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High Temperature Hydrodynamics of Explosion and Shock Wave Phenomena

A. S. Smetannikov*
A. V. Luikov Heat and Mass Transfer Institute,
National Academy of Sciences of Belarus, Minsk, BELARUS

A. V. Teterev
Belarusan State University, Faculty of Applied Mathematics and Computer Sciences, Minsk, BELARUS
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Hydrodynamics of processes occurring in some problems of high energy density physics is considered. Physical models, computation technique and results of simulation of a hydrodynamic flow are discussed. For the description properties of material in hydrodynamic calculations a wide-range equation of states has been used. The following problems have been considered: explosion of an explosive charge above surface, high-velocity meteorite impact on protection shields and falling of space bodies in a water basin. The results of simulations allow one to obtain a detailed spatial-temporal distribution of the arising flow and to study origination, propagation, interaction and attenuation of shock waves.

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1. Introduction

The first edition of the book of Ya. B. Zeldovich and Yu. P. Raizer 'Physics of shock waves and high-temperature hydrodynamic phenomena' has appeared in Russian in 1963. The second edition of this monograph left in 1966 and almost immediately its English translation appears. This book was devoted to a new field of scientific researches – high energy density physics. In occurrence and development of this new field the its connection with the Soviet atomic project is traced (participation in which of Ya. B. Zeldovich was very considerable). Already in the beginning of works under the atomic project, the important role of numerical methods in modeling of physical processes (in particular hydrodynamics) became clear.

We consider a modeling of some problems in the field of high energy density physics. For the description of the flow arising in given problems, the system of gas dynamic equations with corresponding initial and boundary conditions is used [1].

2. Modeling the dynamics of flow in explosion above a surface

Let us consider the modeling of flow dynamics occurring in explosion of high explosive (HE) charges in air at some height above the ground. For numerical solution, the equations of gas-dynamics are approximated by a fully conservative difference scheme with consistency of fluxes in Eulerian cylindrical variables r-z [2]. As an example we consider the explosion of hexogen charge with mass 5 kg with cylindrical shape (length equals to diameter L=D) at height H=2 m. To close the gas-dynamics equations we use the Jones-Wilkins-Lee equations of state for HE and a real equation of state for air (with accounting process of dissociation and ionization). To simplify calculation we do not describes the process of detonation and use the approximation of instantaneous detonation.

