

DEVELOPMENT OF A WATER SPOUT FOR THE ACTIVE EXTINGUISHING OF THE FOCUS OF AN INTENSE FLAME

Stanislav LICHOROBIEC¹, Jana PUPÍKOVÁ²

Research article

Abstract: The topic of the article is devoted to the experimental development of directional charges, which have a front part filled with water and are thus capable of forming a high velocity water jet, which has intense cooling effects and is accompanied by a shock wave created by the explosion of the charge. The water jet can then be used to extinguish the flame from an intense fire epicenter caused, for example, by a gas pipe failure, a tank with flammable liquid or an oil well. The text is accompanied with the visual design of the water spout prototype, including the experimental test of extinguishing the focus of an intense flame caused by various sources.

Keywords: Intense flame, cumulative charge, Semtex, water spout, explosion.

Introduction

Cumulative charges are specially modified pyrotechnic explosive devices with the cavity, that is formed in the front part of the brizant explosive charge. During explosion, the cumulative cavity filled with a soft metal insert has considerable cutting and perforating effects. This type of charge is possible to use to extinguish the focus of a very intense flame caused by leak of flammable gas or liquid, if the cumulative cavity is filled with water. With this step, we create a high-pressure water jet of narrow cross section accompanied by a pressure wave, which blows out the intense flame, and water will remove the heat from the epicenter of the fire and prevent it from burning again.

In the explosion of a brizant explosive, the created after explosion fumes are essentially spreading in all directions, which are precisely determined by the shape of the charge. The greater the detonation velocity of the explosives used, the more clearly are shown these effects of "directionality". These gases created by explosion tend to spread faster from places where the concentration of the explosive is greater than where the concentration is less. By creating a suitable cavity in such an explosive charge, the gas streams are directed by the explosion and connected to a very compact and fast stream. This allows a directed stream of gas at a very high velocity, which corresponds to a huge accumulation of energy.

The stream of these after explosion gases alone is not yet sufficiently dense to have the desired efficiency and could cause greater destruction of the material. Increasing its density and thus a substantial increase in efficiency is achieved, for example, by inserting a metal insert into the cavity formed. This effect is used for the breakthrough of metallic materials, especially in military activities. Another option is to fill this cavity with some medium, such as water.

One of the characteristics of the water is its incompressibility and thus the water will substantially increase its consistency - materializing also the effectiveness of such a directed explosive charge. The modified cumulative charge, by its water-directed beam, can effectively counteract against the intense focus of a flame that is induced by jetting of flammable gas or liquid from a damaged gas line, tank, cistern, or gas cylinder and cause it to extinguish. There are two factors involved in the extinguishing effect of the flame.

The first is a shock wave that spreads in front of the water beam which blows out the flame, and the second factor is the moving water jet, which removes the temperature from the incriminated place, blows out the flame and prevents it from burning again. Detonation pressure is the highest pressure of fumes from explosion in the detonation wave if it obeys the laws of ideal gas according to equation (1), (Cooper and Kurowski, 1996; Vavra and Vagenknecht, 2002):

¹ VŠB - Technical University of Ostrava, Faculty of Safety Engineering, Ostrava, Czech Republic, stanislav.lichorobiec@vsb.cz

² VŠB - Technical University of Ostrava, Faculty of Safety Engineering, Ostrava, Czech Republic, jana.pupikova@vsb.cz

$$p \cdot V = n \cdot R \cdot T \rightarrow p = \frac{n \cdot R \cdot T}{V} \quad (1)$$

where:

p - pressure [MPa], V - volume [m³], n - the number of moles in unit weight of the explosive, R - gas constant, T - temperature [K].

The most well-known example of acceleration of matter in the observed context with the help of explosive is shooting, mining of minerals and rocks, or the destruction of ice on frozen water surfaces. The most convenient way to accelerate water with an explosive is to use a so-called Gurney's model, on the basis of which was derived the rate of explosion of accelerated fragments.

Materials and methods

Determination of the hypotheses

The basis of this model are two assumptions (Vavra and Vagenknecht, 2002):

1. By detonating the given explosive, a certain amount of energy is released per unit mass of the explosive and this energy is divided into an acceleration of the inert material in the form of kinetic energy and energy transferred to the gaseous detonation products,
2. The resulting gaseous products have spatially uniform density and linear 1D velocity profile in the spatial dimensions of the system.

