FRAGMENTATIONS CAUSED BY HYPERVELOCITY COLLISIONS OF DEBRIS PARTICLES WITH PRESSURIZED VESSELS

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ABSTRACT

Collisions and orbital breakups are considered to play the most important role in determining the scenario of debris evolution in low Earth orbits and in geostationary orbit. Hypervelocity collisions with debris fragments could be very dangerous for spacecrafts. Most of spacecrafts contain pressurized gas-filled or fluid-filled vessels as structural elements. Fragmentation of a gas-filled or fluid-filled containment in hypervelocity collision has definite peculiarities and differs from trivial perforations of walls [1]. The primary goal of the present investigation is to follow the transformation of the kinetic energy of the fragments cloud and its contribution to internal loading of the containment. The secondary goal is to investigate if the internal atmosphere filling the containment could serve as an additional bumper shield to protect the rear wall from perforation.

1. PHYSICAL MODEL FOR THE BREAKUP IN HYPERVELOCITY COLLISIONS

Fragmentation of a gas-filled or fluid-filled containment in hypervelocity collision has several characteristic stages. The first stage is fragmentation of the impactor and the front wall in the collision zone and formation of a hypervelocity jet of small fragments penetrating inside the containment. Formation of cracks (and petals) in the collision zone of the front wall does not usually bring to a breakup of the containment at the present stage. The hypervelocity fragments cloud forms a shock wave in the media, filling the containment. In case of a highly compressible media (gas) the edges of the hole in the wall (or petals) are deformed inside the containment, in case of a low compressibility of the media (fluid) the edges of the hole are bulging out.

The cloud of small fragments slows down very rapidly due to the drag forces. The deceleration for fragments is proportional to $1/r_0$ and grows up with the decrease of a characteristic size r_0. On slowing down the cloud the convertion of its kinetic energy into the internal energy of the surrounding gas (or fluid) takes place. The rapid increase of the density of energy in a small volume inside the containment is similar to that for the local explosion. The energy release gives birth to diverging blast waves inside the containment that reflect from the walls thus producing non-uniform loading.

To investigate the cloud slowing down, heating of particles and surrounding atmosphere, atomization of droplets and shock wave formation due to the transformation of the kinetic energy of the cloud into thermal and kinetic energy of the surrounding gas it is necessary to apply the models for multiphase media accounting for the two-way coupling effects for fragments and gas, thermochemical and mechanical destruction of fragments.

Mathematical models for the non-equilibrium polydispersed mixture flows and breakup of pressurized vessels in non-uniform internal loading are described in details in the papers [1 - 8].

2. NUMERICAL MODELING OF A FRAGMENTS CLOUD PROPAGATION IN A GAS-FILLED CONTAINMENT

Numerical modeling of hypervelocity cloud of fragments propagation in a gas-filled cylindrical containment after perforation of the bottom wall near the axis being the result of a hypervelocity impact was performed based on the developed mathematical models. A cylindrical containment of 0.1 m radius and 0.2 m height was regarded, wall thickness 2 mm. A hole 10 mm in diameter was formed as a result of the impact, and the material of the wall formed a cloud of small fragments, characterized by the average diameter 0.3 mm and stochastic deviations 0.05 mm. The fragments initial temperature was 700 K with stochastic deviations $\pm$ 50 K; maximal velocity in the axial direction was assumed to be 1900 m/s, average velocity 1500 m/s with stochastic deviations 400 m/s both in axial and radial directions. The average density of the material was assumed as $\rho = 2000$ kg/m^3, the melting temperature 800 K, viscosity and surface tension in the liquid state 10^{-3} Ns and 10^{-2} N/m respectively. The gas pressure inside the containment was varied from 0.01 MPa up to 1.5 MPa, initial temperature T_0 = 300 K, molar mass 0.028 kg/mol.

The adopted initial data corresponds to a cloud that could be formed in impact of a 5 mm particle at a velocity 5 km/s.

