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THE EFFECT OF INITIAL TURBULENCE DURING DISPERSION OF WHEAT FLOUR AND RICE FLOUR DUSTS TOWARDS EXPLOSION SEVERITY

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ABSTRACT

This thesis presents a dust explosion characteristics of commercial rice flour at different concentration and ignition time. The rice flour with a moisture content of 7.79% (undried) and a mean diameter of D50 = 28.77 μm was used in this work. The moisture in the rice flour was further reduced by oven drying to 2.47% (dried) and both samples were tested for comparison. Experiments were performed in a 20 L spherical explosion chamber to obtain the maximum explosion overpressure (Pmax), rate of pressure rise (dP/dT), minimum explosibility concentration (MEC), and deflagration index (Kst) of undried and dried commercial rice flour. The dust samples and air mixtures were ignited by two chemical ignitors at the ignition time (tv) of 60 and 100 ms. The propagation of pressure wave during the explosion process was measured by the piezoelectric pressure sensor. The Pmax for undried and dried rice flour at tv of 60 ms were found at 11.25 bar and 8.6 bar, respectively. The Pmax was obtained at the highest concentration of dust (1000 kg/m^3). The highest pressure rise of undried sample was obtained at 81 bar/s whereas for dried sample the highest value was obtained at 98 bar/s. MEC of undried sample was found at 600 kg/m^3 and the dried sample at 500 kg/m^3. The Kst of dried rice flour at ignition time 60 ms was found to be the highest at 26.6 bar m/s. It was found that the severity of the dust explosion increases proportionally with the dust concentration. Rice flour with higher moisture content has a lower explosion severity, than that of dried sample. Findings from this work provide a useful safety information about the severity and explosibility of rice flour, for which unsafe handling and operation may be minimized.

ABSTRAK

Tesis ini menunjukkan ciri-ciri letupan debu tepung beras komersial pada kepekatan dan waktu pencucuhan yang berbeza. Tepung beras dengan kadar air 7.79% (belum dikeringkan) dan diameter min D50 = 28.77 μm digunakan dalam kerja ini. Kelembapan dalam tepung beras dikurangkan lagi dengan pengeringan oven menjadi 2.47% (kering) dan kedua-dua sampel diuji untuk perbandingan. Eksperimen dilakukan di ruang ledakan sfera 20 L untuk mendapatkan tekanan letupan maksimum (Pmax), kadar kenaikan tekanan (dP / dT), kepekatan letupan minimum (MEC), dan indeks deflagrasi (Kst) tepung beras komersial yang tidak kering dan kering . Sampel debu dan campuran udara dinyalakan oleh dua penyekat kimia pada waktu penyalaan (tv) 60 dan 100 ms. Perambatan gelombang tekanan semasa proses letupan diukur oleh sensor tekanan piezoelektrik. Pmax untuk tepung beras yang belum dikeringkan dan kering di tv 60 ms masing-masing ialah pada 11.25 bar dan 8.6 bar. Pmax diperoleh pada kepekatan debu tertinggi (1000 kg/m^3). Kenaikan tekanan tertinggi sampel tidak kering diperoleh pada 81 bar / s manakala untuk sampel kering nilai tertinggi diperoleh pada 98 bar/s. MEC sampel tidak kering didapati pada 600 kg/m^3 dan sampel kering pada 500 kg/m^3. Kst tepung beras kering pada waktu penyalaan 60 ms didapati paling tinggi pada 26.6 bar m/s. Didapati bahawa keparahan letupan debu meningkat sebanding dengan kepekatan debu. Tepung beras dengan kandungan lembapan yang lebih tinggi mempunyai keparahan letupan yang lebih rendah daripada sampel kering. Penemuan dari karya ini memberikan maklumat keselamatan yang berguna mengenai keparahan dan letupan tepung beras, yang mana pengendalian dan operasi yang tidak selamat dapat dikurangkan.

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CHAPTER 1

1.1 Introduction

A large number of major and minor dust explosions have happened and found in literature since 1785 (Abbasi & Abbasi, 2007), leading to a significant problem of injuries, fatalities, destruction of equipment and property loss. Severe dust explosions may not only cause loss of life and properties but may also lead to undesirable environmental emissions (Tascón, 2018). One of the first recorded catastrophic of dust explosion was written by Count Morozzo, that took place in a flour warehouse in Turin, Italy (Eckhoff, 2003b). Investigation from United State Chemical Safety and Hazard Investigation Board (CSB) shows that dust explosion had common causes in their findings of three major incidents happened in USA in 2003, in spite of their geographical and industrial diversity. One of the causes is that most Material Safety Data Sheet (MSDS) for explosive powders do not contain dust explosion hazard information (Blair, 2007). Surprisingly the common cause of dust explosion reported by CSB was the same as reported by Department of Safety and Health in Malaysia (DOSH). DOSH reported that on 17th of March 2008, dust explosion occurred at a tunnel of Malayan Flour Mills factory in Lumut, Perak while carrying out welding works. The explosion from mixed types of flour killed four people and two were in serious injuries. DOSH also reported that more than 100 explosion incidents happened in Malaysia between 1980 and 2015 that killed 140 workers, injured 1895 and extensively damaged industrial facilities. Lacking of safety and prevention in handling dust would lead to catastrophic disaster as mentioned on the incidents above. Hence, the key knowledge about the fundamental explosive parameters on dust explosion as well as the influence of the actual dust cloud generation process need to be understood in order to reduce the potential of explosion severity. A dispute has been around for a very long time about the influence of dust dispersion and turbulence inside the laboratory scale experiments as it will give different results as compared to explosion in full industrial scale. For instance, research done by Eckhoff (2015) showed that in all laboratory tests both maximum explosion overpressure (pmax) and maximum rate of pressure rise $(dp/dt)_{max}$ were significantly lower for the soya meal than the wheat grain dust in contrast with the 500 m^3 vented silo cell; the soya meal was severe than the wheat grain dust. Types of explosibility chambers, sizes and their feasibility in providing a reliable explosibility data are also debated over the past years. Siwek (1977) and Bartnecht (1989) found that the turbulence level exist in 20 L spherical chamber and 1 m^3 spherical chamber when the ignition delay were at 60 ms and 600 ms respectively. Their study was accepted as a standard procedure for recommended ignition delay for explosibility of dust clouds in 20 L spherical chamber (ASTM, 2005). Contrary with investigation done by Dahoe *et al.* (2001) showed that equal turbulence level exist in the same chambers at 200ms and 600 ms respectively . In this research, a commercial wheat flour dust and rice flour dust undergo drying process and without drying process would be used as a sample. The samples would be exploded in a 20 L Siwek spherical chamber to measure the explosion characteristics. The explosion sensitivity parameter which is minimum explosibility concentration (MEC) and explosion severity characteristics which include maximum explosion overpressure (Pmax) and dust deflagration index (Kst) would be measured in Siwek 20 L spherical chamber experimentally at different ignition time.

1.2 Statement of Research Problem

Dust explosions have a potential to occur in various industries handling miscellaneous organic and inorganic powders and dust. Those industries include food industries, wood and paper products, metal and metal products, power generation, coal mining and textile manufacturing. Dust explosion usually occurs in various unit operations include mills, grinders, dryers, and other modes of transportation (Eckhoff, 2003b). Over past years, there have been many numerical/correlation models and developed systems towards prevention and mitigation of dust explosion in processing industries. Nevertheless, the fundamental knowledge is still significant in getting thorough understanding on dust explosion hazard as there is an inevitable conflict between the correlation and the complex nature of the process itself in practice. It is crucial to know the physical characteristics and dust behaviour as well as dust explosibility data in order to apply an effective protection and safety systems available to prevent and mitigate the dust explosion in industries. Apart from that, the process related parameters such as degree of dust dispersion, initial turbulence, and dust concentration also play key roles. Full scale of experimental dust explosion is much more favourable than laboratory scale and provides reliable data following the hazards of explosible dust presents in industry. However, due to cost, energy and time, many researches have been done on a laboratory scale. Nevertheless, reproducibility in laboratory scale might create issues due to difference dust cloud turbulence, dust cloud behaviour, and dust concentration in contrast with full scale test. Additional data and development of numerical tools based on computational fluid dynamics (CFD) are required to solve those difficulties. Some researchers have been working on this field for many years by simulating the turbulence of dust cloud in 20 L spherical chamber by using a CFD model (Bind *et al.*, 2011; Daniel *et al.*, 2018; Di Sarli *et al.*, 2013; Di Sarli *et al.*, 2014; Murillo, 2017). It is therefore possible nowadays to locate some data in the literature regarding different types of dust. However, these data should not be considered applicable in all cases, and more data is still required (Abbasi & Abbasi, 2007). The main concern of this study is the role of chemical and physical characteristics of dust, presence of moisture and behaviour of dust cloud turbulence in 20 L Siwek chamber and how does it affect the whole dust explosion parameters within the 20 L Siwek spherical chamber and the influence of ignition time. Salamonowicz *et al.* (2015) and Murillo (2017) have tested the wheat flour dust without drying experimentally and numerically in 20 L spherical chamber to analyse the dust dispersion and turbulence while Eckhoff and Fuhre (1984) studied experimentally the non-dried wheat starch in a $500m^3$ silo cell. The measurement of sensitivity and severity in this study is focused on food industries associated with commercial wheat flour dust and rice flour dust which can be carried out by determining the flammability and explosibility parameters of materials (minimum explosion concentration, maximum explosion overpressure and dust deflagration index).Those explosibility data will be validated with results from numerical modelling by using CFD at different ignition time. A database of GESTIS-DUST-EX showed that rice flour falls under explosibility ranking based on K_{st} Group St1 which shows that rice flour has a potential to explode (GESTIS-DUST-EX, undated). A data from Jan *et al.* (2018) showed that ash content for rice flour was lower for non-basmati rice flour as compared to ash content of wheat flour from a data taken in a research by Fišteš *et al.* (2014) 1.01% and 1.57% respectively. Research done by Chawla *et al.* (1996) showed that ash which is incombustible may act as inertant by absoption or thermal energy released from the combustion reaction. It is very important for this reasearch to study and compare results of rice flour as it has been used widely specifically in Malaysia for cooking and baking dishes. Daniel *et al.* (2018) found that there is a minimum value for the turbulence in 20 L spherical test vessel for an ignition delay time greater than 60-70ms, after which the turbulent kinetic energy was stable and fluctuation of velocity also decreased. The severity data and dust cloud behaviour would be very crucial on hazard analysis for prevention and mitigation of dust explosion and continuous improvement on safety in industries. Compared to other Asian countries such as China and India, there are a sparse research in dust explosion studies for Malaysian context and studies on flour grain dust explosion is critical following many flour factories in Malaysia. The awareness on danger of dust explosion is still lack in Malaysia despite the accident associated with mixed type of flour dust explosion back in 2008 in Malayan Flour Mills, Lumut, Perak.

1.3 Objectives of Research

1) To characterize the chemical and physical properties of rice flour dusts.
2) To measure the explosion severity characteristics (maximum explosion overpressure (Pmax), dust deflagration index (Kst)) and explosion sensitivity parameter (minimum explosible concentration (MEC) of the rice flour dusts with different ignition time.

1.4 Scopes of Research

1) Commercial rice flour dried and undried are used to study the explosion characteristics.
2) Performing dust explosion in Siwek 20 L spherical chamber to obtain the maximum explosion overpressure (P_{max}), rate of pressure rise (dP/dT), dust deflagration index (K_{st}) and minimum explosibility concentration (MEC) at different ignition time (50ms,60ms and 70ms)

CHAPTER 2 : LITERATURE REVIEW

2.1 Dust Explosion

Dust explosion is the very fast burning of fine particles suspended in a large volume of air or other gaseous oxidant. Generally, dust explosion is a deflagration, which the propagation velocity is less than the speed of sound in the unreacted medium (Amyotte & Eckhoff, 2010). Dust explosion is persistent in contributing a constant hazard to process and manufacturing industries in spite of extensive research and development in laboratory scale, full scale and numerical modelling. Dust is defined as any finely divided solid with 420 µm or less in diameter (NFPA, 2002). The type of dust that can explode include natural organic materials such as grain, wood, linen, sugar, etc., synthetic organic materials such as plastics, organic pigments, pesticides, pharmaceuticals, etc., coal and peat as well as metals like aluminium, magnesium, zinc, iron, etc. The materials that stable as oxides such as silicates, nitrates, sulfates, carbonates, and phosphates cannot explode (Eckhoff, 2016). Dust explosion in industries usually happens in process equipment such as mills, dryers, mixers, classifiers, conveyors, storage silos and hoppers (Eckhoff, 2009b).

2.2 Mechanism of Dust Explosion

In dust cloud, opposite to premixed gases, inertial forces can produce fuel concentration gradients (Eckhoff, 2009a). 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” as illustrated in **Figure 2.1** consists of combustible dust, oxidant, ignition source or heat, confinement and mixing. 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 (Cashdollar, 2000). A devastating open space dust explosion happened on 27 June 2015 at “Color Play Asia” party in Taiwan. The organizer sprayed coloured corn starch powder from the stage with high-pressure bottles, and the powder particles were repeatedly blown into the air by air blowers. 498 victims were seriously injured from second to third-degree burns and were transferred to 43 hospitals across Taiwan (Liao *et al.*, 2016). This explosion may be a deflagration or a detonation depending on the rate of reaction and the resulting burning velocity. 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 event but not the detonation due to the quick respond time for the system to sustain.

