EXPLOSION SENSITIVITY AND SEVERITY OF SOUTH EAST ASIAN COALS

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ABSTRACT

There is a risk of coal dust explosion to industries mainly in cement processing industries, power plants as well as other activities associated with handling of pulverized coals. This study aims to investigate the effect of chemical properties of the South East Asian coals on the explosibility of three samples of coal dust which were bituminous Bayan, sub bituminous Tanito and Philippine coals. The minimum explosion concentration (MEC), maximum explosion overpressure (P_{max}) and dust deflagration index (K_{st}) were determined to compare the fundamental data on coal dust characteristics. The explosion experiment was carried out in a Siwek 20 L spherical chamber. The chemical properties of investigated coals such as moisture content, volatile content, fixed carbon content and ash content were analysed by proximate analysis and Thermogravimery analysis (TGA). Both moisture content and ash content of Philippine and Tanito coals were approximately 10 wt %. The coals were hardly exploded at high moisture content and low content of ash gave no influence on explosibility of the coals. High volatility at approximately 40 wt % increases the severity of the dust explosion. Analysis of fixed carbon content and calorific value showed that the coals were in the low ranking class with fixed carbon and calorific value at approximately 40 to 45 wt % and 25000 kJ/kg, respectively. The MEC for the Bayan, Tanito, and Philippine coal dust were 350 kg/m^3, 400 kg/m^3, and 315 kg/m^3, respectively. The high results of MEC for the coals were due to non-uniform particle sizes and high moisture content. The P_{max} for Bayan, Tanito, and Philippine coal dust were 10.15 bar, 7.35 bar and 10.4 bar, respectively. The K_{st} for Bayan, Tanito, and Philippine coal dust were 48.04 bar.m/s, 16.83 bar.m/s, and 52.39 bar.m/s, respectively. High volatility was the reason of high P_{max} and hence K_{st}.

ABSTRAK

Risiko kejadian letupan debu arang batu boleh berlaku dalam industri terutamanya di industri memproses semen, kilang janakuasa dan pelbagai aktiviti lain yang berkaitan dengan arang batu halus. Kajian ini bertujuan untuk mengkaji kesan ciri-ciri kimia terhadap kebolehletupan tiga sampel debu arang batu Asia Tenggara iaitu arang batu bitumen Bayan, separa bitumen Tanito dan Filipina. Kepekatan minimum letupan (MEC), tekanan letupan maksimum (P_{max}) dan indeks deflagrasi debu (K_{st}) dikaji untuk membandingkan data asas ciri-ciri debu arang batu. Eksperimen letupan dijalankan dalam ruang berisipadu 20 L Siwek. Ciri-ciri kimia arang batu yang dikaji ialah kandungan kelembapan, kandungan kemeruapan, kandungan karbon tetap dan kandungan abu yang dianalisis melalui analisis proksimat dan gravimetrik termal (TGA). Kandungan kelembapan dan kandungan abu arang batu Filipina dan Tanito adalah lebih kurang 10 % berat. Arang batu tersebut sukar meletup pada kandungan lembapan yang tinggi manakala kandungan abu yang rendah tidak menjejaskan kebolehletupan arang batu tersebut. Kemeruapan yang tinggi iaitu lebih kurang 40 % berat meningkatkan keamatan letupan debu. Analisis kandungan karbon tetap dan nilai kalori menunjukkan kelas arang batu di dalam kelas yang rendah dengan nilai kandungan karbon tetap dan nilai kalori lebih kurang 40 to 45 % berat dan 25000 kJ/kg setiap satu. MEC bagi debu arang batu Bayan, Tanito, dan Filipina ialah 350 kg/m^3, 400 kg/m^3, and 315 kg/m^3 setiap satu. Nilai MEC yang tinggi bagi setiap arang batu yang dikaji disebabkan oleh saiz partikel yang tidak seragam dan kandungan lembapan yang tinggi. P_{max} untuk debu arang batu Bayan, Tanito, dan Filipina pula adalah 10.15 bar, 7.35 bar and 10.4 bar setiap satu. K_{st} untuk debu arang batu Bayan, Tanito, dan Filipina adalah 48.04 bar.m/s, 16.83 bar.m/s, and 52.39 bar.m/s setiap satu. Kemeruapan yang tinggi menyebabkan P_{max} yang diperolehi tinggi, begitu juga K_{st}.

