Modeling of high-velocity impact in anti-meteorite protection systems of space vehicles

A.S.Smetannikov[1]

Heat & Mass Transfer Institute National Academy of Sciences, Brovka str., 15, Minsk, 220072, Belarus

The research of dynamics of processes takes place at high-velocity impact, is of interest for many problems of space physics and astrophysics: study of meteoric craters, origin of planetary atmospheres, consequences of fall of large space objects on the Earth etc. The experimental data on high-velocity impact concern to velocities which are not exceeding 20 km/s. Thereof, in a range of high velocities of collision, the special importance gets theoretical research of impact dynamics (in particular numerical modeling). The long stay of space vehicles on an orbit results in practically inevitable influence of meteorites on their surface. Thus probability of collision with small particles (micrometeorites) with mass less than 0.01 g especially is great.

At impact velocities of the order of 100 km/s energy density at impact on three order is higher, than at explosion. Therefore particles even of small mass can make significant destructions. For protection of space vehicles against high-velocity impacts of micrometeorites it is offered to use system from several (in simple case - two) shields located on some distance from each other. At collision to the first shield there is a destruction of a meteorite and part of the shield near to a place of impact. The formed jet consisting in basic from a material of the first shield (in plasma and dispersed state), hold off by second shild. Thus it is important, that the action of a jet is considerably less located, than at impact of particle (as the jet strongly extends) and its velocity considerablly below, than a meteorite velocity.

At high velocities (~ 100 km/s) the initial pressure near to a place of impact makes some tens megabar, and the specific energy in hundreds time exceeds sublimation heat. At such action the material completely evaporates. The time of action of high pressure appears rather short (owing to the small size of a meteorite), the shock wave quickly damps. At removal from a place of impact the specific energy decreases, to become possible only melting. Then it falls below than melting energy and there can be only fracturing of material. This process is described by origin and growth of microcracks, that is determined by strength characteristics of material. We shall consider an initial stage of impact, when strength effects are insignificant. For the description of flow arising at impact, the system of gas dynamic equations in r - z coordinates (axial symmetry) is used:

$$\rho\left(\frac{\partial u}{\partial t}+v\frac{\partial u}{\partial r}+u\frac{\partial u}{\partial z}\right)=-\frac{\partial P}{\partial z}, \qquad \rho\left(\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial r}+u\frac{\partial v}{\partial z}\right)=-\frac{\partial P}{\partial r}, \tag{1}$$

$$\frac{1}{\rho}\frac{d\rho}{dt}=-\left[\frac{1}{r}\frac{\partial(rv)}{\partial r}+\frac{\partial u}{\partial z}\right], \qquad \rho\frac{d\varepsilon}{dt}=-P\left[\frac{1}{r}\frac{\partial(rv)}{\partial r}+\frac{\partial u}{\partial z}\right], \qquad P=P(\varepsilon,\rho),$$

where t - time, ρ - density, P - pressure, ε - specific internal energy, v, u - radial and axial components of a velocity vector. The equation of state $P=P(\varepsilon,\rho)$ closes this system of equations.

The complexity of numerical calculation of high-velocity impact is caused by characteristics of arising flow. At an initial stage of impact the flow is sharply spatially non-uniform and there are areas of sliding of materials. Calculation of such flows in lagrange representation is extremely complicated. For later times there is other complexity connected to considerable growth of spatial scale of flow. At modeling gasdynamic processes one of the major requirements producible to numerical algorithms, is the necessity of observance of the conservation laws and balanced relations available in the differential equations. Fully conservative difference schemes (FCDS) in lagrangian variables [1] have shown high quality of the received solutions for set of completely different problems. In the given schemes some additional relations (balance between separate kinds of energy, and not just conservation of total etc.)

are observed in distinction of usual conservative schemes. FCDS in eulerian variables [2-4] were developed later. Thus the necessity of a consistency for convective fluxes of mass and internal energy was shown. For numerical solution the system of gasdynamic equations (1) approximate fully conservative difference scheme in eulerian variables. In this scheme velocities and moments are determined in nodes of grid, and pressure, density, energy etc. - in the centres of cells. For calculation of shock waves introduce the artificial viscosity (combination of linear and square). The description of a technique for numerical calculation is given in [5].

