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Minimum ignition energy of hybrid mixtures of combustible dusts and gases

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ABSTRACT

Mixtures of suspended combustible dust and flammable gas are usually encountered in various processes and systems where substances of different states of aggregate are handled. Knowing the lowest amount of energy needed to ignite such mixtures are critical to identify possibilities of accidental hazards in industry. Investigation of the minimum ignition energy (MIE) of a hybrid mixture of two flammable gases (methane and propane) and eight combustible dusts (wheat flour, starch, protein, polyethylene, peat, dextrin, wood coal and brown coal) were carried out in the modified Hartmann apparatus. The determination of the MIE of the dusts alone was in accordance with the European standard EN 50281. In the case of hybrid mixtures testing, this protocol had to be slightly modified, as hybrid mixtures are not included in the standard mentioned. The device used is limited to a lowest ignition energy of 4 mJ. Thus, the MIE of pure gases could not be as tested directly, as their values are all below that energy. The MIE values as well as the lower explosible limits (LEL) for gases were taken from the literature. To determine the MIE of hybrid mixtures at different concentrations of gas below the respective LEL were added to the pressurized air that used to generate the dust cloud in the MIE apparatus. The experimental results demonstrated a significant decrease of the MIE of the dusts and an increase in the likelihood of explosion when a small amount of gas that was below its LEL was mixed with the dust. For example, the MIE of polypropylene was observed to decrease from 116 to 5 mJ when only 1 vol.% of propane (below its LEL) was added. Moreover, an empirical model to predict the MIE of hybrid mixtures was presented and further compared with the experimental results were done.

1. Introduction

Explosions involving mixtures of flammable gases and combustible dusts are one of the main concerns of the industries that either handle or process dusts and gases or solvents. These mixtures could be found in facilities like paint factories (pigments and solvents), mining (coal and methane), grain elevators (small grains and fermentation gases) or pharmaceutical industries (incipient and solvents). They could also occur in industrial operations such as those in which flammable solvents are removed from powdered dyestuffs, production and subsequent machining and grinding of polymeric materials where the highly volatile or gaseous monomers may be present, and the storage of powdered foodstuffs where methane production may occur.

The minimum ignition energy of hybrid mixtures (MIE-hybrid) is the lowest energy value of a high-voltage capacitor discharge that is capable of igniting an ignitable mixture of different states of aggregate in air within the explosible range. In various hazards and risk assessments, it is very important to know the lowest energy that could ignite the various materials which are being handled or processed in the facility.

Many studies have been carried out and have demonstrated the specific behaviors of single substance and its explosion with respect to the minimum ignition energy (Au et al., 1992; Van Laar, 1983; Bartknecht,

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Table 1 – Preparatory analysis of dusts used.

Dust sample	Particle size (μm)			Volatile content (% mass)	Moisture content (% mass)	Heat of combustion (kJ/kg)	Elemental analysis				
	d_{32}	d_{50}	d_{90}				C	H	O	S	N
Starch	12	14	21	93.77	0.50	15,302	44.3	6.3	48.9	0.4	0
Protein	36	52	115	87.08	0.23	26,630	80.4	1.3	14.0	3.0	0.4
Wheat flour	31	52	121	79.60	0.38	15,641	45.6	6.6	45.9	1.8	0.0
Poly-propylene	22	34	84	98.67	0.68	39,685	86	14	0.0	0.0	0.0
Peat	35	45	176	68.76	1.43	17,466	57.4	5.8	35.3	1.1	0.6
Dextrin	47	56	93	99.17	1.08	13,357	43.8	6.4	49.1	0.7	0.0
Wood coal (char coal)	48	79	264	14.99	0.77	29,364	90.2	2.8	6.7	0.2	0.2
Brown coal	19	37	55	55.12	1.56	21,527	69.1	6.7	5.6	0.6	1.3

1993; Beck et al., 1997; Eckhoff and Enstad, 1976; Eckhoff, 1975). However, research on hybrid mixtures is few as compared to that of a single substance. The main conclusion of these researches could be summarized as follows:

The ignition sensitivity of combustible dust can be strongly increased by an addition of a few percentages of combustible gases or vapors, even with contents lower than the LEL. It has notably been shown that hybrid mixtures can also be explosible when both the concentrations of the dust and the vapor are below their respective explosible limits (Addai et al., 2015a,b,c,d,e; Pilão et al., 2006; Liu et al., 2007; Dufaud et al., 2009). It has been noticed that the minimum explosion energy (MIE) of dust clouds could decrease as soon as a few percentages of combustible gases or solvents were added (Khalili et al., 2012). Influences of adding a small amount of combustible gases (e.g., methane or propane) on the minimum ignition energy of coal, cellulose or PVC dusts were investigated for about three decades (Franke, 1978; Pellmont, 1979, 1980).

