DOI 10.1007/s10598-015-9263-4

Computational Mathematics and Modeling, Vol. 26, No. 2, April, 2015

SIMULATING BLAST WAVE PROPAGATION

S. B. Bazarov[1] **and I. M. Naboko**[2]

UDC 519.6: 534.222

The article focuses on a numerical analysis of the propagation of a blast wave — a wave with a short positive phase — in a gaseous medium. The wave is formed as a result of time and space localized emission of energy modeling the conditions of a concrete physical experiment. The numerical results are compared with experiments.

Keywords: simulation, experiment, blast wave.

Introduction

Our purpose in this study has been to obtain data for predicting the emergence of explosion-hazardous situations when large volumes of a reactive hydrogen–air mixture form as a result of hydrogen leakage accidents in atomic power stations and other hydrogen power facilities, as well as hydrocarbon–air mixture in extraction, processing, and utilization of hydrocarbon fuels. To construct a picture of the development of the wave process, we numerically calculated the propagation of a blast wave in a neutral medium and compared the calculation results with experiments. Previously this had been done for accumulating volumes in conical and pyramidal geometry [1–4].

Improved prediction reliability is one of the main issues in hazard evaluation of hydrogen systems used in transport, engines, and power installations, including atomic power stations. When hydrogen is stored and consumed, or when hydrogen is released during accidents (like that the Fukusima accident in March 2011 in Japan, or previous accidents in Three Mile Island and Chernobyl), its leakage and mixing with surrounding air creates fire and explosion hazards in closed and cluttered spaces.

Combustion processes have been studied in detail under conditions of deflagration and detonation, but so far we have scant results for combustion in the most hazardous nonstationary regimes with maximum load at the blast instant. In these regimes, the nature of destruction and the scale of damage given the same quantity of burning gas may vary by an order of magnitude depending on specific conditions. Reliable hazard evaluation of technological processes in power systems using or producing flammable gas mixtures requires investigating the properties and critical conditions of propagation and extinguishing of fires and detonation-like waves in closed spaces of complex geometry.

However, the current level of formalization of blast wave propagation processes in a reactive gas is insufficient for the construction of a convincing model for numerical analysis. Therefore, to construct a visual picture of possible evolution of the pre-blast wave process that largely determines the intensity and the outcomes of the blast, it is advisable to compare the numerical results with appropriate experiments studying blast wave propagation in a neutral medium. The results of such computer experiments can be applied to assess the development of secondary combustion and blasts in gas-filled spaces, reflecting the outcomes of physical experiments [5, 6].

[1] Faculty of Computational Mathematics and Cybernetics, Moscow State University, Moscow, Russia; e-mail: schreiben@umail.ru.
[2] Faculty of Computational Mathematics and Cybernetics, Moscow State University, Moscow, Russia; e-mail: idnaboko@yandex.ru.

Translated from Prikladnaya Matematika i Informatika, No. 45, 2014, pp. 32–40.

 1046–283X/15/2602–0156

Model of Physical Process

We consider the formation and propagation of blast waves, i.e., waves with a short positive phase, in free space [7–10]. Waves form as a result of time and space localized energy release modeling the conditions of a particular physical experiment. We use the model of inviscid compressible ideal gas without thermal conduction and solve the problem of dispersion of a small volume of gas with elevated (relative to background values) parameters in free space.

Mathematical Model and Numerical Solution

We consider ideal gas flow described in Euler variables. The nonstationary equations of axisymmetrical flow are taken in the following form:

$$\frac{\partial}{\partial t}(\rho y)+\frac{\partial}{\partial x}(\rho u y)+\frac{\partial}{\partial y}(\rho v y) = 0 ,$$

$$\frac{\partial}{\partial t}(\rho u y)+\frac{\partial}{\partial x}\left[\left(\rho u^2+p\right)y\right]+\frac{\partial}{\partial y}(\rho u v y) = 0 ,$$

$$\frac{\partial}{\partial t}(\rho v y)+\frac{\partial}{\partial x}(\rho u v y)+\frac{\partial}{\partial y}\left[\left(\rho v^2+p\right)y\right] = p ,$$

$$\frac{\partial}{\partial t}(\rho e y)+\frac{\partial}{\partial x}\left[(\rho e+p)uy\right]+\frac{\partial}{\partial y}\left[(\rho e+p)vy\right] = 0 .$$

Here t is time, x , y are the space coordinates (axial and radial, respectively), u , v are the components of the velocity vector $\boldsymbol{w}=(u,v)$ in x and y respectively, ρ is density, p pressure, e specific total energy. The system is closed by the equation of state in the form $p=(\gamma-1)\rho(e-(u^2+v^2)/2)$, where γ is the adiabatic index of the gas.

