PREVENTION AND SUPPRESSION OF EXPLOSIONS in GAS-AIR and DUST-AIR MIXTURES USING POWDER AEROSOL-INHIBITOR

Mikhail Krasnyansky, Independent Scientist, PhD (USA)

Abstract

The prevention and suppression of explosions is a very topical field of research because annually hundreds of coal mine workers became their victims. In this research a very effective powder "PSE" ("powder for suppression of explosions") for the suppression of explosions has been developed and tested. The experiments on suppression of explosions of a methane-air mixture (MAM) at a laboratory conditions using "PSE"-powder have been carried out. The possibility of lowering the power of coal-dust explosion with the help of a "PSE"-powder has been investigated. The feasibility of almost instantaneous disperse of powders using intentionally created mini-explosions (ammonal) was investigated. The barrel-suppressor of explosion in the experimental adit (tunnel) was studied and the large-scale tests for suppression of MAM-explosions in experimental adit were also subjects of study.

Keywords: explosions, suppression, prevention, inhibition, powder aerosol.

1. Introduction

The problem of prevention and suppression of gas-and-air and dust-and-air mixtures explosions is extremely important because such explosions are the major source of frequent human deaths and financial damage at coal-mining and other enterprises.

For example, in Ukraine (in Donbass) six large-scale explosions occurred at a number of coal mines during the last five years and one of which took away the lives of 254 miners. Hundreds of miners die annually during explosions at Chinese coal mines.

However the scientific literature doesn't provide authentic data on cases of the successful explosions prevention at really existed coal mines.

2. Experimental

We have conducted experiments aimed at the identifying of ways how to prevent and suppress explosions of mixtures composed of i) methane + air (MAM) and ii) methane, coal-dust and air mixtures (MDAM) using «PSE» aerosol powders (see paragraph 3). The average initial diameter of the powder particles was within the range of 30-40 microns.

The following four sets of experiments were carried out:

A. Experiments in a Laboratory Chamber. For this set of experiments an impaction tube (diameter 0.1 m; length 1.5 m) equipped with the peripheral detectors providing automatic registration of all initial and final parameters was used (fig. 1). The experimental procedures in the explosive chamber were the following. Firstly, a vacuum ($1.1 \cdot 10^{3}$ Pa) was created using the pump 15, then the chamber was charged with the subsequently injected MAM and PSE. In other procedures, for example to simulate the *prevention* of the explosion MAM and PSE were introduced to the chamber simultaneously. During simulations of the *suppression* of a spreading explosion the PSE was injected 50 milliseconds later.

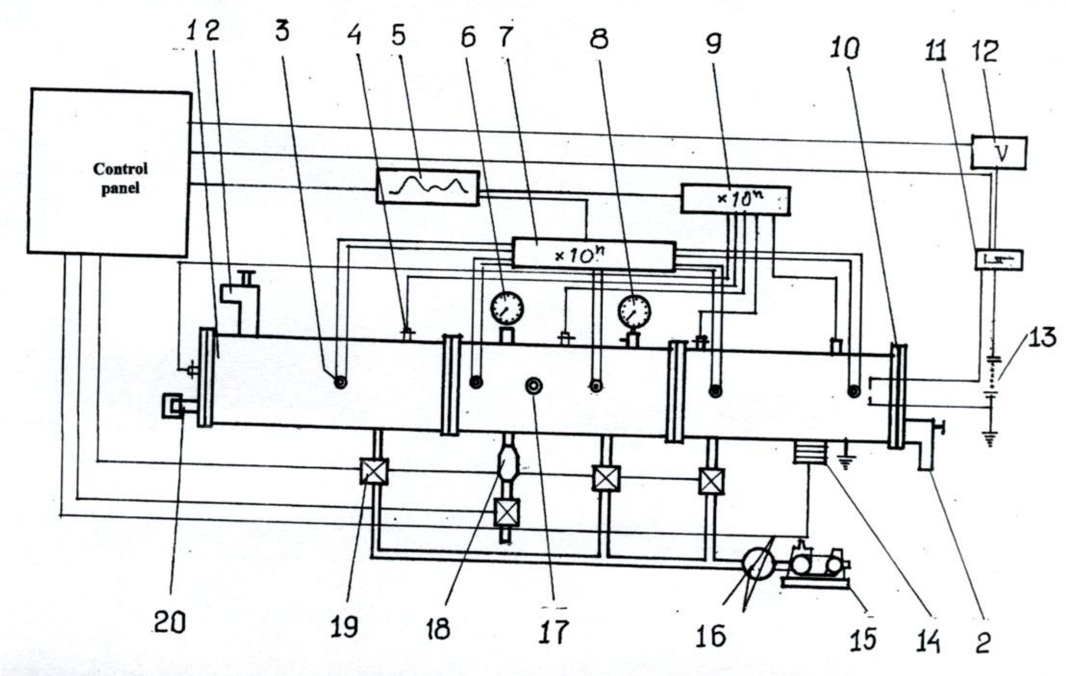

Fig. 1 - Laboratory installation for the research of explosion-suppression efficiency using powders

1 - chamber for detonation of gas mixtures; 2 - gate for sampling gas; 3 - photodiode; 5 - oscilloscope; 6 - vacuum gauge; 7 - amplifier of the photodiode signal; 8 - manometer; 9 - amplifier of a tension; 10 - electrical ignition; 11 - high-voltage contactor; 12 - source of a high voltage; 13 - high-voltage condenser; 14 - vacuum - contact; 15 - vacuum pump; 16 - three-running tap; 17 - automatic sampling of a powder; 18 - mixer for the preparation of gas mixtures; 19 - tap; 20 - powder sprinkler.

