

This is the uncorrected proof (article in press) of the following article

B. Janovsky, J. Skrinsky, J. Cupak, J. Veres (2019). Coal dust, Lycopodium and niacin used in hybrid mixtures with methane and hydrogen in 1 m³ and 20 l chambers. *Journal of Loss Prevention in the Process Industries*. DOI: 10.1016/j.jlp.2019.103945.

This uncorrected proof (article in press) is available from <https://hdl.handle.net/10195/75220>

Publisher's version is available from:

<https://www.sciencedirect.com/science/article/pii/S0950423019301317?via%3Dihub>



This version is licenced under a [Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International](https://creativecommons.org/licenses/by-nc-nd/4.0/).



Coal dust, Lycopodium and niacin used in hybrid mixtures with methane and hydrogen in 1 m³ and 20l chambers

B. Janovsky^{a,*}, J. Skrinsky^b, J. Cupak^c, J. Veres^b

^a University of Pardubice, Faculty of Chemical-technology, Institute of Energetic Materials, Studentska 95, 532 10, Pardubice, Czech Republic

^b VSB-TU Technical University of Ostrava, Energy Research Center, 17. Listopadu 15/2172, 708 33, Ostrava – Poruba, Czech Republic

^c OZM Research, Bliznovice 32, 538 62, Hrochuv Tynec, Czech Republic

ARTICLE INFO

Keywords

Hybrid mixture
20l chamber
1 m³ chamber
EN 14034
Ignition source

ABSTRACT

The aim of the work presented here is a comparison of hybrid mixture explosion parameters obtained in the explosion chambers used in European Standard EN 14034 and explore the influence of the explosion volume and the ignition source on the explosion parameters of the hybrid mixtures. Explosion chambers of the two volumes, 20l and 1 m³, specified in the Standard, were used to carry out standard procedures according to EN 14034 to determine hybrid mixture explosion parameters such as maximum overpressure and maximum rate of pressure rise. Three flammable dusts widely accepted as standards were chosen – Pittsburgh seam bituminous coal dust, Lycopodium Clavatum spores and Niacin. Two flammable gases (methane and hydrogen) were used. Methane and hydrogen are used for standard testing of flammable gas mixtures explosion parameters in explosion chambers. The explosion parameters of various mixtures of flammable dusts, flammable gases and air were measured. Standard ignition sources for dust dispersion, two 5 kJ chemical igniters, were used in both chambers. Explosion parameters were also measured using the standard permanent spark described in EN 15967 as an ignition source for a comparison of the effect of different ignition energies on explosion parameters. The results show a significant increase of normalised maximum rates of pressure rise in a 20l chamber compared with a 1 m³ chamber caused by higher turbulence levels in the smaller chamber. It was also shown that the permanent spark could be used for easily ignitable dusts and, in some cases, can produce even higher rates of pressure rise than chemical igniters.

Abbreviations

$(dP/dt)_{ex}$	the maximum rate of pressure rise during the course of a single deflagration test (bar/s)
$(dP/dt)_{max}$	maximum value for the rate of pressure increase per unit time reached during the course of a deflagration for the optimum concentration of the dust tested. It is determined by a series of tests over a large range of concentrations (bar/s)
K_g	maximum dP/dt of gas-air mixture normalized to a 1.0 m ³ volume (bar m/s)
K_{hybrid}	maximum dP/dt of hybrid mixture normalized to a 1.0 m ³ volume (bar m/s)
K_{st}	maximum dP/dt of dust dispersion normalised to a 1.0 m ³ volume (bar m/s)
MEC	minimum explosible concentration of dust (g/m ³)

P_{ex}	the maximum pressure rise (above pressure in the vessel at the time of ignition) produced during the course of a single deflagration test (bar)
PR	pressure ration, P_{ex} – pressure increase caused by ignitor explosion itself (bar)

1. Introduction

The safety and protection of workers against explosion effects in workplaces covered by European Directive ATEX 137 require continual research in the area of gas and dust dispersion explosions. The basic principles of gas and dust explosions are therefore relatively well understood and there is international legislation covering testing of such materials. In the case of hybrid mixtures, mixtures of a flammable gas and flammable dust with a gas oxidizer, the situation is different and no standard for testing of hybrid mixtures could be found. The first reports describing tests with hybrid mixtures appeared towards the end

* Corresponding author.

E-mail address: bretislav.janovsky@upce.cz (B. Janovsky)

of the nineteenth century (Engler et al., 1885). However, research interest in hybrid mixtures has increased considerably during the past two decades (Ajrash et al., 2016; Amyotte et al., 2009; Cloney et al., 2017; Denkevits, 2007, 2010; Dufaud et al., 2008; 2009; Li et al., 2012; Sanchirico et al., 2011; Pilão et al., 2006; etc.). Most of the papers describe tests with hybrid mixtures in 20l chambers using chemical igniters with various ignition energies starting with 1kJ rising to 10kJ. Only a few papers describe tests using electric spark (Addai et al., 2015; Sanchirico et al., 2011; Garcia-Agreda et al., 2011).

Standard testing of explosion parameters of pure dusts and pure gas (vapours) is done using the different test conditions given by EN 14034 and ASTM 1226 for dust dispersions and EN 15967 for mixtures of gas (vapour) with air respectively. Dust dispersion testing requires dispersion of dust using 20 bar dispersion air to release the dust from the dust container creating a highly turbulent environment inside the test chamber. On the other hand, gas-air mixtures are tested under conditions of no turbulence. The second main difference is in ignition source and its energy. Sanchirico et al. (2011) published experiments with acetone and nicotinic acid in a 20l chamber using only an electric spark described in EN 15967 for gas explosion severity tests. His conclusions were very interesting. He found that: *“The comparison between the explosion violence of gas (vapour)-air mixtures with that of gas/dust-air mixtures has to be revised in order to take into account the role of turbulence”*.