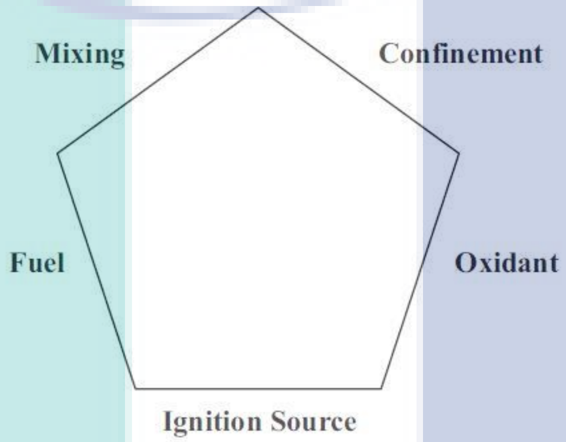

Figure 2.1 The explosion pentagon (Amyotte, 2014)

2.3 Dust Cloud Formation Processes

The explosion generally arises from rapid release of heat due to chemical reaction of fuel and oxygen which then produce oxides and heat (Eckhoff, 2003b). An explosive dust cloud is likely to be happened when a layer or deposit of dust disperses the particles in the air until the dispersion drops into the explosive range (Eckhoff, 2005). A 1 mm layer of dust of 500 kg/m^3 on the floor can generate a cloud with average concentration of 100 g/m^3 if distributed evenly in a 5 m high room (Abbasi & Abbasi, 2007). Dust explosion is initiated with a primary explosion and usually occurs inside the process vessels such as cyclones, hoppers, filters and bucket elevators. The blast from the primary dust explosion can generate the secondary explosion in other vessel ahead of the flame by entraining dust deposits and layers (Eckhoff, 2005). This phenomenon of entrainment of dust layers in the long tubes by the blast wave heading a dust explosion propagating along the tube has been extensively researched by Austin *et al.* (1933) and Kauffman *et al.* (1992). The likelihood of explosion in the second vessel has been found experimentally and relies on the type of venting of the second vessel, the severity of primary explosions, the duct diameters and the presence of any blockage in the connecting duct (Andrews & Lunn, 2000). The ruptures from the primary explosion of containment system may disperse the dust layers into the air causing the secondary explosions which under certain circumstances can be more severe than the primary one depending on the thickness of the dust layers and the area occupied by the dust layers (Davis *et al.*, 2011). What could be rather worst is when a dust explosion domino effect (DEDE) could happen as a result of a series of dust explosions. A model of DEDE has been developed by Mukhim *et al.* (2017) to study the risk analysis of domino effects by using Bayesian Networks where the units or areas with high risks of dust explosions are identified based on a comparison between the unit's characteristics and the required elements of dust explosions. The unit with the most number of necessary factors for dust explosions is considered to be the location of the primary dust explosion. Event tree was used to calculate the likely propagation route of potential domino effects.

2.4 Ignition Processes

A combustible dust cloud will only burn when it becomes ignited by a source of sufficient heat or flame. Ignitions may be triggered in many ways from low energy to high energy ignition sources. However, the ignition sources differ in terms of energy, power and temperature. A potential dust may become explosive by self-heating due to exothermic reaction. Research has shown that under certain circumstances, the deposited dust or dust layer may develop high temperatures which lead to internal combustion as oxygen can enter the particle surface throughout the layers due to the porous structure of dust layer and makes the heat conductivity of the layer becomes low. Contaminants such as oil, water, or wood present in the combustible dust mixture may also contribute to self-heating. A situation where a large mass of dust stored under high initial temperature may also trigger the combustible dust to explode as dust in large quantities has a high surface area and enough air circulation (Abbasi & Abbasi, 2007; Eckhoff, 2003b)

Slow heating of dust deposit is called a smouldering nest. Previous research has shown that smouldering nest is poor ignition source as it fails to ignite most combustible dusts even the temperature is far higher than the minimum ignition temperature (MIT) of the dust cloud. However, it is able to ignite the sulphur clouds at temperature above 700 - 800°C (Gummer & Lunn, 2003). The powerful triggers of ignition are open flame from welding, cutting flames or smoking. It supplies excess oxygen that may give rise to both sensitivity and severity of explosion characteristics and the primary explosion is very likely to happen (Eckhoff, 2003b).

Explosion may be generated from hot work such as welding and cutting as well as hot surfaces such as lamps, steam pipes, heaters or hot surfaces generated unintentionally from moving equipment such as engines, blowers, mills and bearings. The hot surfaces also believed to increase the temperature of dust layer due to thermal insulation which would increase the explosion violence of the dust cloud. Other dust explosion triggers are electrical and electrostatic sparks, lightening and shockwaves (Abbasi & Abbasi, 2007; Eckhoff, 2003b)

2.5 Classification of Dust

Dust can be classified in many ways according to its explosibility value. All explosible dusts are combustible, but not all combustible dusts are readily explosible (Vijayaraghavan, 2004). The main principal to differentiate a combustible dust that presents a flash fire or explosion hazard and a material form that burns as an ordinary combustible is whether a cloud formed by the material can support self-sustaining flame propagation. The dispersion of dust as a cloud in air reduces diffusion limitations on the rate of combustion, allows fast propagating flames (flash fire), and can create powerful overpressures that can cause building to crumble (Rodgers & Ural, 2011). There are also very explosive powders such as gunpowder and dynamite, which can easily burn without oxygen (British Standard, 2006) while anthracite and graphite are not easily explosible, although they have higher value of heat of combustion. According to the classification from HM Factory Inspectorate of the Department of Employment, UK, Group A is classified as the dust that propagated a flame when ignited in the test apparatus. Group B is for the dust that does not propagate a flame in the test apparatus. They are applicable for dusts at or close to atmospheric temperature (25^{o}C) at the time of ignition (Factory, 1968). Dusts which are ignitable but not explosive may explode if blended with fuel dust; for example fly ash may explode when spiked with pulverized coal or petroleum coke (Amyotte *et al.*, 2005).

Dust also can be classified under Combustion Class (CC) which is measured by ignitability of a dust layer and combustibility of dust layer based on the behaviour of a defined dust heap when subjected to a gas flame or hot platinum wire (Gummer & Lunn, 2003; ISSA, 1998). The classification of dust base on Combustion Class is more favourable as it is not dependent on temperature as different dust has different minimum of ignition temperature. The classification is shown in Table 2.1.

4.0. Table 2.1 The classification of dust base on Combustion Class (CC)

Combustion Class (CC)	Description
CC1	No ignition; no self-sustained combustion
CC2	Short ignition and quick extinguishing; local combustion of short duration
CC3	Local burning or glowing without spreading; local sustained combustion but no propagation
CC4	Spreading of glowing fire; propagation smoldering combustion
CC5	Spreading of an open fire; propagating open flame
CC6	Explosible burning; explosive combustion

2.6 Factors Affecting Explosion Sensitivity and Severity of Dust Explosion

2.6.1 Initial Turbulence

Practically, turbulence takes place when the fluid motion becomes very complicated, irregular, and chaotic (Ruelle & Takens, 1971). The initial turbulence also known as cold turbulence is generated between the beginning of dust dispersion and the ignition of the dust cloud (Murillo, 2017). Some of turbulence may always be present in the test equipment before ignition during dust dispersion by using air blast in a closed vessel. The turbulence level may vary from one apparatus to the next depending on factors such as vessel volume and geometry as well as the dispersing of air pressure (Amyotte *et al.*, 1988). The second kind of turbulence is generated by the explosion itself by expansion induced flow of unburned dust cloud ahead of the propagating flame. The degree of this type of turbulence depends on the speed flow and the geometry of the structure (Eckhoff, 2003a). In an industrial context, the turbulence generated by fans or other moving part of machines, may cause the formation of dust cloud or aggravate the hazard in an existing dust cloud. Attention must be taken more on the handling of grain dust area whereby the velocities of dust/air suspension may be high (Swift, 1982). The effects of initial turbulence towards dust explosion parameters can be investigated throughout the analysis of experimental data obtained at different ignition delays (Murillo, 2017). Ignition delay times affect the uniformity and turbulence of dust and it is difficult to differentiate the correlation between them from experimental results according to ignition delay times, unless both the initial turbulence and uniformity are clear (Zhang *et al.*, 2018). In order to find a prescribed procedure with 20 L spherical sphere, Bartnecht (1989) and Siwek (1977) found that severity parameter, K_{st} values tested in 20 L spherical vessel were in agreement with the 1 m^3 spherical vessel when the ignition time was 60 ms. Figure 2.2 shows the K_{st} values of various dusts measured in the 1 m^3 spherical chamber and the 20 L spherical chamber. Contrary with a study done by Dahoe *et al.* (2001), it showed that discrepancies existed for K_{st} when the turbulence levels were equal only when the 20 L spherical vessel and 1 m^3 spherical vessel were tested at ignition delay time of 200 ms and 600 ms respectively. This is due to the fact that combustion rate changes with turbulence. This phenomenon was in agreement with the turbulence level investigated by Pu *et al.* (1991).

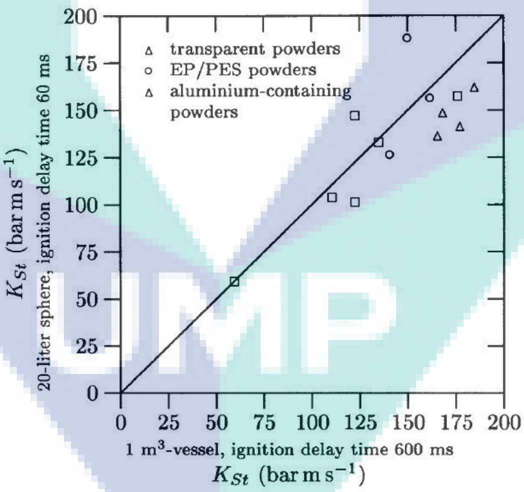

Figure 2.2 Kst values of various dusts measured in the 1 m3 vessel and the 20 L sphere (Bartnecht, 1989)

As more data is needed to ensure that the role of turbulence in dust explosion is understood, a numerical modelling has been done by many researchers recently. The role of variable turbulence in determining the state of mixedness of a dust cloud is a dominant concern in understanding dust explosion likelihood and severity (Amyotte, 2014). Di Benedetto *et al.*

(2013) performed simulations on turbulent flow and dust dispersion in a 20 L explosion vessel. The maximum value of turbulent kinetic energy was achieved in the feeding phase. After the feeding phase, the turbulent kinetic energy decays with time and the dispersed dust gets uniform gradually. During the feeding, uniformity of dust dispersed into the sphere is the worst (Di Benedetto *et al.*, 2013). In order to understand the role of turbulence in a dust/air explosion, it is necessary to study the correlation between turbulence and uniformity in dust dispersion. However, it is difficult to measure the local concentration of dust dispersed in an explosion sphere (Kalejaiye *et al.*, 2010; Serafin *et al.*, 2013). Kalejaiye *et al.* (2010) used optical dust probes to measure optical transmittance through the dust cloud within a 20 L sphere. Unfortunately, their measured results were optical transmittance instead of dust concentration. Di Sarli *et al.* (2013) and Di Sarli *et al.* (2014) simulated numerically the turbulent flow field and the dust concentration distribution in the 20 L bomb. Their results show that the dust concentration is not uniform in the standard test for dust explosion (ASTM, 2010). Zhang *et al.* (2018) simulated numerically a study of turbulence in 20 L spherical chamber at various concentration of aluminium dust. They analysed the dispersion and explosion of the dust with a double nozzle pneumatic dispersion system of hemispherical nozzle with multi holes which were symmetrically mounted in the wall of the chamber. It was observed that turbulence is a significant factor at lower nominal concentration while the uniformity of aluminium dust suspended in air that had more significant influence at higher nominal concentration.

2.6.2 Dust Concentration

Dust in air mixtures must be within a certain concentration in order to make the dust explosion to happen. At concentration below minimum concentration, the heat releases from the combustion of the particles near the ignition source is not enough to promote the ignition of the particles. As a result, flame propagation would not occur. At concentration above the minimum, flame propagation is favoured and the flame speed increases with the increase of coal dust concentration. As the flame speed increases, the time for devolatilization decreases and a smaller percentage of the volatile matter is achieved gradually. Generally, the maximum concentration of dust is very difficult to achieve because of non-uniformity of concentration throughout the vessel and at high concentration, a considerable amounts of carbon monoxide are formed and the dust tends to agglomerate and inhibit the dispersion of dust cloud (Kumar *et al.*, 1992; Woskoboenko, 1988). Cashdollar (2000) reported in his experiment for high volatile bituminous coal dust, at higher dust concentrations, the maximum overpressures and rates of pressure rise become even as all of the oxygen in the chamber is consumed. However several researches have been done to find the upper explosive limits as reported by Mintz (1993). Deguingand and Galant (1981) found that the upper limit for coal dusts which have particle sizes of 13 μm and 50 μm are around 2500 - 3000 g/m^3 roughly. Many methods and apparatuses have been developed to obtain the minimum explosive concentration but there are so many different data depending on the researchers and many factors such as dust cloud formation method, uniformity of dust cloud and details of equipment (Nifuku *et al.*, 2000). The physical structures and chemical properties of dust have greatly influent both explosibility and ignition sensitivity. Hence, the correct sampling and a good method to obtain the chemical characteristic of dust need to be performed in order to get the right assessments of the real industrial hazards (Eckhoff, 2003b). The concentration for organic dust and coal to trigger explosion is ranging from a minimum of 100 g/m^3 to a few kg/m^3 as illustrated in Figure 2.3 (Eckhoff, 2009b). Figure 2.4 shows the explosibility data with different dust concentration which indicates the increase of P_{max} and K_{st} as the dust concentration increases until the optimum concentration is reached (Cashdollar, 2000).