B. Experiments in a restricted tube. In a metallic tube of large diameter (diam. 1.45 m, length 150 m; the tube is closed from one side) - fig. 2.

C. Experiments in a concrete adit (tunnel) - 1.7m x 1.8m x 180m; the tunnel is closed from one side. Our numerous experiments in the tunnel have shown frequent cases when the dense "powder cloud" suppresses explosion, but in some seconds after the partial precipitation of cloud a flame appear suddenly which "jumps out" (penetrates) the border of a cloud and runs away through the "non-burnt" MAM (which

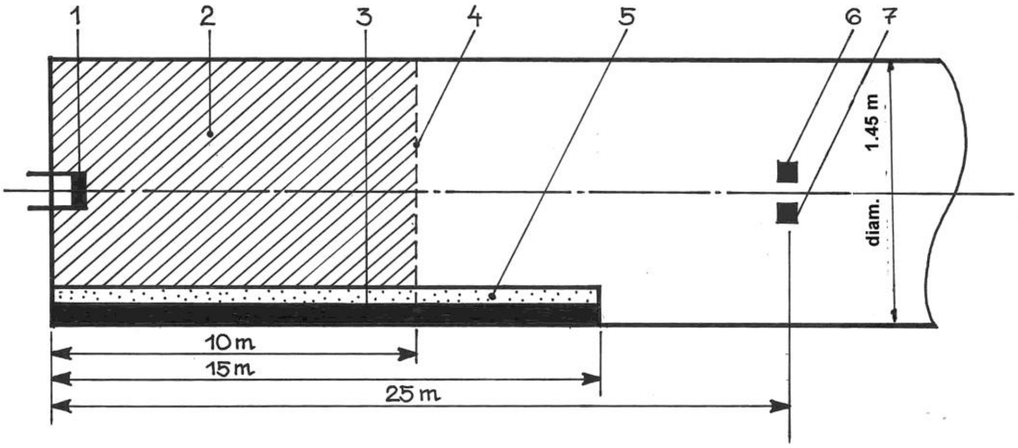

Fig. 2 - The schema of testing in the experimental tube
1 - detonator; 2 - MAM (10% CH_4); 3 - coal dust; 4 - polyethylene membrane; 5 - PSE-powder; 6 - pressure-detector; 7 - flame-detector.

the blast wave allocated along all the tunnel) for 50-100 meters. Therefore we consider the experiment on the explosion suppression as successful one only when the detector moves for 100 m from the center of explosion and when it doesn't fix a flame.

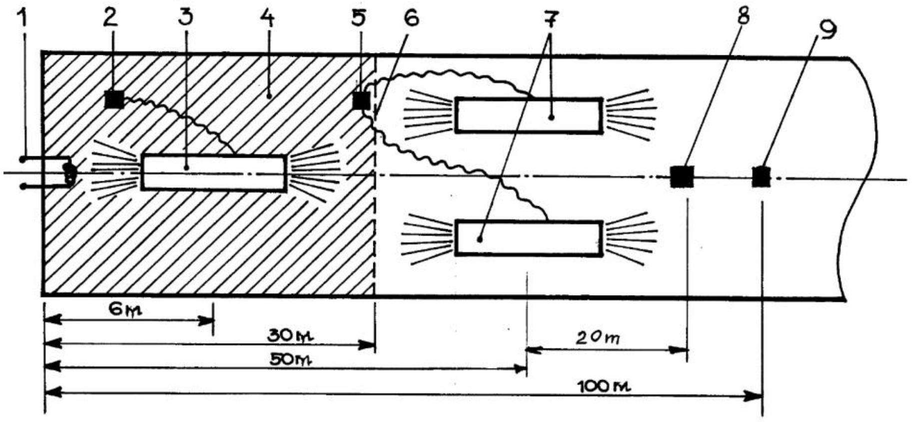

Fig. 3 - The schema of testing in the experimental edit (tunnel)
1 - electrical ignition; 2, 5 - explosion-detectors; 3, 7 - suppressors with "PSE"; 4 - MAM (10% CH_4); 6 - polyethylene membrane; 8 - pressure-detector; 9 - flame-detector.

D. The measurement of the KCl-"cloud" diameter at its dispersion by energy of the "mini-explosion" and also the moment of the suppressor operation with the PSE-powder were fixed with the help of a high-speed movie camera.

