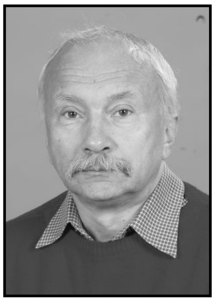
Roman DYGDAŁA, Krzysztof STEFAŃSKI,
Grzegorz ŚMIGIELSKI, Damian LEWANDOWSKI, Michał KACZOROWSKI
SZKOŁA WYŻSZA IM. PAWŁA WŁODKOWICA, PŁOCK; WYŻSZA SZKOŁA GOSPODARKI, BYDGOSZCZ
UNIWERSYTET MIKOŁAJA KOPERNIKA - COLLEGIUM MEDICUM; TORUŃ, BYDGOSZCZ
WYŻSZA SZKOŁA GOSPODARKI, BYDGOSZCZ
SZKOŁA WYŻSZA IM. PAWŁA WŁODKOWICA, PŁOCK
BAKACHEM SP. Z O. O., WARSZAWA

Aerosol produced by explosive detonation

Prof. dr hab. Roman DYGDAŁA



Absolwent Wydziału Matematyki, Fizyki i Chemii w Toruniu. (1972). Doktorat oraz habilitacja zatwierdzone w latach 1981 oraz 1991. Tytuł profesora otrzymany w czerwcu 2002 r. Specjalność fizyka atomowa i molekularna jak również informatyka stosowana. Autor ok. 100 prac naukowych publikowanych w czasopismach międzynarodowych i prezentowanych na konferencjach międzynarodowych. W latach 80-tych i 90-tych liczne staże naukowe w Kilonii oraz w Pizie.

e-mail:romdy1@onet..pl

Mgr Grzegorz ŚMIGIELSKI

Absolwent Wydziału Fizyki, Astronomii i Informatyki Stosowanej UMK w Toruniu. Studia o specjalności Komputerowe Systemy Sterujące ukończył w 2003 roku. Jest zatrudniony na stanowisku asystenta w Zakładzie Systemów Informatycznych WSG w Bydgoszczy. Zainteresowania naukowe dotyczą pomiarów wykonywanych w czasie rzeczywistym, sterowania CNC oraz układów programowalnych.

e-mail: gsmigielski@byd.pl

Mgr inż. Michał KACZOROWSKI

Absolwent Instytutu Inżynierii Chemicznej Politechniki Łódzkiej z 1978 roku oraz studium podyplomowego w specjalności technika strzelnicza na Wydziale Górnictwa Odkrywkowego AGH . Współautor kilku patentów i publikacji oraz kilkudziesięciu wdrożeń w przemyśle wydobywczym i chemicznym w Polsce i w Rosji. Od 1994 roku Prezes firmy „BaKaCHEM" Sp. z o.o. w Warszawie.

e-mail: bakachem@neostrada.pl

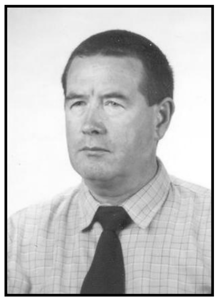
Streszczenie

Artykuł prezentuje główne wyniki badań otrzymane podczas prób poligonowych przeprowadzonych w latach 2002 do 2006. Badania te dotyczyły formowania chmury aerozolu wodnego tworzonego metodą wybuchową w zależności od wielkości kapsuły wodnej i ładunku wybuchowego.

Przy pomocy kamery video zapisującej obraz z szybkością 1000 klatek na sekundę rejestrowano eksplozje worków wypełnionych wodą (kapsuł wodnych), zawieszonych ponad 12 metrów nad ziemią. Wykonano również pomiary ciśnienia fali uderzeniowej za pomocą czujników piezoelektrycznych sprzężonych z komputerem wyposażonym w system czasu rzeczywistego. Wyniki eksperymentalne zostały porównane z opracowanym przez nas modelem teoretycznym formowania chmury.

Słowa kluczowe: gaszenie pożarów, pomiary szybką kamerą, wybuchowe tworzenie aerozolu wodnego, parametry metrologiczne – określenie odległości i prędkości aerozolu wodnego.

