

INVESTIGATION OF THE THERMAL  
BEHAVIOUR AND DUST EXPLOSION  
CHARACTERISTICS OF TEA POWDER



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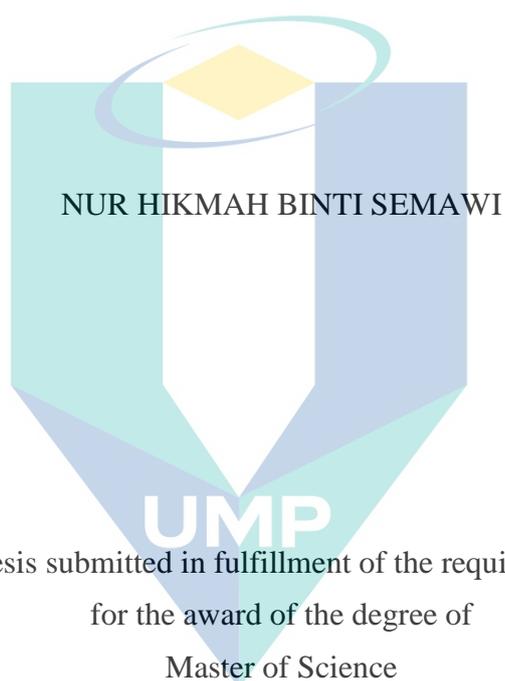
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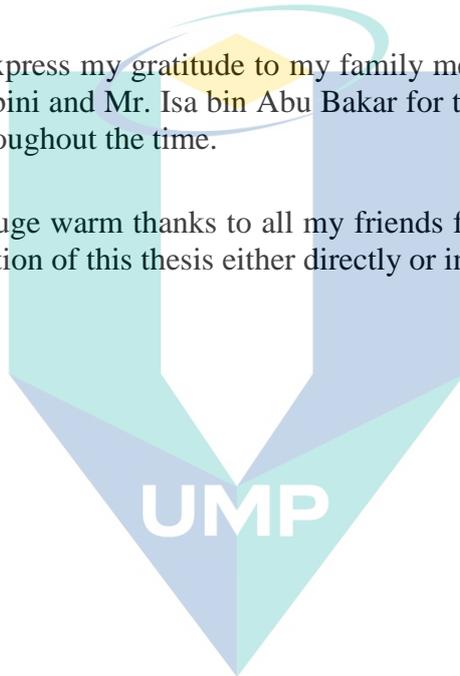
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## ABSTRAK

Debu berasaskan makanan dianggap sebagai debu yang mudah terbakar kerana ia terdiri daripada zarah-zarah yang berbeza, tanpa mengira saiz atau komposisi kimia dan apabila berada di udara atau apa-apa medium pengoksidaan lain, dan dalam pelbagai kepekatan dan terdapat sumber pencucuhan, akan menyebabkan kebakaran atau letupan. Kesan letupan dari debu ini boleh menyebabkan berlakunya bencana kerana gelombang tekanan awal dari letupan pertama boleh mengangkat lebih banyak debu dan mencetuskan reaksi berantai. Parameter yang dapat meningkatkan letupan termasuk saiz zarah debu, kandungan kelembapan dan kepekatan minimum letupan (MEC). Dalam kajian ini, serbuk teh telah digunakan kerana serbuk teh cenderung untuk meletup disebabkan struktur molekulnya yang terdiri daripada ikatan karbon-hidrogen yang mampu melepaskan jumlah tenaga haba yang tertentu. Lima saiz zarah serbuk teh yang berbeza telah dikaji dengan menggunakan analisis termogravimetri (TGA) dan kesannya terhadap letupan telah diuji dalam ruang berisipadu 20 L yang tertutup. Keputusan eksperimen menunjukkan bahawa nilai-nilai tekanan letupan maksimum ( $P_{max}$ ) dan kadar kenaikan letupan maksimum ( $(dP/dt)_{max}$ ) serbuk teh lebih tinggi untuk saiz zarah 125  $\mu\text{m}$  iaitu 6.65 bar dan 74.00 bar/s sebelum pengeringan dan 14.61 bar dan 222.00 bar/s selepas proses pengeringan. Kandungan lembapannya adalah 8.87% berat, kemeruapan adalah 60.51% berat, karbon tetap 25.92% berat dan kandungan abu 5.09% berat. Selain itu, kepekatan 2000  $\text{g}/\text{m}^3$  mencatatkan nilai tertinggi untuk kedua-dua proses sebelum dan selepas pengeringan. Diperhatikan juga bahawa nilai  $K_{St}$  tertinggi yang direkodkan adalah 199.60 bar.m/s dan dikategorikan dalam kelas St 1. Debu halus bertindak balas dengan lebih hebat daripada yang lebih kasar. Apabila saiz zarah berkurangan, kadar perubahan tekanan letupan meningkat, selagi saiznya mampu menyokong pembakaran dan berada dalam had kebakaran.

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## ABSTRACT

Food-based dust is considered as combustible dust as they composed of distinct particles, regardless of the size or chemical composition and when suspended in air or any other oxidizing medium over a range of concentrations and there is an ignition source will present a fire or deflagration hazard. The explosion effect from food-based dust can cause catastrophic consequences because the initial shock wave from the explosion lift up more dust and triggers a chain reaction through the plant. The parameters that can enhance the explosion are including the particle size of the dust, moisture content and minimum explosible concentration (MEC). In this research, tea powder is chosen because it tends to explode due to its molecular structure which contains a carbon-hydrogen bond that can release the significant amount of thermal energy. The chemical properties of five different particle sizes of tea powder were determined by using TGA and their effects on the dust explosion severity were tested in a confined 20 L explosion vessel. The experimental results showed that the values of  $P_{\max}$  and  $(dP/dt)_{\max}$  of tea powder were more severe for the particle size of 125  $\mu\text{m}$  for which are 6.65 bar and 74.00 bar/s before drying and 14.61 bar and 222.00 bar/s after drying process. Its moisture content was 8.87 wt %, volatility was 60.51 wt %, fixed carbon of 25.92 wt % and ash content of 5.09 wt %. Also from the results, the concentration of 2000  $\text{g}/\text{m}^3$  recorded the highest value for both before and drying process. It was also observed that the highest  $K_{\text{St}}$  value recorded was 199.60  $\text{bar}\cdot\text{m}/\text{s}$  and fell in class St 1. The finer dust reacted more violently than coarser ones. As particle size decreases, the rate of explosion pressure change increases, as long as the size is capable of supporting combustion and falls within the explosion limit.

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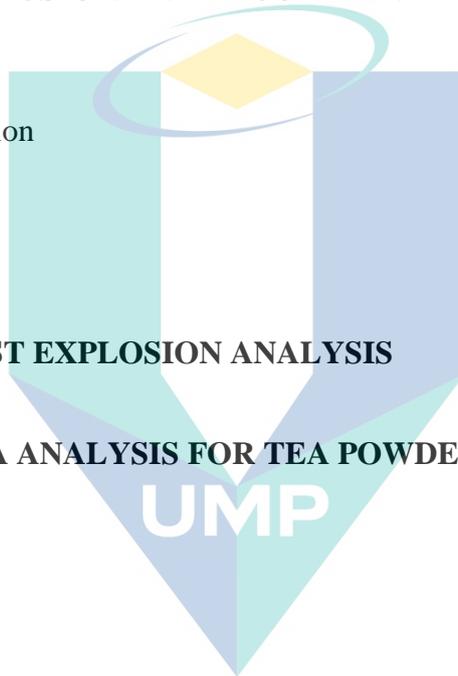
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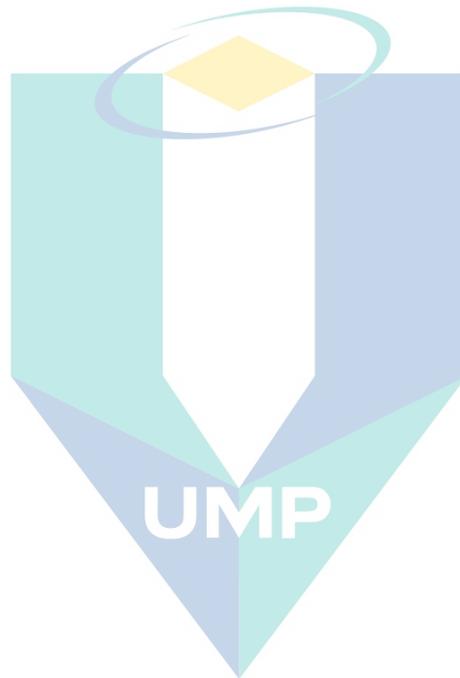
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## LIST OF SYMBOLS

%	Percentage
$(dP/dt)_{\max}$	Maximum rate of pressure rise
°	Degree
°C	Degree Celsius
$\mu\text{m}$	Micrometre
$D[3,2]$	Surface weighted mean
$D[4,3]$	Volume weighted mean
ft	Feet
$\text{ft}^2$	Square feet
g	Gram
kg	Kilogram
kJ	Kilojoule
$K_{St}$	Dust deflagration index
L	Litre
m	Metre
$\text{m}^2$	Square metre
$\text{m}^3$	Cubic metre
ms	Millisecond
$P_d$	Expansion pressure
$P_{ex}$	Explosion overpressure
$P_m$	Corrected explosion overpressure
$P_{\max}$	Maximum explosion overpressure
s	Second
$t_d$	Time delay
$t_v$	Ignition delay time
$u'$	Peripheral velocity
V	Volume

## LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
CSB	Chemical Safety Board
DOSH	Department of Occupational Safety and Health
EDX	Energy dispersive x-ray
FMA	Factories and Machinery Act
ILO	International Labour Organization
ISO	International Organization for Standardization
JK	Jatropha kernel
LFL	Lower flammability limit
LOC	Limiting oxygen concentration
MEC	Minimum explosibility concentration
MIE	Minimum ignition energy
MIT	Minimum ignition temperature
MOC	Minimum oxygen concentration
NFPA	National Fire Protection Association
OSD	Oral solid dosage
OSH	Occupational safety and health
OSHA	Occupational Safety and Health Administration
SCG	Spent coffee ground
SD	Standard deviation
SEM	Scanning electron microscopy
TGA	Thermogravimetry analysis
UFL	Upper flammability limit
VCE	Vapour cloud explosion

# CHAPTER 1

## INTRODUCTION

### 1.1 Introduction

Dust explosions have caused significant losses and damages to humans, assets and the environment. Dust explosion occurs when a flammable cloud, formed by the blending of dust and air within the right proportion during a confined space is ignited and a rapid combustion of the fuel takes place, with the propagation of the flame across the cloud. The flammability/explosibility limits for dust explosion need to be determined as the explosion will occur when the concentration of the dust falls within the explosibility range (Abbasi and Abbasi, 2007). Dust explosion usually occurs in various industries and processes handling variety organic and inorganic powders and dusts. A wide sort of materials which will be explosible in dust form exist in many industries like food, grain, tobacco, wood, plastics, pulp, paper, rubber, pharmaceuticals, pesticides, dyes, coal and metals (Yan and Yu, 2014). These materials are utilized in agriculture, chemical manufacturing, pharmaceutical production, furniture, textiles, fuel power generation, recycling operations, and metal working and processing which incorporates additive manufacturing and 3-dimensional printing. Other than work processes, dusts may also occur naturally such as from pollens, volcanic ashes and sandstorms. By considering the industrial environment, dust is generated as a by-product of several processes that include material crushing, screening, sanding and trimming of excess material. The mechanisms that generate dust and keep it suspended in air arise from aerodynamic forces. Then it will be carried away to another place as a result of air currents (Holbrow, 2013). Although dust generation may occur at one location, dust problems can be experienced at another location away from the source. Nowadays, there are various number of manufacturing processes create very small particles of dust which may become airborne, where they settle on surfaces and in narrow opening or crack throughout the plant (Liu et al., 2013). These particles not only create a housekeeping issue, however if the particles are combustible, they can represent

a potentially explosive dust cloud which can lead to catastrophic consequences (Stroch, 2016).

A combustible dust is fine particles that when suspended in air under certain conditions will present an explosion hazard. According to the National Fire Protection Association (NFPA), combustible dust is defined as a combustible particulate solid that presents a fire or deflagration hazard when suspended in air, or some other oxidizing medium, over a specific range of concentrations, regardless of particle size and shape or dimension. Based on this definition, almost any agricultural product dust has some potential to be classified as a combustible dust. Besides, combustible dust can cause explosion when suspended in air and exposed to a sufficient source of ignition. International Organization for Standardization (ISO 4225-ISO) defines dust consists of small stable particles, conventionally taken as these particles below 75  $\mu\text{m}$  in diameter, which settle out below their own weight however may remain suspended for a few time.

Dust of many materials used every day can form explosive dust clouds. Explosions of such clouds have caused a number of the worst industrial accidents. In Malaysia, there are a small number of accidents involving dust explosions. On March 17, 2008, 4 were killed and 2 injured in explosion involving wheat dust in operation area at Perak. One of the aluminium dust collecting systems at Prai, Pulau Pinang was exploded on early November 2010 due to combustible dust was ignited by spark and fire at polishing machine and 2 were injured during the incident. On November 22, 2014, 3 were killed and 26 injured in explosion involving coal dust in coal mine at Sarawak (DOSH Malaysia, 2016).

On February 7, 2008, an enormous explosion and fire occurred at the Imperial Sugar refinery northwest of Savannah, USA. 14 were killed and 38 others injured during the incident. The explosion started in a conveyor running underneath the sugar silos although the exact cause of ignition is unknown. The accumulated sugar dust on the floor had raised and elevated horizontal surfaces then propagated more dust explosion through the buildings during the primary explosion. The secondary dust explosion occurred throughout the packing buildings, parts of the refinery and therefore the bulk sugar loading buildings. The shockwaves from the explosions heave thick concrete floors and collapsed brick walls, blocking stairwell and other exit routes (CSB, 2009).

On June 27, 2015, 15 were killed and nearly 500 injured in explosion occurred at Formosa Water Park in New Taipei City, Taiwan. During the incidents, a flammable, coloured powder made from cornstarch was sprayed from a stage. In an instant, the powder turned into a fireball that scattered burning dust onto people visit the park. Investigators believe that it came in contact with intense heat from the stage lighting and ignited.

Regarding three catastrophic dust incidents happened in 2013, which caused 14 fatalities, the United States Department of Labour, Occupational Safety and Health Administration (OSHA) has been recommended by United States Chemical Safety and Hazard Investigation Board (CSB) to develop Combustible Dust Rule in 2006 (CSB, 2006). OSHA relies on the General Duty Clause of the Occupational Safety and Health Act of 1970. The clause requires employers to provide workplace free from recognized hazards that are likely to cause death or serious physical harm (Laws, 2016).

In Malaysia, the legislative structure of OSH is led by the Constitution. The Occupational Safety and Health Act 1994 (OSHA 1994), the Factories and Machinery Act 1967 (FMA 1967) and the Petroleum Act (safety measures) 1984 are the major OSH laws (ILO, 2016). Basically, OSHA 1994 replaces the FMA 1967 in the event of any conflicts. The Act is necessary to overcome the limitations of the FMA 1967 in several aspects such as scope of application, prescriptive provisions and approach. The FMA 1967 applies to mainly factories and construction sites and limited to manufacturing industry, mining and quarrying. The Act is important to provide control on factories and for the purpose of registration and inspection of machinery and for matters connected therewith (Laws of Malaysia, 2006). Generally, the aim of these Act is to secure the safety, health and welfare of persons at work against risks to safety or health arising out of the activities of persons at work.

## 1.2 Problem Statement

Over past years in process industries, there are several numerical/correlation models and developed systems towards hindrance and mitigation of dust explosions. Nevertheless, the fundamental knowledge is still significant in getting through understanding on dust explosion hazard as there is an unavoidable conflict between the correlation and the complex nature of the process itself in practice. Types of explosibility

vessels and their feasibility in providing the reliable explosibility data are debated over the past years. In dust explosion studies, the focus has been mainly on dust explosion mechanisms and prevention safety measures on carbonaceous and metal dust explosion (Cao et al., 2012). However, agricultural dust explosion especially in food and beverage industries are seldom seen. Furthermore, many people did not know food-based dust such as flour, grain, sugar, coffee, tea and spices are among of highly combustible dust. One of the research related to a food-based dust is done by Wan Sulaiman et al., (2019). The main objective of the research were to determine the explosion characteristics of commercial rice flour at different concentration and ignition time. Although many of the previous researchers worked on carbonaceous dust, the concepts are applicable to other dusts as well. A primary dust explosion, which usually followed by secondary explosion, will lead to serious damage to nearby units (Abbasi & Abbasi, 2007). The air pressure and flames from primary explosion play a vital role in triggering a secondary explosion.

There are numerous publications regarding dust explosion in confined area but there is limited data on the explosibility of food-based dust from Asia. Tea powder for example has been widely consumed in Malaysia. 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 process industries. Although various safety measures have been recommended to prevent dust explosions, more research is needed due to the limited knowledge about food-based dust explosions. Furthermore, there is no research on the explosion of tea powder yet. Hence, therefore, this research will provide fundamental information on physical and chemical properties of tea powder, moisture content and volatility. The explosibility data covers the maximum explosion overpressure ( $P_{max}$ ), dust deflagration index ( $K_{St}$ ) and minimum explosibility concentration (MEC). MEC is very important as an explosible dust cloud may be formed during operation of the dust.  $P_{max}$  and  $K_{St}$  are widely investigated to design an appropriate dust explosion protection measures such as inerting, suppression or explosion relief venting according to the severity of the dust.

### 1.3 Objectives of Research

The main objective of this research is to investigate the thermal behaviour and dust explosion characteristics of tea powder. The specific research objectives are as follows:

- i. To determine the chemical properties of the tea powder such as moisture content, ash, volatile and carbon content as well as thermal behaviour.
- ii. To obtain the dust explosion sensitivity parameter of the tea powder such as particle size and minimum explosible concentration (MEC).
- iii. To evaluate the explosion severity characteristics such as maximum explosion overpressure ( $P_{max}$ ), rate of pressure rise ( $dP/dt$ ) and dust deflagration index ( $K_{St}$ ).

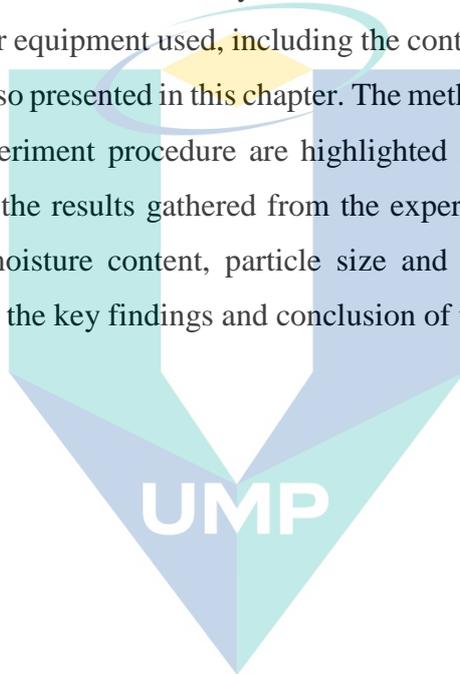
### 1.4 Scopes of Research

The following scopes have been outlined in order to fulfil the objectives of this research:

- i. Tea powder was used as combustible dust.
- ii. In order to identify the optimum size which cause the most severe explosion, the sizes of tea powder tested were 71  $\mu\text{m}$ , 125  $\mu\text{m}$ , 160  $\mu\text{m}$ , 180  $\mu\text{m}$  and 250  $\mu\text{m}$  and sieved by using an analytical sieve shaker.
- iii. Throughout the experiment, the explosion test was performed at an initial ambient temperature and pressure.
- iv. The concentration of tea powder were varies between 1000  $\text{g}/\text{m}^3$  to 2500  $\text{g}/\text{m}^3$  in order to determine the MEC.
- v. The flammability and severity characteristics data such as  $P_{max}$ ,  $(dP/dt)_{max}$ , and  $K_{St}$  were obtained from the 20 L spherical vessel.

## 1.5 Overview of Thesis

This thesis is composed of five chapters. Chapter 1 includes the introduction, problem statement, objectives and scopes of the research. Chapter 2 provides a brief discussion on combustible dust, its characteristics, composition and sources. There are also a review on dust explosion requirements and categories and its parameters and characteristics such as particle size, concentration, maximum explosion overpressure, maximum rate of pressure rise and dust deflagration index. Chapter 3 discusses on the research methodologies used in this study. The schematic diagram of the 20 L spherical vessels as well as other equipment used, including the control unit, and measurement and control system were also presented in this chapter. The method used, analysis of explosion data and detailed experiment procedure are highlighted in this chapter. In Chapter 4, analysis was done on the results gathered from the experimental work. These analyses cover the effect of moisture content, particle size and concentration of tea powder. Chapter 5 summarizes the key findings and conclusion of this study.



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## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Introduction

This chapter provides the related literature review regarding dust explosion. The first part of this chapter gives a brief review on the physical and chemical properties of dust. The second part of this chapter provides the overview on how dust explosions occur. Next, discussion on the researches done by many authors on the explosion severity parameters were included. The last part of this chapter discusses on the factors that affects the explosion severity parameters in details.

#### 2.2 Dust

Dust is defined as a particle having a diameter lower than 76  $\mu\text{m}$  (CSB, 2006; BS2955, 1958). However, NFPA (National Fire Protection Association) holds an opinion that a powder 420  $\mu\text{m}$  or less in diameter should be called dust (NFPA, 2007). Generally, the term dust is used if the maximum particle size of the solid mixture is below 500  $\mu\text{m}$ . Combustible dust widely exists in process industries, such as coal mining and plastic manufacturing and processing industries, and different definitions of dust can be found for different materials. According to OSHA combustible dust is defined as any solid material that is composed of distinct particles and can cause a fire hazard. In food industries, common processes generating explosible dust include flour and provender milling, sugar grinding, spray drying of milk, storage of whole grains and finely divided materials. Some food industry activities may be in danger of fire and explosion through the utilization of finely sprayed oils, mixing with potable ignitable solvents (i.e. ethanol), or sterilization techniques such as high temperature drying or spraying with hydrogen peroxide solutions. The examples of explosible dusts in the food industries include materials such as tea powder, flour, custard powder, instant coffee, sugar, dried milk, potato powder and soup powder.

If the particle size is small and moisture content is low, the majority of powders within the food industry can form explosible dust clouds. Although explosible dust cloud concentrations are not remarkably expected to be present within processing buildings, explosible dust clouds are regularly formed within the material handling or processing instrumentation when bins are being stuffed, powders are being transferred or dust is being collected in a dust collector (Vahid et al., 2019). If any flammable substance is mixed or suspended in air at the right concentrations and contained in a vessel or building when ignition occurs, then a violent explosion may happen. If it is uncontained then a fireball cloud can occur. The typical concentration ranges that can give rise to an explosion are low which is in the range of 75 - 1000 g/m<sup>3</sup>.

Relating to combustible dust, the NFPA has issued several standards. For the food processing industry, there are two main standards which are NFPA 61: Standard for Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities and NFPA 652: Standard of Fundamentals of Combustible Dust. NFPA 61 provides specific for the food industry while NFPA 652 provides general requirements for managing combustible dust fires and explosions across all industries, processes, and dust types.

A dust explosion is the fast combustion of a dust cloud. In a confined or nearly confined space, the explosion is characterized by comparatively fast development of pressure with flame propagation and therefore the evolution of enormous quantities of heat and reaction products. The required oxygen for this combustion is generally provided by the combustion air. The condition necessary for a dust explosion may be a coincidental presence of dust cloud of right concentration in air which will support combustion and a suitable ignition source. An explosion hazard exists once dusts are produced, stored or processed in an exceedingly plant and these materials are present as a mixture in air. An associate explosible mixture is present, once the combustible dusts are present in such quantities in air that the associate explosion happens after an ignition.

Dust explosion is a complex phenomenon involving simultaneous momentum, energy and mass transport in a reactive multi-phase system (Vijayaraghavan, 2011). Particles, once in dust, powder or flake forms from operations like grinding, finishing and processing can be suspended as a dust cloud in air and could ignite and cause serious

injury. If the dust cloud is unconfined the impact is solely one in every of flash fire. If however, the ignited dust cloud is at least partly confined the heat of combustion could end in rapidly increasing pressure and result the explosion effects like rupturing of the confining structure (Manju, 2013).

Dust explosion is different than a fire. To create a fire, only three factors are required, which are oxygen, fuel and an ignition. However, a dust explosion needs two more additional factors, which are the dust must be dispersed at the right concentration in the air and it must be confined in some sort of enclosure. Hence, the conditions necessary for a dust explosion are the dust must be combustible, the dust must be fine, the dust cloud must be explosive concentration, there must be sufficient oxygen in the atmosphere to support and sustain combustion and there must be a source of ignition (Vijayaraghavan, 2011). This is known as “Dust Pentagon”. Figure 2.1 shows the elements in the dust pentagon.

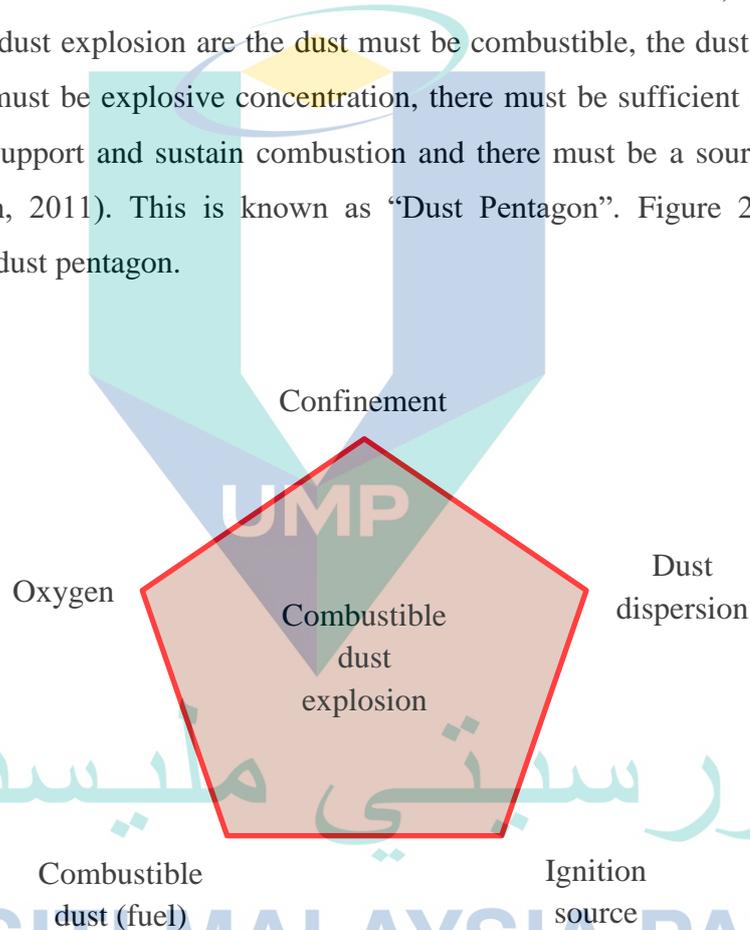


Figure 2.1 Dust explosion pentagon

### 2.2.1 Oxygen

Oxygen is needed by a fire to be able to burn. The velocity of the combustion of the fuel will be increased as the concentration of oxygen in the air is exceeded 21%. When the concentration of oxygen is higher than 10%, the fire will continue (Cashdollar, 1996). The mixture of combustible dust and oxygen in the form of a combustible dust cloud is the necessary element for a dust explosion. In dust deflagration, the lower its minimum

oxygen concentration (MOC), the greater the energy required to ignite the dust. However, a deflagration cannot be prevented by reducing the oxygen concentration. For example, the ignition of corn starch is possible in atmosphere containing 5% oxygen (Babrauskas, 2002). Using nitrogen or argon gas to inert atmosphere can lower the MOC to 0%.

### **2.2.2 Confinement**

When the dust cloud is contained within a closed area, it causes issues with the confinement. The density of the dust cloud is constantly increasing since the dust particles can remain suspended in confined air for days. The confinement will cause enough heat accumulated, some pressure to increase when the dust cloud combust and cause the explosion to occur (Hughes, 2015). For instance, in the case of the Imperial Sugar dust explosion, the dust cloud that is being confined pushed the explosion through tunnels and halls which later led to another confined dust clouds. This caused a chain reaction of combustion, destroying the building and claiming several workers' lives (Barry, 2012).

