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Effectiveness of an active dust and gas explosion suppression system☆

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Abstract

The research aimed to test the effectiveness of gas and dust explosion suppression by means of a super fast explosion suppression system with a volume of 5 dm^3. Smokeless powder as an explosive charge and sodium bicarbonate as a suppressing material were used. The experiments were carried out using a prototype device – a 5 liter steel container, closed by means of an aluminum membrane. Approximately 1.75 kg of extinguishing powder was placed in the container. The membrane was ruptured by exploding a specially developed charge located inside a perforated steel combustion chamber and mounted over the suppressing powder surface. The system was triggered by a signal from the protected volume, sent by a pressure transducer or by a photodiode reacting to a developing flame. The investigations into the efficiency of the active explosion suppression system were carried out in the 1.3 m^3 explosion chamber. The explosion was initiated in a corn starch-air mixture of 0.2 kg/m^3 concentration, or in a methane-air mixture of 7.5% and 8.5% CH_4 concentration. The explosion suppression process occurred through the action of the extinguishing powder blown out from the extinguisher after the compressed combustion products perforated the membrane.

Keywords: dust explosion, suppressing materials, active explosion suppression systems

1. Introduction

Dust-air and gaseous mixtures present an explosion hazard in various industrial environments [1–8]. As part of the workplace safety regime, active explosion suppression systems using extinguishing powders or water are becoming more widespread [9–19].

Explosions at industrial plants usually originate inside tanks, technical systems or corridors, and only later spread through the entire system before finally emerging outside. The best way to prevent major damage to industrial facilities and avoid possible loss of life is to suppress the explosion inside the plant and thereby minimize and ideally localize the resulting damage. To this end automatic explosion suppression systems have been developed [20]. They are designed to deliver early detection of a developing explosion and immediate suppression. The duration of a typical dust explosion inside a tank with a volume of several cubic meters is several tens to several hundred milliseconds. The explosion

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should be suppressed within several milliseconds from initiation, otherwise it may lead to an excessive increase in pressure inside the tank. To meet this extreme requirement, the extinguishing agent must be sprayed at the high speed of about 100 m/s.

Typical devices used in automatic fire extinguishing or explosion suppressing systems are as follows:

- a cartridge mounted inside the protected object and filled with an extinguishing agent which contains a detonator inside. The explosion causes the extinguishing material to disperse throughout the entire volume of the protected facility,
- a cylinder filled with extinguishing agent and compressed gas, e.g. nitrogen, with a valve opened by a signal sent by a detector,
- a container with extinguishing material dispersed in the protected area by the gases produced inside the container by a powder charge explosion.

In every case, the system is triggered by a pressure or optical signal sent from the detector reacting to the developing flame.

In the Combustion Laboratory of the Institute of Heat Engineering, a super-fast, active explosion suppressing system has been tested over a period of several years, [15–17]. The proposed technique is based on the active interaction of the suppressing material on the developing explosion. The active suppression system extinguishes the explosion before it has time to develop to such an extent that can cause damage. Explosions could be detected in two ways:

- by photodiode,
- by pressure transducer.

Both methods have their advantages and disadvantages. The optical method detects an explosion by reacting to the flash of light accompanying the combustion, whereas pressure methods

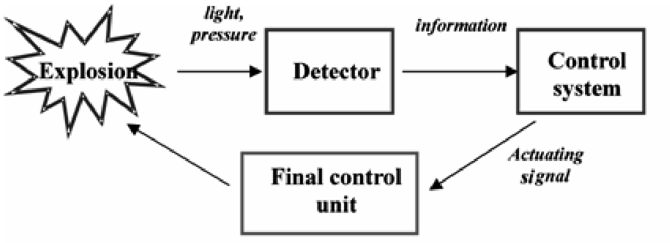

Figure 1: Principle of operation of the suppression system

are triggered by an excess pressure signal. Generally, the operating principles of both detecting systems are the same, Fig. 1.

At the moment of explosion detection, the detector sends a signal to the control system, which initiates ignition of the explosive charge located inside the extinguisher (which can be treated as the final control unit). Explosion of the powder charge causes a rapid increase in pressure in the extinguisher, resulting in rupture of the membrane, and then the suppressing material is ejected from the container and sprayed into the protected volume. The most important factors determining the effectiveness of the suppressing system are: the speed of detection and the speed of triggering the explosion suppression system. The studies that have been carried out show that effective suppression is only possible in the initial stage of the developing explosion.

This paper is devoted to research into the effectiveness of suppression of gas and dust-air explosions by using typical extinguishing powders as the suppressing material.

2. Research

2.1. Experimental stand test procedure

The investigations into the efficiency of dust explosion suppression were carried out in a 1.3 m^3 explosion chamber (Fig. 2). The explosion was initiated in a corn starch-air mixture of 0.2 kg/m^3 concentration. The corn starch dust was dispersed by a special pneumatic system containing 10 nozzles mounted symmetrically in two rows inside the chamber. The system contains one extinguisher located on the top wall of the explosion chamber. Fig. 3 shows a schematic diagram of the

