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DETERMINATION OF EXPLOSION CHARACTERISTICS OF SUGAR DUST CLOUDS

Richard KURACINA[1], Zuzana SZABOVÁ[2], Matej MENČÍK[3]

Research article

Abstract: A dust explosion occurs when an airborne combustible dust cloud encounters an effective ignition source. The resulting pressure and temperature increase can severely injure people and damage surrounding equipment and buildings, and therefore needs to be prevented or controlled (Taveau, 2016). The article deals with the measurement of maximum explosion pressure and maximum rate of explosion pressure rise of sugar dust cloud. The measurements were carried out according to STN EN 14034-1+A1:2011 Determination of explosion characteristics of dust clouds. Part 1: Determination of the maximum explosion pressure p_{max} of dust clouds, the maximum rate of explosion pressure rise according to STN EN 14034-2+A1:2012 Determination of explosion characteristics of dust clouds - Part 2: Determination of the maximum rate of explosion pressure rise $(dp/dt)_{max}$ of dust clouds and Determination of explosion characteristics of dust clouds. Part 3: Determination of the lower explosion limit LEL of dust clouds. The sugar dust cloud in the chamber is achieved mechanically. The testing of explosions of sugar dust clouds showed that the maximum value of the pressure was reached at concentrations of 1000 g/m^3 and its value is 6,89 bars.

Keywords: Dust powder, powdered sugar, lower explosion limit, maximum explosion pressure, explosion prevention.

Introduction

Prevention of dust explosion in industries manufacturing or handling combustible powder or dust is a major challenge (Eckhoff, 2003). All flammable materials in solid state, metals included, that are dispersed in the air in a form of a cloud could form the explosive atmosphere. (Lepik, 2015)

The term "explosion" means rapid expansion or formation of gases. If it happens in an open space, it generates a pressure wave, which is called blast wave. If it happens in a closed space, the pressure in the space is increasing. Usually the closed space will be broken by the increased pressure to also generate blast wave propagating outward. At the explosion, the expansion is induced by several causes, such as combustion of combustible gas and dust, rapid reaction of explosives, sudden rapture of high pressure vessels, and so on. In this paper, gas explosion and dust explosion are focused, which are induced by combustion reaction same as the fire. (Dobashi, 2017)

One of the most important factors when it comes to dust explosiveness is the size of the particles. The reduction of the particles' size significantly increases their total surface, which increases their chemical activity, i.e. their ability to oxidize. In terms of the risk of explosion, smaller particles are always more explosive and dangerous than dust particles of larger dimensions. The upper limit for particle sizes that can cause an explosion is 0.5 mm. (Mračková, 2013)

A dust explosion is initiated by the rapid combustion of flammable particulates suspended in air. Any solid material that can burn in air will do so with a violence and speed that increases with the degree of sub-division of the material (Eckhoff,

1 Slovak University of Technology, Faculty of Materials Science and Technology in Trnava, Trnava, Slovakia, richard.kuracina@stuba.sk

2 Slovak University of Technology, Faculty of Materials Science and Technology in Trnava, Trnava, Slovakia, zuzana.szabova@stuba.sk

3 Slovak University of Technology, Faculty of Materials Science and Technology in Trnava, Trnava, Slovakia, matej.mencik@stuba.sk

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2003). Higher the degree of sub-division (in other words smaller the particle size) more rapid and explosive the burning, till a limiting stage is reached when particles too fine in size tend to lump together. If the ignited dust cloud is unconfined, it would only cause a flash fire. But if the ignited dust cloud is confined, even partially, the heat of combustion may result in rapid development of pressure, with flame propagation across the dust cloud and the evolution of large quantities of heat and reaction products. The furious pace of these events results in an explosion.

While fire is caused when three factors - fuel, oxidant, and ignition - come together to make what has been called 'the fire triangle', a dust explosion demands two more factors: mixing (of dust and air), and confinement (of the dust cloud). The 'dust explosion pentagon' (Kauffman, 1982) is formed when these five factors occur together:

1. presence of combustible dust;
2. availability of oxidant;
3. presence of an ignition source;
4. some degree of confinement;
5. state of mixed reactants.

A point to be noted here is that even partial confinement of an ignited dust cloud is sufficient to cause a highly damaging explosion. In this sense, too, dust clouds behave in a manner similar to clouds of flammable gases (Proust, 2005).