The aim of the preliminary work presented here is a comparison of hybrid mixture explosion parameters obtained in explosion chambers of two sizes (20l and 1 m³) described in European Standard EN 14034 using two types of ignition source – a standard chemical igniter and a permanent spark.

2. Experiments

Experiments were carried out in a 20l chamber (CA 20L) and a 1 m³ chamber (CA 1M3) both made by OZM Research in accordance with the EN 14034 Standard.

2.1. 20l chamber – CA 20L

This stainless-steel chamber is a double-walled spherical vessel with an internal diameter of 336 mm. The vessel is provided with an opening with an interior diameter of 148 mm. The illustrative picture of the instrument is shown in Fig. 1.

A Presto A30 highly dynamic temperature control system by JUALABO was used for temperature control of the chamber. A permanent spark generator was made in accordance with EN 15967 and Tungsten



Fig. 1. Illustrative picture of the CA 20L.

electrodes with a distance of 6 mm were used. A pair of piezoelectric pressure sensors by Kistler, type 701A (natural frequency 70 kHz), measured the explosion pressure. The pressure range for the sensors was set to 2.5 MPa. The data were recorded by a four-channel data acquisition card with a sampling rate of 50k Samples/sec/channel. The whole procedure, including rapid-action valve timing, is controlled by a Siemens Simatic 1215 PLC connected to a PC as a user interface. The chamber was equipped with a thermocouple for temperature monitoring, especially for measurement of the temperature at ignition time. Correct gas mixture composition was assured by the partial pressure method. Internal pressure was measured by a pressure transducer.

Both the electrical discharge according to EN 15967 and the defined current for chemical igniter were used as ignition sources. The amount of dust used varied according to the required dust concentration. The dust was introduced into the dust container after weighing. The vessel was then evacuated to 0.4 bar and the dust container was pressurised with air at 20 barg pressure to disperse the dust into the explosion chamber. The PLC started dispersion and activated the ignition source with a predefined ignition delay time. Pressure change inside the chamber after command for dust dispersion were recorded using piezoelectric pressure sensors. Preliminary tests with Lycopodium and ignition using a 10J electrical spark showed that the Rebound nozzle did not produce a sufficiently homogeneous dust dispersion and that ignition of a dust cloud was not assured for all tests. A semicircular perforated annular nozzle was therefore used for dust dispersion (Fig. 2).

The gas explosion procedure started with evacuation of the chamber to a pressure less than 0.4 bar to leave the required space for the flammable gas. For example, generating a methane concentration of 2% by vol. and 8% by vol. requires the adding of methane, increasing the internal pressure by 0.02 bar and 0.08 bar respectively. Then the evacuation pressures should be 0.38 bara and 0.32 bara respectively. The PLC started the experiment by activating the rapid-action valve and the flammable gas was then mixed by blowing dispersion air. The ignition system, either the electrical discharge or current source for pyrotechnic igniter, was activated at 60 ms after registering the pressure increase in

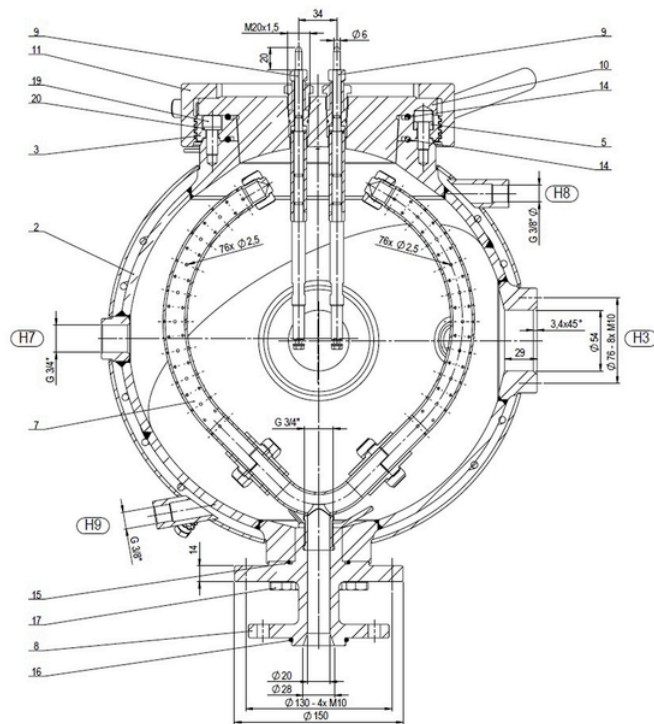


Fig. 2. Dispersion system using semicircular perforated annular nozzle in the 20l chamber.

the chamber and the mixture was ignited. The explosion indices were measured and calculated.

The hybrid mixture procedure combines both the above-mentioned procedures. Hence, either hydrogen or methane is added using the partial pressure method first and then dust is introduced during dispersion. The approximate volume of the dust introduced during dispersion is taken into calculation of pressure for evacuation of the chamber and dosing the flammable gas.

2.2. 1 m³ chamber CA 1M3

This chamber is a spherical vessel with an internal diameter of 1240 mm and a capacity of 1 m³. The vessel is equipped with an opening with an interior diameter of 800 mm and provided with a lockable door. A illustrative picture of the instrument is shown in Fig. 3. The material of the chamber and components comply with the standards for the use of equipment for experiments at atmospheric initial pressure and an initial temperature in the range between 15 °C and 200 °C.

