst. Based on Table 3 combustion, dust can be classified according to the value of severity index. Hence, dust that has a Kst value between 0 and 200 bar.m/s has weak to moderate explosion severity (St1), although according to OSHA most of the food-stuff is in class St1. If the value of Kst from 200 to 300 bar.m/s the explosion classified under St2 which is strong.

Table 3. Explosion characteristics of combustible dust (M < 63μm) (NFPA, 2002)

Type of dust	P_{max} (bar)	K_{st} (bar.m/s)	Dust explosion class, St
Sugar	9	140	1
Coal	8.2	135	1
Aluminium	12.5	650	3
Wood dust	9.4	208	2
Corn starch	10.3	202	2

Lastly, a very strong explosion will describe explosion dust, which records severity index value more than 300 bar.m/s as Aluminium dust. The different equipment widely used for testing include; the Hartmann 1.2 L vertical tube, Siwek 20 L spherical chamber, and the Pittsburgh Research Laboratory (PRL) 20 L near-spherical chamber. Others include the 1 m³ spherical chamber, Fike 1 m³ and ISO 1 m³ chamber [1, 66]. In determining the MIT, a 0.27L Godbert-Greenwald furnace and a 0.35 L Bundesanstaltfür Material prüfung (BAM) furnace are typically used as testing equipment [67]. The Hartmann bomb has been widely used since 1980 [1], but many tests are performed by comparing its results using other chambers [68].

Hartmann 1.2 L vertical tubes are typically used for pilot selection tests and to deduce the MIE [69, 70]. However, the Hartmann tube and other smaller chambers have a large surface area to volume ratio, which significantly affect the heat loss of the chamber walls. Therefore, the chamber underestimates the severity of the explosion [71]. This may give the wrong result for dust that is not easily ignitable with spark but only can be ignited by stronger ignition sources [23]. The large chamber such as the Siwek 20 L spherical chamber and the standard closed 1 m³ ISO chamber can largely overcome these problems, thereby yielding better results than the tubular tube [1]. The 1 m³ chamber yields a more realistic measurement of the maximum explosion pressure, the maximum rate of pressure rise and minimum explosion concentration.

However, it requires more dust samples to be prepared and more time to test in 1 m^3 chamber than the 20 L chamber [23].

6. Explosion Severity Characteristics

6.1. Maximum Explosion Overpressure (Pmax)

The Pmax is the change in the pressure at the onset of ignition under standard pressure to that of the highest point in the pressure-time record of exploded dust [72]. The value of Pmax is determined based on the maximum corrected value of the detonation overpressure across an extensive assortment of fuel concentrations [73]. Büschgens and Pikhard [13] examined different concentrations of icing sugar. The findings showed that the increase in the concentration of sugar dust results in higher values of pressure in the compartment. The value of the highest point of the explosion overpressure was 6.89 bar, which is called Pmax, and the concentration at this point was 1000 g/m^3. This is called the "optimum dust concentration" with lower concentration limit 125 g/m^3. Mintz [39] reported that the optimum dust concentrations typically occur at higher concentrations, as opposed to gases that typically have near-optimal concentration stoichiometry. The minimum value of the dust concentration at which pressure is first observed is referred to as the minimum explosive concentration or the lean flammability limit (LFL).

6.2. Maximum Rate of Pressure Rise (dp/dt) max

The maximum rate of pressure rise (dp/dt) max is the highest rate of pressure rise from the closed explosion of dust. It is measured through a typical test at the optimum concentration of the dust [74]. According to Ramírez et al. [38] the pressure rise rate is defined as the uppermost slope (1st derivative) value on the curve of pressure and time recorded in a closed vessel. It is computed in the course of the detonation of a detailed combination of combustible gases in air or air/inert gases conducted at definite test conditions. Stahmer and Gerhold [75] showed how quickly destructive pressure can occur in an unexpected dust explosion. Hence, the approach is adopted to create various measures for explosion protection. For example, the explosion-pressure resistance or shock-resistant devices, explosion-venting and explosion-suppression. Abbasi and Abbasi [1] noted that the maximum pressure rise characteristics are influenced by the vessel's shape and size, ignition source type and energy, temperature, and pressure, along with turbulence. The maximum pressure rise is also contingent on the rate at which the particles are combusted. Hence, it is possible to observe the random characteristics of Kmax (particle size distribution, geometry, and characteristics of specific process units, possible locations of ignition sources) in an industrial environment. As shown by Eckhoff and Mathisen [76], for the 1 m^3 vessel and the Hartmann bomb, the (dp/dt) max is considerably condensed as the interval between the start of dust diffusion and the increased ignition timing. The conceivable reason is that once the intensity of the dispersed air explosion is reduced, the degree of turbulence of the dust cloud will rapidly drop, causing the flame propagation speed to decrease accordingly. The studies by Büschgens and Pikhard [13] investigated the different concentration of icing sugar. The findings showed that increasing the concentration of the icing sugar dust increased the maximum rate of pressure rise value in the chamber. The value of the highest point of the (dp/dt) max was 39.51 bar/s based on the concentration of 1000 g/m^3, and the Kst was 26.18 bar.m/s for small particle size 18 μm, whereas the large particles size such as 160 μm and 77 μm yielded fewer values of explosion parameters due to small surface area that is in contact with oxygen.

