Effect of Particle Size on the Explosive Characteristics of Grain (Wheat) Starch in a Closed Cylindrical Vessel

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Wheat starch dust explosion poses a serious threat to food processing and handling industries. This study attempts to show the influence of particle size on some explosive characteristics of wheat starch dust. The maximum pressure, maximum rate of pressure rises, and severity factor index were determined in relation to four different particle sizes of wheat starch dust of 38 μm, 45 μm, 53 μm and 71 μm using the 1.2 L Hartmann explosion tube. The result of proximate and elemental analysis conducted showed the sample has a moisture content of 2.1 %, volatile content of 93.3 % and a calorific value of 15,777.2 J/g. The carbon content of the sample was 40 % and the hydrogen content 6.9 %. The result of the explosive parameter tests showed that the maximum explosion pressure of the wheat starch dust sample increased with decreasing particle size with the highest recorded value of 735 kPa for the particle size of 38 μm.

1. Introduction

Dust explosion is considered a serious hazard in the food industries (Skjold and Eckhoff, 2016). It occurs frequently in sectors such as energy, defence, metal burnishing, plastic and pharmaceuticals which usually cause huge financial losses, loss of lives and injuries. In these sectors, operations involving storage, grinding, transportation and pneumatic conveying are subjected to dust explosion hazard. These explosions occur as a result of rapid combustion of clouds of suspended fine particles in the micron range at a concentration sufficient to create such flame when ignited by an ignition source (Bind et al., 2012).

In the process industry, dust explosion is considered the most hazardous alongside vapour cloud explosion (VCE) and boiling liquid expanding vapour explosions (BLEVE). This can be attributed to the fact that more than 70 % of the powders used in this industry are combustible. Majority of these plants have dust extraction equipment and in some cases silos which makes them more susceptible to explosions (Abbasi and Abbasi, 2007). One distinguishing factor between dust and gas explosion is the phase of the fuel. While dust particles are solid, gas explosions are caused by gaseous molecules (Amyotte and Eckhoff, 2010).

Dust explosion is initiated by a rapid combustion of flammable particles in suspended air. Any solid combustible material will burn with violence and speed which increases with decrease in the size of the particle. When ignited dust cloud is confined, even partially, the heat of combustion may result in rapid development of pressure as the flame propagates across the dust cloud generating large quantities of heat and reaction products leading to explosion.

Each year food industries are severely damaged by grain starch dust fires and explosions. Wheat starch poses serious hazard in process industries during processing and handling. Dust explosion violence is largely dependent on particle size due to the interplay of devitalisation, gas phase mixing and dust dispersion. Grain starch explosion at Qinhuangdao Lihua starch Co Ltd in China on February 24, 2010 resulted in 20 deaths, 48 injuries and direct economic loss of 1,773.5 million Yuan. Similarly, on June 6, 2015, flammable starch-based powder exploded on stage during a Colour Play Asia party at Formosa Fun Coast Water Park in Taiwan killing 29 people while injuring 508 with 199 in critical condition (Li et al., 2016). Malaysia recorded three cases in dust explosion, between March 2008 and August 2013 resulting in 6 fatalities and 12 injuries (Ismail et al., 2017). For safer processes involving combustible dusts, adequate safety knowledge is required. One of such

is the explosion characteristics of the dust which involves estimating the maximum explosion pressure P_{max}, maximum rate of explosion rise ((dP/dt) max) and the severity index K_{ST}. The purpose of this study is to evaluate the explosion features of different particle sizes of wheat starch and to consider effective safety systems to prevent and mitigate dust explosion in the food and starch processing industries.