Figures 1 and 2 show the model particles location (a) and pressure distribution inside the containment (b) for the two successive times. The

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initial pressure of gas inside the containment was rather low: p_0 = 0.01 MPa (0.1 atm). The line segments in Figs. 1 b, 2 b illustrate directions and values of velocity vectors in gas. The size of circles showing model particles is much larger than their real size, but directly proportional to it. The intensity of color reflects particles temperature in K as show on the tables in the right hand sides of Figures 1a and 1b.

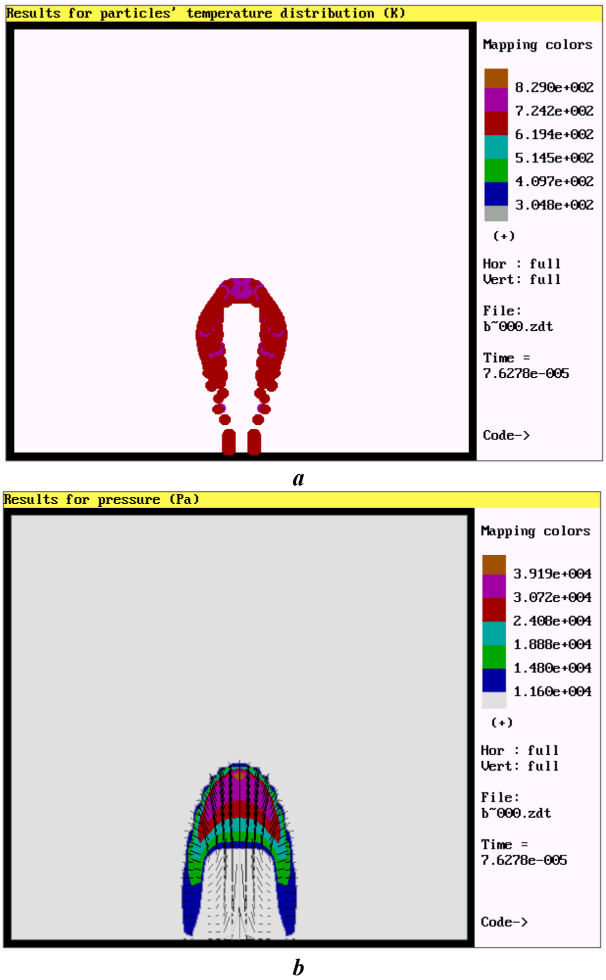


Figure 1. Model fragments location (a) and gas pressure distribution (b) inside the gas-filled containment ($p_0 = 0.01$ MPa) at a time $t = 76\ \mu s$ after a hypervelocity impact.

Figures 1 and 2 show that the cloud of fragments generates compression waves in the gas, but the velocity of the axial propagation of the cloud is too high for the shock waves to overtake it.

The shock wave and the cloud both collide the upper wall of the containment practically simultaneously in the present case of rather low initial pressure of gas filling the containment. Nevertheless, due to the dispersion of fragments in the cloud the total momentum is distributed on a larger area of the upper wall in collision.

The average pressure on the walls of the containment (taking into account the momentum of fragments in impact) is illustrated in Fig. 7 a (curve 0.1 atm). The maximal loading still takes place at the axis of symmetry.

