Dynamics of Physical Explosions: A Tribute to Professor Boris Gelfand

Sergey P. Medvedev
Heterogeneous Combustion Laboratory
N.N.Semenov Institute of Chemical Physics,
Russian Academy of Sciences
Moscow, Russia

Professor Boris Efimovich Gelfand passed away on the 4th of October 2010 in Odintsovo (a small town near Moscow), at the age of 69 after long suffering from cancer. Professor Boris Gelfand made prominent contribution in various fields of shock wave, combustion and detonation science. He was a member of the Russian Academy of Natural Sciences, Doctor of Physical and Mathematical Sciences, Professor in Chemical Physics, Professor of Saint-Petersburg University of State Fire Service Ministry of Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Disasters (EMERCOM), member of the Scientific Counsel on Combustion and Explosion (Russian Academy of Sciences), head of the Heterogeneous Combustion Laboratory (HCL) of the N.N. Semenov Institute of Chemical Physics, Russian Academy of Sciences. He was well known to scientific community through his publications and presentations at the International Colloquiums on Dynamics of Explosions and Reactive Systems and International Shock Wave Symposiums, and many other meetings. Professor Gelfand was an active member of the Institute for Dynamics of Explosions and Reactive Systems. In the last years he was the only representative of former SU in the IDERS Board of Directors.

The scientific interests of Professor Boris Gelfand were extremely wide. He started research work at the end of the 1960s from the study of self-ignition and detonation in two-phase gas-droplets and gas-particles media. In parallel, he achieved a great success in the investigation of propagation of shock waves in liquids with gaseous bubbles. A lot of his works were devoted to the study of the interaction of shock waves with structures, dusty and porous systems. Boris Gelfand always appreciated friendship and joint work with Academician Ya.B. Zel'dovich. Starting from 1984 he developed further insight into the Zel'dovich's gradient mechanism of detonation initiation that currently became a standard of most relevant theoretical investigations. Special mention should be given to the profound research of hydrogen combustion and detonation that was initiated by Professor Boris Gelfand after Chernobyl accident at the end of the 1980s. The results of these long-term

Correspondence to: podwal_ac@yahoo.com

investigations were summarized in his recent monographs that represent part of totally ten monographs and textbooks where he is a title coauthor.

In this memorial lecture we present a review of the works performed by the group of Professor Gelfand on dynamics of physical explosions. A physical explosion is considered as an accidental rupture of a pressurized vessel that can create shock waves in the environment. Professor Boris Gelfand extended examination of physical explosion sources from the high-pressure gas to the multiphase systems such as dusty media and boiling liquids. Basing on the comparative study of different types of explosions the generalized description of the shock waves parameters is suggested.

Laboratory simulation of physical explosions

The start of an extensive study of the parameters of blast wave from different explosion sources in the HCL illustrates unique ability of Professor Boris Gelfand to generate completely new idea in the form of a couple of sentences. In 1984 he simply said: “Let’s fill the high-pressure section of a shock tube by dusty media. What will be shock wave parameters in the dust-free low-pressure section?” This idea was implemented using 50-mm shock tube [1,5]. In the further years (1986-1990), immediately after the Chernobyl accident, the heated shock tube was applied for the investigation of sudden expansion of the overheated liquid [2-4]. The experiments performed at the shock tubes revealed peculiarities of shock wave formation due to the fast depressurization of the dusty and gas-liquid media. The shock-tube data on the pressure wave intensity at the initial stage of different physical explosions together with the suggested correlations served as a basis for the consideration of spherical explosions.

Spherical blast waves were investigated using an open-ended 38^o conical shock tube (CST) of 1.1 m in length [6,7]. Figure 1 represents main parts of the CST. Prior to experiment the conical high-pressure section (HPS) *1* of r_0 = 67 mm in radius was filled by media under investigation (gas, dust or liquid). In gas/dust tests the value of membrane rupture (p_1 = 3 – 30 bar) was achieved by pressurizing HPS with nitrogen (air). The powders of aluminum, aluminum oxide, polystyrene etc. were used (particles diameter 5 – 10 μm). In the experiments with liquid (water, ethanol, freon-113) a specially designed heating chamber *4* (see Fig. 1) was used to sustain saturation conditions in the HPS till the moment of membrane rupture. Fast expansion of gaseous or multiphase media (dust – gas and liquid – vapor) leads to the generation of blast wave which propagates into the low pressure section *3* filled

