



Explosive Formation and Spreading of Water-Spray Cloud – Experimental Development and Model Analyses

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Abstract: The paper presents results of experimental investigations and model analysis concerning the expansion of explosively produced water-spray cloud. The regular shape of water-spray cloud produced by a charge placed in a bag filled with water is attained. Effective dispersion of bags containing 600 up to 1500 litres of water is attained. The rise and deceleration of external zone of water-spray cloud is described analytically. The parameters of pressure field evolving around the explosively formed spray cloud were registered.

Keywords: explosion, water aerosol production, shock wave parameters

Introduction

The water is one of the oldest fire suppressant media [1]. In contemporary developments, still wider fields and methods of water sprays application for fire extinction and combustion suppression are indicated. The methods of use of fine water sprays to quench fire spots in the presence of live electrical equipment are described in [2]. Explosively formed sprays are used to prevent and extinguish a fire and explosion development in dust/gaseous systems. The use of water-filled tanks, provided with a system of indicators, to create water barriers designated to mitigation and suppression of combustion and explosion of coal dust or methane/air mixtures are presented in [3]. The explosively produced water-spray clouds can also help to extend the capacity of classical methods of fire damping [4], especially in the case of extinguishing and preventing large-scale fires (forest fires, oil plant fires etc. [5-7]).

Two ways of water-spray role in fire quenching can be indicated. At first, the water cloud hampers oxygen inflow to the burning surface preventing rise and develop of fire-centre and secondly, water fragmented into tiny droplets can absorb huge amount of heat in a very short time, thus efficiently cooling both the combustion products and the surface of burning material.

In the paper, an explosive system providing the effective water spray production is reported. Some model considerations concerning the velocity of spray cloud rise are presented.

Explosive dispersion system

Upon the model analyses and taking advantage of extended experimental search the effective lay-out of dispersion system was developed. Along with earlier considerations [8] the cylindrical configuration of the dispersing set was adopted as the one that provides most favourable conditions for explosive dispersing. In spherical symmetry, the maximal volume of dispersed water is limited by the maximal thickness of the water layer. In investigations carried out an effective production of a water aerosol by dispersion of bags containing 600 up to 1500 litres of water was attained.

A schematic view of the axial cross-section of the explosive aerosoling system is presented in Figure 1.

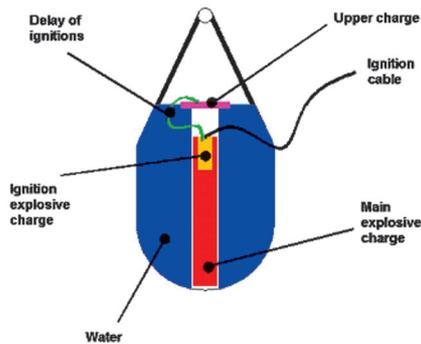


Figure 1. A schematic view of the dispersion system.

The dispersed water was placed in plastic bag. A rod of explosive was fastened along the vertical axis of the bag. Since the container is not rigid, the water-bag becomes egg-shaped at its lower end. However, as the detonation wave moves from top to the base of the bag, the impulse of expanding detonation products imparts into the widened (lower part) water bag. To prevent an inconvenient backward launching of the dispersed water, a correlation charge is mounted in the upper part of the system, to hamper the backflow of detonation products in the axial direction. The exemplary registration of the water cloud production is presented in Figure 2.



Figure 2. The explosively developed water-spray cloud.

The developed configuration guarantees quite high efficiency of the explosion energy transmission to the bulk of water. The prevailing mass of dispersed water expands almost horizontally. Then, the final cloud shape resembles the disc rather than a ball. That increases the ability of the spray cloud to cover a larger surface of the fire area.

Model analysis of cloud expansion

The model analyses have been performed to predict the rules according to which the water cloud develops. To recognize the maximal cloud dimensions, an analysis of the outer band of the water-spray cloud was carried out. The droplets of an external spray zone are assumed to propel rightly to the initial velocity obtained in the process of explosive fragmentation. The droplets are assumed not to interact with each other during deceleration. The trajectory and deceleration of the front droplets is then governed by the rules of their interaction with the air. Upon that assumptions the description of the cloud rise and sizes can be obtained by analysis of individual droplets behaviour in the frontal zone of the cloud.

