COMPUTATIONAL SIMULATION OF SPACECRAFT HONEYCOMB FLUID-FILLED SHIELD BEHAVIOR IN HYPERVELOCITY COLLISION WITH SPACE DEBRIS FRAGMENTS

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INTRODUCTION

For the scenario business as usual without explosions and disposal following prediction by SDPA model the number of fragments larger than 20 cm in size will increase 1.5 times during 200 years. The number of objects with size from 10 to 20 cm will increase 3.2 times, whereas predicted increase of smaller-sized fragments is very essential: 13 - 20 times. The number of small-size, non-catalogued objects will grow exponentially in mutual collisions [1-2]. This rapid growth of the orbital debris population in Low Earth Orbits brings to an increase of collision probability of space vehicles with debris particles, especially with those sizing less than 1 cm [4]. That brought spacecraft designers to the necessity of shielding the space vehicles [3]. The shield should meet the following requirements: to provide an effective protection for the spacecraft in collisions with small size debris at relative velocities up to 12 km per second, and to have a relatively low mass.

The double bumper and multi-shock shield concepts [5 - 7] suggested in the end of 20-th century proved their effectiveness. The new concept suggested in the beginning of the 21-st century [2] states that protecting the spacecraft by a honeycomb of small gas-filled containments could form a much more efficient shield with lower mass. 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 important.

Fragmentation of a gas-filled or fluid-filled containment in hypervelocity collision has several characteristic stages [2]. 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.

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 conversion 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 [2].

1. SHIELDING CONCEPTS IN HYPERVELOCITY COLLISIONS

The classical rigid steel shielding being very effective in protecting from hypervelocity fragments would be useless in space structures protection due to unacceptable weight characteristics. An example of craters formed in steel plate in hypervelocity impact of small steel ball is shown in Fig. 1 [8]. The scale is provided in cm on the right hand side of each figure. A similar ball is placed on the bottom of the crater for comparison.

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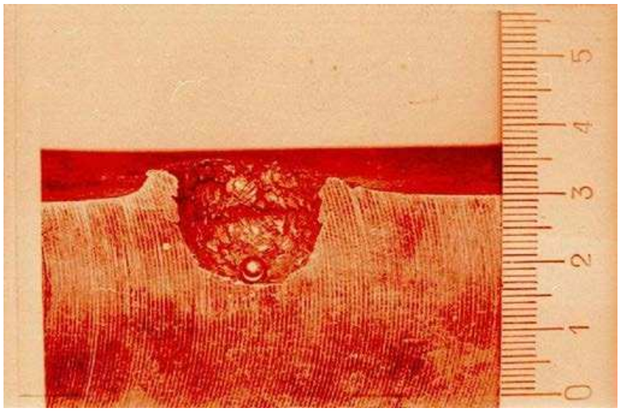

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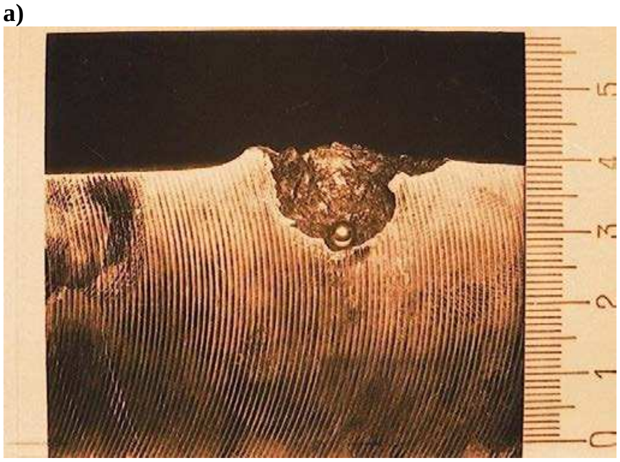


b)

Fig. 1. The crater shape developed in high-speed collision of the steel ball and steel obstacle.