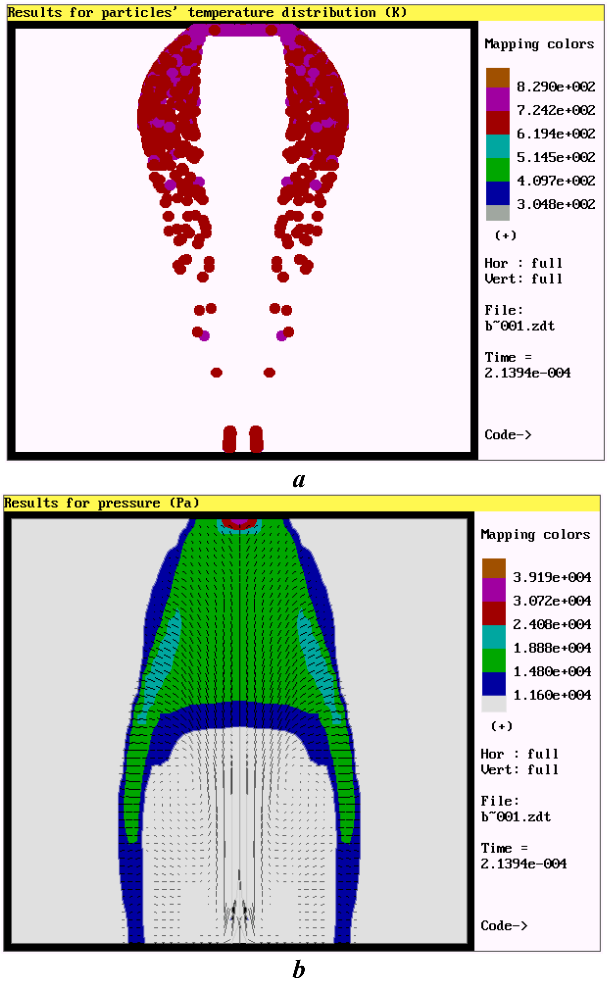


Figure 2. Model fragments location (a) and gas pressure distribution (b) inside the gas-filled containment ($p_0 = 0.01$ MPa) at a time $t = 214\ \mu s$ after a hypervelocity impact.

For comparative purposes Figure 3 contains the experimental data [9] on fragments of debris clouds distribution before and behind the target plate in hypervelocity impact of an aluminum spherical projectile and perforation of a plate. It is seen that the initial velocity distribution and stochastic parameters of the cloud adopted for our modeling provide the shape of the cloud (Figures 1 and 2) that matches exactly the results of experiment. (The quantitative comparison is hardly possible because the target was a two-layer 4mm Ti/1mm W plate.) Thus we'll use the adopted

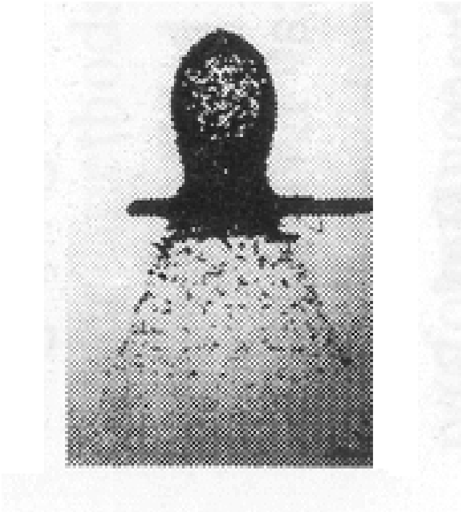
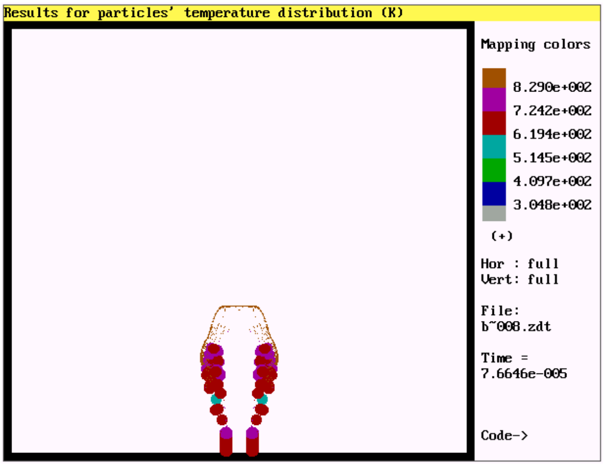


Figure 3. X-ray picture of the cloud formed 30.8µs aluminum sphere impacts 5 mm Ti/W plate at 5.4 km/s [9].