Primarily, the energy that is usable for acceleration of the mass is expressed in the value of dimension of velocity [km.s⁻¹], characteristic for each explosive, respectively its density, and is denoted by an expression ($\sqrt{2 \cdot E}$) so called - Gurney's velocity. The exact determination of this value is carried out experimentally by a "cylinder" test.

For the Semtex-10 SE explosive, at a given table density of 1.44 [g.cm⁻³], the detail of Gurney's velocity ($\sqrt{2 \cdot E}$) is given in this table with a value of 2.3-2.5 [km.s⁻¹].

Depending on the particular explosive used, this value can be calculated from the determined detonation velocity "D" of the given explosive, using equation (2), (Vavra and Vagenknecht, 2002):

$$\sqrt{2 \cdot E} = \frac{D}{2,97} \quad (2)$$

where:

$\sqrt{2 \cdot E}$ - Gurney's velocity [km.s⁻¹], D - detonation speed [km.s⁻¹] and 2,97 - dimensionless coefficient.

After substituting the detonation velocity value of the predictably used explosive Semtex 10-SE, $D = 7,2$ km.s⁻¹, into this equation (2) the value of Gurney's velocity is $\sqrt{2 \cdot E} = 2,43$ km.s⁻¹.

Given that the assembled cumulative water charge will be standing loose in space and directed to the flame epicenter, the mathematical model for calculating the efficiency of this assembly was taken from the structural comparison to the so-called asymmetric sandwich (Cooper and Kurowski, 1996; Vavra and Vagenknecht, 2002).

The mathematical equation for calculating the water acceleration by means of an explosive explosion is given in the arrangement of this sandwich in the sequence - **Water** in front part of the explosive / **Explosive** / **Plug-water** in the back part of the explosive. A schematic of a similar **W/E/P** sandwich arrangement is shown in Fig. 1.

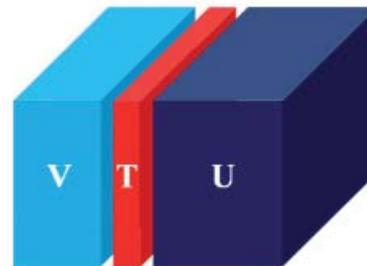


Fig. 1 Construction design of a so-called asymmetric W/E/P sandwich for calculation of water particles accelerated by explosion of explosives (Vavra and Vagenknecht, 2002)

The mathematical calculation of the water acceleration from the explosive during explosion is based on the equations (3) and (4), (Vavra and Vagenknecht, 2002; Zukas and Walters, 1998):

$$\frac{v}{\sqrt{2 \cdot E}} = \left[\frac{1 + A^3}{3 \cdot (1 + A)} + \frac{U}{T} \cdot A^2 + \frac{V}{T} \right]^{\frac{1}{2}} \quad (3)$$

$$A = \frac{1 + 2 \cdot \frac{V}{T}}{1 + 2 \cdot \frac{U}{T}} \quad (4)$$

where:

v - speed of accelerated water particles [km.s⁻¹], $\sqrt{2 \cdot E}$ - Gurney's velocity [km.s⁻¹], U - weight of the plug - water behind the explosive [kg], T - weight of the explosive [kg], V - weight of water in front of the explosive [kg] (Cooper and Kurowski, 1996).

In all types of explosion, the pressure wave spreads depending on the type of explosive, the environment and the reaction with the building structure at

the explosion site. The pressure wave spreads from the epicenter of the explosion in spherical wave fronts which are reflected and modified upon impact. The effectivity of this pressure wave is given by:

- the size of the charge,
- distance and duration of effect.

To minimize its impact on the surrounding objects, the effectiveness of the mentioned pressure wave in the back part of the developing charges must be dampened. When the cumulative charge is used as water spouts, it should therefore work on the principle of directing the working medium at the front part where the medium is cumulated into the high-pressure jet of a certain cross section by means of an explosive. At the back part of this charge there is a given volume of water in the so-called "plugged space" which provides both a greater forward effect of the work beam and also a water fog in the back part of the charge, which prevents the burning of slightly inflammable objects in this zone and at the same time substantially dampens the pressure wave in the back part of the charge. This eliminates damage to surrounding objects and structures in the vulnerable area (Dojcar et al., 1996).