It is assumed that a droplet moving in the air decelerates due to pressure drag in the high velocity (Bernoulli) regime and due to viscosity-based friction in the low velocity (Stokes) regime. The transition from the Bernoulli to the Stokes regime is treated as immediate since the range of velocities in which both the drag and friction acting on a droplet are comparable is rather narrow, and the model is not expected to be extra accurate anyway. The problem is treated as one-dimensional since the gravitation is negligible when compared with the decelerating forces, except for the very final stage of expansion. Under such assumption one can write the following equation for the time-dependence of the droplet's velocity

$$\dot{v} = -\gamma v^2, \quad (1)$$

where v is the droplet's velocity and γ is a coefficient representing drag. Solution of the above equation of motion can be directly integrated over time giving the following formula describing dependence of cloud diameter $D(t)$ on time, for the Bernoulli regime

$$D(t) = \frac{2r}{\gamma} \ln \left(1 + \gamma v_0 \frac{t}{r} \right). \quad (2)$$

Here r denotes the radius of the largest droplet; v_0 denotes its initial velocity. The function (2) is not bounded from above, which means that with Bernoulli drag alone the cloud would have to expand indefinitely (from the theoretical point of view), and its finite diameter follows from the Stokes friction dominating for small velocities.

Taking into account Stokesian friction and solving the appropriate equation of motion the following formula can be obtained

$$D(t) = D_S + 2 \frac{m}{\beta} v_S \left[1 - e^{-\frac{\beta}{m}(t-t_S)} \right]. \quad (3)$$

Here D_S is the cloud's diameter at the zone in which transition to Stokesian deceleration occurs, v_S is a corresponding droplets' velocity and β denotes friction coefficient for water droplets moving in the air. As can be seen, the limiting diameter is given by the formula

$$D(t) = D_S + 2mv_S / \beta. \quad (4)$$

In practice, the second component in Eq. (4) is much smaller than the first one, which means that droplets, before reaching this limit, cover a lion's share of the distance in the regime of Bernoulli deceleration.

Eqs. (2) and (3) imply that after plotting D versus $\log t$ a rectilinear section spanning over majority of the whole diameter ΔD_0 increase should appear, and for $t > t_S$, i.e. for whiles after the Bernoulli – Stokes transition occurs, a concave saturating section should appear in the plot.

The above results have been verified in numerous performed experimental tests.

Experimental registrations

Measuring cloud's diameter increase in time

The measurements of cloud diameter expansion were performed by registration of the cloud shape with a video camera working at the frequency 250 fps. The camera was placed at the distance from the axis of explosion that was chosen to be secure against possible influence of the shockwave and to minimize parallax error.

The time scale was given by the frame number, and diameter of the cloud was estimated from subsequent frames by its comparison with the reference scale indicated either by stakes or by marks, depending on the way the water bag was supported. Readings obtained in this way allow plotting experimental dependence of the diameter on time either in the double-linear scale or in the log-linear scale.

Dependence on time of the diameter of the water-spray cloud obtained after processing the data is presented in Figure 3.

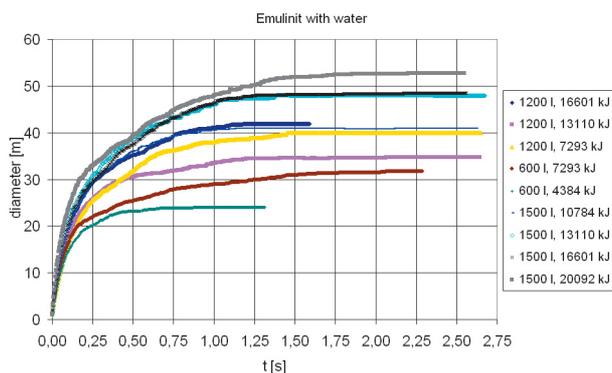


Figure 3. Cloud's diameter as a function of time for various explosion energies and water-bags of various sizes.

The explosive charges were of Emulinit [10], used in standard packages. As can be seen all experimental curves are in general up-convex which means that they all represent deceleration of the cloud's expansion. The time-span between two subsequent frames, i.e. 4 ms, does not cover the time of initial acceleration. One can conclude that the first stage of expansion in which water is being accelerated is about three orders of magnitude shorter than the whole process of expansion.

Despite similarity of general shapes the plots vary in quantitative characteristics and mainly in the maximum diameter attained by the cloud. The cloud diameter extends from slightly more than 20 m in the case of a small bag (600 l) and the smallest explosion energy (4384 kJ) to more than 50 m in the case of a large bag (1500 l) and the maximum used explosion energy (20092 kJ).

In general, for bags of the same size increase of cloud's diameter is observed with increase of explosion energy up to a limiting energy value that depends on the water-bag size. Depositing of the dispersing energies exceeding the limiting value gives no further rise of the cloud diameters. On the contrary,

some pronounced decrease of cloud's diameter may be observed. We call this phenomenon "overblow", as it apparently corresponds to the breakdown of efficiency of energy transfer.

Measuring shock-wave parameters

Tracking of the shock wave parameters can provide information on the general (integral) features of development of explosively formed spray cloud.