The calculation are carried out for impact of a micrometeorite on two plane aluminium shields located on some distance Δ, with speed u_0, directed normally to a plane of shields. The micrometeorite was simulated by the cylinder of length H and diameter D. As a material of a meteorite the aluminium is taken also, as the parameters of apertures and plasma jets practically do not depend on a material of impactor. It is connected that at the large velocities of collision impactor completely evaporates, and mass of material, involved in movement, is much more than mass of a micrometeorite.

For closing the system of gas dynamic equations it is necessary to set the equation of state for materials, i.e. dependence of pressure $P = P(\varepsilon, \rho)$ and temperature $T = T(\varepsilon, \rho)$ fom energy and density. The equations of state of matter in wide range of the phase diagram are necessary for calculation of impact in view of phase transitions solid state - liquid - vapor (plasma). Thus the range of change of thermodynamic parameters makes 7-8 orders on density and 3-4 order on temperature. To satisfy with these requirements it is possible in frameworks of wide-range semi-empirical equations of state [6]. In this case functional dependence of free energy on thermodynamic parameters is set on the basis of known theoretical models, and for definition of numerical coefficients in these dependences the data of experiments are used. The received thus equations of state adequately describe the characteristics of a material of target (shields) and impactor (micrometeorite) in all phase plane of thermodynamic variables from solid to transition in a liquid and further in vapor or plasma. At density of the order 10^{-3} from density of solid matter (in normal conditions) semi-empirical equation of state connected with the equation of state received on the basis of Saha equations with Debye-Huckel corrections. It allows to take into account multiple ionization of atoms. The concrete parameters of wide-range semi-empirical equations of state for aluminium are given in [7]. The results of calculation of the equation of state for aluminium are given in a fig. 1, where are shown isoenergy lines.