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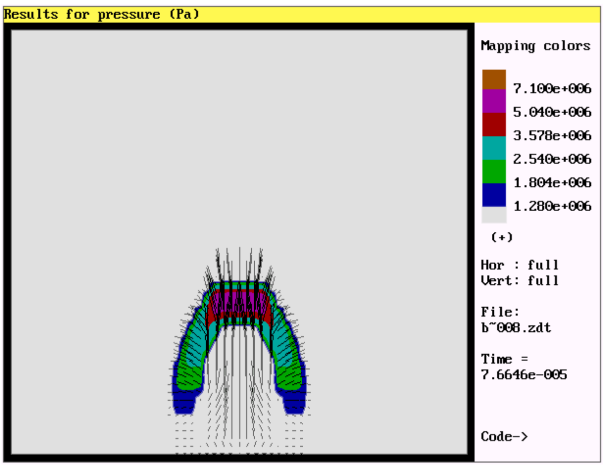
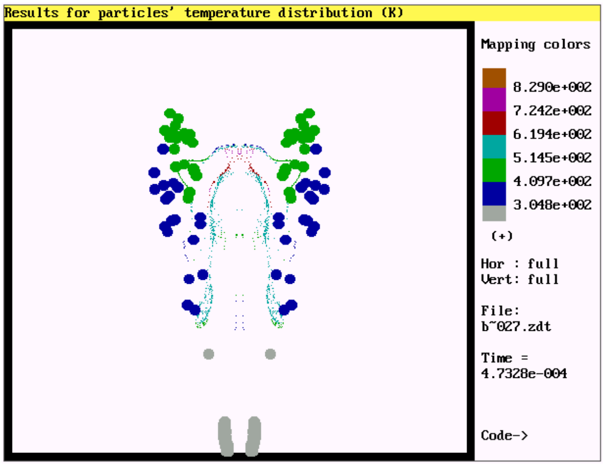


b

Figure 4. Model fragments location (a) and gas pressure distribution (b) inside the gas-filled containment ($p_0 = 1$ MPa) at a time $t = 76$ ìs after a hypervelocity impact.

initial velocity distribution of fragments in the cloud inside the containment for further investigations.

Figures 4, 5 and 6 illustrate the model particles locations (a) and gas pressures (b) for the case of a relatively high gas pressure inside the containment (p_0 = 1 MPa). The aerodynamic drag and heating of the particles are much more essential for the present case. On entering the containment the front particles of the cloud are heated above the melting temperature. Fragmentation of liquid droplets due to their interaction with the atmosphere brings to a formation of very fine droplets in the front part of the cloud (Fig. 4a). A strong shock wave is formed ahead of the cloud (Fig. 4b). The particles, representing smaller fragments, are illustrated by dots in Fig. 4a. Nevertheless, the major mass of the cloud is represented by those dots, and only a smaller number of low velocity particles keeps its initial size.



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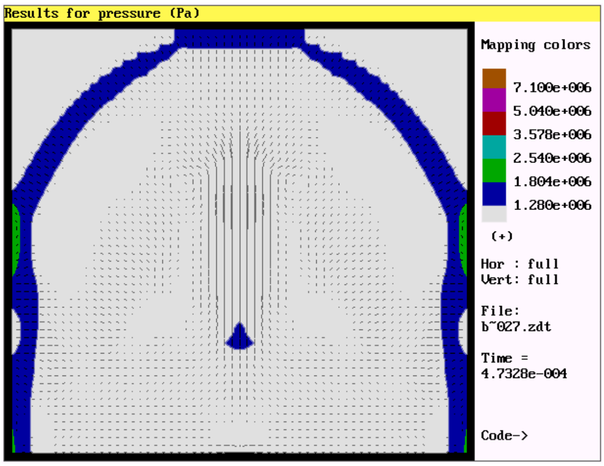