Combustible dusts are like flammable gases and vapours. To form an ignitable concentrations, the volume of dust must be within a certain range of flammability limit. The minimum concentration of combustible dust and air needed to propagate a deflagration is known as MEC and is determined by testing in accordance with ASTM E1515, Standard Test Method for Minimum Explosive Concentration of Combustible Dusts, and associated with the confinement. Combustible dusts do not, for practical purposes, exhibit an upper flammable limit in air. Therefore, maintaining high dust cloud concentrations cannot prevent deflagrations (NFPA, 2002).

### **2.2.3 Dust Dispersion**

Dispersion occurs when the accumulated dust is spread out over the air and creates a dust cloud. The daily activities such as sweeping, exhaust from machinery or cleaning using compressed air can disturb the accumulated dust and send it airborne. Small primary combustion also can cause dust dispersion. The shockwaves from the combustion can cause the dust that had settled to spread throughout the air. This dust can change from the initial fire to an explosion once it has been dispersed (Hughes, 2015). There are two variables related to the dust dispersion which are the depth and the location of the dust (Stooky, 2006).

For many combustible dusts, a layer depth of 1/32-inch or greater covering more than 10% area above the floor that is not accessible may present a dust deflagration hazard. For example, NFPA 664, Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities, states that in buildings with ceiling heights greater than 10 ft and areas greater than 5,000 ft<sup>2</sup> but less than 20,000 ft<sup>2</sup>, housing wood working or wood processing operations, a deflagration hazard may exist if the wood flour layer depth is 1/8-inch or greater and the area of wood flour layer covers more than 10% of the building area (NFPA, 2014).

Combustible dusts or flours in areas that are not easily inspected or accessed such as building structural members, ventilation ducts, electrical bus ducts, cable trays or conduits are locations that allow for the build up of dust layers where the depth is decent to provide enough fuel to propagate dust deflagration. Dust accumulations on the floors of buildings or on the working surfaces of equipment cannot be suspended in air in sufficient volume to propagate a dust deflagration (Stooky, 2006).

#### 2.2.4 Ignition Source

Ignition sources, ranging from hot surfaces to friction sparks, can provide enough temperature or energy required for a dust explosion. The ignition source causes the other elements to combust and creates a dust explosion. It also can be created when something just gets hot enough to ignite something nearby.

Minimum ignition energy (MIE) is the lowest amount to ignite the most readily ignitable dust/air mixture at normal temperature and pressure. The dust/air mixture is more easily to ignite if the MIE is lower. Ignition energies for dust clouds are typically higher than for flammable gases or vapors—dusts generally require 1–10 mJ, versus a gas like hydrogen which only requires 0.3 mJ. MIE is determined by testing the material in accordance with ASTM E2019, Standard Test Method for Minimum Ignition Energy of a Dust Cloud in Air. (Stooky, 2006).

As an essential element of dust explosions, ignition sources can be divided into eight types which are flame and direct heat, hot work, electrical sparks, static electricity, impact sparks, self-heating and smouldering, friction sparks and hot surfaces (Abbasi and

Abbasi, 2007). Figure 2.2 shows the contribution of each type of ignition sources while Figure 2.3 shows the contribution of ignition sources in various industries.

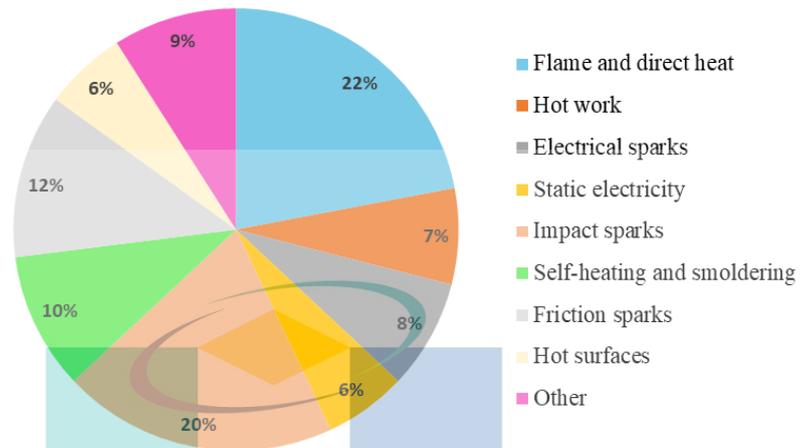


Figure 2.2 Ignition sources for dust explosion  
Source: Abbasi and Abbasi (2007)

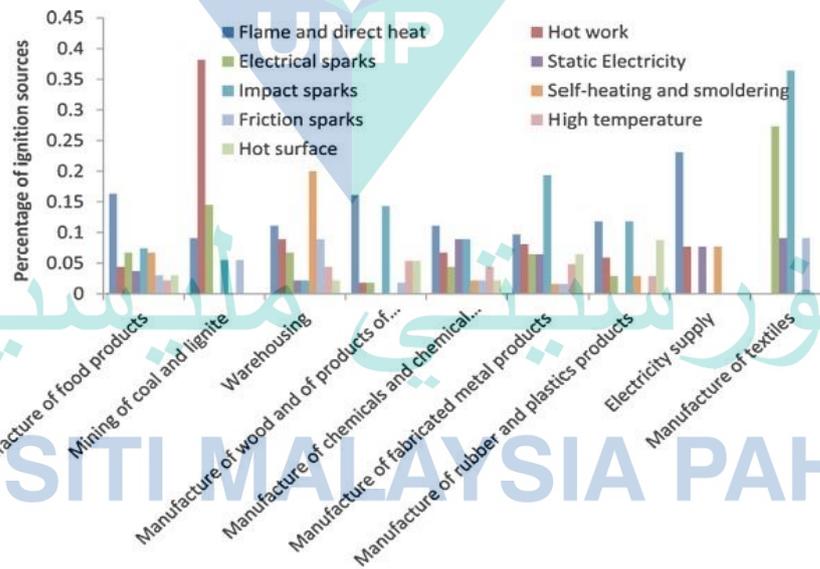


Figure 2.3 Contribution of ignition sources in various industries  
Source: Abbasi and Abbasi (2007)

Figure 2.2 shows a large proportion of dust ignition caused by flames. A flame may be a very effective source of ignition for dust suspensions. A direct-fired equipment is one of the flames sources and it may be eliminated by the use of indirect heating using

hot water or steam. Figure 2.3 shows another principal ignition source for dusts is hot work such as mining of coal and lignite. A spark flame is a very effective source of ignition. In this case it is frequently a dust layer may have an ignition temperature in the range 100 - 200 °C and is readily ignited by hot work. Incidents occur as a result of this hazard is not appreciated and the dust is not cleaned out of the equipment before work is started.

Hot surfaces are another important ignition source. Equipment with a hot surface such as steam pipe or electric lamp is a type of hot surface. A distressed bearing is another overheated moving equipment. Due to a hot surface, an ignition of dust layers is likely to occur. As mentioned earlier, the surface temperature between 100 - 200 °C may result in ignition of a dust layer. The ignition temperature of a dust layer decreases with the increases of the layer thickness. However, it is frequently found that a dust layer can be ignited at an unexpectedly low temperature (Stooky, 2006). The dust itself might contribute to its own ignition. Dust is a poor conductor of heat where a layer of dust on equipment may reduce heat loss to atmosphere and therefore cause the surface to be hotter than it would be. Hot surfaces may additionally occur as a result of distress in machinery like pumps and motors. It should be necessary in some cases to observe options such as bearing temperatures (Vijayahagravan, 2011).

A static spark might occur because of a discharge from electrical instrumentation. Protection against such discharges relies on risky space classification. Electrical sparks occur within the normal operation of certain equipment like switches and relays and may occur in electrical equipment as a result of malfunction. Another vital contributor to incidents is frictional sparks related to rubbing or grinding. These may occur in plant handling dust in many ways. The dust itself might block the equipment and cause overloading, resulting in spark generation. Preventive measures include the management of dust flow and machine overload trips. Foreign substances like tramp iron can cause sparks. Removal of such objects are often effected by magnetic or pneumatic separation, and is particularly desirable if the material is to undergo a mill. Failure of equipment also can produce sparks (Abbasi and Abbasi, 2007).

Self-heating or ignition is another significant ignition source. There are wide sources of reactions, which may produce to self-heating. For several reactions the reaction rate accelerates with temperature (Vijayahagravan, 2011). However there also auto

catalytic reactions, which can accelerate because of the production of a catalyst or removal of an inhibitor. In general terms, the static charge on dust may be a function of the work done on them. Therefore the charge tends to be a stronger function of the method than of the material. For sieving and pouring the charges are low, except for size reduction they are a lot higher. It is tough to screen wherever a static electricity would possibly present a hazard in dust handling.

There are certain sorts of dust handling plant during which static electricity is quickly generated. These include mills, conveyor belts and gas transfer systems, which the hazard in such equipment should be considered carefully. For liquids, static charge can accumulate in the middle of a large storage hopper. Then it should be discharged by an earthed probe. But there is also a hazard distinctive to dusts that of sliding of extremely charged material towards an earthed container wall (Lees, 1995).

#### **2.2.5 Combustible Dust (Fuel)**

The dust ignites and provides a source for the fire or combustion to continue burning. In dust explosion, it is the airborne dust that is providing the fuel and causing it to change from a fire to an explosion (OSHA, 2015). For combustible dust, the variables such as particle size, moisture content and deflagration index play an important role in dust deflagration. Generally, the smaller the dust particle, the more easily it is suspended. A smaller particles has a greater surface area in relation to its mass and does not need a strong ignition source. Moisture affects the ignition and ability to sustain a deflagration. Water in dust particles absorbs the energy of an ignition source. The higher the moisture content, the more difficult the dust to ignite. It also reduces the severity of the deflagration. The dust deflagration severity index measures the relative energy of a dust deflagration. The test criterion is based on ASTM E1226, Standard Test Method for Pressure and Rate of Pressure Rise for Combustible Dusts. The test uses a minimum 20 L vessel and a standard ignition source to measure the maximum rate of pressure increase within the test vessel. The test results are normalized to a 1-cubic-meter volume. The higher the  $K_{St}$  value, the more energy will be liberated during a dust deflagration (Stooky, 2006).

## 2.3 Types of Combustible Dust

Combustible dust can be formed from the vast majority of natural and synthetic organic materials including pharmaceuticals and food, as well as inorganic materials and some metals.

### 2.3.1 Metal Powder

In metal industry, high temperatures and spark flight are cannot be avoided. Overheated parts and smouldering fire can occur during the production and processing, which can result in fire or explosions. Several metals react violently, especially particulate metal fines under 420  $\mu\text{m}$ . Magnesium, aluminium and zinc are the example of mostly produced metals in metal industry. A dust explosion at the AL Solutions metal recycling facility in New Cumberland, West Virginia killed 3 employees and injured a contractor on December 9, 2010. A spark from a blender likely ignited the zirconium powder which resulting fire lifted the metal dust particles and forming a dust cloud (CSB, 2014).

### 2.3.2 Pharmaceuticals

On January 29, 2003, 8 killed included 2 fire-fighters and 38 injured in a powerful explosion and fire ripped through the West Pharmaceutical Services rubber-manufacturing plant in Kinston, North Carolina (CSB, 2005). Many of the solid ingredients used in the formulation of pharmaceutical oral solid dosage (OSD) forms are combustible. As a result, operations typically found in pharmaceutical facility have been potential to generate explosible dust cloud atmospheres (Ebadat, 2012). The explosion hazards related to solid pharmaceutical ingredients tend to be less well understood or controlled. Table 2.1 shows some materials commonly used as excipients in the pharmaceutical industry that cause an explosion hazard.

Table 2.1 Properties of selected pharmaceutical excipients

<b>Ingredient</b>	<b>Explosion severity, <math>K_{St}</math> (bar.m/s)</b>	<b>Minimum ignition energy, MIE (mJ)</b>	<b>Minimum ignition temperature, MIT (°C)</b>
Cellulose	229	100-300	480-500
Cornstarch	202	100-300	380-400
Dextrin	168	50-100	410-430
Gelatin	23	>500	400-420
Lactose (monohydrate)	81	>500	460-480
Lactose (anhydrous)	188	3-5	460-480
Metallic stearates	99-210	5-10	440-460
Methyl cellulose	157-209	>500	360-380
Organic pigments	73-288	10-25	460-480
Stearic acid	159	25-50	380-400
Sugar	138	10-25	340-360

Source: Edabat (2012)

## 2.4 Food

Almost all foodstuffs and ingredients such as grain, starch, sugar, artificial sweeteners, and powdered flavors will burn with difficulty can explode violently once ignited within a sort of dust cloud (Yan and Yu, 2014). Food producing plants are among the foremost vulnerable to these incidents, especially the plants that use tons of flour and sugar within the baking segment. The most common combustible food product dusts include sugar, flour, tea and milk powder. Flour storage, flour milling and sugar grinding are part of common processes which generate explosible dusts in food industry. Food-based dust are considered as combustible dust because they might contain ingredients for the risk potential. For example, under the right conditions, table sugar can be as flammable as wood (which is made of cellulose, or lots of sugar molecules linked together). These dust particles are much more flammable because of their surface area-to-volume ratio (Gao et al., 2013). On February 7, 2008, an explosion caused by static electricity igniting fine sugar dust, which had become too dry, happened in Port Wentworth Imperial Sugar Refinery killed 14 people and injured over 40 (Barry, 2012).

## 2.5 Tea Powder

Tea was primarily originated in South Eastern China but recently it is cultivated in many countries all over the world and has more than 82 different species (Krafczyk and Glomb, 2008). Tea is the extract of leaves, leaf nodes and internodes of plant which is consumed as extract in hot water. It is also known as an aromatic liquid product which has been made by curing the leaves by soaking in hot water (Xiao et al., 2008). The chemical components in tea include alkaloids (theobromine, caffeine, and theophylline), polyphenols (catechins, flavonoids), amino acids, polysaccharides, volatile acids, vitamins, lipids as well as inorganic elements (Xiong et al., 2012).

### 2.5.1 Tea Powder as a Combustible Dust

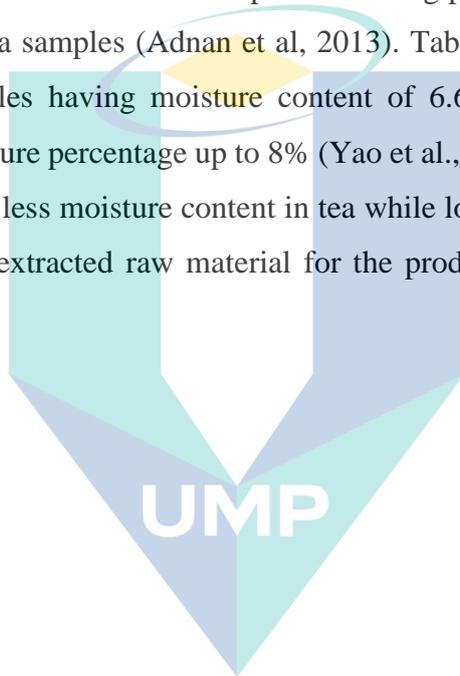
Tea powder is one of the combustible dusts in food industry. During the processing of tea powder, much dust is generated and it leads to a dust explosion hazard (Fumagalli et al., 2016). The explosion impact from food-based dust can cause catastrophic consequences due to the initial blast wave from the explosion elevate up more dust and triggers a sequence reaction through the plant. As the result, there are mass destruction of equipment and buildings, as well as causing possible death or injury to employees (Stroch, 2016). In order to prevent such accident, comprehensive dust explosion characteristics such as maximum explosion pressure, rate of pressure rise, dust explosion index are necessary required (Hassan et al., 2014). According to (Bershad, 2014), tea powder tends to have a  $P_{max}$  of 7.6 barg,  $K_{St}$  of 102 bar.m/s, 6.3 wt % of moisture and minimum explosive concentration of 125 g/m<sup>3</sup> at particle size of 77 μm however, the results obtained from this research were different might be because of the different type of tea powder used or different ambient temperature. Further results will be discussed later in Chapter 4.

### 2.5.2 Analysis of Tea Sample

The moisture content in tea samples was determined by using hot air oven at temperature of 105 °C. The nitrogen content was determined and multiplied with factor 6.25 in order to analyze the crude protein of tea samples. The samples was digested in 1.25% sulfuric acid and 1.25% sodium hydroxide in order to determine the crude fiber

contents of tea samples. The samples were boiled over low flame for 1 hour and then by using hot air oven at 100 °C for 1 hour to determine their ash content (Adnan et al., 2013).

Table 2.2 shows the physicochemical analysis of commercial tea samples. The results indicated significant variations ( $p < 0.05$ ) in different components such as moisture (2.46-7.47%), crude protein (0.87-1.141%), fat (0.94-2.15%), crude fiber (11.23-17.21%), ash (32.34-53.61%) and water extract contents (3.29-5.86%). The maximum and minimum values, means and standard deviation of these components are shown in Table 2.3. The exclusion of fermentation process during processing tea results in higher moisture content in tea samples (Adnan et al., 2013). Table 2.3 also shows that 70% of commercial tea samples having moisture content of 6.6% or less than 30% sample containing more moisture percentage up to 8% (Yao et al., 2006). The higher ash content in tea might be due to less moisture content in tea while lower ash content might be due to adulteration using extracted raw material for the production of tea (Rehman et al., 2002).



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Table 2.2 Analysis and mineral contents of tea samples

Sample codes	S <sub>1</sub>	S <sub>2</sub>	S <sub>3</sub>	S <sub>4</sub>	S <sub>5</sub>	S <sub>6</sub>	S <sub>7</sub>	S <sub>8</sub>	S <sub>9</sub>	S <sub>10</sub>
<b>Moisture (%)</b>	2.46	5.55	4.35	6.43	4.58	6.11	6.07	7.21	5.43	6.15
<b>Protein (%)</b>	0.95	0.96	0.99	0.95	0.95	0.98	1.01	1.03	0.97	0.87
<b>Fat (%)</b>	1.21	1.00	0.94	0.96	1.07	1.16	1.21	2.02	1.73	1.91
<b>Crude fiber (%)</b>	11.23	13.57	16.10	14.57	14.34	15.16	13.33	16.33	16.21	13.84
<b>Ash content (%)</b>	4.52	5.47	5.50	5.16	4.87	5.86	4.69	4.89	5.18	3.29
<b>Water extracts (%)</b>	32.54	38.73	32.51	36.33	36.97	32.34	35.51	35.51	36.36	53.61
<b>Caffeine (%)</b>	2.34	2.82	3.21	3.28	3.04	3.15	3.76	4.02	3.91	4.33
<b>Catechins (mg/g)</b>	0.00	0.47	0.16	0.34	0.00	0.00	0.00	0.00	0.14	3.47
<b>Calcium (mg/l)</b>	2.46	2.55	2.16	2.81	1.46	1.74	1.66	1.47	1.77	1.87
<b>Magnesium (mg/l)</b>	4.49	4.80	3.54	3.69	3.36	3.41	3.36	3.82	2.97	4.00
<b>Sodium (mg/l)</b>	0.39	0.41	0.49	0.41	0.48	0.39	0.58	0.49	0.83	0.58
<b>Potassium (m/l)</b>	3.26	3.47	3.54	3.01	3.13	3.17	3.25	3.05	3.30	3.24
<b>Manganese (mg/l)</b>	1.51	1.51	1.09	1.21	1.24	1.19	1.32	1.29	1.44	2.4

\*S<sub>1</sub>=Lipton Yellow Lable, S<sub>2</sub>=Supreme, S<sub>3</sub>=Tetley, S<sub>4</sub>=Tapal Danedar, S<sub>5</sub>=Al Karak Chai, S<sub>6</sub>=Zaiqa Chandar, S<sub>7</sub>=Rachna, S<sub>8</sub>=Kenya Gold, S<sub>9</sub>=Kenya Super, S<sub>10</sub>=Kenya Bp 14

Source: Adnan et al. (2013)

Table 2.3 Maximum and minimum values, means and standard deviations of chemical components and mineral contents of tea samples

<b>Chemical composition (%)</b>	<b>Max</b>	<b>Min</b>	<b>Mean</b>	<b>SD</b>
Moisture	7.21	2.46	5.53	1.34
Protein	1.03	0.87	0.96	0.04
Fat	2.03	0.94	1.32	0.40
Crude fiber	16.33	11.23	14.46	1.58
Ash content	5.86	3.29	4.94	0.70
Water extract	53.61	32.34	37.04	6.19
Caffeine	4.33	2.34	3.38	0.60
Catechins	3.47	0.00	0.45	1.07
<b>Minerals (mg/l)</b>				
Calcium	2.81	1.46	1.99	0.47
Magnesium	4.80	2.97	3.74	0.55
Sodium	0.83	0.39	0.50	0.13
Potassium	3.54	3.01	3.24	0.16
Manganese	2.43	1.09	1.42	0.38

Source: Adnan et al. (2013)

## 2.6 Dust Explosion Hazard

As mentioned earlier, five elements must be present for a combustible dust explosion to occur, which are fuel, oxygen, an ignition source, dispersion and confinement. Dust might accumulate on surfaces and lie undisturbed for a long time. Then an initial fire or explosion, which is known as a primary dust explosion, shakes it loose and it ignites. The resulting pressure then travels throughout a plant or factory and undisturbed dust that has been lying dormant, serving as fuel for a secondary explosion. Most of the fatalities and therefore the devastating injuries are caused by these secondary dust explosions.

## 2.7 Dust Cloud

Dust explosions are inherently complex phenomena. A dust cloud could be a mechanical suspension, i.e. a system of fine particles dispersed by agitation. Most dust samples have a comparatively wide particle size distribution, and particles of various size react differently to variations within the flow field. This implies that the flow is inherently turbulent, the overall process is inherently transient, and the dynamics of the turbulent structures create local concentration gradients (Skjold et al., 2014). Compared to the state

of a premixed gas mixture, the characterization of the state of a dust cloud is far more complicated. For a dust cloud, the stable state of equilibrium will be complete separation, with all particles settled out at the bottom of the system and always be dynamic. In various industrial environments, gravity and inertia forces act on the dust particles. In the ideal static dust cloud, all the particles will be located in fixed positions (Eckhoff, 2003).

In order for a dust explosion to occur, the dust must be dispersed in the air at the same time that the ignition source is present. The rapid oxidation of the fuel dust leads to a rapid increase in temperature and pressure. This explosion may be a deflagration or detonation, depends on the rate of reaction and velocity burning (NFPA, 2007). As mentioned earlier, the requirements of dust explosion consists of oxygen, confinement, dust dispersion, ignition source and combustible dust. However, it is possible to have a destructive explosion even in open air as long as the reaction as fast that pressure builds up in the dust cloud faster than it can be released at the edge of the cloud (Kosinski et al., 2002). The combustion products are usually gases no matter the reacting material is a gas or a dust.

### 2.7.1 Flame Propagation in Dust Cloud

Flame propagation refers to the propagation of the reaction zone or combustion wave through a flammable mixture and can be divided into two categories that are laminar and turbulent flame. A layer of the flammable mixture may become a source of heat when the transport of heat and active species (free radicals) have initiated chemical reaction within the adjacent layer. It is then capable of initiating reaction in the next layer. A theory of flame propagation should support the transfer of heat and mass from the reaction zone to the unburned mixture (Gunther et al., 1976).

Mechanical phenomenon forces can give a fuel concentration gradients (particle displacement of particles in reference to gas phase) in dust clouds, as against premixed gases. In addition, thermal radiation, depending on the type of particle material (e.g., lightweight metals), may contribute significantly to the unburnt cloud. Further work is needed to examine the role of thermal radiation within the development and course of dust explosions (Eckhoff, 2009).

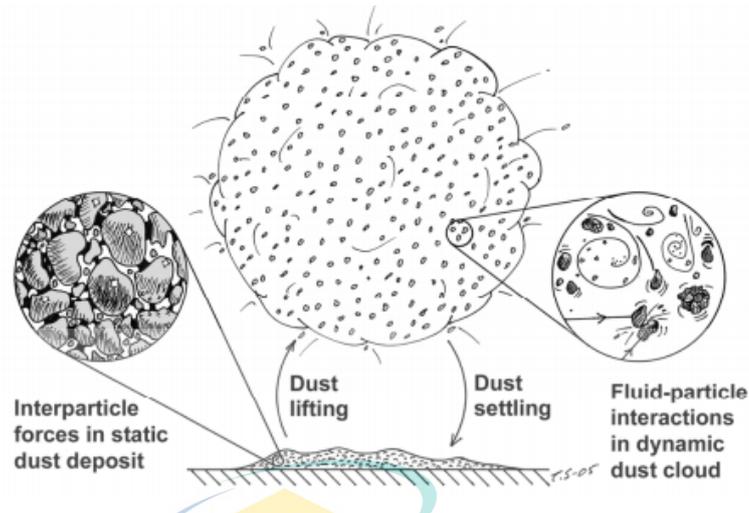


Figure 2.4 Mechanical suspensions of dust clouds

Source: Skjold et al. (2006)

Table 2.4 illustrates some flow-related aspects of dust explosions. It is simple to classify the particle-loaded flow in flammable dust clouds consistent with the particle volume fraction and relative particle spacing (Skjold et al., 2005; Skjold et al., 2006). Dust concentrations starting from the lower flammability limit (LFL), generally 20-60 g/m<sup>3</sup>, to the most reactive mixtures, generally 500-750 g/m<sup>3</sup>, are within the dilute suspension regime where two-way coupling ought to be accounted for (Elghobashi, 1994; Crowe et al., 1998). When the dust concentrations reach the upper flammability limit (UFL), which might be within the range 2-10 kg/m<sup>3</sup>, the flow enters the dense suspension regime where four-way coupling plays a crucial role.

In dust clouds, a flame propagation involves premixed with non-premixed combustion (Williams, 1986). Dust flames are often classified based on the combustion mechanisms for individual particles (Cassel, 1964; Bardon and Fletcher, 1983). Combustion in so-called Nusselt flames involves strictly heterogeneous reactions on the surface of the particles. It applies to materials such as carbon and refractory metals. Another category is volatile flames, where the particles produce vapour before the gas-phase combustion (Rockwell and Rangwala, 2013). The structure of volatile flames varies considerably, depending on processes such as pyrolysis, evaporation, heat and mass transfer, chemical reactions, etc. (Gao et al., 2013). The external heating of the fuel particles results in thermal degradation and liberation of volatiles through pyrolysis, where the volatiles then burn within the surrounding atmosphere, for most of organic solid materials. This implies that the chemical species actually participating in the

combustion reactions may differ considerably from the general composition of the fuel. The mechanism behind the process of flames in dust explosions is the same as for gas explosions: expansion introduces flow, generating turbulence, increased heat and mass transfer within the flow resulting in higher combustion level, creating more expansion, and creating more turbulence (Bjerketvedt et al., 1997). Dust explosions may intensify through the mechanisms of dust lifting prior to the flame front and pressure piling in complex confined geometries.

## 2.8 Spherical Flame Propagation

Central ignition by a spark of a premixed flammable mixture inside a spherical vessel is the simplest geometry for a flame propagation. This is due to the mixture that is ignited at its centre which causes the flame propagates in the outward direction towards and  $90^\circ$  to the wall. This will not trigger boundary layers to be generated as there is no motion on the wall surface (Baker and Tang, 2012; Ogle, 2016). Because of the flame propagates in the outward direction, a spherical symmetry is formed in which a small zone (flame front) forms a two distinctive region as shown in Figure 2.5. These regions are referred to the unburned gas mixture and burned gas mixture.