Based on the findings of the aforementioned research on hybrid mixture explosion, it has been observed that there is high level of complexities in the case of hybrid mixture explosions since the lack of understanding of the actual reactions between gas and dust mixtures. However, this kind of explosions occurs frequently in industries. There are no true data to consider the actual reaction that takes place between the mixture of gas and dust during explosions. Due to this reason, more research is needed in order to provide more data on hybrid mixture explosions so that this kind of hazards could be reduced.

The main goal of the present paper is to undertake an investigation on the MIE of hybrid mixtures of eight combustible dusts and two flammable gases. All tests were performed on the Hartmann apparatus with little modification for hybrid mixture testing. The device used is limited to a lowest ignition energy of 4 mJ. Thus, the MIE of pure gases could not be tested directly, as all of their values are below that energy. To determine the MIE of hybrid mixtures, different concentrations of gases below the respective LEL were added to the pressurized air as used to generate dust cloud in the combustion chamber.

Moreover, the error and uncertainty analysis pertaining to our experimental work were performed. An empirical model was presented and a comparison of this model with our experimental results was also accomplished.

2. Material and experimental procedures

2.1. *Test materials and their properties*

Experimental investigation of the minimum ignition energy of hybrid mixtures of eight different combustible dusts (corn starch, wheat flour, polypropylene, peat, protein, dextrin charcoal and brown coal) and two flammable gases (methane and propane) was presented in this paper. Prior to the experiment, the dust samples underwent various preparatory analyses such as determination of particle size distribution, volatile content, moisture content, heat of combustion and elemental analyses. Table 1 summarizes the various preparatory analyses of the dust used. These analyses were done in order

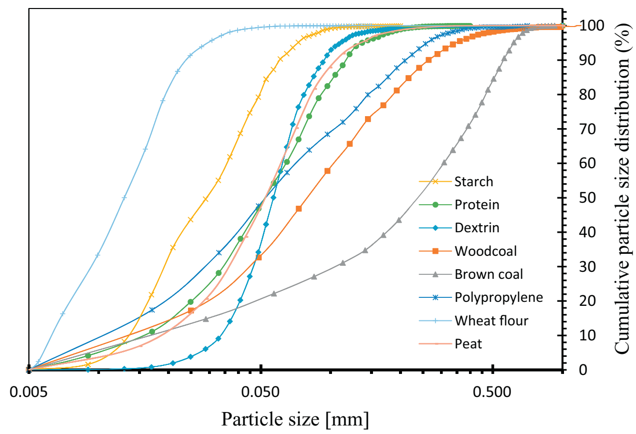

Fig. 1 – Particle size distribution for the dust samples.

to ensure that the dust used conform to the international standard.

The particle size distribution is one of the important properties that affect the minimum ignition energy of dust clouds. As a results of that, the particle size distribution of all the dust used were examined using a standard equipment. Fig. 1 shows a graph of the particle size distribution for the dusts while Table 2 provides the basic thermodynamic, ignition or combustion properties of the gases and solvents used (Standard Thermodynamic Properties of Chemical Substances, 2000; Brandes and Möller, 2013).

Furthermore, in order to reveal the surface structure of the dust particles, scanning electron microscopy (SEM) images for

Table 2 – Properties of gases used (Standard Thermodynamic Properties of Chemical Substances, 2000; Brandes and Möller, 2013).

Properties	Methane	Propane
Molecular formula	CH_4	C_3H_8
Purity (%)	99.87	99.00
Density (kg/m^3)	0.656	2.01
Molecular weight (g/mol)	16	44
Explosible range (vol.%)	4.4–17	1.9–10.8
Melting point (°C)	−161	−187
Specific heat capacity (J/mol K)	35.69	73.60
Boiling point (°C)	−182.5	−42.1
Heat of vaporization (kJ/mol)	−74.87	−103.80
Max. explosion pressure (bar)	8.1	9.8
MIT (°C) (Standard Thermodynamic Properties of Chemical Substances, 2000)	595	490
MESG (mm)	1.14	0.92
Temperature class	T1	T1
Explosion group	IIA	IIA
LOC (vol.%)	12.0	9.4