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ANALYSIS OF PROTECTION SYSTEMS FOR REDUCING THE EFFECTS OF SHOCK WAVES PRODUCED BY EXPLOSIONS IN ENCLOSED SPACES

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Abstract

Explosion-type accidents can cause significant human losses and material damages; therefore, special attention has to be granted to explosion risk assessments and to the development of appropriate explosion-protection measures. Such measures of protection aim to reduce the explosion risk to acceptable levels, in compliance with regulations and standards in force, so as to provide the proper safety level for humans as well as to prevent damage to the surrounding goods and environment. The flash-point, explosivity limits and oxygen concentration limit and define the properties of combustion of flammable substances. A certain material all by itself does not represent an explosion hazard, but in contact or in mixture with air may generate an explosion hazard. In this regard, the properties of the air-flammable substance mixture have to be determined. These properties provide information about the reaction to the firing of a substance and whether it can give rise to fire or explosion.
The present work examines the protective systems intended to limit the effects of an explosion and proposes an automatic system intended for reducing shock waves that occur as a result of an explosion in an enclosed space.

Key words: automatic system, explosions in enclosed spaces, predictive algorithm

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1. Introduction

The risk of explosion can occur in all activities involving flammable substances. These may include many raw materials, intermediate products, end products and waste products from the usual production process (ATEX Directive, 2014). Practically all fields of activity can be affected, because the danger of explosive atmospheres can occur in a wide range of processes and operations.

1.1. Principles of prevention and protection against explosion

Basic principles of prevention and protection against explosion are:

- prevention: avoid or reduce explosive atmospheres and avoiding all possible sources of ignition;
- protection: stopping the explosion and/or limiting the effects of an explosion, through protection measures, for instance through isolation, suppression and explosion resistant constructions. Unlike the first two measures described above, the third one supports the occurrence of an explosion.

However, the first and best option is to avoid the occurrence of an explosive atmosphere. Explosion prevention requirement may be expressed as follows: the probability that an ignition source will appear at the same time with an explosive atmosphere to be minimal, so specific requirements for equipment and protective systems according to use are required.

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When the explosion occurs inside an enclosure, the pressures associated with the initial shock wave will be much higher than in the case of an explosion what occurs outdoors. High temperatures, as well as the accumulation of gases produced as a result of chemical reactions, due to the explosions produced inside the buildings, stress their structure over a period of time, depending on the degree of the building ventilation (Stoicuta et al., 2018; Yandzio et al., 1999; Zeynep et al., 2008). In Fig. 1 three types of explosions, depending on the degree of ventilation of the building are illustrated.

Results of test studies carried out by researchers in the field (Ghicioi et al., 2017) which aimed at determining explosion parameters within the shock-tube, the propagation of the flame front and pressure wave, or explosion pressures at different distances from the pressure discharge source, revealed important technical measures which can be implemented for ensuring explosion protection and for preventing pollution by accidental combustion gases. Characteristics of shock tube are: steel shaped cylinder blasts 10 m long and 107.5 dm^3 volume. The flammable material used for the preparation of the explosive mixtures was methane gas. Certain concentrations of the air-methane mixture have been analysed, but the deflagration to detonation (DTD) phenomena occurred only for concentrations of 9 % vol., 9.5 % vol., and 10 % vol. Results of the study concerning the variation of the pressure explosion is shown in Fig. 2.

To determine the explosive parameters for combustible dust / powder, one of the apparatus used is KSEP-20. This apparatus consists of an explosion-proof spherical blast-furnace made of stainless steel with a volume of 20 dm^3 (Fig. 3). A water jacket has the role of absorbing the heat produced by the explosions. To perform the test, the dust to be analysed is dispersed within the sphere of the pressure dust receptacle through a quick acting valve and a dispersing nozzle. The quick acting valve is pneumatically opened and closed by an auxiliary piston. The compressed air valves are electrically activated. The ignition source is located in the centre of the sphere (Jurca et al., 2005).

Depending on the parameter to be determined, the commands to the test facility are transmitted using an interface and a dedicated software. After the test, the data obtained using this software is collected, generating based on recorded data the graphs necessary for the evaluation of the explosive parameters (Fig. 4).