There is a dispersion system installed in the chamber. The system consists of a dust reservoir with a capacity of 5.5 dm³. The reservoir is designed for operating pressures up to 3 MPa and a testing pressure of 4 MPa. A rapid-reaction pneumatic ball valve with an opening time of less than 50 ms is attached to the conical bottom of the container. A semicircular perforated annular nozzle (Fig. 4) was also used for experiments.

The CA 1M3 explosion chamber is equipped with the same measuring system as the CA 20L chamber and control is also provided by a Siemens Simatic 1215 PLC connected to a PC as a user interface.

Two ignition sources were used again, electric discharge according to EN 15967 and current source for chemical igniter. After weighing, the dust is introduced into the dust reservoir. The vessel is then evacuated to 0.89 bara and the dust reservoir is then pressurised with air at 20 barg to disperse the dust into the explosion chamber. The PLC initiates dispersion and, with a predefined ignition delay time, activates the ignition source. Explosion pressure is then recorded.

The procedure for the gas explosion started with evacuation to a pressure less than 0.89 bar to leave a required volume for the gas. For example, generating methane concentrations of 2% by vol. and 8% by vol. requires the addition of methane increasing the internal pressure by 0.02 bar and 0.08 bar respectively. Then the evacuation pressures should be 0.87 bar and 0.81 bar respectively. The PLC started the experiment by activating the rapid-action ball valve and the flammable gas was mixed by blowing dispersion air. The ignition system, either the

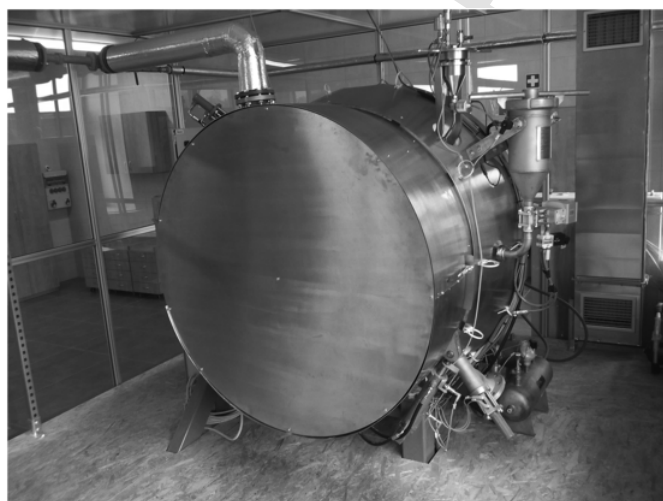


Fig. 3. Illustrative picture of the CA 1M3.

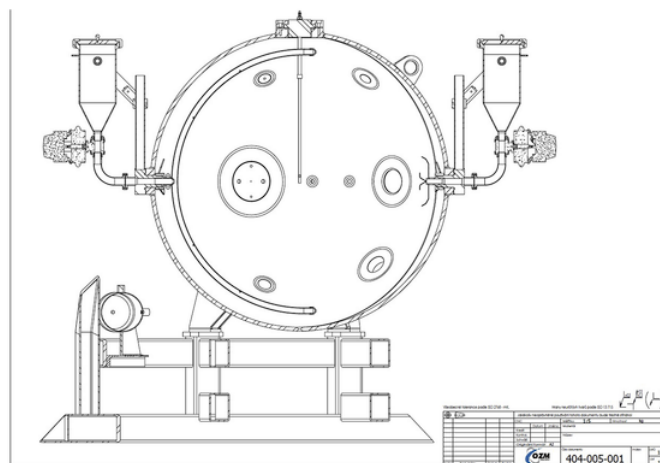


Fig. 4. Dispersion systems in the CA 1M3, semicircular perforated annular nozzle on the left and Rebound nozzle on the right.

electric discharge or defined current for pyrotechnic igniter, was activated with a delay time of 600 ms after activation of the ball valve. The explosion indices were measured and calculated.

The hybrid mixture procedure combines both the procedures. Hence, hydrogen or methane is added by the partial pressure method first and then the dust is dispersed.

2.3. Dusts used

Lycopodium Clavatum, Nicotinic Acid and Pittsburgh seam bituminous coal dust were used for measurements in both chambers. Granulometric distribution was measured using a type 1090 CILAS particle size analyser. Moisture content was measured using a Mettler Toledo type 256 moisture analyser. Results of the measurements are shown in Table 1.

3. Results and discussion

3.1. Hydrogen, Lycopodium and air mixture

Experiments with Lycopodium and hydrogen started with the permanent spark as the ignition source. The results are shown in Figs. 5 and 6 for the maximum explosion overpressure and the maximum rate of pressure rise respectively.

The comparison of the maximum pressures generated does not show significant differences in the maximum values measured. The only difference is in the optimal concentration of Lycopodium for generating the maximum explosion parameters which decrease with increasing hydrogen concentration. The maximum rate of pressure rise of Lycopodium dust is more influenced by addition of hydrogen. It was therefore decided that the concentration of hydrogen would be only 10% in the subsequent tests and hydrogen would be used only for hybrid mixtures containing niacin as the dust. This concentration is sufficient for ignition and stable burning of the hydrogen in mixture with

Table 1
Granulometric distribution of dusts used.