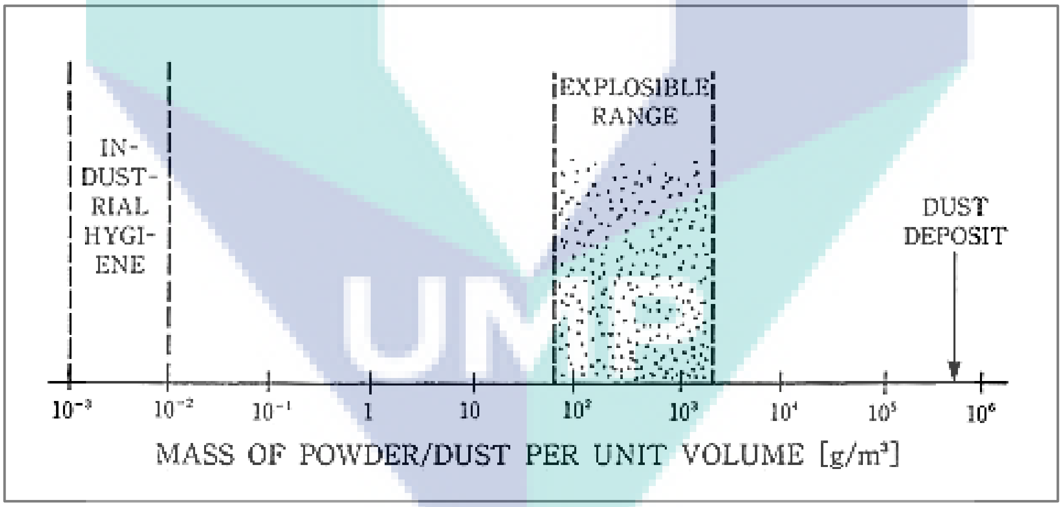

Figure 2.3 Range of explosive dust concentrations in air at normal temperature and pressure for a natural organic dust (Eckhoff, 2009b)

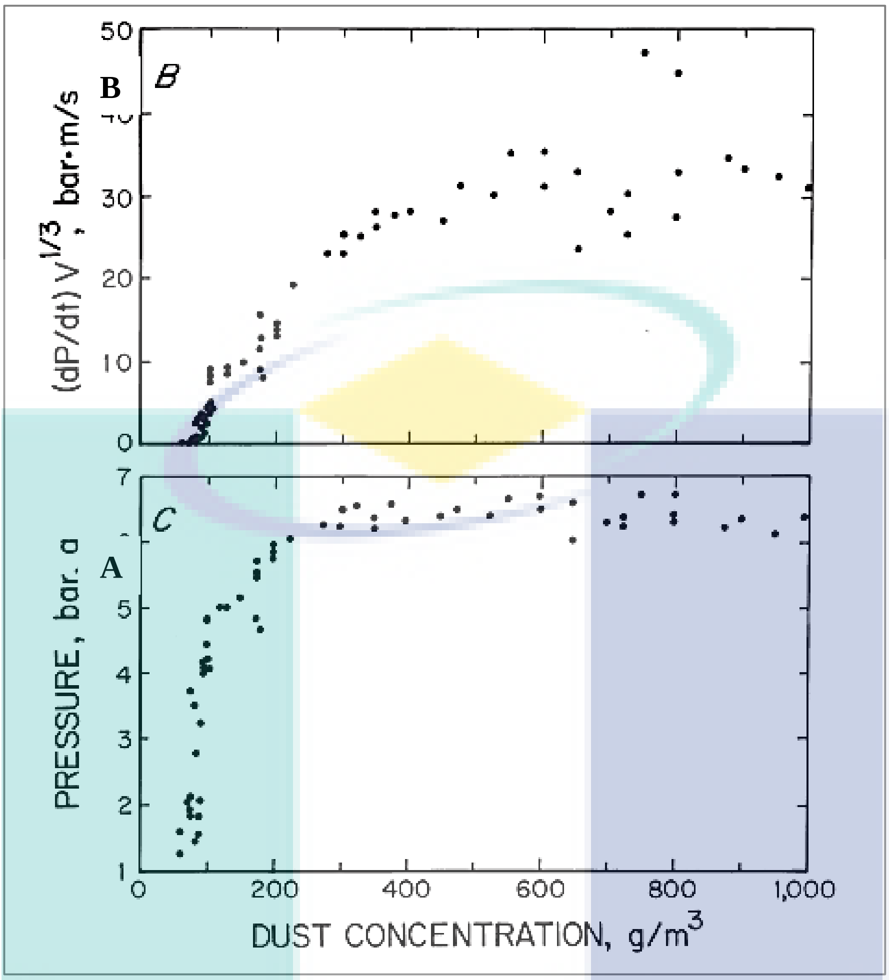

Figure 2.4 Explosibility data for high volatile bituminous coal dust (Cashdollar, 2000)

2.6.3 Presence of Moisture

It is worth to note that explosibility decreases as moisture increases. Moisture present in the dust may reduce both the explosion violence and ignition sensitivity of dust clouds. Figure 2.5 shows how increasing dust moisture content significantly reduces the ignition sensitivity of the dust. The effect of moisture content towards minimum ignition energy is quite significant especially for tapioca dust (van Laar & Zeeuwen, 1985). Mintz (1993) had done an explosion test to both dried and undried cornstarch with particle sizes between 120 µm to 150 µm. It was found that the dried sample becomes explosive while another one is not explosible. Study by Woskoboenko (1988) has shown that the explosion severity increases marginally with decreasing of moisture content as illustrated in Figure 2.6. The work involves two different particle sizes of 21.4 µm and 13.2 µm where the moisture content was varied between 0 % to 14 %. It is found that the dust deflagration index increases linearly with decreasing of moisture content and change the classification of the dust from explosive (St1) to the strongly explosive (St2) category at about 4 % moisture. For the very fine dust, moisture content becomes the major factor. The coal flammability of high content moisture particles is reduced due to the longer time for devolatilization and oxidation as the particles have a tendency to absorb multilayer of water. The explosible concentration range was observed to increase from 0.16 - 7.0 kg/m^3 to 0.10 – 10 kg/m^3 yet, it is only valid for minimum concentration with difference of 0.01 kg/m^3 (Woskoboenko, 1988). Another study reported that the impact of moisture is strongly depends on the chemical properties of the particles. The water may inhibit or increase the explosibility and severity of the particles depending on how the water is exposed to the particles. For example, the maximum rise of pressure rate of aluminium dust increases with the increase of water content after stored in controlled humidity for a period of time. This is due to an adsorption process that modified the particles chemically. Generally, humidity tends to lower the ignition sensitivity of organic materials, depending on the hydrophobic or hydrophilic nature (Traoré *et al.*, 2009). This is because when aluminium is exposed to water vapour, the water could be trapped as hydrates, and reacted with alumina to form hydroxide, through hydroxyl bounds or adsorbed onto the surface (Pethrick *et al.*, 1996).

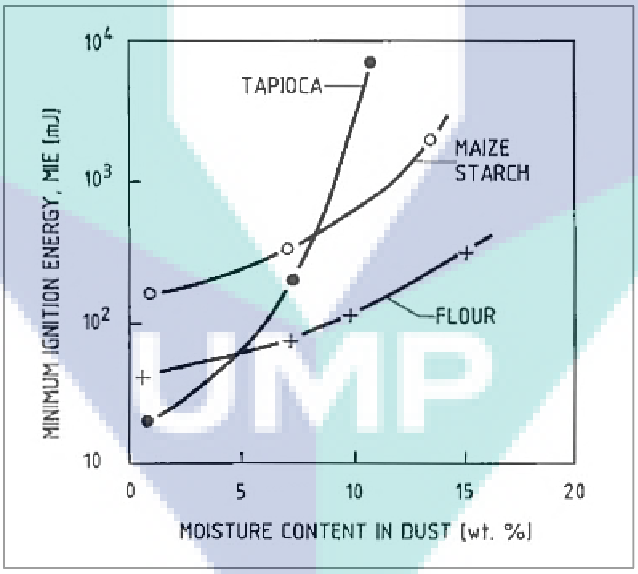

Figure 2.5 Influence of dust moisture content on minimum electric spark ignition energy of three types of dust (van Laar & Zeeuwen, 1985)

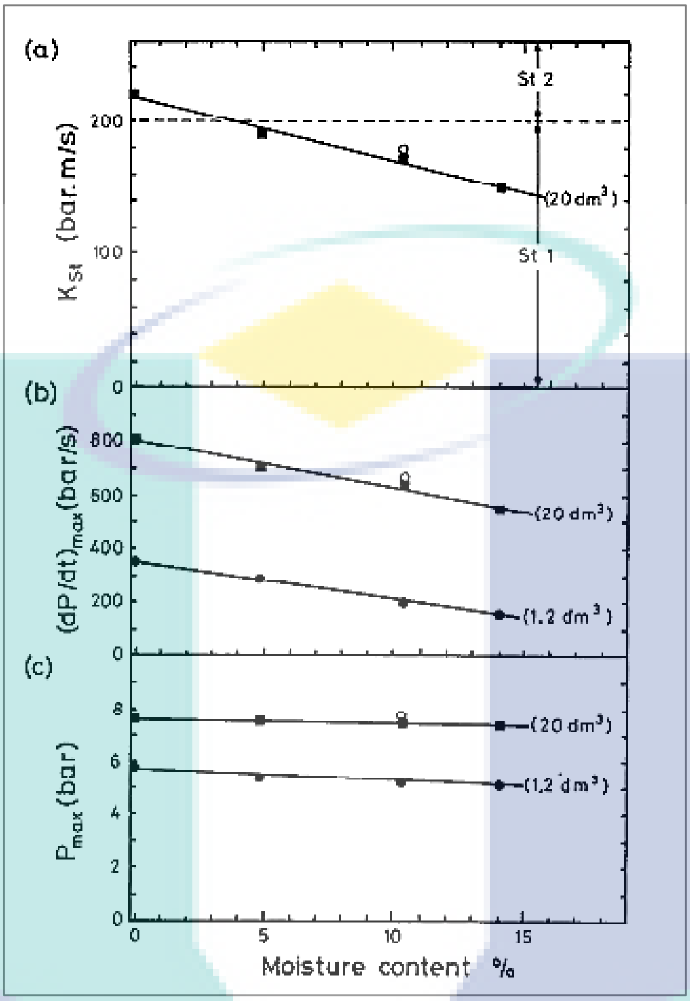

Figure 2.6 The effect of moisture content on the explosibility of Morwell coal dust by using 20 dm^3 chamber and 1.2 dm^3 chamber (Woskoboenko, 1988)

2.6.4 Particle Size

It has been widely accepted and well-known fact that the particle size of dust has strong influence on the dust explosibility. The explosibility increases as the dust particle size decreases. Study by Cashdollar (2000) reported that smaller particles are dispersed more readily, remained airborne longer and participated in the burning process easily. Lower energy is required for the smaller dust particles and will decrease the minimum concentration as well as minimum ignition temperature. This is due to the smaller particles have greater surface area per mass.   also reported that mixing a coarse non explosible polyethylene dust with 5 % of a fine explosible polyethylene dust would make the mixture explosible. The minimum explosibility concentration (MEC) is independent of size for the very finer particle size but at larger sizes, particularly above 100 µm, the MEC increases with particle size until it cannot be easily ignited. The smaller particle sizes have greatly affected the maximum explosion overpressure, (P_{max}) and maximum rate of pressure rise, (dP/dT). The optimum concentration for P_{max} increases significantly when the particles size increases (Dufaud *et al.*, 2010; Soundararajan *et al.*, 1996). The overpressures of very fine and reactive dust can reach up to 26 bar and can even change the transition to quasi-detonative combustion (Kauffman *et al.*, 1992). Further decrease in particle size for most organic materials and coals will no longer increase the combustion rate as the devolatilization no longer controls the explosion rate (Eckhoff, 2009b). Tascón (2018) studied the experimental results of explosion severity reported by Castellanos *et al.* (2014) and Li *et al.* (2016) for influence of particle size distribution skewness (Sk_G) on aluminium dust and coal dust respectively with the same median diameter (D_{50}) but with different values of particle size polydispersity (σ_D). Figure 2.7 showed that higher maximum overpressure (P_{max}) obtained for smaller values of Sk_G which means that the samples had more fine particles than coarse particles.

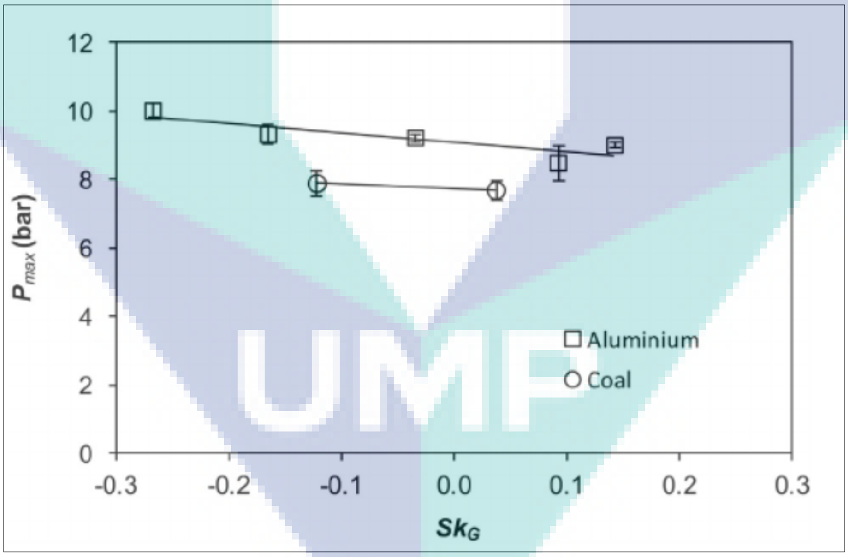

Figure 2.7 Correlation of the maximum explosion pressure (Pmax) with skewness (Sk_G) for aluminium (Castellanos *et al.*, 2014) and coal (Li *et al.*, 2016) dust samples.

