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Study of Influence of Combustible Gas on Explosion Parameters of Black Coal Dust

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The article focuses on the matters of explosion parameters of coal dusts and the effect of the addition of small amount of combustible gas methane on them. This work presents laboratory tests of the influence of the addition of various amount of methane to the mixture of coal dust with air and its effect on maximum pressure and maximum rate of pressure rise.

1. Introduction

In fire safety praxis explosion is an unwanted event, at which in very short period of time large amount of energy is released in form of heat. Heat effects mass of gasses. This results in quick rise of volume, therefore rise of pressure, that can lead to strong destructions, losses in technologies, property and even mortality. To make an explosion possible, three conditions have to be fulfilled: space, strong enough ignition source and explosive atmosphere, created by mixture of combustible material with air in necessary concentration. Explosive mixtures with air can create either combustible gasses, fumes of combustible liquids, as well as solid materials in form of dust and various combinations of these. These combinations of combustible materials in various states of matter, called hybrid mixtures, are most dangerous. Any small addition of combustible gas or vapour of combustible liquid into the mixture of combustible dust and air causes rapid decrease of lower explosion limit and expansion of explosive range. At the same time the minimal ignition energy and the optimal concentration are decreasing rapidly, therefore the mixture is easily set on fire. The maximal explosion parameters, especially maximum explosion pressure and maximum rate of explosion pressure rise, are markedly increasing. This increment and its dependence is the major point of this paper.

2. Maximal explosion parameters

After ignition of explosive mixture, larger amount of heat is produced, than it is drained to surrounding environment. In closed space, this effect leads to significant rise of pressure. Continuance of pressure rise in dependence on time is represented by explosion chart (Figure 1).

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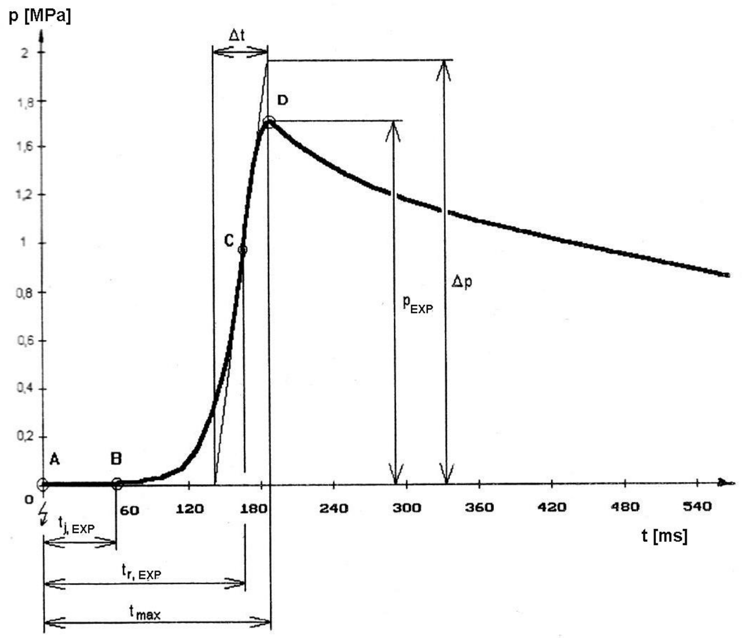


Figure 1: Explosion chart (Damec 1993)

After ignition in A, time $t_{i,\ exp}$ passes before pressure rise manifests (co called ignition period). This is the time of preparation for the mixture to burn. From point B pressure rises. Due to the temperature increase, rate of reaction rises until point C is reached, where the rate of a pressure rise is fastest. Value of this rate of pressure rise is expressed by the slope of the tangent line in inflection point C:

$$tg\alpha' = \left(\frac{dp}{dt}\right)_{\exp} \cong \frac{\Delta p}{\Delta t} \tag{1}$$

Term $\left(\frac{dp}{dt}\right)_{exp}$ expresses rate of pressure rise of mixture at concentration c_x in closed volume V. Due to decrease of reactant substances the rate of pressure rise from C to D is slowing down until in point D it is zero. Point D is the maximum of the curve, pressure at this point is maximal, it is called explosion pressure and it is denoted by p_{exp}. From this point, pressure is decreasing. This is caused by temperature decrease and hot gases condensation. Shape of the curve, therefore also values p_{exp} and $\left(\frac{dp}{dt}\right)_{\exp}$, as well as $t_{i,\ exp}$, $t_{r,\ exp}$ and t_{max} significantly changes with concentration of explosive mixture. Highest values of p_{exp} and $\left(\frac{dp}{dt}\right)_{\exp}$ are reached at optimal concentration c_{opt}. These values are called maximum explosion pressure and maximum rate of pressure rise and they are denoted by p_{max} and $\left(\frac{dp}{dt}\right)_{\exp}$. Optimal concentration is by gasses and fumes similar to stoichiometric concentration. By dusts it is:

$$c_{opt} = (2to3) \cdot c_{stoich} \tag{2}$$

Going higher or lower from c_{opt} both explosion pressure and rate of explosion pressure rise are lowering until they reach explosion limits, lower explosion limit (LEL) and upper explosion limit (UEL). Outside explosion range (between LEL and UEL) the explosion is not possible. For our measurements, optimal concentrations of dust were chosen because from safety point of view a risk of damage is highest at p_{max} (Damec 1993), (Mračková 2008)

3. Hybrid mixtures

Hybrid mixture is a mixture of air and combustible materials of different states of matter. When little amount of combustible gas or fumes of combustible liquid is added to the mixture of air and dust, LEL, optimal concentration and minimal ignition energy (MIE) are lowering rapidly. MIE of the mixture is reaching MIE of pure gas-air mixture. With growing amount of methane, maximal explosion parameters are rising, especially maximum rate of pressure rise. Maximum pressure is less influenced, as visible on Figure 2. Rate of pressure rise is converted to normalized rate of pressure rise K_{st} according to cubical law (V = volume of vessel):

$$\left(\frac{dp}{dt}\right)_{max} \cdot V^{\frac{1}{3}} = K_{st} \qquad (3)$$

In Figure 2, the rise of both maximum pressure and K_{st} is apparent and it is linear.

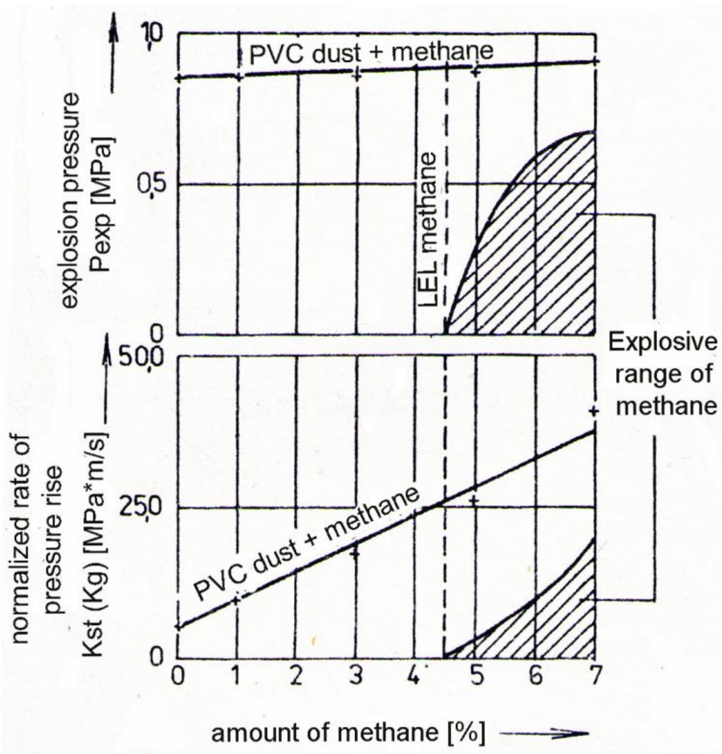
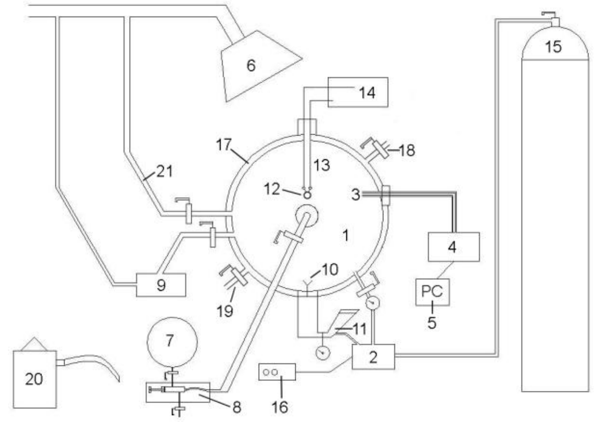


Figure 2: Explosion parameters of PVC/methane/air mixture (Damec 1993)

Hybrid mixtures are really dangerous, because explosion is possible when either combustible dust or gas are present in really small amounts (both below their LEL). Hybrid mixture is possible to be ignited with significantly lower energy than original dust/air mixture (Damec 1993).