Figure 2.5 Dust explosion mechanism

Source: Marks et al. (2013)

The flame propagates at laminar burning velocity at the first stage of the propagation. Because the flame propagates into the unburned gas mixture, it serves as a 'leaky piston' and forces unburned dust/air mixture towards the wall of the vessel. Nonetheless, a number of the unburned dust/air mixture is allowed to enter the flame throughout this process. In this instance, the flame front is stable as it experiences the strongest stretch effect due to its small flame front radius resulting in greater curvature

(Buffel, 2014). As the flame front radius increases as it propagates, its curvature decreases, causing it to become unstable due to the weak stretch impact, thus increasing burning velocity (Buffel and Bauwens, 2014). The flame front deforms, experiences instability and develops cellularity hence becomes turbulent (Buffel and Bauwens, 2014). The mixture velocity at the center of the vessel wall is zero similar to the velocity at the vessel wall (Ogle, 2016). As the flame propagates and grows considerably as it passes the vessel wall, the pressure increases gradually and when it touches the vessel wall it reaches its final value. Nevertheless, the pressure decreases slowly as the flame reaches the vessel wall (Ogle, 2016) due to the decreasing surface area of the flame and thus the mass burning rate decreases (Tang et al., 2009). Since the flame propagates outwardly from the vessel's centre, a uniform temperature or combustion species distribution should not be required (Ogle, 2016). The combustion process of an externally spherical flame propagation is therefore described as a one-dimensional (1D) direction in which a temperature versus concentration profile could be obtained.

## 2.9 Flame Transition

The most basic outcome to all combustion processes is flame. It is often categorized as laminar and turbulent flame. A laminar flame has a smooth flame front whereas a turbulent flame has a wrinkled flame front. A laminar flame is formed in explosions right after the ignition. When the flame is turbulent, the front of the flame wrinkles, corrugates and then transforms into cellular flame, causing turbulent combustion (Sulaiman, 2015; Xiao, 2015). In gas and dust atmospheres the process of explosion may also be very similar (Proust, 2007; Gao et al., 2012; Eckhoff, 2003). It has been reported for dusts like flour and starch burning in air, laminar, cellular and turbulent flame regimes. The laminar flame regime obeys the same mechanisms, where the reactants in front of the combustion zone are heated by conduction to be pyrolysed so that the combustion happens in gaseous phase.

A flow becomes turbulent as soon as the low speed layers of the flow roll up with the higher speed layers within a boundary layer (velocity gradient) to form eddies which quickly appear and dissipate (Proust, 2007). Such structures are “chaotic” and represent the flow “turbulence” (Hinze, 1975). The related theories introduce the notion of “turbulent cascade” in line with the idea that the initial eddies are demolished in smaller

structures before molecular diffusion dissipates in such a way that there is a mechanical interaction between all the turbulence structures. In note, this process of “cascading” is viewed as an inherent process, independent of the mean flow. Therefore, to thoroughly describe the turbulence, it is then sufficient to understand the characteristics of the biggest eddies, those directly emitted from the common flow field. Those characteristics are the magnitude of the biggest eddies ( $L$ ) and their peripheral velocity ( $u'$ ). The parameter  $u'$  is a space average variable in principle, and  $L$  is the region under the curve that gives the evolution of the coefficient of correlation of the velocity signals around a reference point. The matter can also be assumed to be comparable with dust clouds (Tezok, 1985). However, this is often not quite obvious, the direct observation shows that the particles are being pushed around the turbulent eddies (Proust, 2007; Bozier and Veysiere, 2006). The mixture does not stay homogeneous locally, and as the result, the burning might occur especially at the eddies' boundaries and without doubt between them as shown in Figure 2.6.



Figure 2.6 Visual aspect of a turbulent flow of starch dust air mixture and turbulent flame propagating in that cloud

Source: Proust (2007)

## 2.10 Generation of Primary and Secondary Dust Explosion

Dust explosion can be categorized as either primary or secondary. A primary explosion occurs in a confined space such as a container, room or piece of equipment which is ignited and explodes. Burning dust and gases are expelled into the surrounding area from the explosion. The accumulated settled dust will be disturbed by the primary explosion. Secondary explosion refers to this dust which can support a larger explosion

once airborne. The explosion can cause severe damage to surrounding plant buildings and could be worse than the first explosion (Lees, 2005).

### **2.10.1 Generation of Primary Dust Cloud**

For an explosive dust cloud to be formed from a layer/deposit, the layer/deposit must be exposed to a process that suspends the particles within the air until the dust concentration drops into the explosive range. Most frequently such dispersion of dust to produce explosive clouds takes place within the process equipment. The dust cloud structure including the spatial distributions of effective particle size, dust concentration, turbulence, and global flow are often predicted which will be generated in numerous practical situations in industry. Knowing this initial cloud structure is crucial for predicting the cloud's ignition sensitivity to numerous ignition sources and for predicting the path of primary explosion production that result from ignition (Eckhoff, 2009).

In addition, it is vital to notice that one of the main differences between the dust explosion and flammable gas hazard is that gas/vapour explosions seldom happen inside vessels as there is not enough air to support explosions. However in process equipment it is typically suspended in air with dust, which could allow the conditions for dust explosion to occur. This can then cause the vessel to rupture only if the pressure release devices/venting is insufficient or if its design pressure is just too low (Amyotte et al., 2005).

### **2.10.2 Generation of Secondary Dust Cloud**

The shock wave from a primary dust explosion would cause the secondary explosive clouds by causing deposits and layers of dust to form. These are triggered when the primary explosion disturbs the lying dust and creates a second dust cloud, which is then ignited by the heat released from the primary explosion. Once the small amounts of lying dust take up very little space are disturbed, hazardous clouds can easily form. A 1 mm layer of dust of 500 kg/m<sup>3</sup> can produce to a 5 m deep cloud of 100 g/m<sup>3</sup> dust (Vijayaraghavan, 2011).

A series of explosions consisting of a primary dust explosion and one or more subsequent secondary dust explosion(s) has been reported in most dust explosion

accidents. Such chain of dust explosions are often mentioned as a dust explosion domino effect (Yuan et al., 2016).

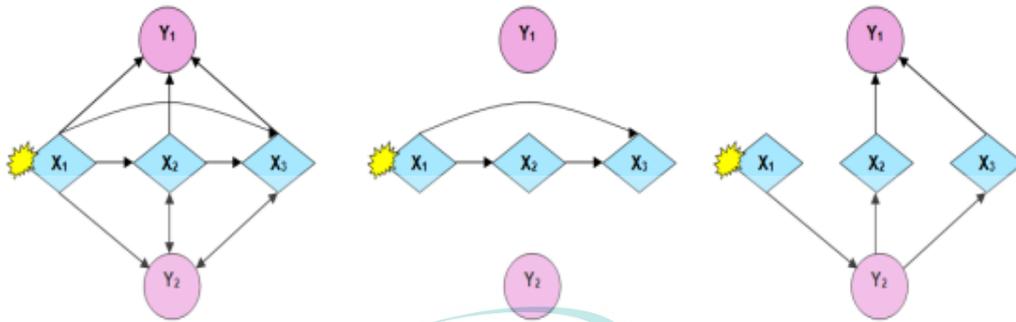


Figure 2.7 Schematic of domino effect

Source: Yuan et al. (2016)

Figure 2.7 shows the schematic of domino effect generation. From the figure, consider  $X_1$ ,  $X_2$  and  $X_3$  are the units exposes to dust explosion while  $B_1$  and  $B_2$  are the units for which fire and vapor cloud explosion (VCE). From Figure 2.7(i), it shows a series of a chain of dust explosion. Several domino effects can occur with a primary dust explosion in  $X_1$ . Figure 2.7(ii) shows the primary dust explosion in  $X_1$  can trigger a dust explosion in  $X_2$  which then cause a dust explosion in  $X_3$ . However, the explosion might not give any damage to  $Y_1$  and  $Y_2$ . In this case, both  $X_2$  and  $X_3$  are considered as a secondary explosion since  $X_1$  does not directly cause a dust explosion in  $X_3$ . Based on Figure 2.7(iii) VCE in  $Y_2$  is caused by the primary dust explosion in  $X_1$ . The simultaneous dust explosions in  $X_2$  and  $X_3$  can be triggered by the overpressure and the flame caused by the VCE which then cause  $Y_1$  to be damaged (Yuan et al., 2015).

## 2.11 Parameters Affecting Dust Explosion

There are several factors that contribute the dust explosion to occur such as particle size, moisture content and thermal behaviour (Todaka et al., 2016).

### 2.11.1 Particle Size

The particle size of the dust is another vital property that influences the explosibility of the dust cloud. The finer the particles, the larger the surface area per unit mass and therefore more explosible a given dust is probably going to be. When the cloud

is consist of a series of particle sizes, ranging from fine to coarse, the fines play a distinguished part in the ignition and also the explosion propagation. As dust settles, larger particles drop out of suspension, leaving the finest particles to produce the dust cloud. During a process stream, the presence of dusts should be acknowledged despite the initial particle size of the material (Hazardex, 2019).

The pyrolysis or devolatilization step is very fast when dust particle size is smaller than a critical value. This can lead to gas combustion which controls the dust explosion. When coarser particles exist, devolatilization and particle heating could control the explosion process (Benedetto et al., 2010). Lower flammability limit coincided well with the condition when the mass density of smaller particles (smaller than 60  $\mu\text{m}$  in diameter) was above limit. Other than that, the shape and size of powders had a strong influence on their explosion. These parameters were related to the particles' volumetric surface and play an important role in the combustion kinetics (Gao et al., 2012).

The likelihood of dust explosion is of particular concern for particles  $<500 \mu\text{m}$  (OSHA, 2009). Particle size distribution on flame propagation has been studied by Gao et al. (2013). They stated that dust clouds with different particle size distribution would form entirely different flame structures which are continuous flame front and discrete flame front, that are shown in Figure 2.8.

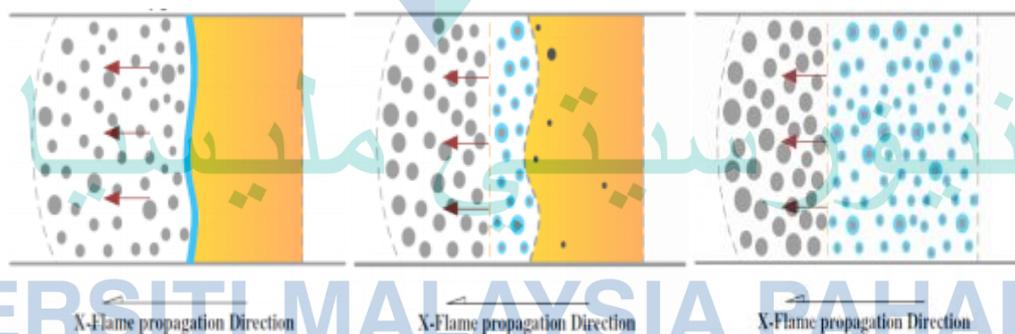


Figure 2.8 Flame structures

Source: Gao et al. (2013)

From Figure 2.8, the combustion of the smaller particles principally maintains the leading part of the propagating flame that governs the propagation of dust flames. The flame that propagated within the dust cloud with a smaller particle size was characterized by a regular shape and a spatially continuous combustion structure. Once the flame

propagated through the dust cloud with a coarser particle size, discrete blue luminous spots appeared around the yellow luminous zone. Blue spots flame appeared mostly within the flame propagation process when the diameter was further increased.

From the literature, it can be concluded that the flame was characterized by a uniform shape and spatially continuous combustion zone structure if there was relatively a large mass density of smaller particles. Besides, flame propagation mechanism was considerably completely different with the standard relay ignition mechanism. Firstly the flame propagated towards the small particles were utterly pyrolyzed, the local pre-mixing flame would continue to heat the larger particles which establishing the local diffusion flame.

### 2.11.2 Moisture Content

The sensitivity of dust explosion is determined by the moisture content in particle. The influences of moisture content on the ignition and explosion processes has been studied by testing the lower heat value, explosion severity and explosive limit (Wade *et al.*, 2013). With the rise of moisture content, the ignition sensitivity of dust weakens significantly, and therefore the heat value of dust reduces linearly. The effectiveness of moisture will increase with the reduction of lower heat value of dust, however weakens with the decrease of particle size. Consequently, the maximum explosion pressure and rate of pressure rise have a decrease in linear with the increase of moisture content (Du *et al.*, 2012). The explosions of small size dust, the variation of explosion severity and explosive limits is in accordance therewith that of the larger size beneath lower moisture content. Unexpected increased inhibition on explosion severity and explosive limit is often determined for the explosions of small size dust if the moisture content is high enough.

### 2.11.3 Maximum Overpressure ( $P_{max}$ ) and Deflagration Index ( $K_{St}$ )

In dust explosion correlation, a basic principle is that the dust explosibility can be presented in terms of  $P_{max}$  value and the  $K_{St}$  value (Ebadat, 2010). These two parameters have been studied by Yan and Yu (2014) and were tested in the confined 20 L vessel. Figure 2.9 shows the overpressure time history for a single lycopodium dust explosion test obtained when dust concentration is  $750 \text{ g/m}^3$ . The pressure increases after dust

dispersion (start from point A) and ignition (at point B) till reaches the maximum value (at point D). During this process, the rate of pressure rise has a maximum value (at point C).

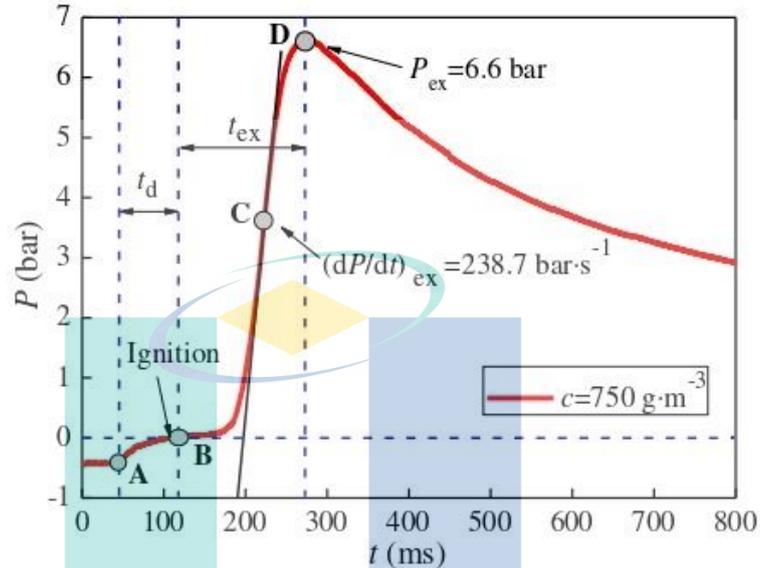


Figure 2.9 Overpressure evolution during lycopodium dust explosion at  $750 \text{ g/m}^3$  in 20 L vessel

Source: Yan and Yu (2014)

According to the definition, the maximum explosion overpressure,  $P_{ex}$  of  $750 \text{ g/m}^3$  concentration is 6.6 bar and the maximum rate of pressure rise  $(dP/dt)_{ex}$  is  $238.7 \text{ bar}\cdot\text{s}^{-1}$ . The maximum values of  $P_{ex}$  and  $(dP/dt)_{ex}$  over a wide range of concentrations are noted as  $P_{max}$  and  $(dP/dt)_{max}$  respectively.

Figure 2.10 and Figure 2.11 show the evolution of  $P_{ex}$  and  $(dP/dt)_{ex}$  as a function of dust concentration. From Figure 2.10,  $P_{ex}$  increases up to  $750 \text{ g/m}^3$  and decreases for larger concentrations. The result is similar to  $(dP/dt)_{ex}$  except the data is more scattered because the rate of pressure rise is decided by the burning velocity, which is more sensitive to influencing factors of dust explosion such as uniformity of dust clouds and the turbulence level of dispersed dust (Dufaud et al., 2010). The relationship of deflagration index and maximum overpressure is shown in equation below:

$$K_{St} = (dP/dt)_{max} \cdot V^{1/3} \quad (2.1)$$

According to Cashdollar (1996),  $P_{\max}$  increases linearly with increase in initial pressure, over the range of 1-4 bar and  $K_{St}$  also increases with initial pressure.

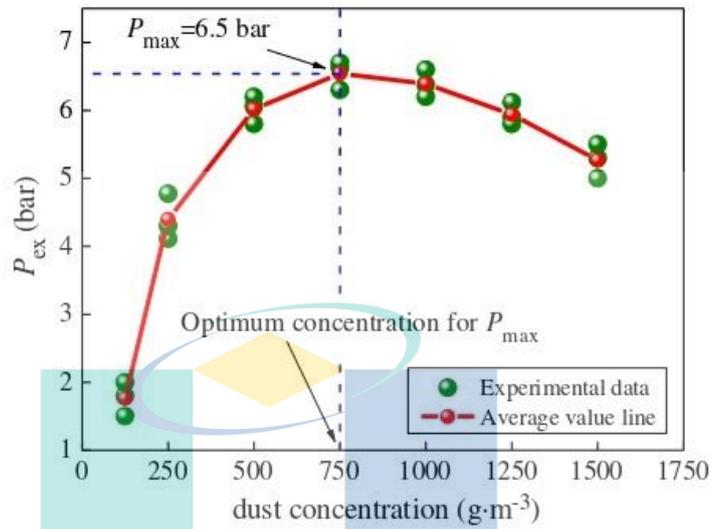


Figure 2.10 Development of the maximum explosion overpressure with lycopodium dust concentration

Source: Yan and Yu (2014)

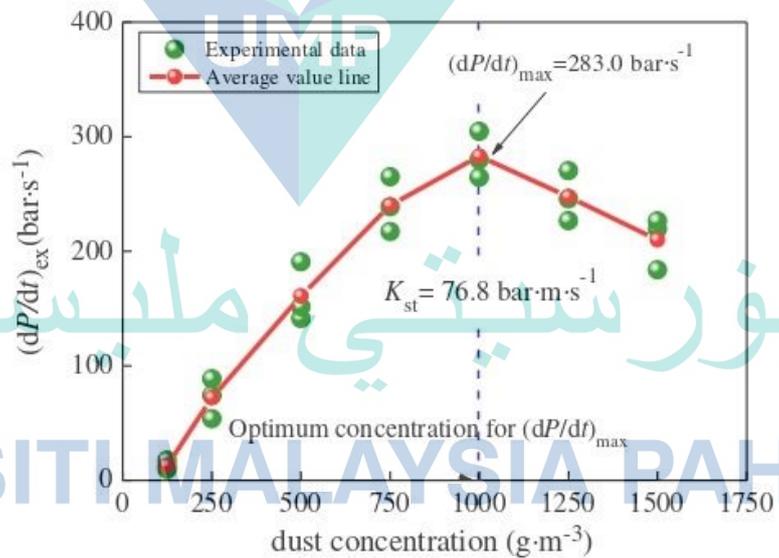


Figure 2.11 Development of the maximum rate of pressure rise with lycopodium dust concentration

Source: Yan and Yu (2014)

#### 2.11.4 Minimum Explosive Concentration (MEC)

Minimum explosive concentration (MEC) determines the lowest concentration of a dust or powder that will allow combustion. Combustible dust cloud cannot be ignited when its concentration is lower than MEC. According to Eckhoff (2003), MEC values are not very sensitive to particle diameter for diameters smaller than about 60  $\mu\text{m}$ , however increase significantly with increasing diameter above this approximate threshold. Table 2.4 summarizes the data of MEC from various authors. Based on research done by Gummer and Lunn (2003), large distances could transport the glowing agglomerates through otherwise empty piping with air transport velocities of 10 and 20 m/s. Although the dust concentration was above the MEC, the glowing was distinguished rapidly for non-burning dust. Different tests showed that burning nests failed to ignite fine sawdust in the transport duct, however as it reached the filter media dust collector at the end of the duct the sawdust cloud did ignite. Besides, Kuracina et al. (2017) based on the explosion characteristics of wheat flour, they concluded that the pressure inside the vessel increased as the concentration of the dust increased. From the time-pressure measured, the rate of pressure rise of the wheat dust could be further assessed.

Table 2.4 MEC from different type of dust from various authors

Author	Type of dust	Particle size ( $\mu\text{m}$ )	MEC ( $\text{g}/\text{m}^3$ )
Todaka et al. (2016)	Oil-retaining spent coffee ground	75	35
Todaka et al. (2016)	Oil-extracted spent coffee ground	105	120
Anwar et al. (2018)	Wheat starch	38-71	500
Makkar et al. (1998)	Lycopodium	35	35-45
Yokoyama and Imou (2009)	Cellulose	50	60

#### 2.11.5 Minimum Ignition Energy (MIE)

The minimum ignition energy (MIE) is defined as the smallest amount of heat or electrical energy required to ignite a dust/air mixture. The smaller the MIE, the more volatile the dust will be. There are a number of physical characteristics that influence MIE which are chemical composition (organics and metals have lower MIE), particle size (the

smaller the particle, the lower the MIE) and moisture content (the lower the moisture, the lower the MIE) (Going et al., 2000). Dust explosion characteristics of cellulose ethers and cellulose acetate have been studied by Kowhakul et al. (2016). They concluded that MIE do correspond to moisture content for cellulose. Table 2.5 shows the MIE values of samples for 125-177  $\mu\text{m}$  based on researched done by Todaka et al. (2016).

Table 2.5 MIE values for samples under absolute dry state

Sample	Treated	Particle size ( $\mu\text{m}$ )	MIE (mJ)
Spent coffee ground (SCG)	None	125-177	Below 3000
Spent coffee ground	Oil-extracted	125-177	Below 3000
Jatropha kernel (JK)	Oil-extracted	125-177	1515
Jatropha kernel	None	125-177	Below 3000

Source: Todaka et al. (2015)

The result shows that MIE of oil-retaining SCG, oil-extracted SCG and JS were all greater than 3000 mJ, which means these powders had a low ignition risk. MIE of oil-extracted JK was 1515 mJ indicates a higher risk than for the other studied materials. The energy required to initiate an explosion of SCG materials was very high, but dust explosions were still possible at low dust concentrations.

### 2.11.6 Oxygen Concentration

The limiting oxygen concentration (LOC) of combustible dust/air mixtures is typically determined in time consuming and expensive experiments. However, when using an assumption for the flame temperature, it is often derived from thermo-chemical principles in a simple way. The LOC of a fuel/air mixture is a crucial safety index for the application of inerting as an explosion protection measure. Experimentally, the LOC for dust/air mixtures is decided consistent with the standard testing procedures. Practically the 20 L spherical explosion vessel is usually used. Experience shows a moderate dependence of the LOC on the inert gas used which according to (Hensel and Cashdollar, 2000) is often explained by the molecular structure of the inert gas with the trend that the inerting impact is the better with more atoms of the inert gas molecule contains.

Table 2.6 shows the LOC of fifteen different dusts determined experimentally with the use of ignition sources with three different magnitudes of energy. As mentioned previously, the results confirm the findings of Going et al., (2000) of a reduction of the LOC with increasing ignition energy. LOC values appeared to be between 4 and 8 % in volume fraction higher than for the 2 kJ chemical igniter when the electrical igniter is used. The variations in the LOC values obtained with ignition energies of 2 kJ and 10 kJ never exceeded 2 % in volume fraction of oxygen. This suggests that taking into account the effect of “overdriving” as reported by Going et al., (2000) for the 10 kJ igniters, an ignition energy of 2 kJ would be perhaps the most appropriate choice for LOC tests in the 20 L vessel.

Table 2.6 LOC of dust/air mixture with three ignition energies

Sample	Electrical 10 J		Chemical 2 kJ		Chemical 2 kJ	
	LOC (vol %)	Concentration (g/m <sup>3</sup> )	LOC (vol %)	Concentration (g/m <sup>3</sup> )	LOC (vol %)	Concentration (g/m <sup>3</sup> )
Lycopodium	13	500	8	375	6	375
Starch	14	1000	7	500	6	250
Wheat flour	13	1000	8	500	6	500
Cocoa	16	1250	9	1000	8	750
Alfalfa	16	1500	9	1000	8	750

Source: Going et al. (2010)

## 2.12 Concluding Remarks

Throughout this chapter, thorough information and literature review regarding dust, the explosion and its characteristics have been given. Therefore, in this section, a brief summary on the critical sections is given as a conclusion to the topics discussed.

Dust explosions can occur where any dispersed powdered combustible material is present in high-enough concentrations in the atmosphere or other oxidizing gaseous medium, such as pure oxygen and therefore the optimum concentration of the tea powder was determined. The deflagration processes happens so rapidly in dust explosion. An extreme air pressure could be released by the heated air and gaseous fire products (such as carbon dioxide) which can blow out walls and destroy structures. If combustible dusts

ignite, there are often two explosions referred as primary and secondary explosions. The first explosion is known as a primary dust explosion. When a dust suspension in a confined space (such as a room, container or piece of equipment) ignited and explodes, it will trigger the primary explosion. Other dust that has accumulated will be shaken by the primary explosion. The dust will also ignite when it becomes airborne. This primary dust explosion is often less destructive than the secondary one.

Flammable dust clouds can exist inside process equipment during normal operation, where high degree of confinement is inherently present. In a sufficiently confined and/or congested geometry, the release of chemical energy from the combustion process will result in a rapid increase in pressure, potential damage to structures, and possibly further escalation through structural collapse, outflow of material, impact of projectiles, etc. Dust flames can initiate fires and represent a hazard to personnel. The rate of combustion in dust clouds depends on parameters related to the fuel (chemical composition, particle size distribution, etc.), the oxidant (chemical composition), the mixture (dust concentration, flow conditions, pressure, temperature, etc.), the ignition source (location, duration, total energy release, etc.) and therefore the degree of congestion and confinement (i.e. geometrical boundary conditions). The strong effect of material properties on the reactivity of dust clouds implies that safety parameters, such as  $P_{max}$  and  $(dP/dt)_{max}$ ,  $K_{St}$  value, must be determined through testing of representative samples in standardized equipment.

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## CHAPTER 3

### METHODOLOGY

#### 3.1 Introduction

This chapter describes the experimental procedure involved during the explosion test. The apparatus was located in an open space at the gas engineering laboratory section in the chemical engineering laboratory. The apparatus set up is shown in Figure 3.1 while Figure 3.2 depicts the overall experimental process methodology.



Figure 3.1 Apparatus set up

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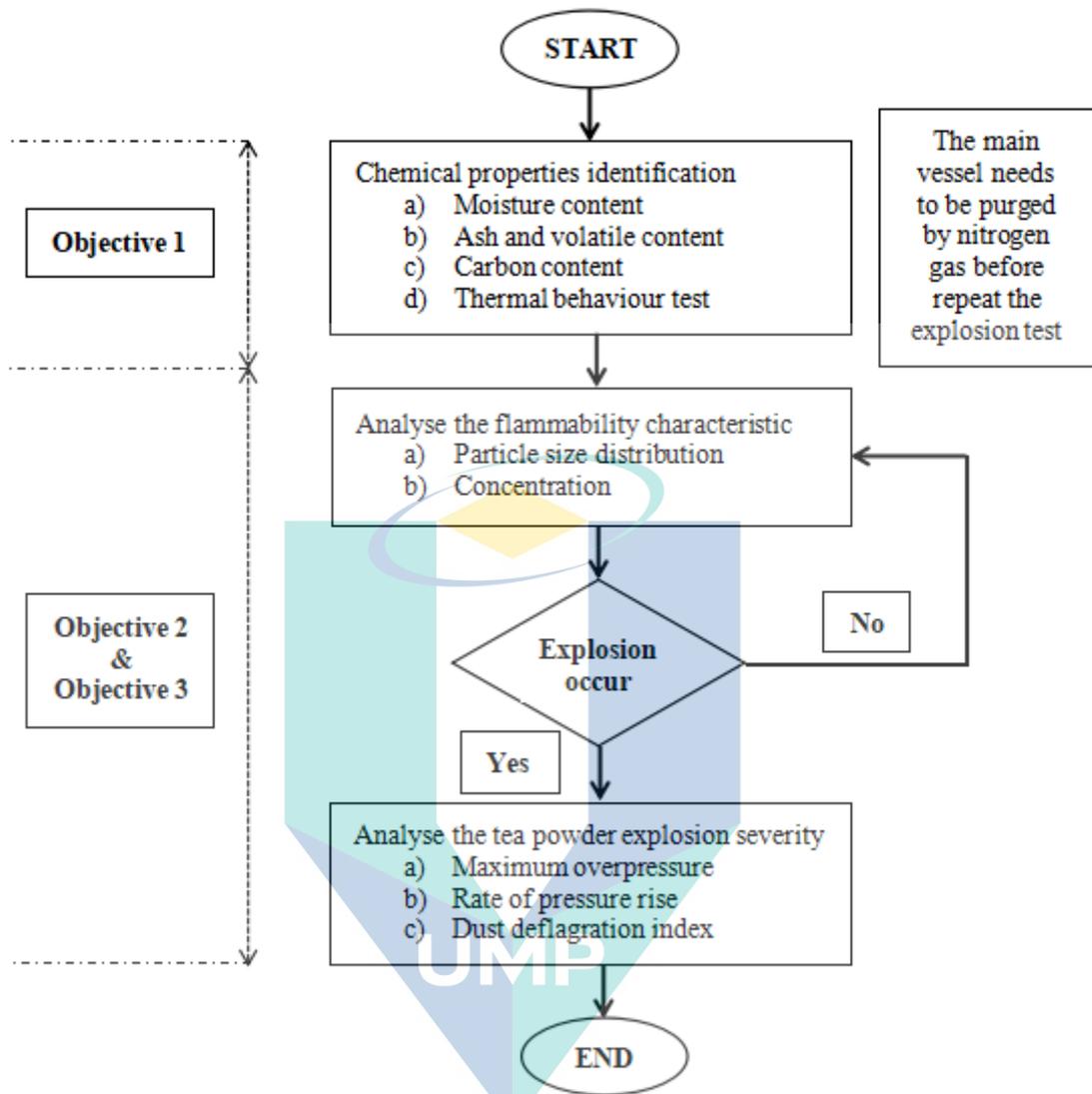


Figure 3.2 Overall process methodology

### 3.2 Sample Preparation

The samples used in this research was a general tea powder (BOH) which can be purchased from the local stores and the selection was done on the basis of brand popularity. The samples were ground by using a high-performance laboratory grinder. After the grinding process, the samples were sieved into five different sizes which were 71  $\mu\text{m}$ , 125  $\mu\text{m}$ , 160  $\mu\text{m}$ , 180  $\mu\text{m}$  and 250  $\mu\text{m}$ . Upon testing, the samples would be dried at a temperature of 105  $^{\circ}\text{C}$  in an oven for an hour to get rid of the moisture (Adnan et al., 2013).