The equipment for measuring the parameters of shock wave was arranged of four piezoelectric pressure sensors ICP, of a unit for measurement conditioning, and of an industrial PXI computer. The pressure sensors were positioned at distances of 5, 10, 20, and 30 m from the axis of the water-bomb, fastened on the tops of four long vertical stakes which is schematically shown in Figure 4.

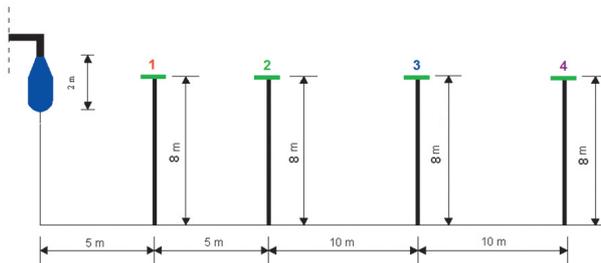


Figure 4. Placement of pressure sensors with respect to the water-bomb.

To ensure comparable accuracy of pressure measurements at all four distances from the explosion axis, three types of sensors are used and their parameters are given in Table 1.

Table 1. Parameters of the piezoelectric sensors used in the measurements of the shock-wave pressure

Sensor's No.	Sensitivity [mV/kPa]	Maximum Pressure [kPa]	Resolution [kPa]
1	0.145	34.5	0.69
2	2.9	34.5	0.001
3 & 4	14.5	6.9	0.069

The registration was triggered at the moment of explosion by the start sensor inserted into the charge. The measuring systems allow to register 105 samples of pressure at the sampling frequency $5 \cdot 10^5$ samples per second. It allows to cover time interval of 200 ms with time resolution 2 μ s. Acquisition and processing of

the results was made by an PXI computer supplied with the software LabVIEW RT, and equipped with a measurement card. The shock wave pressure was registered with reference to the air at ambient pressure. Exemplary course of obtained time profiles of the pressure are shown in Figure 5.

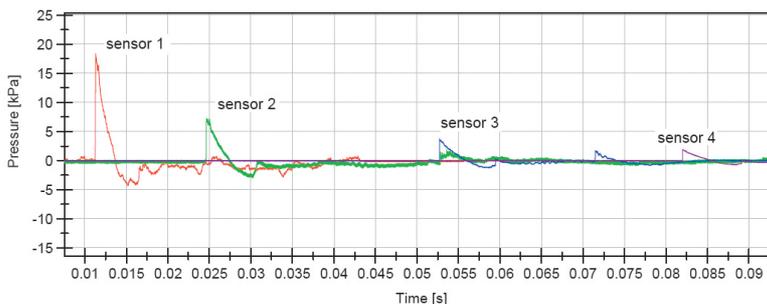


Figure 5. An example of the shockwave pressure time profiles.

The left-hand oriented peaks allow to determine maximum pressure in the front at the distances from the axis of explosions at which the sensors were located. Respectively, the time intervals between explosion and arrival of the shock wave front to subsequent sensor can be determined. The maximum pressure decreases with the distance from the axis of explosion. Detailed results of measurements averaged for a number of tests are shown in Table 2.

Table 2. Maximum pressure in the shock-wave front registered in various tests by the sensors 1-4. The abbreviations for the names of the used explosives are as follows: E – Emulinit, S – Saletrol, P – Plastic explosive

Parameters of the test			Maximum pressure [kPa] registered by the sensors 1-4			
Bag size [l]	Explosive	Energy [kJ]	1	2	3	4
600	E	10784	21.7	8.4	4.6	2.3
1500	E	10784	20.7	9.7	4.7	2.4
1200	E	10784	27.6	9.0	4.7	2.3
600	S	4384	17.2	8.6	3.9	2.1
600	S	7293	22.1	9.3	4.8	2.2
600	S	10784	21.7	8.3	5.5	2.5
1500	S	20092	19.3	10.3	6.3	3.1
1500	E	20092	13.8	7.6	4.5	2.4
1500	P	20092	37.2	9.3	5.5	2.8

As can be seen, at the sensor No. 4 the maximum pressure varies from 2.1 to 3.1 kPa. That means, that the shock wave at this distance transforms into the overpressure wave.

The most distinct features that can disclose the properties of the phenomenon of explosive dispersion of a liquid layer can be read from the data registered at the sensor No. 1. It is interesting, that for Emulinite, (the first three verses) the parameters of shock wave in small degree depend on the amount of dispersed water. It can be concluded then, that the intensity of the shock wave arising around the driven water layer depends mainly on constitutive parameters of the explosive employed in the dispersion system. Similarly, in the case of Saletrol, the amount of the released energy has negligible influence on the pressure jump at the front of the shock wave. Some differences, observed by changing of the magnitude of dispersion energy (verses 4 to 6) or amount of driven liquid (verses 1-3), may be explained by more detailed analysis of the dynamics of the dispersing system (magnitude, placement and geometry of driving explosive charges).