3. Selecting an optimal powder composition

It is important to understand that the physical and chemical processes in the epicenter of an explosion essentially differ from normal processes of combustion, therefore the conventional fire-extinguishing agents and equipment (among these are the pyro-aerosols) are completely inadequate to deal with such explosions. Firstly, because of their low ability for the quick heat absorption and secondly, because their responsive-operation time (in average, 1-5 minutes) is too long.

The velocity of movement of an exploding MAM in the first part of its way (10-50 m from the ignition point) increases to 200-300 m/s (Fialkov, 1996). After 150 m of way it is close to the detonation velocity (1500-1800 m/s). This implies that at the distance from the location of the MAM flash up to the nearest explosion-protection systems, for example, 20 m the explosion "would run" this distance for 0,07-0,1 seconds. I.e. these split seconds are that maximal duration which is necessary for the full operation of an automatic system of explosion extinguishing.

The powder selected for the suppression of explosions needs to be very different from the conventional fire-suppressing powders since the reactions taking place during burning greatly differ from those in the epicenter of an explosion. If in a flame free radicals are formed by means of the chain reactions of type $O_2 + H = O + OH$ or $CH_4 + OH = CH_3 + H_2O$ [Semionov, 1957; Gardiner-Jr, 1985), then the temperature in an epicenter is >2000 °C and there is a direct destruction of chemical bonds between atoms of fuel and oxidizer: $O_2 = O + O$ or $CH_4 = CH_3 + H$ (Basevich, 1975).

We have selected two substances which we believe will be efficient in removing heat from the epicenter of the explosion- $(NH4)_2SO_4$ (ammonium sulphate) and $(NH)_2CO$ (urea). The simple calculations with the use of the traditional thermochemical and thermodynamic methods of the heat absorption arising from their complete decomposition give the result - 4,7 kJ/g for $(NH4)_2SO_4$ and 5,5 kJ/g for $(NH)_2CO$ (for reference: water - 3,6 kJ/g).

The ammonium phosphate and urea DTA analysis show that the ammonium phosphate essentially loses its weight starting from 180 up to 250°C (in 32 minutes 40 % weight loss), while urea in the interval of 130-340°C for the SAME TIME loses 60 % of its weight.

We have measured the "duration of a semi-decomposition" of these substances (i.e. the relative time of loss of half of weight at heating in the vertical ceramic furnace at 1000°C; a ceramic vessel with the substance drowned in a furnace is fastened to the metal thread of electronic scales; the "duration of a semi-decomposition" of $NaHCO_3$ is accepted as a unit). This clearly demonstrates that this parameter for $(NH_4)_2SO_4$ (466,8) is 85 times higher than for $(NH)_2CO$ (5,5). It means that while 1 gram of the ammonium sulfate will be fully destructed having swallowed up at a flame 4,7 kJ, the urea will have swallowed up 85 x 5,5 = 467 kJ. I.e. at the explosions suppression the kinetic parameters have much greater values, than thermodynamic ones!

In order to intensify the explosion-suppression effect we have added a well-known inhibitor KCl (Jensen, 1979) (moreover, the researches made by V. Pak show that KCl is evaporated in a flame (Pak, 1985). In the article (Corecki, 1987) the influence of the fine-pounded inorganic salts on the suppression of coal dust explosion was investigated; the following results were obtained: $(NH_4)_2SO_4$ - 16,7 mas.%, $NaHCO_3$ - 32 %, KCl - 35,2 %. Thus, the explosion-suppression "PSE"-powder of the following optimum structure has been elaborated: urea-78%, KCl- 20%, modified fumed silica (aerosil SiO_2---CH_3) - 2%. The average diameter of particles of the powder should be between 30-40 μ (rationale of the surprisingly large diameter - see below).

4. Results and Discussion

4.1) Two series of the explosion-suppression experiments were carried out in the laboratory tube. It is necessary to note that real speeds of the MAM-burning at coal mines and other similar tunnels (which have a correlation diameter/length 1:15-1:45) have quantity within the limits of 200-800 m/s, i.e. "between" the deflagration and the detonation (it is area of the "double non-stationary bursts (tearings)" – this study is executed by the Academy of Sciences of the USSR (Shchelkin, 1963).

In the first series the prevention process was simulated and the PSE-powder was added to the MAM simultaneously with the ignition (Fig. 4). In the second series to simulate the suppression of a spreading explosion the powder was added to MAM 50 milliseconds after the ignition (Fig. 5).