Dr hab. Krzysztof STEFAŃSKI



Absolwent Wydziału Matematyki, Fizyki i Chemii w Toruniu. (1973). Doktorat oraz habilitacja zatwierdzone w latach 1981 oraz 1992. Specjalność naukowa: fizyka teoretyczna, dynamika nieliniowa i jej zastosowania. Autor ponad. 30 prac publikowanych w czasopismach międzynarodowych i przedstawianych na konferencjach międzynarodowych.. W latach 80. i 90. staże naukowe w USA, Izraelu i Japonii.

e-mail: krzysztof.stefanski1@neostrada.pl

Mgr inż. Damian LEWANDOWSKI

Absolwent Wydziału Inżynierii Środowiska Politechniki Warszawskiej z 2001 roku. Studia podyplomowe z matematyki, fizyki i informatyki. Zainteresowania naukowe dotyczą programowania i metod numerycznych. Jest zatrudniony w ZSZ nr 2 w Płocku jako nauczyciel matematyki.

e-mail: damian_lew2@wp.pl

Aerosol produced by explosive detonation

Abstract

This report presents main results achieved during field tests. The tests, as well as series of earlier tests performed from 2002 to 2005, were devoted specifically to the problem of the water-spray cloud formation depending on the water-bag load and on the explosive charge as well as for determination of some metrological parameters.

The registration of explosions of water-bags in a static tests mode hanging more than 12 meters above the ground using a video-camera with time resolution of 1000 frames per second and measurements of a pressure shock wave as a function of explosive charge and water bag load have been also performed (Fig. 1). The experimental results were compared with theoretical models of cloud formation elaborated by us.

Keywords: fire extingushing, ultrafast camera measurement, explosive aerosol production, metrological parameters of aerozol expansion

1. Introduction

Aerosol Damping System that in this paper will be denoted ADS can be used for damping or preventing explosions [1,2] in the case of forest fires and fires and explosions in industrial plants [3,4]. Extinguishment of such fires with presently available techniques is, in many cases, not efficient since they cannot be used on large areas [5]. The extinguisher to be developed consists of a bag filled with water, powder or water-powder, e.g. in the form of suspension that is the extinguishing agent which is spread over an area in the form of aerosol after bursting the bag with an internal explosion.

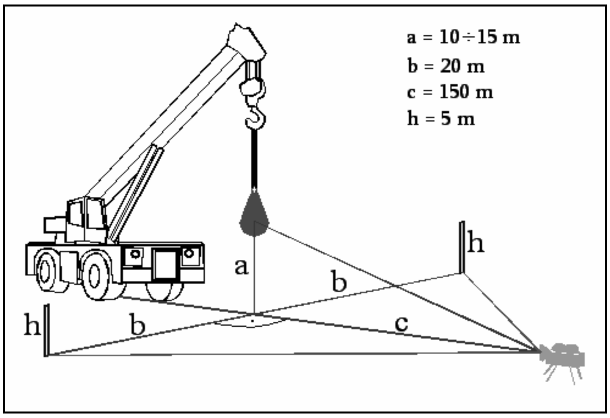


Fig.1. The experimental setup in the static mode configuration

The spray dissolves the fire-feeding oxygen and the explosion removes a part of it from the surrounding. Explosive formation and spreading of a spray water cloud is a complex phenomenon whose complete and unified theoretical description may be extremely difficult and may ultimately require extensive numerical modelling [6]. At first we present relatively simple models that represent different aspects of the phenomenon that provide a framework for designing and interpretation of high precision measurement. We devise special attention to the process of drag-related slowing-down of a water droplet resulting in limited diameter of the water-spray cloud. All tests have been performed for the cylindrical configuration (Fig. 2), which our theoretical investigation had shown to be the best.

A

B

C

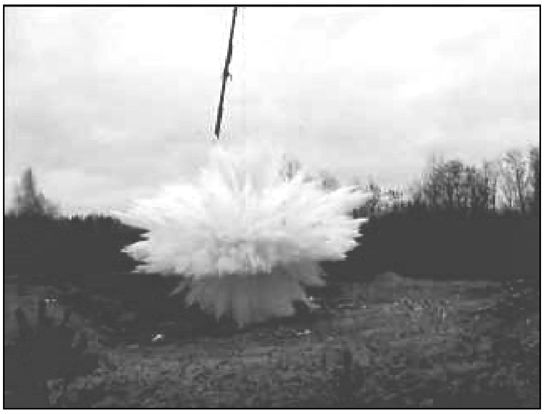


Fig.2. The formation of a water aerozol cloud (cylidrical configuration) : A – 40 ms, B – 80 ms and C – 160 ms after begining of explosion

The three frames shown in Fig. 2 illustrate geometry of the formating water-spray cloud in the case of the cylindrical configuration. Apparently the main bulk of the spray cloud expands horizontally as a toroid, and only residual vertical jets are visible.

