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Application of Water Cumulative Charges as a Water Spouts for Intensive Flame Extinguishing

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ABSTRACT

Shape cumulative charge is a set of explosive components that uses directional energy accumulation. The water cumulative charges are filled with water, which forms a water-directed beam that has the ability to effectively counteract the intense flame that is induced by gaseous flammable gas or liquid from the damaged gas duct and extinguishes it. Study contains description of the experimentally constructed cumulative charge as well as the analysis of results of experiments carried out in real conditions. Based on the facts gained from the experiments we can conclude that the cumulative water charge has a significant potential and possibilities to extinguish an intense flame.

Keywords: Water cumulative charge; Birkhoff's impact model; Smtex; Hexogen; TNT; Water spout; Explosion; Hydrodynamic model

NOMENCLATURES

W	Water
E	Explosive
P	Plug
j	Jet
t	Target
p	Pressure [MPa]
ρ	Density [kg.m^3]
V_s	Volume [m^3]
n	Number of moles
R	Gasconstant
T	Temperature [K]
v	Velocity [km·s^{-1}]
m_s	Weight of the seal [kg]
m_e	Weight of explosive [kg]
m	Weight of water [kg]
V	Speed of progressing jet [km·s^{-1}]
U	Speed of penetration [km·s^{-1}]
u	Flow speed [km·s^{-1}]

1. INTRODUCTION

Shape cumulative charge is a set of explosive components which uses directional energy accumulation. As a rule, it allows to apply - with a relatively high drive and accuracy - all the dynamic energy component of the explosion to a predetermined location[1].

They most often have a cylindrical shape which includes a parabolic, conical or half-spherical cavity. If the cavity is not lined with a liner, the charge is called as 'hollow charge' or 'unlined-cavity charge'. If the cavity charge contains a shaped insert which borders the cavity surface we designate the charge as a shaped charge or cumulative charge[2] (as shown in Fig. 1).

The aforementioned insert changes its shape and forms to a jet due to the directional action of dynamic forces. If the cavity is properly geometrically shaped, it is most often produced so-called blast-shaped jet called the explosively formed penetrator. In other cases there are created separate shots or a single stream of separated jet particles of the liner. The shape of the jet depends on the material, diameter and thickness of the liner, shape and angle of the cavity cut. The most common liner forming materials are metals, their alloys, but also other materials such as glass, ceramics or composites.

Effects of cumulative charges had been realised on the basis of empirical research by mining workers who had noticed that the application of explosives of conical shape creates deeper cavities in rock layers. Later, it also came to the conclusion that the created jets may have a devastating effect on the perforation of the armour of the armoured vehicles. This was already used during the First World War[3].

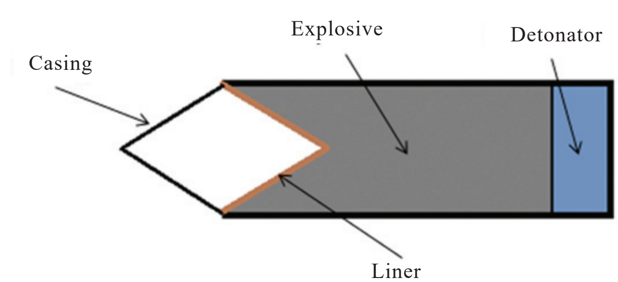

Figure 1. Structure of cumulative charge with liner[3].

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2. HYDRODYNAMIC MODELS

Hydrodynamic models serve mainly to predict the shape of developed cavity. The initial experiments of cumulative shaped charges indicated that the thickness of the target material did not play any role. Therefore the first models were simplified in such a way that the bullet and the target material were considered to be liquid after the impact. Further tests have shown that the width of the material has to be taken into account and that it is also necessary to take into account more types of state at more material thickness[2,4].

3. BIRKHOFF'S IMPACT MODEL

The simplest model for describing the penetration of unpressurised fluid stream of a given density ρ_j into a similarly fluid medium of density ρ_t is the Birkhoff model. The Birkhoff model is based on the Helmhottz theory of tortuous flow. Suppose a missile of length L and density ρ_j and velocity V in a two dimensional reference system. When a liquid jet impacts on the surface of a liquid of density ρ_t, the jet begins (in a still stand) to extrude static liquid on its surface, creating a free-flow cavity on the intersection of two interfaces. Two liquid mediums are separated by an interface (the medium divide, as shown in Fig. 2).