Parameter	Lycopodium	Niacin	Pittsburgh coal
Diameter at 10% (µm)	4.41	4.79	7.02
Diameter at 50% (µm)	28.46	22.99	45.68
Diameter at 90% (µm)	42.79	63.85	92.19
Mean diameter (µm)	27.63	29.82	48.02
Moisture (% by mass)	1.01	3.52	2.41

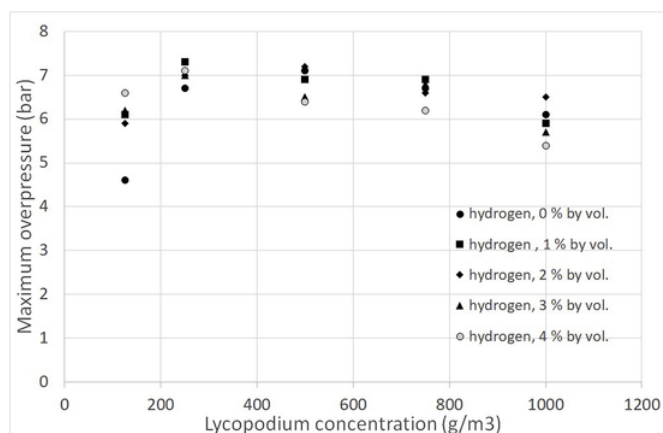


Fig. 5. Maximum overpressure for various concentrations of Lycopodium and hydrogen.

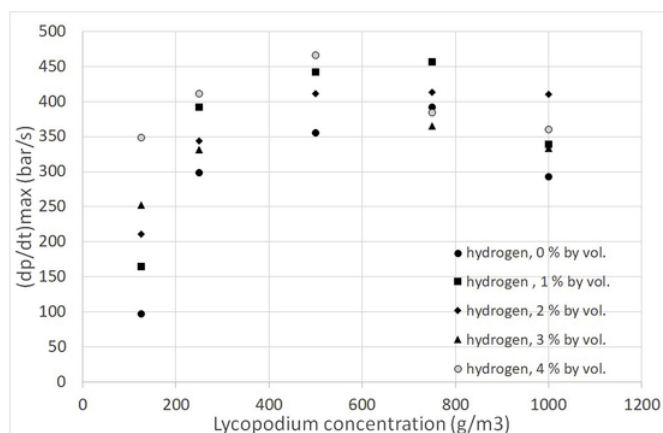


Fig. 6. Maximum rate of pressure rises for various concentrations of Lycopodium and hydrogen.

air and well below concentrations giving maximal values of P_{ex} and $(dP/dt)_{ex}$ for mixtures of hydrogen and air. This concentration allows for comparison of explosion parameters using various ignition sources and sizes of the chamber for gas, dust and hybrid mixture explosions.

The testing continued with comparisons of the data obtained during Lycopodium tests where 4% of hydrogen was added and ignition was done by two chemical igniters with ignition energy of 5kJ. The difference between two pressure plots recorded during the tests with 250 g/m³ and 4% of hydrogen by vol. and different ignition sources is shown in Fig. 7. Ignition delay time was 60ms in both tests.

The comparison of pressure records shows that the explosion pressure is not significantly influenced. But the curve for chemical ignition shows a higher rate of pressure rise. However, it is seen that the maximum pressure is reached about 20ms earlier in the case of chemical ignition. These 20ms cause a different turbulence level in the chamber together with different dust particle distribution throughout the chamber volume. Reaction of two 5kJ chemical igniters itself generates about 1 bar of pressure increase in the 20l chamber (ASTM 1226). This 1 bar should be taken into account when comparing the results of the tests using chemical ignition with those using a permanent spark in the 20l chamber.

The results are shown in Fig. 8 for the maximum explosion overpressure P_{ex} together with the pressure reduced by the pressure of the igniters P_{red} and in Fig. 9 for the maximum rate of pressure rise $(dP/dt)_{ex}$.

If the pressure effect of the ignition sources were to be neglected, the maximum explosion overpressure generated using chemical ignition has values only slightly higher than in the case of using a permanent

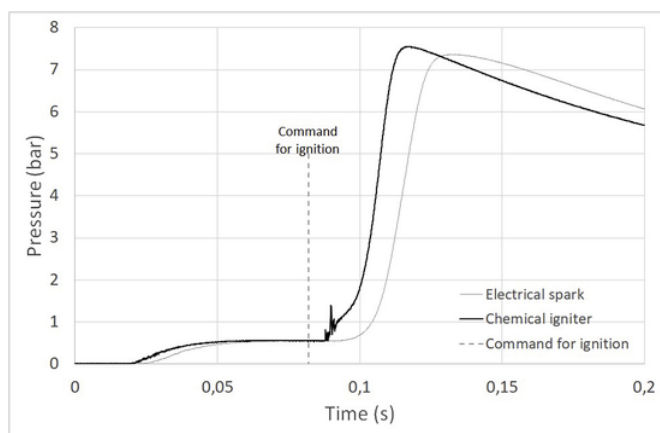


Fig. 7. Pressure plots recorded during tests with 250 g/m³ and 4% of hydrogen by vol. and different ignition sources.

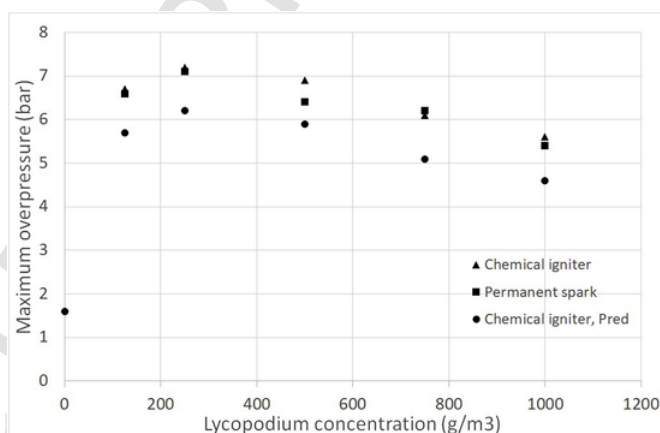


Fig. 8. Maximum overpressure for various concentrations of Lycopodium and 4% by vol. of hydrogen.