The cloud diameter is defined as its span in the horizontal direction (this definition is directly based on the standard definition of the diameter of a set in a metric space i.e. the largest distance between its elements). Since the cloud is designed to assume toroidal shape, its horizontal extension is larger than its vertical extension.

The momentary diameter is measured by comparison of the cloud's extension with a scale painted on the crane-beam at the corresponding frame taken by the ultrafast camera. We claim that such a technique produces small inaccuracy, since our earlier measurements performed with more than one camera have shown that the cloud exhibits only small deviations from the rotational symmetry with respect to the vertical axis, and registration with only one camera is sufficient.

Inaccuracies of he measurements are caused mainly by these small deviations from the perfect symmetry. Parallactic errors are smaller and may be neglected since the camera is placed several cloud diameters from the center of explosion, that is positioned directly under the beam. We estimate the maximum error of cloud diameter as ± 2 m while in the initial stage of the cloud formation the error is much smaller. Determination of the error in diameter of the measured cloud depends of course on many more parameters such a weak wind, non-central position of explosive material and so on. Anyway our expirience in determination od theses diameters from few cameras simulteneously gave us the knowledge, that the error in the diameter is smaller than ± 2 m, espacially in the region of interest. On the other hand the diameter of the spray clouds could be determined by various computer methods.

The paper is arranged as follows. The problem of the influence of geometrical factors on efficiency of the energy transfer is discussed at the beginning. Next we consider pulverization of the water bulk, and the problem of spreading the spray cloud. Finally we present metrological results of field test of real cloud formation via exploding a water-bag filled with water and stuffed with an explosive rod placed along the symmetry axis The experiments, whose main objective consisted in the analysis of formation and expansion of the water spray cloud, based on the method of determination of the cloud's diameter as a function of time, have been performed for various parameters characterizing explosive aerosol production:

- the water-bag size (capacity),
- the mass of the explosive charge inserted into the water-bag (explosion energy),
- the distribution of the explosive charge inside the water-bag,

- the type of the explosive material inserted into the water- bag,
- the type of the liquid with a special attention to its surface tension coefficient.

The water bag volume varied from 600 to 1500 dm^3. Two various configurations of the explosive material inside the bag have been considered: the cylindrical configuration and the spherical configuration. The mass of the explosive material varied in the interval corresponding to the explosion energy ranging from about 4 MJ to 33 MJ. Three types of explosives were used in the tests: Emulinit (Emulsion EM Emulinit 2), Plastic (plastic EM MPW C-4) and Saletrol (ANFO). The desired explosion energies have been recalculated to corresponding masses using the "ideal explosion work" (cf. Table .1). Such parameters of the explosive materials as the detonation velocity, explosion heat etc. were taken from the data published by the producers. Additional measurements of their values would require considerable amount of time and money, and it would essentially exceed the assumed scope of this work.

Table 1. Parameters of the explosives used in the tests (Emulinit was used in both the first and the second stage testes; in the latter Saletrol and Plastic were used too)

Parameter	Plastic EM MPW C-4	Emulsive EM Emulinit 2	Saletrol (ANFO)
Detonation velocity [m/s]	7733	5460	2140
Lead block cavity volume [cm^3/kg]	370	306	198
Relative work efficiency [% of the analogous efficiency of hexogen]	73	63	57
Density [g/cm^3]	1,5	1,26	0,9
Specific volume of explosion products [dm^3/kg]	843,8	853,8	972,6
Explosion heat [kJ/kg]	5089,2	2746,4	3552,5
Energy concentration [kJ/dm3]	7633,8	3460,5	3268,3
Explosion temperature [K]	3770	2249	2653
Explosion pressure [MPa]	1770,4	897,6	832,8
Ideal explosion work [kJ/kg]	4394,1	2326,6	2933,5
Specific energy [kJ/kg]	1180,3	712	957,3

The test were carried on in several steps due to financial reasons and due to the influence of the obtained results on planning further investigations and extending their range.
Analysis of the obtained results is presented due to the steps.
In the first part („The first stage of the experiment") the results and conclusions based on the test registered with video-cameras working in the regime of 25 fps (video-camera Sony DCR-SR30) are presented. At that stage Emulinit only was used to produce water spray. The objective of the tests consisted in checking general usability of water spray for fire extinguishing, and in:

– determination of the suitable bag sizes,
– determination of the optimum bag shape,
– finding the best distribution of the explosive material inside the water bag,
– determination of he range of the mass of the explosive (and correspondingly the explosion energy) that may be inserted in the water bag,
– determination of the area on which fire can be extinguished with a single shot,
– comparison of theoretical predictions with experimental data.