4. Measurement equipment and method

All measurements were done on autoclave VA – 20 (also known as „20 litre-sphere“ or „20-l-Apparatus“). This is standard laboratory equipment used worldwide. The apparatus consists of explosion chamber, dispersion and ignition system, pressure measurement system and automatically control system. In our set-up, a system of methane infusion was added. Scheme of the set-up is on Figure 3. The explosion chamber is a double-layered spherical stainless steel vessel of 20 L volume. Working pressure is up to 2 MPa (Kalejaiye et al. 2006).



1 - explosion chamber	12 - ignition, pyrochemical ignitor
2 - KSEP 310 control unit	13 - ignition, electrodes
3 - pressure sensors	14 - power supply
4 - KSEP 332 measurement and control unit	15 - pressure air cylinder
5 - PC, software KSEP 6.0	16 - manual switch
6 - fouling exhaust	17 - water layer
7 - methane tank	18 - water inlet
8 - system for adding methane	19 - water outlet
9 - air pump	20 - vacuum cleaner
10 - dispersion nozzle	21 - fouling exhaust
11 - dust sample vessel	

Figure 3: Measuring equipment set-up scheme (Cesana, Siwek)

First, the dust sample was placed into dust sample vessel. 5 grams of coal dust were used for 20 L volume (optimal concentration is 250 g.m^{-3}). Second step was addiction of gas. From 1 to 6 vol % of methane were used gradually. The chamber is vacuumed and required amount of methane is added that way (1 % for 20 L vessel is 200 mL of gas), that the pressure in the chamber before dust injection is - 0.7 bar. Then the dust sample in the dust vessel is dispersed into the test chamber by compressed air and the pressure is compensated to standard pressure (101.325 kPa). After a pre-defined ignition delay (normally 60 ms), pyrotechnical igniter (with energy 10 kJ) was used to try to ignite the hybrid mixture cloud. The pressure history in the chamber is recorded by the pressure sensor and data acquisition system. Explosion pressure p_{max} and rate of explosion pressure rise (therefore normalized rate of pressure rise K) can be obtained by analysis of the pressure history curve.

5. The examined matters

To create hybrid mixture, gas methane was used because it is used by VVUÚ a.s. laboratories as a calibration gas, so its characteristics and explosion parameters are well known. As the coal dust, we used black coal from Ukraine, which explosion parameters were also known (Foniok 1985).

Black coal dust – Coal is dryed and grinded to very fine dust of particle size < 40 μm (0.040 mm).

Water:	W_{ex} = 5.0 %
Analytic water:	W^a = 3.2 %
Ash:	A^a = 3.0 %
Subtle parts (evaporate at less than 105°C):	V^a = 34.8 %
Fixed carbon:	C^a = 59 %
LEL (E_i = 9000 J):	LEL_{9000} = 51 g.m^{-3}
LEL (E_i = 100 J):	LEL_{100} = 113 g.m^{-3}
Maximum explosion pressure:	p_{max} = 7.3 bar
Maximum rate of pressure rise (V = 20 l):	$(\frac{dp}{dt})_{max}$ = 611 bar.s^{-1}

For better possibility of mutual comparison, values of $(\frac{dp}{dt})_{max}$ measured on 20 L apparatus (0.02 m^3) are converted to normalized rate of pressure rise according to cubical law (Equation (3)). These values are not dependent on the volume of the vessel on which they were measured.

Normalized maximum rate of pressure rise: $K_{st,max}$ = 166 m.bar.s^{-1}

Methane – Methane is the simplest hydrocarbon and its molecular formula is CH_4. At standard room temperature it is nontoxic gas without colour and smell. It is lighter than air (relative density is 0.55 at 20 °C). In nature it is present in atmosphere but mostly underground as the main component of natural gas, dissolved in oil or as a part of mining gas. Although its auto ignition point is very high (595 °C), when even a small ignition source is present, e. g. spark or flame, a mixture of methane with air is easily brought to explosion (MIE is 0.28 mJ). Explosion range is quite wide, from 4.4 to 15 % by volume.