2.6.4 Dust Explosibility Testing Methods and Apparatuses

The major obstacle in predicting the course and consequences of dust explosions in practice is the discrepancies of method used to determine the parameters affecting the dust explosion i.e. dust particle size and turbulence. The widely accepted standard available to determine the characteristic of dust is mostly adopted from British Standard Institution (British Standard, 2006) and ASTM International (ASTM, 2010). However, Japan also attempted to implement their own standard to determine the dust explosion characteristics as part of their Japanese Industrial standard (JIS) (Nifuku *et al.*, 2000). Another standard method is proposed by International Electrotechnical Commission (IEC) (Chawla *et al.*, 1996) and has been applied in a Siwek 20 L spherical chamber while ASTM has a method that can be applied in United States Bureau of Mines in a 20 L chamber (USBM) (ASTM, 2007) and the Siwek 20 L spherical chamber (ASTM, 2010). Detailed experimental and theoretical studies of the physics and chemistry of dust cloud generation and combustion need to be standardized to avoid any discrepancies on accuracy and precision of the data itself. Performing laboratory-scale tests to investigate the characteristics of dust explosion as full-scale mine tests are time-consuming and ineffective economically yet it does give discrepancies on data obtained in terms of methods used, the tested dusts and equipment involved. Even though the relationship between real life industry condition and laboratory test conditions is not always direct, the laboratory tests may provide the quantitative data for the various hazards related to dust explosions (Eckhoff, 2003b). Going *et al.* (2000) found that the explosibility data for 20 L chamber using 2.5 kJ igniter has the best agreement with 10 kJ igniter for 1 m^3 chamber. This is due to the potential of explosion to be overdriven if the ignition source is too strong as compared to the chamber volume, resulting in overestimation of maximum overpressure as well as the deflagration index, K_{st} (Abbasi and Abbasi, 2007). Full scale tests done in USA, Poland and Canada found that the minimum explosible concentration for Pittsburgh bituminous coal dust shows a very good agreement between the laboratory and the large scale tests at ~60 gm/m^3 when using 5 kJ ignition energy for 20 L chamber; however, it deviates for 80 g/m^3 with the 2.5 kJ igniter (Kumar *et al.*, 1992; Lebecki *et al.*, 1995; Sapko *et al.*, 2000). Kumar *et al.* (1992) found good agreement in determination of the maximum explosion overpressures for coal dusts and cornstarch used in a 10.3 m^3 cylindrical vessel when results were compared with a smaller vessel.

Different methods adopted for determination of dust explosion characteristics also contribute to different values for the same type of dust and equipment. For example, Chawla *et al.* (1996) examined the minimum explosible concentration (MEC) of bituminous Pittsburgh coal and bituminous Pocahontas coal, as well as gilsonite and oil shale in Siwek 20 L spherical chamber using ASTM and IEC method. They found that the MEC values from ASTM test method were higher than the values from IEC test method. The main reason leads to the differences is the recommended ignition energy used between the two methods was different. Other factors that influence the values of explosion characteristics are physical characteristics of dust, particle size and dust concentration. A coal sample from Qitaihe mine was exploded in a large scale tube to determine the effect of particle size on explosion characteristics with two different particle sizes prepared; ranges between 90 - 105 µm and 45 - 70 µm, respectively. It is found that the maximum overpressure (P_{max}) of coal with particle size ranges between 45 - 70 µm was 74 kPa but the P_{max} of particle size distribution of 90 - 105 µm was 66 kPa. It showed that finer dust is more explosive than coarser dust, even though volatile content, mass concentration and other parameters are similar. However, as the dust concentration increased, it would lessen the influence of particle size on the dust explosion process. It was found that when the concentration was greater than 960 gm/m^3, the overpressure of the finer and the coarse coal were similar (Liu *et al.*, 2010).

The purposes of testing the explosibility of dust are for mitigating the explosion, preventing the ignitions and reducing the severity in case of explosions. The laboratory tests that normally performed are categorized into two groups; the explosion sensitivity parameters that test the likelihood of an explosion and the explosion severity characteristics that test the consequences and the severity of the explosion (Ebadat, 2010). Before determining the severity of the combustible dust, explosion classification test is done to evaluate whether the dust/powders will explode or not when scattered as a cloud (Abbasi & Abbasi, 2007; Ebadat, 2010). The dust explosibility can be classified under K_{st} value. Table 2.2 gives the example on how K_{st} is classified by dust explosion class, St. The dust explosion class, St is explained further in section 2.9.2.

4.1. Table 2.2 Explosion characteristics of combustible dusts (M < 63µm) (NFPA, 2002)

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

The apparatus which are widely used over the world for the testing are Hartmann 1.2 L vertical tube, Siwek 20 L spherical chamber, Pittsburgh Research Laboratory (PRL) 20 L nearly spherical chamber as well as the 1 m^3 spherical chamber, Fike 1 m^3 and ISO 1 m^3 chamber (Abbasi & Abbasi, 2007; Kalejaiye *et al.*, 2010). On the determination of minimum ignition temperature, a 0.27 litre Godbert-Greenwald furnace and 0.35 litre *BundesanstaltfürMaterialprüfung* (BAM) oven are often used as testing equipment (Benedetto *et al.*, 2010; Siwek, 1996)

Although Hartmann bomb has been commonly used since 1980 (Abbasi & Abbasi, 2007), many tests have been made by using other chambers for results comparison (Continillo *et al.*, 1991). Hartmann 1.2 L vertical tube is normally used for preliminary screening tests and for determination of minimum ignition energy (MIE) (Nagy & Verakis, 1983; Williams *et al.*, 1960). However, Hartmann and other smaller chambers gave larger surface area to volume ratio and it would significantly affect the heat losses to the walls of the chamber. As a result, small chambers would underestimate the explosion severity (Woskoboenko, 1988) and may give wrong result for dusts that are not easily ignitable with spark but only can be ignited by stronger ignition sources (Cashdollar, 2000). The problems have been largely overcomed with larger chambers i.e. Siwek 20 L spherical chamber and standard closed 1 m^3 ISO chamber, in which gave better results than tubular tube (Abbasi & Abbasi, 2007). The 1 m^3 chamber is agreed to have more realistic measurements of maximum explosion pressures, maximum rates of pressure rise as well as minimum explosible concentrations, but larger amount of dust samples need to be prepared and more time need to be spent for the testing in 1 m^3 chamber than the 20 L chamber (Cashdollar, 2000).

2.7 Explosion Sensitivity Parameters

2.7.1 Minimum Explosibility Concentration

Minimum explosibility concentration (MEC) or also known as lean flammable limit is the lowest concentration of dust cloud dispersed in air that can propagate an explosion upon ignition (Ebadat, 2010; Going *et al.*, 2000; Yuan *et al.*, 2012). A result with pressure rise of 0.4 bar excluding igniter effect will be taken as MEC as proposed by International Electrotechnical Commission (IEC) after being tested at different dust concentration (Chawla *et al.*, 1996). MEC values depend on the method use, ignition energy, physical and chemical characteristics of dust as well as the size of equipment. A modified Hartmann dust explosion tube was used to determine the MEC of three Pakistani agricultural wastes: bagasse, rice husk and wheat straw with different particle sizes and moisture content. These agricultural waste had higher content of ash and moisture which influence the sensitivity parameters. Wheat straw had the highest value of MEC in the <63 mm size range due to highest ash content that made it the least reactive (Saeed *et al.*, 2015).

2.8 Explosion Severity Characteristics

2.8.1 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 time record resulting from dust explosion (Reyes *et al.*, 2011). P_{max} is obtained from the highest corrected value of explosion overpressure over a wide range of fuel concentration (Cesana & Siwek, 2000). Continillo *et al.* (1991) performed a 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 Figure 2.7. The test was performed in Siwek 20 L spherical chamber. From the graph, it can be said that explosion overpressures will increase as the dust concentration increases. The value at the highest point of explosion overpressure is known as P_{max} while the concentration at that point is the 'optimum dust concentration'. Mintz (1993) reported that optimum dust concentration usually occurs at much higher concentrations, opposite with the gas which usually has optimum concentration near stoichiometric. Figure 2.8 illustrates he maximum pressure obtained during the explosion of wheat flour at different concentrations by Kuracina *et al.* (2017), whereby the P_{max} was obtained at the concentrations of 600 kg/m^3 and its value is 8.31 bar. At minimum value of dust concentration where the pressure is first observed is called minimum explosibility concentration or lean flammable limit.

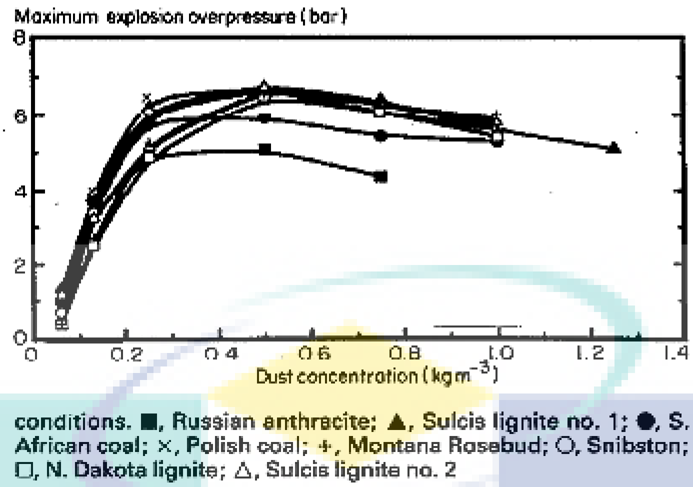

Figure 2.8 Maximum explosion overpressure as a function of dust concentrations on coals (Continillo *et al.*, 1991)

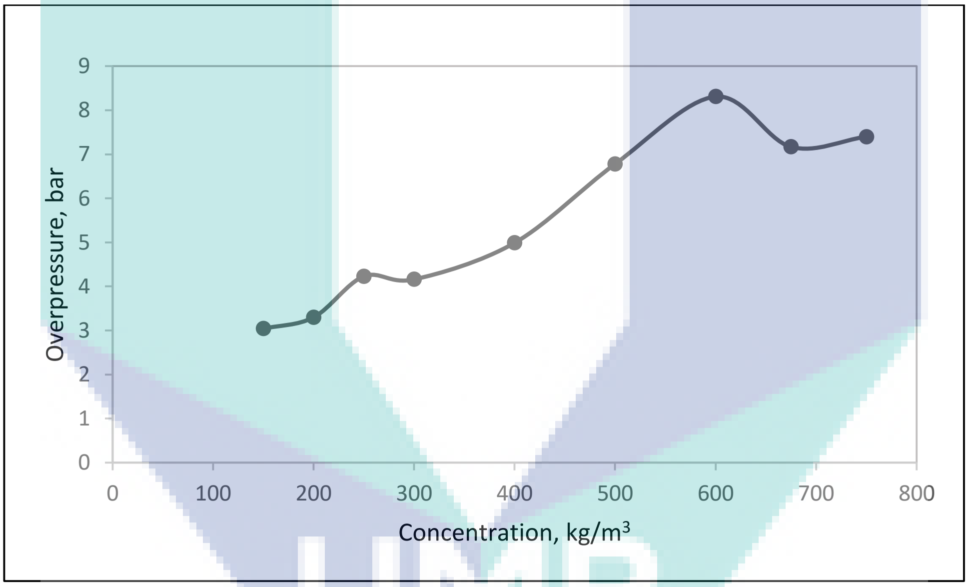

Figure 2.9 The maximum pressure obtained during the explosion of wheat flour at different concentration (Kuracina *et al.*, 2017)

2.8.2 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 in Equation (2.1)

$K_{st} = (dP/dT)_{max}. V^{1/3}$ (2.1)

This concept was introduced by Bartnecht (1978) for scaling the maximum rates of pressure rise to larger volumes by normalizing them. Besides, he also introduced the categorization of dust based on K_{st} value. The explosibility ranking based on K_{st} is illustrated in Table 2.3

Table 2.3 : Explosibility ranking based on K_{st}

K_{st}	Group St0	Non-explosible
$0 < K_{st} < 200$	Group St1	Weak
$200 < K_{st} < 300$	Group St2	Strong
$300 < K_{st}$	Groupm St3	Very Strong

The higher the value of K_{st}, the higher the chance of dust to explode. The cube root law is only valid in a geometrically similar vessel, if the flame thickness is negligible compared to the chamber radius, and if the burning velocity as a function of pressure and temperature is identical in all volumes (Eckhoff, 2003b). K_{st} is also known as deflagration index or volume-normalized maximum rate of pressure rise (Amyotte & Eckhoff, 2010). Result from explosion severity usually can be used for a reference to design the explosion protection and mitigation such as explosion relief venting and explosion suppression but it depends entirely on the validity of the cube root law (Eckhoff, 2003b; Reyes *et al.*, 2011). Kumar *et al.* (1992) 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 Figure 2.9). 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 bar.m/s compared to 70 bar.m/s 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.

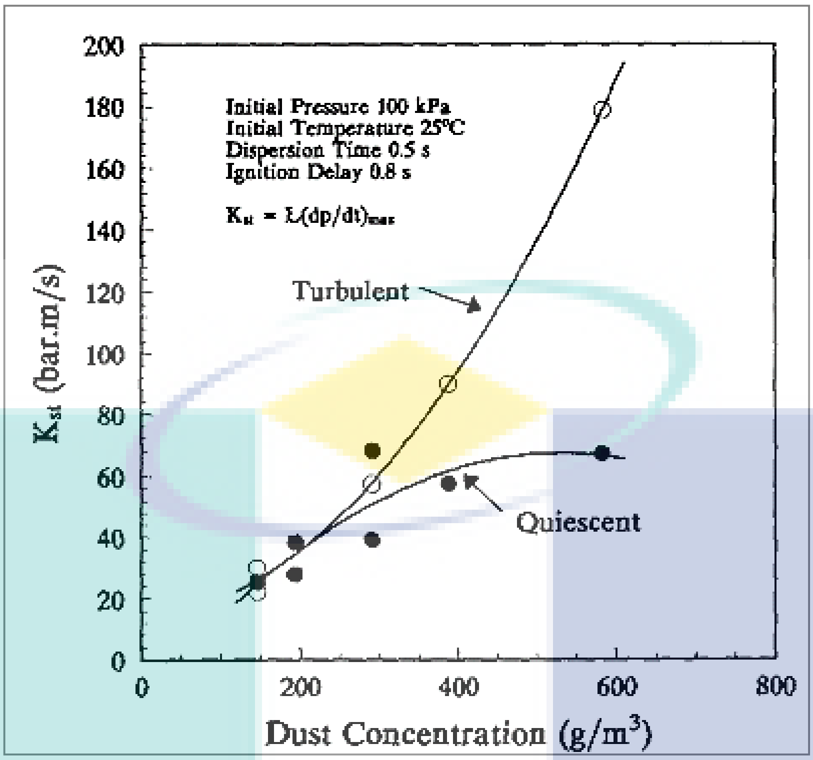

Figure 2.10 Comparison of K_{st} for cornstarch/air mixtures with and without fan generated turbulence (Kumar *et al.*, 1992)