By changing the kind of explosives (verses 6-9), significant differences in the intensity of the shock wave induced by the expanding water layer are obtained.

Upon analysis of the time intervals at which the peaks were registered the average velocity of propagation of shock and pressure waves may be computed. Values of the average velocities obtained for the same tests as presented in Table 2 are shown in Table 3.

Table 3. Average velocities of the shock-wave front propagation at the distance between the axis of explosion and the subsequent sensors

Parameters of the test			Average front velocity [m/s] on the distances 1-4			
Bag size [l]	Expl. mat.	Energy [kJ]	1	2	3	4
600	E	10784	384	372	357	330
1500	E	10784	371	372	357	332
1200	E	10784	437	370	353	338
600	S	4384	417	373	354	328
600	S	7293	389	373	358	331
600	S	10784	390	374	358	330
1500	S	20092	377	376	362	334
1500	E	20092	399	362	357	334
1500	P	20092	385	370	358	333

The propagation values observed at the 4th distance (the average propagation velocity between sensors Nos. 3 and 4) confirm that the shock wave velocity decreases to the sonic velocity. The registrations of the shock intensity (Table 2) and arrival times (Table 3) enables one to discern the rules and mutual correlations between the droplet velocity (Section 2 and 3 of the paper) and the parameters of the overpressure field developing around the dispersed layer of liquid.

Composite results

To facilitate the simultaneous analysis of phenomenon of explosive dispersion the statement of the results of water-spray cloud expansion measurements together with the shock-wave front trajectory were set up. The composite results are presented in Figure 6. Three configurations of the dispersive system are depicted.

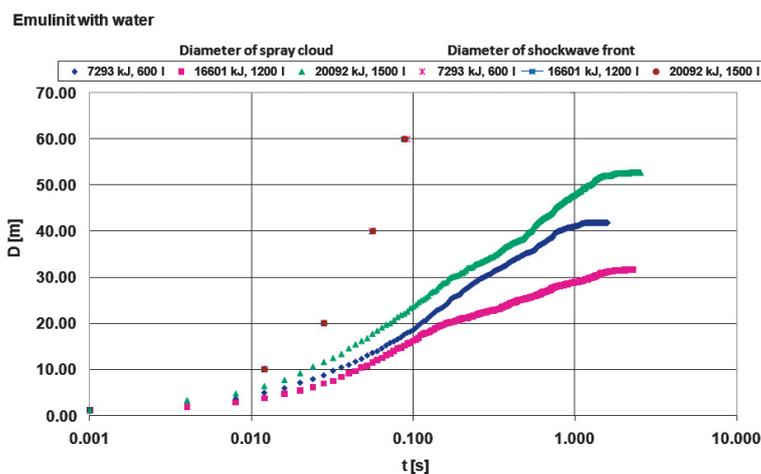


Figure 6. Diameter of the spray cloud vs time (in log scale) and an exemplary trajectory of shockwave front (the sparse rectangles).

As can be seen, in all plots the visible changes the slope of the cloud's diameter versus log time can be observed. That confirms the assumed distinction between the Bernoulli and the Stokes stages, in droplet cloud expansion. An abrupt change of the slope of the droplets trajectory marks the transition between the modes in which an apparent change of the drag coefficient occurs. The quantitative analysis of this attribute will be the matter of further study.

The shock wave trajectory is marked by squares. As the course of the plot shows, the cloud's front is overrun by the front of the shock wave at a very early stage of explosion. The dispersed droplets are to move in the disturbed air. The parameters of the surrounding air (mass velocity, the increased mass density) will influence the motion of dispersed droplets.

Summary and Conclusions

In the paper development and expansion of explosively produced water-spray cloud are investigated. The explosive dispersion set is described. Effective dispersion of bags containing 600 up to 1500 liters of water is attained. The disc-like final shape of the spray cloud is attained.

The model analyses predicting the regimes of rise and deceleration of the external zone of water-spray cloud are carried out. The general agreement of the derived relations with time-profiles of expansion of explosively formed droplet cloud is observed.

The experimental registrations of the characteristics of spray cloud rise in time are carried out. The limiting range of explosive energy deposition to the driven liquid layer is noted.

Shock wave parameters induced in the surrounding atmosphere by the expanding droplet cloud are investigated. The analysis of the dependence of the shock wave intensity upon the quantity of explosion energy and the amount of the driven water is carried out. The significant conclusion on the decisive influence of the detonative properties of explosive charge upon the intensity of shock wave induced in the air is drawn up.

The performed analyses and investigations provide the data to disclose the rules and correlations between parameters of explosive charge and the characteristics of explosively formed spray cloud.

Acknowledgments:

The work was supported by the Grant of Polish Ministry of Science and Higher Education 8003/R/T00/2007/03.

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