6.3. Dust Deflagration Index (Kst)

Kst is described as the cubic, cubic root rule or the dust constant. The term "St" is derived from the German word for dust called "Staub". The Kst is otherwise known as the severity index or volume normalised rate of maximum pressure rise [29]. The Kst value is derived from the maximum rate of pressure rise (dp/dt) max multiplied by the volumetric cube root of the detonating compartment. The relation is termed the cube root rule as presented in Equation 1.

$$Kst = \left(\frac{dp}{dt}\right)_{max} V^{1/3} \qquad\qquad (1)$$

The concept proposed by Bartknecht and Zwahlen [2] as standardisation to extend the maximum pressure rise rate to a larger volume. Similarly, the dust classification system based on Kst values was proposed by the author based on explosiveness as arranged below:

$\quad$ Kst $\quad\quad$ = $\quad\quad$ Group St 0: Non-Explosible

$\quad$ 0 < Kst < 200 $\quad$ = $\quad\quad$ Group St 1: Weak

$\quad$ 200 < Kst < 300 $\quad\quad\quad$ = $\quad\quad$ Group St 2: Strong

$\quad$ 300 < Kst $\quad\quad$ = $\quad\quad$ Group St 3: Very strong

The values indicate that the higher the value of Kst, the greater the possibility of a dust explosion. Furthermore, the rule is contingent on similar geometric containers whose flame thickness is negligible compared to the chamber radius. In addition, the rule is valid if the rate of combustion is the same as the pressure and temperature function in all volumes [11]. Kst is also defined as the index of deflagration or the maximum pressure rise rate normalized to the volume [29]. The severity results for an explosion are regularly adopted as the design reference for explosion protection and mitigation. For example, it is used for explosion-relief, explosion suppression, and venting exhaust, although it is completely reliant on the efficiency of the rule of the cube root [11, 72]. Furthermore, the effect of Kst on dust concentration of the corn starch/air mixture for static and turbulent flow as described in the literature by Kumar *et al.* [12] is assumed by applying the fan to turbulent conditions. The results showed that the turbulent state caused the Kst value of the dust to increase the dust concentration. For example, for a corn starch/air mixture of 600 g/m^3, the Kst of the turbulent state results in 180 bar.m/s, whereas the quiescent state is 70 bar.m/s. Presumably, the Kst value varies depending on the dynamics of the dust cloud, that is, turbulence or quiescent and its combustion rate.

6.4. Minimum Explosibility Concentration (MEC)

The MEC or LFL is the lowermost concentration of dust clouds distributed in the air that can be propagated by an explosion during ignition [45, 65]. In addition to the ignition effect, the result of a pressure increase of 0.4 bar was considered as the MEC proposed by the IEC (International Electrotechnical Commission) after testing at different dust concentrations [7]. The higher the volatility, the higher the risk of dust explosion. Andrews *et al.* [77] showed different devices used to estimate MEC give different values as shown in Table 4. The reason for the difference in the MEC value of the different devices used in the test (refer to Table 4) is due to the MEC value depends on the method used, the ignition energy and the size of the device. However, literature values for MEC measured in the Hartmann tube are in cases not so different from those measured in the 1 m^3 or 20 L sphere [78]. For mixed dust, there is no MEC and the inert mass fraction is above 50%, which means no deflagration of dust is observed during the test. The outlined results indicate the inactive mass fraction influences the propagation of the flame in the cloud of dust. Hence, a large proportion of the inactive dust constrains the flame from spreading from among other particles undergoing combustion which raises the MEC [54]. When the level of flammable dust concentration in the cloud is below the MEC, the operating and or other conditions cannot be circumvented. Consequently, additional safety procedures are essential to regulate the development of a dangerous cloud of dust such as safer housekeeping, which could diminish or wholly eliminate the occurrence of combustible sources [1].

Table 4: Comparison of measured MEC values [77].

Dust	Hartmann (g/m^3)		$1m^3$ or 20L (g/m^3)		$1m^3$ (g/m^3)	
Sugar	45		60		60	
Milk powder	50		60		60	
Aluminium	30 40	6μm 17μm	30 6 60	(22-29) μm <10 μm 41 μm	30	29 μm
Cellulose	55		60	51 μm	60	33 μm
Wheat Starch	45		60	20 μm	30	
Lycopodium	22		-		30	
Polypropylene	30-35		30	25 μm	30	
polyethene	30		30	<10 μm	30	<10 μm
Sulphur	20		30	20 μm	30	
Peat	100		60-125		125	

7. Damage Control for Dust Explosion

According to Amyotte *et al.* [79], it is difficult to remove the risk of dust explosion despite the numerous and complex methods that exist. However, the measures required to considerably control or decrease the destruction resulting from the detonation or lessen the damage, trauma, process downtime [80]. The dust explosion damage control approach revolves around suppression, isolation, containment, and explosive ventilation.