In construction of the special directional or cumulative charges are mainly used explosives with greater detonation velocity, which moves above the limit of $6000 \text{ m}\cdot\text{s}^{-1}$ for example:

- Hexogen RDX ($8520 \text{ m}\cdot\text{s}^{-1}$),
- Oktogen HMX ($9100 \text{ m}\cdot\text{s}^{-1}$),
- Semtex 1A, 1H, 10 ($7200, 7400, 7300 \text{ m}\cdot\text{s}^{-1}$),
- Semtex 10-SE ($7200 \text{ m}\cdot\text{s}^{-1}$).

Development of a water spout prototype with the help of cumulation

Due to the ease of manipulation with plastic form of explosion, it is experimentally advantageous to use the Semtex plastic explosives 10-SE, which is supplied by the manufacturer in sheet form with a thickness of 2 mm, a width of 300 mm and a length of 10 meters. Its design is adherently sticky and can be placed on any shape of the cumulative cavity. Its detonation capabilities are stable and uniform across the whole diameter, see photo of the experimental test in Fig. 2.

In the framework of the initial tests, a measurements of the spread of shock wave were carried out in the vicinity of the test sample of this explosive. The explosive was shaped into a spherical shape, at sample weights of 100, 200 and 300 grams.



Fig. 2 Test of the uniformity of explosion of the Semtex 10-SE explosive, $t = 5,236 \text{ ms}$

Fig. 3 shows the spatial geometry of the placement of pressure sensors of the shockwave meter in the vicinity of the epicenter of the explosion, in the distances shown in Tab. 1, in order to obtain relevant information about the magnitude of the shock wave, which will spread in all directions through space at the point of explosion of cumulative charges of different weights.

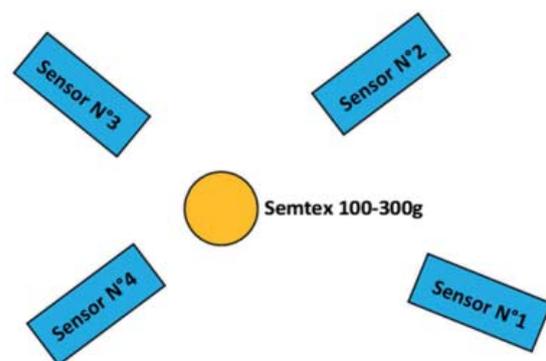


Fig. 3 Geometry of placement of pressure sensors for shock wave measurement

Tab. 1 Distances of pressure sensors from the epicenter of the explosion

Sensor number	1	2	3	4
Distance [m]	5	4	3	2

On the graphs, see Fig. 4, are displayed the processes and magnitudes of shockwave at defined distances from the measured sample of the explosive - epicenter of explosion. The results correspond to the explosive Semtex 10-SE weighing 300 g.

On Fig. 6 and 7 can be then seen two magnitudes of so provisory made cumulative charges with the use of canisters with a volume of 5 and 10 liters of water overall in the front and rear part of the explosive (on the left) and already prepared cumulative charge with explosive and initiator, prior to filling with water (on the right) to carry out experimental water spout efficiency tests.