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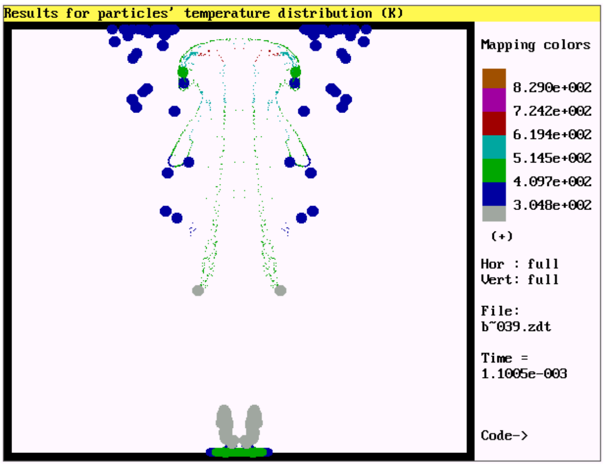
Figure 5. Model fragments location (a) and gas pressure distribution (b) inside the gas-filled containment ($p_0 = 1$ MPa) at a time $t = 473$ ìs after a hypervelocity impact.

Rapid slowing down of fragments in a dense atmosphere brings to a situation, when the shock wave overtakes the cloud and reflects from the upper and side walls while the fragments are still in the center of the vessel (Fig. 5). The small droplets slow down very rapidly and loose their kinetic energy much faster then the large ones. thus the large fragments, that had initially much lower velocity, come to overtake the small ones (Fig. 5a). Those fragments are, actually, the first to collide the upper wall (Fig. 6a). The reflected shock wave prevents the small droplets from colliding the upper wall for some time (Fig. 6b).



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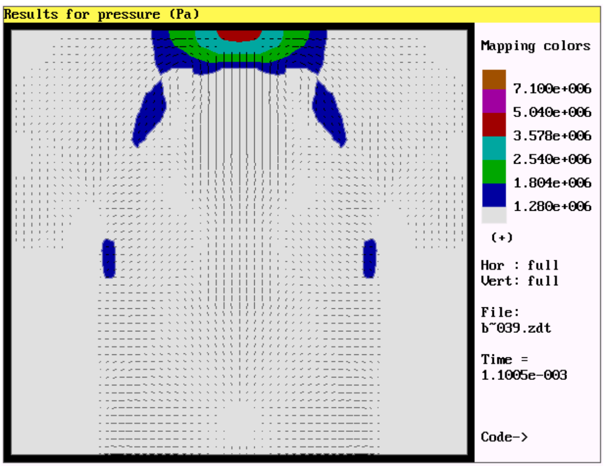


b

Figure 6. Model fragments location (a) and gas pressure distribution (b) inside the gas-filled containment ($p_0 = 1$ MPa) at a time $t = 1100$ ìs after a hypervelocity impact.

The average wall overpressure profile for the corresponding time (t = 1.1 ms) is shown in Fig. 7b (curve 10 atm). It is seen, that contrary to the previous case, the overpressure is distributed rather uniformly along the top, bottom and side walls of the containment. Its maximal value could be still found on the top wall at the axis of symmetry. But the maximal average overpressure for the present case is more than an order of magnitude lower.

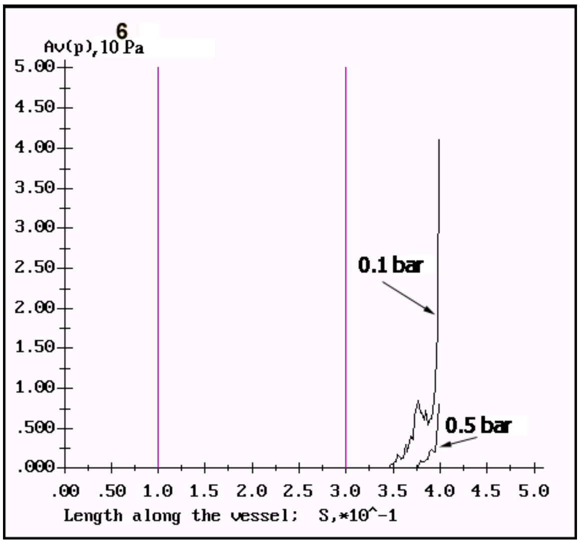
3. INTERNAL WALL LOADING IN HYPERVELOCITY COLLISIONS OF DEBRIS PARTICLES WITH PRESSURIZED VESSELS

Hypervelocity collision of a debris particle with a thin-walled containment brings to a formation of a cloud of fragments penetrating the containment and expanding in a radial direction (Figure 3). On reaching the opposite wall the cloud impacts a wider zone thus reducing the specific kinetic energy of the impact per square unit. If the kinetic energy is still large enough perforation of the opposite wall takes place. Thus in the absence of any filling substance inside the containment hypervelocity collision could bring to a formation of maximum two holes in the opposite walls.