For formation of explosion of combustible dust it is necessary to fulfil following conditions:

- sufficient fineness of combustible dust,
- and concentration of the mixture inside explosive cloud between upper and lower explosive limit. (Veličková, 2014)

Flame propagation is observed as a function of dust particle size, dust concentration, ignition energy, temperature, etc. Even as the Hartmann vertical tube and its variants - the horizontal tube, and the inflammatory apparatus - have been extensively utilized in the past, it has been increasingly realized that the Hartmann tube is not apt to give uniform conditions for dust dispersion and turbulence. Further, it is subject to wall effects; after the flame goes through initial spherical expansion, it travels as two fronts up and down the tube. These conditions give a lower rate of combustion and of pressure rise than the actual; consequently, the strength of the pressure rise one records with the Hartmann bomb is less than one gets from more advanced apparatus. The Hartmann tube may also yield false negatives for dusts that are difficult to ignite with a spark but are ignitable by stronger ignition sources (Cashdollar, 2000).

In the UK these are used to divide dusts into two groups:

- Group A - dusts able to ignite and propagate a flame;
- Group B - dusts that do not propagate a flame.

As in all explosion testing, the sample selected for testing must be representative of the material in the plant at risk. Best practice is to ensure that the sample is as dry as the driest material in the plant and that the size distribution of the test dust is similar to the finest size fractions that are likely to occur in any part of the process. Also, it is important that the classification pertains to the conditions, for example, the temperature, under which the dust will be handled. It is not sensible to conduct an explosibility assessment at room temperature when the process temperature is to be substantially higher. Some dusts, classified as Group B at room temperature, can ignite at higher temperatures. A series of tests has been devised allowing explosibility classification under increasingly severe conditions (Barton, 2002).

Explosibility characteristics

Fire characteristics mean the properties of a substance expressed in quantifiable value or determined on the basis of measurable values of more partial properties or phenomena that describe the behaviour of the substance in the process of combustion, or related to it. (Decree, 2001)

The basic fire characteristics of powder materials include:

- Lower explosive limit;
- Ignition temperature of settled dust;
- Ignition temperature of dust clouds;
- The maximum explosion pressure;
- The maximum rate of pressure rise (brisance);
- Explosion Constant;
- Minimum ignition energy;
- Susceptibility to spontaneous combustion. (Veličková, 2015)

A quantitative assessment requires further testing to measure explosion characteristics that are important to the design of explosion protection methods such as venting, suppression, and containment. These explosion characteristics are:

- The maximum explosion pressure, P_{max}. This is the highest explosion pressure developed by

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an enclosed dust explosion. It is measured in a standard test at the optimum dust concentration.

- The maximum rate of pressure rise, $(dP/dt)_{max}$. This is the highest rate of pressure rise generated by an enclosed dust explosion. It is measured in a standard test at the optimum dust concentration (Barton, 2002).

The procedures for measuring these characteristics are given in an ISO standard available as EN 14034. The standard test vessel for these determinations is the 1 m^3 vessel, but the standard also allows the use of alternative vessels provided it can be shown that they give comparable results.

The peak value of the maximum rate of pressure rise $(dP/dt)_{max}$, is used to calculate a dust specific explosibility characteristic called the K_{st} value. The K_{st} value is given by formula:

$$K_{st} = (dP/dt)_{max} \, V^{1/3} \qquad (1)$$

where $(dP/dt)_{max}$ is the peak maximum rate of pressure rise [bar.s^{-1}] and V is the total volume of the vessel [m^3]. The units of K_{st} are bar.m.s^{-1}.

Tab. 1 Definition of dust explosion classes (1 m^3 apparatus, 10 kJ ignition source) (Barton, 2002)

Dust explosion class	K_{st} [bar m s^{-1}]	Characteristics
St0	0	Non-explosible
St1	$0 < K_{st} \leq 200$	Weak to moderately explosible
St2	$200 < K_{st} \leq 300$	Strongly explosible
St3	$300 < K_{st} \leq 800$	Very strongly explosible

The K_{st} value is derived only from measurements in either the 1 m^3 vessel or the 20-litre sphere. The K_{st} value can be used to classify dusts into one of several groups. Tab. 1 shows the classification that is generally adopted. Comparisons of results from the 1 m^3 vessel and the 20-litre spherical tester generally show that:

- The values for the maximum explosion pressure, P_{max}, measured in the 20 litre sphere is slightly lower than those measured in the 1 m^3 apparatus;
- The K_{st} values are equal up to about 600 bar.m.s^{-1}.