The second part of this subsection („The second stage of the experiment") comprises results of the tests registered with the video-camera working in the regime of 250 fps (video-camera FASTCAM – Ultima 1024). At this stage water spray was produced with all three various types of explosives. The main objective consisted in detailed testing the aspects of the experiment that had been considered as most important on the ground of the preceding tests. To shed light on those problems we have performed, among others:

– tests of usability of various types of explosives for water spray production,
– tests checking influence of surface tension reduction on the water spray production,
– tests for the optimum time delay in exploding various parts of the explosive charge from the point of view of maximizing the cloud diameter,
– measurements of the pressure and velocity of the shock wave generated by the explosion.

Presentation of these results concludes the paper.

2. Model and experimental results on the water-cloud formation

The registered results of tests performed on a collection of water bags with sizes of 600, 1200 and 1500 liters and various charges of different explosive materials were analyzed on the basis of a theoretical model of deceleration of a droplet in the air due to pressure drag in the high velocity regime (called also Bernoulli regime) and due to viscosity-based friction in the low velocity regime (called also Stokes regime). As follows from the theoretical model, the Stokes regime plays an important role in making the droplet range finite but may be neglected while the objective consists in estimating the droplet range as function of time for comparison with moderate accuracy experimental measurements as in the case of the described tests [7]. Therefore one may use the following formula for the time dependence of the water-cloud diameter

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

where r denotes the radius of the largest droplet, v_0 denotes its initial velocity, and γ is a dimensionless coefficient [8].

The logarithmic dependence of the diameter on time should be noticed. The results for the collection of smaller-size water-bags with various explosive charges (and, consequently, with various explosion energies) are shown in Fig. 3. No doubt that the general shape of the dependence of the cloud diameter on time is reminiscent of the logarithmic dependence of Formula (1). Before going into a more detailed analysis of this problem, however, it should be pointed out that in general a tendency is observed that the maximum cloud diameter increases with increase of the explosion energy.

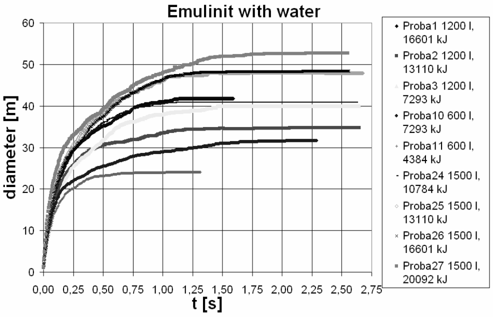


Fig. 3. Cloud diameter as a function of time for various explosion energies for a different water load water-bag. Based on the registration with an ultra-fast camera

To check how good the theoretical prediction is one may plot time in the logarithmic scale. If the model is right, a linear dependence of D on the log t should be obtained. Such plots for various explosive charge are shown in Fig. 4. One can easily notice that there is a time interval for which the dependence is linear, and this can be interpreted as the time interval in which droplets are decelerated under the Bernoulli drag cf. Eq.(1). For shorter times one observes a superlinear dependence of the diameter on time, which may be explained in terms of acceleration of the droplets by the explosive shock wave. On the other hand, for times exceeding the Bernoulli interval, one observes a sublinear depedence with saturation due to Stokes friction. The expansion of the cloud-diameter in the Stokes regime (i.e. for times $t > t_S$) is described by the equation:

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

where D_S denotes the cloud diameter, and v_S – the droplet velocity at time t_S and β/m is mass scaled friction coefficient [8].

In some of these plots one can observe a piece-wise linear dependence inside the Bernouli interval with two various slope coefficients. At first glance one might suspect that such a “fracture” of the dependence may be caused by transition from the supercritical to the sub-critical sub-regime inside the Bernoulli regime, connected with an abrupt increase of the drag coefficient while the Reynolds number for a decelerating droplet experiences such a transition due to decrease of velocity. Quantitative estimates, however, show that realistic motion of even the largest droplets must be in subcritical regime.

A more realistic explanation is based on the layer stripping phenomenon, that causes decrease of the droplet diameter, and, consequently, increase of the deceleration ratio. In fact, a glance at Equation (1) reveals that decrease of the droplet radius r is equivalent to increase of the coefficient γ. The problem of a “collective” stripping effect is presently under study.

It should be stressed that the above analysis of these results considers the situation where the droplets accelerated by the explosion gases move in the presence of drag from almost still air, which is a reasonable assumption for a static bag configuration. In the case of a bag moving with a considerable velocity at the moment of explosion and the spray cloud expanding in a high-velocity air stream generated by the rotor of a hovering helicopter, such assumptions should be treated with some caution. The helicopter tests, however, have shown similar dependences for the cloud diameter on the time as we present above.