The system was solved numerically by the Godunov method [11]. The stability of the corresponding difference scheme was investigated for a linear system with constant coefficients and linearized equation of state. The time increment for calculations was chosen as $\Delta t = K\min(h_x,h_y)/\max\limits_{i,j}(D_L,D_R)$, $i=1,2,\ldots,N_x$, $j=1,2,\ldots,N_y$, where h_x, h_y are the grid increments in the corresponding space coordinates, N_x, N_y is the number of grid cells in the corresponding coordinates, D_L, D_R are the velocities of the leftmost and rightmost wave formed when the blast breaks up on the boundary between numerical cells. The reserve coefficient K $(0 < K < 1)$ has the following meaning: higher values of the reserve coefficient "improve the form" of the numerical solution (for instance, ensure a steeper shockwave profile); but as K approaches 1, the numerical solution develops instabilities that make further calculations impossible.

Simulation has been carried out with dimensionless parameters (the bar denotes the corresponding dimensional variables): $p=\bar{p}/\bar{p}_0$, $\rho=\bar{\rho}/\bar{\rho}_0$, $x=\bar{x}/\bar{x}_0$, $u=\bar{u}/\sqrt{\bar{p}_0/\bar{\rho}_0}$, $t=\bar{t}\sqrt{\bar{p}_0/\bar{\rho}_0}/\bar{x}_0$. The following standardizing values were used: $\bar{p}_0 = 101325\ \mathrm{N/m^2}$, $\bar{\rho}_0 = 11.225\ \mathrm{kg/m^3}$, $\bar{x}_0 = 1$ m.

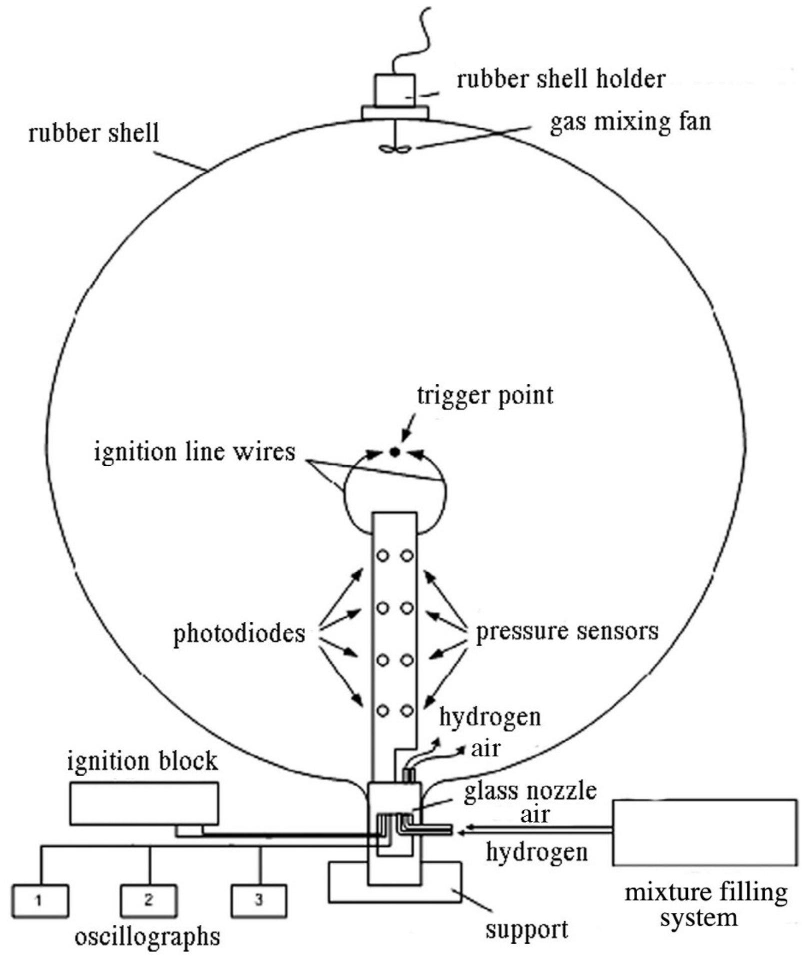

Fig. 1. Experimental setup for investigating spherical flame and blast wave propagation in a gaseous medium.