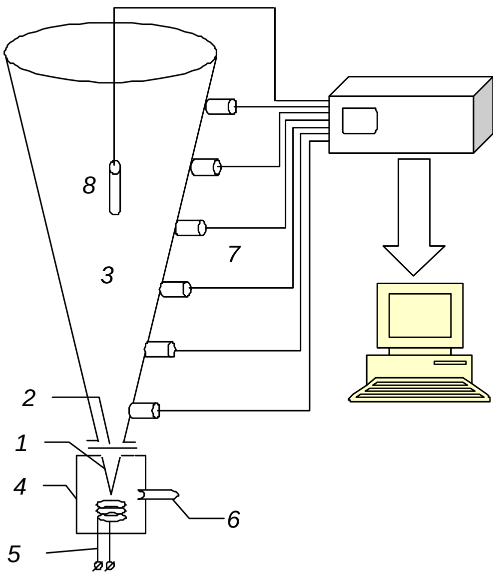

Figure 1. Conical shock tube. *1* – high-pressure section, *2* – membrane, *3* – low-pressure section, *4* heating chamber, *5* – heater, *6* - thermocouple, *7* - wall flush-mounted pressure transducers, *8* – pencil-type pressure transducer.

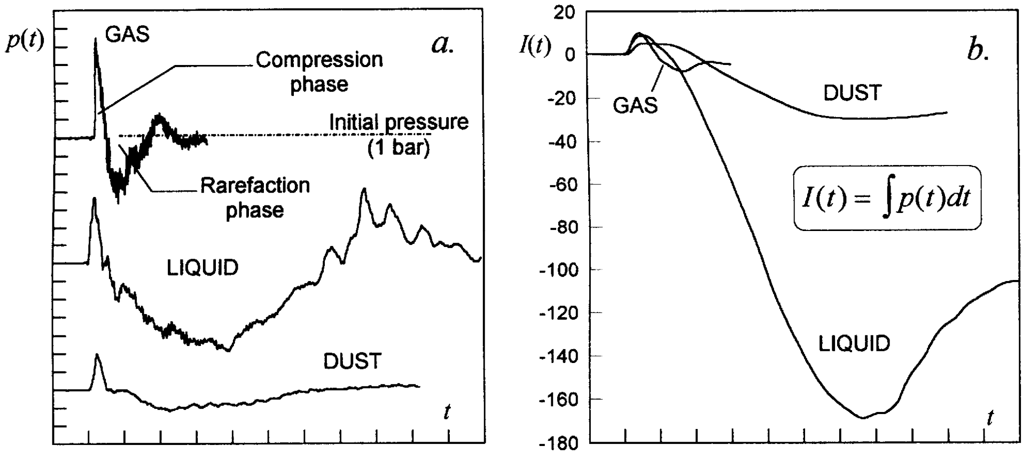

Figure 2. Pressure (*a*) and impulse (*b*) records at different kinds of physical explosions. Pressure scale: 0.1 bar/div.; time scale 1 ms/div. Impulse scale: Pa×s. GAS - nitrogen; DUST - aluminum oxide + nitrogen; LIQUD - freon-113.

with air at normal conditions (p_0 = 1 bar, T_0 = 295± 1 K). The parameters of blast wave were recorded by the flash-mounted piezoelectric pressure transducers *7* along with the pencil-type pressure sensor *8* (Fig. 1). By symmetry, the conical shock tube setup is a generator of spherical blast waves. Figure 2a demonstrates selective examples of the profiles of pressure waves generated by different driver media at approximately the same initial pressure p_1 = 22 ±1 bar. As seen from Fig. 2*a*, the pressure profiles are similar in appearance and can be characterized by the first compression phase ($p(t)$ > 1 bar) followed by the rarefaction phase ($p(t)$ < 1 bar). The main difference lies in the amplitude and duration of the phases. This inevitably gives rise to the distinctions in impulses of the proper phases (Fig. 2*b*). Compared with the gas explosion, the expansion of multiphase media leads to the significant increase of blast wave duration. When considering the destructive effect of sudden expansion of multiphase medium, special attention should be paid to the rarefaction phase of the blast wave.