Detonation of explosives creates a region

*E-mail: ass@hmti.ac.by

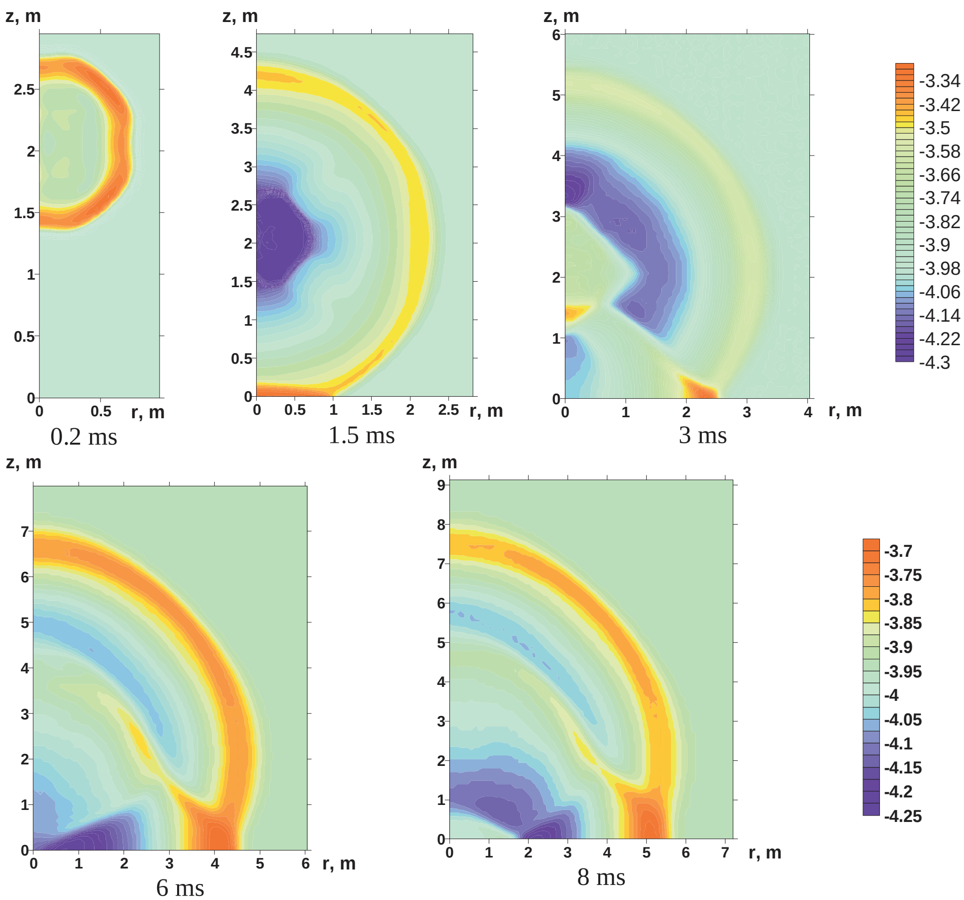

FIG. 1: Pressure fields (log P, 10 kbar) for several time moments. (In colour).

with high temperature and pressure. A large pressure difference results in expansion of explosion products and formation of a shock wave (SW) in the surrounding air, which quickly obtain nearly spherical shape. The dynamics of flow development is given in Fig. 1, where the pressure distribution is shown for different instants of time. A rarefaction wave propagates from the boundary explosive-air inside the charge and a low-pressure area forms in the products of explosion. This leads to the formation of the secondary SW moving to the center of the charge. This flow cumulates on symmetry axis, the secondary SW is reflected and moves outside. Somewhat earlier, the primary SW reaches the ground surface and reflects from it. Then, the reflected SW interacts with the secondary SW that expands from the charge center and goes through it. The angle between the primary SW and the surface gradually increases and at t = 2.9 ms there appears a new SW that is perpendicular to the ground surface and propagates along it (Mach SW). The secondary SW continues to expand and at 6ms reflects from the surface thus generating one more reflected SW. Then, the formed structure increases in size and the intensity of waves in it gradually decreases. More detailed description of this processes and numerical technique is given in [3].

The calculation results allow one to obtain a detailed space-time picture of the arising flow, to study the origination, propagation and subsequent attenuation of shock waves. The results of the computational experiments and their analysis can be used for estimating the consequences of explosions and development of engineering techniques on decreasing the risk of emergency of nature and anthropogenic character.

3. Modeling a high-velocity meteorite impact on protection shields

For protection of space vehicles against micrometeorites impact, it is offered to use a system from two shields located on some distance from each other [4]. At collision with the first shield there is destruction of a meteorite and part of the shield near to a place of impact. The formed jet keeps off by the second shield. It is important, that the action of a jet is considerably less located, than an impact of a particle, and its velocity is lower than the velocity of a meteorite. Characteristic parameters of micrometeorites are the following: velocity: 10 − 70 km/s and most hazardous size 0.001 − 0.1 cm. For numerical solution the gas-dynamic equations are approximated by a fully conservative difference scheme in Eulerian cylindrical variables r-z.

The calculations are carried out for impact of a micrometeorite on two plane shields located on distance z, with velocity u_0 directed normally to a plane of shields. For calculation we use wide-range equation of state, which takes into account phase transitions solid state–liquid–vapor–plasma [5]. As an example of calculation we consider the next variant: impactor is a cylinder with the diameter equals to its length $D = H = 0.1$ mm, initial velocity $u_0 = 50$ km/s. The thickness of the first shield is given as $H_1 = 0.2$ mm, and for the second $H_2 = 0.3$ mm, distance between them $\Delta = 1$ mm. Material of impactor and shields is aluminum. Let us discuss the results of calculations in the first variant. In a place of impact the parameters quickly grow and reach a maximum in 1 ns ($P = 19$ Mbar, $\rho = 4.6$ g/cm^3, $T = 18$ eV). Thus there are two shock waves (SW) – one in the target, another one is propagated on a body of impactor towards to its movement. Impactor goes deep into a target and forms a crater, spreading on its surface. On edge of a crater the jet going upwards is formed. SW, going on impactor, quickly increases the specific energy of matter and evaporates it. Second SW, going downwards on the first foil, to 5 ns gets the half-spherical form and the maximal parameters are decreased. Dynamics of processes is easy for looking after on Fig. 2. To $t = 5$ ns SW, going on a material of a foil, reaches back side of a first shield and is formed a plasma jet in a direction to the second shield. Practically, in 100 ns the aperture in the first shield was generated and we can define its size and shape. The axial velocity of a jet after punching the shield makes 6 km/s. In the further jet is flowed on the second shield, is reflected and spreads in a lateral direction. Let us note, that at impact evaporated mass makes $\sim 20M_0$ and melted $\sim 130M_0$ (M_0 is the mass of the micrometeorite).