2. Methodology

2.1 Experimental Set-up

Physical and chemical properties of grain (wheat) starch dust will be examined while the explosive properties of wheat starch dust will be determined using the 1.2 L Hartmann dust explosion tube built according to ASTM E 789-95 (re-approved 2011) standard test method for dust explosion in a cylindrical vessel. The test equipment consists of a vertically mounted closed steel combustion chamber (commonly called the Hartmann tube), a dust dispersion system using clean air, tungsten ignition arc, pressure sensor and recording oscillograph. Figure 1a shows the schematic setup diagram while Figure 1b shows the pilot rig set up.
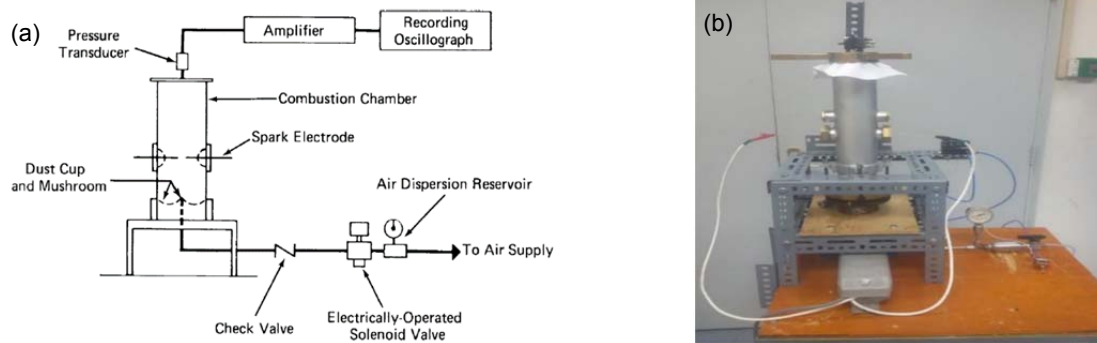

Figure 1 (a): Schematic diagram of experimental setup (ASTM 2001) (b) Pilot rig setup

The vessel consists of a closed steel combustion chamber, 14.605 cm diameter and 30.48 cm long, vertically mounted and designed to withstand a maximum pressure of 1,210 kPa. Total volume of the explosion chamber is 1,229.03 cm^3 and it is attached to a metal base and a dispersion cup by hinged bolts. Air flows into the chamber and impinges on a mushroom-shaped deflector located in the bottom of the dispersion cup. To ensure that the dispersed dust remains confined, the uppermost part of the Hartmann tube is sealed with a paper.

2.2 Dust Dispersion, Ignition System and Data Acquisition System

Grain wheat starch dust dispersion will be obtained by a single blast of air from a 49.16 cm^3 reservoir that is pressurised to 100 psig. The dispersing air is controlled by a ½ -in full port, electrically operated solenoid valve.
The ignition system comprises of two ends of 10 kJ tungsten electrodes that produce a continuous spark and it is adjusted to a gap length of ¼ in at the mid-section of the Hartmann tube. The power of the ignition spark is from a luminous tube transformer having a rate of 240 V input and 8 kV secondary output
The data acquisition system comprises of an electronic transducer which detects pressure in the range of 100 psi to 1 kpsi and sends the signal to an amplifier and recording equipment. The pressure as a function of time is recorded on an oscillograph. The pressure and rate of pressure rise developed from the experiment are determined by pressure time records. The readings on the oscillograph are converted to pressure units in psi. The conversion formula is a function of the excitation voltage, the full-scale capacity of the pressure sensor and the calibration factor. It is expressed by Eq(1) where C_{fs} = Full Scale Capacity- the minimum pressure which the transducer should receive; V_{ex} = Excitation voltage- the recommended input voltage; V_{meas} = Measured Voltage – the raw voltage returned to the sensor; and CF = Calibration Factor – the output of the transducer, usually expressed in mV/V.

$$\text{Pressure (psi)} = \left(\frac{C_{fs}}{V_{ex}}\right)\left(\frac{V_{meas}}{CF}\right) \tag{1}$$

2.3 Sample Preparation

Grain wheat dust was obtained from Johor Bahru Flour Mill Sdn Bhd along with MSDS and information regarding its properties. The samples were sieved through sieve trays of 71 μm, 53 μm, 45 μm and 38 μm,

which fall within the range prone to powder explosion. Proximate analysis of the wheat starch dust sample was conducted to determine the moisture content, volatile content and calorific value. Summary of the tests performed is shown in Table 1.

Table 1: Summary of tests performed

S/No	Test	
1	Sieving	Particle size separation (38, 45, 53 & 71 µm)
2	Drying	T = 75 ºC for 2 h in an oven
3	Moisture content	T = 105 ºC for 1 h
4	Volatile content	T = 925 ºC for 7 min
5	Elemental analysis	Analysis of Carbon, Hydrogen, Nitrogen and Sulphur content
6	Calorific value	Bomb calorimeter procedure
7	Maximum Explosion Pressure (P_{max})	Highest peak of overpressure over the wide range of concentration
8	Deflagration Index (K_G)	Highest value of (dP/dt) normalised with the volume of the spherical chamber

The particle concentration involved in each test was determined by weighing a specific amount of wheat starch dust and dividing it by the volume of the explosion tube (Eq(2)).