Conditions of Physical Experiment

One of our aims was to design an experimental setup suitable for studying the evolution of a spherical flame front propagating in large volumes filled with a reactive gas mixture. One of the tasks in studying combustion of gaseous mixtures in large volumes is to determine the evolution of a spherical flame propagating in a premixed gas mixture. This fundamental problem of physical gas dynamics and chemical physics is of considerable applied importance. It is associated with issues of blast evolution and high-intensity fast supersonic combustion, and also questions relating to the conditions of existence of a Chapman–Jouguet spherical self-sustaining stationary detonation.

One of the main issues here is the formation of a high-intensity shockwave preceding the accelerating flame front. The conditions of formation and the shape of the shockwave preceding the spherical flame front have accordingly received considerable attention during the development and installation of the diagnostic system.

We also plan to study the possibility of controlling combustion, detonation, and explosion of gas mixtures in large volumes with the aid of small additions of chemically active substances.

In the present stage we have formulated the research program, determined the measurement procedure, and created the hardware for studying explosion and nonstationary combustion of gas mixtures. An extensive series of experiments have been carried out.

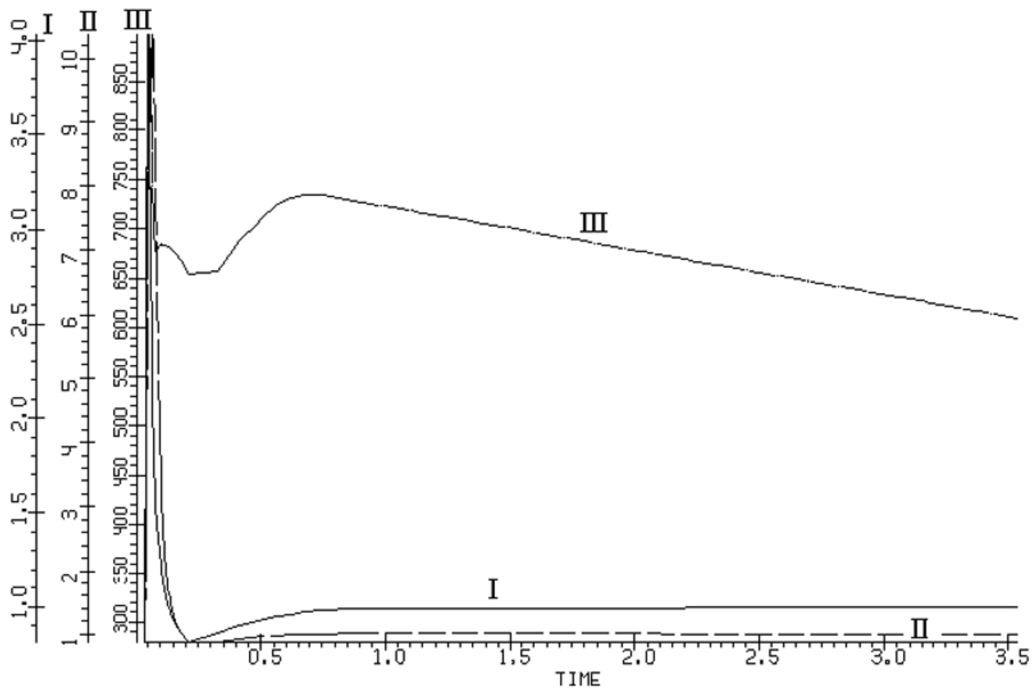

Fig. 2. Pressure (I), total pressure (II), and temperature (III) versus time as measured by the first sensor (closest to the trigger point).

In the physical experiment used for comparison with numerical results, an charge is exploded in a large volume filled with air under normal initial conditions. The charge energy was 15 kJ in the first case and 2.3 kJ in the second case. The volume of the spherical chamber used in the experiment was 900 m^3. The pressure developing in the blast wave – a wave with a short positive phase – is measured by four sensors arranged in a straight line at distances of 0.34 m, 0.674 m, 0.993 m, and 1.313 m from the trigger point.

A schematic diagram of the experimental setup is shown in Fig. 1. The combustible gaseous mixture is held in a spherical volume bounded by a thin rubber shell. Before the experiment, the volume filled with reactive mixture has a spherical shape and may contain from 7 to 30 cubic meters of gaseous mixture. The mixture is triggered at the center of the sphere, with trigger energy between 6 J and 20 kJ. Ionization sensors capture the movement of the flame front.