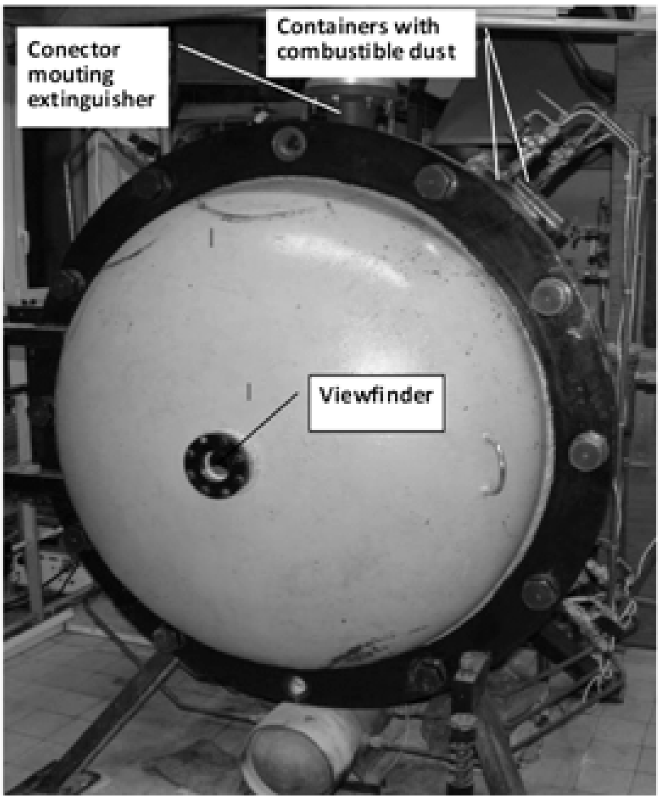

Figure 2: Explosion chamber with 1.3 m^3 volume

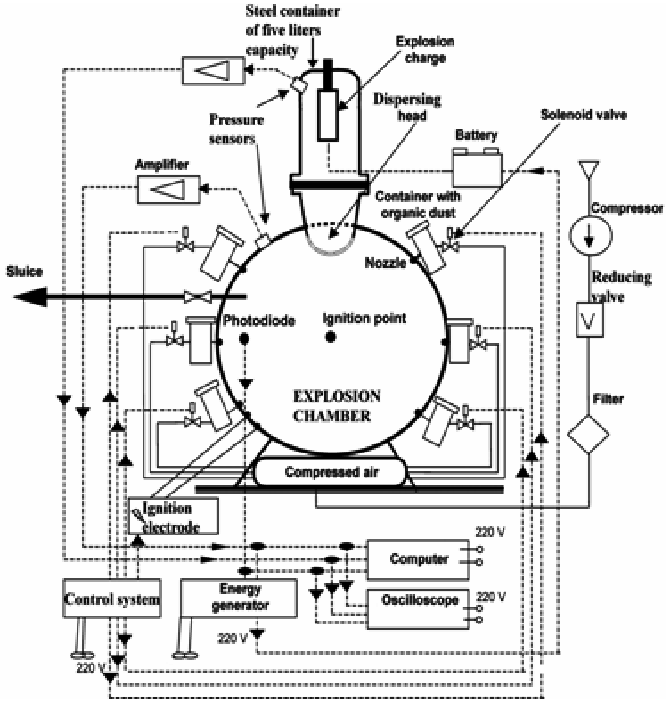

Figure 3: Schematic diagram of the research stand with 1.3 m^3 explosion chamber – for dust explosion investigations

research stand for studying the explosion suppression process including all the elements described above.

Research into the effectiveness of gas-air explosion suppression was performed in the same explosion chamber as for the dust-air mixtures. For this purpose, the test stand underwent considerable reconfiguration. Containers for organic dust, dispersing heads and power supply systems were disassembled, and then all unnecessary holes were closed and leaks sealed. Additional connections were made to enable the chamber to be filled with the gas mixture of appropriate pressure and composition. A gaseous mixture was prepared in bottles using the special stand shown in Fig. 4. The stand enabled the mixture to be prepared using the partial pressure method. The stand was equipped with steel bottles, a vacuum pump and a set of precise manometers with high reading accuracy of 0.001 bar.

As before, (e.g. for dust explosion), a conical connector was mounted at the top of the chamber to which the explosion suppression device filled with the extinguishing medium was connected. The dispersing head was mounted to the screw threaded end of the connector, inside the explosion chamber. (Fig. 5). A general scheme of the research stand for the investigation of gaseous mixture explosion suppression is shown in Fig. 6.

The main element of the suppression system is a 5 liter steel container (extinguisher) capped by an aluminum membrane (Fig. 7). Below the membrane, there is an exhaust connector pipe ending in a dispersing head. Approximately 1.75 kg of extinguishing powder was placed inside the container. The membrane was ruptured by the explosion of a specially developed smokeless powder charge, located inside the perforated steel combustion chamber (Fig. 8) and mounted over the suppressing powder surface. The gases produced during combustion of the explosive charge was sufficient to perforate the membrane and disperse the extinguishing powder into the protected volume. There was no initial overpressure inside the container.

Table 1: Sodium bicarbonate ($NaHCO_3$)

Items		Requirements
$NaHCO_3$content, %		Claimed volume±1.0
Apparent density, g/ml		≥0.85
Attractive moisture, %		≤3.0
Blocking resistance (needle penetration), mm		≥16.0
Particle distribution, %	0.250 mm	0.0
	0.250–0.125 mm	5.0±3.0
	0.125–0.063 mm	14.0±6.0
	0.063–0.040 mm	16.0±6.0
	Bottom plate	≥50.0

Figure 4: General view of the stand for precise preparation of the tested gaseous mixtures