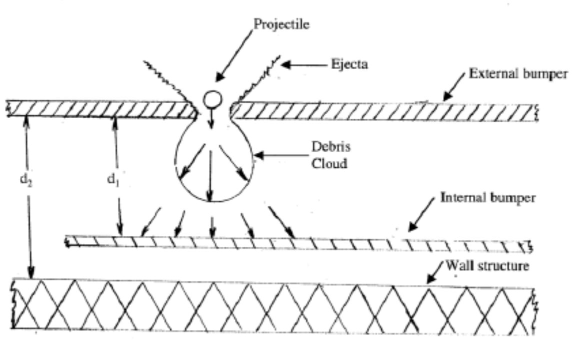
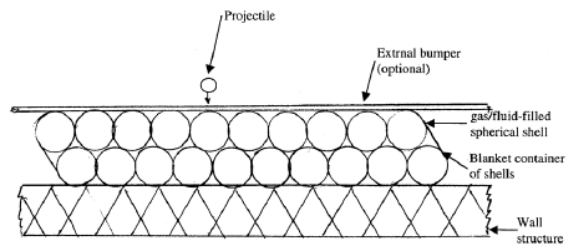


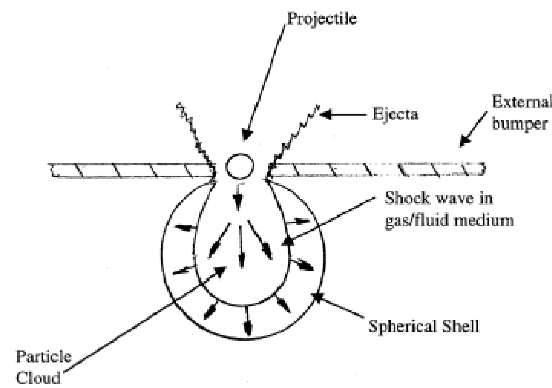
Fig. 2. The double bumper and multi-shock shield.

The double bumper and multi-shock shield suggested at the end of 20-th century [5-7] was a good solution in protecting from debris fragments both in terms of effectiveness and weight. The multi-sheet shielding concept uses thin shield elements to repeatedly shock the impacting projectile to cause its melting and vaporization. (Fig. 2) Besides, the momentum and energy delivered to the target by the impactor are redistributed on a larger area of the wall thus making local pressure in collision much less.

The new concept [2] states that protecting the spacecraft by a honeycomb of small gas-filled containments could form a much more efficient shield with lower mass (Fig.3a). The new gas-filled containment shield concept makes use of continuous effect of pressurized gas causing fragments slowing down, heating, melting, atomization and evaporation. On the other hand, using gas-filled bumpers makes it possible increasing the area of the zone of impact energy redistribution including in it 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.



a)general view of the shield



b) compressible gas flow and shock wave formation on impactor penetrating a single cell

Fig. 3. Honeycomb fluid-gas filled shield providing 3-D impact energy dissipation.

In hypervelocity collision of fragment with a cell filled in with compressible fluid or gas the process of interaction 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 (Fig. 3b).

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 pressure increase. 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. Deceleration of fragment cloud takes place much faster in fluid than in gas, thus releasing energy more close to the front wall, which could cause its irreversible deformations and breakup. Fig. 4 illustrates the fragment of a front wall of a fluid filled containment after hypervelocity collision with a metallic fragment [9].