A specific feature of the process is the relatively low intensity of the trigger charge. For such low intensity charges, we have no solutions that provide a sufficiently reliable prediction of the variation of intensity of a finite-amplitude wave during its propagation; nor are there solutions that can be used to assess the outcomes of the formation of such a wave in a reactive medium [12]. Therefore, we consider flow in a neutral medium as the first stage of numerical simulation of the problem of explosion and fire hazards associated with formation and propagation of weak waves – waves of finite amplitude – in flammable mixtures.

Comparison of the results with the findings of specially staged physical experiments (as described above) makes it possible to substantiate the choice of the model and the numerical method. It should also highlight the significance of the numerical experiment for the range of problems considered.

Simulation Results

Simulation was carried out in a 2.5 × 2.0 region (dimensionless units) to avoid possible influence of the boundaries on the observed flow. The flow parameters at successive time instants were recorded at the dimen-

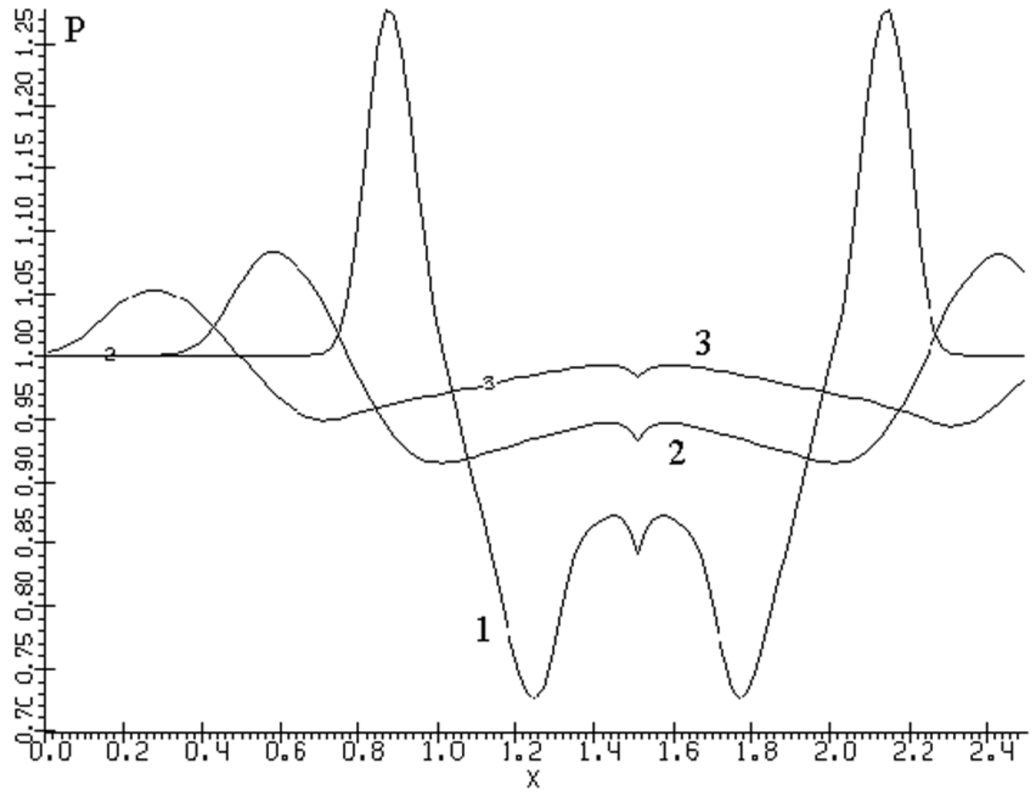

Fig. 3. Pressure distribution along the x-axis at time instants 0.22 (1), 0.48 (2), and 0.74 (3).