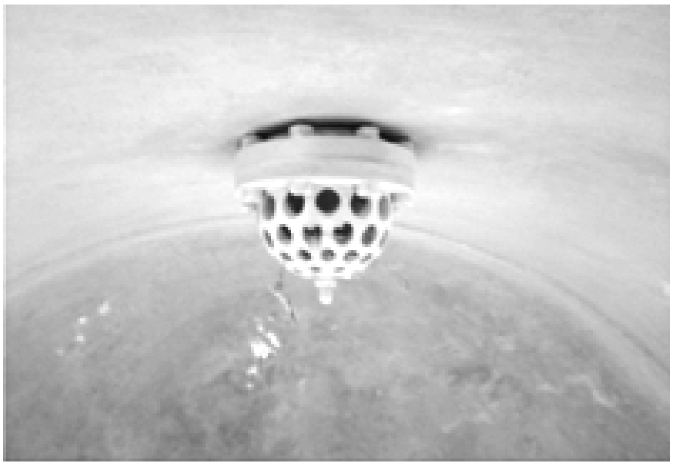

Figure 5: View of dispersing head mounted inside the test chamber

2.2. Test procedure

After filling the 1.3 m^3 test chamber with a dust-air or methane-air mix of a specified concentration, the explosion was initiated by using a chemical igniter of 2 kJ energy, located in the middle of the explosion chamber. The course of explosion pressure in the chamber was measured using a Kistler pressure transducer. The suppression system was activated by a signal from a photodiode fixed on a specially adapted sight-glass on the front wall of the chamber, which reacted to the light generated by the developing explosion. The pressure inside the extinguisher was measured using the Kistler pressure transducer in order to better identify the phenomena occurring inside the extinguisher, especially the process of voiding the container of the extinguishing powder. The extinguishing agent used was a typical extinguishing powder consisting essentially of sodium bicarbonate (BC type fire extinguishing agent), with parameters shown in Table 1. An analysis of experimental tests showed that sodium bicarbonate powder appeared to be more effective as an extinguishing medium for dust explosions [21, 22] than ammonium phosphate (ABC type fire extinguishing agent). Sodium bicarbonate, therefore,

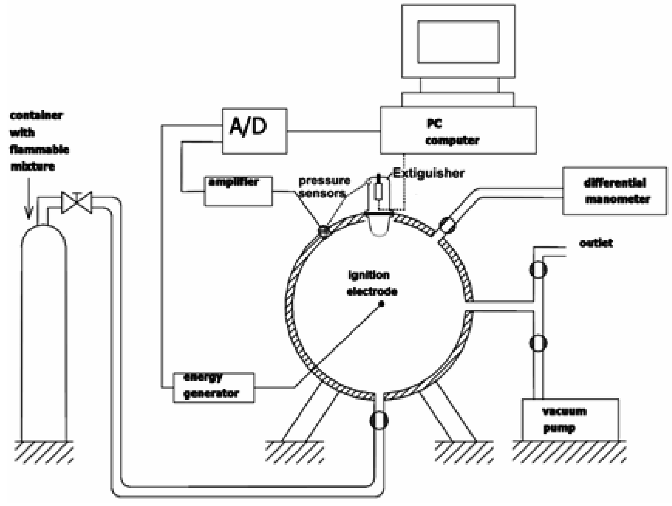

Figure 6: Schematic diagram of the research stand with 1.3 m^3 explosion chamber – for investigation of gaseous explosion suppression

was selected for use in experiments.

2.3. Experimental results

Preliminary studies were conducted prior to the basic test. They focused on verifying the correctness of all the recorded signals. The explosion suppression system was activated by a signal from the photodiode. A signal equal to 0.5 V was assumed as the extinguisher triggering signal. The dust explosion (for 0.2 kg/m^3 cornstarch dust) was initiated by using a chemical igniter of 2 kJ energy. The courses of pressure inside the chamber and voltage from the photodiode during the explosion as well as the voltage triggering signal causing extinguisher activation (e.g. causing ignition of the smokeless powder inside an extinguisher and in effect membrane rupture) are shown in Fig. 9. All signals were recorded correctly and the extinguisher triggering voltage signal occurred at the right time after the photodiode signal reached the value of 0.5 V. As can be seen, the explosion pressure for this dust mixture is approximately 5.7 bar, and the rate of pressure rise is dp/dt ~ 82 bar/s, hence the standard rate of pressure rise is K_{ST} ~ 89.5 bar·m/s.

The main parameters taken into consideration during the tests:

1. sensitivity of the suppressing system, which responds to the developing explosion (in the 1.3 m^3 explosion chamber),
2. final explosion pressure in the 1.3 m^3 explosion chamber,
3. pressure inside the extinguisher.