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LIST OF SYMBOLS/ABBREVIATIONS

ASTM	-	ASTM International
BAM	-	*Bundesanstalt für Materialprüfung*
BS	-	British Standard
Btu	-	British thermal unit
CBDC	-	Cape Breton Development Corporation
CC	-	Combustion Class
CFD	-	Computational fluid dynamics
CSB	-	US Chemical Safety and Hazard Investigation
DESC	-	Dust Explosion Simulation Code
D_{med}	-	Mass median particle diameter
d_s	-	Surface-area-weighted mean diameters
d_w	-	Mass-mean diameters
dP/dt	-	Rate of pressure rise
FLACS	-	Flame Acceleration Simulator
Ib	-	Pound
ISO	-	International Organization for Standardization
ISSA	-	International Social Security Agency
kg	-	Kilogram
kJ	-	Kilojoule
K_{st}	-	Dust deflagration index
L	-	Litre
LOC	-	Limiting oxygen concentration
MJ	-	Megajoule
m	-	Metre
m^3	-	Cubic metre
mm	-	Milimetre

ms	-	Milisecond
MEC	-	Minimum explosibility concentration
MIE	-	Minimum ignition energy
MIT	-	Minimum ignition temperature
MSDS	-	Material Safety Data Sheet
NFPA	-	National Fire Protection Association
OSHA	-	Occupational Safety and Health
P_{max}	-	Maximum explosion overpressure
PRL	-	Pittsburgh Research Laboratory
T	-	Temperature
t_v	-	Ignition delay time
USBM	-	United States Bureau of Mines
wt	-	Weight
μm	-	Micrometre
^oC	-	Degree Celcius
%	-	Percentage

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CHAPTER 1

INTRODUCTION

1.1 Introduction

A large number of accidental dust explosions have been reported in literature since 1785 (Abbasi and Abbasi, 2007), leading to a significant problem of injuries, fatalities, destruction of equipment and loss of properties. Dust explosion occurs when a flammable cloud, formed by the mixing of dust and air in the right proportion in a confined space is ignited and a rapid combustion of the fuel takes place, with the propagation of the flame across the cloud. 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 handling miscellaneous organic and inorganic powders and dust. Those industries include wood and paper products, grain and foodstuffs, metal and metal products, power generation, coal mining and textile manufacturing. Dust explosion usually occurs in various unit operations include mills, grinders, dryers, and other modes of transportation (Amyotte and Eckoff, 2010).

It was recorded that one case of dust explosion incidents on average, could happen in each industrialized country every day (Abassi and Abassi, 2007). Unfortunately, there is almost zero material whether in printed or soft copies for past years in developing countries such as India and Libya in contrast with ample information available on dust explosions for developed countries such as United

Kingdom and United State of America (USA) (Abassi and Abassi, 2005). One of the most expensive and destructive accidents in the history of USA had happened on February 1, 1999 in a powerhouse of the Ford Motor Company in Michigan. The catastrophic incident which killed six workers and injured fourteen others was reported to be caused by secondary explosion involving coal dust. The loss at over US one billion destroyed the powerhouse building facilities (MIOSHA, 1999). Investigation from United State Chemical Safety and Hazard Investigation Board (CSB) shows that dust explosion had common causes in their findings of three major incidents happened in USA in 2003, in spite of their geographical and industrial diversity. One of the causes is that most Material Safety Data Sheet (MSDS) for explosive powders do not contain dust explosion hazard information (Blair, 2007). Surprisingly the common cause of dust explosion reported by CSB was the same as reported by Department of Safety and Health in Malaysia (DOSH). DOSH reported that in November 2010, an explosion involving aluminium dust has occurred at a motorcycle rim manufactured factory located in Penang. Ten workers were injured and two of them were in severe condition. Another accident involved dust explosion occurred at Malayan Flour Mills in Lumut, Perak on 17th of March 2008 which dust explosion from mixed types of flour killed four people and two were in serious injuries. Lacking of safety and prevention in handling dust would lead to catastrophic disaster as mentioned on the incidents above. Hence, the key knowledge about the fundamental explosive parameters on dust explosion as well as the effect of physical and chemical properties on explosive parameters need to be understood in order to reduce the potential of explosion severity.