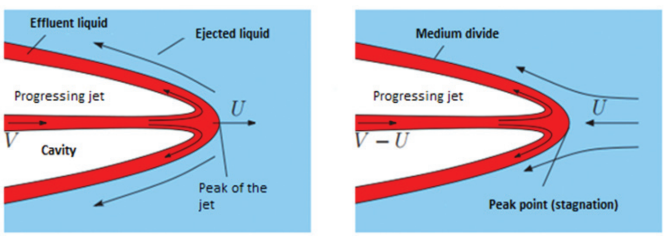

Figure 2. (left) On the left see a V-shaped fluid jet impacting on the fluid in a equilibrium state penetrates at velocity U On the right you can see the course of hydrodynamic penetration with high lighted peak point where stagnation of penetration occurs[4].

Speed of penetration is indicated by U. The effect of gravity is neglected in this case. For a situation that is depicted in Fig. 2, we can write according to Bernoulli's theory of the relationship between the jet and the penetrated medium as follows:

$$\frac{p_j}{\rho_j} + \frac{1}{2}\left|u_j\right|^2 = \frac{1}{2}(V-U)^2 \qquad (1)$$

$$\frac{p_t}{\rho_t} + \frac{1}{2}\left|u_t\right|^2 = \frac{1}{2}U^2 \qquad (2)$$

where u is the flow velocity, p indicates the fluid pressure, index j denotes the shot (jet) and t target. In this relationship the Bernoulli constant was calculated from the zero flow values in infinity and from the zero pressure at the free surface of the cavity interface. Pressure has to be the same at the top of the projectile - at the point of stagnation according to this assumption we can calculate the penetration rate cording to the following relation:

$$U = \frac{V}{\left(1 + \sqrt{\frac{\rho_t}{\rho_j}}\right)} \qquad (3)$$

The depth of penetration can be approximated as $U.T$ where T is the penetration time interval. The calculation is based on the assumption that the penetration time interval is $L/(V - U)$ and therefore the penetration depth d can be calculated as:

$$d = L\sqrt{\frac{\rho_j}{\rho_t}} \qquad (4)$$

The shape curves of stream can be calculated in the two-dimensional reference system by means of other complex variable techniques in which we can use the four planes. First - the Ω plane - represents the total potential of stream. Secondly - the Q plane - represents in its imaginary component the flow direction (jet flight). We can derive a relation for calculating of the velocity potential using the Schwarz-Christoffel mapping techniques and then the relationship for the calculation of the stream shape or the resulting cavity:

$$x = 2\log\left(\frac{y}{4}+1\right) - \left(\frac{y}{4}+1\right)^2 \qquad (5)$$

For large x values, y can be derived by following relationship $y \sim \pm 4h\sqrt{-x}$

This simplified model for penetrating of the liquid stream into the fluid environment approximates the shape of resulting cavity, but it has unlimited solutions for large negative x values[3,4].

An alternative model for calculating the shape of the resulting cavity is model developed by Hopkins and the his team. The proposed model deviates from Helmoltz theory and does not assume a constant momentum at the point where the flow of the stream is turned to the opposite direction. At these locations, the flow is slowed down by turbulence and eddy currents. We can obtain a relation to determine the final width for the large negative values x using the conformal mapping function for this consideration[4].

$$y \sim \pm h\left(\frac{2V\sqrt{\rho_j}\pi}{V\sqrt{\rho_j} - U\sqrt{\rho_t}}\right) \qquad (6)$$

3.1 Water Cumulative Charges as Water Spouts

The principle of water cumulative charge is the cavity filled with water and surrounded by an explosive. The construction is without a metal liner. Water is almost incompressible. This property can be used sufficiently to create the necessary dynamic forces. Water beam can cause by its dynamic action extinguishing fire produced by burning gases under pressure or vapours of combustible liquids released from a pipe or other source. It uses two factors to extinguish the fire. The first important factor is formation of pressure wave propagating ahead and snuffing out the flame, and behind it a water jet moves and decreases high temperature, blows the flame off, also inhibits the reignition[5].