7.1. Containment of Explosion

When contained in a definite space, the possible destruction caused by a dust explosion to the neighbouring surroundings can be averted [29]. Containment is an appealing alternative due to the largely passive approach that evades the distress of release removal. However, the complete design of dust treatment equipment to withstand the pressure generated by the explosion of dust is unfeasible [81]. This is particularly true for large factories. For minor devices and specific equipment, it is imaginable to establish containment. A good example is a grinder that could be designed to be appropriately strong to endure the explosion of dust. The maximum pressure of explosion for much combustible dust and gaseous substances is in the range of 7-10 bar [82, 83]. However, the solitary principle is not static pressure as the upward pressure rate is great during the explosion of dust. Hence, the designed apparatus must be able to endure the dynamic load during some explosion stage. Furthermore, the equipment must be designed according to the revolving symmetry to avoid large flats and corners [84]. Specific consideration is needed at the point where the dust is injected or recovered from the production facility and the point of connection in the devices. For highly toxic powder or dust, there is a need for easily reliable restrictions [85].

7.2. Isolation of Explosion

The prevention of exploding dust from dispersing from the primary explosion location to other processing units is the objective of explosion-proof isolation strategies [1]. As a result of the build-up of pressure, an excessive turbulent preliminary and jet-initiated ignition generates very high-pressure peaks. This takes place in well-ventilated containers alike, which therefore needs active explosion protection in interconnected systems [10]. According to Ebadat [65], two techniques are generally used, namely; material chokes and a quick valve for shut-off. For isolation or explosion-proof that involves a rapid close-off valve, the valve is installed in a pipe that connects one container to another. The valve is activated by an explosion

detector typically fortified with sensors for optics and pressure. The first is generally chosen since the visual sensor could be blind. However, the sensor for pressure is unable to trace very weak pressure waves that the optical sensor can detect. The time required for the valve to close depends on the remote pressure or the distance between the flame sensor and the valve. There may also be a type of dust the valve must be closed or even quicker within 50 milliseconds. According to Frank [86], isolation can also be affected by material blockage and may be taken into consideration where dust flow between the devices is required. The two conventional rotary valves and worm conveyors based chokes are adopted. Amongst the outlined, a rotating regulator is fixed at the vertical route and operated by a motor typically aimed at hindering internal dust explosions even there is lack of dust. When the regulator is installed at the entrance of the hopper, then the hopper is completed. Furthermore, it has to be arranged to prevent the former from continuing to rotate. This could motivate ignition due to dust overheating or motor overload.

7.3. Suppressing Explosion
For any processing facility with a dust explosion threat, a system can be placed and activated when the explosion begins or repressed rapidly [87]. Furthermore, proper inert material selection can prevent it from rejuvenation. In turn, this will significantly lessen the danger of explosion since the devices for spontaneous explosion suppression are created to attain this objective [26]. According to Krasnyansky [88], the systems designed for suppressing explosion need to meet four basic properties:
- It needs to answer to the detonation of the smallest time delay with a quick activation.
- It should inject a sufficient quantity in the limited time frame in a manner to counteract the preliminary detonation and prevent the propagation of the flame.
- To close down the manufacturing facility.
- To avoid the resumption of the plant until the detonation is diminished.

Field [89] states that the effectiveness of the suppression system depends on the velocity at which the sensor responds to an emergent detonation and the system efficiency of the inhibitor injection. The last part must be adept at rapidly introducing an enormous amount of inhibitor and covering the entire parts of the threatened area. It must be capable of discharging at a high-quality rate, high discharge speed, so proper "throwing" an excellent angle coverage. Dastidar *et al.* [90] over time, powders such as proprietary mono-ammonium phosphate (MAP) have become increasingly popular in explosion suppression systems. Due to the potential risk of product contamination, the MAP cannot be used in the food processing industry. However, water-soluble and food-grade well-matched passive agents such as powdered sodium bicarbonate inhibitors have been developed and effectively utilised. Two other properties linked to the suppression systems for dust explosion are shutting down and preventing the plant from resuming until safety is guaranteed. Lastly, standard equipment and control practices are adopted to link the pressure sensors.