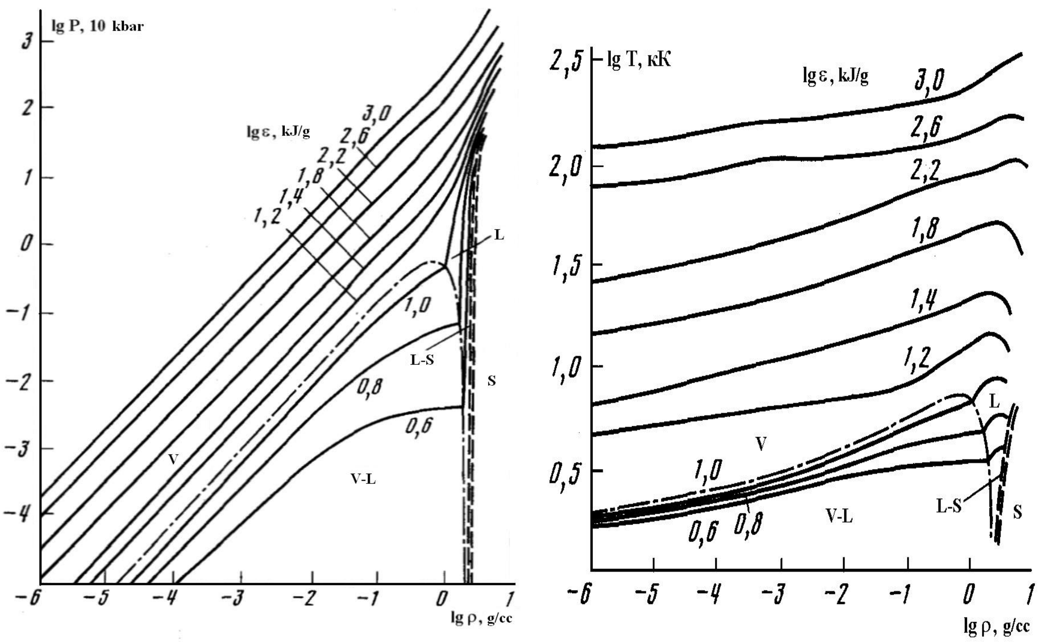

Fig. 1. The equations of state for aluminium. The dashed lines correspond to liquid – solid, and the dash-dotted line limits liquid - vapor area.

Let's discuss results of calculations. As the picture of various variants of calculation qualitatively does not vary, we shall consider detailed only one variant. Impactor parameters are following: the diameter is equal to length D = H = 0.1 mm, initial velocity u_0 = 50 km/s. The thickness of shields are equal H_1 = 0.4 mm, H_2 = 0.1 mm, and distance between them is equal Δ = 0.5 mm. Initial density as shields, and impactor is equal 2.7 g/cc, density of an environment 10^{-6} g/cc. The calculation grid is constructed as follows. On radius the size of the first 10 cells is constant (in impactor's area) and makes 0.005 mm, and further size of cells is increased in a geometric series with exponent q = 1.07. On an axis z from