The calculation of two-dimensional gas dynamical problems on a basis of fully conservative difference schemes in Eulerian variables shows satisfactory quality of the solutions obtained with this technique. The results of calculation allow to estimates the efficiency of anti-meteoric protection, to determine the shape and sizes of formed apertures. Besides, the numerical calculations enable to study dynamics of plasma jets and its interaction with shields etc.

4. Modeling of the fall of space body into water basins

We will illustrate the possibilities of numerical modeling on an example of the fall of a cometary nucleus into a water reservoir with the bottom relief having an underwater plateau. In this problem a radius of cometary nucleus is chosen as 0.3 km, initial velocity is 60 km/s, maximum depth of the reservoir is 3 km. The method of large particles in cylindrical variables

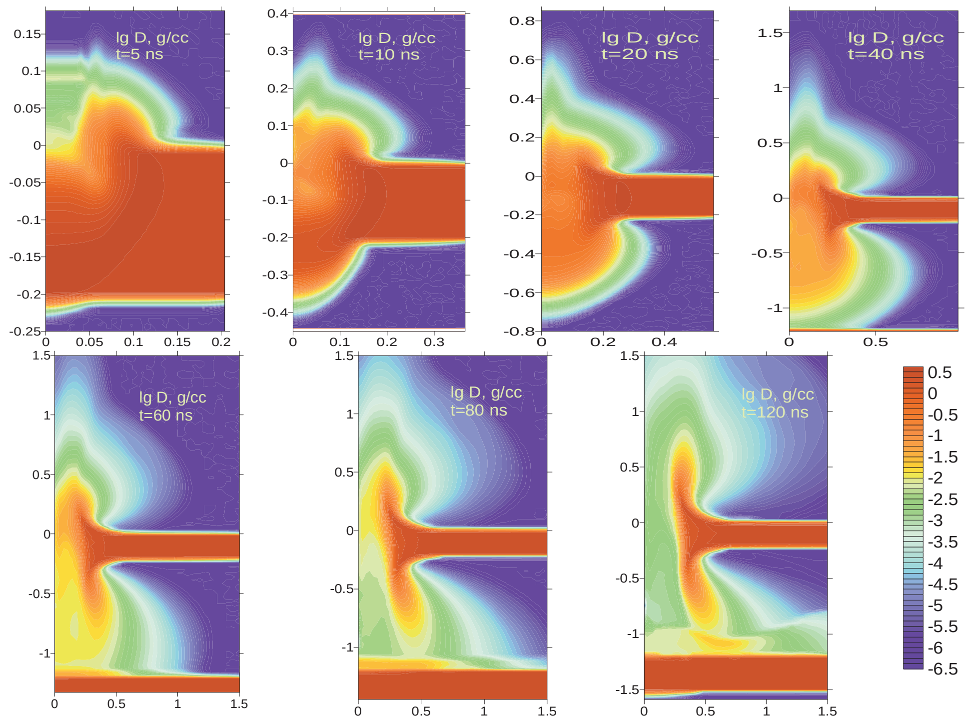

FIG. 2. Fields of density (log D, g/cm^3) for several time moments (vertical line is axial coordinate z in mm and horizontal one – radial coordinate r in mm). (In colour).

r-z is used for numerical solution of the system of gas-dynamic equations [6]. In calculation the gravitational field and real properties of materials (air and water-ice) are taken into account.

The dynamics of flow development is given in Fig. 3, where a spatial distribution of the density is shown for several instants of time. At time $t =$ 0.2 s the shock wave in water is attained depth 2.5 km and shock wave in air reaches a height of 3 km on the symmetry axes. Thereafter the shock wave in water is reflected from the bottom and interact with the primary wave. At t = 0.2 s the shock wave in water is located at r = 6 km and already propagates over the underwater plateau. Later on, a water crest is formed due to the intense rise of water over the plateau. At time moment $t = 7.2$ s water crest lift up to the height of 5 km and propagates forward and reaches the bank of the reservoir at $t = 40$ s. Then the water crest entirely leaves the computational domain and only the water spread over the solid surface remains in it. After time t = 50 s there occurs the fall of water from the underwater plateau into the deep-water part of the reservoir and the deep-water region begins to rapidly fill-in. At t = 200 s the level of water in the deep-water part of the reservoir and on the plateau is practically equalized and the bank is entirely freed from water.

The calculation results allow one to study the propagation, interaction and attenuation of shockwaves and obtain a full spatial-temporal picture of the flow. The computational results and their analysis can be used for estimating the consequences of high-velocity impact of space bodies with Earth surface and its influence on environment.