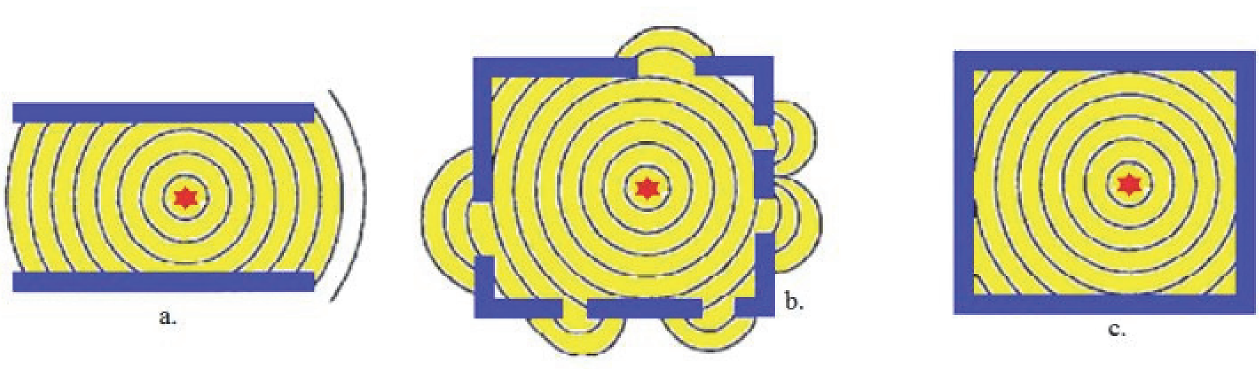

Fig. 1. Types of internal explosions according to the degree of ventilation (Yandzio et al., 1999)
a. Fully ventilated; b. Partially vented, c. Fully enclosed

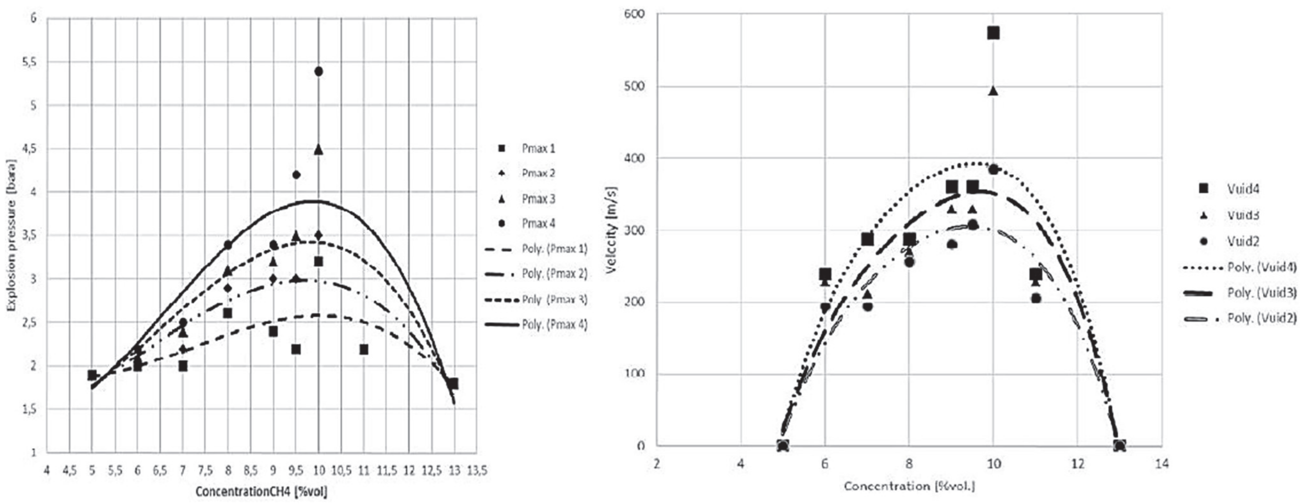

Fig. 2. Explosion pressure variation and variation of the inverse wave velocity

Fig. 3. The KSEP-20 test facility
1-water outlet; 2-pressure transducers; 3-manometer; 4-dust container (0.6 dm3); 5-air intake opening; 6-ignition source; 7-spray nozzle; 8-quick-acting valve; 9-inlet for water; 10-exhaust outlet (air, reaction products)