$$\text{Concentration (g/m}^3) = \frac{\text{mass of sample (g)}}{\text{volume of vessel (m}^3)} \qquad (2)$$

Proximate analysis of wheat starch dust was conducted. The moisture content, volatile matter and calorific value were determined. The analysis was conducted to determine the percentage of water in the sample. The moisture content was determined by first weighing an empty crucible, reweighing after 1 g of sample were added and then heating the sample and crucible for one hour at 105 ºC in an oven. The crucible along with the sample was allowed to cool in a desiccator and reweighed. The amount of moisture in the sample will be determined using Eq(3).

$$\% \text{ of Moisture} = \frac{\text{Mass of water removed (}W_{initial} - W_{final})(g)}{\text{Mass of original sample (}W_{initial})(g)} \text{ x } 100 \text{ \%} \qquad (3)$$

The volatile content refers to the total contents except moisture that is present in a sample and liberated at high temperature in the absence of air. The volatile content of wheat starch was determined by weighing an empty crucible and reweighing when 1 g of sample is added to the empty crucible. The crucibles were then placed in an oven and heated to 925 ºC for 7 min. The crucible was removed from the oven and allowed to cool down to room temperature before transferring to a desiccator for further cooling. The cooled crucible was removed from the desiccator, weighed and the volatile content was determined using Eq(4).

$$\% \text{ of Volatile} = \left(\frac{\text{Mass loss after sample heating(}W_{initial} - W_{final})(g)}{\text{Mass of original sample (}W_{initial})(g)} \text{ x } 100 \right) \% \text{ moisture} \qquad (4)$$

The calorific values were determined using a bomb calorimeter. A weighted sample is placed in a sample container made of heavy walled stainless-steel reaction vessel in the bomb calorimeter. The reaction vessel was immersed in an insulated water bath and the sample was burned with sufficient oxygen gas. Electric current passes through an iron fuse wire in contact with the wheat starch sample which resulted in combustion reaction. Heat that were released from the combustion reaction were absorbed by the water and other parts of the calorimeter leading to a rise in temperature which measured by the calorimeter. The calorific value was estimated as shown Eq(5).

$$\text{Heat of combustion } H_g = \frac{tW - E3}{M} \qquad (5)$$

Where tW is the temperature of water, E3 is the electric current and M is the weighted sample.

2.4 Where H_g = Dust Explosion Procedure

First a weighted amount of wheat starch dust was spread on the dispersion cup. Secondly the air dispersion pressure in the air reservoir was adjusted to 690 kPa. Then the spark electrode was turned on. After that the dust dispersion cup after the pneumatic valve was opened. Subsequently, the transducer sends signals to recording instrument. Finally result of pressure time-profile and dP/dt was calculated. Results obtained were

analysed and compared. This comparison was done to ascertain the behaviours of each sample at the event of an explosion during storage.

The steel combustion chamber was separated from the dispersion cup base. Blasts of air were used to clear the dispersion cup of any remaining dust from previous test. A weighted amount of wheat starch dust was spread evenly on the dispersion cup. The steel combustion chamber is replaced, and the tungsten electrode is fitted to the steel chamber and adjusted to a gap of 6.4 mm. The uppermost part of the combustion chamber was covered with paper and the signal transducer is placed directly above the paper covering. The air pressure was adjusted to 100 psig and the tungsten electrodes were connected to the mains. The air supply valve is closed, and the air dispersed the dust sample when the solenoid valve was opened with the help of a switch. The maximum explosion pressure P_{max} and maximum rate of pressure rise (dP/dt) is recorded using the data acquisition system comprising the amplifier and oscillograph. The explosion severity was determined from the rate of pressure rise using Eq(6).

$$\text{Explosion severity } K_{st} = dP/dt \cdot V^{1/3} \tag{6}$$

Where V is the volume of the cylindrical vessel. Several wheat starch dust explosion tests were conducted for different particle sizes and at different dust concentrations and the results of the maximum explosion pressure at different dust concentrations were plotted.

3. Results and Discussion

3.1 Physical and Elemental Analysis of wheat starch

The combustion properties of dust are influenced by its physical and chemical properties. The properties influence the thermodynamics and kinetics of the dust, hence affecting the severity of the explosion. The moisture and volatile content were determined using ASTM standards D4442 - 15. Table 2 shows the physical properties of the wheat starch sample.