As can be seen on the Figure 4 the explosion is prevented at the 10 g/m^3 concentration of the powder (curve 5); at the lower concentrations (2.9, 5.6 and even 8.5 g/m^3) the explosion continues with almost no decrease in the maximum pressure. In other words, the process of prevention of the explosion has distinctly «threshold» nature: if 100% of a concentration of the agent for the suppression of explosion is not present inside the volume

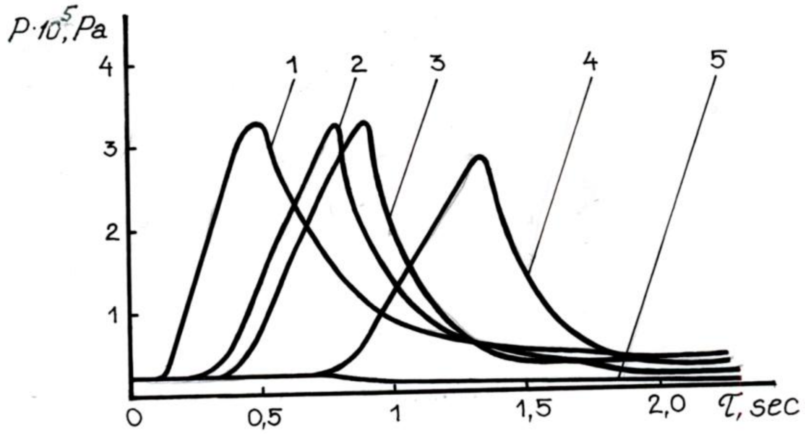

Fig. 4 - Explosion prevention of a methane-air mixture (MAM) by "PSE"-powder at the initial stage in a laboratory tube:
1-pure MAM; PSE concentrations in MAM: 2- 2.9 g/m^3; 3- 5.6 g/m^3; 4- 8.5 g/m^3; 5- 10.1 g/m^3 (explosion is prevented at the initial stage)

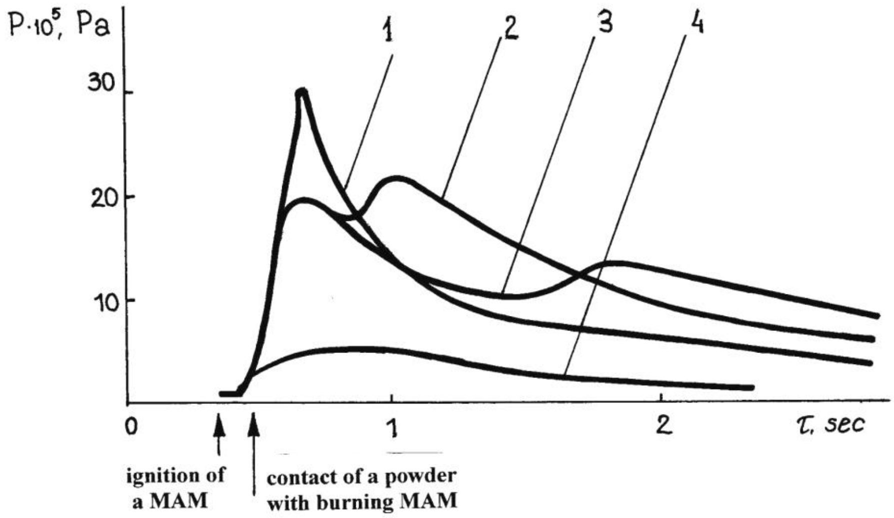

Fig. 5 - Suppression of the developed methane-air mixture explosion (MAM) by "PSE"-powder in a laboratory tube:
1- pure MAM; PSE concentration in MAM: 2 - 290 g/m^3; 3 -330 g/m^3; 4- 420 g/m^3 (explosion is suppressed)

then the effect of the explosion prevention is eliminated (even with 90% concentration achieved!). But the presence of some quantity of powder aerosol in MAM not influencing on the explosion pressure considerably influences on other parameter- the lagging time of explosion (the time of induction). On the Figure 4-5 it can be seen by lengthening of the left acclivous part of curves 1-4: in the lagging of the explosion of pure MAM was 100 milliseconds (curve 1), it increases three times when 5.6 g/m^3 of PSE-powder is added to MAM and in seven times when 8.6 g/m^3 is added.

In case of suppressing the developed explosion (fig. 5) the increase of the volume concentration of the PSE-powder in MAM evidently causes the decrease of a maximum gas-pressure from $29 \cdot 10^5$ Pa for pure MAM down to $19 \cdot 10^5$ Pa (330 g/m^3, curve 3). It is interesting that there is a second maximum on the curve ($13 \cdot 10^5$ Pa) which is explained by the secondary ignition of MAM after precipitation of the main part of the PSE-powder "aerosol cloud" mass. At last, at the concentration of 420 g/m^3 the suppression of the explosion has occurred (curve 4) - the gas-pressure sharply decreases to zero. It should be noticed that for the suppression of the initial stage of the explosion the consumption of the powder inhibitor is 40 times less than for the suppression of the gas-air-mixture burning and which reached high speeds, close to a detonation. These data are close to Sholl result (Sholl, 1979)**,** where flame with the speed of 70 m/s was suppressed by 6.5 kg/m^2 of a powder («Tropolar»), and with 2000 m/s - 210 kg/m^2, i.e. 30 times more.