In case the containment is filled in with some atmosphere a definite part of the kinetic energy of fragments would be transformed into the energy of the surrounding gas giving birth to shock waves propagating in all the directions, reflecting from the walls and bringing to an overpressurization under certain conditions. Thus internal loading of the walls would be the sum of momentum of particles colliding the walls and pressure growth due to reflections of shock waves. Under these conditions loading is exercised not only by a limited zone on the opposite wall of the containment but by all its internal surface. That brings to a much wider spectrum of possible breakup scenario.

Depending on the loading and strength of material three different scenario are possible. The intense non-uniform internal loading could bring to a breakup of the whole containment as if in an explosion and formation of fragments of a definite distribution versus mass. A detailed analysis of breakups taking place under the present scenario was performed by the authors [1,5,6]. The coupled non-uniform internal loading by impacting particles and shock waves could bring to a perforation of the opposite wall only due to maximal values of the cumulative load. The loaded zone and loads distribution will naturally depend on the density of the atmosphere inside the containment. And the third possible scenario illustrates the conditions under which the redistribution of loading on all the internal surface of the containment and rapid slowing down of debris particles due to aerodynamic drag forces lowers down the cumulative loads below the breakup limit and the rear wall remains undamaged.

To determine the conditions under which all these scenario could take place in is necessary to investigate the internal loading for the regarded cases. The local overpressure on the shell can be determined by the following formula:



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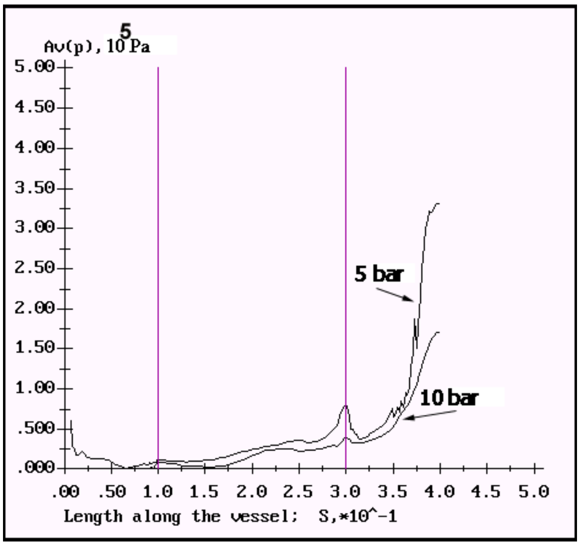

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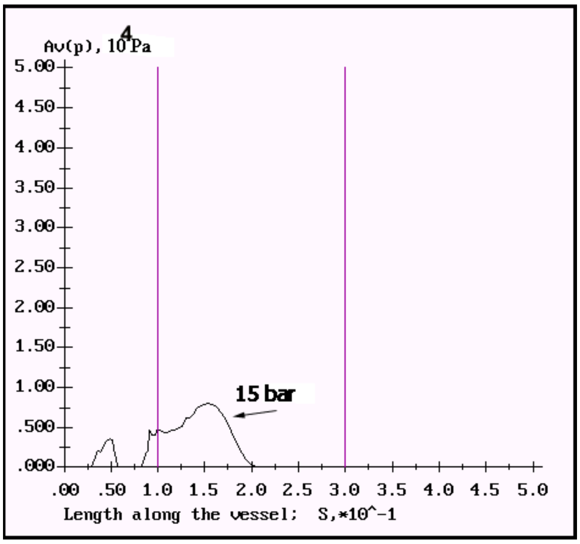

c

Figure 7. Average wall overpressure distribution accounting for the momentum of impacting fragments for different initial gas pressures: 0.1 bar, 0.5 bar, 5 bar, 10 bar, 15 bar.