2.9 Numerical Modelling of Dust Explosion Through Computational Fluid Dynamics(CFD)

Over the last years, several studies have been performed, aiming to apply computational fluid dynamics (CFD) simulations in order to understand the behavior of combustible dust in the standard tests, besides, numerical simulation models may be designed for prevention and mitigations of dust explosion in practice (Eckhoff, 2005). Kjäldman (1992) has been a pioneer in applying the computational fluid dynamics (CFD) to turbulent dust explosion propagation. The corresponding dust explosion code Dust Explosion Simulation Code (DESC) has been developed by using Flame Acceleration Simulator (FLACS) code which was originally developed by Hjertager *et al.* (1988). It seems sensible that an extensive numerical models is generated in various practical situations in industry for predicting the dust cloud structures to get the spatial distributions of effective particle size, dust concentration, turbulence and global flow. Knowing this initial cloud structure is essential because it has a major impact both on the ignition sensitivity of the cloud and the course of development of the primary explosion (Eckhoff, 2005). Table 2.3 listed the previous works of the studies of dust dispersion, turbulences and explosion in 20 L vessel

Table 2.4 Previous works of the studies of dust dispersion, turbulences and explosion in 20 L vessel.			
Type of dust	**Setup & CFD model**	**Findings**	**Author**
Coal (dust density=2046 kg/m^3;dust diameter=10µm)	• Tested for 3 nominal dust concentration of 100gm, 250gm, and 500g/m^3 • Fluent ANSYS • Siwek 20 L spherical chamber • Time-averaged NavierStokes equations (Eularian approach) written in polar coordinates.	• At low concentration (100gm/m^3), the dust mainly accumulates at the boundary of the vortices, while at higher concentration (500gm/m^3) the dust prevails giving rise to highly concentrated regions close to the vessel walls.	Di Sarli *et al.* (2014)
Aluminium	• Fluent • Siwek 20 L spherical chamber • Species transport & finite rate chemistry model • Standard k-Ɛ turbulence model	• The predicted final overpressure is higher than the experimental data,except for the case of very fine dust of 6.69µm size.	Bind *et al.* (2011)
Maize starch (Meritena A & Maizena)	• Tested at different ignition delay times • FLACS-DESC • USBM 20 chamber	• At a nominal dust concentration of 800 g/m^3, indicate a systematic decrease in estimated	Skjold *et al.* (2006)

	• Eulerian approach in the limiting case when the Stokes number approaches zero, so-called equilibrium.	laminar burning velocities for longer ignition delay times.	
Coal	• Dust dispersion within the sphere was investigated by using perforated annular nozzle. • The results were compared with rebound nozzle by Di Benedetto *et al.* (2013). • Fluent-ANSYS • Siwek 20 L spherical chamber • The particle-laden flow approach was adopted with the Eulerian approach used for the fluid phase and the Lagrangian approach used for the solid phase.	• Simulation results have shown that the turbulent kinetic energy is rather uniformly distributed and its values are significantly lower than those attained with the rebound nozzle • The perforated annular nozzle is able to generate a uniform dust/air cloud. However, a consistent fraction of the dust remains trapped inside the nozzle without participating in the reactive process.	Di Sarli *et al.* (2015)

A type of dust	• Dust dispersion within the sphere was investigated with different size of dust • Fluent-ANSYS • Siwek 20 L spherical chamber • time-averaged Navier-Stokes equations (Eulerian approach) written in polar coordinates.	• The dust dispersion is getting worst on increasing the diameter	Di Sarli *et al.* (2013)
Wheat starch (density=610kg/m^3)	• Turbulence within the sphere was investigated at different ignition time. • Siwek 20 L spherical chamber • Mesh generation by using CCM+ • Detached Eddy simulation model for turbulence model, large eddy simulation (LES) on small turbulence	• There is a minimum value for the turbulence in the explosion vessel corresponding to an ignition delay time greater than 60-70 ms, after which turbulent kinetic energy stabilizes and the velocity fluctuation decreases significantly	Daniel *et al.* (2018)

Aluminium nanoparticles	• Turbulence within the sphere was investigated with different sizes of aluminium dust • Ansys-FLUENT • Siwek 20 L spherical chamber • the fluid phase is described by the numerical solutions (Finite volume method) of the Navier-Stoke equation as it considers the air as a continuous medium. • It was conducted using a Euler-Lagrange approach where the flow variables are characterized with two phase during the dispersion process	• The contour of turbulent kinetics for nanosize aluminium was higher than the micron size particles.	Kadir *et al.* (2016)
A dust with density of 2046 kg/m3, diameter=10µm,dust concentration=250g/m^3	• Turbulence within the sphere was validated with data from measurement of time histories of pressure and root mean square velocity available in literature	• Further studies are needed in order to evaluate the effect of dust size and size distribution, dust concentration and dust shape.	Di Benedetto *et al.* (2013)

	• Ansys-FLUENT • Siwek 20 L spherical chamber • Eulerian approach was used for the fluid phase and the Lagrangian approach used for the solid phase. • Fluid flow was simulated by solving the time averaged Navier stokes equation written in polar coordinates.		
Coal dust	• The severities of coal dust/air mixtures in a 20 L spherical chamber were investigated. • Ansys-FLUENT • Siwek 20 L spherical chamber • Assumption of particle to be regular spherical particle • Eddy-dissipation model • k−ε model as turbulent calculation model	• The simulation results reflect the changes in pressure behaviors during the coal dust explosion process, and the results are consistent with the experimental observations.	Cao *et al.* (2017)
Aluminium dust and starch dust	• CFD simulation to model the propagation of dust explosion	• Either using, or without using particle scale model for CFD	Bind *et al.* (2012)

	• Ansys-FLUENT • Siwek 20 L spherical chamber • Particle scale model for aluminium dust • Species transport & finite rate chemistry • Dust-air mixture approach • Without particle scale model for starch dust.	simulation, model has been validated against experimental data. Qualitatively and quantitatively similar results were obtained compared to experimental results for both aluminium and starch combustion.	
A dust with density of 2046 kg/m^3	• Turbulence within the sphere was investigated with and without the fan • Ansys-FLUENT • Siwek 20 L spherical chamber • the solid phase was solved using the discrete phase model (DPM) (Lagrangian approach).	• In the presence of only one fan, the dust entrained by the fluid flow mainly accumulates at the top of the sphere. After having switched-off the fan, the dust starts moving along the wall without penetrating into the center of the sphere.	Di Benedetto *et al.* (2015)

Aluminium dust	• Turbulence within the sphere was investigated at different dust concentration • Ansys-FLUENT • 20 L sphere with double nozzle pneumatic dispersion system of hemispherical nozzle with multi-holes • The turbulence model used in the calculation is the standard k − ε model. • Through discrete phase model and stokes tracking (random trajectory) trajectory model, the differential equation of the forces acted on particles was solved under the Lagrangian coordinates to obtain the particle track of the dust	• The effects of turbulence on aluminium dust/air explosions are varied with the nominal concentrations. At the lower nominal concentration, the turbulence is a significant factor affecting an aluminum dust/air explosion. However, at the higher nominal concentration, it is the uniformity of aluminum dust suspended in air that has a more significant influence on an aluminum dust/air explosion.	Zhang *et al.* (2018)

As summarized in table 2.4, many different types of dust were studied in 20 L spherical chamber except for a study by Skjold *et al.* (2006) which used 20 L USBM chamber. Di Sarli *et al.* (2014) and Zhang *et al.* (2018) studied the effect of initial turbulence on explosion of coal dust and aluminium dust respectively at different nominal dust concentrations. Di Sarli *et al.* (2013) and Kadir *et al.* (2016) studied on the effect of particle sizes on the dust dispersion and turbulence. Apart from the effect of physical characteristics of the dust towards dispersion and turbulence, Di Benedetto *et al.* (2015) studied the effect of the presence of fan towards the initial turbulence. From their studies, it showed how importance the influence of factors such as dust concentration, particle sizes and presence of fan towards the dispersion and initial turbulence of dust explosion. However, there's so many other factors that need to be investigated such as presence of moisture, agglomeration and different background of chemical properties towards dust dispersion and turbulence by using CFD simulation.

2.10 Summary

It is essential for this research to investigate the chemical and chemical characteristics of the samples to understand the behaviour of the samples exploded inside the 20 L spherical chamber by investigating the initial turbulence and how it affects the sensitivity parameters and sensitivity characteristics of the rice flour dust. Other factors such as effect of moisture, time ignition, particle sizes will also be scrutinized. Therefore, the explosion will be done in 20 L spherical chamber. Details of the development will be discussed in Chapter 3.

CHAPTER 3 : METHODOLOGY

3.1 Introduction

Samples that will be used in the research is rice flour dusts. Those samples are commercial flour in a packaging used for cooking and baking. As mentioned in the procedure by Cesana and Siwek (2000) the dust sample should have a median particle size not exceed 63 µm and should be in a dry state. Particle size distribution, PSD will also be done in Malvern Mastersizer. After that, the samples would be stored in a glass bottle with tight lid in order to minimize the probability of moisture loss. Upon testing, the dusts would be dried at 75ºC for two hours in an oven at ambient pressure to get rid of the moisture (Cesana & Siwek, 2000). However, since the research required that the samples also will be tested without drying, some of the samples would not undergo the drying process. As mentioned by the procedure by Cesana and Siwek (2000), it is allowed for not drying the sample in justified exceptional cases. A summary of the tests that will be performed with Siwek 20L spherical chamber is shown in Figure 3.1.

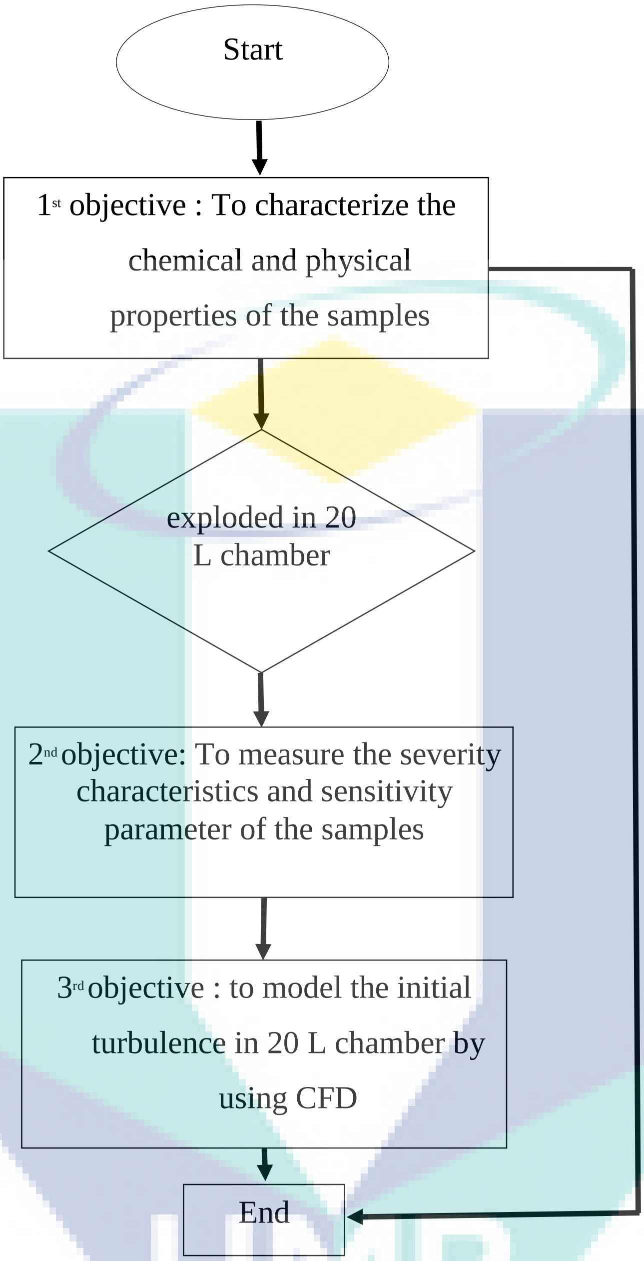

Figure 3.1 Process flowchart of the research

3.2. Proximate Analysis

The physical and chemical properties of the sample is further investigated through proximate analysis for analysis of carbohydrate content, fat content, protein content, ash content and moisture content. The analysis is carried out according to British Standard 1016 Part 6; Analysis and testing of coal and coke: Proximate analysis of coal (British Standard, 1999) for moisture content. Analysis for fat content, protein content and content are according to (AOAC, 1990). The carbohydrate content is obtained by the percentage remaining.