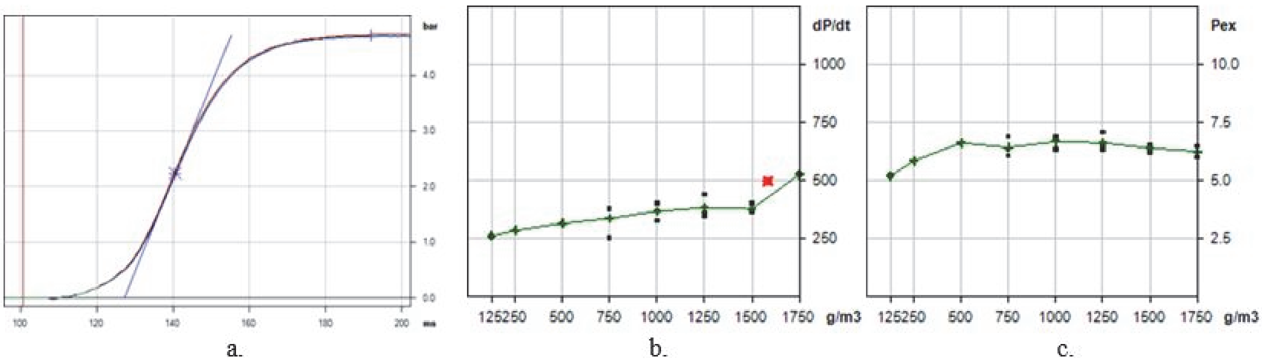

Fig. 4. Parameters determined for a dust collected
a- explosion pressure p_{ex} chart; b- maximum explosion pressure speed $(dp / dt)_{max}$;
c- maximum explosion pressure (p_{max})

Test dust was collected from a container, the dust samples having a distribution of particles with the size under 63 µm. Dust concentration was 125 ($g \cdot m^{-3}$) and for these parameters, the measured explosion overpressure was p_{ex} = 4.7 bar (Fig. 4a). A widespread method for reducing the effects of an explosion (reduction of maximum pressure) within a building is the method of venting the space where the explosion occurs. The ventilation must be made to a safe location where combustion cannot be sustained, away from crowded areas, other installations or other buildings (SR EN (IEC) 14797, 2017).

Dust explosions compared to gas explosions can be, in some cases, much more devastating. It is necessary to clarify that limits of explosivity and oxygen concentration s should define properties of combustion of combustible dust/powder, while the maximum explosion pressure and maximum increase velocity should define the behaviour of their explosion. Also, to identify the dangers of ignition, ignition properties must be determined by an explosive atmosphere, namely minimum ignition energy, minimum ignition temperature of the explosive atmosphere and the minimum temperature ignition of the dust layer (or dust cloud).

New concepts for prevention and protection against explosion develops new strategies for the prevention of the spread of mass destruction or limitation of the effects of explosions, which entails taking into consideration the aspects of closure (limitation, restriction, delimitation) of the explosive mixture. It should also be taken into account that the dust, in order to be considered as explosive to be suspended in the air, to have a particle size distribution able to propagate and burning and a certain concentration within the limits of explosivity.

All the information above gives a clear picture of conditions for explosion and allows identification of security measures for the design, manufacture, assembly and maintenance of the installations in order to prevent the formation of explosive atmosphere, preventing ignition sources or for reducing the effects of eventual explosion protective systems.

The characteristic specifying the dust explosion index (K_{st}) is an independent feature calculated considering the cube root of volume in Eq. (3):

$$(dp/dt)_{\max} \cdot V^{1/3} = const. = K_{st} = K_{\max} \tag{3}$$

Depending on the dust explosion index (K_{st}) dust can be classified into the following classes according to the Table 1 (Jurca et al., 2014).

Table 1. Characterization of dust according to the explosion index value

Dust explosion index	K_{St} *[mbar/s]*	*Characterization*
St 0	0	No explosion
St 1	> 0 ÷ 200	Poor explosion
St 2	> 200 ÷ 300	Strong explosion
St 3	> 300	Extreme explosion

Protective systems are devices other than components of equipment which are intended to halt incipient explosions immediately and/or to limit the effective range of an explosion and which are separately made available on the market for use as autonomous systems (ATEX Directive, 2014).

Facilities working with flammable gases, vapours, liquids or combustible dusts, must be fitted with:

- mechanisms and processes that prevent, decrease or eliminate the occurrence of explosions;
- mechanisms and processes that limit the consequences or explosions.