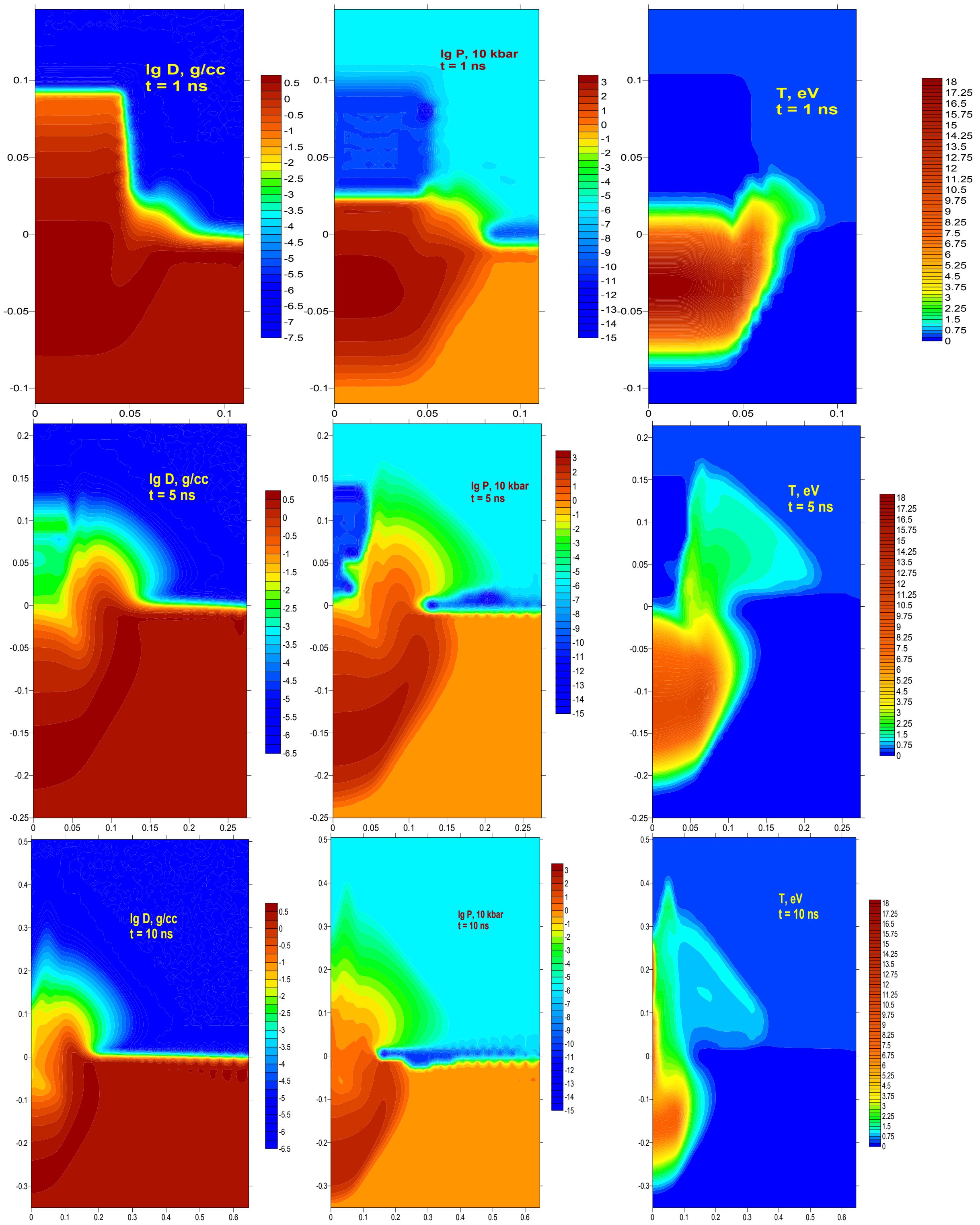

Fig. 2. Distributions of density, pressure and temperature for 1, 5 and 10 ns.

0.1 mm up to -1 mm (impactor, two foils and space between them) the size of cells is constant 0.01 mm, and in areas for impactor and after the second foil grows in a geometric series with q = 1.1. In the subsequent figures the vertical line designates axial coordinate z (mm), and horizontal line - radial coordinate r (mm).

In the initial time moment impactor there comes in contact with the first foil - their boundary is located at z = 0. In a place of impact the pressure quickly grows and reaches maximum in 20 Mbar (1 ns). Thus maximal density makes 4.7 g/cc, and temperature - 19 eV. There are two shock waves - one go deep into target, another propagates on impactor's body towards to its movement. To the moment 5 ns the maximal pressure is reduced up to 6 Mbar, the maximum of density makes 4.3 g/cc, and temperature - 10.5 eV. Impactor goes deep into a target, the crater is formed and the material of impactor spreads on a surface of a crater. On edge of a formed crater the jet going upwards is formed. The shock wave (SW), going on impactor's body, quickly increase specific energy of matter and evaporate it. The second shock wave going downwards on material of the first foil, gradually (to 10 ns) gets the half-spherical form. To this moment of time the maximal parameters in flow field become equal 3 Mbar, 4.1 g/cc, 9.2 eV. Dynamics of these processes is shown on fig.2, where the fields of density, pressure and temperature for three time moments (1, 5 and 10 ns) are given.

The subsequent development of flow is submitted on fig. 3, where are shown two-dimensional distribution of density for time 20, 40, 80 and 120 ns. To 20 ns the shock wave going on a material of the first foil, reaches the back side of foil. On this contact boundary there is splitting a shock wave on