Concern is also raised over handling of pulverized coal suspension in cement processing industries, power plants as well as other activities associated to the risk of coal dust explosion. The coal stored in open air is in contact with oxygen from atmosphere and might undergo low temperature oxidation which in the end result in autocatalytic self-heating of a coal piles (Nelson, 1989). The risk increase when the confined systems for transportation and storage of pulverized of coal is implemented due to the current environmental regulations (Mittal, 2013). The coal stored in a confined space when reaches temperature of 40°C might accumulate hydrogen gas and it would create another problem as the explosive risk of hydrogen should be taken into account (Grossman *et al.*, 1995). Compared to other Asian countries such as China and India, there are a sparse research in dust explosion studies for Malaysian context and from the author's knowledge, studies on coal dust explosion have never been conducted and the awareness on danger of coal dust explosion is lacking in Malaysia. This research studies on the chemical properties of coal dust of Philippine coal originated from Phillipines and sub bituminous Tanito and bituminous Bayan coal from Indonesia. Explosibility tests were also carried out by using Siwek 20 L spherical chamber, by adopting international standard for determining explosion severity for dusts (BS EN 14034-3, 2006; Siwek, 1985).

The main concern of this study is the role playing by different type of coals i.e the rank and class which have different physical structures and characteristics. The coal is studied based on several parameters include the effect of coal ranking, volatility and moisture content towards explosibility data. For example, research done by Woskoboenko (1998) found that brown char is more explosive in comparison with anthracite. Anthracite is the highest rank of coal which has the highest number of carbon content but not easily explosible (Hertzberg, 1981). This is because even though higher rank of coals have high heat of combustion, they are not easily explosible as they have different chemical properties and physical structures. Many investigations involve on the effect of physical and chemical properties on coal explosibility (Amyotte *et al.*, 1991; Cashdollar, 2000; Liu 2010; Mittal, 2013; Woskoboenko, 1988). Cashdollar (2000) found in his study that finer coal dust particles are more explosive than larger dust particles as the finer particles have larger surface area per mass therefore, the explosible dusts would easily participate in combustion process. This comprehensive study included the analysis of the existing data from other researchers which covers a wide range of coal dust samples from other regions such as United State of America, Canada, Africa and China (Hertzberg *et al.*,1981; Cashdollar, 2000; Continillo *et al.*, 1991; Amyotte *et al.*, 1991; Li *et al.*, 2012). Those explosibility data would be very crucial on hazard analysis for prevention and mitigation of dust explosion and continuous improvement on safety in industries. Inherent safe process design can be adopted as well as adhering to certain housekeeping practice to ensure that the formation of hazardous dust cloud is reduced as minimum as possible (Abbasi and Abbasi, 2007).

1.2 Statement of Research Problem

Over past years, there have been many numerical/correlation models and developed systems towards prevention and mitigation of dust explosion in processing industries. Nevertheless, the fundamental knowledge is still significant in getting thorough understanding on dust explosion hazard as there is an inevitable conflict between the correlation and the complex nature of the process itself in practice. Types of explosibility chambers and their feasibility in providing the reliable explosibility data are debated over the past years. Full scale coal dust explosion test is much more favorable and provides reliable data following the hazards of explosible dust presents in underground coal mining.

Even though no coal mining industry is commercialized in Malaysia, there is a risk of having coal dust explosion on transportation, storage and uses of coal in power generation industry, cement industry and other manufacturing industries. There are numerous publications regarding dust explosion in confined area, but to the author's knowledge, there is limited data on the explosibility of coal dust from Asia. Bituminous coal has been used widely in Malaysia as a source of heat specifically in cement industries and power plant industries due to its high heating value while sub bituminous is added and mix together with bituminous coal in low composition to lower the cost of operation. Sub bituminous coal also has lower sulphur content and this will reduce the environmental pollution.

It is crucial to know the physical characteristics and dust behaviour as well as dust explosibility data in order to apply an effective protection and safety systems available to prevent and mitigate the dust explosion in industries. Therefore, this research will provide fundamental information on physical and chemical properties of coals whether the coals are sub bituminous or bituminous coal type, moisture content, and volatility of coals. The explosibility data covers maximum explosion overpressure (P_{max}), dust deflagration index (K_{st}) and minimum explosibility concentration (MEC). Different chemical properties may influence the sensitivity and severity of coal explosibility. Hence, knowing the minimum explosible dust concentration is very important as an explosible dust cloud may be formed during operation or transportation of the dust. Maximum explosion overpressure (P_{max}) and dust deflagration index (K_{st}) are widely investigated over wide range of coals to design appropriate dust explosion protection measures such as inerting, suppression, or explosion relief venting according to the severity of dust.