Professor Boris Gelfand always emphasized that the experimental investigations of the complicated explosion phenomena can serve as a basis for development of simplified approaches and relationships suitable for the practical use. Analytical predictive techniques for description of parameters of blast waves from different explosion sources were elaborated in parallel with the extensive experimental investigations [6-10]. Below we represent the approach of [8] with recent slight modifications.

Description of blast wave parameters at different physical explosions

Two principles are basis for the development of universal predictive technique of the pressure field generated by sudden expansion of gaseous or multiphase system: 1) to use common relationships for all kinds of explosions; 2) to find an interrelation between the blast wave parameters and physical properties of the media to be expanded. As a first approach we use formula suggested by Lannoy (1984):

$$p(t) = p_{S1}\frac{\sin\left(\pi\frac{(t-t_{S1})}{t_{S2}}\right)}{\sin\left(-\pi\frac{t_{S1}}{t_{S2}}\right)}\exp\left(-k\frac{t}{t_{S1}}\right) \qquad (1)$$

Here p_{S1} is overpressure at the front of the wave (maximum pressure in first compression phase), t_{S1}, t_{S2} – duration of first compression phase and rarefaction phase respectively, k – damping coefficient. The scaling procedure is given by the commonly accepted relations: $P_{S1} = p_{S1}/p_0$ – scaled amplitude of first shock, $T_{S1} = t_{S1}/t_0$ – scaled duration of first compression phase, $T_{S2} = t_{S2}/t_0$ – scaled duration of rarefaction phase, $R = r/(E/p_0)^{1/3}$ – scaled distance. Here $t_0 = E^{1/3}a_0^{-1}p_0^{-1/3}$ (a_0 – sound speed in the low pressure section). For the energy E we use Baker formula:

$$E = \frac{p_1}{\gamma_1 - 1}\left[1 - \left(\frac{p_1}{p_0}\right)^{\frac{1-\gamma_1}{\gamma_1}}\right]\frac{4}{3}\pi r_0^3 \tag{2}$$

where γ_1 is the ratio of specific heats in the explosion source. For the amplitude of first shock a simple approximation of experimental results is given by:

$$P_{S1} = KP_{S0}\left(\frac{R_0}{R}\right), \quad K = 0.7 \pm 0.1 \tag{3}$$

Here $R_0 = r_0(p_0/E)^{1/3}$ and P_{S0} - the dimensionless shock overpressure at the instant of burst which is defined by a well-known relationships given by the shock-tube theory:

$$\frac{p_1}{p_0} = \left(P_{S0} + 1\right)\left[1 - P_{S0}\frac{a_0}{a_1}\frac{\gamma_1 - 1}{2\gamma_0}\left(1 + \frac{\gamma_0 + 1}{2\gamma_0}P_{S0}\right)^{-1/2}\right]^{-\frac{2\gamma_1}{\gamma_1 - 1}} \tag{4}$$

As applied to multiphase media with dust particles of less than 10 μm in diameter, the characteristics of the explosion source can be calculated in the frame of the equivalent gas model. Hence, $a_1 = a_M$ – "equilibrium" sound speed and $\gamma_1 = \gamma_M$ - ratio of specific heats in the equivalent gas. For two-phase media with high concentration of particles (or drops) suspended in gas we have $\gamma_M \to 1$. Thus, the relationships (2),(4) can be rewritten in a convenient form:

$$E = p_1 \ln\left(\frac{p_1}{p_0}\right)\frac{4}{3}\pi r_0^3; \qquad \frac{p_1}{p_0} = \left(1 + P_{S0}\right)\exp\left[\frac{a_0}{a_M}\frac{P_{S0}}{\gamma_0}\left(1 + \frac{1 + \gamma_0}{2\gamma_0}P_{S0}\right)^{-1/2}\right] \tag{5}$$

As it was shown in [5,7], in the case of expansion of dusty gas the amplitude of first shock can be satisfactorily evaluated using

$$a_M \approx \left(\frac{p_1}{\rho_p \varphi\,(1 - \varphi)}\right)^{1/2} \tag{6}$$

where ρ - density of dust particles material, φ - particles volume fraction.