7.4. Venting Explosion
An explosion occurs when all attempts to prevent dust explosions fail. Hence, the effective prevention of explosion can minimise its adversative consequences [91]. Further related to poisonous dust, ventilation can drastically lessen the destructive possibility of a dust explosion. In the beginning glance, venting seems to be a reasonably easy operation [92]. If any section of the construction is predisposed to the explosion of dust, the pressure resistance of the remainder of the structure is considerably reduced through the use of a slimmer panel or can be allowed to fail in the initial phases of the blast. By properly determining the size of this vent, the operator can ensure that the vents operate as quickly as possible. Hence, the overpressure can exceed a certain safety threshold and rapidly release a sufficient amount of gas (and particulates) to prevent the pressure inside the protected area from reaching a destructive level [10]. For size, the venting location needs to understand all the elements that control the rigorousness of the exploding dust. The consideration includes the device's geometry that supplies the explosive venting, preliminary turbulence, primary pressure, dust concentration, original temperature, and detonation source for the combustible dust or inert gases [93]. All the defined elements impact on the pressure of the explosion particularly in terms

of pressure rise rates. Furthermore, the abridged pressure of explosion along with the area, pressure, distribution, and panel of the vents must be considered. In addition, the inclusion of protective ventilation is not the most critical consideration in ventilation for dust explosion [94]. The explosive waves and flames that vent to the surrounding environment can be dangerous, no longer to say the risks of unburnt dust, fumes and soot which can have all of sudden arisen spraying from a vent in a large number of ways [95, 96]. The maximum dimensions of the flame cleared out of the vent could be 10 times the cube root of the ventilation container volume [97]. If the vents emit too much unburned flammable material, it may even be ignited by a ventilated flame causing a secondary explosion [98]. The task of designing the vent spreads to removing the dangerous effects of venting substances particularly the flames. Therefore, it is critical to reiterate the importance of providing safe and effective ventilation. For example, if the pipe is installed at the vent, it may safely discharge the ventilation quality and energy. However, the process can prevent the complete suppression of the explosion pressure [10, 99].

8. Conclusions

The paper presented a brief overview of the various classifications of dust along with the various mechanisms, severity and ignitability factors, explosibility testing method, explosion severity characteristics, and damage control of dust explosion. The classification analysis indicates that dust can be broadly categorised based on its explosive value. However, the conditions required for explosion along with the pressures required for explosion include; moisture, particle size, dust concentration, oxidant concentration, and degree of turbulence. The mechanism of dust explosion indicates that explosions occur when particles or layers of dust are distributed in the air such that the concentration of dust falls inside the explosive range. Typically, the requirement for a dust explosion is described based on the "explosive pentagon", which states that dust explosion occurs due to the confinement and mixture of combustible dust, oxidants, ignition sources or heat. The process of dust cloud formation indicates that explosions occur due to the rapid evolution of heat and gases when fuel particles undergo oxidation reactions. Due to the high risks of dust explosion to manufacturing processes along with human health, safety, and the environment, numerous testing methods have been proposed, developed and implemented over the years. The major tests adopted reducing explosions, ignitions and the severity of explosion as categorised into the severity of the explosion and the explosion sensitivity parameters. The review also examined the characteristics of explosion severity which include the maximum explosion overpressure (Pmax), maximum rate of pressure rise (dp/dt) max, dust deflagration index (Kst), and minimum explosibility concentration (MEC). However, the control measures for mitigating the damaging effects of dust explosion are aimed at the containment, isolation, suppression, and venting of the explosion. Overall, the review highlighted the role of dust particles and clouds as crucial dynamics in the fire and explosion as well as the human health and safety in the industry.

References

[1]   Abbasi, T., and Abbasi, S., Dust explosions–Cases, causes, consequences, and control, *Journal of hazardous materials,* 2007, vol. 140, pp. 7-44.

[2]   Bartknecht, W., and Zwahlen, G., *Dust explosions: course, prevention, protection*, 1989, Springer.

[3]   Armstrong, G., Dust explosions: The potent power of powder, *Journal of Failure Analysis and Prevention,* 2004, vol. 4, pp. 6-8.

[4]   Eckhoff, R.K., Understanding dust explosions. The role of powder science and technology, *Journal of loss prevention in the process industries,* 2009, vol. 22, pp. 105-116.

[5]   Worsfold, S.M., Amyotte, P.R., Khan, F.I., Dastidar, A.G., and Eckhoff, R.K., Review of the explosibility of nontraditional dusts, *Industrial & Engineering Chemistry Research,* 2012, vol. 51, pp. 7651-7655.

[6]   Nifuku, M., Matsuda, T., and Enomoto, H., Recent development of standardization of testing methods for dust explosion in Japan, *Journal of loss prevention in the process industries,* 2000, vol. 13, pp. 243-251.

[7]   Chawla, N., Amyotte, P.R., and Pegg, M.J., A comparison of experimental methods to determine the

     minimum explosible concentration of dusts, *Fuel,* 1996, vol. 75, pp. 654-658.