3.2.1. Moisture Content

To carry out the moisture content test, an empty glass crucible (diameter of 6 cm) is weighted. Then, approximately 1 ± 0.1 gm of the sample is added to the crucible. The new weight of the crucible and the sample is recorded. The crucible and contents are placed in an oven for one hour at a temperature of 105 ± 5ºC as a drying process. The crucible is then cooled in a desiccator and reweighed. The amount of moisture in the sample is then calculated using Equation (3.1)

$$\% \text{ of Moisture} = \frac{\text{Mass of water removed (g)}}{\text{Mass of original sample (g)}} \tag{3.1}$$

3.2.2 Fat Content

Fat is determined by Soxhlet extraction with a suitable solvent. The sample is placed in the extraction chamber, which becomes filled with the solvent by evaporation and condensation. Each time the chamber becomes full, the extract, containing an appropriate proportion of the fat, is discharged through the siphon onto the receiver. After extraction, the extracted fat is weighed. Complete extraction normally requires 30 syphoning cycles (depending on the sample). This corresponds to an extraction time of approx. 4 to 8 hours with conventional Soxhlet apparatuses. This is reduced to about 1 to 2 hours with the Buchi Soxhlet extraction apparatus. The percentage of fat is calculated by using Equation (3.2)

$$\% \text{ Fat} = \frac{(B - A) \times 100}{C} \tag{3.2}$$

Where A = weight of extraction cup prior to extraction, in g

B = weight of extraction cup after drying, in g

C = sample weight

3.2.3 Protein Content

Protein content is obtained by using The Kjeldahl method for determining total nitrogen involves firstly heating with concentrated sulphuric acid in a long-necked digestion flask. The reaction rate is accelerated by adding sodium or potassium sulphate to raise the boiling point and catalysts containing usually copper, mercury or selenium. The oxidation causes the nitrogen to be converted to ammonium sulphate. After making alkaline with concentrated sodium hydroxide solution (and adding thiosulphate if mercury is included in the catalyst), the ammonia is distilled into either excess of boric acid or standard acid and is estimated by titration. The percentage of protein is calculated by using Equation (3.3)

$$\% \text{ Protein} = \frac{(\text{ml sample} - \text{ml blank}) \times \text{Conc HCl} \times 1.4007 \times \text{Factor}}{\text{sample weight (g)}} \quad (3.3)$$

3.2.4 Total Ash

To carry out the total ash test, an empty glass crucible (diameter of 6 cm) is weighted. Then, approximately 3 to 5 ± 0.1 gm of the sample is added to the crucible. The new weight of the crucible and the sample is recorded. The crucible and contents are placed in a furnace at a temperature of 550 ± 5°C until a whitish or greyish ash is obtained or to constant weight or until weight change is less than 4% of previous weight or 0.5 mg, which is less. The crucible is then cooled in a desiccator and reweighed. The amount of total ash in the sample is then calculated using Equation (3.4)

$$\% \text{ Total ash} = \frac{W_1 - W_2 \times 100}{W_s} \quad (3.4)$$

Where W_1 = Weight of ash and ashing dish

W_2 = Weight of ashing dish

W_s = Weight of sample

3.3 Dust Explosion Apparatus

The flammability and severity characteristics data reported here are obtained in the 20 L spherical chamber as shown in Figure 3.2. The vessel is made of stainless steel and is rated to resist up to 30 bar (static pressure). The explosion experiments are performed by using two 5 kJ chemical igniters as the standard ignition source. The igniters need to be trimmed by using scissors or pliers to expose the wire before it is connected to the ignition leads. The ignition delay time t_v is fixed at 60 ms. The pressure inside the spherical chamber is measured by two "Kistler" piezoelectric pressure sensors. The pressure transducers are mounted on the wall of the chamber. In the experiments, dusts are loaded directly to the storage container and would be dispersed with the rebound nozzle connected to an outlet valve located at the bottom of the chamber by using compressed air pressurized at 20 bar (gauge). A water jacket surrounds the spherical bomb for the control of the internal wall temperature. The detail of experiment is illustrated in Figure 3.3. The dust concentration loading is started at 10 g before gradually increased until constant pressure achieved. The same method is used to determine the lean limit concentration by gradually stepping down by step change of 10 g until there is no explosion/flame propagation shown on captured data. The chamber is interfaced with a computer, which controls the dispersion/firing sequence and data collection by using control system named KSEP. As part of the experimental programme, two repeat tests would be performed on each test and these demonstrated good reproducibility, with peak pressures varying by less than ±5 % in magnitude.

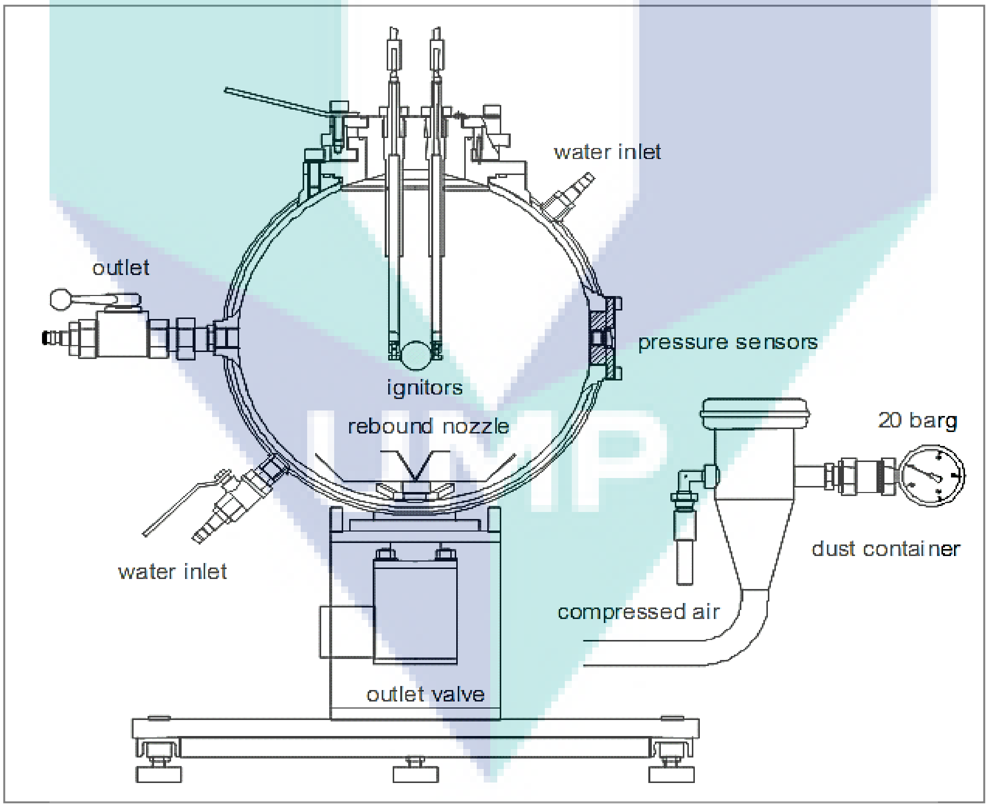

Figure 3.2 Schematic diagram of Siwek 20 L spherical chamber (Cesana & Siwek, 2000)

Pre weighed amount of dust was placed in the dust storage container

↓

The trimmed igniters (5 kJ each) were connected to ignition leads and the chamber was closed

↓

Dispersion air pressure was set to 20 bar gauge and the chamber was partially evacuated to 0.4 bar absolute

↓

The dust from storage chamber was dispersed to the sphere chamber

↓

Test was immediately run from programme KSEP on personal computer

↓

The result of pressure-time profile and dP/dT would be provided by the programme

Figure 3.3 Test procedure for dust explosion in Siwek 20 L sphere chamber

3.3.1 Siwek 20 L Spherical Chamber

The test chamber as illustrated in Figure 3.2 is a hollow sphere made of stainless steel, with a volume of 20 L. A water jacket used to dissipate the heat of explosions or to maintain thermostatically controlled test temperatures. For testing, the dust is dispersed into the sphere from a pressurized storage chamber via the outlet valve and a nozzle. The outlet valve is pneumatically opened and closed by means of an auxiliary piston. The valves for the compressed air are activated electrically. The ignition source is located in the center of the sphere. On the measuring flange two "Kistler" piezoelectric pressure sensors are installed. The second flange can be used for additional measuring elements or for the installation of a sight glass.

3.3.2 Control Unit KSEP 310 and KSEP 332

The control unit KSEP 310 is installed as an auxiliary unit behind the sphere on the same base plate. The KSEP 332 unit uses piezoelectric pressure sensors to measure the pressure as a function of time and controls the valves as well as the ignition system of the 20 L spherical chamber. The measured values to be processed by a personal computer are digitized at high resolution. The use of two completely independent measuring channels gives good security against erroneous measurements and allows for self-checking.

3.3.3 Compressed Air

Compressed air is used to power the outlet valve and is also connected to the inlet valve of the dust storage chamber. The pressure in the storage chamber corresponds directly to that of the external compressed air system (standard = 20 bar overpressure = 21 bar absolute). The 20 bar compressed air connection must have an adequate cross section. It must be possible to pressurize the storage chamber (V = 0.6 L) within 5 seconds. For the 20 L spherical chamber, only normal compressor compressed air may be used (in cylinders). With the use of, e.g. synthetic compressed air explosion indices which are clearly different were obtained.

3.3.4 Vacuum

Prior to dispersing the dust, the 20 L spherical chamber is evacuated to such a degree, that the remaining pressure, together with the air contained in the storage chamber, result in the desired starting pressure for the explosion test. For that purpose, the ball-valve on the vacuum connection of the sphere is opened and the sphere is evacuated via the vacuum filter until the vacuum meter shows the desired vacuum. The vacuum filter can easily be removed for cleaning.

3.3.5 Equipment Check

Before testing, the 20 L spherical chamber need to be checked as stated in Table 3.1

Table 3.1 Safety Procedure while using the Siwek 20 L chamber

No.	Cause / Description	Action
1	Compressed air	Normal compressor is used before testing while airpressure of the compressed air bottle was set at 40 bar
2	Leakage	The dust storage needs to be pressurized to 20 bar (gauge). The seals of outlet valve need to be checked if the pressure drops more than 1 bar within one minute.
3	Cooling	The cooling water must be set to be flow minimum more than 0.5 litre / minute and the temperature of the water flowing is cool
3	Test check	A test check need to be done to ensure that the system of 20 L spherical chamber is functioning well. Test check is an automatic test sequence which needs to be done by using neither dust nor chemical igniters in order to ensure that the function of the entire system is checked in easy way and fast. The test check is strongly recommended to be repeated at the onset of each test series. The ignition delay is fixed at 60 ms. The compressed air pressure is set at 20 bar (gauge). The spherical chamber is then need to be evacuated to -0.6 indicator or 0.4 bar absolute. An automatic test need to be started from KSEP programme. Meanwhile, vent valve need to be opened slowly and only a little air should flow in and out. Caution also need to be taken that only ambient pressure is flow in and out.

3.4 Analysis of Explosion Data

3.4.1 Maximum Explosion Overpressure (P_{max})

The data given by the computer would be recorded as explosion overpressure. The peak of the graph would be recorded as a value of pressure for that concentration (P_{ex}). The value of a pressure over time diagram of a dust explosion is illustrated in Figure 3.4. P_m value given by the KSEP programme indicates the pressure value for that concentration due to and pressure effects and cooling caused by chemical igniters (Cesana & Siwek, 2000).

A number of explosion tests would be conducted with different amount of dust concentrations to get the value of explosion overpressure. The value of explosion overpressure at different amount of dust concentrations would be plotted as a graph as illustrated in Figure 3.5. P_{max} is the highest value of explosion overpressure at optimum dust concentration. P_{max} of bituminous coal Bayan, sub-bituminous coal Tanito and Philippine coal would be tested separately and would be compared.

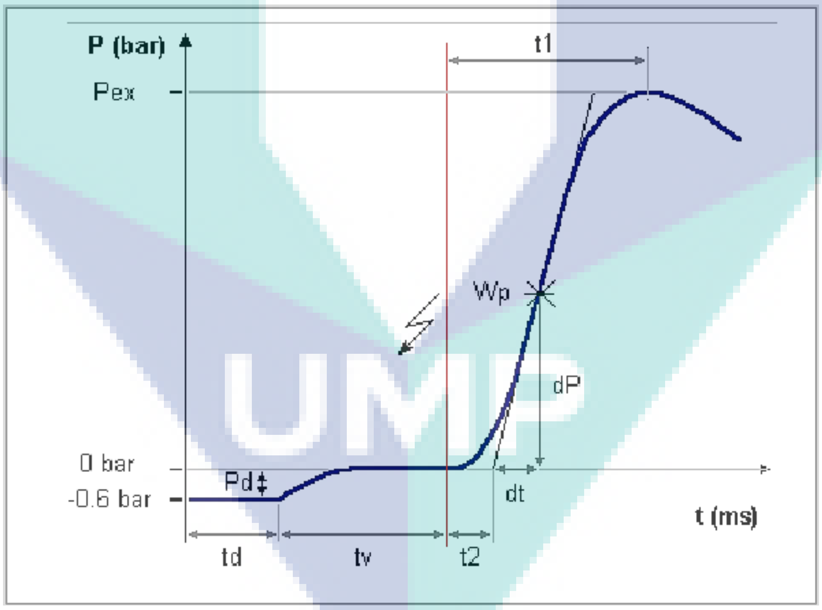

Figure 3.4 Pressure over time diagram of a dust explosion (Cesana & Siwek, 2000)

P_{ex} = Explosion overpressure is the difference between the pressure at ignition time with normal pressure and the pressure at the highest point would be the maximum explosion overpressure.

P_m = Corrected explosion overpressure would be given by KSEP programme due to pressure effects and cooling due to ignition energy released in the chamber, the value of P_{ex} need to be corrected.

(dP/dt) = Rate of pressure rise over time at nominal dust concentration.

t1 = time difference between the activation of the ignition and the highest point
t2 = time difference between the activation of the ignition and the intersection of the inflexion tangent with the 0 bar line.

T_d = time delay of the outlet valve.

T_v = Ignition delay time.

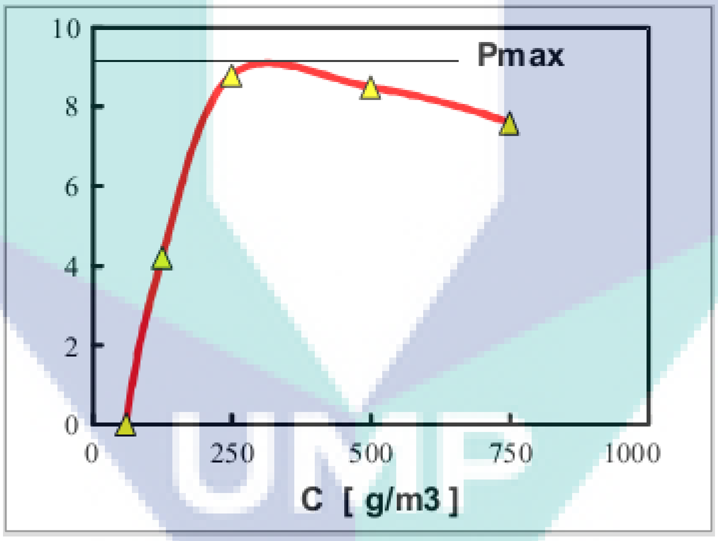

Figure 3.5 Explosion overpressure over concentration of dust (Cesana & Siwek, 2000)

3.4.1.1 Correction of The Explosion Overpressure at P_{ex} > 5.5 bar

Due to the less favorable surface to volume ratio, the explosion pressure measured in the 20 L spherical chamber is in general slightly lower than the one measured in the 1 m^3 spherical chamber. This is due to cooling effects. Comparisons of pressure/time recordings also show that the pressure drop after the explosion is much faster in the 20 L spherical chamber. Therefore a correction has to be made according to Equation (3.9)

$$P_m = 0.775 \cdot P_{ex} \, 1.15 \qquad (3.9)$$

With this correction, the P_m in the 20 L spherical chamber then agrees with those measured in the 1 m^3 spherical chamber.