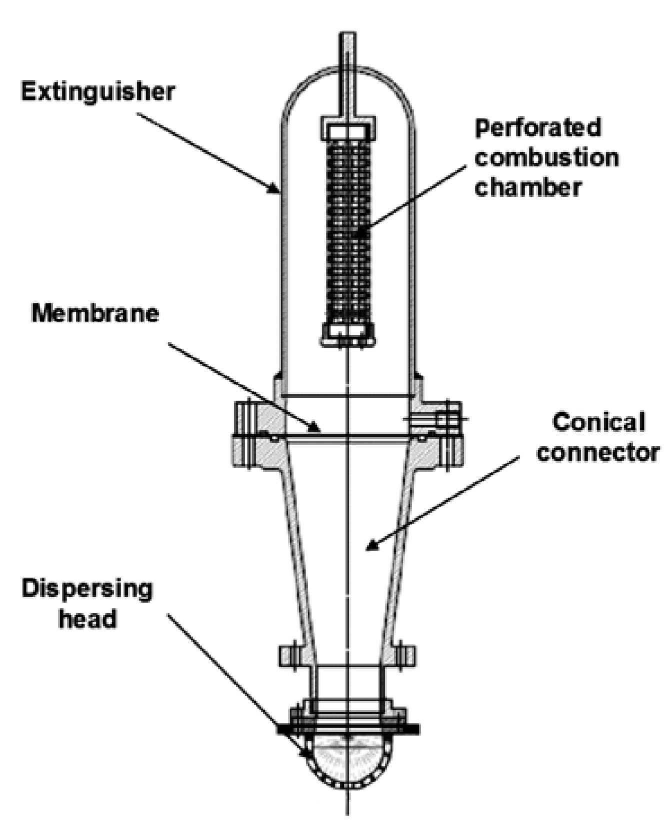

Figure 7: Schematic diagram of the extinguisher

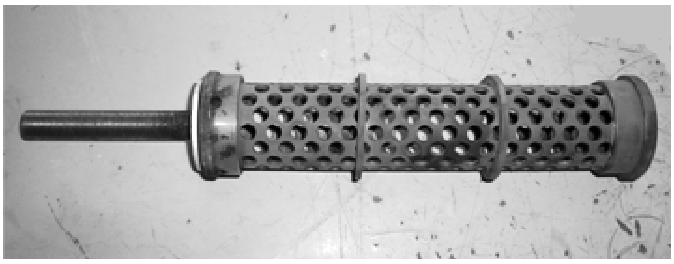

Figure 8: View of the perforated steel combustion chamber

It should be noted that the explosion pressure resulting from the developing explosion inside the chamber was considered as the pressure increase above the reference overpressure. The reference overpressure ΔP_{ref} was the sum of the overpressure growth from the pneumatic dispersion of the combustible dust $\Delta P_1 \approx 0.24$ bar, (but for the gaseous mixture $\Delta P_1 \approx 0$ bar) and the pressure increase from the activation of the extinguisher

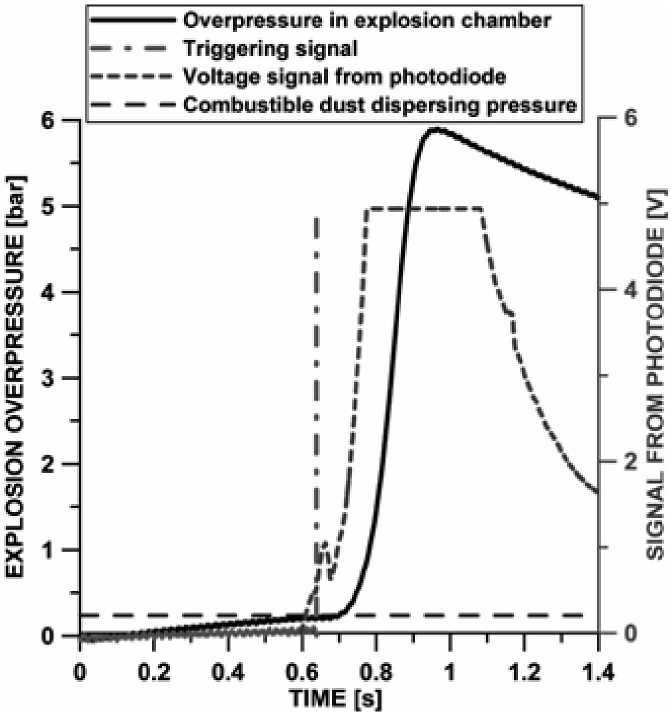

Figure 9: Courses of the overpressure inside test chamber and photodiode voltage signal obtained during explosion of the corn starch dust (C = 0.2 kg/m^3), without suppression. Explosion overpressure ΔP = 5.7 bar

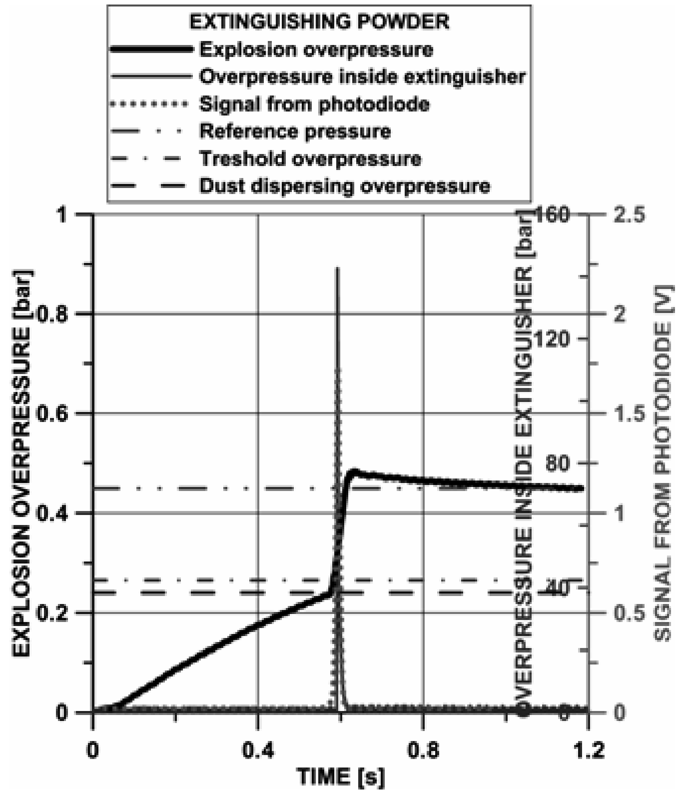

Figure 10: Courses of the overpressure inside the 1.3 m^3 test chamber during explosion of corn starch dust (C = 0.2 kg/m^3) and inside the extinguisher. Activation from photodiode signal at the level of 0.3 V. Explosion overpressure ΔP = 0.035 bar

$\Delta P_2 \approx 0.2$ bar. From the viewpoint of industrial plant safety, the threshold overpressure ΔP_T is a very important parameter, and it was counted as overpressure above the level $P_a + \Delta P_1$ (where P_a is atmospheric pressure) at which the suppression system is activated.