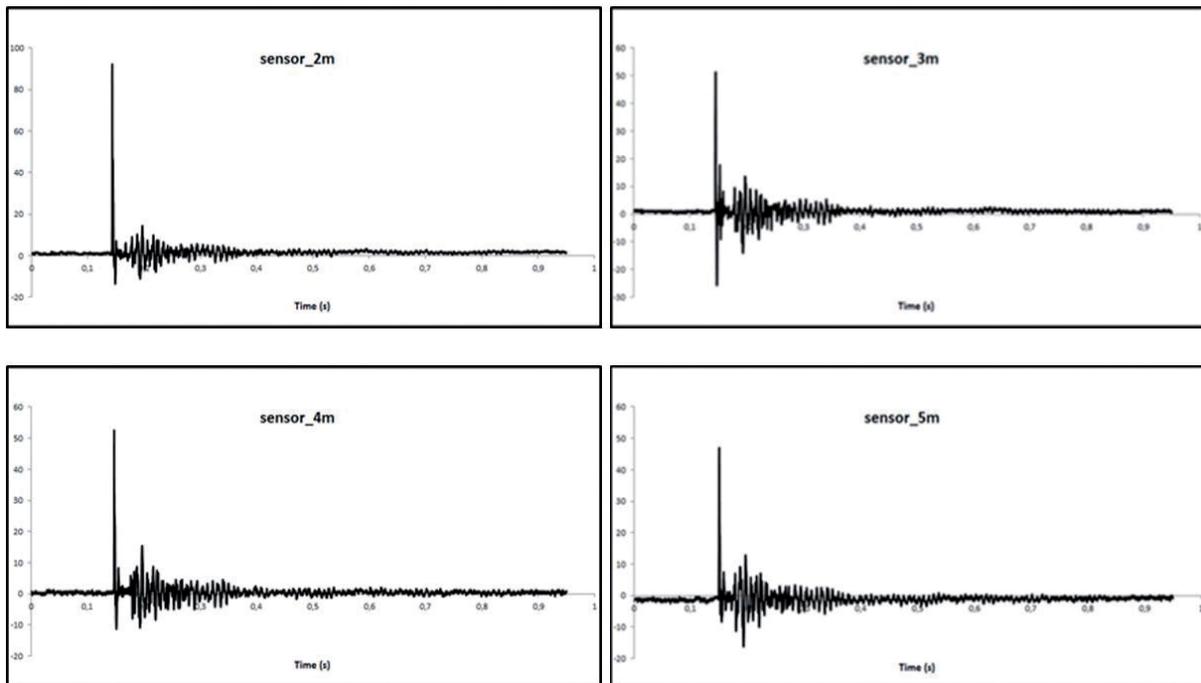


Fig. 4 Processes of shockwaves of the explosive Semtex 10-SE, 300 g

To confirm the mentioned asymmetric sandwich theory, the water spout prototype construction was designed for the practical implementation of the tests with an objective, if the created cumulative pressure water jet will be enough to act on the given epicenter of the fire source. The tests should also confirm the efficiency of the water mass in the plugged compartment, in order to eliminate the shockwave at the rear part of the charge. A conventional plastic canister was chosen as the charge container to cut the top so as to put in place a cumulative plastic insert with an explosive, see Fig. 5, where:

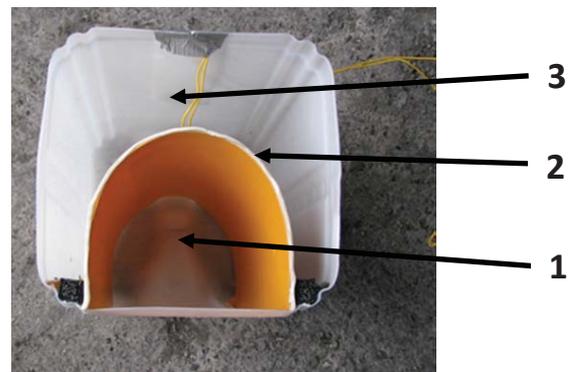


Fig. 5 Construction of a cumulative charge in a plastic canister

- No. 1 is a space of cumulative cavity for the placement of working water mass,
- No. 2 is a Semtex 10-SE type explosive, glued to a cumulative cavity with a detonator,
- No. 3 is the back space of the charge for placing the mass of water, which acts as a plug.



Fig. 6 and 7 Produced charges in two sizes and with placed explosive

Fig. 8 and 9 documents the creation of a pressurized water jet in the front part of the charge flying at a speed of about $580 \text{ m}\cdot\text{s}^{-1}$.



Fig. 8 and 9 Test of an improvised water charge 5 l, $t = 0.6 \text{ ms}$ and 10 l, $t = 1.5 \text{ ms}$

Results

Ideological design of a water spout prototype

The overall ideological design of a cumulative water charge prototype is given by so-called spatial design visualization of individual components. Fig. 10 then documents the layout of individual functional parts of the prototype in the colored version as follows:



Fig. 10 Ideological design of a cumulative charge prototype as a water spout

Inner canister - (Purple color) is operational. Its water fill is directed during explosion of the explosive into a massive cumulative working water jet. It should be able to contain about 8-10 liters of extinguishing liquid. The explosive is located at the rear part so as to form a compact whole of water cumulative charge for better handling. It is inserted into the front cavity of the outer canister.

Explosive - (Red color) is like a charge shaped into a cumulative shape by copying the shape of the inner canister. As already mentioned, it is a plastic explosive of a type Semtex 10-SE. It must be fixed in a certain way to a defined shape on the canister so that it is not later deformed by sliding into an outer canister that performs the function of the rear plug.