For the case of expansion of saturated liquid one can use the relation given by [3]:

$$a_1 = \left[\frac{2\gamma_1 p_1}{B - AT_1}\right]^{1/2}, \tag{7}$$

where T_1 - saturation temperature at pressure p_1. A,B – coefficients depending on kind of liquid [3]. The use of Eqs.(2)–(7) enables to estimate the value of p_{S1} in Eq.(1) basing on the physical properties of an expandable media. The behavior of another blast wave parameters involved in Eq.(1) can be described by applying special procedure of time scaling. We use modified scaling parameter t_M instead of standard parameter t_0:

$$t_M = \left(\frac{E}{p_0}\right)^{1/3}\frac{1}{a_0}\left(\frac{a_0}{a_1}\right)^N \tag{8}$$

Where N=0.75 (gas), 0.6 (gas-dust), 0.9 (gas-liquid).

In spite of significantly different properties of the considered expandable media, all experimental data can be satisfactorily fitted by using common relationships for the duration of first and second compression phases:

$$t_{S1} \approx t_M(0.2\ \ln R + 0.4); \qquad t_{S2} \approx 1.2 t_M \tag{9}$$

Finally, the parameter k in (1) is defined as follows:

$$k = 0.5 \text{ (gas)}; \quad k(R) = 0.4R + 0.1 \text{ (gas-dust)}; \quad k = 0.01 \text{ (gas-liquid)} \qquad (10)$$

Figures 3,4 represent examples of the comparison between experimental pressure records (solid curves) and the results of calculations by use of Eqs. (1)-(10) (dashed curved). A satisfactory agreement between experimental data and analytical estimations demonstrates the advantage of the developed technique for adequate description of the most important parameters of the blast loading from different kinds of physical explosions.

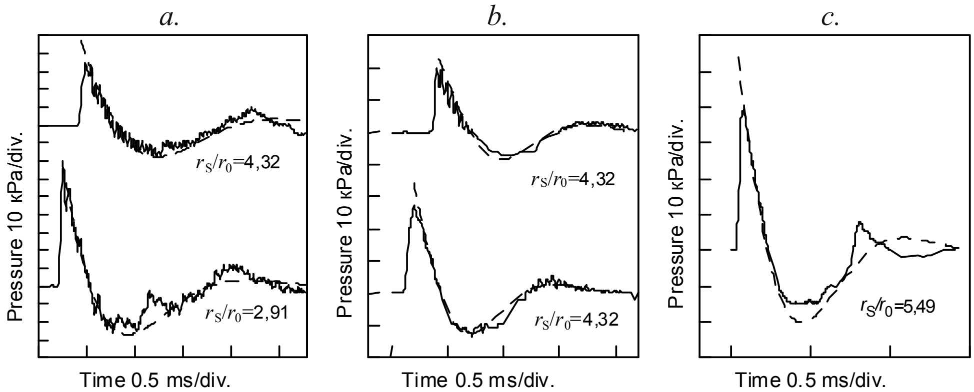

Figure 3. The comparison between measured pressure records (solid curves) and analytical predictions (dashed curved). *a*) nitrogen p_1 =23 bar (conical shock tube); *b*) nitrogen p_1 =6.7 bar (conical shock tube); *c*) air p_1 = 52 bar (bursting sphere – Esparsa&Baker (1977)).