### 3.3 Determination of Chemical Properties of Tea

The physicochemical properties such as moisture content, ash, volatiles, carbon content, calorific value and thermal behaviour of tea powder will be characterized in order to achieve the first objective.

#### 3.3.1 Proximate Analysis

The characteristic of the sample was investigated through a proximate analysis by drying and combustion in the oven or furnace for moisture, ash and volatiles based on British standard procedure (BS 1016-104, 1999). Equation (3.1) to (3.4) were used to analyze the mass loss and differential mass loss curved data.

##### 3.3.1.1 Moisture Content

In order to carry out the moisture content test, an empty glass crucible with a diameter of 6 cm was weighed. Next, approximately  $1 \pm 0.1$  g of the sample was added onto the crucible. The new weight of the crucible and the sample was recorded. As a drying process, the crucible and its contents was placed in an oven for an hour at a temperature of  $105 \pm 5$  °C. The crucible was cooled in a desiccator and reweighed. Then, the amount of moisture in the sample was calculated by Equation (3.1).

$$\% \text{ of moisture} = \frac{\text{initial weight (g)} - \text{final weight (g)}}{\text{initial weight (g)}} \times 100 \quad (3.1)$$

##### 3.3.1.2 Ash Content

To analyze the ash content, a clay crucible with 2 cm diameter was weighed and approximately  $1 \pm 0.1$  g of the sample was added onto the crucible. After the new weight was recorded, the crucible is placed in a furnace for 6 to 6 hours at a high temperature between 500 - 600 °C. Then, the crucible was cooled down at room temperature for about one minute and being left inside a desiccator. After that, the sample was reweighed and the weight percentage of ash was determined by using Equation (3.2).

$$\% \text{ of ash} = \frac{\text{weight of crucible and ash (g)} - \text{weight of crucible (g)}}{\text{weight of crucible and sample (g)} - \text{weight of crucible (g)}} \times 100 \quad (3.2)$$

### 3.3.1.3 Volatility

To determine the volatile matter in the tea powder, an empty crucible with 3 cm diameter together with the lid was weighed. Next, approximately  $1 \pm 0.1$  g of the sample was added onto the crucible. The new weight of the crucible with the lid and the sample was recorded. The crucible then was placed in a high temperature furnace which was preheated to  $700\text{ }^{\circ}\text{C}$  for 5 minutes. The crucible was removed from the furnace and was cooled at a room temperature for about one minute. The crucible was kept inside a desiccator and allowed to cool and reweighed. The volatile percentage was calculated by using Equation (3.3).

$$\% \text{ of volatile} = \left[ \frac{\text{weight of residue after heating (g)}}{\text{weight of initial sample (g)}} \times 100 \right] - \% \text{ of moisture} \quad (3.3)$$

### 3.1.1.4 Analysis by Thermogravimetry (TGA)

The chemical properties of tea powder was also determined by using thermogravimetry analysis (TGA). The equipment was used in order to measure the amount and the rate of change of weight of material as a function of temperature or time in a controlled atmosphere. First, approximately 5 mg of sample was weighed in a platinum pan. Next, the programme of ramping was chosen and the sample was heated at a heating ramp of  $10\text{ }^{\circ}\text{C}$  per minute until the temperature reached  $900\text{ }^{\circ}\text{C}$ . The components were calculated based on the specific temperature i.e. for moisture content,  $T = 105\text{ }^{\circ}\text{C}$ , volatility,  $T = 500\text{ }^{\circ}\text{C}$  and fixed carbon  $T = 600\text{ }^{\circ}\text{C}$  while ash was determined as the residual. The Equation (3.4) to Equation (3.7) were used to analyze the mass loss and the differential loss.

$$\% \text{ of moisture} = \left( \frac{W - W_{105}}{W} \right) \times 100 \quad (3.4)$$

$$\% \text{ of volatile} = \left( \frac{W_{105} - W_{500}}{W} \right) \times 100 \quad (3.5)$$

$$\% \text{ of ash} = \frac{W_{600}}{W} \times 100 \quad (3.6)$$

$$\% \text{ of fixed carbon} = \left( \frac{W_{500} - W_{600}}{W} \right) \times 100 \quad (3.7)$$

Where  $W$  was the initial mass of the sample (mg),  $W_{105}$ ,  $W_{500}$  and  $W_{600}$  were the mass of the sample at the temperature of 105 °C, 500 °C and 600 °C respectively.

### 3.3.2 Analysis of Calorific Value

The calorific value of tea powder was analyzed by using a bomb calorimeter (Parr Oxygen Bomb Calorimeter). First, the sample was placed in a sample container of heavy walled stainless steel reaction vessel in the bomb calorimeter. Next, the reaction vessel was immersed in an insulated water bath. The sample was then burned with sufficient oxygen gas. An electrical current passed through an iron fuse wire in contact with the coal sample which resulted in combustion reaction. The heat released from the combustion reaction was absorbed by the water and other parts of the calorimeter and therefore causing the temperature of the calorimeter to rise. Since the calorimeter is adiabatic, all the heat liberated by the reaction remained inside the calorimeter, which meant no heat escaped to the surrounding. The temperature rise was measured by using a thermometer. The calorific value of the tea powder was calculated by using Equation (3.8).

$$\text{Heat of combustion, } H_g = \frac{TW - E3}{M} \quad (3.8)$$

Where  $T$  was the temperature rise,  $W$  was 2409.26 cal/°C,  $E3$  was correction calories factor (time by 2.3) and  $M$  was mass of sample.

### 3.3.3 Analysis of Particle Size Distribution

The Mastersizer 2000 was used to measure the size of tea powder particles or, more specifically, the distribution of different sizes within a sample. First, the sample was prepared and dispersed to the correct concentration and then delivered to the optical bench. Then, the capturing of the scattering pattern from the prepared sample - this is known as the “measurement”. The detector array within the optical bench was made up of many individual detectors which each detector collects the light scattering from a particular range of angles. A typical light scattering pattern was shown in Figure 3.3.

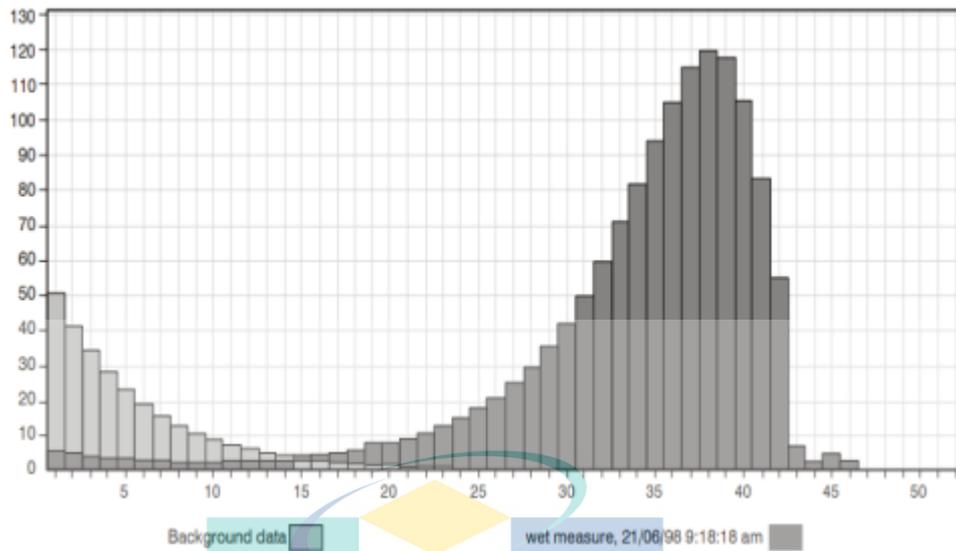


Figure 3.3 Data graph – light scattering

Source: Malvern (2007)

Each bar in the histogram represented the light scattering from one of the detector elements which known as a channel. The detector array took a “snapshot” of the scattering pattern. Obviously this snapshot only captured the scattering pattern from the particles that are passing through the analyser beam at that particular time. Typically over 2000 snaps were made for each measurement, with each snap taking 1ms. Once the measurement was completed, the raw data from it was analyzed by the Malvern software using Fraunhofer model or Mie theory. Once the data has been analyzed the information could be displayed in various ways (Malvern, 2007).

### 3.3.4 Analysis of Particle Shape and Porosity

The scanning electron microscope (SEM) was used to determine the morphology (texture), chemical composition, and crystalline structure orientation of materials forming the sample. The microscope’s detection was as much as 1  $\mu\text{m}$  from the sample surface. First, the sample was coated with a thin layer of metal (usually gold or gold-palladium) which made the sample conductive. Then, the electrons were allowed to pass right through the sample. The lenses were placed in a vacuum chamber in order to avoid obstruction and contamination by other particles and directed the electrons towards the sample. The electron imprint was converted to a three-dimensional image which was visualized digitally.

### 3.4 Dust Explosion Apparatus

For the second and third objectives, the 20 L spherical vessel as shown in Figure 3.4 was used to obtain the flammability and severity data. The explosion experiments were performed by using two 5 kJ chemical igniters which represent the standard ignition source. The igniters were trimmed by using scissors or pliers to expose the wire before it was connected to the ignition leads. The ignition delay time,  $t_v$  was set and fixed to 60 ms. The pressure inside the spherical vessel was measured by two “Kistler” piezoelectric pressure sensors. The pressure transducers were mounted on the wall of the vessel. In the research, tea powder was loaded directly to the storage container and dispersed with the rebound nozzle connected to an outlet valve located at the bottom of the vessel by using compressed air pressurized at 20 bar (gauge). The dust concentration loading was used to determine the lean limit concentration by gradually stepping up by step change of 10 g until no explosion or flame propagation showed on captured data. The vessel was connected to a computer, which controlled the dispersion or firing sequence and the control system named KSEP was used to collect data. As part of the experimental programme, three repeated tests were performed on each test and these demonstrated good reproducibility, with peak pressures varying by less than  $\pm 5\%$  in magnitude.



Figure 3.4 20 L spherical vessel

### 3.4.1 20 L Spherical Vessel

The test vessel was a 20 L volume, a hollow sphere and made of stainless steel. To maintain the test temperature, a water jacket is dissipated the heat of explosions. For testing, the dust was dispersed into the sphere from a dust storage vessel via the outlet valve and a nozzle. The outlet valve was opened and closed by means of an auxiliary piston. The valves for the compressed air were activated electrically. The ignition source was located at the center of the sphere. Two "Kistler" piezoelectric pressure sensors were installed on the measuring flange. For extra measurement components or for the installation of a sight glass, the second flange was used.

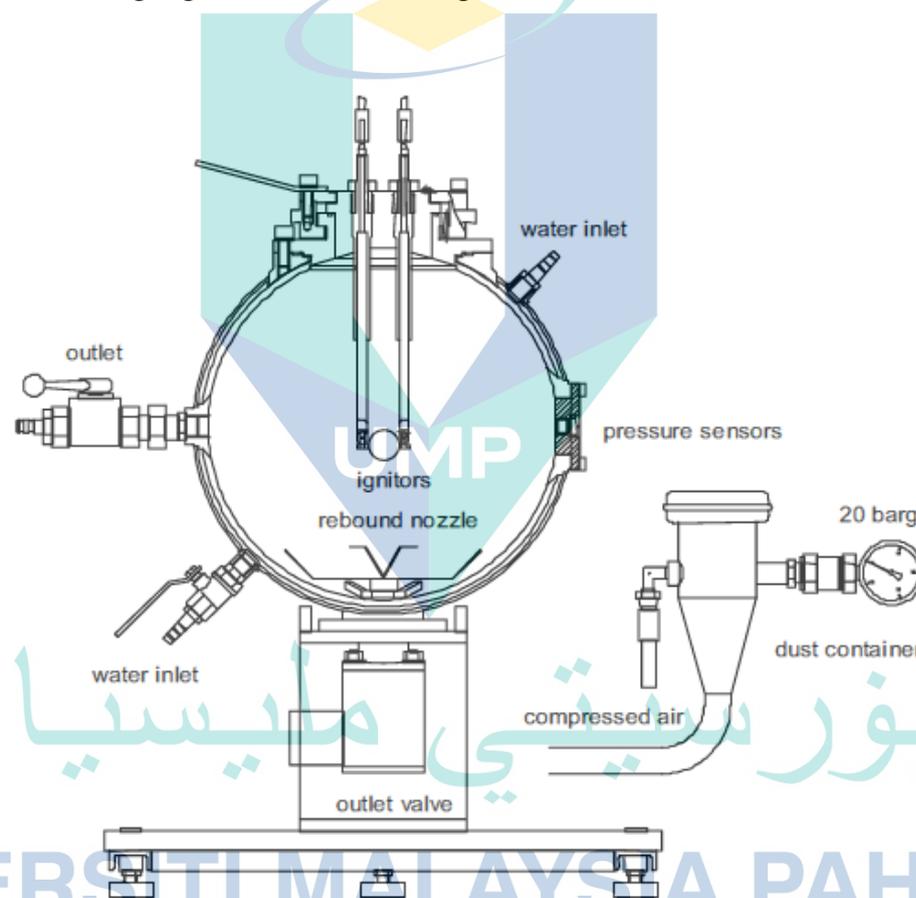


Figure 3.5 Schematic diagram of 20 L spherical vessel

Source: Cesana and Siwek (2000)

Prior to explosion test, the vessel was cleaned thoroughly and the igniter were attached to the ignition leads before the vessel was closed. Next, the tea powder was added into the dust container and the compressed air was added directly into the vessel by using a high precision digital pressure gauge. Then, the vessel was vacuumed until its pressure reached 0.6 bar. Finally, the explosion test was run from the KSEP software. The

explosion test were repeated with a minimum of three times before the average reading were taken. Table 3.1 shows the technical data of the 20 L spherical vessel.

Table 3.1 Technical data of 20 L spherical vessel

Properties	Specifications
Material of construction No.	1.4435
Wall thickness of inner jacket	Min. 4 mm
Wall thickness of outer jacket	Min. 2 mm
Volume of sphere	20 L
Volume of water jacket	1.5 L
Design pressure of sphere	30 bar
Design pressure of jacket	10 bar
Test pressure of sphere	39 bar
Test pressure of jacket	14.3 bar
Design temperature	60 °C
Bayonet ring aperture	96 mm diameter
Cleaning aperture	140 mm diameter
Sight glass	30 mm diameter
Measuring flange	3 tapped bores M14 x 1.25
Venting connection	Hose ID. 12 mm
Vacuum connection	Serto, ¼" G
Water connections	Hose ID. 10 mm
Overall dimensions (w,h,d)	650 x 875 x 820 mm
Weight	75 kg

Source: Cesana and Siwek (2000)

### 3.4.2 Control Unit KSEP 310 and Measurement and Control System KSEP 332

The control unit KSEP 310 (Figure 3.6) was installed as an auxiliary unit behind the sphere on the same base plate. To measure the pressure as a function of time and controlled the valves as well as the ignition system of the vessel the KSEP 332 (Figure 3.7) unit used piezoelectric pressure sensors. The measured values to be processed by a personal computer are digitized at high resolution. The technical data for control unit KSEP 310 and KSEP 332 unit were shown in Table 3.2 and Table 3.3 respectively.

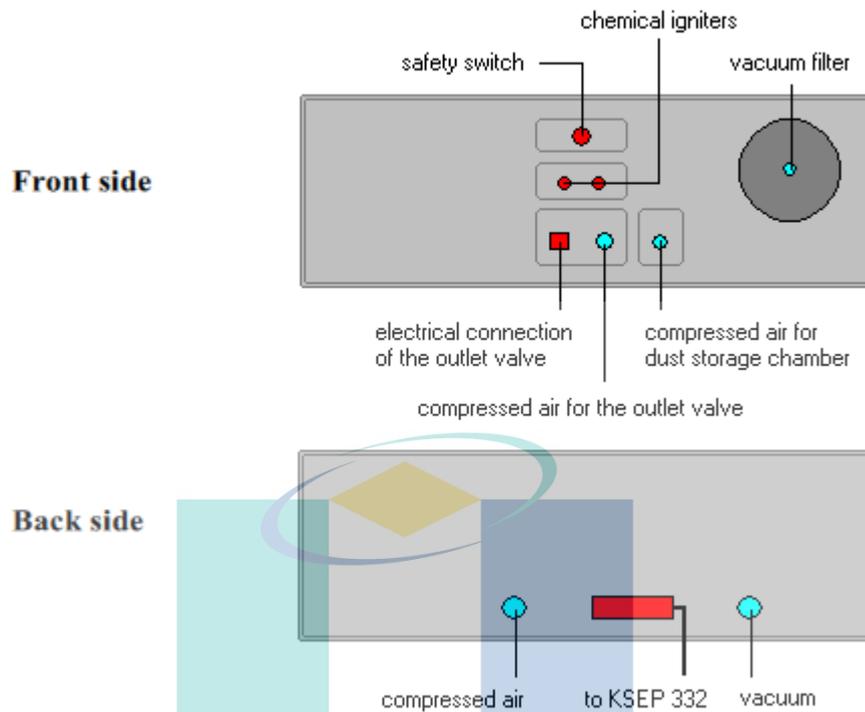


Figure 3.6 Control unit KSEP 310  
Source: Cesana and Siwek (2000)

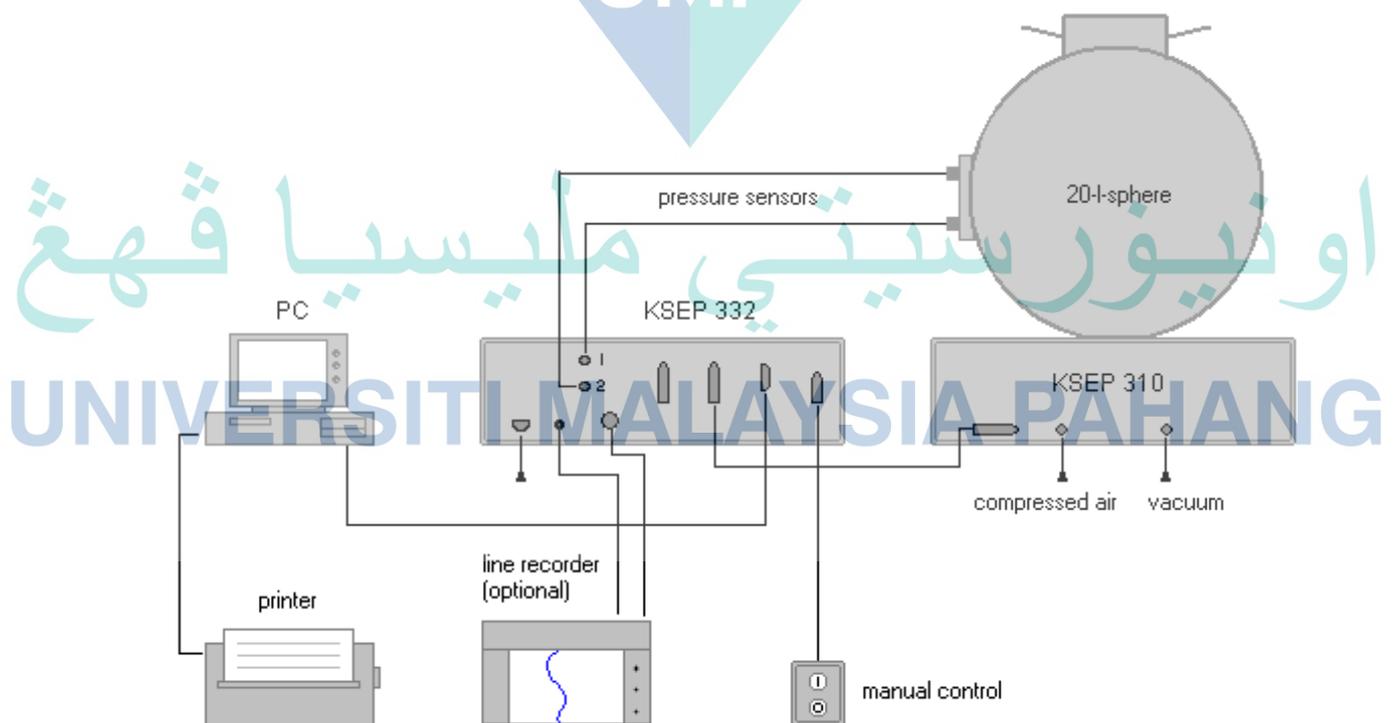


Figure 3.7 Measurement and control system KSEP 332  
Source: Cesana and Siwek (2000)

Table 3.2 Technical data of KSEP 310

Properties	Specifications
Compress air connection on back`	Fitting: Serto ¼” G Nominal pressure: 20 bar Maximum pressure: 30 bar
Vacuum connection on back	Fitting: Serto ¼” G
Overall dimensions (w,h,d)	510 x 215 x 370 mm
Weight	13 kg

Source: Cesana and Siwek (2000)

Table 3.3 Technical data of KSEP 332

Properties	Specifications
Pressure range	+/- 20 bar
Pressure resolution	10 mbar
Sampling time	0.2 ms
Recording time	2.0 s
Pressure transducer (2)	Kistler Type 701A
Charge amplifiers (2)	Kistler Type 5041A
Recorder output	5.25V = +20 bar / 0V = -1 bar

Source: Cesana and Siwek (2000)

### 3.4.3 Equipment Check

Before testing, the equipment was checked. Compressed air (in cylinder) is used and the pressure of bottle was set above 40 bar. To ensure there was no leakage, the dust storage vessel was pressurize manually to 20 bar over pressure. The minimum flow of the cooling water was set to 0.5 liter per minute and the outlet temperature of the cooling water must below 25°C for the operating temperature.

#### 3.4.4 Vacuum

The sphere is evacuated to such a degree prior to dispersing the dust, where the remaining pressure, together with the air contained in the storage vessel and resulted in the desired starting pressure for the explosion test. Therefore, the ball-valve on the vacuum connection of the sphere was opened and the sphere was evacuated via the vacuum filter until the vacuum meter showed the desired pressure. For cleaning purpose, the vacuum filter could be removed easily.

#### 3.4.5 Compressed Air

Compressed air was used to power the outlet valve and also connected to the inlet valve of the dust storage vessel. The pressure in the storage vessel corresponded directly to that of the external compressed air system. The 20 bar compressed air connection must have an adequate cross section. It must be possible to pressurize the storage vessel within 5 seconds.

#### 3.4.6 Operating Temperature

Cooling water was used in order to keep the operating temperature at approximately 20°C. The operating temperature should correspond to room temperature. Thermo-static control of the cooling water is not necessary, but care should be taken that there is always some flow of water and that the outlet temperature of the cooling medium not exceeds 25°C.

#### 3.4.7 Test Check

A test check was carried out in an empty vessel, without the dust and without chemical igniters. Thereby, the correct function of the entire system was checked in a simple way. It was strongly recommended that the check be repeated at the onset of each test series. For the test, the ignition delay time was set to 60 ms. Compressed air pressure was adjusted to 20 bar. Next, the vessel was evacuated to 0.4 bar absolute and later an automatic test sequence was started. The vent valve (left) was open slowly where just a little air should flow in or out.

### 3.5 Analysis of Explosion Data

#### 3.5.1 Maximum Explosion Overpressure ( $P_{\max}$ ) and Maximum Rate of Pressure Rise $(dP/dt)_{\max}$

The explosion overpressure,  $P_m$  and the rate of pressure rise,  $dP/dt$  described the violence of reaction of dust/air mixtures of random concentration after ignition in a closed vessel. The maximum explosion pressure,  $P_{\max}$  and the maximum rate of pressure rise,  $(dP/dt)_{\max}$  of combustible dusts were determined in closed standard equipment by means of tests over a wide range of concentrations as shown in Figure 3.8 while Figure 3.9 showed the diagram of a fuel explosion.

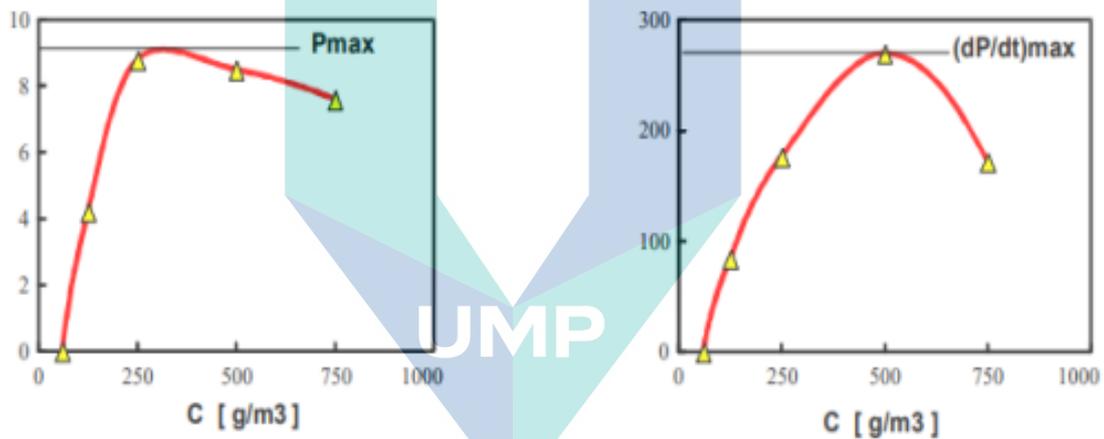


Figure 3.8 Determination of the explosion indices

Source: Cesana and Siwek (2016)

The maximum explosion pressure, when determined in closed, spherical or cubic vessels of sufficient size with central ignition source, was practically independent of the volume of the vessel. But the maximum rate of pressure rise depended on the volume. It decreased with increasing volume.