Explosion limits

Explosion limits describe the concentration range of dust/air mixtures in which explosions are possible. Usually, only the lower explosion limit (LEL) is determined. These measurements are important if the avoidance of an explosible dust cloud forms part of the basis for safety.

For the determination of the lower explosion limit both the 1 m^3 apparatus and the 20 litre sphere apparatus are commonly used. CEN Technical Committee 305 is currently preparing a standard for the test procedure. Essentially the concentration of an explosible dust is systematically reduced in a series of tests until the dust suspension can no longer be ignited. The highest dust concentration at which the dust/air mixture can no longer be ignited in the tests is specified as the LEL (Barton, 2002).

Materials and methods

Experimental modified KV 150-M2 chamber has been used during experiment. Scheme of a chamber is shown in Fig. 1. Dust clouds in this unit are carried out mechanically. The compressed air is transmitted from the tank of by fast opening of the valve to inner space of chamber. The chamber has a volume of 291 liters.

The sample is located on disperser, fig. 2 and spread by compressed air. This compressed air is directed to the sample through the metal profiled sheeting. The sample is initiated by a chamber nitrocellulose igniter after the spreading of the sample. The igniter works on a resistive principle, fig. 3. Immediate ignition of nitrocellulose is achieved by the voltage value (48 V AC) which is supplied to the resistance wire and results into an immediate burning and interruption of wire. Time to ignition of igniter is 45 ms. (Kuracina, 2017b) Ignition energy of nitrocellulose used in initiator is 10 kJ. Igniter is placed at the centre of the explosion chamber and firing in opposite directions (EN 14034, 2011)

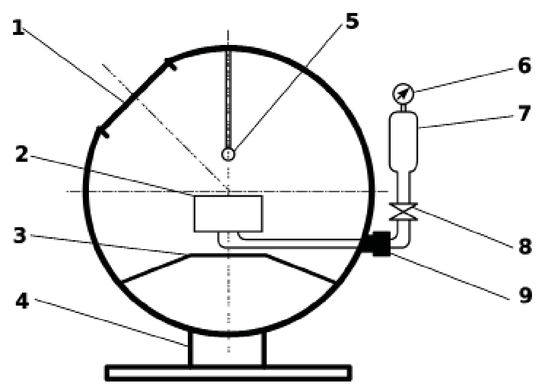

Fig. 1 Scheme of modified chamber KV 150-M2 (1 - lid, 2- nozzle for spreading of sample, 3 - desk, 4 - base, 5 - nitrocellulose igniter, 6 - manometer, 7 - pressure air tank, 8- fast opening valve, 9 - window (Kuracina, 2017a)

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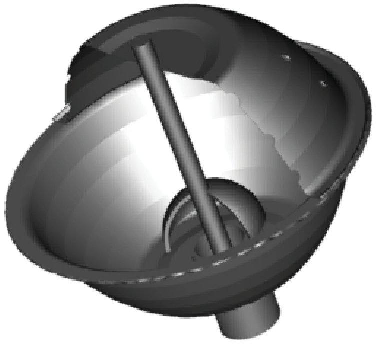

Fig. 2 Cross section of disperser used in detonation chamber

Initiation of dust and its agitation is timed with dual digital timing relay. The relay has a fixed time interval set between opening of the fast opening valve and with connecting power to clamps of initiator. The pressure changes inside the chamber are recorded through an industrial pressure transducer with mA output and the maximum measurable overpressure value of 16 bar. The pressure transducer is powered by a stabilized DC source. Response time of the sensor is 1ms and the current value is recorded through the datalogger.

Measurement of parameters was carried out on apparatus described above. The igniter was nitrocellulose with a weight from 1.10 to 1.20 g. As mentioned above, the weight of the nitrocellulose corresponded the energy of igniter with the value of 10 kJ.