Minimal ignition energy:	MIE 0.28 mJ
LEL (E_i = 10 J):	LEL_{10} = 4.6 vol. %
UEL (E_i = 10 J):	UEL_{10} = 14.2 vol. %
LEL (E_i = 10 kJ):	LEL_{10000} = 3.6 vol. %
UEL (E_i = 10 kJ):	UEL_{10000} = 17.5 vol. %
Maximum explosion pressure:	p_{max} = 7.4 bar
Maximum rate of pressure rise (V = 20 l):	$(\frac{dp}{dt})_{max}$ = 203 bar.s^{-1}
Normalized maximum rate of pressure rise:	$K_{st, max}$ = 55 m bar.s^{-1}

6. Measurement results

Coal dust was measured at optimal concentration 250 g.m^{-3}, for our 20 L apparatus the sample was 5 g. First, maximal explosion parameters of pure dust/air mixture were measured. Then from 1 to 6 percentage by volume of methane were gradually added (1 % by vol. for 20 L vessel is 200 mL of methane). Every test was repeated trice and the arithmetic mean was calculated. The results are summarized in following Table 1.

Table 1: The amount of methane and its effect on explosion parameters of black coal dust

Amount of methane	**p_{max}**	**Rise by percentage p_{max}**	**$(dp/dt)_{max}$**	**K_{st}**	**Rise by percentage**
(% by vol.)	(bar)	(%)	(bar.s^{-1})	(bar.m.s^{-1})	(%)
0	7.6	-	572	155	-
1	9.2	21	722	196	26
2	9.6	26	799	217	40
3	9.7	28	897	243	56
4	10.0	32	1084	294	90
5	10.8	42	1183	321	107
6	11.1	46	1392	378	143

The results are also presented in graphic form. In Figure 4, the effect of addition of methane on maximum explosion pressure of mixture of black coal dust with air is presented.

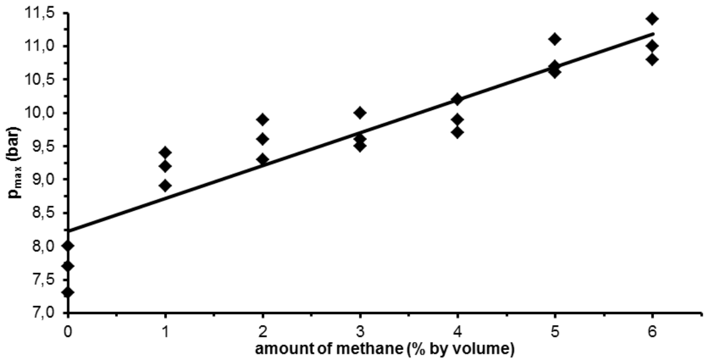


Figure 4: The effect of addition of methane on maximum explosion pressure of mixture of black coal dust with air

Figure 5 presents the effect of addiction of small amount of methane on normalized maximum rate of explosion pressure rise of mixture of black coal dust with air according to cubic law.

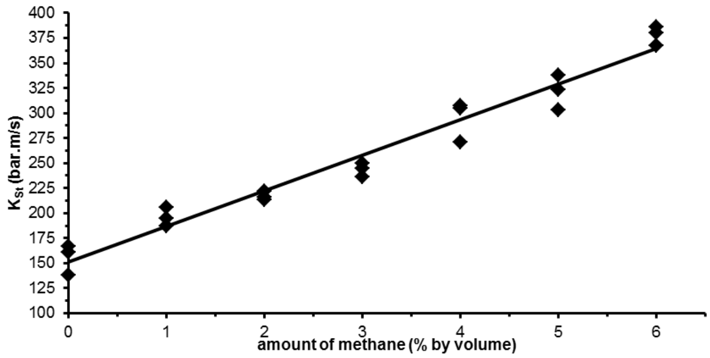


Figure 5: The effect of addiction of small amount of methane on normalized maximum rate of explosion pressure rise of mixture of black coal dust with air

7. Conclusions

Our measurements confirmed theoretical assumptions, that the addition of small amount of combustible gas methane to the mixture of coal dust with air will cause linear increasement of explosion parameters, especially the maximum rate of explosion pressure rise. The value of maximum explosion pressure is less influenced. Compared to pure dust/air mixture, the rise was 46 % at the addition of 6 % of methane. This rise of 46 % is significant, compared to other authors works (usually the rise is c. 10 – 15 %). It is presumed that this is caused by the characteristics of measured coal dust itself. Very fine dust of particle size < 40 μm (0.040 mm) with high percentage of subtle parts was used. The maximum rate of pressure rise at the addition of 6 % of methane increased by 143 %, compared to pure dust/air mixture. This increasement meets theoretical assumptions and is similar to measurements presented by other authors.

Acknowledgment

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