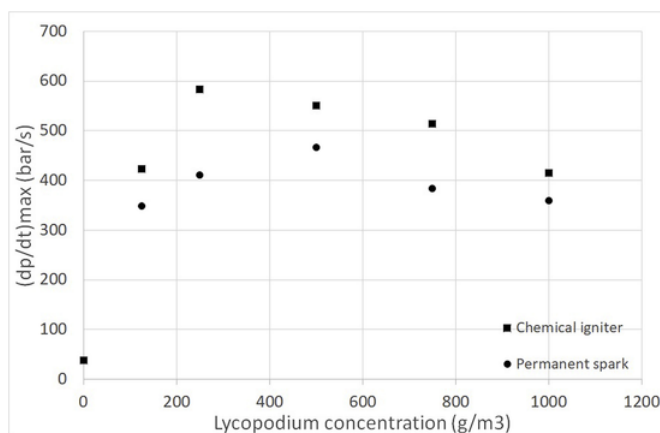


Fig. 9. Maximum rate of pressure rise for various concentrations of Lycopodium and 4% by vol. of hydrogen.

spark. But taking this effect into account, it is seen that higher overpressures are generated when using permanent spark ignition. The chemical ignition uses a balanced pyrotechnic mixture and therefore it is believed that no air from the chamber is consumed during burning. To prove this assumption, two chemical igniters were ignited with oxygen concentration decreased to 3% of oxygen in the gaseous atmosphere. The explosion parameters were the same as in the case of air. On the other hand, a pyrotechnic mixture containing zirconium produces

very large heat radiation during burning. This heat radiation can heat up the surrounding gas which can decrease the expansion ratio and therefore the maximum explosion overpressure.

3.2. Lycopodium, methane and air mixtures

The tests continued with a mixture of Lycopodium with methane and air. The results of the measurements are shown in Tables 2 and 3 for ignition using a permanent spark and chemical ignition respectively. Concentrations of Lycopodium were chosen in accordance with the standard measurement of the maximum pressure and the maximum rate of pressure rise in this preliminary study. This was done in order to validate the instruments and procedure. A limited amount of dust sample led to a reduction in the number of tests in the 1 m³ chamber.

The data recorded show the well-known dependency of explosion parameters on fuel concentration. When only the dust was ignited, the

Table 2
Comparison of results of Lycopodium-methane-air explosion using electrical spark ignition in 1 m³ and 201 chambers.

Concentration (g/m ³)	1 m ³		201		
	P_{ex} (bar)	K_{hybrid} or K_{st} (bar m/s)	P_{ex} (bar)	P_{re} (bar)	K_{hybrid} (bar m/s)
Methane concentration: 0% by vol.					
125	7.2	80	4.6	–	26
250	8.3	138	6.7	–	81
500	7.3	116	7.1	–	96
750	–	–	6.7	–	106
Methane concentration: 4% by vol.					
125	8.1	152	5.0	–	29
250	8.0	162	6.8	–	103
500	6.9	111	6.3	–	109
750	–	–	5.2	–	137
Methane concentration: 8% by vol.					
125	8.1	210	6.6	–	240
250	7.5	187	6.0	–	407
500	6.4	120	5.5	–	228
750	–	–	5.0	–	183

Table 3
Comparison of results of Lycopodium-methane-air explosion using two chemical igniters (5 kJ each) in 1 m³ and 201 chambers.

Concentration (g/m ³)	1 m ³		201		
	P_{ex} (bar)	K_{hybrid} or K_{st} (bar m/s)	P_{ex} (bar)	P_{red} (bar)	K_{hybrid} (bar m/s)
Methane concentration: 0% by vol.					
125	7.4	79	5.8	4.8	61
250	8.0	121	7.3	6.0	118
500	7.2	117	7.9	6.5	135
750	–	–	6.5	5.4	138
Methane concentration: 4% by vol.					
125	8.0	120	7.0	6.0	97
250	7.9	149	7.2	6.2	136
500	6.7	112	6.7	5.7	164
750	–	–	5.8	4.8	123
Methane concentration: 8% by vol.					
125	7.7	179	7.2	6.2	208
250	7.2	162	6.6	5.6	295
500	6.0	102	5.6	4.6	227
750	–	–	5.4	4.4	184

optimal concentration of Lycopodium was 250 g/m³ in the 1 m³ chamber. Both explosion parameters measured had maximal values at this concentration. With an increase in the methane concentration, the maximum value of the explosion pressure did not change much, but the values of the maximum rate of pressure rise increases for almost each dust concentration in both chambers. Optimal concentration shifts to lower dust concentration and reaches a minimum at 8% by vol. of methane in 1 m³. This general behaviour is the same for both types of ignition. Contrary to expectations, higher values of both explosion parameters were obtained using a permanent spark as the ignition source.

Measurements in the 201 chamber showed similar trends but the optimal concentration for the maximum explosion pressure and the maximum rate of pressure rise was different. The maximum explosion pressure reached its maximum at 500 g/m³ while the concentration of 750 g/m³ was necessary to reach the maximum value for the rate of pressure rise. The optimal concentration then shifted with increased concentrations of methane to 125 g/m³ for the maximum pressure and to 250 g/m³ for the maximum rate of pressure rise respectively. The type of ignition influences explosion parameters in a slightly different manner. Contrary to the situation with the 1 m³ chamber, the permanent spark produces lower explosion parameters up to addition of 8% by vol. of methane. The mixtures containing 8% by vol. of methane produced the highest rates of pressure rise.

3.3. Pittsburgh coal, methane and air mixtures

In the following series of tests, Pittsburgh coal was mixed with methane and air. The results of the measurements are shown in Tables 4 and 5 for ignition using a permanent spark and chemical ignition respectively. Concentrations of Pittsburgh coal were the same as those used in the case of Lycopodium.