[8]   Babrauskas, V., and Handbook, I., Fire Science Publishers, *Society of Fire Protection Engineers, Issaquah WA,* 2003, vol. pp.

[9]   Randeberg, E., and Eckhoff, R.K., Initiation of dust explosions by electric spark discharges triggered by the explosive dust cloud itself, *Journal of loss prevention in the process industries,* 2006, vol. 19, pp. 154-160.

[10]   Eckhoff, R., Current status and expected future trends in dust explosion research, *Journal of loss prevention in the process industries,* 2005, vol. 18, pp. 225-237.

[11]   Eckhoff, R.K., *Dust explosions in the process industries: identification, assessment and control of dust hazards*, 2003, elsevier.

[12]   Kumar, R., Bowles, E., and Mintz, K., Large-scale dust explosion experiments to determine the effects of scaling on explosion parameters, *Combustion and Flame,* 1992, vol. 89, pp. 320-332.

[13]   Büschgens, C., and Pikhard, O., Assessment of dust explosions in the sugar industry with regard to screening technology, *SUGAR INDUSTRY-ZUCKERINDUSTRIE,* 2017, vol. 142, pp. 416-419.

[14]   Vijayaraghavan, G., Impact assessment, modelling, and control of dust explosions in chemical process industries, *MTech Thesis, Department of Chemical Engineering, Coimbatore Institute of Technology,* 2004, vol. pp.

[15]   EN, B., Determination of explosion characteristics of dust clouds-Part,2006, British Standards Institution (BSI), London, United Kingdom.

[16]   HM Factory, Dust explosions in factories, (Department of Employment, Ed.),1968, HM Factory Inspectorate, SHW 830, H.M.S.O., London, United Kingdom (UK).

[17]   Amyotte, P.R., Basu, A., and Khan, F.I., Dust explosion hazard of pulverized fuel carry-over, *Journal of hazardous materials,* 2005, vol. 122, pp. 23-30.

[18]   ISSA, Determination of the combustion and explosion characteristics of dusts,1998, International Social Security Agency, Mannheim Mannheim, Germany.

[19]   Gummer, J., and Lunn, G., Ignitions of explosive dust clouds by smouldering and flaming agglomerates, *Journal of loss prevention in the process industries,* 2003, vol. 16, pp. 27-32.

[20]   Eckhoff, R.K., Dust explosion prevention and mitigation, status and developments in basic knowledge and in practical application, *International Journal of Chemical Engineering,* 2009, vol. 2009, pp.

[21]   Kauffman, C., Agricultural dust explosions in grain handling facilities, *Fuel-air Explosions, University of Waterloo Press, Waterloo, Ontario, Canada,* 1982, vol. pp. 305-347.

[22]   Cashdollar, K.L., and Hertzberg, M., *Industrial Dust Explosions: Symposium on Industrial Dust Explosions: Pittsburgh, Pennsylvania, 10-13 June 1986*, 1987, Astm International.

[23]   Cashdollar, K.L., Overview of dust explosibility characteristics, *Journal of loss prevention in the process industries,* 2000, vol. 13, pp. 183-199.

[24]   Zhi, Y., Dynamic risk analysis of dust explosions,2015, Memorial University of Newfoundland, Canada.

[25]   Songmene, V., and Olufayo, O., Advances in Fine and Ultrafine Particles Emission and Dispersion in Machining: cases of metals and granite, In *2020 IEEE 11th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT)*,2020, pp 36-45, IEEE.

[26]   Du, B., Huang, W., Kuai, N., Yuan, J., Li, Z., and Gan, Y., Experimental investigation on inerting mechanism of dust explosion, *Procedia Engineering,* 2012, vol. 43, pp. 338-342.

[27]   Andrews, S., and Lunn, G., A report on some tests on the jet ignition of dust clouds, In *Proceedings of the II Internet Conference on Process Safety*,2000.

[28]   Davis, S.G., Hinze, P.C., Hansen, O.R., and van Wingerden, K., Does your facility have a dust problem: Methods for evaluating dust explosion hazards, *Journal of loss prevention in the process industries,* 2011, vol. 24, pp. 837-846.

[29]   Amyotte, P.R., and Eckhoff, R.K., Dust explosion causation, prevention and mitigation: An overview, *Journal of Chemical Health & Safety,* 2010, vol. 17, pp. 15-28.

[30]   Norman, F., Berghmans, J., and Verplaetsen, F., The dust explosion characteristics of coal dust in an

oxygen enriched atmosphere, *Procedia Engineering,* 2012, vol. 45, pp. 399-402.

[31]   Di Benedetto, A., and Russo, P., Thermo-kinetic modelling of dust explosions, *Journal of loss prevention in the process industries,* 2007, vol. 20, pp. 303-309.

[32]   Gao, W., Mogi, T., Sun, J., Yu, J., and Dobashi, R., Effects of particle size distributions on flame propagation mechanism during octadecanol dust explosions, *Powder technology,* 2013, vol. 249, pp. 168-174.