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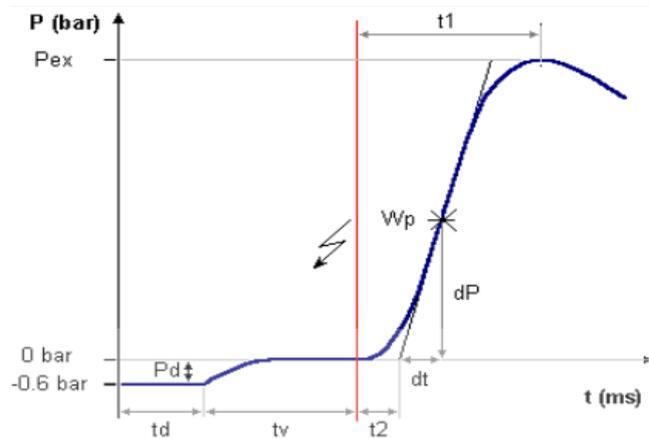


Figure 3.9 Pressure vs time diagram of a dust explosion

Source: Cesana and Siwek (2016)

Where,

Explosion overpressure ( $P_{ex}$ ) is the difference between the pressure at ignition time and the pressure at the highest point could be the maximum explosion overpressure at nominal fuel concentration.

Corrected explosion overpressure ( $P_m$ ) due to cooling and pressure effects caused by the chemical igniters in the vessel, and the  $P_{ex}$  must be corrected

Maximum explosion overpressure ( $P_{max}$ ) is the maximum value of  $P_m$  determined by tests over a wide range of fuel concentrations or average data of  $P_m$ .

Rate of pressure rise with time at nominal fuel concentration  $(dP/dt)_m$  is defined as the maximum slope of a tangent through the point of inflexion ( $W_p$ ) in the rising portion of the pressure vs time curve.

$(dP/dt)_{max}$  is the maximum rate of pressure with time which maximum value of  $(dP/dt)_m$  determined by tests over a wide range of dust concentrations.

$K_{max}$  is the product specific constant,  $0.27144 \times (dP/dt)_{max}$ .

$t_1$  is the duration of combustion where time difference between the activation of the ignition and the culmination point.

Induction time ( $t_2$ ) is the time difference between the activation of the ignition and the intersection of the inflexion tangent with the 0 bar line

Expansion pressure ( $P_d$ ) of storage container is the difference between "pre-vacuum" and normal pressure. The standard value is 0.6 bar.

Time-delay ( $t_d$ ) of the outlet valve is the time between electrically activating the valve and beginning of pressure rise in the vessel. This time-delay were in the range of 30 to 50 ms; otherwise the valve and/or the dispersion device were probably dirty.

Ignition delay time ( $t_v$ ) influenced the degree of turbulence. This is the most important control parameter.

### 3.5.1.1 Correction of The Explosion Overpressure at $P_{ex} > 5.5 \text{ bar}$

Due to the less favorable surface to volume ratio, the explosion pressure measured in the 20 L vessel was in general slightly lower than the one measured in the 1m<sup>3</sup> vessel. This was caused by cooling effects. Comparisons of pressure/time recordings also showed that the pressure drop after the explosion was much faster in the 20 L vessel. Therefore a correction had to be made according to Equation (3.9).

$$P_m = 0.775 \cdot P_{ex}^{1.15} \quad (3.9)$$

With this correction, the  $P_m$  in the 20 L vessel then agreed with those measured in the 1m<sup>3</sup> vessel.

### 3.1.1.2 Correction of The Explosion Overpressure at $P_{ex} < 5.5 \text{ bar}$

Due to the small volume of the 20 L vessel, below 5.5 bar the pressure effect caused by the chemical igniters must be taken into account. A blind test i.e. with IE = 10000 J chemical igniters alone, gave a maximum overpressure of 1.6 bar. But during a dust explosion with rising  $P_{ex}$  the influence of the igniters would be more displaced by the pressure effect of the explosion itself. The influence of igniters with less than IE = 1000 J could be neglected entirely. Correction values can be calculated by using Equation (3.10).

$$P_m = 5.5 \cdot (P_{ex} - P_{ci}) / (5.5 - P_{ci}) \text{ bar} \quad (3.10)$$

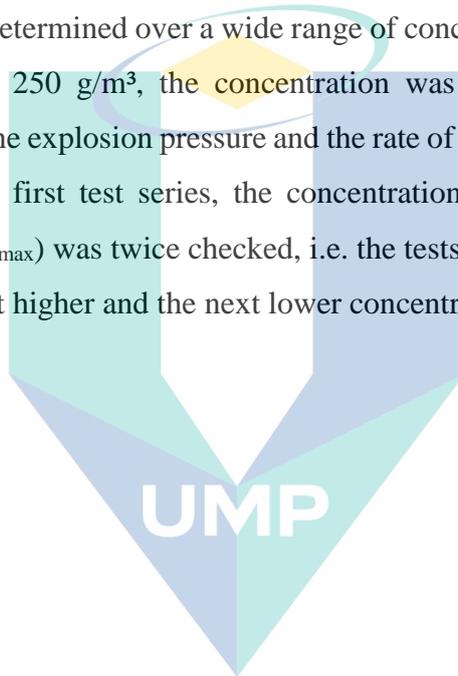
Where  $P_{ci}$  (pressure due to igniters) = 1.6 bar • IE / 10000

### 3.5.2 Dust Deflagration Index, $K_{St}$

The value of  $K_{St}$  would be obtained from the highest value of  $dP/dt$  normalized with the volume of the vessel as illustrated in Figure 3.9.  $K_{St}$  of tea powder would be tested separately and would be compared based on the particle size.

### 3.5.3 Minimum Explosible Concentration, MEC

In a first test series, the maximum explosion overpressure and the maximum rate of pressure rise were determined over a wide range of concentrations. Starting with a low dust concentration of  $250 \text{ g/m}^3$ , the concentration was increased in steps, until the maximum values for the explosion pressure and the rate of pressure rise have clearly been determined. After the first test series, the concentration range close to the observed maxima ( $P_{max}$ ,  $(dP/dt)_{max}$ ) was twice checked, i.e. the tests were repeated at the optimum concentration, the next higher and the next lower concentration.



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## CHAPTER 4

### RESULTS AND DISCUSSION

#### 4.1 Introduction

This chapter describes the analysis of data and interpretation of the findings resulting from this research. As mentioned in Chapter 2, there are a few parameters, which are used to describe the explosion severity. Therefore, in this chapter, the discussion will be focused on the effect particle size, concentration, maximum explosion overpressure ( $P_{max}$ ), maximum rates of pressure rise ( $(dP/dt)_{max}$ ) and deflagration index ( $K_{St}$ ) of tea powder. Particle size has long been known to play a key role in dust fires and explosions. Particle size has been shown affected on the ignition tendency (or thermal susceptibility) of dust deposits and also the ignitability and explosibility of dust clouds (i.e. the convenience and violence with which a dust cloud explodes). In this research, five samples of tea powder with different sizes which are 71  $\mu\text{m}$ , 125  $\mu\text{m}$ , 160  $\mu\text{m}$ , 180  $\mu\text{m}$  and 250  $\mu\text{m}$  were tested in terms of physical and chemical properties and explosibility characteristics. For physical properties of the tea, the results were based on the Malvern mastersizer and SEM while for the chemical properties the results were based on the thermogravimetry analysis (TGA). The explosibility characteristics were discussed on the basis of the explosion test on tea powder.

#### 4.2 Physical Properties Determination of Tea Powder

The physical characteristics of the dust-air mixture such as particle size distribution of a powder is a critical influence on dust explosion characteristics and it plays an important role in the flame propagation process. It is a dominant physical parameter that affects explosion severity and ease the ignition of combustible dust (Eades et al., 2018). Figure 4.1 below provides a typical particle size distribution of five different sizes of tea powder samples measured using a Malvern mastersizer 2000 laser diffraction particle size analyzer while Table 4.1 shows the physical characteristics of tea powder.

Based on Figure 4.1, it shows that 6.8% of the sample was under 71  $\mu\text{m}$ , 4.9% was under 125  $\mu\text{m}$ , 11.3% was under 160  $\mu\text{m}$ , 12.0% was under 180  $\mu\text{m}$  and 12.1% was under 250  $\mu\text{m}$ . As shown in Table 4.1, the tea powder at size 71  $\mu\text{m}$  had the largest specific surface area which is 0.39  $\text{m}^2/\text{g}$ , followed by the size 125  $\mu\text{m}$  of 0.26  $\text{m}^2/\text{g}$ , 160  $\mu\text{m}$  of 0.10  $\text{m}^2/\text{g}$ , 180  $\mu\text{m}$  of 0.03  $\text{m}^2/\text{g}$  and 250  $\mu\text{m}$  of 0.02  $\text{m}^2/\text{g}$ . From the results, the surface area of the tea powder decreases as the size increases.

Derived diameters were used to calculate the statistics of the distribution from the results. According to Beck et al., (1997), it is used to be common practice to identify the material investigated using solely the median diameter  $D_{50}$  (i.e the size value below which 50% of the cumulative distribution is present, on a volume (or mass) basis), especially in the field of dust fire and explosion research. In many research papers published, the median diameter was complemented by providing the size distribution at selected intervals, indicating the percentage of sample volume (or mass) that was finer, or alternatively coarser, than a particular size value. However, the number of size intervals provided was usually low and did not allow for reproduction of the real particle size distribution curve. Currently, researchers usually complement the median diameter  $D_{50}$  with  $D_{10}$  and  $D_{90}$  values, and in some cases also include the complete density distribution, or more rarely the cumulative distribution (Tascon, 2018). From Table 4.1, the mass median diameter for particle size 71  $\mu\text{m}$  - 250  $\mu\text{m}$  were 65.29  $\mu\text{m}$ , 91.99  $\mu\text{m}$ , 205.03  $\mu\text{m}$ , 243.08  $\mu\text{m}$  and 279.53  $\mu\text{m}$  respectively.

Self-heating, ignition and explosion processes involved the particle size distribution also exerts a strong effect on the various phenomena. Cashdollar (1996) and Soundarajan et al., (1996) concluded that it is the finer particles in a broad distribution that contribute most to hazards. Kuai et al., (2011), Callé et al., (2005) and Gao et al., (2015) concluded that the particle size distribution affects the onset and peak temperatures while the maximum reaction rate depends on the particle size. According to the experiments with maize starch reported by Zhang et al., (2017), the thickness of the flame reaction zone increases constantly with the increase in particle size, and the burning rate and burning time are also affected by particle size distributions.

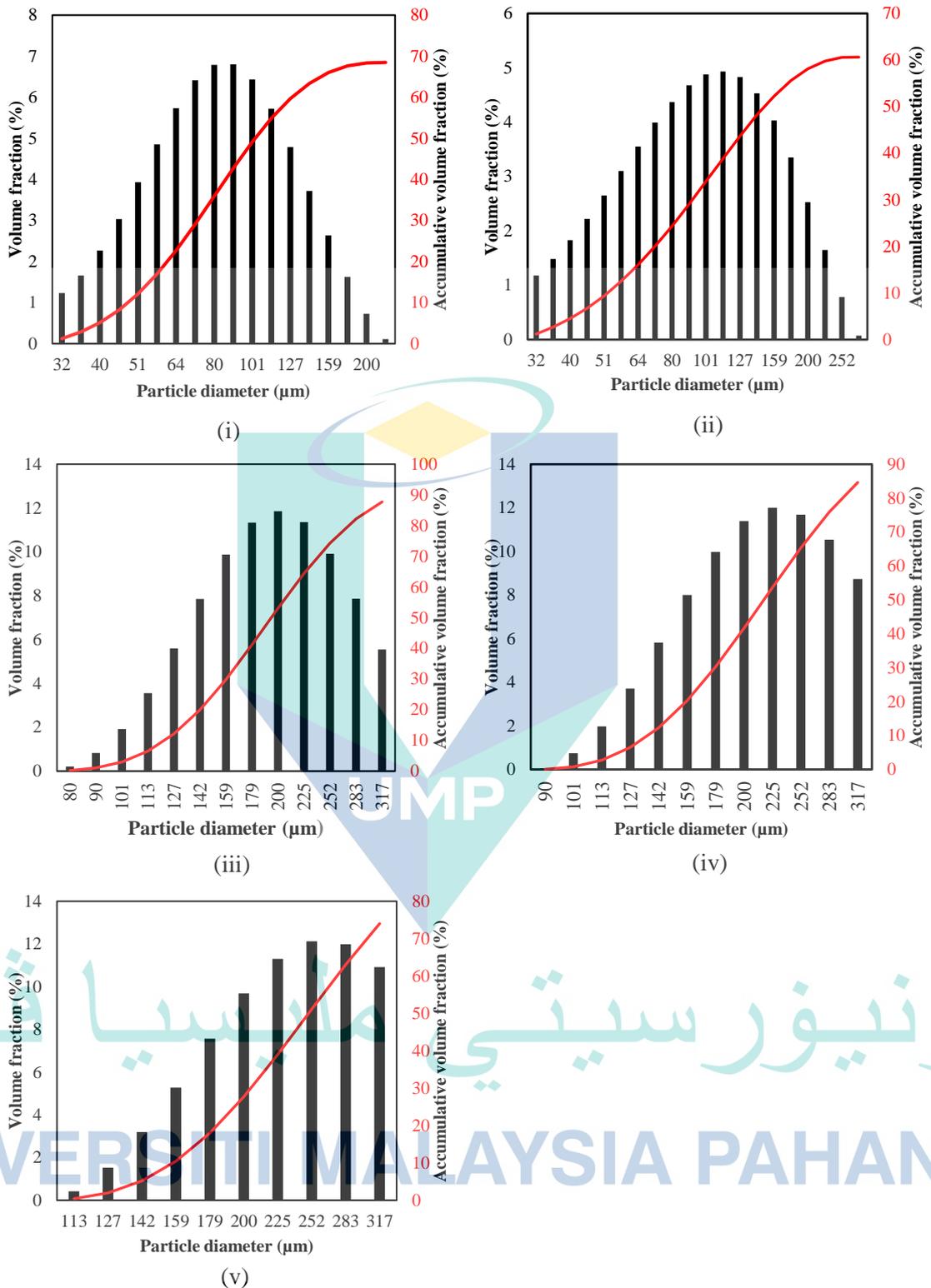


Figure 4.1 Graph of particle size distribution for tea powder: (i) 71µm; (ii) 125 µm; (iii) 160 µm; (iv) 180 µm; (v) 250 µm

Gao et al., (2013) stated that the characterization of the combustion process should consider not only the nature of the fuel but also the average size, shape, concentration and distribution of the particles, moisture, oxygen concentration, the initial pressure and the initial turbulence intensity. These variables become important after considering their effects on the dispersibility of the dust and the heat and mass transport in the different regions that compose the reactive mixture.

During the dispersion process, the size distribution of a solid material might present significant variations. This property has a direct effect on the conditions of the dust cloud; hence it can affect the behaviour of the mixture during the determination of the explosibility parameters of the dust (Tascon, 2018). This condition is observed because the characteristics of the dust cloud might promote or reduce the presence of fine particles. Therefore, the mass and energy transport phenomena are affected by the dispersion process as well. Consequently, the variations of the transport phenomena that are influenced by the particle size distribution also affect the combustion mechanisms of the solid compounds. For this reason, this parameter becomes a determining factor on the development of the flammability test methods.

In order to improve the explosion protection practice, Eckhoff (1977) used the specific surface area to study the influence of particle size on the maximum rate of pressure rise  $(dP/dt)_{\max}$ , which will be discussed later. This parameter can be determined from the surface-weighted mean diameter or Sauter diameter, denoted as  $D_{3,2}$ , since this represents the diameter of a sphere with equal surface area. From Table 1, the surface-weighted mean diameter for particle size 71  $\mu\text{m}$  - 250  $\mu\text{m}$  were 15.36  $\mu\text{m}$ , 22.82  $\mu\text{m}$ , 60.28  $\mu\text{m}$ , 228.66  $\mu\text{m}$  and 263.68  $\mu\text{m}$  respectively. The volume-weighted mean diameter or  $D_{4,3}$ , is relevant for many samples as it reflects the size of those particles which construct the bulk of the sample volume. According to Castellanos et al., (2014),  $D_{4,3}$  on the other hand, is not recommend for particle size characterization, since it has been proved unable to distinguish dust samples with the same  $D_{50}$  but different particle size distribution curves.

The finer sizes are more effective at explosion inerting and suppression than coarser size fractions. Moreover, the probability of decomposition increases as the particle decreases. This fact implies that mechanism is not a rate limiting step in relation to dust devolatilization.

Table 4.1 Characteristics parameters of the particle size distribution

Size ( $\mu\text{m}$ )	71	125	160	180	250
Surface area ( $\text{m}^2/\text{g}$ )	0.39	0.26	0.10	0.03	0.02
Surface weighted mean D [3,2] ( $\mu\text{m}$ )	15.36	22.82	60.28	228.66	263.68
Volume weighted mean D [4,3] ( $\mu\text{m}$ )	67.19	212.65	210.28	259.07	297.81
D (0.1) ( $\mu\text{m}$ )	5.04	7.14	115.98	152.59	176.89
D (0.5) ( $\mu\text{m}$ )	65.29	91.99	205.03	243.08	279.53
D (0.9) ( $\mu\text{m}$ )	137.34	766.07	325.96	389.07	445.52

As well as particle size, the particle shape and porosity can also have a significant effect on the particle surface area and the reaction rates. The particle shape can be used to determine the state of dispersion of particulate materials, specifically if agglomerates or primary particles are present. Thus, the dust particle size and shape are important in relevant to dust explosibility characteristics (Cashdollar, 2000). In order to analyze the surface of tea powder, the analysis were performed by using scanning electron microscopy (SEM). As can be seen from Figure 4.2, the stacked and irregular structures were observed in five samples.

Particle shape may be a crucial physical parameter. The shape of the particle is also a factor in deciding the agglomeration of the dust particles. If the dust particles are almost spherical in shape, the agglomeration will become more. Because in such case, the orientation of the particles is not a problem in contrast to the irregularly formed particles, in which their orientation will not allow them to link to each other effectively as shown in Figure 4.2. The inter-particle forces play a major role in the case of the strongly bonded agglomerates, which require a large shear force to break them. Therefore, for the complete dissociation of strongly bonded agglomerates into smaller particles, high velocity impacts resulting from high dust dispersion-air pressures are required (Eckhoff, 2009).

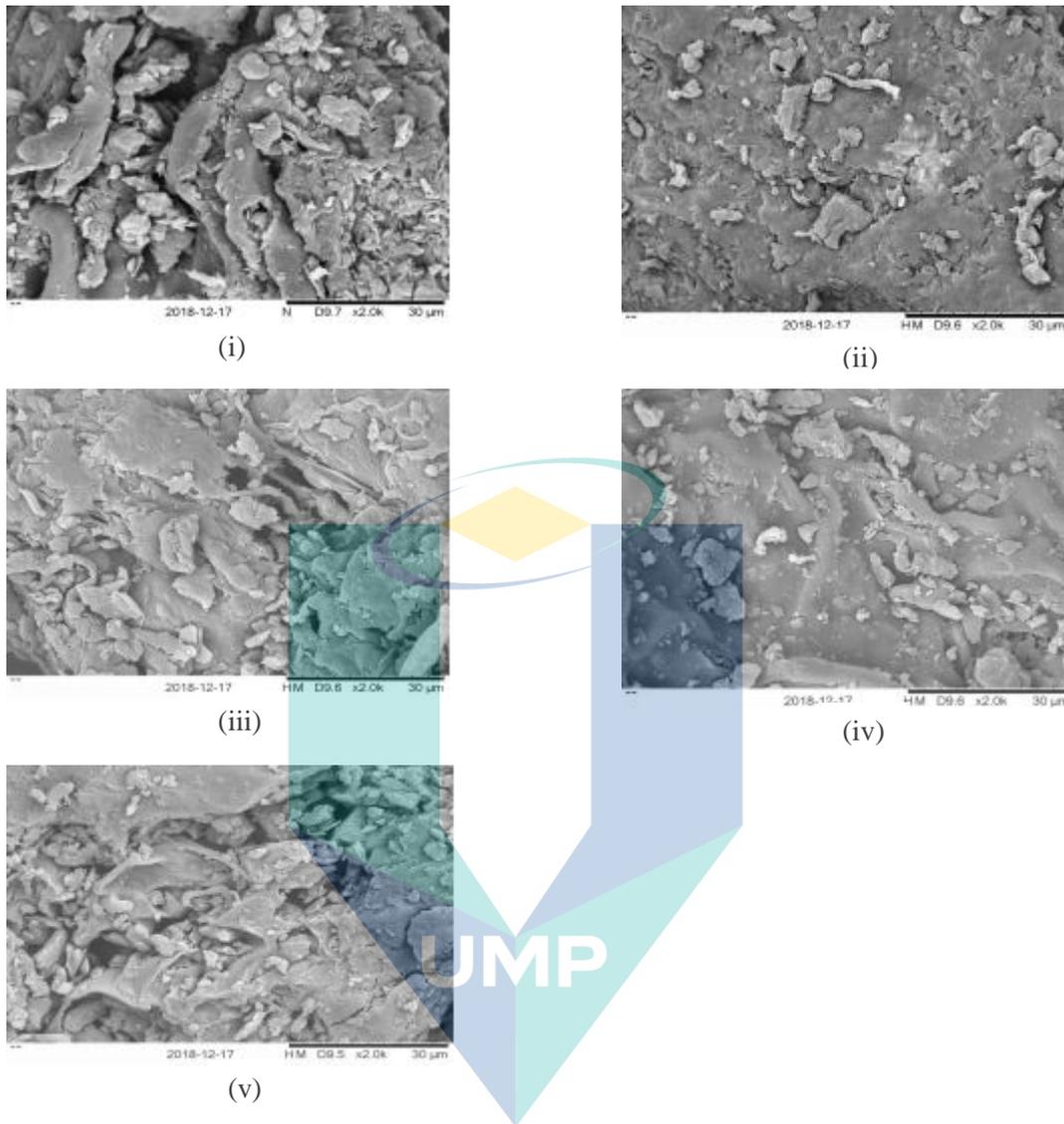


Figure 4.2 The images of SEM: (i) 71 $\mu\text{m}$ ; (ii) 125  $\mu\text{m}$ ; (iii) 160  $\mu\text{m}$ ; (iv) 180  $\mu\text{m}$ ; (v) 250  $\mu\text{m}$

The elemental compositions of tea powder were identified via energy dispersive x-ray (EDX) analysis. EDX systems are SEM attachments or instruments in which the microscope's imaging feature recognizes the specimen of interest. The data generated by EDX analysis consists of spectra with peaks corresponding to the elements that make up the true composition of the analyzed sample, which is shown in Figure 4.3. In addition, an elementary mapping of a sample and an analysis of the image is also possible. EDX is conventionally a powerful technique that allows for an elemental analysis of the sample surface.

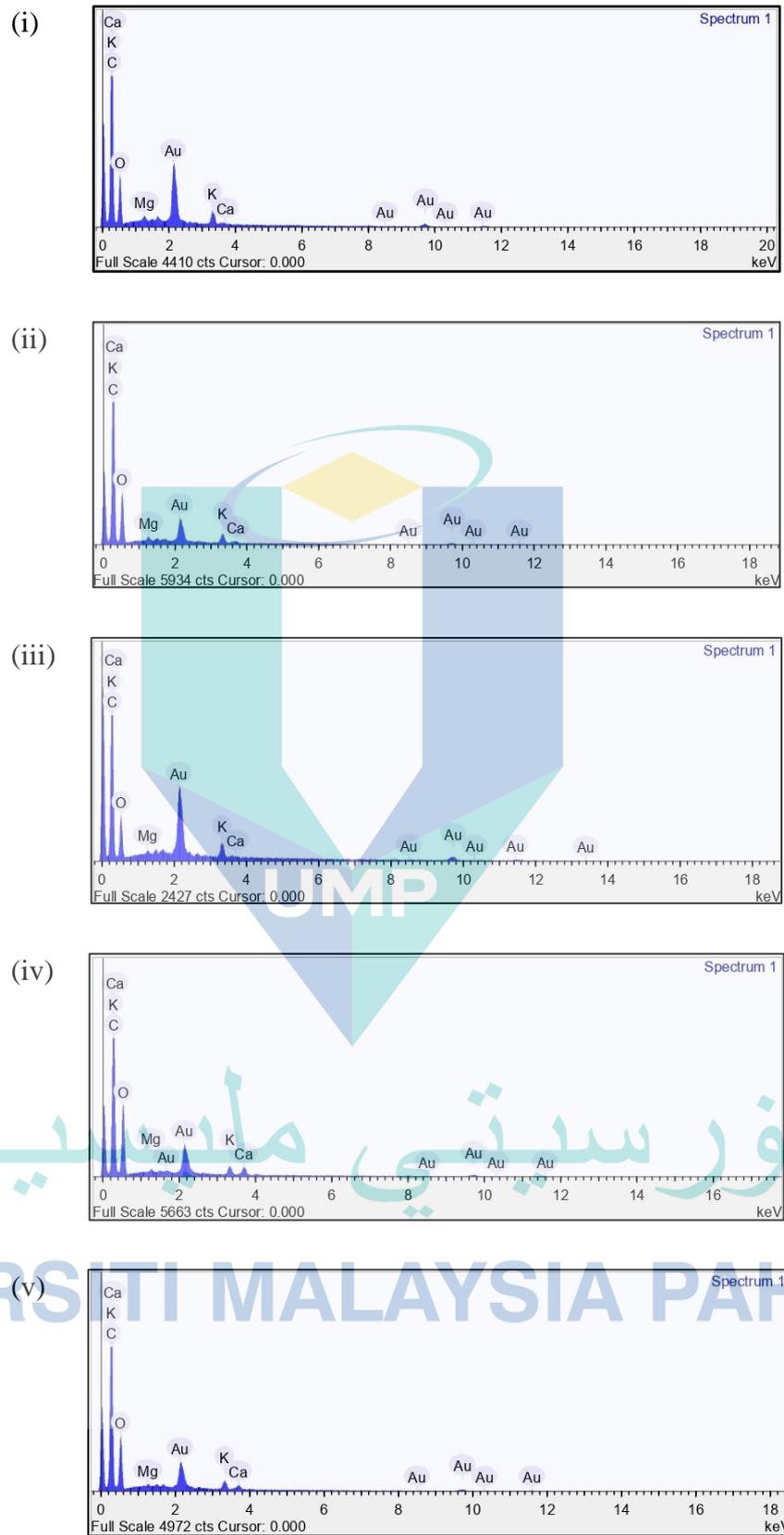


Figure 4.3 The images of EDX: (i) 71 $\mu\text{m}$ ; (ii) 125  $\mu\text{m}$ ; (iii) 160  $\mu\text{m}$ ; (iv) 180  $\mu\text{m}$ ; (v) 250  $\mu\text{m}$

Table 4.2 shows the composition of the tea powder. The elements in tea include carbon, oxygen, magnesium, potassium and calcium. From Table 4.2, the tea powder is mostly contain carbon and oxygen. The carbon content is made up of about 60 wt % for each particle size of tea powder. From a scientific point of view, combustion is a method of breaking chemical bonds and forming a new chemical bonds. Carbon is the principal combustible of solid fuel (tea powder) mixed with an equal amount of oxygen to form carbon dioxide. Carbon monoxide, which is further reacted to form carbon dioxide may also be formed for incomplete combustion. The presence of these elements makes the tea powder a combustible dust.

Table 4.2 Chemical compositions of tea powder

	Size ( $\mu\text{m}$ )	71	125	160	180	250
Element (wt %)	Carbon	61.94	61.98	60.14	60.00	60.88
	Oxygen	22.53	29.57	20.82	34.62	30.04
	Magnesium	0.32	0.35	0.27	0.23	0.17
	Potassium	1.87	1.38	2.02	1.16	1.28
	Calcium	0.10	0.26	0.15	1.19	0.67

#### 4.3 Chemical Properties Determination by Thermogravimetry Analysis (TGA)

Following the explosion intensity characteristics and explosion sensitivity parameters, the chemical properties of the tea powder are very important because it has strong influence to thermodynamics and kinetics of dust explosion (Eckhoff, 2003). Thermogravimetry (TGA) method based on ASTM (2008) procedure was applied to determine the explosion severity characteristics of the tea powder. The percentage of weight loss of the five different sizes of tea powder can be calculated from the TGA curves. From the data obtained, the chemical parameters such as moisture, volatility, fixed carbon and ash content can be determined.

Figure 4.4 shows the percentage weight loss of the samples for the tea powder. As a function of temperature the derivative weight gave the rate of weight loss. If the rate of weight loss over temperature for one component is at its highest, the derivative weight

graph may show the peak. The rate of weight loss over temperature would be lower if the temperature increases and other component decomposition occurs afterwards.