The detonation pressure (in case of ideal gas) is calculated by Eqn. (7):

$$p \cdot V_s = n \cdot M \cdot R \cdot T \rightarrow p = \frac{n \cdot M \cdot R \cdot T}{V_s} \qquad (7)$$

where p - pressure [MPa], V_s - volume [m^3], n - number of moles in 1 kg explosive, *R* - gas constant, *T* - temperature [K], *M* - explosive mass [kg].

The most well-known example of acceleration of matter in context of explosive is shot, mining of minerals and rocks, or destruction of ice on frozen water surfaces. So-called Gurney model is most suitable tool to count the speed of fragments accelerated by explosion[6].

Water cumulative charges will be attached on the wall of objects. This system has similar structure as asymmetric sandwich, so we can use its mathematical formulas to evaluate the effectivity of the water cumulative charges[5]. The mathematical determination for calculation of water acceleration in case of explosion lies in constructing of this sandwich to the following structure– Water / Explosive / Plug (water) - W / E / P. Diagram of the sandwich arrangement is shown in Fig. 3.

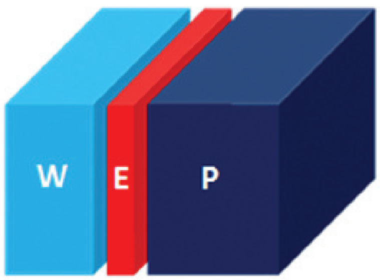

Figure 3. A schematic of design of the asymmetric sandwich[5].

Mathematical calculation of the acceleration of water ahead of explosive during explosion is based on the above Eqns.(8) and (9)[6-8].

$$\frac{v}{\sqrt{2\cdot E}} = \left[\frac{1+A^3}{3\cdot(1+A)} + \frac{m_s}{m_e}\cdot A^2 + \frac{m}{m_e}\right]^{-\frac{1}{2}} \tag{8}$$

$$A = \frac{1+2\cdot\frac{m}{m_e}}{1+2\frac{m_s}{m_e}} \tag{9}$$

where v –velocity of accelerated water particles $(km\cdot s^{-1})$, $\sqrt{2\cdot E}$ – Gurney's velocity $(km\cdot s^{-1})$, m_s weight of the seal - water behind explosive (kg), m_e – weight of explosive (kg), *m* – weight of water ahead of explosive (kg).

There are some conditions which affect propagation of the pressure wave, such as sort of explosive, building structure and ambient environment. Pressure wave propagates from explosion epicenter in the ball waves and reflects and modifies itself by impact on the obstacle. Its efficiency depends on following parameters:

- Dimensions of charge
- Range and time of action

Effectiveness of pressure waves in the back of the charged shells must be dampened enough to minimise its effect on surrounding objects.

The simplest form of water projectile is a water high-speed high-pressure projectile. The projectile is designed to create a desired depth cavity in the target material. Leach and Walker's research on water missiles was conducted. They experimented both with high-speed water jets up to 1 km/s (pressures up to 500 MPa), and with bullets at lower speeds up to 340 m/s (pressures up to 60 MPa).

Cumulative charges rectify water and other particles (medium) forward, and this medium is accumulated by explosive in a high pressure jet of a certain cross section. Very important is the back part of the water cumulative charge, which is formed as a water phase. This water phase has two important properties. Firstly, it provides the forward effect of the water cumulative charge and also when the explosive explodes, it creates a protective back cover preventing the ignition of surrounding high flammable materials[7,9].

There are mostly used explosives with a bigger detonation velocity exceeding 6000 $m\cdot s^{-1}$ for construction of cumulative charges, for example:

- Hexogen RDX (8520 $m\cdot s^{-1}$),
- A-IX-1 (8700 $m\cdot s^{-1}$),
- H/TNT – 50/50 (7270 $m\cdot s^{-1}$),
- H/TNT – 60/40 (7800 $m\cdot s^{-1}$),

3.2 Development of a Water Spout when using Cumulation

It is more efficient to use the plastic explosive Semtex 10-SE (plasticity properties). The manufacturer most often produces this explosive in the following dimensions: 2mm x 300mm x 10m. It is adherent. It can be attached to any place inside of the charge. It is stable (regarding detonation capabilities).