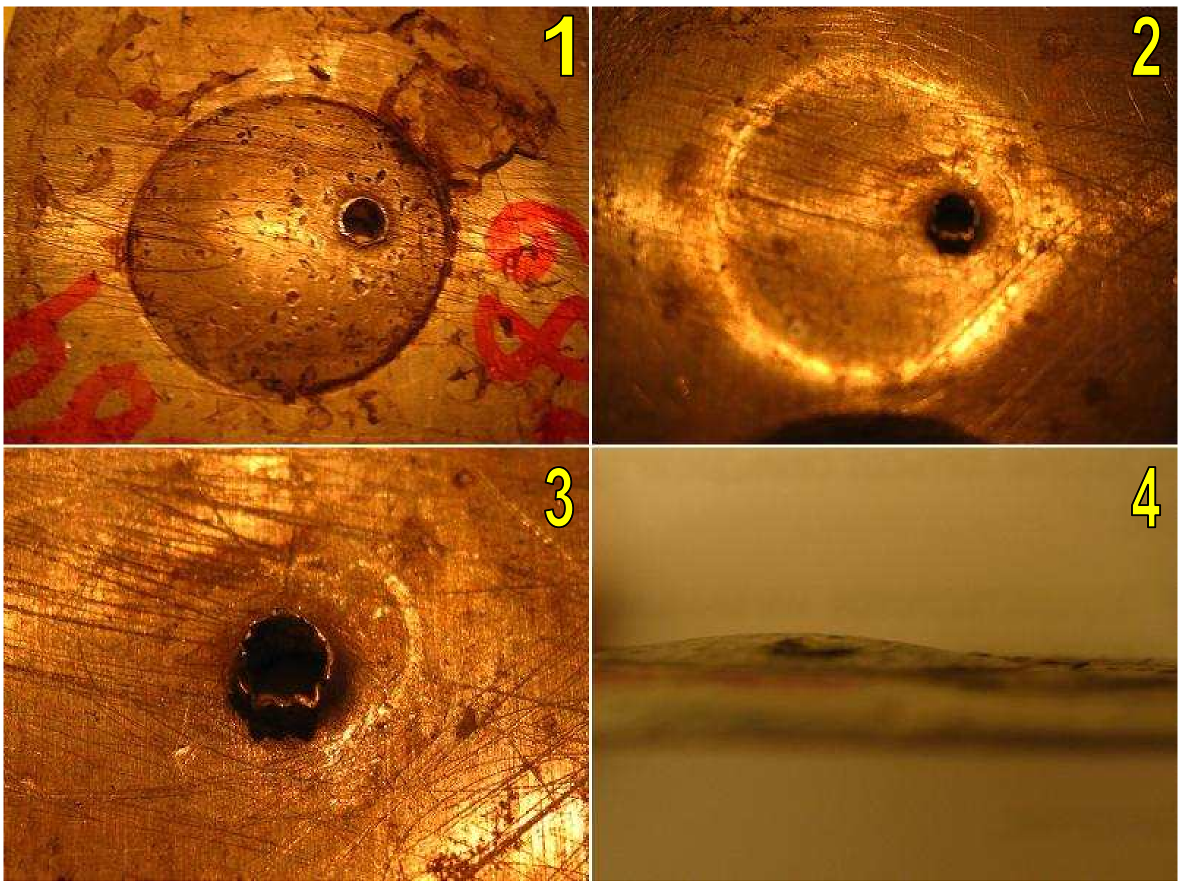


Fig.4. Perforated wall of the water-filled containment after impact of steel element mass 0.2g at a relative velocity 2km/s: 1-front view, 2-back view, 3-magnified back view, 4-side view.

The length of the containment was 200 mm.
The impactor had the following characteristics:

- shape - sphere
- material – steel
- diameter $D = 3,6\ 10^{-3}$ m
- mass $m = 2\ 10^{-4}$ kg
- density ρ =7900 kg/m ^{3}
- impact velocity $V_0 = 2000$ m/s

The target had the following characteristics:

- shape - plate
- material – aluminum
- thickness $z = 2\ 10^{-3}$ m

- density ρ =2700 kg/m ^{3}
- liquid behind the target – water

Fig. 4.1 shows the front wall from outside (from the side of impact). Fig. 4.2. shows the rear side of the wall contacting the water. Fig. 4.3. shows magnified crater from inside. Fig. 4.4 shows the side view. The figures illustrate the circular bulging part of the wall, which appeared due to internal loading by shock wave formed in fluid after absorption of impactor energy. The side view of the plate testifies that. It is seen from Figs. 4.1 and 4.2 that ejected mass in perforation makes crater walls on both sides of the plate. The crater diameter is 3 mm.

Thus the performed experiment testifies our concept of transmitting the impact energy mostly to the front wall rather than to the back wall behind which the spacecraft structure being protected is located.

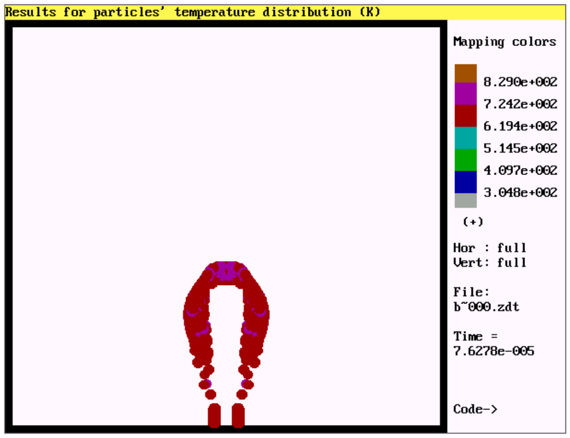
2. NUMERICAL MODELING OF FRAGMENTS CLOUD PROPAGATION IN A GAS-FILLED HONEYCOMB SECTION OF A SHIELD

The mathematical model for multiphase fragment cloud interaction with gaseous atmosphere was used for performing numerical simulations [2].