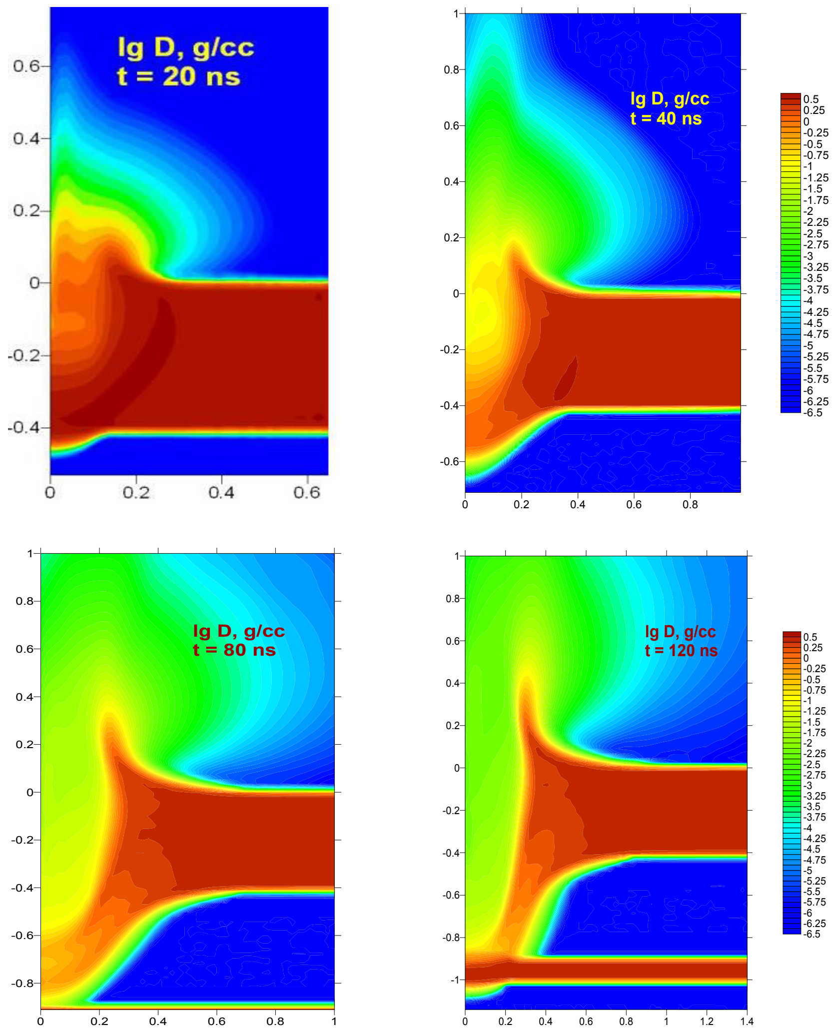

Fig. 3. Distribution of density for 20, 40, 80 and 120 ns.

past and reflected. Reflected goes back on a material of foil and interacts with falling SW, and past forms a plasma jet extending in direction of the second foil. The special interest have data on the form and sizes of apertures in the first screen arising at impact. Just this information allows to estimate efficiency of anti-meteorite protection. As boundary of an aperture it is natural to accept isoline of density, on 10 % of smaller normal solid-state density. This size almost coincides with density of aluminium in a melting point. In 120 ns the aperture in the first screen practically was formed. On fig.3 for this time moment second isoline in the area of first shield answers this density. The complex form of an aperture is well visible which it is impossible to describe in any one parameter (for example, radius).

Let's note some features of the formed aperture. The input size of an aperture is a little less than output. On the front side of the shield is formed sharp edge. On the back side of shield characteristic cavity and two sharp tooth is formed. The axial velocity of a jet after punching the first shield and up to achievement of second (85 ns) appears almost constant and makes approximately 6 km/s. At incoming of a jet on the second shield the maximal pressure makes 100 kbar, and temperature in it - 1.5 eV. Such action does not destruct of the second shield, i.e. its thickness is sufficient for protection. In subsequent the jet is reflected from the shield and spreads in a lateral direction. Let's note, that at impact maximal evaporated mass makes 23 M_0 and melted - 142 M_0 (M_0 - mass of a micrometeorite).

In summary we shall note the following. The calculation of two-dimensional gasdynamic problems on a basis of fully conservative difference schemes with consistency of fluxes in eulerian coordinates shows satisfactory quality of the solutions received on this technique. The numerical modeling is practically unique method of study of impact destruction at high velocities of collision with take in account real properties of materials. The results of calculations allow to estimate efficiency of anti-meteorite protection, to determine the form and sizes of formed craters and apertures. Besides, the numerical modeling allows to find phase composition of destruction products, to study dynamics of plasma jets etc.

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[1] ass@hmti.ac.by