4.2) There are two principal methods of supplying inhibitor to the epicenter of an explosion: i) using the energy of a compressed gas (as in fire-extinguishers) and ii) the method in which the energy of the "micro-explosion" of a small quantity of an explosive (of ammonite type) is used. For the purpose of the explosion suppression, taking into account the very short time limit of 100 milliseconds, the only practical method is the second. In our experiments the KCl powder (with the average diameter 250 microns) was placed into thin polyethylene bag together with the ammonite and detonator (3.4 kg of KCl and 0.15 kg of ammonite) - Fig. 6. Judging by Fig. 6 the «powder cloud» of 3 m in radius formed within 20 milliseconds after detonation (after spraying by explosion of the ammonite). The fractional analysis of KCl powder particles (using copper sieves and phase-contrast optical microscopy at 945 x magnification [**1**]) showed that using the explosion method an additional milling effect on the particle size arising from the energy of explosion is also present.

For example, before spraying the average diameter of the KCl particles was 250 microns, while after spraying with the help of ammonite it became 8-9 times less, i.e. 25-30 microns (Table 1).

Table 1. Milling of KCl particles by energy of a mini-explosive explosion

Fraction, μ	Mass part, %	
	before spraying	after spraying
more 1000	11.7	1.0
1000-400	37.8	3.7
400-200	21.1	8.5
200-100	15.8	20.3
100-50	6.7	14.2
less 50	5.9	52.3

Thus, using the explosion energy to spray powder aerosol provides the required speed of action of the explosion-suppressing devices. In addition, the efficiency of the powder aerosol is increased, firstly, due to the considerable increase of the fine fraction (i.e. of the total aerosol surface) and secondly, due to the fact that this surface is freshly-formed and has a high chemical activity. For this reason, the optimum particles size of powder for the explosions suppression (in contrast to an extinguishing aerosol) should not be less than 30-50 μ. To mill such powders to still smaller particles sizes would be superfluous, because it is made by the explosion energy!

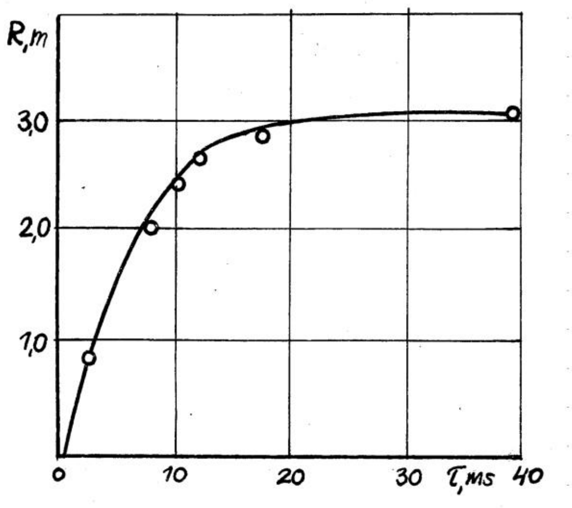

Fig. 6 - Dynamics of increase of the KCl "aerosol cloud" radius vs time during its dispersal by mini-explosion

5. Large-scale tests on explosion suppression

5.1) The testing of PSE-powder efficiency under the conditions of suppressing dust-and-air mixtures explosions has been carried out in a metallic tube (diam. 1.45 m, length 150 m; the tube is closed from one side; Figure 2). The 15 m of the adit (tunnel) was coated with the coal dust (20 kg), and above it the PSE-powder was placed (4 kg), i.e. the ratio is 0.2 kg of powder per kg of coal dust. At ten meters distance from the source of ignition in the tunnel a polyethylene diaphragm was placed and the closed volume (30 m^3) was filled with the methane to reach its final concentration of 10% in the air. The monitoring of the explosion was carried out with pressure detectors (PD) and a flame detector (FD) placed at 25 m distance from the source of ignition.

The researches of some authors (for example (Ishihama, 1979) showed that a large mutual decrease in the limits of the methane-air and coal dust mixtures ignition takes place. For example, the upper limit of explosion of a coal dust doubles at the presence of the methane (6 %) in the air (from 1500 up to 3000 g/m^3) and presence in the air of a coal dust of 50-100 g/m^3 in 2,5 times lowers a limit of the methane ignition (from 5 up to 2 %).

In a coal dust explosion in the experimental adit "Tremonia" (Germany) with a cross-section of 8 m^2 the maximal pressure of explosion was found to be $18{\cdot}10^5$ Pa (Michelis, 1987).