1.3 Benefit of Research

a) This research will give additional fundamental data on dust explosion characteristics of South East Asian coal dusts based on chemical properties of the coal dusts.

b) This research may give additional information towards application on the severity of the explosion where appropriate protection and mitigation could be applied accordingly.

1.4 Objectives of Research

a) To measure the chemical properties (moisture content, ash, carbon content and volatile content) of coal dusts.

b) To measure the explosion severity characteristics (maximum explosion overpressure (P_{max}), dust deflagration index (K_{st})) and explosion sensitivity parameter (minimum explosible concentration (MEC)) of the coal dusts.

c) To evaluate the effect of chemical properties of the coal dusts towards the explosion sensitivity characteristics and explosion sensitivity parameter of the coal dusts.

1.5 Scope of Research

a) The studied coal dusts are bituminous coal (Bayan), sub bituminous coal (Tanito) from Indonesia and coal from Philippines.

b) Performing proximate analysis and Thermogravimetric analysis (TGA) for each coal to measure the chemical properties of the studied coals such as moisture content, ash, carbon content, volatility as well as calorific value.

c) Performing dust explosion in Siwek 20 L spherical chamber to obtain the maximum explosion overpressure (P_{max}), rate of pressure rise (dP/dT), dust deflagration index (K_{st}) and minimum explosibility concentration (MEC).

CHAPTER 2

LITERATURE REVIEW

2.1 Coal

In this study, coal dust is chosen as a subject matter due to different types of coal may give different results on investigation of explosion sensitivity and severity of coal dust. Coal is solid but brittle, carbonaceous black sedimentary rock that is combustible. It is made up of carbon, hydrogen, oxygen, nitrogen, and lesser amount of sulphur and other trace elements. Over the years, many classification systems have been proposed for coal and the first attempt is in 1599 by A. Libavius. The classification is generally based on the properties of coal (chemical, physical, mechanical, and petrographic). Parr (1928) included calorific value along with volatile matter and fixed carbon content as classification parameter of the coals. His study has been used as United State standardized coal classification system (Chen, 2009). Standard classification of coals by rank would be used in this study according to ASTM (ASTM, 2012). The coal is ranked based on carbon content and heating value as well as calorific value from lignite to anthracite. The rank also base on volatility of the coal as illustrated in Table 2.1.

Table 2.1 Classification of coals by rank (ASTM, 2012)

Class / group	**Fixed carbon Limits (dry mineral-matter-free basis) %**		**Volatile Matter Limits (Dry, Mineral-matter-free Basis) %**		**Gross Calorific Value Limits (Moist, mineral-matter-free Basis)**			
					Btu/Ib		**MJ/kg**	
	Equal or Greater Than	**Less Than**	**Equal or Greater Than**	**Less Than**	**Equal or Greater Than**	**Less Than**	**Equal or Greater Than**	**Less Than**
Anthracite:								
Meta-anthracite	98	-	-	2				
Anthracite	92	98		8				
Semianthracite	86	92		14				
Bituminous:								
Low Volatile	78	86	14	22				
Medium Volatile	69	78	22	31				
High Volatile A	-	69	31	-	14,000	-	32.6	-
High Volatile B					13,000	14,000	30.2	32.6
High Volatile C					11,500	13,000	26.7	30.2
Sub bituminous:								
Sub bituminous A					10,500	11,500	24.4	26.7
Sub bituminous B					9,500	10,500	22.1	24.4
Sub bituminous C					8,300	9,500	19.3	22.1
Lignite:								
Lignite A					6,300	8,300	14.7	19.3
Lignite B					-	6,300	-	14.7