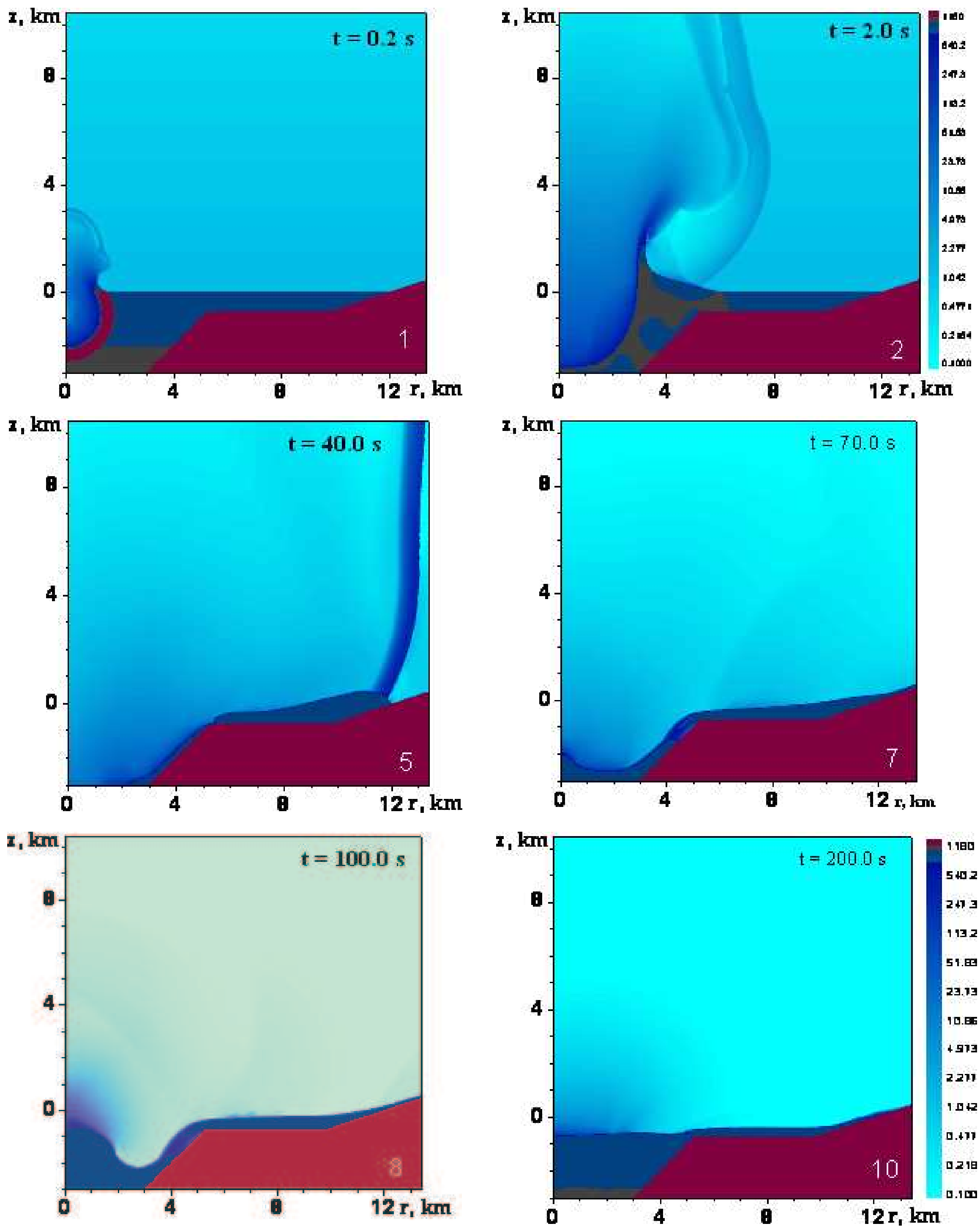

FIG. 3: Density fields (in kg/m^3) for several moments of time. (In colour).

5. Conclusion

We illustrate the possibilities of numerical modeling on some problems of high energy density physics. In simulation the real properties of materials have been taken into account. The simulation results allow one to obtain a detailed space-time distribution of the arising flow and study the origination, propagation, interaction and attenuation of shock waves. The results of the computational experiments and their analysis can be used for estimating efficiency of anti-meteoric protection, consequences of explosions, high-velocity impact of space bodies with the Earth surface an so on.

More than 25 years Ya. B. Zeldovich passed away. But his ideas about combustion, shock and detonation waves, high-velocity impact, equations of state are fundamentals of modern researches in area of high energy density physics still now.

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