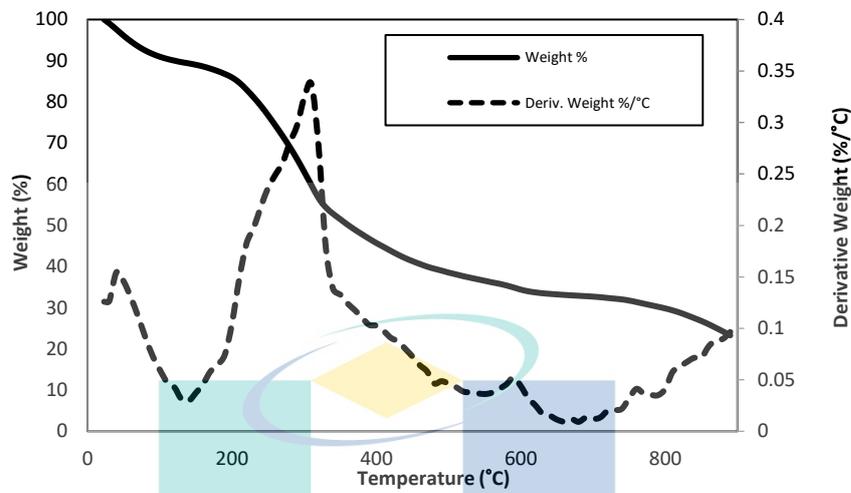


Figure 4.4 Graph of percentage weight loss for tea powder

Table 4.3 Chemical properties of tea powder

Size ( $\mu\text{m}$ )	Moisture (%)	Volatility (%)	Fixed carbon (%)	Ash (%)
71	6.52	64.78	23.73	4.97
125	8.87	60.51	25.92	5.09
160	9.08	56.30	30.46	5.41
180	10.52	53.37	3.08	22.73
250	13.54	51.23	4.04	23.18

From Figure 4.4, the initial decomposition temperature was 50 °C which was the point where the tea powder started disintegrating and measured the thermal stability of the tea powder. At 310 °C, the component in the tea powder was decomposing. It is known as the maximum rate of decomposition temperature. At 390 °C 50 wt % of the tea powder has decomposed. For the final residue, the amount of tea powder left after the end of the heating gave the final composition of the tea powder.

As shown in

Table 4.3, the moisture content was the highest for the size of 250  $\mu\text{m}$  followed by the size of 180  $\mu\text{m}$ , 160  $\mu\text{m}$ , 125  $\mu\text{m}$  and 71  $\mu\text{m}$ . It shows that by increasing the particle size, the tea powder tends to absorb air moisture and a layer of water molecules will form on the surface of the particle. It can be summarized that the moisture content increases when particle size increases. This is due to the layer of water molecules which agglomerate the particle, which could increase the virtual particle size and decrease the surface area. As the of moisture content increases, the ignition sensitivity of dust significantly decreases and the lower heat intensify of the dust decreases linearly where the energy of an ignition source was absorbed by the water in the particles (Du et al., 2012; Wade et al., 2013). The moisture content in tea powder may influence the level of inertion mitigation and prevention of dust explosion. Consequently, with the rise of moisture content, the maximum explosion pressure and the rate of pressure rise decrease. Higher moisture content had a dramatic effect in reducing the sensitivity to the ignition and the rate of oxidation and devolatilization.

Another parameter obtained from Table 4.3 is the volatility of tea powder. Based on Table 4.3, the volatility of tea powder of 71  $\mu\text{m}$  was 64.78 wt %, 125  $\mu\text{m}$  of 60.51 wt %, 160  $\mu\text{m}$  of 56.30 wt %, 180  $\mu\text{m}$  of 53.37 wt % and 250  $\mu\text{m}$  of 51.23 wt %. In dust explosion mechanism, the smaller the particle size of the dust, the more volatile are expelled (Abbasi and Abbasi, 2007). The increase in heating rate would generally lead to an increase in mass loss (ISO, 1997). For example, the dust explosion is extensively regulated by dust cloud's constituent particle size. The dust deflagrates primarily through a homogenous mechanism in which the combustion of the dust particles precedes devolatilization (Du et al., 2012). Indeed the explosion process is dominated by the volatile-air mixture combustion process (Du et al., 2014). For example, based on a research conducted by Eckhoff (2003) on coal dust, the devolatilization of the particles is a rapid phase and is driven by the rate of oxygen combustion on the carbon dust surface resulting in the release of volatile particles from the coal dust. The release of volatiles, which may be caused by the breaking of chemical bonds (Hertzberg et al., 1988) and desorption of low molecular weights (Vijayakumar et al., 2006) depends primarily on the specific surface area of the dust particles. It is a well-known fact that specific surface area of some amount of dust is inversely proportional to the particle size constituent. The high

volatility of dust could also give higher deflagration index value, hence high dust explosion severity.

Other than that,

Table 4.3 also shows the fixed carbon of tea powder. Fixed carbon is the solid flammable residue that will remain until heating up the sample and removing the volatile matter. The value was calculated from the difference between 100 and the sum of the moisture, volatile matter and ash. The TGA result showed that the fixed carbon of tea powder ranging from 3 to 30 wt %. From

Table 4.3, the particle size of 160  $\mu\text{m}$  has the highest value of fixed carbon which is 30.46%. This might be due to the greater surface area of the particle and the content of the moisture, volatile matter and ash of the sample.

The last parameter obtained from

Table 4.3 is the ash content. Ash is the substance that remains after cooling and organic matter has been extracted with the use of oxidizing agents through a heating process. Ash was calculated as the residual and as a function of temperature the derivative weight provided the weight loss rate. From the results obtained, the ash content of tea powder were ranging from 4 to 23 wt %. The ash present in the dust sample is a measure of the organic material content and it also represents the fraction which is incombustible (Cashdollar, 2000; Bershad, 2014; Fumagalli et al., 2016). As shown in

Table 4.3, the ash content increases as the particle size increases. The higher content of ash could be due to the less moisture in the sample. Incombustible ash will serve as inertant (Chawla et al., 1996) and it does not cause the combustion and explosion. It can be concluded from these results that as the particle size increases, the moisture and ash content also increase as volatility decreases.

#### 4.4 Tea Dust Explosion Characteristics

In order to identify the explosion characteristics of tea powder, the tea powder was tested and performed within a 20 L vessel. The  $P_{\text{max}}$  is one of the predicted explosive properties for calculating the magnitude of a dust explosion within the experiment. It measures the maximum explosion overpressure of explosion generated within the vessel. The  $(dP/dt)_{\text{max}}$  is the maximum rate of pressure rise during the course of a single explosion test. The value is concerned with an explosion's heat release rate, and involves a strong kinetic component.

#### 4.4.1 Effect of Moisture Content

A series of explosion tests were tested on tea powder at room temperature (before drying) and at 105 °C (after drying). Figure 4.5 below shows the  $P_{\max}$  for tea powder of 125  $\mu\text{m}$  and at concentration 2000  $\text{g}/\text{m}^3$  before and after drying process. Based on the Figure 4.5, the time taken for the tea powder to complete the combustion was 1.03 s before drying process while after drying was 0.35 s. The  $P_{\max}$  was higher after the drying process which was 14.61 bar compared to before drying which was 6.65 bar. From the results, it can be seen that when the moisture content was lower, the  $P_{\max}$  was higher and linearly reduced with the rise of the moisture content.

A dust's moisture content will affect a dust cloud's ability to ignite, and its ability to sustain an explosion. Increasing moisture content will increase the ignition energy up exponentially. The heating and evaporating the moisture provided an inert heat sink. Once the water vapour combined with pyrolysis gases that has been evaporated and made less reactive, resulting in greater effective particle size. This may be the reason for the rapid complete combustion for dry tea powder compared to the wet tea powder.

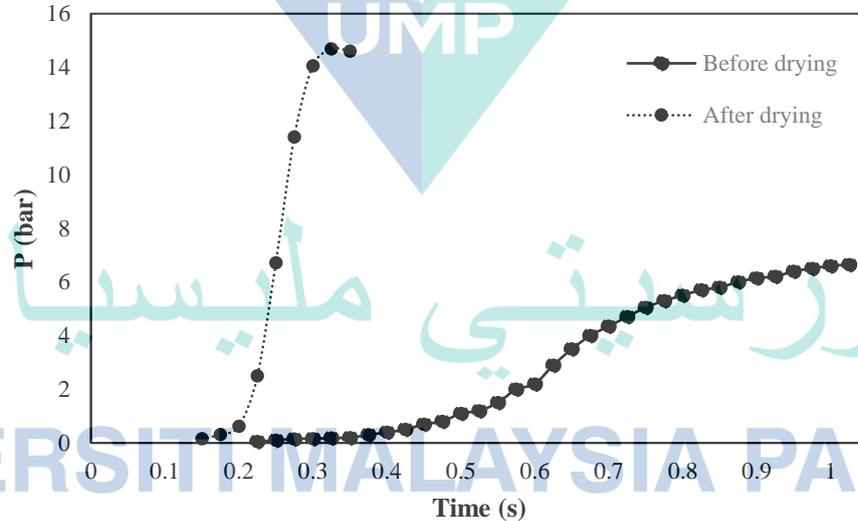


Figure 4.5 Graph of  $P_{\max}$  vs time for tea powder of 125  $\mu\text{m}$  at 2000  $\text{g}/\text{m}^3$

Figure 4.6 shows the  $(dP/dt)_{\max}$  of tea powder of similar size and concentration before and after drying process. Result showed that the  $(dP/dt)_{\max}$  had a similar variation to the  $P_{\max}$  with the rising moisture content. The  $(dP/dt)_{\max}$  before drying was 74 bar/s and increased to 222 bar/s after drying. The  $P_{\max}$  and  $(dP/dt)_{\max}$  variance behaviours were explainable by analyzing process of combustion of dust particles in the presence of

moisture. At lower moisture content, the moisture would mainly consume the reaction heat of dust explosion by temperature rise and phase change. In this situation, the measured explosion severity decreased gently and linearly with the rising moisture content. Nevertheless, as the moisture content continues to rise, due to the stronger inter-molecular cohesion between particles (Eckhoff, 2003), in addition to the heat consumption, the existence of moisture would also cause the agglomeration of dust particles and thus increase the effective particle size of dusts and weaken the dust cloud dispersion. Consequently, the decrease in the magnitude of the blast became more impressive, and even the dust cloud cannot be ignited.

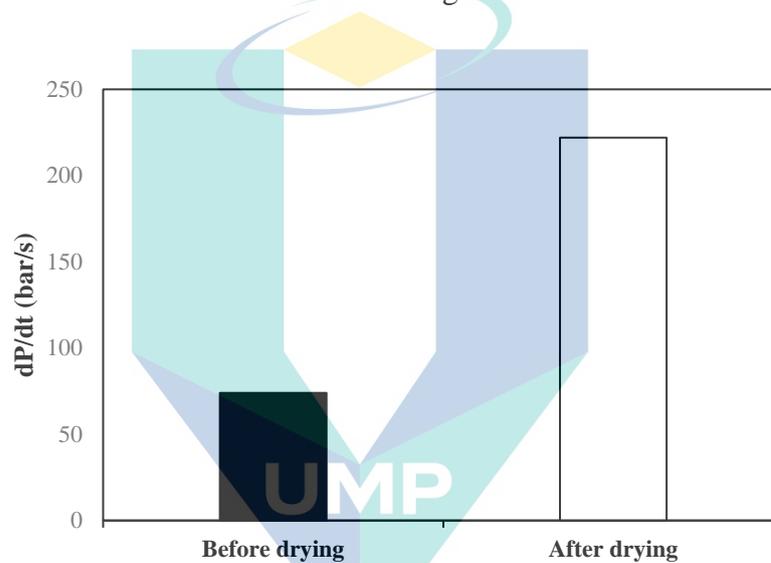


Figure 4.6 Graph of  $(dP/dt)_{max}$  for tea powder of  $125 \mu\text{m}$  at  $2000 \text{ g/m}^3$

Additionally, the moisture content of a sample can act as a prevention or mitigation factor for dust explosions. As mentioned earlier, with increasing moisture content, the explosibility of dust and the maximum rate of pressure rise decreased. This is because the moisture in the dust acted as a heat sink by absorbing the heat for the dust explosion. For higher levels of moisture, where the dust particles coalesce and bind together, agglomeration is common, so that the substance no longer behaves as fine powder. In such cases, there was no risk of dust cloud formation and the solvent vapour risk was the sole flammability issue.

Water is also an extremely effective inerting agent, so elevated moisture content could counteract the properties of dust explosion. The greatest impact of water has prevented the cloud formation by inducing agglomeration of particles (as described above).

The effect of residual water was significant for the electrostatic properties where water was generally highly conductive. This extreme sensitivity to the moisture content applies to the effect of the moisture content (relative humidity) in the atmosphere.

As mentioned before, moisture induced particle agglomeration will prevent dust explosion by weakening the particle dispersibility. There are two primary causes for this phenomenon of agglomeration of dust. First, the moisture adhered to the particle surface can significantly reduce the effective distance between two touching particles (Eckhoff, 2003), so that the stronger attraction forces and tendency to agglomerate between wet particles would occur. Second, the moisture in particle gaps may act as an adhesive to form liquid bridges between partial particles, further increasing the likelihood of agglomerating dust. In addition, the micro-structure of developing dust particles dust particles may also play a positive role in dust agglomeration. According to the SEM pictures of tea powder (Figure 4.2), the surfaces of dust particles are not always smooth, but often roughness. Because of this developed micro-structure, strong air adsorption may occur on the particle surfaces to form an air film (Liu et al., 2013), which to some extent, would impede the diffusion of moisture and in turn increase the residence time of the moisture in particle gaps and surfaces. Because the influence of these above-mentioned factors would notably increase with the rising moisture content and the inter-particle distance for a given concentration of dust mass would decrease proportionally with the particle size, the dust agglomeration would become more pronounced at higher moisture content or finer particle size. Based on the analysis of various moisture inhibition mechanisms, the relative importance of these mechanisms appears to change with the variation of the moisture content or particle size.

Meanwhile, from an explosion perspective, moisture can also be considered as a kind of inert medium for inhibiting explosion of dust. By comparing the pressure inhibition efficiency obtained at different concentrations of dust, it is found that the presence of moisture in particles will narrow the range of explosible concentrations of combustible dusts, especially at high moisture content. In addition, the moisture has a higher level of inhibition and more effective for inhibiting tea dust explosions, compared to a solid inert media under certain conditions. The relative importance of these inhibition mechanisms would significantly change with the variation of the moisture content of particle size. The primary mechanisms are heat extraction and oxygen dilution, for lower

moisture content or greater particle size. As the moisture content increased or the particle size decreased, the prevailing mechanisms will slowly turn into kinetic inhibition reaction and particle agglomeration.

#### 4.4.2 Effect of Particle Size

Particle size plays an important role towards the inflammability and explosibility of particles. The effect can be devastating and with possible loss of life or injury when ignited at high dispersal pressures. To analyze the effect of particle size on the explosion severity, the tea powder of five sizes were tested at a fixed concentration. Figure 4.7 below shows the results for various sizes of tea powder before and after drying.

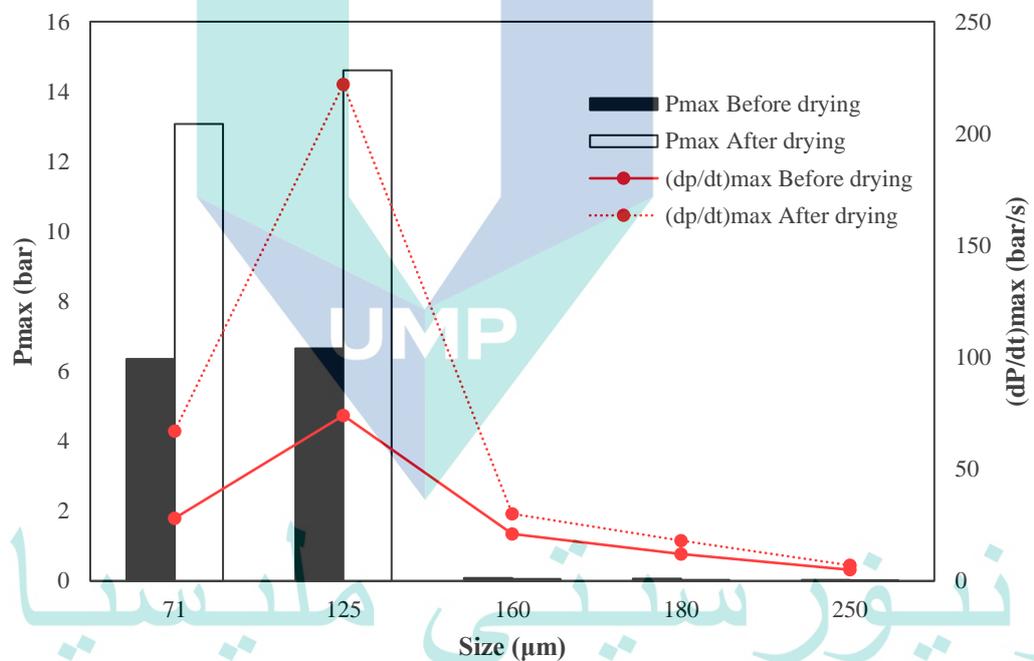


Figure 4.7 Graph of  $P_{max}$  and  $(dP/dt)_{max}$  for tea powder of various sizes at  $2000 \text{ g/m}^3$

From the figure, the result of tea dust before drying, the highest  $P_{max}$  recorded was 6.65 bar for tea powder size 125 µm, followed by 71 µm of 6.35 bar, 160µm of 0.09 bar, 180 µm of 0.07 bar and 250 µm of 0.03 bar. After drying, the tea powder of 125 µm had the highest  $P_{max}$  which was 14.61 bar, followed by 71 µm of 13.07 bar, 160 µm of 0.06 bar, 180 µm 0.03 bar and 250 µm 0.02 bar. For all the particle sizes, the  $P_{max}$  was recorded at a concentration of  $2000 \text{ g/m}^3$ . The behaviour of the dust explosion is strongly depends on the particle size (Lemkowitz et al., 2014). When the particle size decreased, the minimum energy required igniting the dust cloud decreases and thus the  $P_{max}$  increased.

Furthermore, the moisture content can reduce the amount of static electricity needed for ignition which makes the larger size dust which were 160  $\mu\text{m}$ , 180  $\mu\text{m}$  and 250  $\mu\text{m}$  more difficult to ignite. This is shown in Figure 4.7, where  $P_{\text{max}}$  values decline slowly with increasing of particle size.

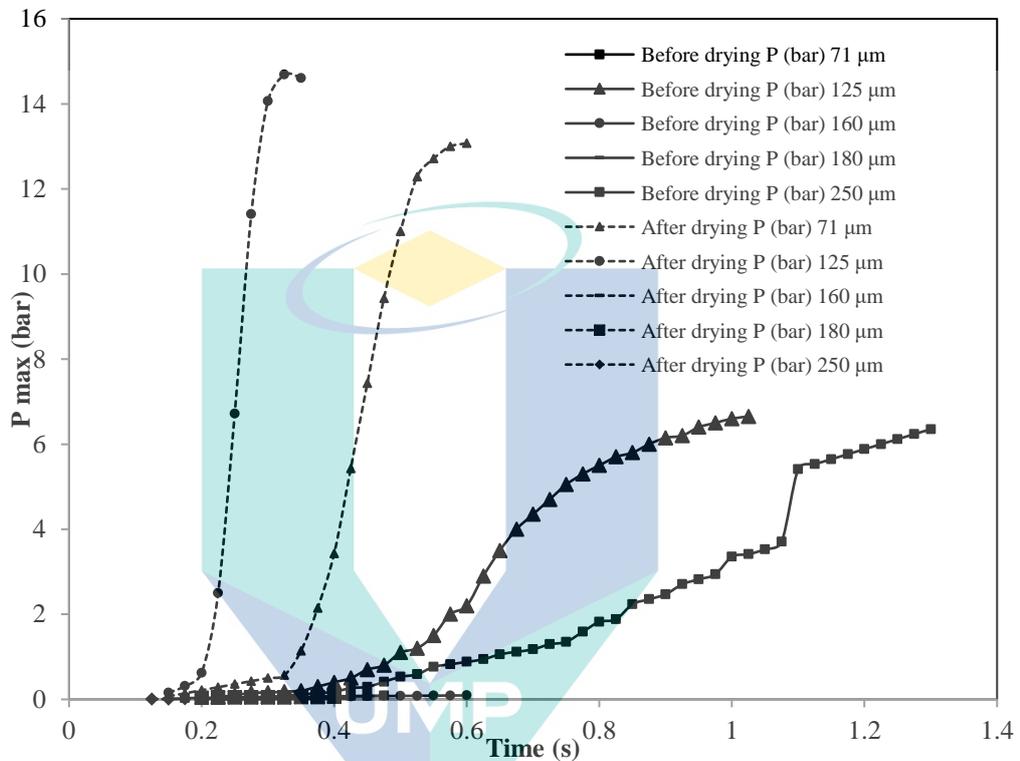


Figure 4.8 Graph of  $P_{\text{max}}$  vs time for tea powder of various sizes at  $2000 \text{ g/m}^3$

Figure 4.8 shows the  $P_{\text{max}}$  function of time. Based on the Figure 4.8, all dust started to ignite at  $t = 0.15 \text{ s}$ . A slow combustion was performed for all dust sizes. After some times, the combustion turned fast due to the flame acceleration as the mass burning rate increase. However, the particle size of 71  $\mu\text{m}$  took the longest time to complete the combustion and explosion which was about 1.3 s before and 0.6 s after drying. A flammable mixture in a closed vessel that has been deflagrated and ignited in the centre, and the flame spherically extends from the centre of the vessel until it hits the wall. Therefore, it can be said that the pressure in the vessel constantly rising throughout this process. When the flame reached the vessel's wall, both the pressure and the rate of pressure rise reached a maximum.

In fact, particle size had a significant influence on velocity and acceleration. The particle with smaller size and greater surface area was able to absorb heat more readily

and quickly form ignitable mixtures. Based on the research done by Suhaimi et al., (2015), the mass burning rate will speed up the propagation of the flames and result in the highest and steepest explosion overpressure development which represents the pressure versus time curves shown in Figure 4.8. From Figure 4.8, the particle size of 125  $\mu\text{m}$  shows the significant steep rising from 0.48 bar to 6.40 bar before drying and 0.63 bar to 14.06 bar after drying. The burning rate for particle size of 160  $\mu\text{m}$ , 180  $\mu\text{m}$  and 250  $\mu\text{m}$  were slow due to the higher moisture content of the dust.

Also based on Figure 4.7,  $(dP/dt)_{max}$  before drying for particle size 71  $\mu\text{m}$  - 250  $\mu\text{m}$  before drying were ranging between 5 bar/s - 74 bar/s. After drying,  $(dP/dt)_{max}$  increased to 67 bar/s, 222 bar/s, 30 bar/s, 18 bar/s and 7 bar/s, respectively. From the results obtained in Figure 4.7, it shows that  $(dP/dt)_{max}$  decreased as the particle size increased. This might be due to the distribution of the particle size. Particulates with a similar average particle size usually had a different distribution of particle size. Merkus (2017) claimed that under the standard test conditions the dust with exactly the same chemical composition but with a smaller particle size distribution around the same median size may not explode at all. Nevertheless, the same dust with a greater distribution of particle size will result in a high explosion severity and sensitivity. This is because a small fine fraction of the dust found was more prone to ignition than the fraction of the coarse fraction. The particles may have irregular shapes resulting in a large surface area than the sphere having the same making the dust more explosive. Also, the larger particle size had higher moisture content which increase the ignition energy and reduced the  $(dP/dt)_{max}$  value.

For flame propagation mechanism, Cashdollar (1996) indicated that a smaller size of particles would likely react faster than a larger size of the same material. The smaller particles could disperse more easily and remain airborne longer, which was why the particle size of 125  $\mu\text{m}$  gives the highest  $(dP/dt)_{max}$  compared to other sizes. The shape and porosity of the particles can also impact the surface area and the rate of reaction. The shape with a larger surface area will more readily propagate the flames and thus be more dangerous.

In fact, a smaller particulate will produce a faster and stronger explosions, since this will significantly increase the value of  $(dP/dt)_{max}$ . It may result in a more powerful pressure wave, as it represents how much pressure within a second has developed. Based

on Figure 4.7, the particle size of 125  $\mu\text{m}$  showed the highest  $(dP/dt)_{\text{max}}$  before and after drying process. Although the smaller particle size could give greater  $P_{\text{max}}$  and  $(dP/dt)_{\text{max}}$ , the surface area-to-volume ratio must be taken into consideration. Eckhoff (2009) stated that the further reduction in particle size will no longer increase the rate of combustion for most organic materials, as the devolatilization no longer controls the rate of explosion. This explained why the particle size of 71  $\mu\text{m}$  had low  $P_{\text{max}}$  and  $(dP/dt)_{\text{max}}$  although the size was the smallest.

The data in Figure 4.7 also indicate that the decrease in  $(dP/dt)_{\text{max}}$  was more remarkable than that in  $P_{\text{max}}$  as the particle size of dust increases, that was, when the specific area decreases. In addition, the particle size variance would mainly affect the particle reactivity that impacts the kinetics of the reaction, so that the  $(dP/dt)_{\text{max}}$  was more sensitive to the particle size than the  $P_{\text{max}}$ . Based on this fact, since the purpose of particle agglomeration was to increase the effective particle size of dusts, the  $(dP/dt)_{\text{max}}$  would be more prone to moisture due to the agglomeration than the  $P_{\text{max}}$ . This conclusion can be made by the curves shown in Figure 4.7, where the  $(dP/dt)_{\text{max}}$  data occurs at lower moisture content relative to the  $P_{\text{max}}$  data.

Since the presence of dust agglomeration will greatly increase the variability of explosion assessments, it is necessary to limit the moisture content in practice when assessing the intensity of the explosion. Based on the comparison of data in Figure 4.7, for the tea powder at particle 125  $\mu\text{m}$ , in order to avoid misleading explosion risk assessments, it appears that the moisture content to test the  $P_{\text{max}}$  and  $(dP/dt)_{\text{max}}$  should not exceed 5 wt % and 10 wt %, respectively.

Based on the research done by Eckhoff (2009), which showed that the maximum pressure for an explosion of wheat starch dust at constant concentration, 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 engage in the flame propagation as opposed to smaller particle sizes and are less readily dispersed. The particle size plays an important part in the importance of  $(dP/dt)_{\text{max}}$  value. The highest ranges of  $(dP/dt)_{\text{max}}$  was reported for the smaller particle size, as observed from the test. This can be compared to the result from the experiment of maize starch (11 % moisture) in by Eckhoff (2003) which shows that the maximum  $(dP/dt)_{\text{max}}$  peaks at a concentration of 500  $\text{g}/\text{m}^3$  and it decreases consistently with increase in particle size.

The size of the dust particles used to conduct the tests greatly influences both the  $P_{\max}$  and  $(dP/dt)_{\max}$ . The size of the dust particles acts on the suspension's explosive properties in two distinct ways. First, the manner in which dust follows the movement of the dispersion air has changed. This will have an effect on the drag to inertia as the dust particle size changes. The drag is proportional to the dust particles diameter whereas the inertia is proportional to the dust particle mass or volume. As the particle size increases, then the momentum increases faster than the drag. The effect is that their ability to follow the movement of the dispersion air will also change as the size of the dust particles increase. This will affect the degree of dust suspension stratification and the amount of dust which will reach the combustion vessel's wall. As the size of the dust particles increases, more dust appears to reach the wall and fall out of suspension, allowing less dust to participate in the process of combustion. Less dust in the suspension translates into lower maximum overpressure performance.

The second way  $P_{\max}$  and  $(dP/dt)_{\max}$  influences the size of the dust particles has been changing the burning of the dust particles. Since burning of dust particles happens on the particle surface, no gases are released as the particles are heated in the flame's preheat region. In this way burning occurs only on the surface of the particles of dust (Sichel et al., 1995; Eckhoff et al., 2009). As the flame reaches the particle surface, the intense heat can vaporize the dust and burning may occur in the gas phase, but the heat transfer rate is still limited by the dust particle surface area. The specific dust grain surface area is inversely proportional to the size of the dust particles. Therefore, by changing the particle size of the dust will change the specific area where burning will occur, affecting the propagation rate of the flame front.