2.2 Chemical Properties of Coal Dust

Chemical properties and structures of coal dust have major impact towards the coal dust explosibility. In order to analyze the explosibility of coal dusts in details, chemical properties should be understood to correlate whether the dust is explosible or not, depending on its carbon content, calorific value, moisture content, volatile content as well as physical characteristics such as porosity as well as the particle sizes. Conventionally, the amount of moisture, volatile matter, and ash can be obtained by various proximate analysis involving heating the sample in furnace under certain conditions adopted from ASTM (ASTM, 2011) or British Standard (British Standard, 1999). However, those determinations are time consuming and require significant amount of samples. Cashdollar (1988) followed the method adopted in ASTM to determine the volatile matter for coals; one gram of coal was heated at 950°C for 7 minutes in a furnace. The result was compared with the method developed by The Bureau of mine (Hertzberg and Ng, 1987) to determine the volatility by heating the small arrays of dust with a 250 Watt carbon dioxide laser under rapid heating. The result showed that the volatilities of dust were generally higher than ASTM method. The volatilities of Pittsburgh bituminous coal by applying ASTM method and the method using carbon dioxide laser were 36.5 % and 45.3 % respectively. Yet, the dust volatility value obtained by British Standard gave the same value as ASTM since both offered almost similar method, only the coal need to be heated at 900±5°C for 7 minutes in a furnace for British Standard.

Thermogravimetric analysis (TGA) is another method to obtain the chemical properties of the dust; besides it is time-cost saving method compared to conventional method. Analysis time can be reduced from several hours to a range of 8 to 45 minutes (Sadek and Herrell, 1984). TGA is a general technique to determine the amount of moisture, volatile matter, combustible material and ash content in coals and cokes based on weight change of a compound with temperature or time under specific condition. This method is chosen to perform a compositional analysis in order to evaluate the coal ranking, the ratio of combustible to incombustible constituents and for other various purposes of study related with physical and chemical properties of a compound whether in liquid or solid form. TGA has been studied extensively recently as its ability in giving similar values as proximate analysis (Karatepe and Kücükbayrak, 1993; Mayoral *et al.*, 2001; Warne, 1996). Shi *et al.* (2012) investigated the moisture content, ash and volatilities of 34 types of Chinese coals by doing proximate analysis following the Chinese National standard as well as TGA. Shi *et al.* (2012) found a good agreement with the result of volatility obtained from TGA; only 5.9 % less than by the proximate analysis. Aylmer and Rowe (1984), Ottaway (1982) and Mayoral (2001) also found a similar result with ASTM conventional method, even though various conditions were used by different researchers on methods of TGA. By knowing the coal chemical properties and its rank, it is feasible to explore the impact of coal to dust explosion, as discussed below.

2.3 Dust Explosion

Dust explosion is the very fast burning of fine particles suspended in a large volume of air or other gaseous oxidant. Generally, dust explosion is a deflagration, which the propagation velocity is less than the speed of sound in the unreacted medium (Armstrong, 2004; NFPA, 2004). Dust explosion continues to represent a constant hazard to process and manufacturing industries despite extensive research and development. Dust is defined as any finely divided solid with 420 μm or less in diameter whereas the explosion is initiated by the rapid combustion of flammable particulates suspended in air (NFPA, 2002, Abbasi and Abbasi, 2007). Dust explosion in industries usually happens in process equipment such as mills, dryers, mixers, classifiers, conveyors, storage silos and hoppers (Eckhoff, 2009b).

The major obstacle in predicting the course and consequences of dust explosions in practice is the discrepancies of method used to determine the parameters affecting the dust explosion i.e. dust particle size and turbulence. The widely accepted standard available to determine the characteristic of dust is mostly adopted from British Standard Institution (BS EN 14034-3, 2006) and ASTM International (ASTM, 2010). However, Japan also attempted to implement their own standard to determine the dust explosion characteristics as part of their Japanese Industrial standard (JIS) (Nifuku *et al.*, 2000). Another standard method is proposed by International Electrotechnical Commission (IEC) (Chawla *et al.*, 1996) and has been applied in a Siwek 20 L spherical chamber while ASTM has method that can be applied in United States Bureau of Mines in a 20 L chamber (USBM) (ASTM 2007) and the Siwek 20 L spherical chamber (ASTM 2010). Detailed experimental and theoretical studies of the physics and chemistry of dust cloud generation and combustion need to be standardized to avoid any discrepancies on accuracy and precision of the data itself. Performing laboratory-scale tests to investigate the characteristics of dust explosion as full-scale mine tests are time-consuming and