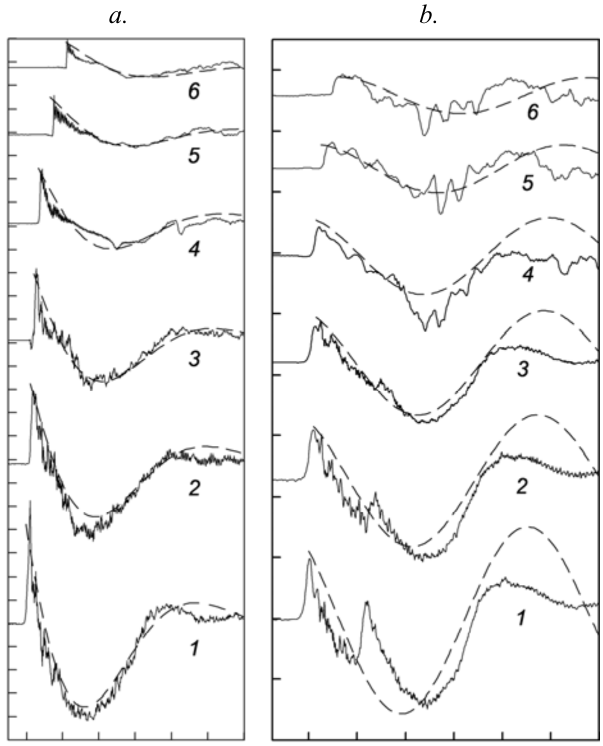

Figure 4. The comparison between measured pressure records (solid curves) and analytical predictions (dashed curved). *a*) polystyrene+nitrogen p_1 =23 bar; *b*) water p_1 =10 bar, T_1 = 445 K.
r/r_0 = 2,31 (*1*); 2,91 (*2*); 3,43 (*3*); 4,32 (*4*); 6,41 (*5*) и 8,5 (*6*).

The described investigations illustrate an approach of Professor Boris Gelfand to resolving complicated problems of dynamics of explosion that currently is continued at the Heterogeneous Combustion Laboratory of the N.N. Semenov Institute of Chemical Physics, Russian Academy of Sciences.

Selected publications of Prof. B.E. Gelfand on dynamics of physical explosions

[1] Gelfand BE, Gubanov AV, Borisov AA, Medvedev SP, Timofeev EI, Tsyganov SA (1984). Shock waves generated by expanding high pressure gas loaded with solid particles. First Intern. Colloq. on Explosibility of Industrial Dusts (Poland, Baranow). Book of papers.-Pt.2: 211.

[2] Gelfand BE, Medvedev SP, Polenov AN, Frolov SM (1991). Shock waves from vapor explosion in a shock tube. Progress in Astronautics and Aeronautics (12th ICDERS Ann Arbor, USA).-134: 295.

[3] Medvedev SP, Polenov AN, Gelfand BE, Tsyganov SA (1993). Shock waves by sudden expansion of hot liquid. Progress in Astronautics and Aeronautics (13th ICDERS Nagoya, Japan).-154: 449.

[4] Gelfand BE, Medvedev SP, Bartenev AM (1994). Vapor explosion research at Institute of Chemical Physics, Moscow. Energie-Technik-Umwelt, Festschrift, Herrn Professor Dr.-Ing. Hermann Unger zum 60. Geburtstag gewidmete Arbeiten, Ruhr-Univ. Bochum.: 103.

[5] Medvedev SP, Polenov AN, Gelfand BE (1994). Blast waves induced by sudden expansion of pressurized dusty systems. Proc. Sixth Intern. Colloq. on Dust Explosions, Shenyang, P.R.S., Northeastern Univ. Press, Shenyang: 289.

[6] Medvedev SP, Polenov AN, Gelfand BE (1995). Simulation of non-ideal explosions in a conical shock tube. Proc. 19th Int. Symp. on Shock Waves, Springer. 4: 381.

[7] Gelfand BE, Medvedev SP, Polenov AN, Khomik SV (1997). Parameters of pressure waves in non-ideal explosions. Fluid Dynamics. 32: 724.

[8] Medvedev SP, Bartenev AM, Gelfand BE (2000). Predictive technique for description of parameters of blast waves from bursting pressurized spheres. Proc. 22nd Intern. Symp. on Shock Waves / Eds. G.J.Ball, R.H.Hiller, G.T.Roberts, Univ. Southampton. 2: 959.

[9] Gelfand BE (2001). Features and simulation of non-ideal explosions. Proc. of 3rd Seminar (Intern.) on Fire and Explosion Hazards / D. Bradley, D. Drysdale, G. Makhviladze (Eds). CRFES. Preston, UK: Univ. of Central Lancashire. 43.

[10] Gelfand BE, Silnikov MV (2003). Chemical and physical explosions. Poligon publ. St.-Petersburg, 416 p. (in Russian)