[33]   Dufaud, O., Traoré, M., Perrin, L., Chazelet, S., and Thomas, D., Experimental investigation and modelling of aluminum dusts explosions in the 20 L sphere, *Journal of loss prevention in the process industries,* 2010, vol. 23, pp. 226-236.

[34]   Kauffman, C.W., Sichel, M., and Wolanski, P., Research on dust explosions at the University of Michigan, *Powder technology,* 1992, vol. 71, pp. 119-134.

[35]   Cashdollar, K.L., and CHATRATHI, K., Minimum explosible dust concentrations measured in 20-L and 1-m3 chambers, *Combustion Science and Technology,* 1993, vol. 87, pp. 157-171.

[36]   Bideau, D., Dufaud, O., Le Guyadec, F., Perrin, L., Genin, X., Corriou, J.-P., and Caleyron, A., Self ignition of layers of powder mixtures: Effect of solid inertants, *Powder technology,* 2011, vol. 209, pp. 81-91.

[37]   Westran, M., Sykes, F., Hawksworth, S., and Eaton, G., Dust explosion in sugar silo tower: investigation and lessons learnt, In *INSTITUTION OF CHEMICAL ENGINEERS SYMPOSIUM SERIES,*2008, p 1097, Institution of Chemical Engineers; 1999.

[38]   Ramírez, Á., García-Torrent, J., and Aguado, P.J., Determination of parameters used to prevent ignition of stored materials and to protect against explosions in food industries, *Journal of hazardous materials,* 2009, vol. 168, pp. 115-120.

[39]   Mintz, K., Upper explosive limit of dusts: experimental evidence for its existence under certain circumstances, *Combustion and Flame,* 1993, vol. 94, pp. 125-130.

[40]   Van Laar, G., and Zeeuwen, J., On the minimum ignition energy of dust-air mixtures, *Archiv fur Combustion,* 1985, vol. 5, pp. 145-159.

[41]   Traoré, M., Dufaud, O., Perrin, L., Chazelet, S., and Thomas, D., Dust explosions: How should the influence of humidity be taken into account?, *Process Safety and Environmental Protection,* 2009, vol. 87, pp. 14-20.

[42]   Dastidar, A., Amyotte, P., Going, J., and Chatrathi, K., Inerting of coal dust explosions in laboratory- and intermediate-scale chambers, *Fuel,* 2001, vol. 80, pp. 1593-1602.

[43]   Janès, A., Vignes, A., Dufaud, O., and Carson, D., Experimental investigation of the influence of inert solids on ignition sensitivity of organic powders, *Process Safety and Environmental Protection,* 2014, vol. 92, pp. 311-323.

[44]   Kuai, N., Huang, W., Yuan, J., Du, B., Li, Z., and Wu, Y., Experimental investigations of coal dust-inertant mixture explosion behaviors, *Procedia Engineering,* 2011, vol. 26, pp. 1337-1345.

[45]   Going, J.E., Chatrathi, K., and Cashdollar, K.L., Flammability limit measurements for dusts in 20-L and 1-m3 vessels, *Journal of loss prevention in the process industries,* 2000, vol. 13, pp. 209-219.

[46]   Lepik, P., Gabel, D., Adamus, W., Mokos, L., Mynarz, M., and Serafin, J., Determination of the minimum ignition energy on different devices, *TRANSACTIONS of the VŠB–Technical University of Ostrava, Safety Engineering Series,* 2015, vol. 10, pp. 8-14.

[47]   Amyotte, P., Chippett, S., and Pegg, M., Effects of turbulence on dust explosions, *Progress in Energy and Combustion Science,* 1988, vol. 14, pp. 293-310.

[48]   Russoa, P., and Di Benedettob, A., Review of a dust explosion modeling, *Chemical Engineering Transactions,* 2013, vol. 31, pp.

[49]   García-Torrent, J., Conde-Lázaro, E., Wilén, C., and Rautalin, A., Biomass dust explosibility at elevated initial pressures, *Fuel,* 1998, vol. 77, pp. 1093-1097.

[50]   Kim, Y.S., Lee, M.C., and Rie, D.H., Explosion characteristics of combustible wood dust in confined system: Analysis using oxygen consumption energy, *Journal of Mechanical Science and Technology,* 2016, vol. 30, pp. 5771-5779.

[51]   Zhang, H., Chen, X., Xie, T., Yuan, B., Dai, H., He, S., and Liu, X., Effects of reduced oxygen levels

on flame propagation behaviors of starch dust deflagration, *Journal of loss prevention in the process industries,* 2018, vol. 54, pp. 146-152.

[52]   Mittal, M., Limiting oxygen concentration for coal dusts for explosion hazard analysis and safety, *Journal of loss prevention in the process industries,* 2013, vol. 26, pp. 1106-1112.