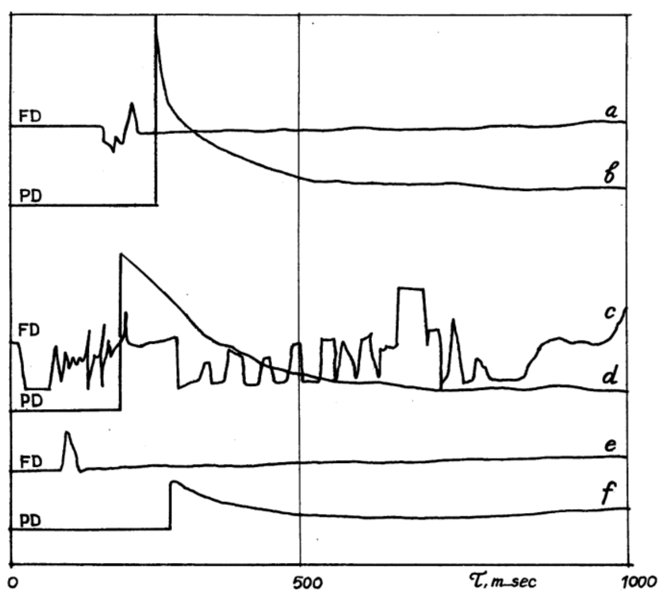

Fig. 7. - Oscillogram of the methane-air mixture (MAM) and coal dust

explosion in experimental tube:
a, b- pure MAM; **c, d**-MAM and coal dust (1 kg/m^2);
e, f- MAM, coal dust (1 kg/m^2) and PSE (0.2 kg/m^2)

On the Fig. 7 the typical oscillogram of these processes is shown. When the explosion of "pure" MAM takes place the detectors show the presence of a flame (curves a, b). During the methane and coal dust explosions (curves c, d) the explosion's pressure increased to $6{\cdot}10^5$ Pa (due to participation of coal dust). At the same time, the FD registered almost continuous outbursts during the period up to 1 s (curve «c»), this underscores the danger of the uncontrolled coal dust at coal mines. During the next experiment the coal dust had been strewn by PSE at a ratio of 0.2 kg per kg of dust. The outburst of MAM from the source of ignition (curve «e») took place at a low explosion pressure - $1.2{\cdot}10^5$ Pa (curve «f»); further, practically straight lines are observed in the oscillogram - it denotes suppression of the MAM explosion by powdered PSE and the nonparticipation in explosions of a coal dust owing to its inhibition the same PCE-powder.

5.2) For the large-scale tests we have elaborated an automatic powder explosion-suppressant device consisting of a single or several barrel-type sprayers and explosion detectors capable to instant operation. (fig. 8, 9).

The suppressor was developed on the basis of the open-ended glass-plastic tube of 0.2 m in diameter and having the length of 1.3-1.5 m; the detonator connected to the detector via amplifier is located in the middle of the tube. The rubber "cartridge" (bung) is intended to smooth out the maximum pressure onto the suppressor walls during the explosion of a mini-explosive. The tube is filled with PSE-powder from both sides (10 - 15 kg on each end). The ends of the tube are covered with an airtight polyethylene diaphragm and are supplied with special metallic annular sprayers. The mini-explosive operates in response to a signal from the detector and within 100 milliseconds on both sides of the suppressor a powder cloud with the length of 20-25 m is formed. The ejection of powder on both sides of the sprayer has two advantages: a) there is no «recoil» during operation b) even after successful suppression of an explosion the flame still often penetrates behind the suppressor, that is why it is also desirable to have a