1.2. Requirements for protective systems

Protective systems must satisfy the following:

- protective systems are sized in order to reduce the effects of an explosion at a sufficient level of security;
- protective systems must be so designed as to be able to prevent explosions to spread through chain reactions or dangerous flashover;
- protective systems must retain the ability to function for a sufficient period to avoid a dangerous situation;
- protective systems must not be damaged as a result of interference from outside;
- protective systems shall be so designed as to withstand the shock wave produced without losing system integrity.

1.3. Presentation of protective systems

In many cases it is not possible to avoid the accumulation of explosive atmospheres and sources of ignition. In this case it must be adopted measures to limit the effects of an explosion to an acceptable extent. Such measures are:

- pressure-resistant concept;
- releasing the pressure;
- explosion suppression;
- decouple the explosion;
- preventing the spread of flame and explosion.

1.4. Explosion venting devices

Explosion release through safety devices represents a safeguard which prevents the explosion pressure in a container or other enclosed volume to exceed its design strength (through the release of explosion compressed gases by using a protective system installed in the walls of the container – Fig. 5 and Fig. 6).

2. Material and methods

The present work gives a clear picture of conditions for explosions and allows identification of security measures for the design, manufacture, assembly and maintenance of the installations in order to prevent the formation of explosive atmosphere, preventing ignition sources or for reducing the effects of potentially explosions by using protective systems.

2.1. Dust explosion venting protective systems

Explosion venting devices represents a measure of protection for containers (ex. grain silos, bunkers etc.), which prevents the occurrence of unacceptably high explosion overpressure.

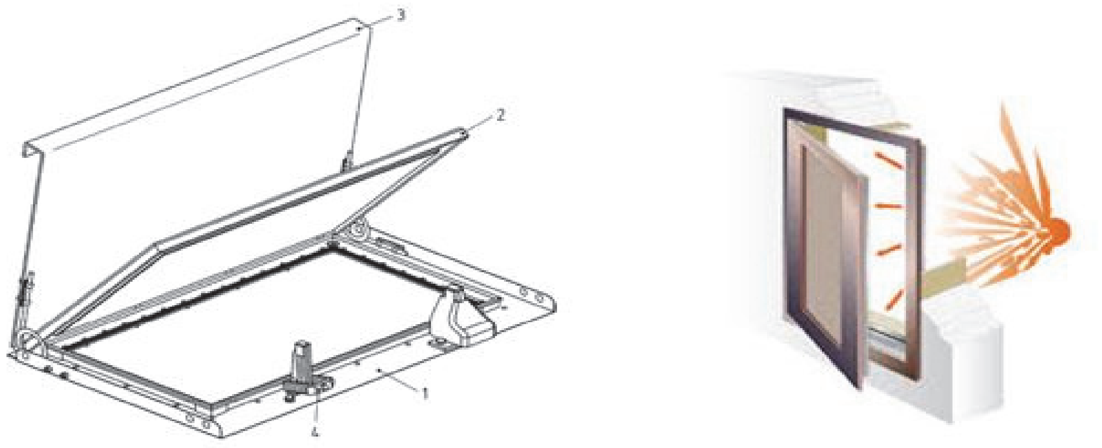

Fig. 5. Example of a protective system - explosion door
1-supporting frame; 2-venting element; 3-baffle; 4-retaining elements

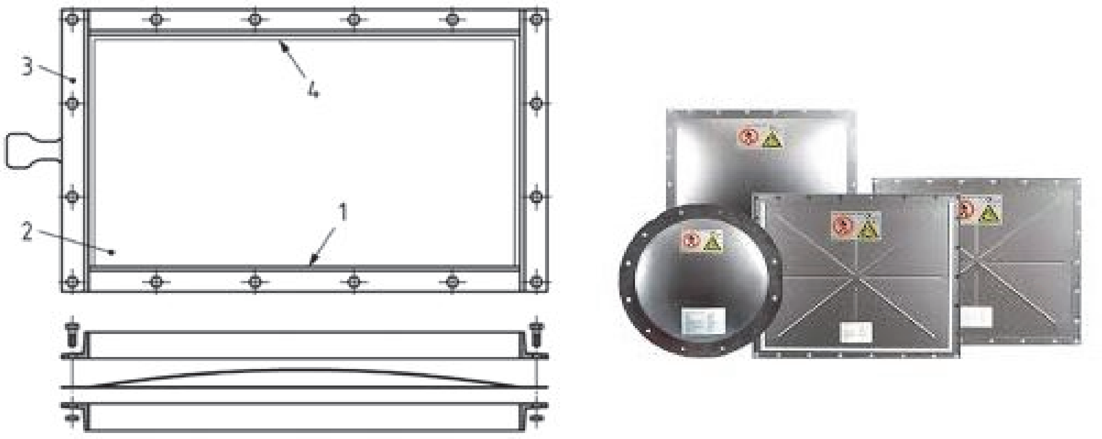

Fig. 6. Example of a protective system - bursting panel device
1-fixed side; 2-area of the explosion venting device; 3-supporting frame; 4-sides yielding during venting process