Specific electrical properties of the Pittsburgh coal cause large energy losses during ignition using electric spark. Therefore, higher ignition energies are needed for ignition of the coal dust. This does not influence thermodynamic of the explosion and maximum explosion pressure is not influenced by type of the ignition source. On the other hand, kinetics of the explosion is influenced by the level of the ignition energy much. The maximum rate of pressure rise is therefore higher using chemical ignition. Tests show that further testing is necessary to be able to conclude more in this area.

3.4. Niacin, hydrogen and air mixtures

Niacin, as the most reactive dust among the three dusts used, was mixed with hydrogen and air in the last series of tests. The results of

Table 4
Comparison of results of Pittsburgh coal-methane-air explosion using electrical spark ignition in 1 m³ and 201 chambers.

Concentration (g/m ³)	1 m ³		201		
	P_{ex} (bar)	K_{hybrid} or K_{st} (bar m/s)	P_{ex} (bar)	P_{red} (bar)	K_{hybrid} (bar m/s)
Methane concentration: 0% by vol.					
125	1.1	2	–	–	–
250	7.4	42	4.9	–	11
500	7.2	41	5.9	–	26
750	–	–	5.6	–	28
Methane concentration: 4% by vol.					
125	7.6	88	5.6	–	35
250	7.7	77	6.3	–	83
500	7.0	86	6.0	–	81
750	–	–	5.1	–	96

Table 5
Comparison of results of Pittsburgh coal-methane -air explosion using two chemical igniters (5 kJ each) in 1 m³ and 201 chambers.

Concentration (g/m ³)	1 m ³		201		
	<i>P_{ex}</i> (bar)	<i>K_{hybrid}</i> or <i>K_{st}</i> (bar m/s)	<i>P_{ex}</i> (bar)	<i>P_{red}</i> (bar)	<i>K_{hybrid}</i> (bar m/s)
Methane concentration: 0% by vol.					
125	5.6	23	5.6	4.6	35
250	7.7	58	6.3	5.3	83
500	7.3	74	6.0	5.0	81
750	–	–	5.1	4.1	96
Methane concentration: 4% by vol.					
125	7.4	79	7.1	6.1	185
250	7.7	117	6.7	5.7	157
500	7.0	43	6.2	5.2	160
750	–	–	5.3	4.3	134

measurements are shown in Tables 6 and 7 for ignition using a permanent spark and chemical ignition respectively. Concentrations of niacin were the same as in the case of Lycopodium.

The combination of the most reactive dust and gas produced the highest rates of pressure rise throughout the whole testing. Addition of hydrogen further increased explosion parameters. Highly reactive dust

Table 6
Comparison of results of niacin-hydrogen-air explosion using electrical spark ignition in 1 m³ and 201 chambers.

Concentration (g/m ³)	1 m ³		201		
	<i>P_{ex}</i> (bar)	<i>K_{hybrid}</i> or <i>K_{st}</i> (bar m/s)	<i>P_{ex}</i> (bar)	<i>P_{red}</i> (bar)	<i>K_{hybrid}</i> (bar m/s)
Hydrogen concentration: 0% by vol.					
125	5.3	31	4.4	–	28
250	7.7	89	6.9	–	150
500	7.9	121	7.0	–	143
750	–	–	6.7	–	159
Hydrogen concentration: 10% by vol.					
125	7.1	169	6.1	–	385
250	8.0	219	6.5	–	478
500	7.5	237	5.9	–	425
750	–	–	5.7	–	358

Table 7
Comparison of results of Niacin-hydrogen-air explosion using two chemical igniters (5 kJ each) in 1 m³ and 201 chambers.

Concentration (g/m ³)	1 m ³		201		
	<i>P_{ex}</i> (bar)	<i>K_{hybrid}</i> or <i>K_{st}</i> (bar m/s)	<i>P_{ex}</i> (bar)	<i>P_{red}</i> (bar)	<i>K_{hybrid}</i> (bar m/s)
Hydrogen concentration: 0% by vol.					
125	5.9	48	5.3	4.3	75
250	7.9	86	7.2	6.2	146
500	8.0	112	7.7	6.7	213
750	–	–	7.3	6.3	222
Hydrogen concentration: 10% by vol.					
125	7.4	161	6.8	5.8	281
250	7.6	206	7.0	6.0	314
500	7.4	170	6.7	5.7	306
750	–	–	6.5	5.5	309

caused the ignition by permanent spark to be comparable with chemical ignition in 1 m³ chamber only for niacin explosion and was even more effective after the addition of 10% by vol. of hydrogen.

3.5. Discussion

The maximum values of the explosion parameters are compared in the following figures. Only the maximum values of the explosion parameter obtained in the series of test with same flammable gas concentration varying the dust concentration are compared. The ratios of the maximum explosion overpressures in the 1 m³ and 201 chambers are plot in Fig. 10 when 1 m³ is taken as the standard. The ratios of maximum values of the deflagration indexes *K_{hybrid}* and *K_{st}* in the 1 m³ and 201 chambers using both ignition sources are plot in Fig. 11 when 1 m³ is taken as the standard. Comparison of the two ignition sources in both chambers as the ratio of the maximum explosion overpressures is plotted in Fig. 12. Chemical igniter (ChIg) is taken as the standard for ratio. The same comparison, but as the ratio of the of deflagration indexes is shown in Fig. 13.