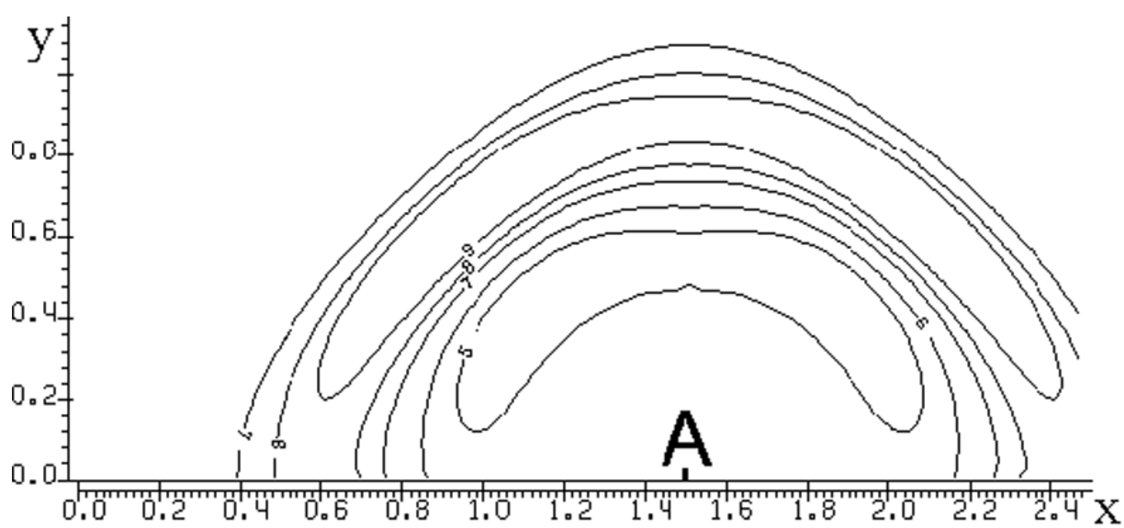

Fig. 4. Lines of equal pressure at time 0.48.

sionless points (1.16, 0), (0.826, 0), (0.507, 0), and (0.187, 0) corresponding to the location of the sensors in the physical experiment. Initially, the pressure and density values were set to 1 and the velocities to 0 in the entire numerical field; in one cell **A** with the coordinates $(x = 1.5, \; y = 0.0)$ elevated pressure and density parameters were specified, ensuring that the readings of the first "numerical" sensor matched the corresponding experimental readings (Fig. 2).

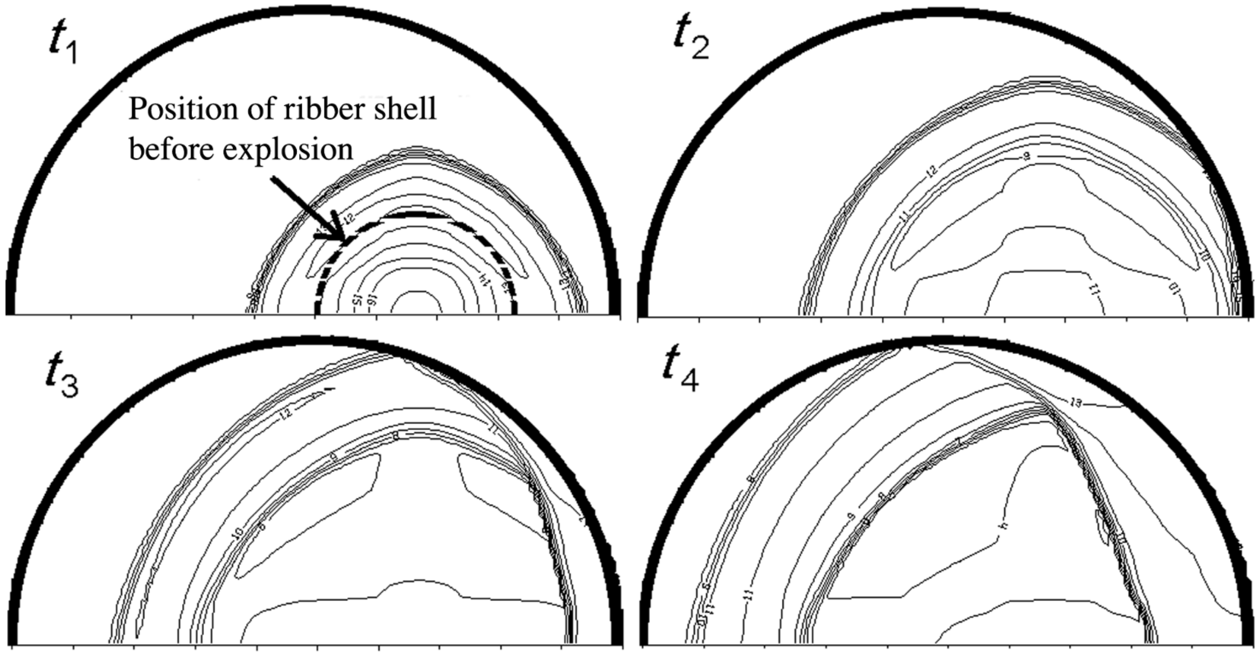

Fig. 5. Propagation of waves inside the enclosing spherical shell. Lines of equal pressure at four time instants $(t_1 < t_2 < t_3 < t_4)$.