The example results of the experimental dust explosion suppression process are shown in Figs. 10–12. The assumed levels of the photodiode triggering signal were 0.3 V, 0.6 V and 1.0 V respectively. The aim of subsequent experiments, of which the results are presented in Figs. 10–12, was to show how increasing the level of the triggering signal from the photodiode affects the efficiency of explosion suppression. The voltage generated by the photodiode increases along with the increase in luminous intensity of the light source incident on the photodiode (in this case it is associated with the increased intensity of the explosion). Increasing, therefore, the level of the triggering voltage signal from the photodiode causes a delay in activation of the explosion suppression system, (because to obtain a sufficiently high voltage generated from the photodiode, there must be an appropriate development of the explosion). A sufficiently high level of the triggering signal from a photodiode can be very important in relation to the safety, reliability and stability of the active explosion suppression system.

The best results were obtained when the system was triggered by a signal from the photodiode with the level 0.3 V (Fig. 10). Fig. 10 shows that the explosion suppression system works very effectively. Explosion overpressure in the chamber is about 0.48 bar. After deducting the reference pressure, it can be assumed that the suppressed explosion pressure does not exceed 0.035 bar. Fig. 10 also shows (for the same time scale as that of the course of explosion pressure in the explosion chamber) the course of pressure during the explosion of an explosive charge inside an extinguisher. The maximum value of pressure in the extinguisher is about 145 bar. The

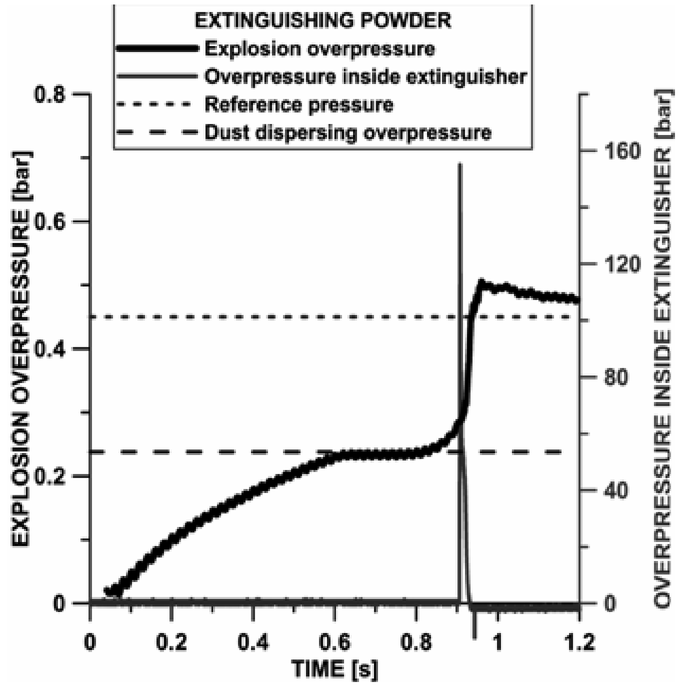

Figure 11: Courses of the overpressure inside the 1.3 m^3 test chamber during explosion of corn starch dust (C = 0.2 kg/m^3) and inside the extinguisher. Activation from photodiode signal at the level of 0.6 V. Explosion overpressure ΔP = 0.055 bar

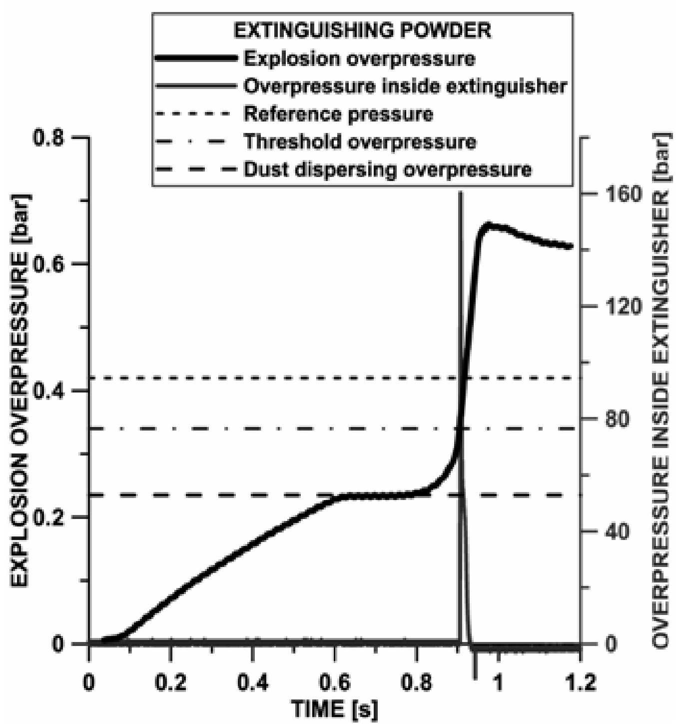

Figure 12: Courses of the overpressure inside the 1.3 m^3 test chamber during explosion of corn starch dust (C = 0.2 kg/m^3) and inside the extinguisher. Activation from photodiode signal at the level of 1.0 V. Explosion overpressure ΔP = 0.24 bar

pressure in the test chamber, corresponding to the moment of start of the pressure increase in the extinguisher, can be approximately treated as the actual threshold pressure (the value is about 0.025 bar). This also confirms the course of the signal generated by the photodiode. It can be seen that the moment of obtaining the value of 0.3 V (assumed level of the trigger signal), corresponds to the moment of pressure increase inside the extinguisher.

As can be noticed from the course of the pressure in the test chamber presented in Fig. 12, the suppression system triggered by a signal from the photodiode with the level 1.0 V works only slightly less efficiently than in the previous cases (Figs. 10–11). The explosion overpressure in the chamber is approximately 0.67 bar. After deducting the reference pressure, it can be found that the suppressed explosion pressure does not exceed 0.24 bar. The maximum value of pressure in the extinguisher is about 160 bar and the actual threshold pressure is about 0.11 bar.