[53]   Addai, E.K., Gabel, D., and Krause, U., Experimental investigations of the minimum ignition energy and the minimum ignition temperature of inert and combustible dust cloud mixtures, *Journal of hazardous materials,* 2016, vol. 307, pp. 302-311.

[54]   Ganesan, B., Parnell Jr, C.B., and McGee, R.O., Impact of inert mass fraction on explosible dusts, *Transactions of the Asabe,* 2014, vol. 57, pp. 13-19.

[55]   Deshmukh, A., Varma, S., Sakpal, N., Wakale, S., Agwan, A., and Patwardhan, S.D., Assessment of Explosion Hazards Associated With Nano-Powders, In *SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition,*2017, Society of Petroleum Engineers.

[56]   Pritchard, D., *Literature review: explosion hazards associated with nanopowders*, 2004, Health and Safety Laboratory.

[57]   Eckhoff, R.K., Influence of dispersibility and coagulation on the dust explosion risk presented by powders consisting of nm-particles, *Powder technology,* 2013, vol. 239, pp. 223-230.

[58]   Eckhoff, R.K., Does the dust explosion risk increase when moving from μm-particle powders to powders of nm-particles?, *Journal of loss prevention in the process industries,* 2012, vol. 25, pp. 448-459.

[59]   Blair, A.S., Dust explosion incidents and regulations in the United States, *Journal of loss prevention in the process industries,* 2007, vol. 20, pp. 523-529.

[60]   Dobashi, R., Studies on accidental gas and dust explosions, *Fire Safety Journal,* 2017, vol. 91, pp. 21-27.

[61]   Cao, W., Cao, W., Peng, Y., Qiu, S., Miao, N., and Pan, F., Experimental study on the combustion sensitivity parameters and pre-combusted changes in functional groups of lignite coal dust, *Powder technology,* 2015, vol. 283, pp. 512-518.

[62]   Amyotte, P.R., Solid inertants and their use in dust explosion prevention and mitigation, *Journal of loss prevention in the process industries,* 2006, vol. 19, pp. 161-173.

[63]   Gao, W., Mogi, T., Yu, J., Yan, X., Sun, J., and Dobashi, R., Flame propagation mechanisms in dust explosions, *Journal of loss prevention in the process industries,* 2015, vol. 36, pp. 186-194.

[64]   Beck, H., Glienke, N., and Möhlmann, C., *Combustion and explosion characteristics of dusts*, 1997, HVBG.

[65]   Ebadat, V., Dust explosion hazard assessment, *Journal of loss prevention in the process industries,* 2010, vol. 23, pp. 907-912.

[66]   Kalejaiye, O., Amyotte, P.R., Pegg, M.J., and Cashdollar, K.L., Effectiveness of dust dispersion in the 20-L Siwek chamber, *Journal of loss prevention in the process industries,* 2010, vol. 23, pp. 46-59.

[67]   Siwek, R., Determination of technical safety indices and factors influencing hazard evaluation of dusts, *Journal of loss prevention in the process industries,* 1996, vol. 9, pp. 21-31.

[68]   Continillo, G., Crescitelli, S., Fumo, E., Napolitano, F., and Russo, G., Coal dust explosions in a spherical bomb, *Journal of loss prevention in the process industries,* 1991, vol. 4, pp. 223-229.

[69]   Dorsett, H.G., *Laboratory equipment and test procedures for evaluating explosibility of dusts*, 1960, Vol. 5624, US Department of the Interior, Bureau of Mines.

[70]   Nagy, J., *Development and control of dust explosions*, 1983, Vol. 8, CRC Press.

[71]   Woskoboenko, F., Explosibility of Victorian brown coal dust, *Fuel,* 1988, vol. 67, pp. 1062-1068.

[72]   Reyes, O.J., Patel, S.J., and Mannan, M.S., Quantitative structure property relationship studies for predicting dust explosibility characteristics (K st, P max) of organic chemical dusts, *Industrial & Engineering Chemistry Research,* 2011, vol. 50, pp. 2373-2379.

[73]   Cesana, C., and Siwek, R., Operating instructions 20-l-apparatus, 6.0, *Adolf Kühner AG,* 2001, vol. pp.

[74]   Barton, K., *Dust explosion prevention and protection: A practical guide*, 2002, Elsevier.

[75]   Stahmer, K.-W., and Gerhold, M., The relationship between the explosion indices of dispersed dust and particle surface area and the heat of combustion, *Chemical Engineering Transactions,* 2016, vol. 48, pp. 295-300.

[76]   Eckhoff, R., and Mathisen, K., A critical examination of the effect of dust moisture on the rate of pressure rise in Hartmann bomb tests, *Fire Safety Journal,* 1978, vol. 1, pp. 273-280.