For larger dust particles (160  $\mu\text{m}$  - 250  $\mu\text{m}$ ), the specific surface area being smaller than for smaller dust, the propagation of the flame front will be slower. The result being a lower  $(dP/dt)_{\max}$ . The slower burning did not directly affect the amount of dust burned in such a way so as to not alter the  $P_{\max}$ . Nevertheless, the longer propagation time allows for more dust settling and thus reduces the  $P_{\max}$ . This effect can be quite significant especially when the slow propagating velocities are combined with the high settling rate of large dust.

It can be seen that the level of  $P_{\max}$  decreasing as the size of the particles increases. It means less dust is burned as the dust increases in size. If all forms of dust were properly dispersed, the overpressure level would be the same. The fact that the overpressure level was lower indicated less dust is in suspension. The lower results of  $P_{\max}$  of the large dust particles show that there is significant difference in the dispersibility of the various dusts. Thus as the size of the dust particles increases, the dispersion system capacity decreases and there is less dust in the suspension. The  $(dP/dt)_{\max}$  is much higher for the particles of 125  $\mu\text{m}$  than for the particles of 160  $\mu\text{m}$ , 180  $\mu\text{m}$  and 250  $\mu\text{m}$ . This is what was expected, since the specific surface area is smaller for the larger particles. The lower  $(dP/dt)_{\max}$  also due to the fact that when used with larger dust particles, less dust is present in the suspension. From the test, it showed that the particle size of 125  $\mu\text{m}$  was the optimum size of tea powder that could generate high  $P_{\max}$  and  $(dP/dt)_{\max}$ .

#### 4.4.3 Effect of Concentration

Particle size usually determines the ease of ignition and extent of a combustible dust explosion. But other factor such as dust concentration also influences the dust's explosiveness. Dusts, like gases and vapours, will form explosive clouds if the concentration of dust is between certain limits, known as the lower explosion limit (LEL) and upper explosion limit (UEL).

Figure 4.9 shows the test result of the explosion pressure on the four different concentrations of 1000  $\text{g}/\text{m}^3$ , 1500  $\text{g}/\text{m}^3$ , 2000  $\text{g}/\text{m}^3$  and 2500  $\text{g}/\text{m}^3$  tea powder at 125  $\mu\text{m}$  before and after drying. Before drying,  $P_{\max}$  rises gradually from 0.09 bar with the increase of concentration, and reached 8.00 bar at the concentration of 2500  $\text{g}/\text{m}^3$ . After drying process, the  $P_{\max}$  increased from 11.32 bar and reached the peak of 14.61 bar at concentration of 2000  $\text{g}/\text{m}^3$ . The  $P_{\max}$  decreased with the increase of concentration ranging from 2000  $\text{g}/\text{m}^3$  to 2500  $\text{g}/\text{m}^3$  and dropped to 12.04 bar at the concentration of 2500  $\text{g}/\text{m}^3$ . For  $(dP/dt)_{\max}$ , the concentration of 2000  $\text{g}/\text{m}^3$  recorded the highest value for both before and after drying which was 74 bar/s and 222 bar/s respectively, followed by the concentration of 1500  $\text{g}/\text{m}^3$ , 2500  $\text{g}/\text{m}^3$  and 1000  $\text{g}/\text{m}^3$  for both processes.

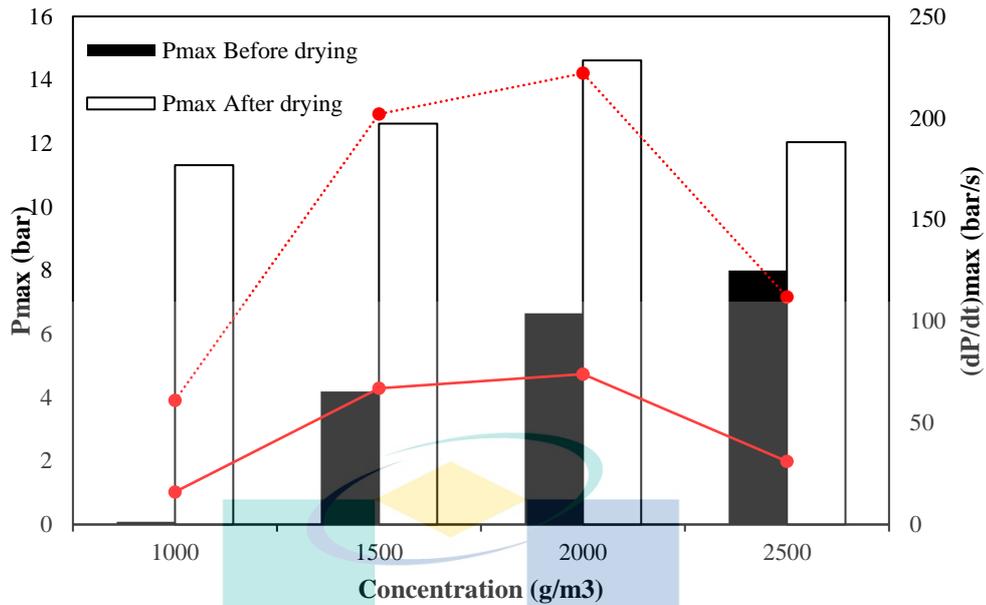


Figure 4.9 Graph of  $P_{\max}$  and  $(dP/dt)_{\max}$  for tea powder of various concentrations at 125  $\mu\text{m}$

The results were as expected because of the significant rise of volatiles yield, the  $P_{\max}$  increases rapidly with the increasing concentration initially, and then reaches its highest value at some specific concentration. Once the concentration becomes absolutely rich (2000  $\text{g}/\text{m}^3$ ), the  $P_{\max}$  gradually goes down due to high heat loss and lack of oxygen at highly loaded dust cloud (Yuan et al., 2014). Similar evolution trends also can be observed for the data of  $(dP/dt)_{\max}$  in Figure 4.8. Given that the  $(dP/dt)_{\max}$  includes a strong kinetic portion, the initial increase of  $(dP/dt)_{\max}$  may be due to an increase in volatiles release rate resulting in an increase in burning velocity. As Hertzberg et al., (1998) stated, the solid phase fuel first has to devolatilize before it can mix with the air. As long as enough volatiles have been produced to form a stoichiometric concentration of volatiles in air, the flame front propagates rapidly through the mixture until volatile excess fuel can be created. As for the decrease of  $(dP/dt)_{\max}$  at high concentration, perhaps an additional reason may be the slower inert-particle heat transfer (which causes a delay in the devolatilization process) at highly charged dust cloud.

Based on these findings, it appears that the magnitude of the explosion test depends significantly on the concentration of dust. When the concentration of tested dust cloud was exceedingly low or high, the minimal volatiles yield or the excess unburned particles would be subject to explosion tests. In order to eliminate this concentration effect, it is best to perform the explosion tests in the worst case of dust concentration

where the highest values of severity parameters would be acquired when investigating the influences of the moisture content (NFPA, 2007). However, note that these data in Figure 4.8 indicate that the highest values of  $P_{\max}$  and  $(dP/dt)_{\max}$  occur at different concentrations of 2000 g/m<sup>3</sup> and 2500 g/m<sup>3</sup> before drying process. This means that the worst-case concentration of dust determined by the  $(dP/dt)_{\max}$  is greater than that determined by the  $P_{\max}$ . This phenomenon is possibly caused by the fact that during an explosion, the transmission of the wave of combustion still lags behind the heat release.

There are, in principle, rich limits to dusts. The large mass of excess fuel will eventually become too much of a heat sink and the temperature of the flames will be reduced below its limit value. However, dusts can be considered as having no rich limit of explosibility for most practical purposes. Explosions of the dust cloud can only occur when the dust concentration has been within certain limits. The lowest concentration of dust that can give a dust explosion is generally about 50 - 100 g/m<sup>3</sup> and the maximum is 2000 - 3000 g/m<sup>3</sup>. Those limits depended on the specific chemical component and on the distribution of particle size. The worst cases have typically been when the concentration of dust is well above the concentration of stoichiometry. The minimum quantity of oxygen needed for explosion was dictated by the upper concentration limits, the lower limits by the minimum quantity of particles needed to sustain combustion.

Relatively, dust and  $(dP/dt)_{\max}$  explosibility decreased with increasing moisture content, while the minimum ignition temperature and minimum explosible concentration increased with higher moisture content. The explosion hazard tends to increase with increasing volatile content. With rising volatile material, the explosion hazard tends to increase. The threat of explosion tends to rise with rising volatile content. A high volatile content decreased the minimum explosive concentration and ignition temperature, thus increasing  $(dP/dt)_{\max}$  (Anwar et al., 2018).

#### 4.5 Deflagration Index, $K_{St}$

$K_{St}$  is often referred to as the cubic or cube root law or simply called as the dust constant. The value defines a combustible dust's normalized rate of pressure rise. The  $K_{St}$  value is calculated from multiplying the maximum rates of pressure rise,  $(dP/dt)_{\max}$  by the cube root of the volume of the explosion vessel. The equation is called cube root law as shown below:

$$K_{St} = (dP/dt)_{\max} \cdot V^{1/3} \quad (4.1)$$

From the equation, it is clear that there is a very close relationship between the values. Both the  $K_{St}$  and burning velocity are proportional to the  $(dP/dt)_{\max}$  and both depend on the cubic root of the combustion vessel's volume, which is equal to the combustion vessel radius. The consequences of the extent of the explosion severity may be used to design the basis for explosion safety and prevention such as explosion relief venting and explosion suppression but it depends on the validity of the cube root law. Cube root law is only valid in geometrically similar vessels if the thickness of the flame is negligible compared to the radius of the vessel and the velocity of burning is equal in all volumes as function of pressure and temperature (Eckhoff, 2003).

The results of severity values for this experiment are shown in Table 4.4. Dusts were classified into 4 groups based on the severity of their explosion (Abbasi and Abbasi, 2007). Those that fall into group St 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 St 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.

Table 4.4  $K_{St}$  values for various tea sizes and concentrations

Concentration n (g/m <sup>3</sup> )	1000		1500		2000		2500	
	$K_{St}$ (bar.m/s)							
Size (µm)	Before dryin g	After dryin g	Before dryin g	After dryin g	Before dryin g	After dryin g	Before dryin g	After dryin g
71	71.01	166.88	103.29	117.15	76.00	181.87	21.43	99.29
125	43.43	165.58	121.87	168.31	100.87	199.60	84.15	104.01
160	21.72	108.58	51.57	81.43	57.00	104.72	46.15	54.29
180	10.86	35.29	21.72	48.91	32.57	67.86	29.86	40.72
250	5.43	27.14	8.14	19.06	13.57	21.72	8.14	13.57

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 199.60 bar.m/s was recorded for particle size of 125  $\mu\text{m}$  at a concentration of 2000  $\text{g}/\text{m}^3$ . The  $K_{St}$  peaks at the concentration of 2000  $\text{g}/\text{m}^3$  for all particle sizes. The  $K_{St}$  decreased at concentrations above this, as the excess fuel acts as a drain of heat and reduces the  $(dP/dt)_{max}$ . Given that the dust concentration exceeds the stoichiometric average, due to oxygen deficiency, some of the particles cannot be fully ignited.

As discussed above, smaller particle size has greater surface area and is more volatile compared to larger particle size. The threat presented was more drastic, with the increase in volatile content. This suggested that the high volatility dust could give a higher  $K_{St}$  value and hence high dust explosion severity. In addition,  $K_{St}$  decreases linearly with moisture content increasing. Water can reduce particle explosibility and intensity, and tends to decrease the material's ignition sensitivity. This explained why the particle size of 160  $\mu\text{m}$ , 180  $\mu\text{m}$  and 250  $\mu\text{m}$  had lower  $K_{St}$  as their moisture content were higher than the particle size 71  $\mu\text{m}$  and 125  $\mu\text{m}$ .

According to OSHA (2015), most of the food-based dusts are class St1. Research work has been done by Ramirez et al., (2014) on the materials such as wheat grain dust and alfalfa have  $K_{St}$  value of 148 bar.m/s and 50 bar.m/s respectively. Even though the classes are the same, however, the moisture content and the particle size did not match with the tea powder sample in this research.

The  $K_{St}$  value factor is closely related to the burning velocity. For this reason, the  $K_{St}$  factor will be constant for the same combustible mixture which has the same turbulence strength will be constant. Since turbulence affects the velocity of burning, it will also affect the  $K_{St}$ . By applying the fan for turbulence condition, Kumar et al., (1992) gave the  $K_{St}$  effect on the concentration of corn starch/air mixtures for quiescent and turbulent dust. It is found that turbulent condition for increased concentration of dust gave rise to  $K_{St}$  value of the dust. This can be said to vary the  $K_{St}$  value, depending on the dynamic state of the dust cloud in turbulent or quiescent example and its rate of combustion. While these materials are class St 1, these  $K_{St}$  values could create sufficient power to cause a flash fire, compromise containment on a piece of equipment or blow out the walls of a building.

## CHAPTER 5

### CONCLUSION AND RECOMMENDATION

#### 5.1 Conclusion

In conclusion, the explosion of tea dust in industry will pose a threat to both personnel and properties depending on the explosibility and extent of the dust explosion. The physical and chemical properties of tea powder also play a major role in the explosibility and severity of the explosion of dust. The crucial parameters which need to be evaluated were particle size, minimum explosion concentration (MEC), maximum explosion overpressure ( $P_{max}$ ) and dust deflagration index ( $K_{St}$ ). The thermogravimetry analysis (TGA) gave analysis of moisture content, volatile content, fixed carbon as well as ash content.

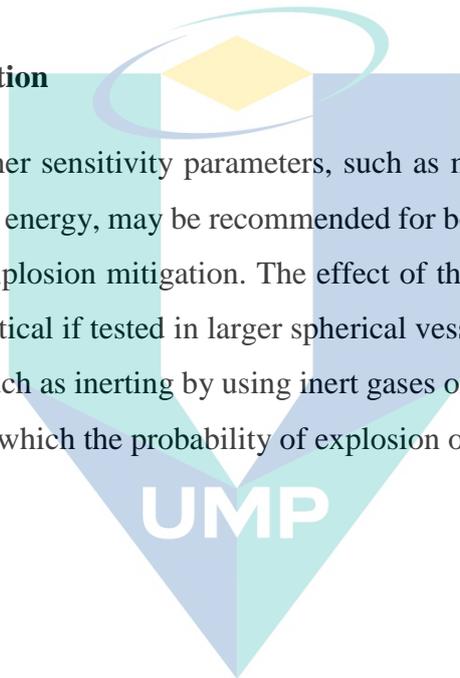
From the analysis, it showed that moisture content of tea powder at size 250  $\mu\text{m}$  was the highest at 13.54 wt %, followed by 180  $\mu\text{m}$  of 10.52 wt %, 160  $\mu\text{m}$  of 9.08 wt %, 125  $\mu\text{m}$  of 8.87 wt % and 71  $\mu\text{m}$  of 6.52 wt %. The amount of moisture content increases as the particle size increases due to the layer of water molecules that agglomerate the particle which could increase the virtual particle size and reduce the surface area. The volatility of tea powder were ranging from 51 to 65 wt %. High volatility leads to high severity of dust explosion. The fixed carbon were ranging from 4 to 30 wt % with tea powder at size 160  $\mu\text{m}$  having the highest value at 30.46 wt % due to the greater surface area of the particle and moisture content, volatile matter and ash of the sample. Ash content of the tea powder were ranging from 5 to 23 wt % and would not affect much on the explosibility as well as severity characteristics of tea powder.

From the explosibility test, it was found that the time taken for tea powder to complete the combustion was shorter for dry tea powder as compared to wet tea powder. The maximum overpressure ( $P_{max}$ ) and the maximum rate of pressure rise  $(dP/dt)_{max}$  were higher and linearly reduces with the rise of moisture content. By increasing the moisture content, the ignition energy would increase exponentially. The minimum explosible concentration (MEC) of the tea powder was 1000  $\text{g}/\text{m}^3$ .  $P_{max}$  and maximum  $(dP/dt)_{max}$

was the highest at concentration of  $2000 \text{ g/m}^3$  for particle size of  $125 \text{ }\mu\text{m}$ .  $P_{\text{max}}$  increased rapidly with the increasing concentration initially, then reached its highest value at some specific concentration. The similar trends also observed for  $(dP/dt)_{\text{max}}$ . It can be concluded that the explosion severity significantly depends on the dust concentration. The results of deflagration index ( $K_{\text{St}}$ ) were ranging from 5 to 200 bar.m/s with the highest value of 199.60 bar.m/s was recorded. Dryness may be said to have given a significant factor in determining the severity of the tea powder itself. The increased volatility and lower moisture content would increase the dust explosion severity and sensitivity.

## 5.2 Recommendation

Testing the other sensitivity parameters, such as minimum ignition temperature and minimum ignition energy, may be recommended for better precaution and design for protection and dust explosion mitigation. The effect of the properties of dust explosion will also be more practical if tested in larger spherical vessel such as  $1 \text{ m}^3$  ISO spherical vessel. Further tests such as inerting by using inert gases or rock dust can also be done to determine the level at which the probability of explosion of dust is minimized.



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UMP

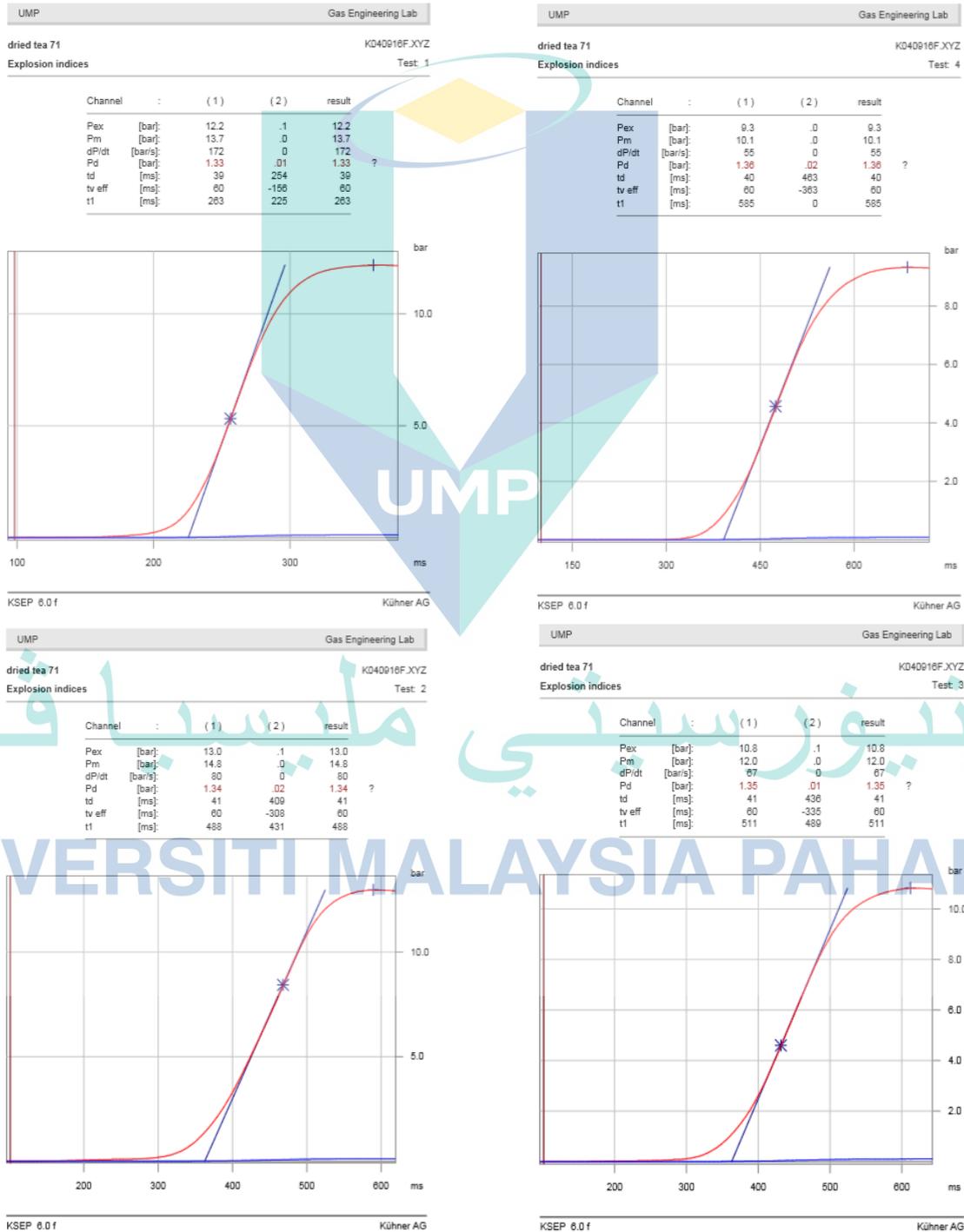
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# APPENDIX A DUST EXPLOSION ANALYSIS

## APPENDIX A1

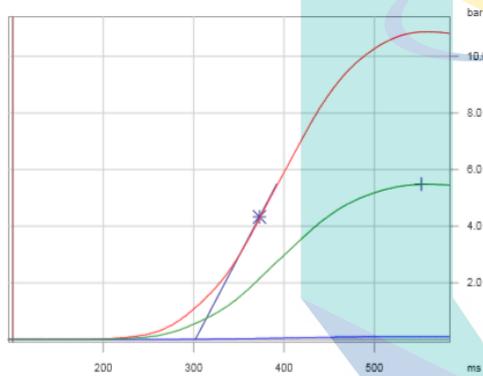
### Raw Results of Tea Powder at 71 $\mu\text{m}$ from KSEP Programme of 20 L Spherical Vessel



## APPENDIX A2

### Raw Results of Tea Powder at 125 $\mu\text{m}$ from KSEP Programme of 20 L Spherical Vessel

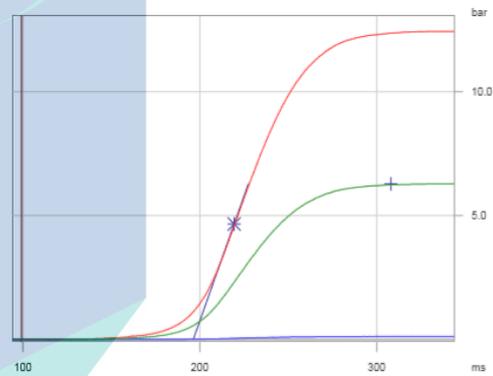
UMP		Gas Engineering Lab		
dried tea 125		KD40916E.XYZ		
Explosion indices		Test: 1		
Channel	:	(1)	(2)	result
Pex	[bar]:	10.9	.1	5.5 ?
Pm	[bar]:	12.1	.0	5.5 ?
dP/dt	[bar/s]:	61	0	61 ?
Pd	[bar]:	1.29	.02	.66
td	[ms]:	40	366	203 ?
tv eff	[ms]:	60	-267	-103 ?
t1	[ms]:	455	449	452



KSEP 6.0 f

Kühner AG

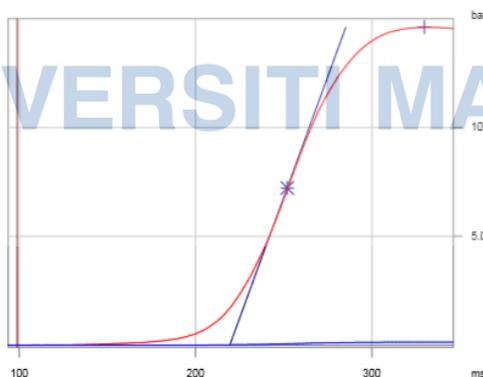
UMP		Gas Engineering Lab		
dried tea 125		KD40916E.XYZ		
Explosion indices		Test: 2		
Channel	:	(1)	(2)	result
Pex	[bar]:	12.4	.1	6.3 ?
Pm	[bar]:	14.1	.0	6.4 ?
dP/dt	[bar/s]:	202	0	202 ?
Pd	[bar]:	1.31	.02	.66
td	[ms]:	39	218	128 ?
tv eff	[ms]:	60	-117	-26 ?
t1	[ms]:	228	190	208



KSEP 6.0 f

Kühner AG

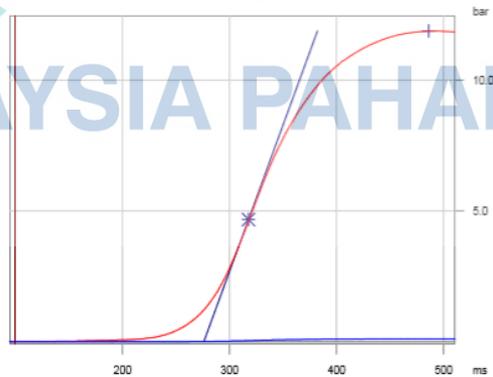
UMP		Gas Engineering Lab		
dried tea 125		KD40916E.XYZ		
Explosion indices		Test: 3		
Channel	:	(1)	(2)	result
Pex	[bar]:	14.6	.1	14.6
Pm	[bar]:	16.9	.0	16.9
dP/dt	[bar/s]:	222	0	222
Pd	[bar]:	1.32	.02	1.32 ?
td	[ms]:	39	236	39
tv eff	[ms]:	60	-137	60
t1	[ms]:	231	206	231



KSEP 6.0 f

Kühner AG

UMP		Gas Engineering Lab		
dried tea 125		KD40916E.XYZ		
Explosion indices		Test: 4		
Channel	:	(1)	(2)	result
Pex	[bar]:	11.9	.1	11.9
Pm	[bar]:	13.4	.0	13.4
dP/dt	[bar/s]:	112	0	112
Pd	[bar]:	1.30	.02	1.30 ?
td	[ms]:	40	311	40
tv eff	[ms]:	60	-211	60
t1	[ms]:	367	316	367



KSEP 6.0 f

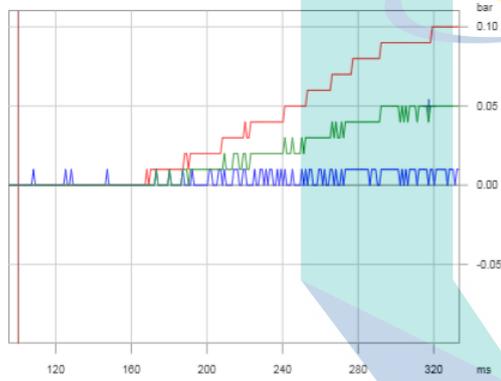
Kühner AG

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## APPENDIX A3

### Raw Results of Tea Powder at 160 $\mu\text{m}$ from KSEP Programme of 20 L Spherical Vessel

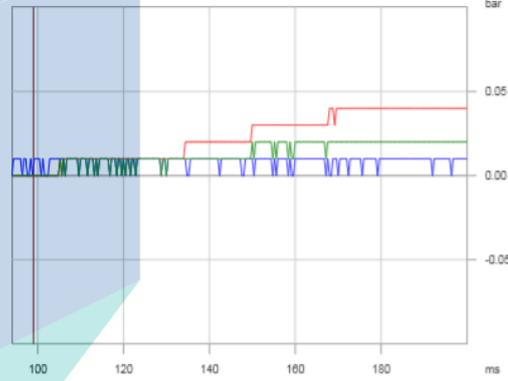
UMP		Gas Engineering Lab		
dried tea 160		KD40916D.XYZ		
Explosion indices		Test: 1		
Channel	:	(1)	(2)	result
P <sub>ex</sub>	[bar]	.1	.0	.1
P <sub>m</sub>	[bar]	.0	.0	.0
dP/dt	[bar/s]	0	0	0
P <sub>d</sub>	[bar]	1.12	.01	.56 ?
t <sub>d</sub>	[ms]	40	0	20 ?
t <sub>v eff</sub>	[ms]	60	100	80 ?
t <sub>1</sub>	[ms]	217	0	217