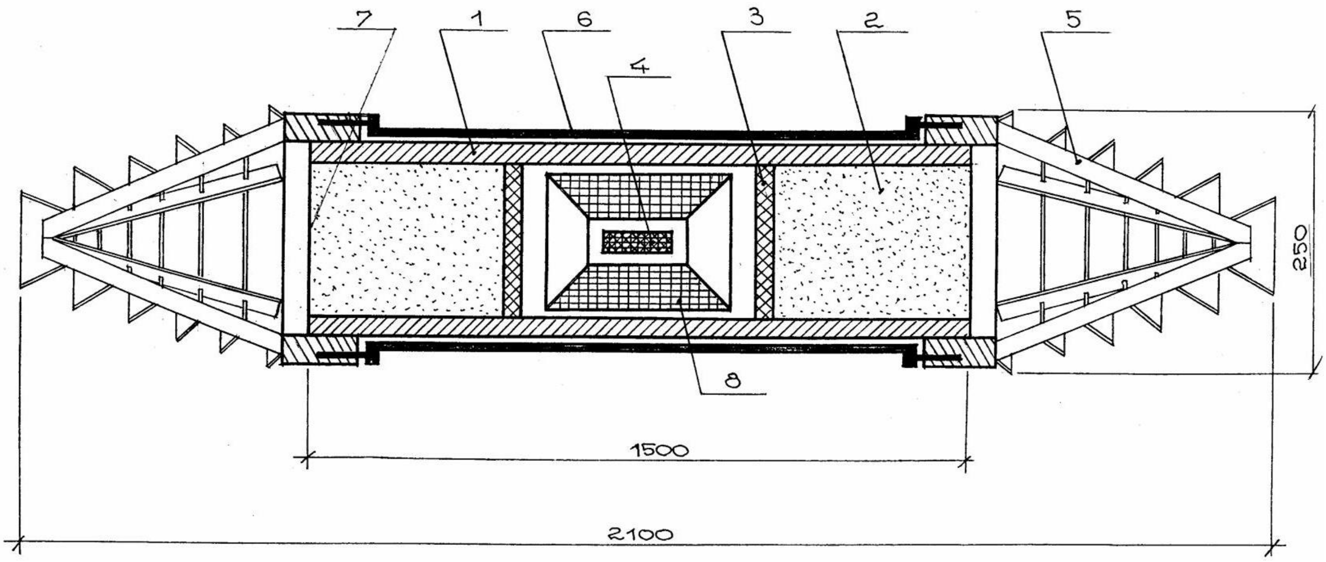

Fig. 8. - Automatic double-action explosion suppressor:
1 -1500 mm in diameter and 200 m long glass-reinforced plastic tube; 2- PSE-powder; 3- porous- plastic stopper (wad); 4- explosive substance (ammonal) with detonator; 5- metal dissector; 6- metal coupling; 7- thin polyethylene membrane; 8- rubber cartridge for absorption of explosion energy.

powdered cloud behind on the length of 10-15 m (for additional safety). The scheme of application of the explosion suppression device is given on the Fig. 3.

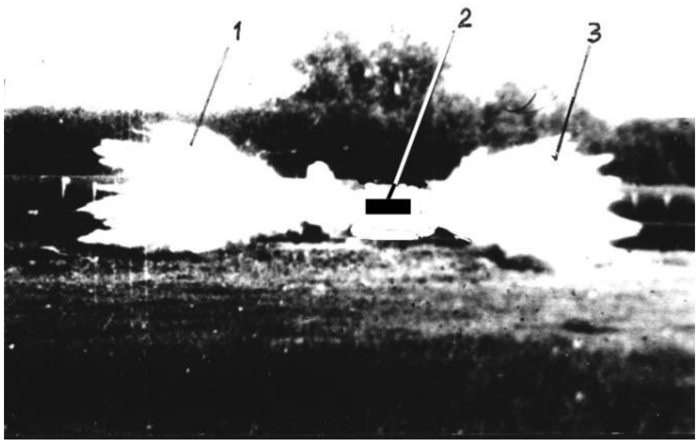

Fig. 9. Explosion suppressor at the moment of action
1, 3 - "aerosol cloud" (PSE-powder); 2 - suppressor.

Note: This suppressor was created for carrying out large-scale tests on suppression of explosions of methane in an experimental tunnel. For the use at a coal mine it will have to be modified and undergo more exhaustive testing.

5.3) The suppressors were tested in a concrete experimental tunnel (adit) - 1.7x1.8x180 m (fig.3). The 30 m of the tunnel were separated by the polyethylene membrane and this space was filled with 10% MAM. The electrical-ignition was made from the edge of the gas-filled section. A single suppressor (3) was placed in the gas-filled zone at a distance of 6 m from the ignition, and the non-inertial detector of explosion (2) was close to the point of an ignition (simulation of explosion prevention; suppressors 7 and detector 5 - were disabled). The detectors (2, 5) had function for the instant start of the suppressors only.

For simulation of the developed explosion two suppressors (7) were placed beyond the gas-filled space and the detector (5) was in front of polyethylene membrane (suppressor 3 and detector 2 - were disabled). The result of operation of suppressors was fixed by the detector of pressure (8) and by the detector of flame (9). The flame velocity was calculated based on the oscillograms (flame-velocity up to 120-180 m/s). The test was considered successful if after operation of the suppressors not only the explosion-detector (8) did not register the pressure but and the flame-detector (9) did not register the outbreak of the flame.

<u>The results of the experiments:</u>

A) In the case of the prevention of explosion imitation (flame-velocity up to 25-35 m/s) the PSE ratio is 0.15 - 0.2 kg/m^3 of the volume being protected;

B) In the case of a developed explosion (flame-velocity up to 140-170 m/s) - the PSE ratio varies from 0.7 - 0.9 kg/m^3;

C) With the flame velocities more 200 m/s all currently available automatic means of the explosion protection are useless.

Conclusions and recommendations

The above described laboratory investigations allow us to make the following conclusions:

1) The process of explosion suppression has a «threshold» character, i.e. for the suppression of explosions it is necessary to have strictly 100% of the explosion-suppressing agent simultaneously in each "micro-volume" of the space being protected.
2) Because the delay time of pure MAM explosion is approximately 100 milliseconds, it must be the complete maximum time of duration of an operation of the system of explosion protection as a whole.

3) Momentary and complete spraying of the explosion-suppressing powder aerosol is possible only using the energy of explosion of a mini-explosive.
4) With the increase in speed of a blast wave from 20-30 up to 180 m/sec (i.e. at the transition from the prevention of explosion to its suppression) the consumption of a powder grows very sharply.
5) The most promising components of powder aerosol for the protection or suppression of explosions are urea, KCl and $NaHCO_3$.
6) The following consumption rates of powder inhibitor were established:
   - for the prevention of an explosion (flame velocity up to 35 m/s) between 0.15 and 0.20 kg/m^3
   - for the suppression of a developed explosion (flame velocity up to 180 m/s) between 0.7and 0.9 kg/m^3
   - for the prevention of coal dust explosion- 0.2 kg per 1 kg of coal dust

♦ on the fig. 10 the probable scheme of application of powder-suppressors for the prevention of explosions at coal mine is shown.