The weaker areas of the container walls open in an early stage of the explosion, the material that burns or combustion products are released, and the excess pressure inside the container is reduced (SR EN (IEC) 14491, 2013). The necessary information for the calculation of venting surface include container resistance to explosion, explosion characteristics of dust, the shape and size of container, static overpressure, and other features of the venting closing system the ventilation and state the dust cloud is found inside the container (Cooper, 1998).

Discharging of explosion must not be made if unacceptable quantities of materials classified as toxic, corrosive, irritant, carcinogenic, teratogenic or mutagenic can occur and dust or products of combustion can pose an immediate danger to the environment (Prodan et al., 2014). If there is no alternative to discharging the explosion pressure, then a hazardous area shall be specified. There may be many reasons for a dust explosion inside a building, such as:

- a controlled explosion discharge within a building from the process equipment;
- an uncontrolled explosion inside a building from the process equipment;
- any of the previous two, followed by a secondary explosion in the building itself; or
- an explosion initiated in the building.

The development of an explosion in a building depends on several parameters, such as the shape of the building, the presence of equipment and structural elements, the possibility of spreading from one room to another and the presence of combustible dust deposited on the window sills, pipe and flooring etc.

Dust explosion may be limited to a small fraction of the total volume. Development of pressure can vary depending on the situation.

Whenever a building is vulnerable to an explosion, the first requirement is that an explosion inside the building should not cause a progressive collapse of the building by moving load-bearing walls or columns. A secondary requirement is that the effects of an explosion in the building should lead to minor risks for people outside the building.

For buildings, the equation for calculating the recommended ventilation surface is as follows (Eq. 4):

$$A = C \cdot A_S \cdot p_{red.\max}^{-0.5} \quad (4)$$

where: A-vent area, m^2; A_V-area of the explosion venting device, A_V=A/E_f, m^2; E_f- venting efficiency of the explosion venting device; A_S- the inner surface of the encapsulation, m^2; $p_{red.max}$- the maximum overpressure developed by the explosion in a ventilated encapsulate during a ventilated explosion, bar; C- is constant the equation for calculating surface ventilation:

$0 < K_{st} \leq 100$: $C = 0.018^{0.5}$ bar;
$100 < K_{st} \leq 200$: $C = 0.026^{0.5}$ bar;
$200 < K_{st} \leq 300$: $C = 0.030^{0.5}$ bar.

2.2. Gas explosion venting protective systems

Explosion venting devices are safety devices comprised of a pressure sensitive membrane fixed to and forming part of the structure that it protects, designed to intervene in the event of an explosion at a predetermined low pressure, to immediately open a vent area sufficient to ensure that the maximum pressure attained by the explosion within the enclosure does not exceed its designed resistance to pressure (SR EN (IEC) 14994, 2008).

Explosion venting devices is a protection measure that prevents the creation of an unacceptably high overpressure explosion inside the enclosures. Such non-resilient areas located in the walls of the enclosure open at an early stage of the explosion, releasing outward/ downstream gases / vapours and combustion products outwardly, and thus reducing overpressure inside the enclosure.

Ventilation area represents the most important factor for the determination of the maximum explosion pressure. The information necessary for the calculation of the surface pressure of discharge include the design of the enclosure, the characteristics of the gas explosion, the size and shape of the enclosure, the presence of elements that favour the turbulence (including congestion) of inside the enclosure, static pressure and other characteristics of the device, as well as the condition of the explosive atmosphere inside the enclosure.

Explosion venting devices do not prevent an explosion, it limits the pressure of the explosion. These devices must be provided and taken into account in the practical effects of flame and pressure outside the enclosure, as well as remnants of the atmosphere projected blast explosion.