3.4.1.2 Correction of The Explosion Overpressure at P_{ex} < 5.5 bar

Due to the small volume of the 20 L spherical chamber, below 5.5 bar the pressure effect caused by the chemical igniters must be taken into account. A blind test i.e. with ignition energy of 10 kJ chemical igniters alone, will give a maximum overpressure of 1.6 bar. But during a dust explosion with rising P_{ex} the influence of the igniters will be more and more displaced by the pressure effect of the explosion itself. The influence of igniters with less than 1 kJ can be neglected entirely. Correction values can be taken from Equation 3.1

$$P_m = 5.5 \cdot (P_{ex} - P_{ci}) / (5.5 - P_{ci}) \text{ bar} \qquad (3.1)$$

where pressure due to chemical igniters (P_{ci}) = 1.6 bar • IE / 10’000

3.4.2 Dust Deflagration Index (K_{st})

The value of maximum rate of pressure rise at different amount of dust concentration given by 20 litre sphere explosion data would be plotted as a graph. The value of (dP/dt) for several number of concentrations as illustrated in Figure 3.3 would be recorded. The value of K_{st} would be obtained from the highest value of (dP/dt) normalized with the volume of spherical chamber as illustrated in Figure 3.6. K_{st} of bituminous coal Bayan, sub-bituminous coal Tanito and Philippine coal would be tested separately and would be compared.

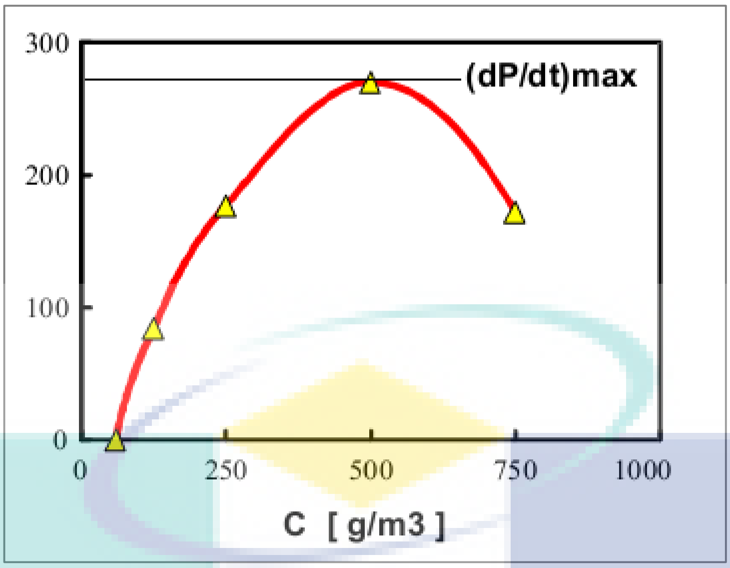

Figure 3.6 The rate of pressure rise over concentration of dust (Cesana & Siwek, 2000)

3.4.3 Minimum Explosible Concentration (MEC)

Minimum explosible concentration (MEC) or also known as lean flammable limit is the lowest concentration of dust cloud dispersed in air that can propagate an explosion upon ignition. The value of minimum explosible limit is the minimum value of dust concentration where the pressure is first observed in the chamber. There is no ignition if the value of overpressure is less than 2 bar (P_{ex}) or less than 0.4 bar excluding ignitor effects (P_m) in the 20 litre spherical chamber is observed. MEC can be obtained from an explosion overpressure over dust concentration graph as illustrated in Figure 3.5 for explosion overpressure less than 0.4 bar.

CHAPTER 4 : RESULTS & DISCUSSION

4.1. Analysis of the Physical and Chemical Properties of the Samples

The physical and chemical properties of rice flour in comparison with wheat flour were summarized in Table 1. Rice flour has a calorific value of 15500 kJ/kg, which is comparable to the wheat flour (16820 kJ/kg), which could be attributed to its higher carbohydrate content. Total carbohydrate content in rice flour is about 83.8%, which is comparable to the wheat flour (85.2%) (Cardoso *et al.*, 2019). The result from proximate analysis showed that dust explosion of rice flour is potentially as severe than that of wheat flour owing to its high calorific value. In comparison, the rice flour has about 60% of the calorific value of the coal dust studied by Wan Sulaiman (2014). The calorific value implies that severity of rice flour dust explosion is approximately similar to that of wheat flour, but much lower than that of coal. The rice flour has a very low ash content (0.3%), which indicates that most of the particle content is made of a combustible material. The rice flour contains 8% of protein, which is also a combustible material. For instance, whey protein which contains about 90% protein is classified as a strong dust explosion hazard by the Department of Labour (Labour, 1985).

Particle size distribution of the rice flour is shown in Figure 4.1. The size distribution of the rice flour particles is characterized by D_{10} at 5.57 µm, D_{50} at 28.77 µm and D_{90} at 103.80 µm, which implies that 90% of the particles has a diameter below 103.8 µm. The existence of the second peak with particle size ranging from 200 µm to 1 mm is due to the existence of agglomerates made of primary particle as seen in the SEM image (Figure 4.2).

Figure 4.2 shows the surface morphology of rice flour before and after the explosion. The SEM image shows that the primary rice flour particle has an irregular shape. Agglomerates are also observed, which explained the existence of dual peak in the particle size distribution. Agglomeration was observed to be more prevalent in the undried sample (Figures 4.2a to 4.2b) compared to that of dried ones (Figures 3c to 3d), owing to the sticky properties of rice flour at higher moisture content. The rice flour after undergoing explosion is markedly different to that of the initial sample. In Figures 3b and 3d, the rice flour agglomerates are clearly seen made of many primary particles. However, after the explosion (Figures 3f and 3h) the agglomerates show some kind of glassy properties indicating a glass transition induced by explosion heat has taken place.

Table 4.1 Results of physical and chemical properties of dust samples

Samples		Moisture (%)	Ash content (%)	Energy (kJ/kg)	Protein (%)	Total fat (%)	Total Carbohydrate (%)	Dietary fiber (%)	Reference
Rice flour (undried)		7.79	0.3	15500	8.0	0.2	83.8	7.9	This work
Rice flour (dried)		2.47	0.3	15500	8.0	0.2	83.8	7.9	This work
Wheat flour		14.1	0.61	16820	13.2	0.9	85.2	-	Cardoso *et al.* (2019)
Bayan coal		4.33	11.11	25945	-	-	-	-	Wan Sulaiman (2014)

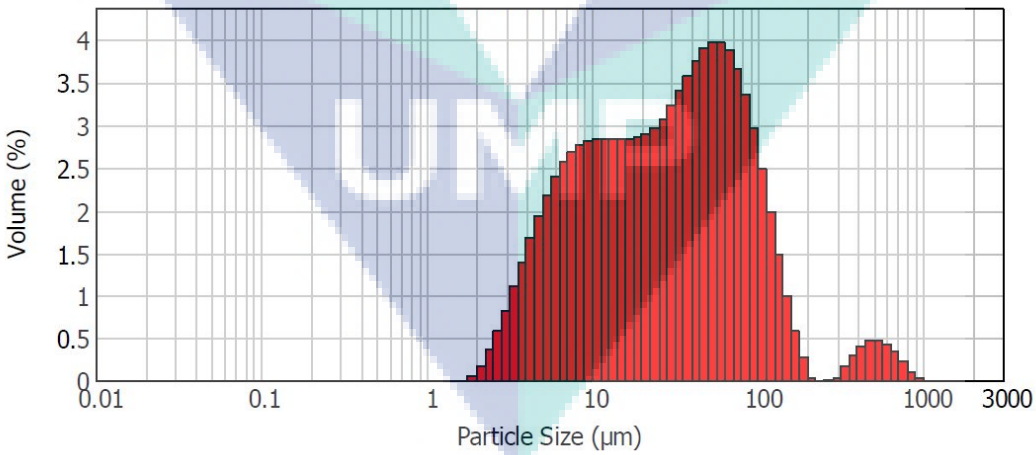

Figure 4.1 Particle sizes distribution for both undried and dried samples

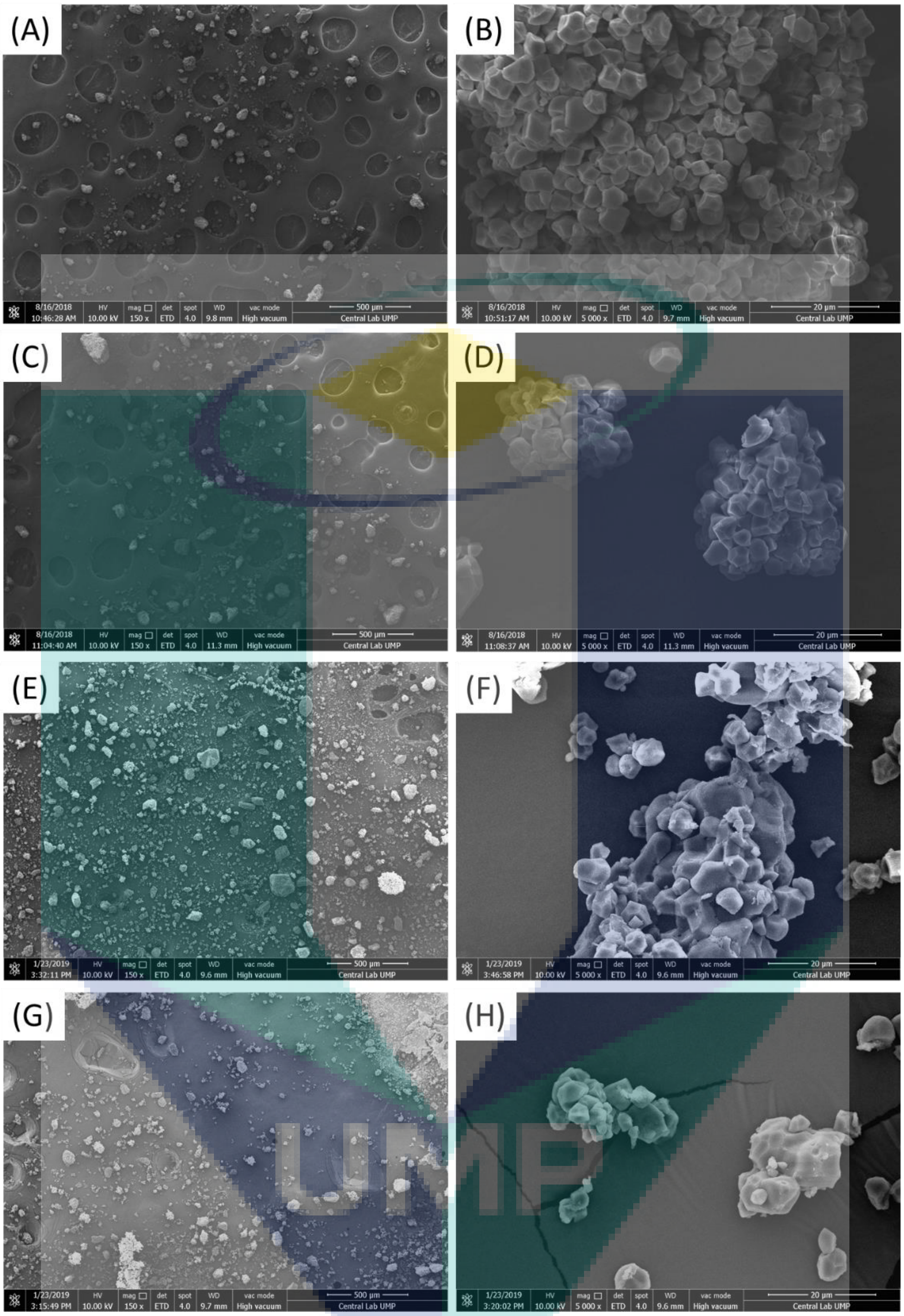

Figure 4.2 SEM images of rice flour samples at various magnification. (a) to (b) for undried samples before explosion, (c) to (d) for dried samples before explosion, (e) to (f) for undried samples after explosion and (g) to (h) for dried samples after explosion.

4.2. Rice Flour Explosibility at Various Dust Concentration

The explosibility of the sample at various particle concentration is determined by the existence of shockwave pressure in the explosion chamber when the ignition source is provided. Result from the experiment in Figure 4.3 shows that MEC for dried rice flour (500 kg/m^3) is lower than the MEC of undried rice flour (600 kg/ m^3). The lower MEC is attributed to the lower moisture content in the dried rice flour (2.47%) after oven drying compared to 7.79% in the undried sample. The sample with less moisture content can easily ignite even at lower dust concentrations. It is known that lower moisture content may increase the dust explosibility as the reaction heat of dust explosion would be partly dissipated by the phase change of moisture and the rise of temperature (Yuan *et al.*, 2014).