The main aim of this work was the comparison between hybrid explosion parameters measured in standard 1 m³ chamber and standard 201 chamber. This study shows well known difference of the maximum explosion overpressures on the size of the chamber. The Overpressures reached in the 1 m³ chamber are higher than those obtained in the 201 chamber. The normalised maximum rates of pressure rise (*K_{st}* and *K_{hybrid}* values) differs depending on the type of the ignition. Permanent spark ignites deflagrations producing higher normalised maximum rates of pressure rise *K* in the 1 m³ chamber in contrast with the chemical igniters, which ignites more severe deflagrations in the 201 cham-

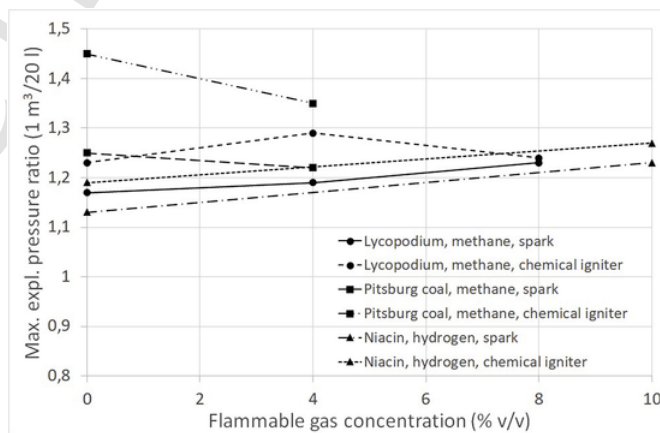


Fig. 10. Ratio of maximum explosion overpressures in the 1 m³ and 201 chambers.

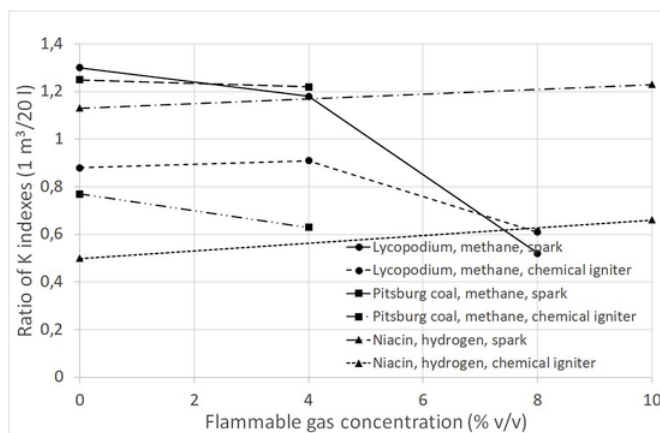


Fig. 11. Ratio of deflagration indexes K in the 1 m³ and 201 chambers.

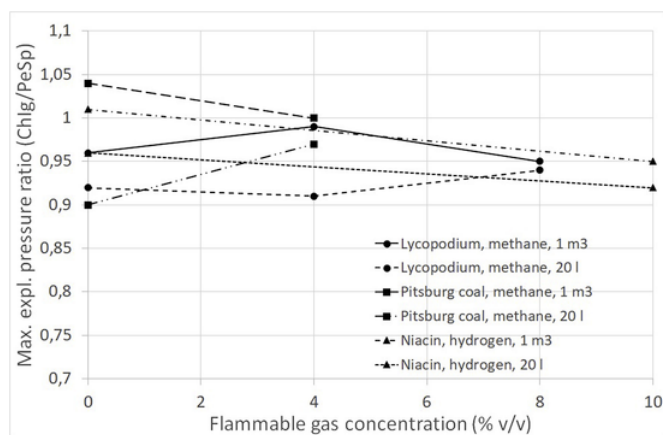


Fig. 12. Ratio of maximum explosion overpressures in both chambers using chemical ignition (Chlg) and permanent spark (PeSp).

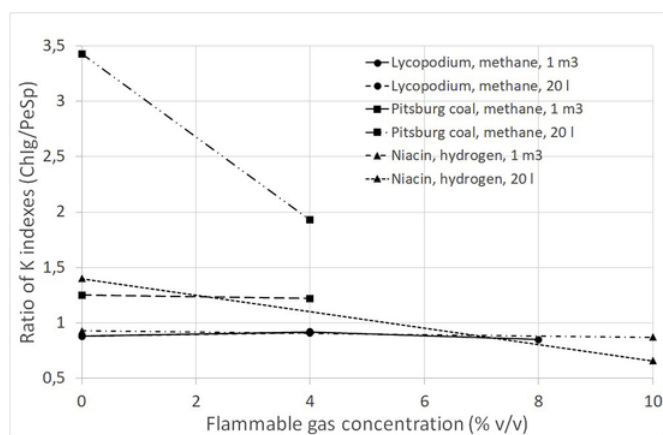


Fig. 13. Ratio of deflagration indexes K in both chambers using chemical ignition (Chlg) and permanent spark (PeSp).

ber. The differences increase with increasing gas concentration. K_{hybrid} values measured in 20 l chamber are much higher than those measured in 1 m³ chamber. This supports the conclusions by Sanchirico et al. (2011) about the significant role of turbulence in the 20 l chamber.

A hybrid mixture is the combination of solid and gas materials requiring different conditions for explosion parameter measurement. EN 15967 (2011) requires a stable atmosphere without any turbulence for measurement of explosion parameters of flammable gas mixtures and therefore it is necessary to wait for 2 min after mixing has stopped. This is in contrast with the requirements of standard methods of dust explosion parameter measurement described in EN 14034 (2004) and ASTM 1226 (2012) concerning ignition delay time as a measure of turbulence level which will be always presented in the chamber during dust dispersion. Required ignition delay time for the 20 l chamber was 60 ms starting with the measurable pressure increase in the chamber. The time remaining for turbulence decay after the end of dispersion is not greater than 30 ms and decreases with increase of dispersed dust volume. The results obtained show that 30 ms is not a sufficient time for turbulence decay to reach a level low enough to influence flammable gas burning comparable to burning in 1 m³ chamber after dispersion. EN 14034 (2004) requires an ignition delay time of 600 ms starting from the command to open a valve on the dust reservoir for 1 m³ chamber. The turbulence decay time in 1 m³ chamber could be up to 200 ms (Janovsky et al., 2016) depending on the dust concentration and dust density. From the point of view of the different turbulence decay times in both chambers, it seems that the 1 m³ chamber is

more suitable for hybrid mixture explosion testing because of the lower turbulence level at the time of ignition.