Table 1

Sensor	1	2	3	4
Experiment	4	1.37	1.23	1.06
Calculation	4.03	1.21	1.06	1.04

Table 2

Sensor	1	2	3	4
Experiment	1.1	1.02	1.01	1.003
Calculation	1.1	1.015	1.008	1.001

Note that unlike the variation of pressure in the sensor (rapid increase, decline, and subsequent slight increase, signifying virtually time-independent behavior), temperature always varies over time, not necessarily monotonically.

The graph of pressure along the x-axis (Fig. 3) shows that the propagating blast wave leads to a decrease of pressure in the neighborhood of the trigger point and gives rise to a secondary wave in the depressed pressure region.

The lines of equal pressure in Fig. 4 provide an indication of the spatial character of flow.

The maximum pressure registered by the sensors is shown in Table 1 for energy release of 15 kJ (in cell **A**, pressure $p = 5200$, density $\rho = 520$) and in Table 2 for energy released of 3.2 kJ (in cell **A**, $p = 1350$, $\rho = 135$).

Further development of the process of dispersion of shock-heated gas leads to rupture of the rubber shell and propagation of the gas inside a large spherical capacity (900 cubic meters) with a rigid surface. The expanding spherical wave is reflected from the hard surface and a reflected shockwave is formed (Fig. 5). Then multiple reflections and wave interactions take place inside the closed spherical capacity.

CONCLUSION

The simulation has shown that the proposed numerical procedure is suitable for assessing the parameters of fast energy release in a small region and subsequent propagation of the arising blast wave. Simulation of explosions of larger chargers leading to formation of higher intensity blast waves will produce numerical results that are closer to physical experiments.

REFERENCES

1. S. B. Bazarov and I. M. Naboko, "Focusing of blast waves: three-dimensional mathematical modeling," *Khim. Fizika*, **27**, No. 10, 58–63 (2008).
2. S. B. Bazarov and I. M. Naboko, "Interaction of waves with cavities," *Matem. Modelirovanie*, **14**, No. 9, 34–40 (2002).
3. V. A. Petukov, I. M. Naboko, and V. E. Fortov, "Explosion hazard of hydrogen–air mixtures in the large volumes," *Int. J. Hydrogen Energy*, **34**, No. 14, 5924–5931 (July 2009).
4. A. N. Andrianov, S. B. Bazarov, A. B. Bugerya, P. I. Koludarov, and I. M. Naboko, "Focusing of blast waves: modeling on parallel computers," *Khim Fizika*, **25**, No. 11, 53–58 (2006).
5. I. N. Naboko,N. P. Bublik, P. A. Gusev, V. A. Petukhov, and O. I. Solntsev, "Combustion and explosion of a hydrogen –air mixture under conditions modeling volume elements in gas-filled premises," *Khim. Fizika,* **28**, No. 5, 25–33 (2009).
6. V. A. Petukhov, I. N. Naboko, N. P. Bublik, P. A. Gusev, O. I. Solntsev, and I. D. Gutkin, "Experimental modeling of blast wave propagation in hydrogen –air mixtures with variable composition," in: *33rd Int. Symp. Combustion*, Tsinghua Univ., Beijing, China, 1–6 August (2010).
7. M. A. Sadovskii, "Mechanical effect of air shockwaves from the results of experimental investigations," *Fizika Vzryva, Moscow, AN SSSR,* No. 1, 41 (1952).
8. V. V. Adushkin, "Formation of shockwaves during dispersion of blast byproducts in air," *Prikl. Mekhan. Tekhn. Fiz.,* No. 5, 37 (1963).
9. A. V. Kashirskii, Yu. V. Korovin, and L. A. Chudov, "Explicit difference method for calculating two-dimensional nonstationary problems involving motion of detonation byproducts," *Vychiil. Metody Programm.,* Izd. MGU, No. 19, 97–107 (1972).
10. A. A. Grib, O. S. Ryzhov, and S. A. Khristianovich, "Shortwave theory," *Prikl. Mekhan. Tekhn. Fiz.,* No. 1, 65 (1960).
11. S. K. Godunov, A. V. Zabrodin, M. Ya. Ivanov, et. al., *Numerical Solution of Multidimensional Problems in Gas Dynamics* [in Russian], Nauka, Moscow (176).
12. W. E. Baker, P. A. Cox, P. S. Westine, J. J. Kulesz, and R. A. Strehlow, *Explosion Hazards and Evaluation*, Elsevier, Amsterdam (1983).