A similar study, in terms of the cornstarch mixture with air, was also conducted for methane-air mixture. Basic research was carried out for the methane-air mixture at a methane concentration of 7.5%. The course of the gaseous explosion of this mixture in a test chamber with a volume of 1.3 m^3 is shown in Fig. 13. As can be seen, the explosion pressure for this mixture is approximately 5.9 bar, and the rate of pressure rise dp/dt ~ 76 bar/s, hence the standard rate of pressure rise is K_G ~ 85 bar·m/s.

The example results of the investigation into the explosion suppression process in methane-air mixture are shown in Figs. 13–15. The assumed levels of the photodiode triggering signal were 0.3 V, 0.6 V and 1.0 V respectively. It was stated that for all tested levels of the photodiode triggering signal, an effective suppression of the explosion of the tested methane-air mixture was obtained. The values of overpressure of the suppressed explosions were 0.06 bar, 0.075 bar and 0.21 bar respectively.

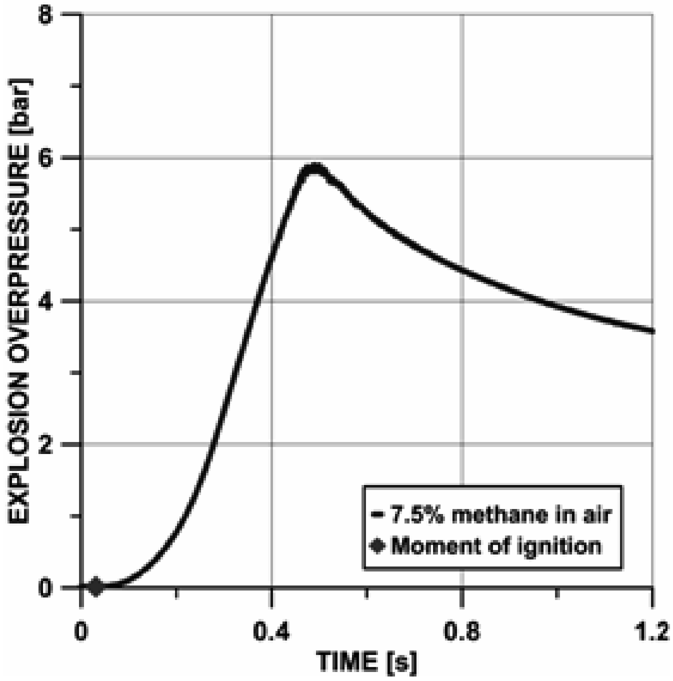

Figure 13: Courses of the overpressure inside the 1.3 m^3 test chamber during explosion of a methane-air mixture (7.5% CH_4)

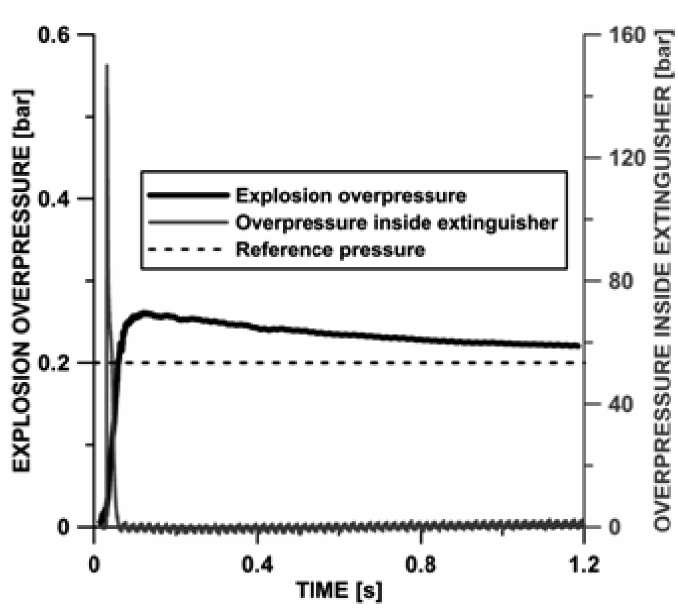

Figure 14: Courses of the overpressure inside the 1.3 m^3 test chamber during explosion of a methane-air mixture (7.5% CH_4). Activation from photodiode signal at the level of 0.3 V. Explosion overpressure $\Delta P = 0.06$ bar

The research shows that the tested explosion suppression system is able to effectively suppress explosions initiated in the dust or methane-air mixtures in a test chamber of 1.3 m^3 volume in conditions shown in Figs. 10–13, even for a relatively high threshold triggering voltage signal from a photodiode. It was decided to check whether the explosion suppression system was able to suppress even more intense explosions.

Finally, for this purpose, a mixture of methane-air at a methane concentration of 8.5% was selected. The course of the explosion of this mixture in the 1.3 m^3test chamber is shown in Figure 17. As can be seen, the explosion pressure for this mixture is almost 7 bar, and the rate of pressure rise of dp/dt ~ 90 bar/s, hence the standard rate of the pressure rise is $K_G \sim 100$ bar·m/s. The level of the triggering signal from the photodiode was assumed to be 0.3 V.

As can be observed from the course of the pressure in the test chamber (Fig. 18), the system worked very effectively in suppressing an explosion. Explosion overpressure in the chamber was about 0.57 bar. After deducting the pressure increase in the explosion chamber, caused by gases exiting the fire extinguisher (reference pressure), it can be assumed that the suppressed explosion pressure does not exceed 0.37 bar. The suppression of such an intense explosion (P = 7 bar, $K_G \sim 100$ bar·m/s) in a relatively small volume (1.3 m^3) to the value P = 0.37 bar illustrates the high efficiency of the gas explosion suppression system.