At the beginning of experiments, a measurement of magnitude of blast wave propagation was performed in the vicinity of the test sample of the selected explosive. Measurements were performed with a plastic explosive Semtex 10-SE. The samples used in the experiments had the following weights:100 g, 200 g, 300 g. Figure 4 shows the geometry of deployment of pressure sensors deployed around the epicenter of the explosion at the distances shown in Table 1.

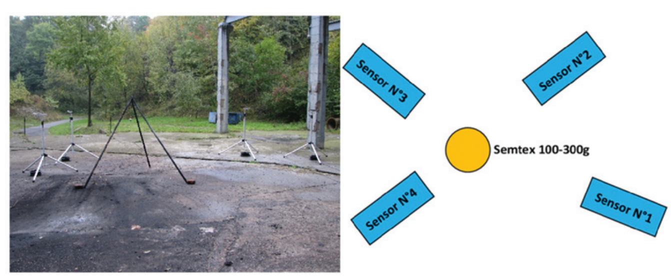

Figure 4. The geometry of deployment of pressure sensors. Sensors were placed dat the same height as explosive – 1,5 m. Location: Experimental gallery, Štramberk, Czech Republic.

Table 1 also shows an uneven distribution of pressure at a location at different distances from the epicenter of the explosion. The cause is not clear, probably it is due to the adverse meteorological conditions present at the place of the experimenter. Figure 5 shows pressure distribution of blast

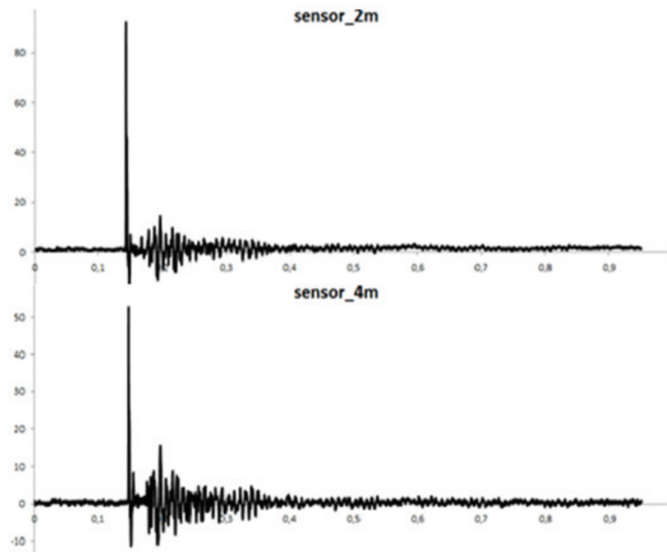

Figure 5. **Courses of blast waves (Semtex10-SE, 300 g).**

wave at distances 2 m and 4 m from the explosive sample - explosion epicenter (with using of 300 g Semtex 10-SE).

Table 1. Geometry of deployment of pressure sensors deployed around the epicenter of the explosion

Number of sensor	4	3	2	1
Distance (m)	2	3	4	5
Pressure– 100g charge (kPa)	58	16	23	23
Pressure– 200g charge (kPa)	38	42	40	44
Pressure– 300g charge (kPa)	92	54	54	48

To prove the correctness of the above discussed thesis, a prototype of water cumulative charge was constructed. to carry out experiments to determine whether sufficient cumulative pressure water stream with an extinguishing effect at a fire place is developed. The tests were also performed to prove the efficiency of the water mass as a sealing space. The prototype is a plastic container that has been cut off on the top to insert an explosive to proper place, see Fig. 6:

(i) Space for insertion of water medium,
(ii) Explosive with detonator,
(iii) Space for insertion of water medium(rear part of the prototype). It functions as a seal.

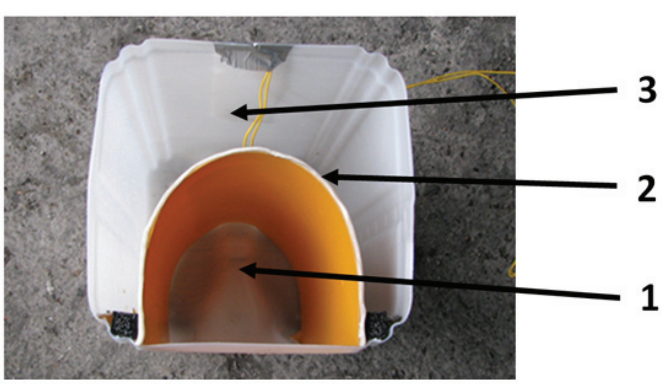

Figure 6. Design of a cumulative charge in a plastic container.