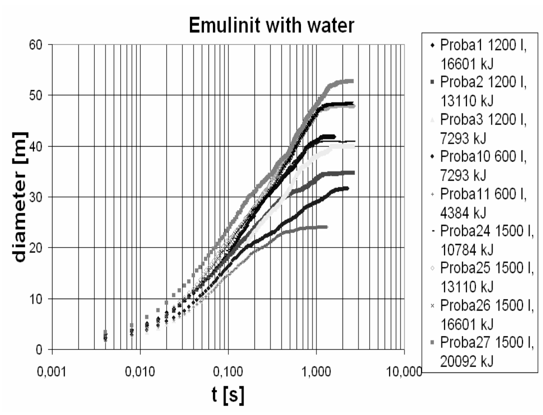


Fig. 4. Cloud diameter as a function of time plotted in the logarithmic scale for the different explosion energy and differet water load. Based on the registration with an ultra-fast camera

Plots of droplet velocities as function of times shown in Fig. 5 illustrate basic assumptions of our model presented above. The plots for the two largest charges are almost identical, which can be explained in terms of overcharging – for this particular water-load increasing explosion energy from 13.1 MJ to 16.6 MJ is useless, since the surplus of energy is lost. It contributes neither to pulverization nor to acceleration of the droplets.

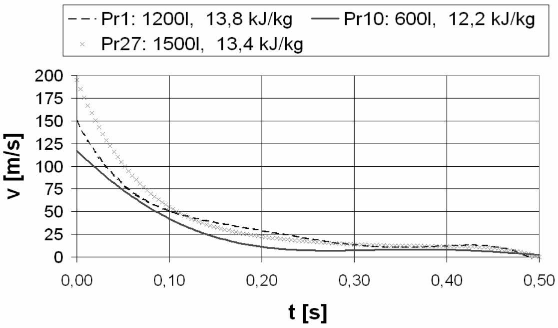


Fig. 5. Velocities of the largest (frontal) droplets as functions of time for the same water-load (1200 l) and three various charges of Emulinit, giving explosion energies of 16.6 MJ, 13.1 MJ and 7.3 MJ

The plot for the smallest explosion energy shows a considerably smaller initial velocity. What is interesting, after about 0.1 s droplet velocities are very close to each other for all three cases.

The shape of these functions for the time interval between 0.1 s and 0.5 s suggests that the layer stripping due to drag-generating air may be an important mechanism influencing the spray cloud expansion. This mechanism is interesting enough, and it will be investigated in detail in our future work.

3. Conclusions

The results of measurements presented in this paper are in qualitative agreement with our theoretical models. To check how far they agree quantitatively it will be necessary both to develop the models and to refine the measurement techniques. It should be stressed that the latter are extremely demanding due to many uncontrollable and irremovable factors like variable wind velocity, fluctuations of the spray cloud geometry etc. that influence considerably the results of measurements thus decreasing their accuracy.

4. Acknowledgments

The paper was partially supported by the Grant of Polish Ministry of Higher Education and Science.

5. References

[1] W. Teie: Firefighter’s handbook of wildland firefighting, Dear Valley Press, Recue CA 1994.
[2] E. Kuhrt, J. Knollenberg, V. Martens, Annals of Burns and Fire Disasters 14 (2001) 151.
[3] Z. Liu, A. K. Kim, D. Carpenter: Extinguishment of large cooking oil pool fires by the use of water mist system, in Combustion Institute/Canada Section, Spring Technical Meeting, May 9-12, 2004, pp. 1-6.
[4] International ESMG Symposium Process Safety and Industrial Explosion Protection, March 16-18, Nurnberg.
[5] S. Shoigu, Annals of Burns and Fire Disasters 6 (1993) 187.
[6] A. A. Zukas, W. P. Walters (eds.): Explosive Effects and Applications, Springer, New York 2003.
[7] W. F. Houghes, J. A. Brighton: Fluid Dynamics, McGraw-Hill, New York 1967. 12
[8] Roman S.Dygdała, Krzysztof Stefański, Damian Lewandowski, Maria Ingwer-Żabowska, Michał Kaczorowski; „Aerosol Produced by Explosive Detonation in a Water Bag as Fire Extinguishant.”, 3rd International Conference IPOEX 2006, Ustroń – Jaszowiec 20 –22 czerwca 2006 r.

Artykuł recenzowany