3. Discussion of results

The study shows that the tested suppression system is almost equally effective at suppressing dust and gas explosions with regard to parameters such as: explosion pressure, rate of explosion pressure rise and the standard rate of explosion pressure rise [17, 23, 24]. For the assumed levels of the photodiode triggering signal: 0.3 V, 0.6 V and 1.0 V in the case of dust explosion suppression, the obtained explosion pressure values were: 0.035 bar, 0.055 bar and 0.24 bar respectively, whereas in the case of gas explosion the explosion pressure values were: 0.06 bar, 0.075 bar and

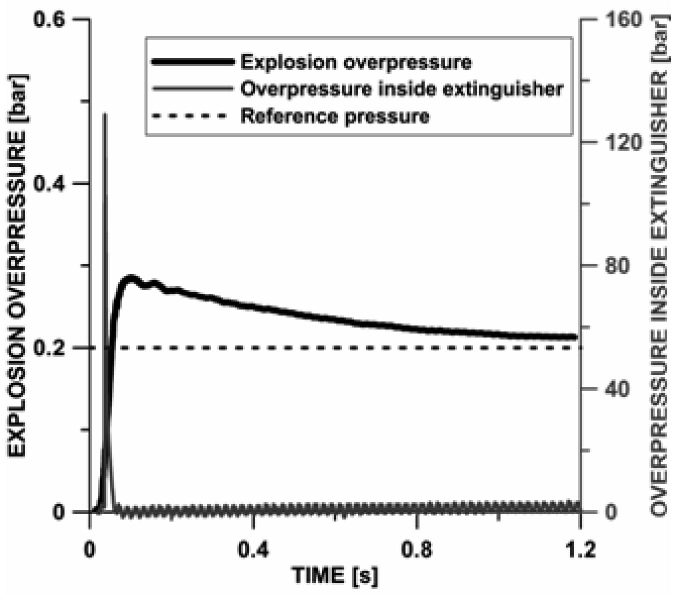

Figure 15: Courses of the overpressure inside the 1.3 m^3 test chamber during explosion of a methane-air mixture (7.5% CH_4). Activation from photodiode signal at the level of 0.6 V. Explosion overpressure ΔP = 0.075 bar

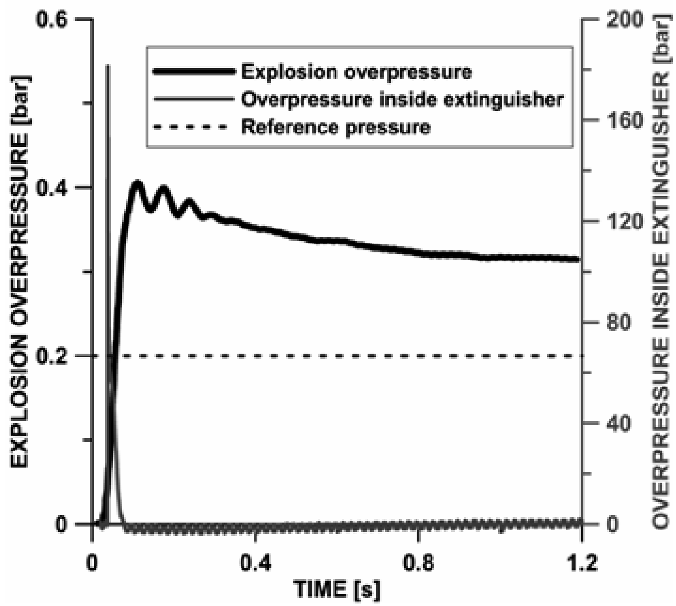

Figure 16: Courses of the overpressure inside the 1.3 m^3 test chamber during explosion of a methane-air mixture (7.5% CH_4). Activation from photodiode signal at the level of 1.0 V. Explosion overpressure ΔP = 0.21 bar

0.21 bar respectively. This indicates that the extinguishing powder mechanism is probably similar for the two tested types of dust and gaseous mixtures. The mechanism of its action on the flame is well known and the following effects of the mechanism can be selected [9–13]:

1. physical effect concerning heat absorption by the suppressing powder as a result of heat exchange with surrounding gas,
2. chemical inhibition that can be divided into:
   - homogeneous, taking place in the gaseous phase,
   - heterogeneous, taking place on particle surfaces.

Any attempt to evaluate the particular effects for defined conditions is very difficult and requires good knowledge of the dynamics of suppression powder decomposition in the flame. The above process is connected with suppressing powder parameters such as particle size and its ability to transform into the gaseous phase.

It was found, on the basis of pressure courses recorded inside the fire extinguisher during the explosion of an explosive charge (Fig. 19), that the estimated time of emptying a fire extinguisher of extinguishing powder ranged from 25 to 30 ms – which enabled the effective suppression of even a very strong explosion (Fig. 17).

The range of pressures in the extinguisher during the explosion of an explosive charge, which were obtained for the fast and accurate opening of the membrane, i.e. without detached fragments (Fig. 20) was approximately from 130 to 190 bar.

4. Summary and conclusions

From the conducted experiments the following conclusions can be drawn:

1. the rapid, active explosion suppression system enjoys high efficiency and reliability,
2. the significant influence of the level of the photodiode triggering signal on the course of the suppression process was confirmed,
3. the tested suppression system is almost equally effective in suppressing dust and gas explosions.