Compact insulated enclosure for ventilation is a method for sizing the openings of ventilation of premises. The method applies to isolated areas and virtually without encouraging the turbulence. The method assumes that the explosive atmosphere inside the enclosure is practically at rest in the moment of ignition. According to this method, the surface shall be calculated using the following equation (Eq. 5):

$$A=\left\{\left[\left(0.1265\cdot\lg\left(K_G\right)-0.0567\right)\cdot p_{red}^{-0.5817}\right]+\left[0.1754\cdot p_{red}^{-0.5722}\cdot\left(p_{stat}-0.1bar\right)\right]\right\}\cdot V^{2/3}$$

$$A_V=\frac{A}{E_f} \quad (5)$$

where: A-vent area, m^2; A_E-area of the explosion venting device with efficiency $E_d > 1$, m^2; K_G- gas explosion constant, bar·m·s^{-1}; p_{red}-reduced explosion pressure, bar; p_{stat} - static activation pressure of vent explosion, bar; E_f- venting efficiency of the explosion venting device; V-volume, m^3.

3. Results and discussions

Considering the above, the main objective of the article is to propose a new type of device, intended for venting a container, where an explosion can occur. The proposed explosion venting devices is an active one, driven by means of an automatic system.

The control system is composed of one or more transducers used in automatic detection of explosion (pressure transducers, flame transmitters), whose information is transmitted to a microcontroller, which on the basis of a programme based on a predictive algorithm, establishes the order of execution to carry out the venting of the container where the explosion occurs. The proposed explosion venting device is shown in Fig. 7. The ventilation device consists of the following elements: 1 - steel panels (4 pieces); 2 and 3 - steel fastening bars; 4-way, rigid, steel, clamp connectors (4 pieces); 5-tension spring hinge and electromagnet (4 pieces); 6- metallic grid.

Each panel is connected to the second through the hinge screws. The hinge can be adjusted manually, which is used to open the panel. The hinge is made up of an electromagnet used to hold a panel in a closed position. The four panels of the ventilation device are closed as long as the coils of the 4 electromagnets are powered. When powering the electromagnets is interrupted, the tensile springs in the four hinges will open the four steel panels very quickly. The scheme of the ventilation control system is shown in Fig. 8.

The control system (Fig. 8) is comprised of the following measuring elements:

- a pressure sensor (MEX-3);
- a flame detector based on ultraviolet light (UV) and infrared (IR) light, emitted from the source;
- and an ultrafast detector of flames and sparks (IR-13).

The data acquired from the sensors are processed through a system developed around a microcontroller. Within the microcontroller three algorithms are deployed, working in parallel, in order to determine the growth rate of the dynamic pressure positive phase of the explosion. In Fig. 9 it may be observed that when the pressure rise during the positive phase of explosion is higher than the value imposed by the system, the microcontroller disables the optocoupler (OP). In this case, electromagnetic coils are not going to be powered up and the springs tensed within the hinge will rapidly open the steel panels of the venting device.

The command system with microcontroller is connected in the scheduled area, being powered by a photovoltaic system, with a voltage of 12 Vdc, sensors, and must be chosen according to the explosive area in which they are fitted (http://www.ieptechnologies.com).