Table 2: Physical properties of wheat starch sample and dust sample elemental analysis

Proximate Analysis (Physical Properties)	Test Result	Element (Elemental Analysis)	Test Result
Moisture % of Original sample	7.5 %	Carbon	40 %
Moisture % of Dried sample	2.1 %	Hydrogen	6.97 %
Volatile Matter %	93.3 %	Nitrogen	1.9149 %
Calorific Value	15,777 J/g	Sulphur	0.0231 %

The moisture content of a sample may act as a prevention or mitigation factor for dust explosions. The explosibility of dust and the maximum rate of pressure rise decreases with increasing moisture content while the minimum ignition temperature and minimum explosible concentration increases with increase in moisture content. This is because the moisture in the dust serves as a heat sink by consuming the heat for the dust explosion.

The explosion hazard tends to increase with increasing volatile content. A high volatile content decreases the minimum explosible concentration and ignition temperature while increasing the maximum rate of pressure rise. The heat of combustion (calorific value) was recorded as 15,777 J/g. The higher the heat of combustion, the more severe the explosion. The elemental analysis was conducted using Vario Micro Cube analyser to determine the elemental composition of wheat starch and average values have been taken. The presence of chemical groups such as chlorine, bromine, fluorine and nitrogen compounds reduces the explosibility of dust samples (Table 3).

3.2 Explosive Characteristics of wheat Starch Dust

The explosive characteristics and severity of wheat starch dust were analysed. The effect of particle size was discussed further. The particle size plays a significant role towards the ignitability and explosibility of dust. When ignited at high dispersion pressures, the result can be damaging and with probable loss of life or injury. Hence, the need to recommend safety measures in handling and transportation of wheat starch dust. The voltage readings from the oscilloscope were converted to pressure in psi using Eq(7).

$$\text{Pressure (psi)} = \left(\frac{C_{fs}}{V_{ex}}\right)\left(\frac{V_{meas}}{CF}\right) \tag{7}$$

The full-scale capacity C_{fs}, of the transducer is 1,000 psi and it has an excitation voltage V_{ex} of 25 V, the measured voltages are the voltages recorded for each explosion test and the calibration factor, C_F is 2 mV/V. The results in psi were then converted to pressure in kPa.

Figure 2a shows the result of experiment with corn starch (2.1 %) moisture, the highest maximum explosion pressure recorded was 730 kPa for particle size 38 μm at a concentration of 500 g/m^3. For all the particle sizes, the maximum explosion was recorded at a concentration of 500 g/m^3. It was observed that the maximum explosion pressure reached a fairly constant value at a concentration of 700 g/m^3 for all particle sizes. Additionally, the P_{max} have been observed to increase with decreasing particle size with highest values recorded for particle size 38 μm along all tested dust concentrations.
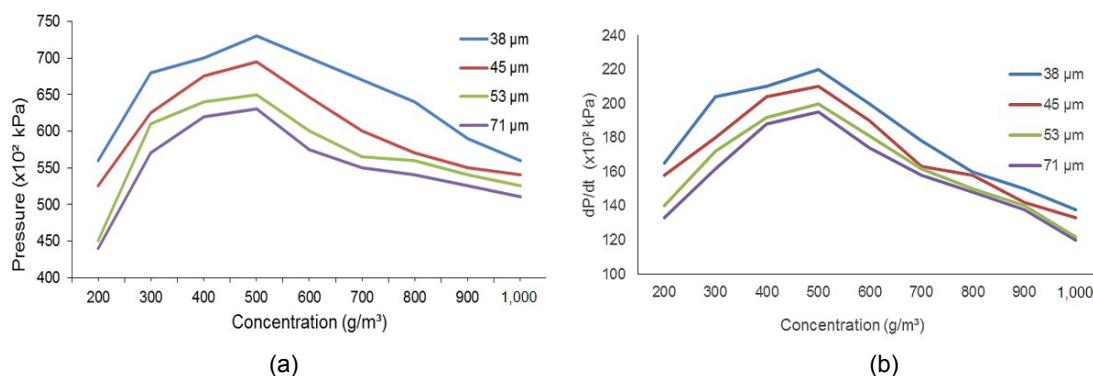

(a)   (b)

Figure 2: (a) Maximum explosion pressure for Malaysian wheat starch (b) Maximum rate of pressure rise for wheat starch dust sample

The finding is similar to the work of Eckhoff (2009) which showed that the maximum pressure for wheat starch dust explosion using a 1.2 L Hartmann tube 44 reaches a fairly constant level in the ranges of 500 g/m^3 and upwards and the ease with which a combustible dust explodes and the violence with which it explodes increases with decreasing particle size. This is because the larger particle sizes participate inefficiently in flame propagation as compared to smaller particle sizes and are less easily dispersed (Abbasi and Abbasi, 2007).