Figure 7. Manufactured charges of two sizes (left).

Figures 7 shows two prototypes (experimentally developed) of different volumes: 5 l, 10 l.

3.3 Experimental Design of a Water Spout Prototype

As part of the necessary tests, a prototype of a cumulative water system was created. Figure 8 shows the schematic composition of the prototype. For greater clarity, the parts are distinguished in colour:

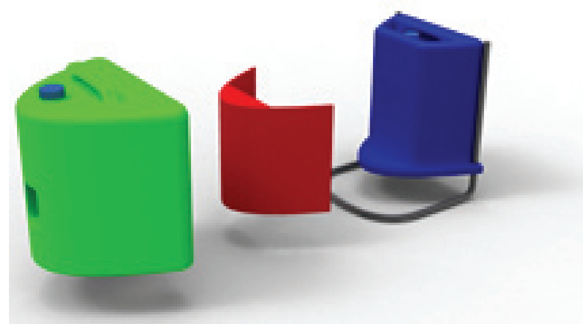

Figure 8. Unfolded idealogicall design of the water cumulative charge prototype.

The interior canister - (blue colour) is working. Its water content is directed to the cumulative working beam. It should contain about 8 - 10 liters of liquid to form a massive stream of water. In the lower part there is a height-adjustable base (gray colour), for correction of the height of the prototype in its particular location.

Explosive - (red colour) – Semtex 10-SE -copies shape of the interior canister. This explosive has to be constructed to defined shape on the canister and in such way that it is not to be deformed by the insertion of an external canister which functions as a rear seal.

The external canister - (green colour) is a stuffing box. Ensures a better use of the pressure wave forwards and, in the event of an explosion, the outside liquid creates a cloud of water mist. It is putted into the working canister covered with explosive to form a compact unit of water cumulative charge. It should contain about 60 l - 80 l of water.

Based on this idea a prototype of the water spout was constructed with the above mentioned parameters. Figure 9 documents an effective extinguishing capability of cumulative charge prototype which were applicated to the area of intense flame epicenter induced by initiation of pyrotechnic ground lights PS-25 in the explosion. Figure 9 also documents distribution of a water droplets. The intended flame source produces an intense flame up to a height of about 60 cm at a temperature of 2000 ºC. The real speed of the water mass was calculated at approximately 580 m/s (for this calculation was used the approximation method, based on changes of positions of water droplets determined from the video frames during the experiments). The entire successful fire intervention was carried out in 1.15 s (time was measured from the initiation of the explosive to the extinction of the flame epicenter.

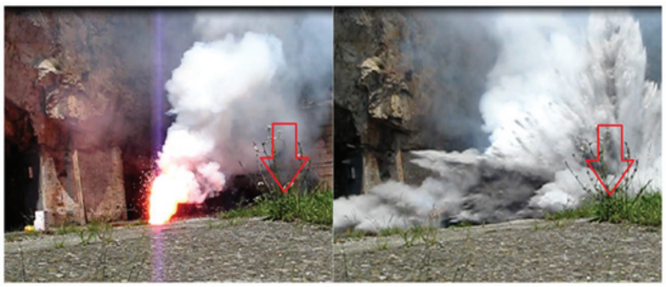

Figure 9. A Practical test of flame extinguishing by using the water spout (flame was initiated by 20 PS-25S). Location of water cumulative charge was marked.

4. CONCLUSIONS

Water cumulative charges provide many benefits that can make firefighters or other components more efficient. Among these advantages lies especially: Simple cunstruction, short time of its preparation, high security level, etc. We can conclude (according facts which were gained from tests) that cumulative water charge has a significant potential and possibilities to extinguish an intense flame. However, more practical experiments need to be carried out to confirm discussed theses.

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Contribution in the current study, he carried out experiments with water cumulative charges and provided data from these experiments with his comments.

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Contribution in the current study, he participated in the experiments with water cumulative charges and provided data from these experiments with his comments.