[77]   Andrews, G.E., Sattar, H., Heuscar-Medina, C., Slatter, D.M., Saeed, M.A., Phylaktou, H.N., and Gibbs, B.M., Dust Explosions: Recent Developments Including Pulverised Biomass Plenary Lecture, In *Proceedings of the 11th International Symposium on Hazards Prevention and Mitigation of Industrial Explosions,*2016, ISHPMIE.

[78]   Huéscar Medina, C., Explosion safety of biomass and torrefied biomass powders,2014, University of Leeds.

[79]   Amyotte, P.R., Pegg, M.J., and Khan, F.I., Application of inherent safety principles to dust explosion prevention and mitigation, *Process Safety and Environmental Protection,* 2009, vol. 87, pp. 35-39.

[80]   Mitchell, D., Preventing industrial dust explosions, *Occupational health & safety (Waco, Tex.),* 2002, vol. 71, pp. 52.

[81]   Carrol, D., and Frost, D., Managing catastrophic explosive dust risk in sugar handling: Installation at Imperial Sugar, Georgia, USA, *INTERNATIONAL SUGAR JOURNAL,* 2013, vol. 115, pp. 353-357.

[82]   Frank, Lees, M., Lees, F.P., and Mannan, S., *Lees' loss prevention in the process industries*, 2005, Butterworth-Heinemann.

[83]   Lees, F., *Lees' Loss prevention in the process industries: Hazard identification, assessment and control*, 2012, Butterworth-Heinemann.

[84]   Dufaud, O., Perrin, L., and Laurent, A., State of the art: promotion of early inherently safer design against dust explosions, *Chemical Engineering Transactions,* 2010, vol. 19, pp. 365-370.

[85]   Hassan, J., Khan, F., Amyotte, P., and Ferdous, R., A model to assess dust explosion occurrence probability, *Journal of hazardous materials,* 2014, vol. 268, pp. 140-149.

[86]   Frank, W.L., Dust explosion prevention and the critical importance of housekeeping, *Process Safety Progress,* 2004, vol. 23, pp. 175-184.

[87]   Eckhoff, R., Prevention and mitigation of dust explosions in the process industries: A survey of recent research and development, *Journal of loss prevention in the process industries,* 1996, vol. 9, pp. 3-20.

[88]   Krasnyansky, M., Prevention and suppression of explosions in gas-air and dust-air mixtures using powder aerosol-inhibitor, *Journal of loss prevention in the process industries,* 2006, vol. 19, pp. 729-735.

[89]   Field, P., Dust Explosions, vol. 4,2012, Elsevier, Hertfordshire, England.

[90]   Dastidar, A.G., Amyotte, P.R., and Pegg, M.J., Factors influencing the suppression of coal dust explosions, *Fuel,* 1997, vol. 76, pp. 663-670.

[91]   Stern, M.C., Ibarreta, A., and Myers, T.J., Assessment and mitigation of combustible dust hazards in the plastics industry, In *AIP Conference Proceedings,*2015, p 180003, AIP Publishing LLC.

[92]   Holbrow, P., Andrews, S., and Lunn, G., Dust explosions in interconnected vented vessels, *Journal of loss prevention in the process industries,* 1996, vol. 9, pp. 91-103.

[93]   Taveau, J., Secondary dust explosions: How to prevent them or mitigate their effects?, *Process Safety Progress,* 2012, vol. 31, pp. 36-50.

[94]   Ferrara, G., Willacy, S., Phylaktou, H., Andrews, G., Di Benedetto, A., Salzano, E., and Russo, G., Venting of gas explosion through relief ducts: Interaction between internal and external explosions, *Journal of hazardous materials,* 2008, vol. 155, pp. 358-368.

[95]   Lunn, G., Brookes, D., and Nicol, A., Using the KSt nomographs to estimate the venting requirements in weak dust-handling equipment, *Journal of loss prevention in the process industries,* 1988, vol. 1, pp. 123-133.

[96]   Schwab, R., Guide to dust explosion prevention and protection—part 3: venting of weak explosions

and the effect of vent ducts: BMHB, design guide for practical systems: GA Lunn The Institution of Chemical Engineers, 165–171 Railway Terrace, Rugby, CV21 3HQ, UK, 1988, pp 185,1989, Elsevier.

[97] Schumann, S., and Wirkner-Bott, I., Dust Explosion Venting: Secondary Explosion for Vessel Volumes up to 250 m^ 3, *EuropEx Newsletter,* 1993, vol. 22, pp. 2-2.

[98] Jiang, X., Fan, B., Ye, J., and Dong, G., Experimental investigations on the external pressure during venting, *Journal of loss prevention in the process industries,* 2005, vol. 18, pp. 21-26.

[99] Tamanini, F., and Valiulis, J.V., A correlation for the impulse produced by vented explosions, *Journal of loss prevention in the process industries,* 2000, vol. 13, pp. 277-289.