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 5 shows the model particles location and temperature distribution inside the containment for two successive times. The initial pressure of gas inside the containment was rather low: p_0 = 0.01 MPa (0.1 atm). 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.



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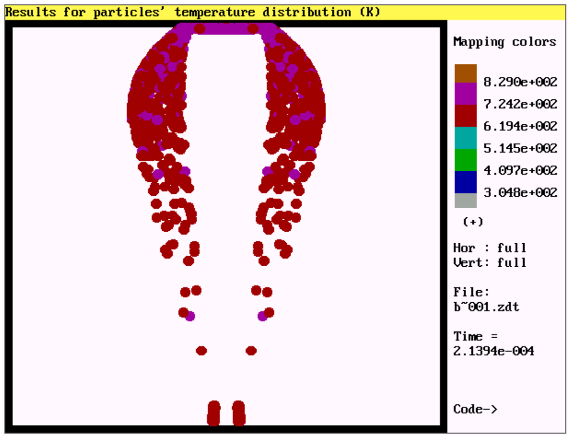


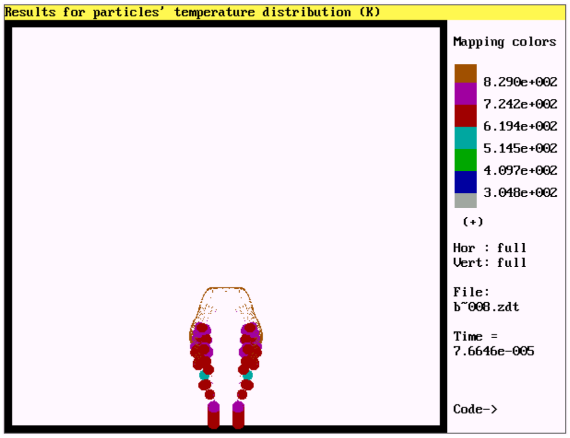
b

Fig. 5. Model fragments location inside the gas-filled containment ($p_0 = 0.01$ MPa) at a time $t = 76$ μs (a) and $t = 214$ μs after a hypervelocity impact.

Fig.5 shows that the velocity of the axial propagation of the cloud is too high and could not be essentially slowed down by the rarefied gas atmosphere.

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. 9 a (curve 0.1 atm). The maximal loading still takes place at the axis of symmetry.



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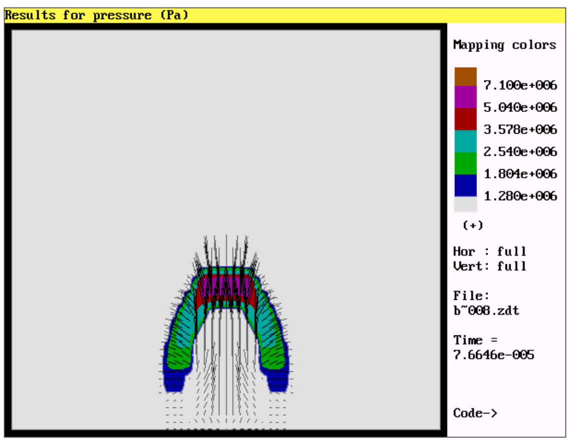
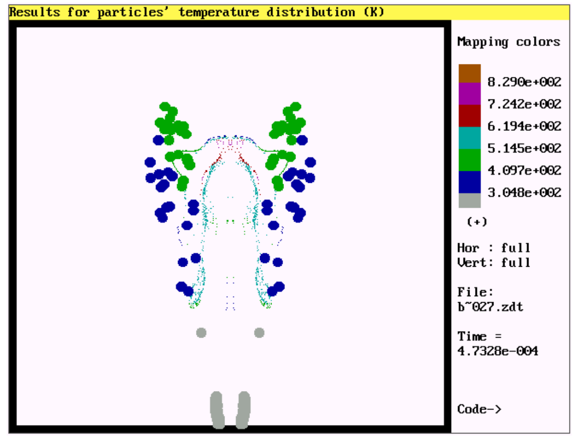


b

Fig. 6. Model fragments location (a) and gas pressure distribution (b) inside the gas-filled containment ($p_0 = 1$ MPa) at a time $t = 76$ μs after a hypervelocity impact.