The experiments carried out for this paper enable a comparison of two ignition sources – the permanent spark as the weak ignition source and two chemical igniters with ignition energy of 5 kJ (each) as the strong ignition source. Niacin and Lycopodium dusts, which are easy to ignite, are in contrast to Pittsburgh coal, which is barely ignitable by the permanent spark method. The results imply that the permanent spark is suitable for niacin and Lycopodium and could produce even higher explosion parameters compared with chemical ignition. On the other hand, the permanent spark is a weak ignition source in cases of poorly ignitable dusts in both hybrid explosion regimes.

4. Conclusions

The study presented here was focused on the hybrid mixture explosion parameters influenced by the size of the explosion chamber and the ignition type. Explosion chambers of two standard sizes (20 l and 1 m³) were used. Two standard ignition systems were compared – two chemical igniters with total ignition energy of 10 kJ and permanent spark used as the standard ignition source for gas explosion testing.

It can be concluded that the 1 m³ chamber is more suitable for hybrid mixture testing due to a lower effect of turbulence. Burning of the hybrid mixture is therefore more enhanced by turbulence in a 20 l chamber than in a 1 m³ chamber which increases the explosion parameters. Ignition by the permanent spark appeared to be suitable for easily ignitable dusts such as Lycopodium and niacin and produced higher explosion parameters for these dusts. However, permanent sparks generated lower explosion parameters in the case of Pittsburgh coal and therefore chemical igniters seem to be necessary for this type of dust.

Acknowledgement

The presented work was financially supported by the project “Innovation for Efficiency and Environment - Growth”, identification code LO1403 with financial support from the Ministry of Education, the Youth and Sports of the Czech Republic in the framework of the National Sustainability Programme I.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jlp.2019.103945>.

References

- Addai, E., Gabel, D., Krause, U., 2015. Lower explosion limit of hybrid mixtures of burnable gas and dust. *J. Loss Prev. Process. Ind.* 36, 497–504.
- Ajrash, M., Zanganeh, J., Moghtaderi, B., 2016. Effects of ignition energy on fire and explosion characteristics of dilute hybrid fuel in ventilation air methane. *J. Loss Prev. Process. Ind.* 40, 207–216.
- Amyotte, P., Lindsay, M., Domaratzki, R., Marchand, N., Di Benedetto, A., Russo, P., 2009. Prevention and mitigation of polyethylene and hydrocarbon/polyethylene explosions. In: *Proceedings of 43rd Loss Prevention Symposium*, pp. 541–556.
- ASTM 1226, 2012. Standard Test Method for Explosibility of Dust Clouds, ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA.
- Cloney, C.T., Ripley, R.C., Pegg, M.J., Amyotte, P.R., 2017. Evaluating regime diagrams for closed volume hybrid explosions. *J. Loss Prev. Process. Ind.* 49, 912–918.
- Denkevits, A., 2007. Explosibility of hydrogen-graphite dust hybrid mixtures. *J. Loss Prev. Process. Ind.* 20, 698–707.
- Denkevits, A., 2010. Hydrogen/dust explosion hazard in ITER: effect of nitrogen dilution on explosion behaviour of hydrogen/tungsten dust/air mixtures. *Fusion Eng. Des.* 85, 1059–1063.
- Dufaud, O., Perrin, L., Traoré, M., 2008. Dust/vapour explosions: hybrid behaviours? *J. Loss Prev. Process. Ind.* 21, 481–484.
- Dufaud, O., Perrin, L., Traoré, S., Chazelet, S., Thomas, D., 2009. Explosion of vapour/dust hybrid mixtures: a particular class. *Powder Technol.* 190, 269–273.
- EN 14034, 2004. Determination of Explosion Characteristics of Dust Clouds, European Committee for Standardization (CEN), Brussels.
- EN 15967, 2011. Determination of Maximum Explosion Pressure and the Maximum Rate of Pressure Rise of Gases and Vapours, European Committee for Standardization (CEN), Brussels.

- Engler, C., 1885. Beitrage zur kenntniss des staubexplosionen, Chemische Industrie, pp. 171–173.
- Garcia-Agreda, A., Di Benedetto, A., Russo, P., Sanchirico, R., 2011. Dust/gas mixtures explosion regimes. Powder Technol. 205, 81–86.
- Janovsky, B., Dastidar, A.G., Skrinsky, J., Skrinska, M., Veres, J., 2016. Some aspects of dust dispersion in 1 m³ chamber. In: Proceedings of the 11th International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions, Dalian, China, pp. 449–463.
- Li, Q., Lin, B., Dai, H., Zhao, S., 2012. Explosion characteristics of H₂/CH₄/air and CH₄/coal dust/air mixtures. Powder Technol. 22, 222–228.
- Pilão, R., Ramalho, E., Pinho, C., 2006. Explosibility of cork dust in methane/air mixtures. J. Loss Prev. Process. Ind. 19, 17–23.
- Sanchirico, R., Di Benedetto, A., Garcia-Agreda, A., Russo, P., 2011. Study of the severity of hybrid mixture explosions and comparison to pure dust-air and vapour-air explosions. J. Loss Prev. Process. Ind. 24, 648–655.

UNCORRECTED PROOF