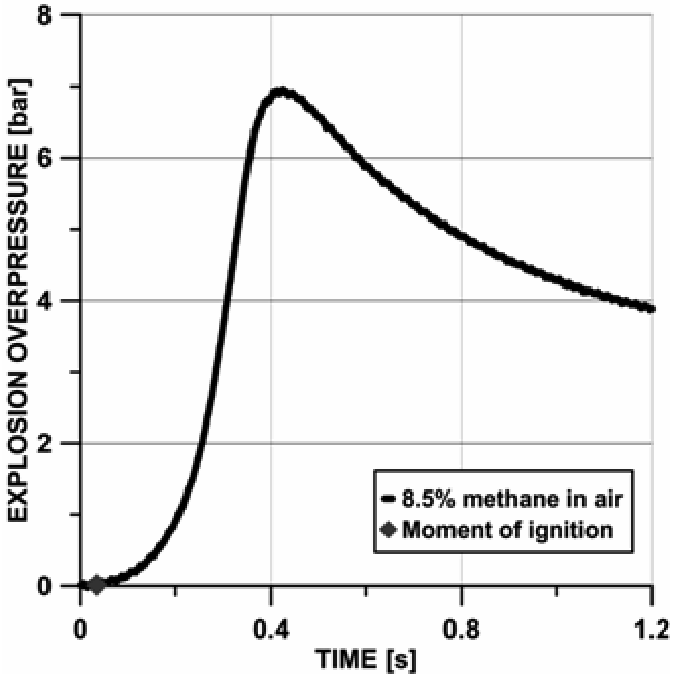

Figure 17: Courses of the overpressure inside the 1.3 m^3 test chamber during explosion of a methane-air mixture (8.5% CH_4)

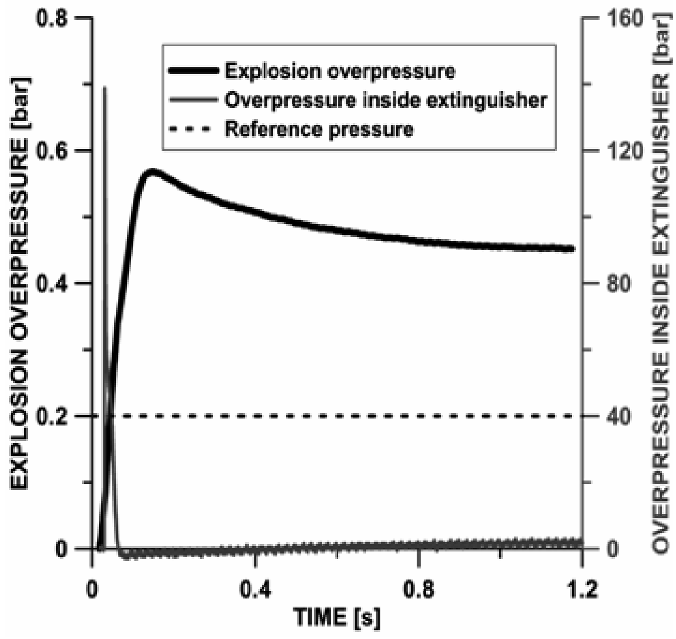

Figure 18: Courses of the overpressure inside the 1.3 m^3 test chamber during explosion of a methane-air mixture (8.5% CH_4). Activation from photodiode signal at the level of 0.3 V. Explosion overpressure $\Delta P = 0.37$ bar

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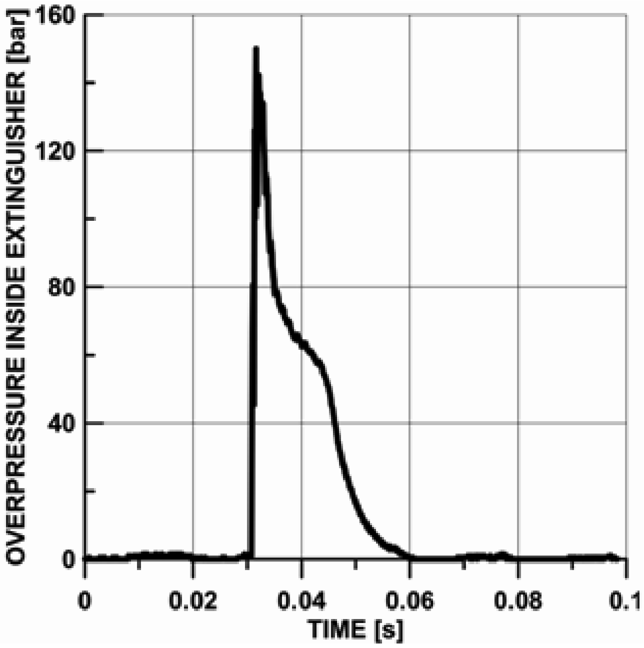

Figure 19: Example course in fire extinguisher pressure recorded during the test explosion suppression

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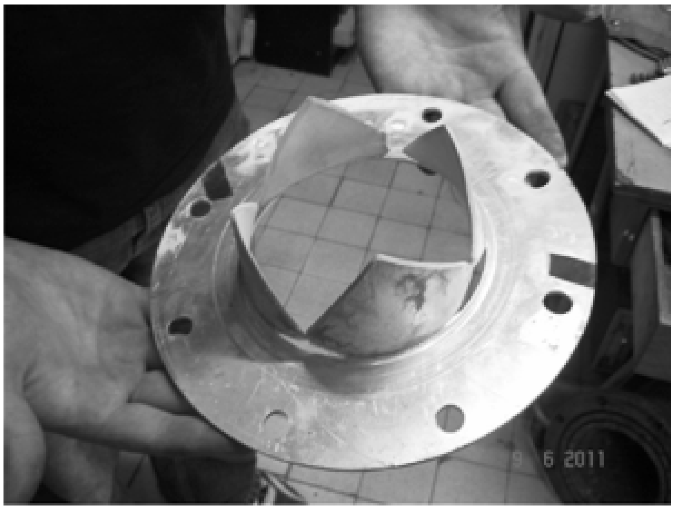

Figure 20: The appearance of the correctly opened membrane after the test