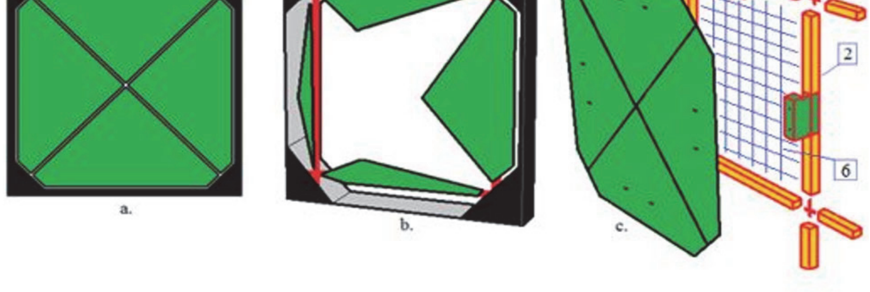

Fig. 7. Explosion venting devices

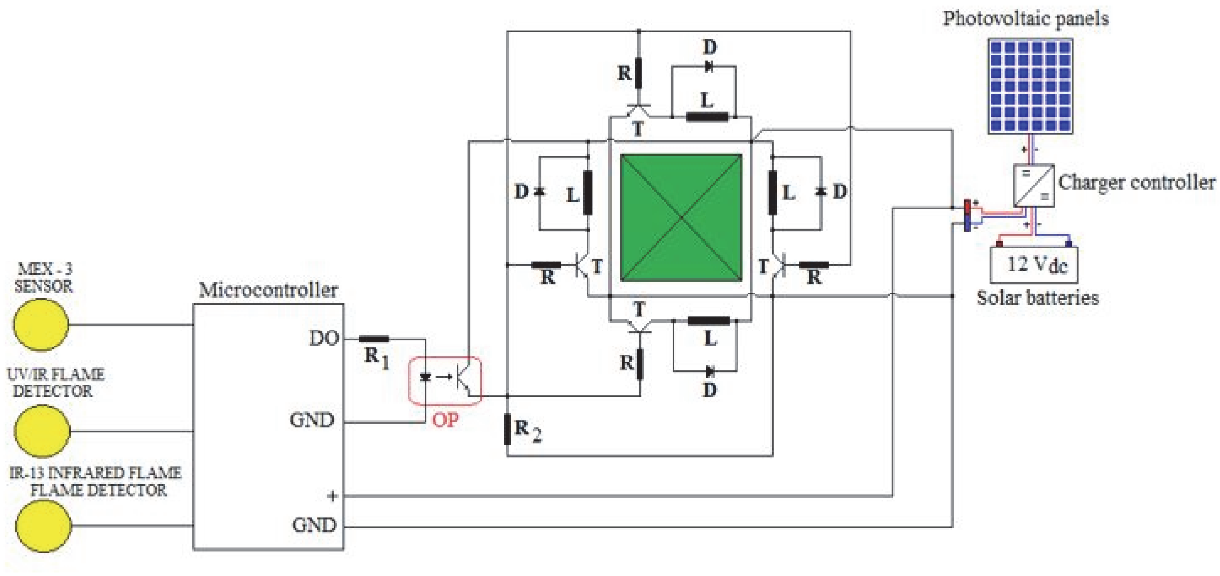

Fig. 8. Explosion venting device control system

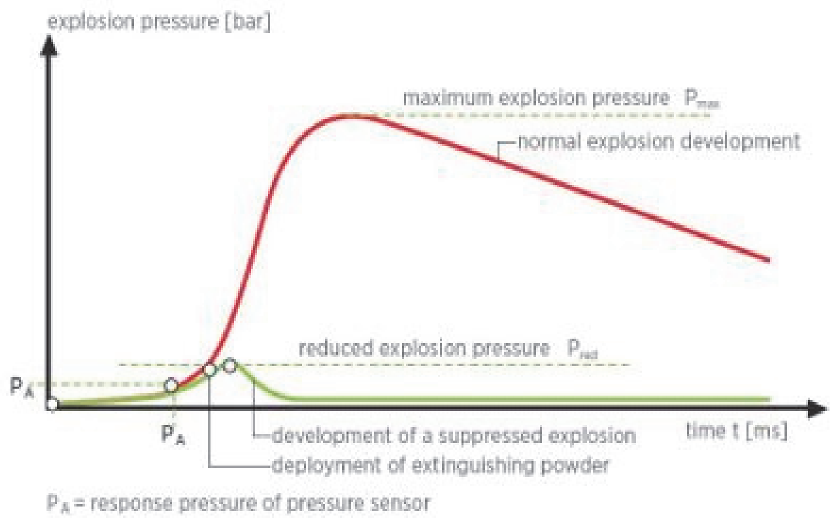

Fig. 9. Pressure reduction with explosion venting device

On the other hand, it is known that grow rate depends on the pressure, concentration and volume of explosive material. For this reason, the system with microcontroller and programming, allows to adapt the software to process conditions.

The automatic system together with the venting device, can reduce considerably the disadvantages in the existing explosion venting systems (damage due to fatigue, damage due to heat, damage due to flexing membranes and due to pulsating pressures).

4. Conclusions

The risk for an explosive atmosphere to be ignited can be reduced by using equipment, components and protective systems designed in compliance with the provisions of explosion protection regulations and standards in force. Also, the explosion risk assessment takes into account determinations and interpretations of combustible gas/powder/dust parameters.

The aim of the explosion risk assessment is to increase the safety level in places where an explosive atmosphere may occur.

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