$$Av(p) = p - p_0 + \sum_{i=1}^{N(\tau_*)} m_i \vec{V}_i \vec{n} / \tau_* , \qquad (1)$$

$$\tau_* = \frac{2h}{c_s}; \qquad c_s = \sqrt{\frac{E}{(1-\nu^2)\rho_{s0}}} , \qquad (2)$$

where E, ν are the Young modulus and Poisson coefficient of the material of the shell, ρ_{s0} - density of the material in the initial undisturbed state, τ_* - characteristic time for dynamical deforming of the shell, h - thickness, m_i, V_i - mass and velocity of the i-th fragment colliding the wall, $\vec{n}$ - external normal vector, $N(t, \tau_*)$ - the number of particles colliding the wall during the time interval (t, $t+\tau_*$). The results of analysis show, that for homogeneous clouds of fragments N is proportional to τ_*. Then, as it follows from formula (1), the dependence of $Av(p)$ on the value of characteristic time is not very strong.

Figure 7a-c illustrates average wall overpressures $Av(p)$ for one and the same fragments cloud propagating inside the containment, but for different initial gas pressures in the containment. The coordinate axis "*s*" starts in the center of the bottom part of the cylinder and following the wall reaches the center of the top plate. Vertical lines in Fig. 7 mark the connections of the side wall of the cylinder with the top and bottom plates.

The results show, that on increasing the initial pressure (and density) of the gas filling the containment the maximal overpressures decrease. For the case p_0 = 1.5 MPa the overpressures are negligible (Fig. 7c) and present only on the bottom and side walls. All the fragments are split into small droplets and slowed down. No disturbance reaches the upper wall.

4. A CONCEPT FOR SHIELD DESIGN

The double bumper and multi-shock shield concepts [10 - 12] suggested more than ten years before proved their effectiveness. The above results bring us to a conclusion, that gas-filled containments after some optimization studies could serve a reliable shield protecting the space structures. As multi-sheet shielding concept uses thin shield elements to repeatedly shock the impacting projectile to cause its melting and vaporization, so is the new gas-filled containment shield concept still using continuous effect of pressurized gas to cause fragments slowing down, heating, melting, atomization and evaporation. Besides, using gas-filled bumpers makes it possible to increase the area of the zone of impact energy redistribution including the side and front walls due to the property of gas to transmit pressure in all directions. That is a considerable advantage of the present concept.

The gas-filled bumper shields could be reusable, as the rate of gas phase leakage on depressurization is rather low and the loss of mass is negligible during the characteristic time of impact. The influence of molar mass of the gas phase and other parameters on the rate of impact energy consumption and transformation is to be investigated.

5. FLUID FILLED CONTAINMENTS

In case of a fluid-filled containment an overheated expanding gaseous cloud is being formed in the zone of fragments deceleration due to the concentrated energy release. The expansion of the gas-vapor cloud brings to a formation of a diverging shock wave. Reflections of shock waves in fluids from elastic walls take place in the form of the rarefaction waves that brings to the formation of the cavitation zones near the walls. The collapse of those zones usually results in breakup of the walls. The succession of the processes of internal loading of the fluid-filled containment: energy release in deceleration of fragments, gas-vapour cloud formation and expansion, blast wave propagation, reflection from an elastic shell, cavitation and collapse of cavities - can be also described making use of the mathematical models for dynamics of multiphase media accounting for chemical and physical transformations [4].

CONCLUSIONS

The developed physical and mathematical models for description of hypervelocity impact on pressurized structures will be very useful in evaluation of potential damages for space vehicles in collisions with debris particles which turn to the more and more probable.

The effects of energy dissipation in hypervelocity collisions of particles with gas-filled vessels can be used successfully in working out principles for shielding space vehicles by damageable gas-filled or fluid-filled bumper shields accumulating and transforming the kinetic energy of the impact.

ACKNOWLEDGEMENTS

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