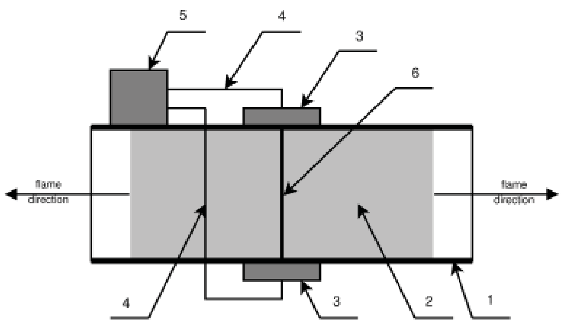

Fig. 3 Scheme of igniter body (1 - aluminium tube of igniter, 2 - nitrocellulose charge, 3 - resistance wire holder, 4 - supply conductors, 5 - supply conductor holder, 6 - resistance wire)

Nitrocellulose was placed into the chamber of igniter at a side of the resistance wire. Nitrocellulose with energy of 10 kJ was used for any measured concentration. The pressure value in the tank of compressed air before the swirling has been 9.5 bars for each measurement. The air pressure of 9.5 bar in the tank is optimal for this type of dispersion system. The time interval between opening of fast opening valve and the connecting power of clamps of the initiator was 260 ms. Starting the whole mechanism (dispersing of the dust and the initiation) was carried out manually with a switch. The pressure transducer was powered by a stabilized DC voltage source with a value of 24 V and a current limiter set to 1 A. The current in the circuit was measured with datalogger. The values were recorded at rate of 2000 values/second. The nitrocellulose igniter produces about 10 liters of gas. The pressure limit for LEL is therefore 0.7 bar. The pressure changes during the explosion of dust clouds was measured at the following concentrations: 100 g/m^3, 125 g/m^3, 150 g/m^3, 200 g/m^3, 250 g/m^3, 300 g/m^3, 400 g/m^3, 500 g/m^3, 750 g/m^3, 1000 g/m^3. The sugar dust sample was also measured at concentrations of 1100 and 1250 g/m^3. At these concentrations, thermal degradation of the sample (caramelization estimated at more than 30 % by weight) occurred. This caused a significant reduction in the measured pressure. For this reason, we do not report measured data in graphs.

Results and discussion

The sugar sample used to determine the explosion parameters was composed of 97 % saccharose and 3 % of starch. The sample moisture was 1.5 %. Tab. 2 shows the granulometry of the sugar sample, with a median value of 84 micrometres.

Tab. 2 Granulometry of sugar sample

Weight of sample	**218,24 g**			
The size of holes in sieve	**Weight of sample**		**Size of fraction [μm]**	**Part of sample w [%]**
	m [g]	**w [%]**		
500	0,648	0,30	> 500	97,97
250	28,749	13,17	0 - 500	97,68
200	22,630	10,37	0 - 250	84,50
150	32,858	15,06	0 - 200	74,13
90	43,610	19,98	0 - 150	59,08
71	38,081	14,45	0 - 90	39,09
56	21,696	9,94	0 - 71	21,70
0	25,542	11,70	0 - 56	11,70
Loss of weight	4,426	2,03	-	

The values obtained by the measurement of pressure depending on the time are shown in Fig. 4 - 9. The individual concentrations are colour coded on the graph.

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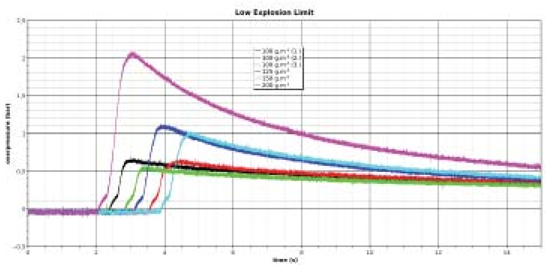

Fig. 4 Lower Explosion Limit of sugar dust clouds (Chovancová 2017)

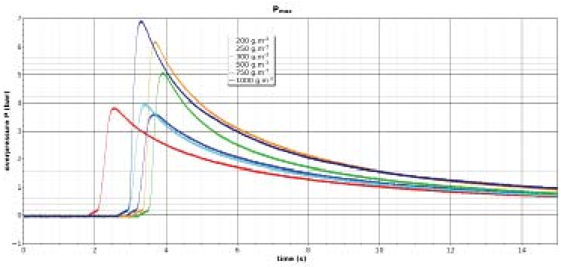

Fig. 5 The maximum explosion pressure of sugar dust clouds depending on the concentration of dust (Chovancová, 2017)