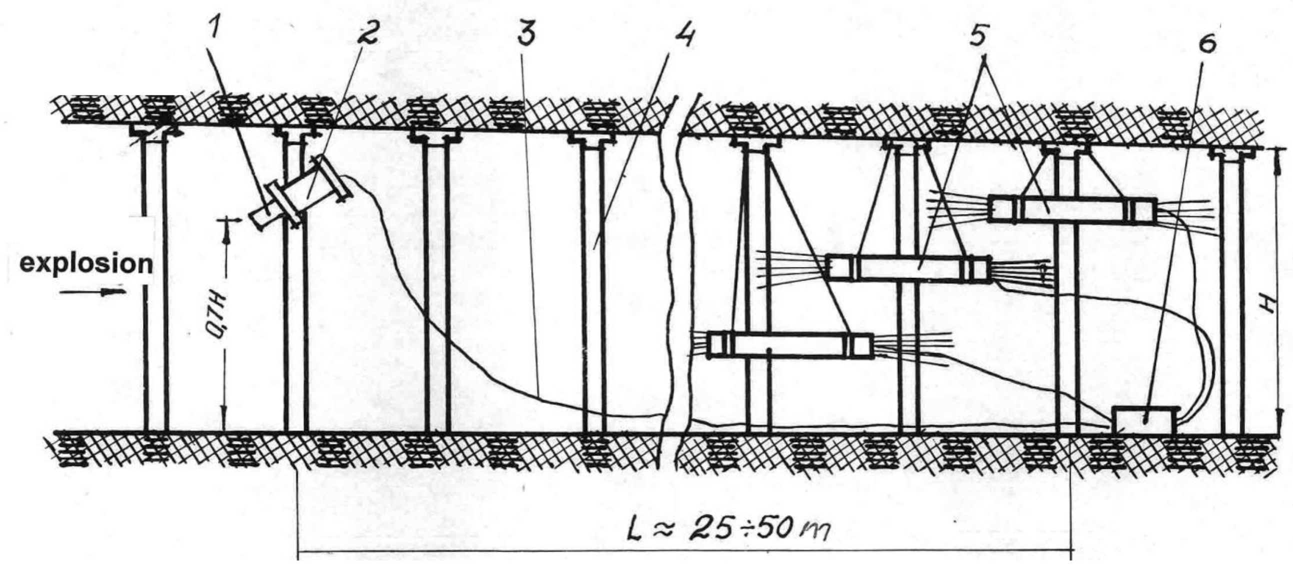

Fig. 10 - Automatic system for the suppression of explosions using PSE-powder:
1 - explosion-detector; 2 - metallic safety; 3 - communication cable; 4 - adit column;
5 - suppressors; 6 - electronics.

References

Fialkov B.S., & Shebeko Yu.N. (1996). Researches of distribution of a flame in big semi-open pipe. *Journal Fire-explosion-safety (Moscow),* 1, 20-24.

Semionov N.N. (1957). *About chain reactions and the theory of burning. The Nobel lecture*. Pre-print of the Academy of Sciences of the USSR. 1-32.

Gardiner-Jr W.C. (1985). *Combustion chemistry*. New York-Berlin-Heidelberg-Tokyo: Springer-Verlag.

Basevich V., Kogarko S, & Posviansky S. (1975). Kinetics reactions at distribution of a methane-oxygen flame. *Physics of Combustion and Explosion (Russia),* 2, 242-247.

Jensen D.E. Jones G.A., & Mace A., & Christopher H. (1979). Inhibiting the flame by a potassium. *Journal Chemical Society Faraday Trans.* 10 (75), 2377-2385.

Pak V., & Hieftje G.M. (1985). Evaporation of particles of chlorides of alkaline metals in a flame. *Spectrochimical Acta.* 1-2 (40), 209-216.

Corecki J., & Szkred T. (1987). Influence of inorganic additives on explosion hazard of a coal dust. *Proceedings of the I Shenyang International Symposion Dust Explosions, Shenyang, China* (p. 528-538).

Shchelkin K.I. (1963). *Gas-dinamic of burning*. Moscow: Academy of Sciences of the USSR.

Sholl E. V., & Vimann V. (1979). Suppression of explosions in mine working by automatic systems BVS. *Glukauf*. 10, 38-46.

Ishihama V., Takar I., & Elomoto X. (1979). Explosive characteristics of a mix of a coal dust, methane and air. *Proceedings of the XVIII Internanional Conference Combustion. Dubrovnik, Yugoslavia* (p. 179-194).

Michelis J., Margenburg B., & Muller G., & Kleine W. (1987). Large-scale experiences on studying explosions of a dust in a 700-meter adit. - Archives Combustion. 1-2 (7), 127-143.

*****

Note. The full text of article is published: "Journal of Loss Prevention in the process industries", 19, 2006, p. 729-735