Outer canister - (Orange color) is plugging. It partially participates in the acceleration of the directed water jet forwards. The liquid placed in the backspace provides the creation of a mist to compensate for the combustion heat, shock and pressure waves. It is placed on a height-adjustable mobile base (Brown color), which ensures the height correction of the whole assembly and the directionality of the rotation in its particular position, see Fig. 11. It should be able to contain about 60-80 liters of water.

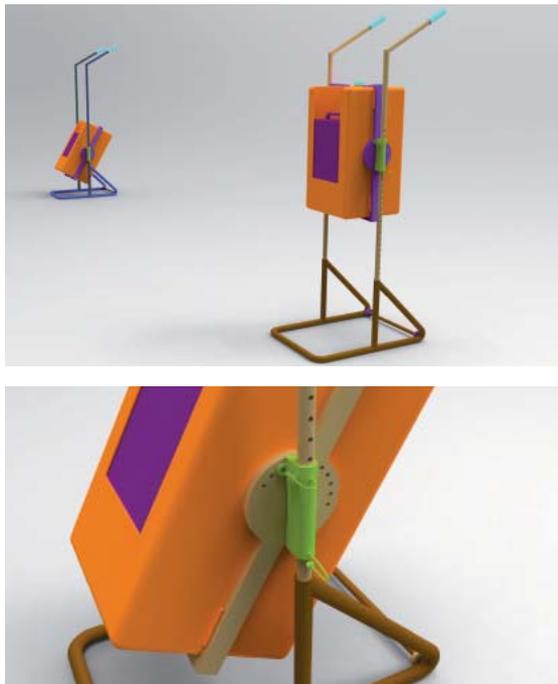


Fig. 11 Detail of elevation and directional adjustment of the water spout on its variable base

Practical test of water spout

As an intense source of flame for practical tests of the developed water spout, two types of flame sources were selected:

- Pyrotechnic ground light sources type PS-25,
- Heptane flammable.

Ground light sources type PS-25 are pyrotechnic light signaling devices for daytime and nighttime signaling, which are also used to imitate the machines on fire or fire epicenters. The initiation is performed using the TZ-M lighter or the EPIO electric pyrotechnic initiator, which is screwed into the hole in the middle of the can, see Fig. 12.



Fig. 12 View on the details of different color versions of ground lights

The PS-25 ground light sources are cylindrical with the lid and the following parameters:

- Diameter 51 mm,
- Height 60 mm,

- Weight 180-190 g (depending on the ground lights color),
- Duration of the function 20-30 s,
- The flame formed is about 0.5 m high,
- The burning temperature exceeds 2000 °C.

Highly flammable liquid and vapors under the name HEPTAN is a volatile, clear, colorless liquid that evaporates even under normal temperature and pressure conditions. Vapors may form explosive mixtures with the air, they are heavier than air, and spread close to the ground.

It has the following parameters:

- Upper explosive limit - 7 % (V),
- Lower explosive limit - 1,1 % (V),
- Relative density 0,66 g.cm⁻³ (20 °C),
- Auto-ignition temperature 223 °C,
- Viscosity - 0,4 mPa.s (20 °C),
- Water-insoluble substance.

On Fig. 13 we can see the distinct extinguishing reaction on the intense flame epicenter created by the initiation of 20 pieces of pyrotechnic product PS-25 in the explosion and formation of a water spout beam. Using the approximation method of the positional reading of the water droplet velocity from the recorded videos during the performed tests, the actual velocity of the water flow was determined at about 580 m.s⁻¹. The whole successful fire extinguishing action was carried out at 10 ms from the initiation of the explosive after till the flame epicenter was extinguished.



Fig. 13 Practical test of water spout when extinguishing the flame created by using 20 pcs of PS-25