The maximum rate of pressure rise is the rate of pressure rise per time during the course of explosion. From the result of the experiment with wheat starch dust, the highest value obtained was 22,200 kPa/s at a concentration of 500 g/m^3 for particle size 38 μm. Figure 2b shows the result of (dP/dt) max for all particle sizes. It can be observed that the highest value of maximum rate of pressure rise for all particle sizes was recorded at a concentration of 500 g/m^3. The particle size plays a significant role on the value of the maximum rate of pressure rise. As observed from the result, the highest ranges of dP/dt max were recorded for the smallest particle size (38 μm) with a resulting decrease as the particle size increases to 71 μm.

This can be compared to the result from the experiment of maize starch (11 % moisture) in a closed Hartmann tube by (Eckhoff, 2003) which shows that the maximum rate of pressure rise peaks at a concentration of 400 - 500 g/m^3 and it increases consistently with decrease in particle size.

3.3 Severity Index

The results of severity values for this experiment are shown in Table 3. Dusts are classified into 4 groups based on the severity of their explosion (Abbasi and Abbasi, 2007). Those that fall into group S_t 0 categories have a K_{st} value of 0 and are categorised as non-explosible. Explosible dusts between 0 - 200 K_{st} are classified as weak or moderately explosible and fall under group S_t 1. Stronger explosible dust come under group St 2 and 3 with K_{st} values within the range of 200 < K_{st} < 300 and 300 < K_{st} and termed strongly and very strongly explosible dusts. The K_{st} was determined using the formula of Lewis von Elbe (Di Benedetto et al., 2010) as shown in Eq(8). From Equation 8, it can be seen that the K_{st} is a product of the maximum rate of pressure rise and the cubic root of the volume of the Hartmann cylindrical dust explosion tube, which in this case is 0.0012 m^3. The results of the K_{st} values of the sample studied shows that the sample is weak to moderately explosible because the values for all the different particle sizes tested fall within the range of 0 < K_{st} < 200. It was also observed that the highest K_{st} value of 2,535 kPa.m/s was recorded for particle size of 38 μm at a concentration of 500 g/m^3.

$$K_{ST} = ((dP/dt)\ max).V^{1/3}$$ (8)

The K_{st} peaks at the concentration of 500 g/m^3 for all particle sizes. At concentrations above this, the K_{st} decreases since the excess fuel acts as a heat sink and reduces the maximum temperature rise. It was found

that highly dust cloud results in decreasing turbulence. As the concentration of dust exceeds the stoichiometric ratio, some of the particles cannot be completely ignited due to oxygen deficiency.

Table 3: Explosion severity K_{st} for wheat starch sample

Concentration g/m^3	K_{st}			
	38 µm	45 µm	53 µm	71 µm
200	17.92	15.1	13.31	12.66
300	22.9	20.88	19.2	17.72
400	23.53	21.09	20.9	19.8
500	25.35	23.96	22.13	20.91
600	22.91	20.94	19.88	17.46
700	20.98	19.32	15.66	15.81
800	18.84	16.95	14.02	14.95
900	16.76	15.21	14.22	13.75
1,000	15.38	14.95	13.87	12.95

4. Conclusions

Malaysian wheat starch dust sample has a moisture content of 7.5 %, volatile content of 93.3 % and a calorific value of 15,777 J/g. The particle size influences the maximum explosion pressure, maximum rate of pressure rise of wheat starch dust. The K_{st} for all the particle sizes fall under group S1 of the severity index, implying that wheat starch dust is a weak-moderately explosible dust. Wheat starch process can be moderated by increase in particle size distribution which can reduce the risk of dust explosion. The four different particle sizes of wheat starch studied 38 µm, 45 µm, 53 µm and 71 µm were found to have a maximum pressure in a closed 1.2 L Hartmann tube vessel of 735 kPa, 702 kPa, 655 kPa and 636 kPa at a concentration of 500 g/m^3. The highest maximum rate of pressure rise was recorded as 22,200 kPa/s giving a K_{st} factor of 2,535 kPa.m/s.

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