KSEP 6.0 f

Kühner AG

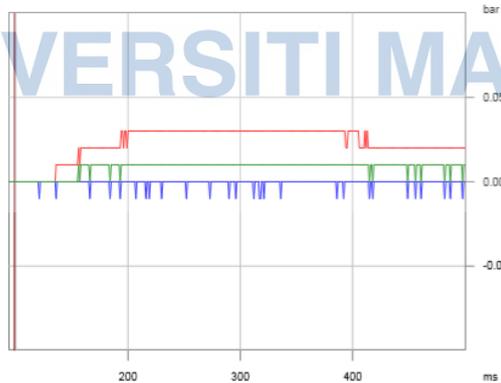
UMP		Gas Engineering Lab		
dried tea 160		KD40916D.XYZ		
Explosion indices		Test: 2		
Channel	:	(1)	(2)	result
P <sub>ex</sub>	[bar]	.0	.0	.0
P <sub>m</sub>	[bar]	.0	.0	.0
dP/dt	[bar/s]	0	0	0
P <sub>d</sub>	[bar]	1.18	.01	.60
t <sub>d</sub>	[ms]	39	0	20 ?
t <sub>v eff</sub>	[ms]	60	99	79 ?
t <sub>1</sub>	[ms]	0	0	0



KSEP 6.0 f

Kühner AG

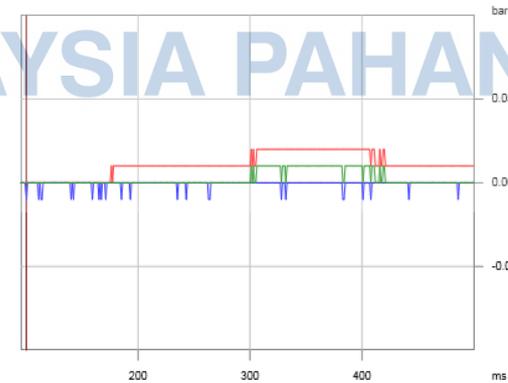
UMP		Gas Engineering Lab		
dried tea 160		KD40916D.XYZ		
Explosion indices		Test: 3		
Channel	:	(1)	(2)	result
P <sub>ex</sub>	[bar]	.0	.0	.0
P <sub>m</sub>	[bar]	.0	.0	.0
dP/dt	[bar/s]	0	0	0
P <sub>d</sub>	[bar]	1.22	.02	.62
t <sub>d</sub>	[ms]	39	0	20 ?
t <sub>v eff</sub>	[ms]	60	99	79 ?
t <sub>1</sub>	[ms]	0	0	0



KSEP 6.0 f

Kühner AG

UMP		Gas Engineering Lab		
dried tea 160		KD40916D.XYZ		
Explosion indices		Test: 4		
Channel	:	(1)	(2)	result
P <sub>ex</sub>	[bar]	.0	.0	.0
P <sub>m</sub>	[bar]	.0	.0	.0
dP/dt	[bar/s]	0	0	0
P <sub>d</sub>	[bar]	1.25	.02	.64
t <sub>d</sub>	[ms]	40	0	20 ?
t <sub>v eff</sub>	[ms]	60	100	80 ?
t <sub>1</sub>	[ms]	0	0	0



KSEP 6.0 f

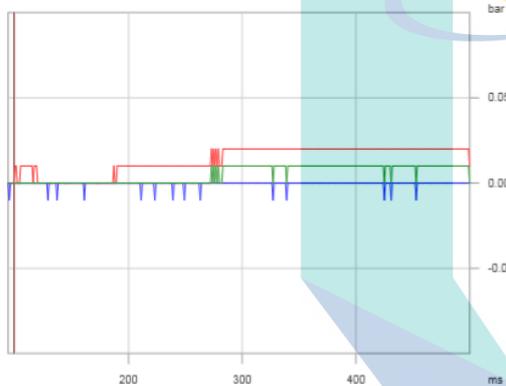
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# APPENDIX A4

## Raw Results of Tea Powder at 180 $\mu\text{m}$ from KSEP Programme of 20 L Spherical Vessel

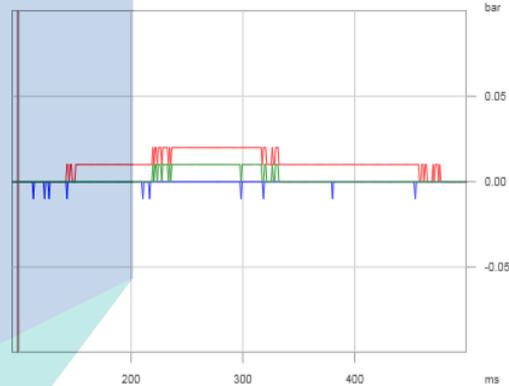
UMP		Gas Engineering Lab		
DRIED TEA 180		KD40916C.XYZ		
Explosion indices		Test: 1		
Channel	:	(1)	(2)	result
P <sub>ex</sub>	[bar]:	.0	.0	.0
P <sub>m</sub>	[bar]:	.0	.0	.0
dP/dt	[bar/s]:	0	0	0
P <sub>d</sub>	[bar]:	1.30	.02	.66
t <sub>d</sub>	[ms]:	40	0	20
t <sub>v eff</sub>	[ms]:	60	60	79
t <sub>1</sub>	[ms]:	0	0	0



KSEP 6.0 f

Kühner AG

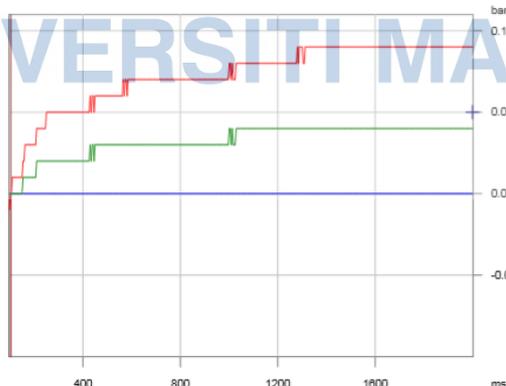
UMP		Gas Engineering Lab		
DRIED TEA 180		KD40916C.XYZ		
Explosion indices		Test: 2		
Channel	:	(1)	(2)	result
P <sub>ex</sub>	[bar]:	.0	.0	.0
P <sub>m</sub>	[bar]:	.0	.0	.0
dP/dt	[bar/s]:	0	0	0
P <sub>d</sub>	[bar]:	1.30	.01	.66
t <sub>d</sub>	[ms]:	30	0	20
t <sub>v eff</sub>	[ms]:	60	60	70
t <sub>1</sub>	[ms]:	0	0	0



KSEP 6.0 f

Kühner AG

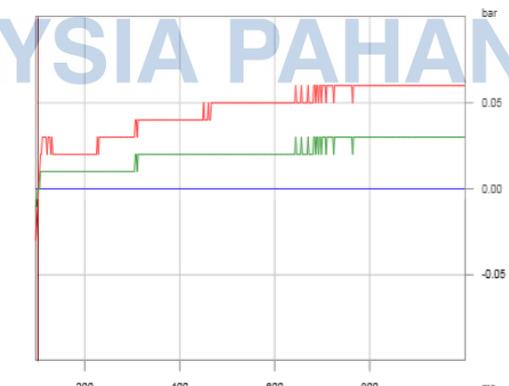
UMP		Gas Engineering Lab		
DRIED TEA 180		KD40916C.XYZ		
Explosion indices		Test: 3		
Channel	:	(1)	(2)	result
P <sub>ex</sub>	[bar]:	.1	.0	.1
P <sub>m</sub>	[bar]:	.0	.0	.0
dP/dt	[bar/s]:	0	0	0
P <sub>d</sub>	[bar]:	.81	.01	.41
t <sub>d</sub>	[ms]:	44	0	22
t <sub>v eff</sub>	[ms]:	60	103	82
t <sub>1</sub>	[ms]:	1806	0	1806



KSEP 6.0 f

Kühner AG

UMP		Gas Engineering Lab		
DRIED TEA 180		KD40916C.XYZ		
Explosion indices		Test: 4		
Channel	:	(1)	(2)	result
P <sub>ex</sub>	[bar]:	.0	.0	.0
P <sub>m</sub>	[bar]:	.0	.0	.0
dP/dt	[bar/s]:	0	0	0
P <sub>d</sub>	[bar]:	.66	.02	.46
t <sub>d</sub>	[ms]:	42	0	21
t <sub>v eff</sub>	[ms]:	60	102	81
t <sub>1</sub>	[ms]:	0	0	0



KSEP 6.0 f

Kühner AG

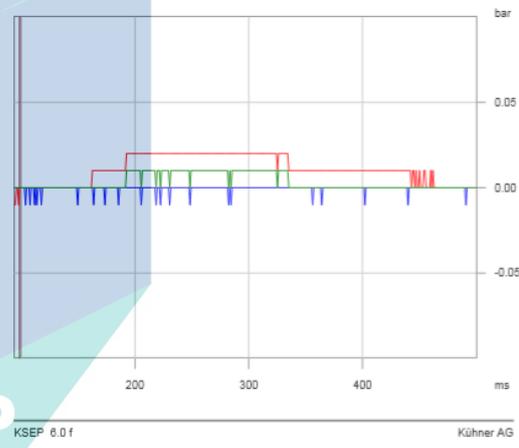
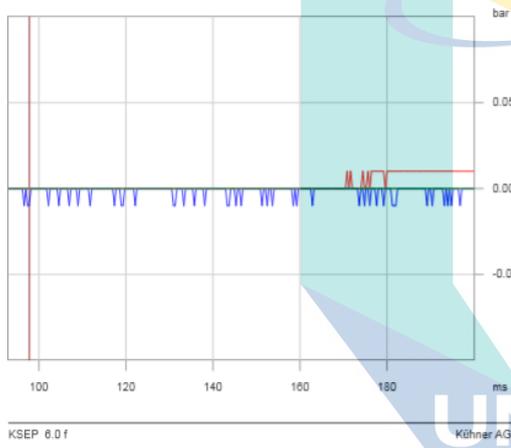
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# APPENDIX A5

## Raw Results of Tea Powder at 250 µm from KSEP Programme of 20 L Spherical Vessel

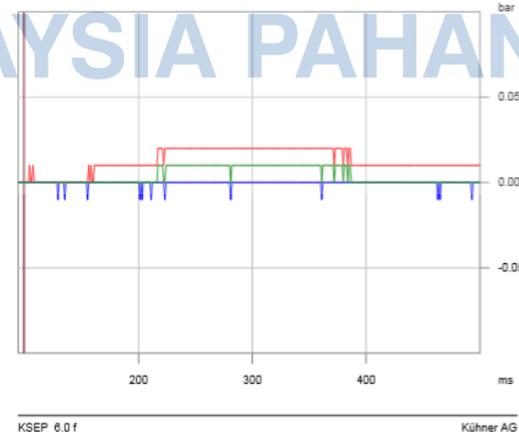
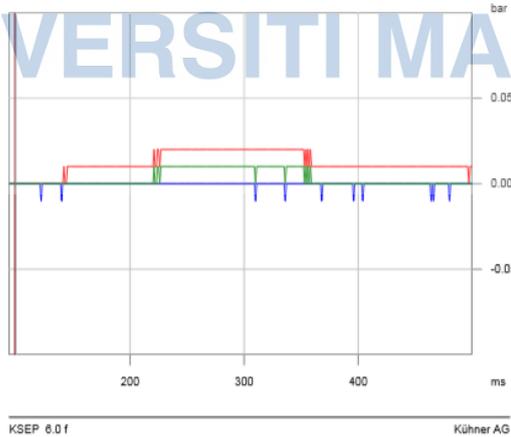
UMP		Gas Engineering Lab		
DRIED TEA 250		KD40916A.XYZ		
Explosion indices		Test: 1		
Channel	:	(1)	(2)	result
Pex	[bar]:	.0	.0	.0
Pm	[bar]:	.0	.0	.0
dP/dt	[bar/s]:	0	0	0
Pd	[bar]:	1.29	.01	.85
td	[ms]:	38	0	19 ?
tv eff	[ms]:	60	98	79 ?
t1	[ms]:	0	0	0

UMP		Gas Engineering Lab		
DRIED TEA 250		KD40916A.XYZ		
Explosion indices		Test: 2		
Channel	:	(1)	(2)	result
Pex	[bar]:	.0	.0	.0
Pm	[bar]:	.0	.0	.0
dP/dt	[bar/s]:	0	0	0
Pd	[bar]:	1.30	.02	.86
td	[ms]:	39	0	19 ?
tv eff	[ms]:	60	99	79 ?
t1	[ms]:	0	0	0



UMP		Gas Engineering Lab		
DRIED TEA 250		KD40916A.XYZ		
Explosion indices		Test: 3		
Channel	:	(1)	(2)	result
Pex	[bar]:	.0	.0	.0
Pm	[bar]:	.0	.0	.0
dP/dt	[bar/s]:	0	0	0
Pd	[bar]:	1.30	.02	.86
td	[ms]:	39	0	20 ?
tv eff	[ms]:	60	98	79 ?
t1	[ms]:	0	0	0

UMP		Gas Engineering Lab		
DRIED TEA 250		KD40916A.XYZ		
Explosion indices		Test: 4		
Channel	:	(1)	(2)	result
Pex	[bar]:	.0	.0	.0
Pm	[bar]:	.0	.0	.0
dP/dt	[bar/s]:	0	0	0
Pd	[bar]:	1.30	.02	.86
td	[ms]:	39	0	20 ?
tv eff	[ms]:	60	98	79 ?
t1	[ms]:	0	0	0

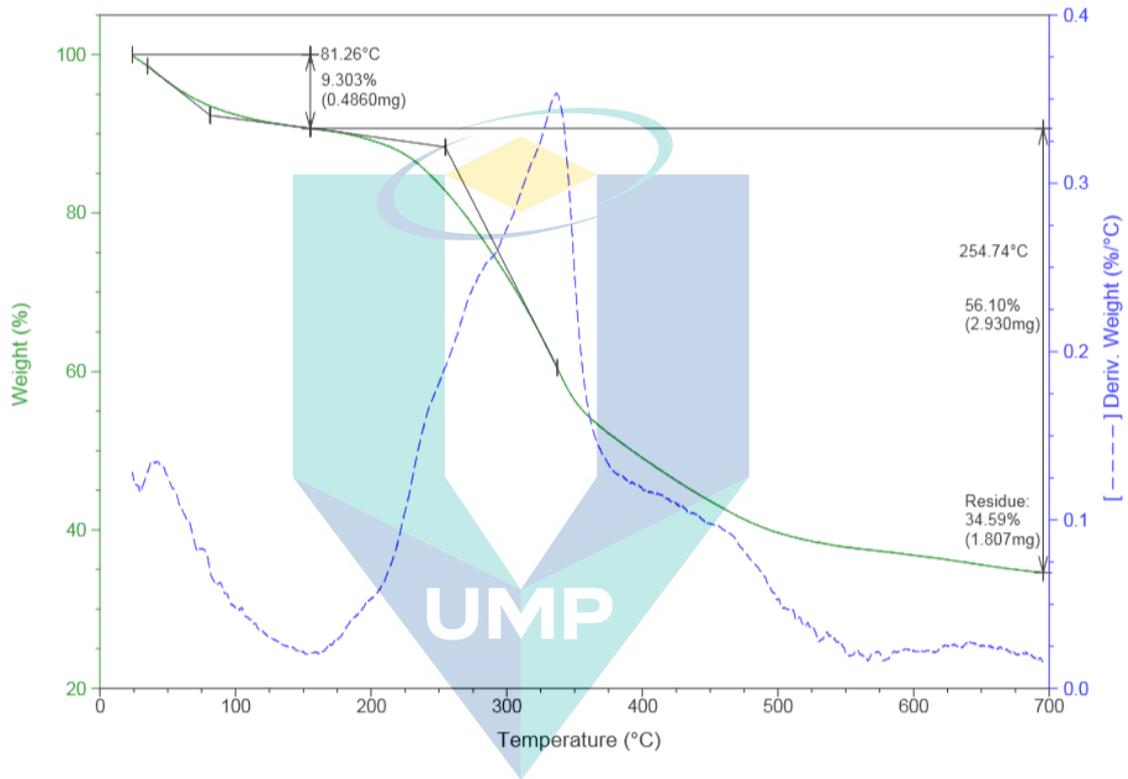


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**APPENDIX B  
TGA ANALYSIS FOR TEA POWDER**

**APPENDIX B1**

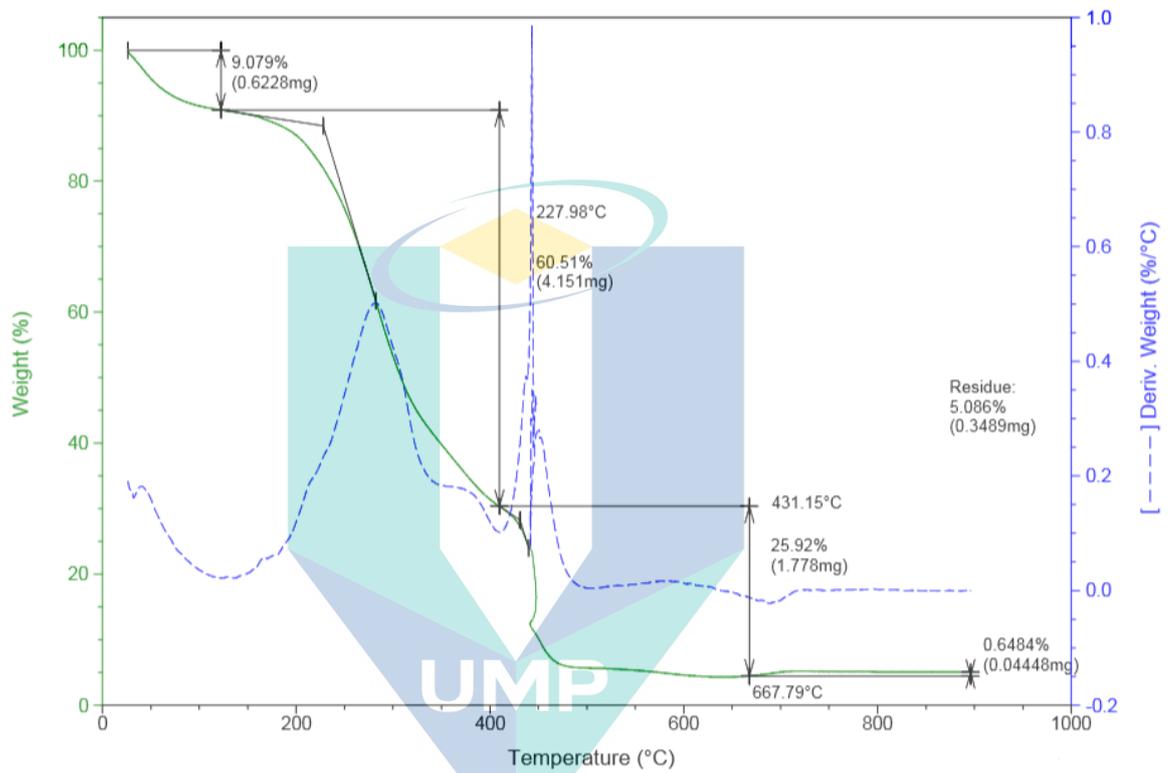
**Raw Result of Tea Powder at 71 µm from TGA**



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## APPENDIX B2

### Raw Result of Tea Powder at 125 $\mu\text{m}$ from TGA

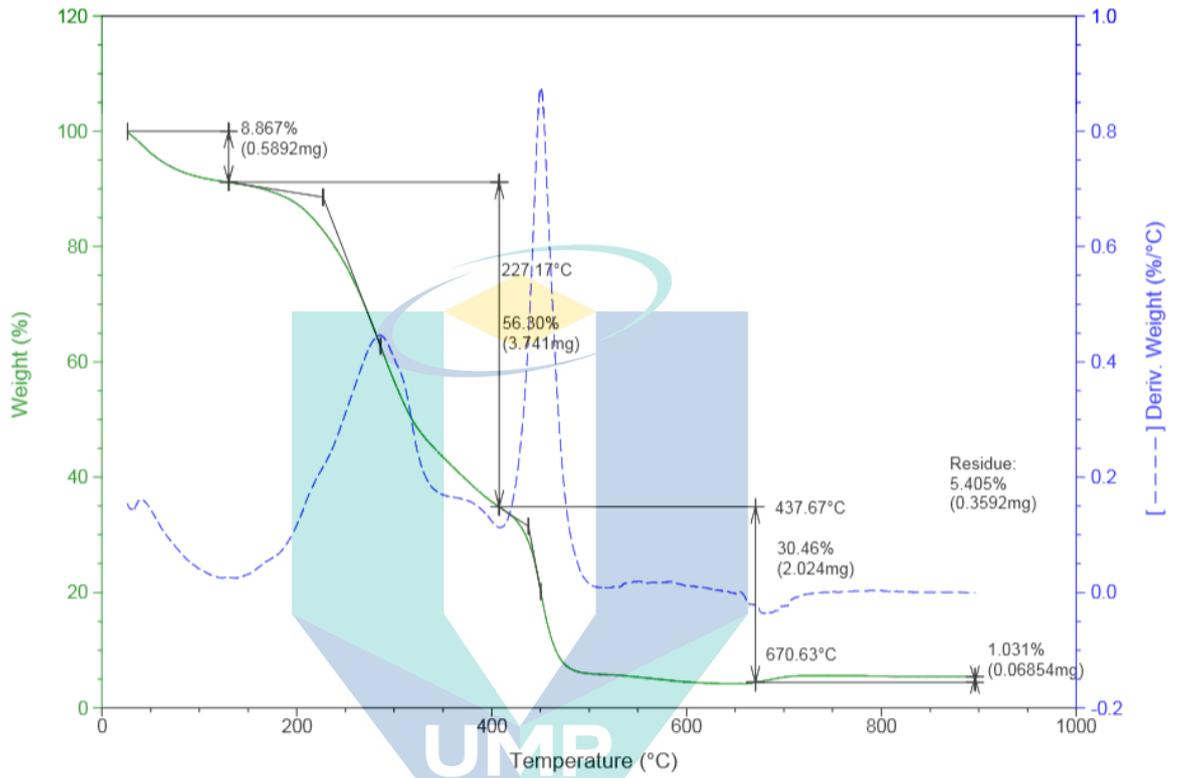


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### APPENDIX B3

#### Raw Result of Tea Powder at 160 $\mu\text{m}$ from TGA

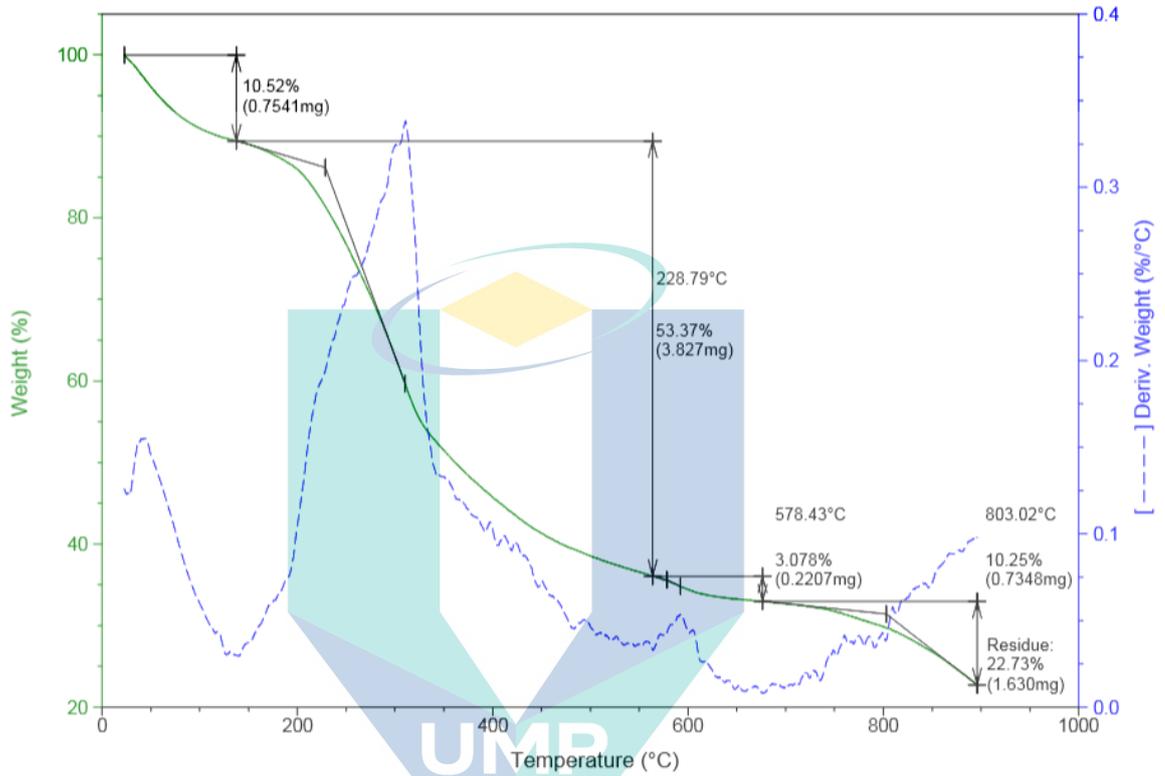


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APPENDIX B4

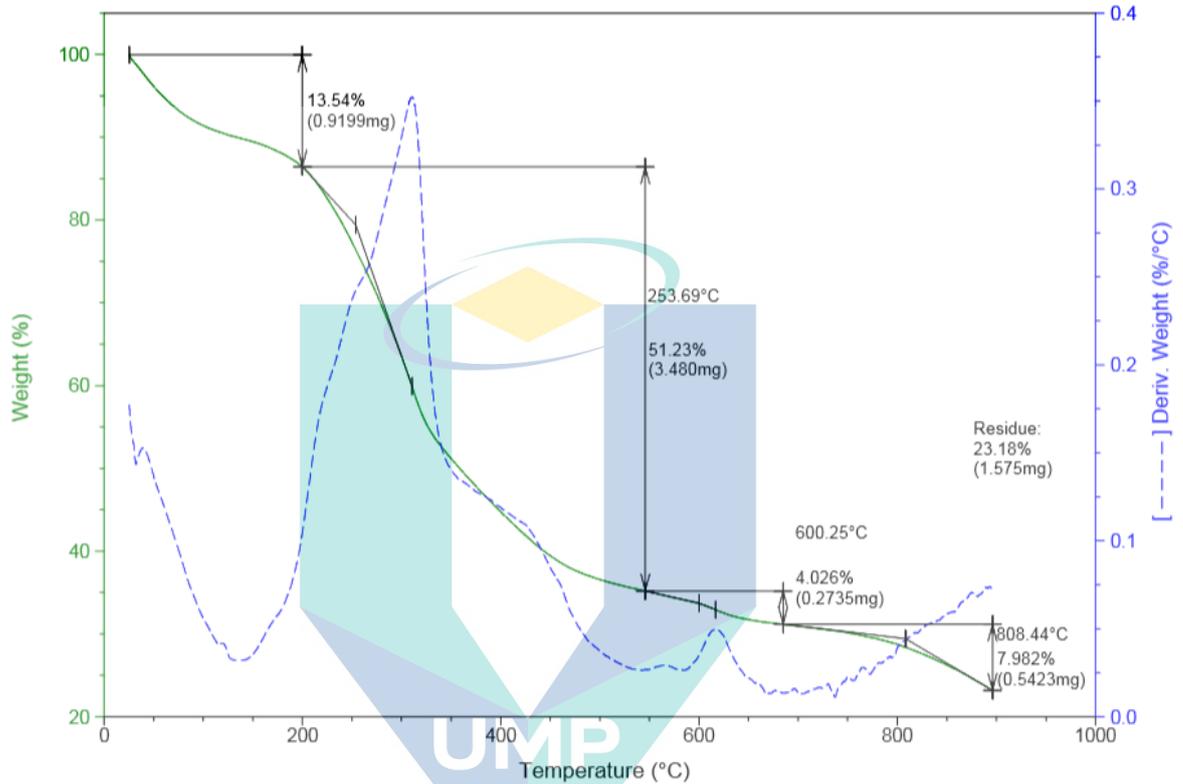
Raw Result of Tea Powder at 180  $\mu\text{m}$  from TGA



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APPENDIX B5

Raw Result of Tea Powder at 250  $\mu\text{m}$  from TGA



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