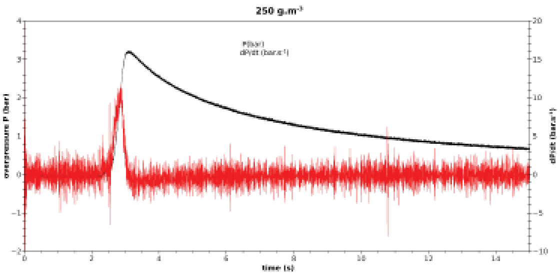

Fig. 6 The maximum explosion pressure and maximum rate of pressure rise for sugar dust clouds with concentration 250 g.m^{-3}

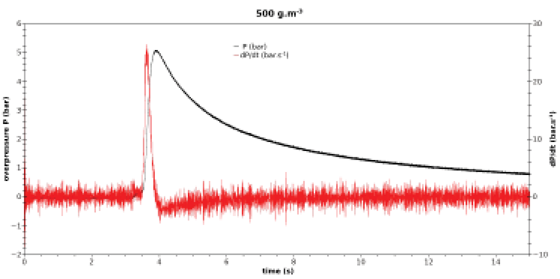

Fig. 7 The maximum explosion pressure and maximum rate of pressure rise for sugar dust clouds with concentration 500 g.m^{-3}

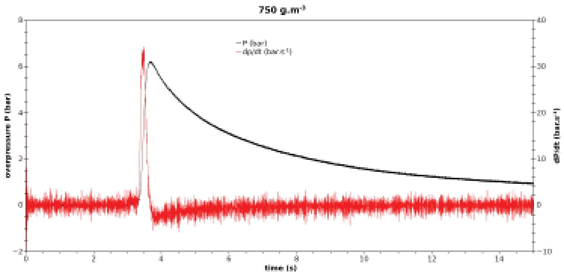

Fig. 8 The maximum explosion pressure and maximum rate of pressure rise for sugar dust clouds with concentration 750 g.m^{-3}

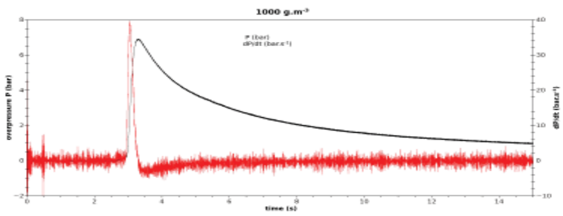

Fig. 9 The maximum explosion pressure and maximum rate of pressure rise for sugar dust clouds with concentration 1000 g.m^{-3}

Tab. 3 Explosion pressure and rate of pressure rise at various concentrations of sugar dust clouds

Concentration of dust cloud [g.m^{-3}]	**P_{max} [bar]**	**dP/dt_{max} [bar.s^{-1}]**
100 (1st)	0,63	-
100 (2nd)	0,62	-
100 (3rd)	0,53	-
125 (LEL)	1,08	-
150	0,99	-
200	3,82	16,81
250	3,18	11,54
300	3,93	16,34
400	4,67	26,20
500	5,05	26,12
750	6,16	33,93
1000	6,89	39,51

$$K_{st} = dP/dt_{max} \cdot \sqrt[3]{V} = 39{,}51 \text{ bar.s}^{-1} \cdot \sqrt[3]{0{,}291 \text{ m}^3} = 26{,}18 \text{ bar.m.s}^{-1} \qquad (2)$$

The maximum explosion pressure and the maximum rate of pressure rise was measured at a concentration of 1000 g.m^{-3}. The maximum explosion pressure of the sugar sample was 6.89 bar. The maximum rate of pressure rise for sugar sample was 39.51 bar.s^{-1}. This value corresponds to an explosion constant of 26.18 bar.m.s^{-1}.

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Conclusion

Combustible dust explosions are among the most serious criticalities affecting a broad number of industries around the world. (Fumagalli, 2016)

Sugar is a flammable substance and is explosive in the form of dust cloud with a lower explosive limit of 125 g.m^{-3}. The results of research allow us to conclude that the increasing concentration of the dust leads to the increase of the pressure value in the chamber.

The highest explosion parameters were obtained at sugar concentration of 1000 g.m^{-3}. The measured values are comparable to values reported in the GESTIS-DUST-EX database for sugar with a median value of 80 micrometres.

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