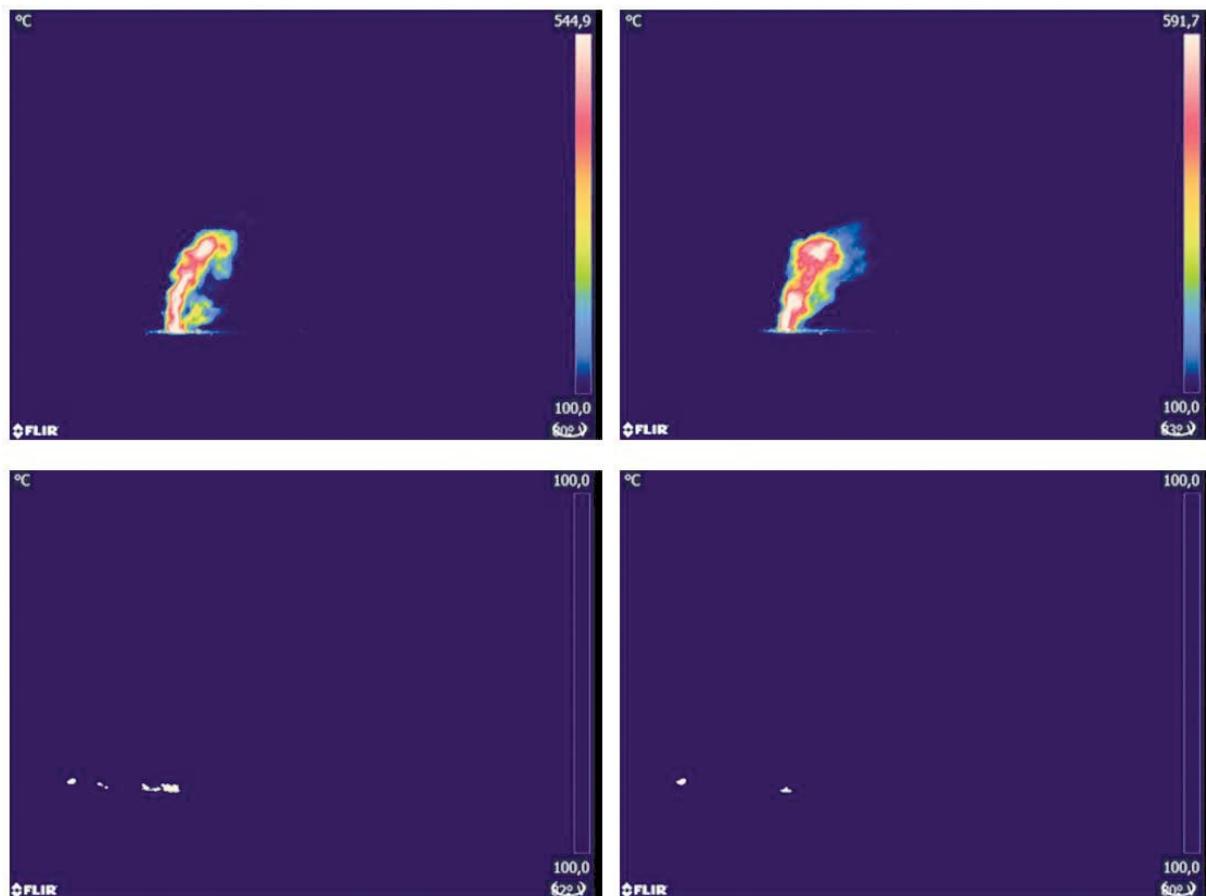


Fig. 14 A look through the thermocamera on the flame created by the pyrotechnic light PS 25 just before (images at the top) and 1 second after squirt of a developed water spout (images below)

Discussion

Advantages of the prototype

- Simple construction - one whole element, consisting of two separate parts, which shall be provided with an explosive with an initiator and shall be filled with water.
- The transport time, composition and activation on site will be very short.
- Production of segmented canisters is not complicated, so the final product will not be costly.
- It does not contain metallic elements, so there is no risk of fragmentation with metal shrapnel.
- Flight of plastics residues with the use of improvised water accumulation charges constructed in canisters has taken up to a maximum of 5-8 meters.
- Explosion shock wave, visible on video frames from a high-speed camera that has a quenching effect in the intensive flame epicenter, is moving ahead of the water jet created by cumulation. The water jet itself has a cooling effect, so it removes heat from the place and prevents the flame from burning again. Using these phenomena when carrying out other practical tests should confirm this theory.
- The rear plugging container should have a sufficient volume of water to form a water mist to suppress the fire and heat effect of the explosion of the working charge. This helps to avoid secondary fires and at the same time reduces the impact of the shockwave spreading to the back part of the water spout, which will not endanger the surrounding objects and buildings in the area. (Lichorobiec and Barcova, 2015)

Conclusion

Based on the mentioned facts from the initial experiments, it can be said that the development of the cumulative water charge in the form of a water spout and its practical implementation in the future will substantially add to the range of means for safe disposal of the intensive flame focus and is creative to deal with this problem in the next development phase. These pyrotechnic devices with a massive flame extinguishing capability are currently missing in the equipment of the FRS units, which solves these problems in their gesture.

Acknowledgments

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