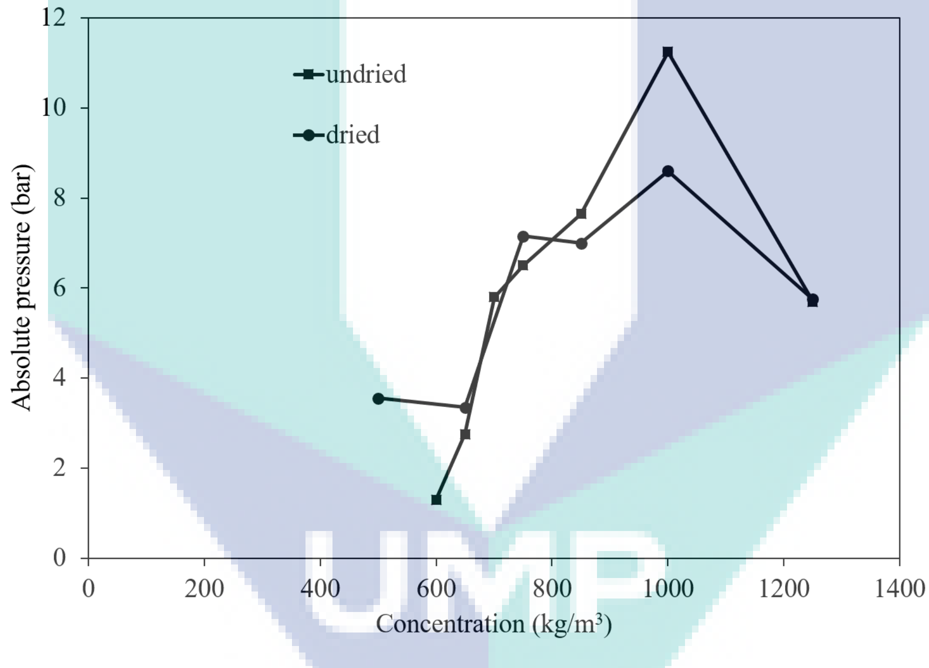

Figure 4.3 Absolute pressure at the time of ignition (P_m) as a function of dust concentration

4.3. Absolute Pressure and Rate of Pressure Rise (dP/dT) at Various Dust Concentration

The maximum explosion pressure, P_{max}, can be obtained from the graph of absolute pressure at the time of ignition (P_m) versus dust concentration (Figure 4.3). The graph shows that the pressure from undried rice flour escalates to more than 11 bar as the concentration increases. Meanwhile, the explosion pressure of the dried rice flour also increases sharply with dust concentration until 8.6 bar at 1000 kg/m^3. The highest explosion pressure was obtained at a concentration of 1000 kg/m^3, for both dried and undried samples. The P_{max} for the undried and dried rice flour are 11.25 bar and 8.6 bar, respectively. The explosion pressures of undried and dried rice flour decreases at concentration of 1250 kg/m^3. As discussed earlier (Figures 2 and 3), higher moisture content cause formation of more particle agglomerates, which can significantly increase the uncertainty of explosion tests Yuan *et al.* (2014). The high values of P_{max} for both undried and dried rice flour samples is attributed to the major content (90%) of small particles < 103.8 µm as shown in Figure 2. Earlier, J. Wang *et al.* (2019) studied the explosibility and flame propagation velocity of oil shale dust at three different particle sizes. They found that the explosibility and the flame propagation velocity increases as the particle size decreases. Smaller particles enabled the rice flour dust to explode easily in the explosion chamber with a relatively high value of P_{max}. Rice flour has a low ash content (0.3%) as shown in Table 1, implying that most of the particle content is combustible, hence contributing to higher values of P_{max}. Ash is an incombustible component which prevent the flame propagation by absorbing the thermal energy from the combustion (Chawla *et al.*, 1996).

The rate of pressure rise in various rice flour concentrations is shown in Figure 4.4. The rate of pressure rise was observed to increase proportionally with the increase in dust concentration until concentration of 1000 kg/m^3, but decreases afterwards. It shows that the values of dP/dT for undried rice flour is always lower than that of dP/dT for dried rice flour for all dust concentrations tested. The highest value of dP/dT over concentration is 81 bar/s for undried flour and 98 bar/s for dried rice flour.

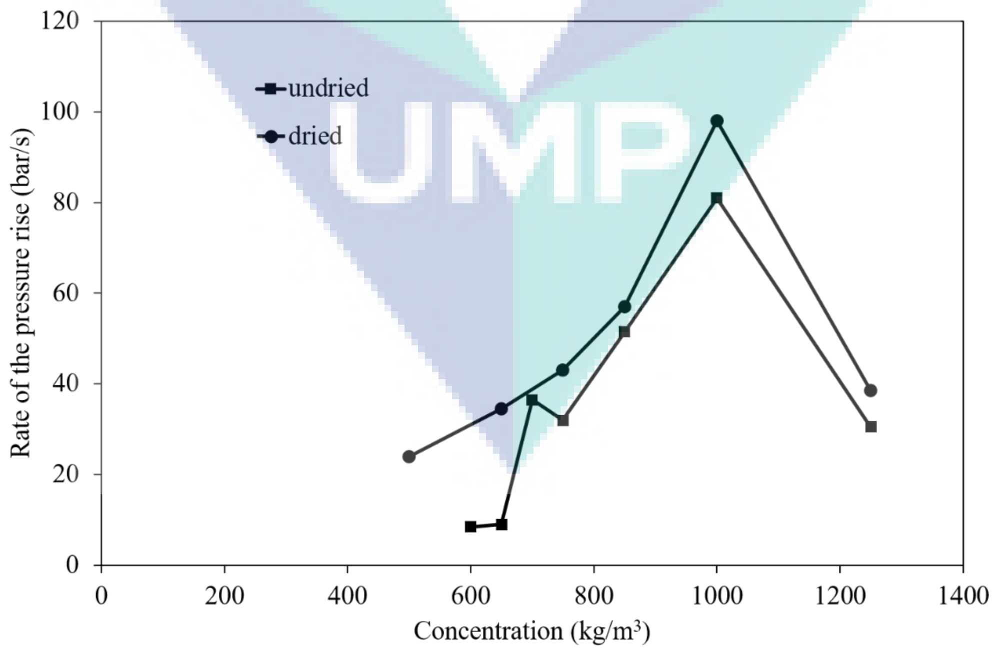

Figure 4.4 Rate of pressure rise (dP/dT) as a function of dust concentration

4.4. Deflagration Index (K_{st}) at Various Dust Concentration

The deflagration index, K_{st}, is regarded as an important parameter to describe the severity of dust explosion in a closed system. Figure 4.5 shows the K_{st} value for undried and dried rice flour at ignition time of 60 ms and 100 ms. Figure 6 clearly shows that different ignition time has a notable effect towards the severity of the rice flour explosion. Graph of dried sample with t_v of 100 ms at first increase over concentration, but decrease after 750 kg/m^3. The other three samples show the K_{st} were obtained at concentration of 1000 kg/m^3. The highest value of K_{st} is 26.6 bar.m/s obtained from dried rice flour with t_v = 60 ms. A study by Daniel *et al.* (2018) reported that particle size distribution and dust cloud turbulence cannot be neglected when assessing the severity and explosibility of dust explosion. They compared wheat starch dust explosion in the similar setup as this work (20 L spherical explosion) at t_v 20 ms, 60 ms and 100 ms. They recommended to use t_v from 60 to 80 ms, enhance the consistency of the results when the experiment is repeated. The t_v higher than 80 ms may enhance the consistency of the results, but the particle dispersion and cloud sizes may be affected by sedimentation. This is especially true when the density of particle tested is very much denser than air, and that the turbulent flow induced dispersion is insufficiently strong to induce particle suspension in air. They also reported that the mean diameter of the wheat starch decreased during the dispersion inside the test explosion chamber possibly due to dust agglomerates fragmentation. Newer study using the 20 L spherical chamber by S. Wang *et al.* (2019) reported that P_{max} and dP/dT were the highest at t_v 60 ms and the lowest at t_v 40 ms. They observed that the highest dP/dT contributed to the highest K_{st} as well. They measured the explosion severity of coal dust at t_v of 40, 60, 90 and 150 ms. The optimum t_v depended on the velocity of dust particles, kinetic energy of dust turbulence and dust suspension behavior.

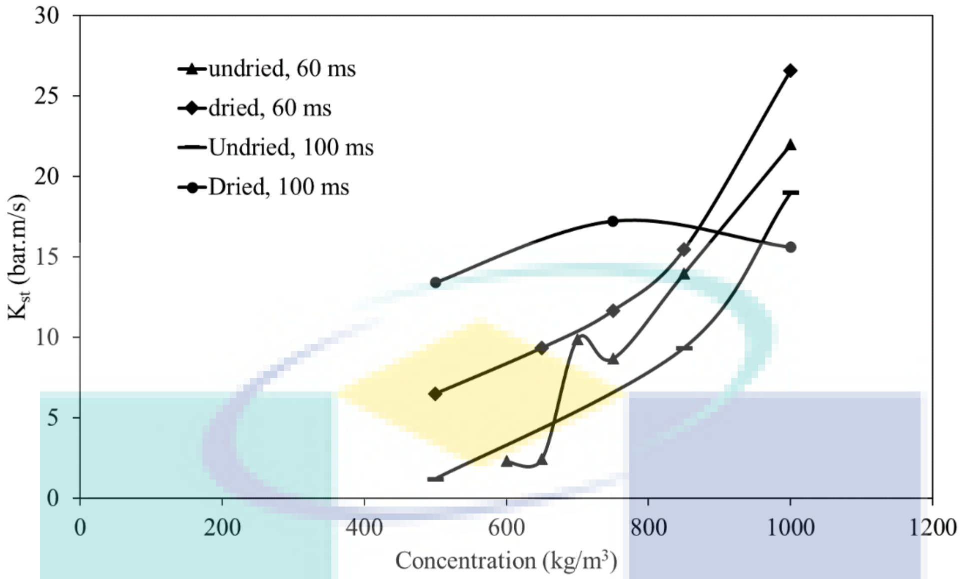

Figure 4.5 K_{st} as a function of dust concentration

Table 4.2 shows a comparison of dust explosion severity obtained in this work with other food related material other researchers. It shows that both rice flour undried and dried in this study has lower value of K_{st} compared to the ones reported by German Association Database, BIA (GESTIS-DUST-EX) (*BIA-Report 13/97*, 1997). The values of K_{st} for the rice flour dust in this experiment fall under the group of ST1 base on the severity ranked by K_{st}, $0 < K_{st} < 200$ which is considered weak (OSHA, 2009). The lower K_{st} value in this work may be attributed to the physical properties of the rice flour powder used in the experiment. For instance, the particle size and moisture content of rice flour used in this work differ markedly to the ones tested by BIA. It is also not known, if the calorific value of rice flour used in BIA experiment significant differ to the one in this work. The calorific value of rice flour varies slightly according to the exact subspecies of rice used to produce the flour.

Rice flour in this work is also compared with maize starch and wheat starch reported by Tascón *et al.* (2016), which shows that the highest K_{st} of this study, 26.60 bar.m/s is lower than K_{st} of wheat starch (150 bar.m/s). As mentioned earlier, the difference in K_{st} value may be attributed by the difference in the physical properties of the powder used. However, K_{st} of wheat starch reported by Kuracina *et al.* (2017) at 14.72 bar.m/s is lower than all results obtained in this work. It can be concluded that the value of K_{st} obtained in this work is comparable to the value reported in the literature after considering the difference in the physical properties of the powder used.

Table 4.2 Comparison between the food dust explosion severity

Material	Moisture (%)	Median value, D_{50} (μm)	Energy (kJ/kg)	K_{st} (bar.m/s)	Ignition time (ms)	Testing chamber	Reference
Rice flour (undried)	7.79	28.77	15500	22.0	60	20 L spherical chamber	This work
Rice flour (dried)	2.47	28.77	15500	26.60	60	20 L spherical chamber	This work
Rice flour (undried)	7.79	28.77	15500	19.0	100	20 L spherical chamber	This work
Rice flour (dried)	2.47	28.77	15500	17.2	100	20 L spherical chamber	This work
Rice flour	9.3	150	N.A	57	60	20 L spherical chamber / 1 m^3 chamber	BIA Report (*BIA-Report 13/97*, 1997)
Wheat starch	15	84	N.A	14.72	260	Modified chamber KV-150 M2	Kuracina *et al.* (2017)
Maize starch	11.5	15.7	N.A	174	60	20 L spherical chamber	Tascón *et al.* (2016)
Wheat starch	10.3	36.6	N.A	150	60	20 L spherical chamber	Tascón *et al.* (2016)

CONCLUSION

The effect of moisture content and ignition time on the explosibility and severity of explosion of rice flour was investigated using 20 L spherical explosion chamber for the first time. The rice flour dust explosion behavior was correlated to its physical properties. It was found that higher moisture content decreased the explosibility of rice flour dust explosion with MEC of 600 kg/m^3 for undried sample, a slightly less explosive than dried rice (MEC = 500 kg/m^3). The maximum explosion overpressure of undried rice flour is higher than that of dried ones. The P_{max} for the undried and dried rice flour are 11.25 bar and 8.6 bar, respectively. The rate of pressure rise of dried rice flour (98 bar/s) is greater than the dP/dT of undried rice flour (81 bar/s).. The severity was observed to increase proportionally with the increase in dust concentration until it reached optimum concentration at 100 kg/m^3.Investigation at ignition time of 60 ms and 100 ms shows the highest deflagration index of dried rice flour at 26.6 bar.m/s obtained at the standard ignition time of 60 ms. Results obtained from this work provide a useful safety information about the severity

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LIST OF PUBLICATIONS

Conferences

1) Energy Security and Chemical Engineering Congress (ESChE) 2019
   Venue : Parkroyal Resort, Penang, Malaysia
   Date : 17-19 Jul, 2019
   Title of Paper : Explosion of rice flour at different concentration and moisture content.

2) 11th Malaysian Technical Universities Conference on Engineering and Technology (MUCET 2019)
   Venue : Bukit Gambang Resort City, Pahang
   Date : 19 – 22 Nov 2019
   Title of Paper : EXPLOSION OF UNDRIED & DRIED RICE FLOUR AT IGNITION TIME OF 20MS

3) Loss Prevention Asia (LPA 2019)
   Venue : Hotel Istana, Kuala Lumpur
   Date : 25 – 26 Nov 2019
   Title of Paper : EXPLOSION OF UNDRIED AND DRIED RICE FLOUR AT DIFFERENT CONCENTRATION.

Journal Articles

4) Journal : Process Safety Progress
   Title of Paper : Assessment of explosibility and explosion severity of rice flour at different concentration and ignition time.

5) IOP Proceeding : Materials Science and Engineering
   Title of Paper : Explosion of rice flour at different concentration and moisture content