Figures 6, 7 and 8 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. 6a). A strong shock wave is formed ahead of the cloud (Fig. 6b). 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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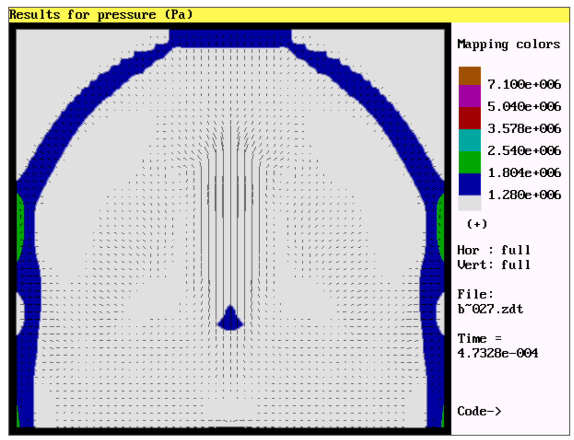

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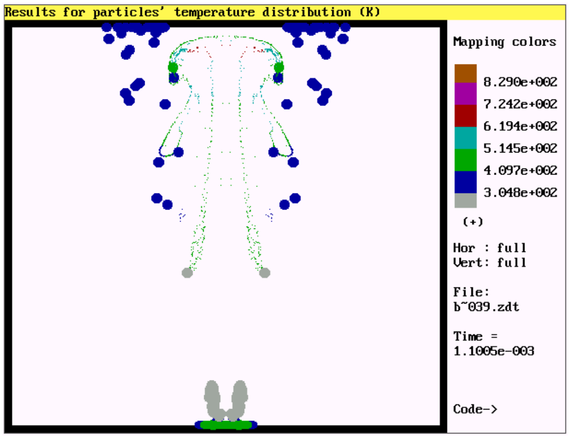
Fig. 7. Model fragments location (a) and gas pressure distribution (b) inside the gas-filled containment ($p_0 = 1$ MPa) at a time $t = 473$ μs after a hypervelocity impact.

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. 7). 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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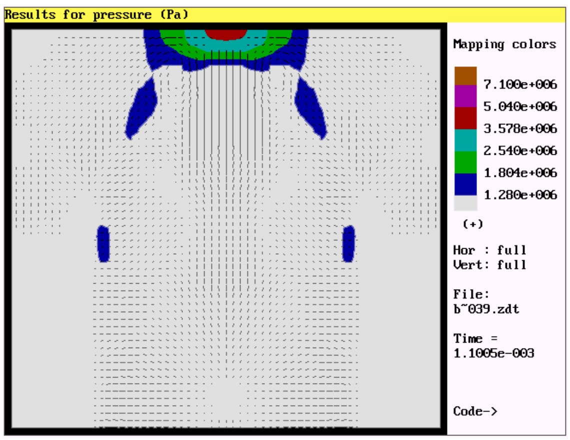

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Fig. 8 Model fragments location (a) and gas pressure distribution (b) inside the gas-filled containment ($p_0 = 1$ MPa) at a time $t = 1100$ μs after a hypervelocity impact.

The average wall overpressure profile for the corresponding time (t = 1.1 ms) is shown in Fig. 9b (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:

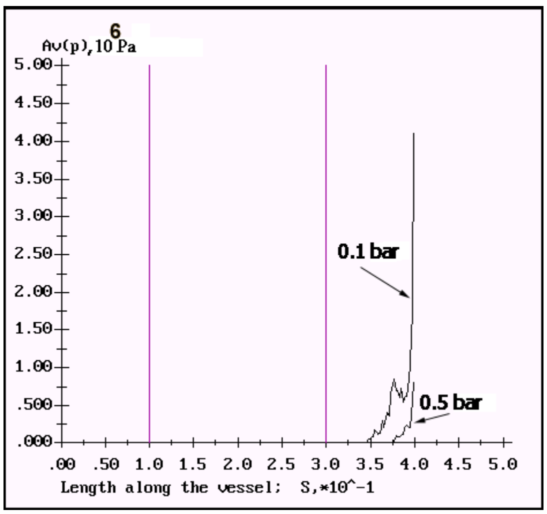
$$Av(p) = p - p_0 + \sum_{i=1}^{N(\tau_*)} m_i \vec{V}_i \vec{n} / \tau_* , \qquad (1)$$

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

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, τ*)* - the number of particles colliding the wall during the time interval (*t*, *t*+*τ**). 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.

Fig. 9a-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. 9 mark the connections of the side wall of the cylinder with the top and bottom plates.



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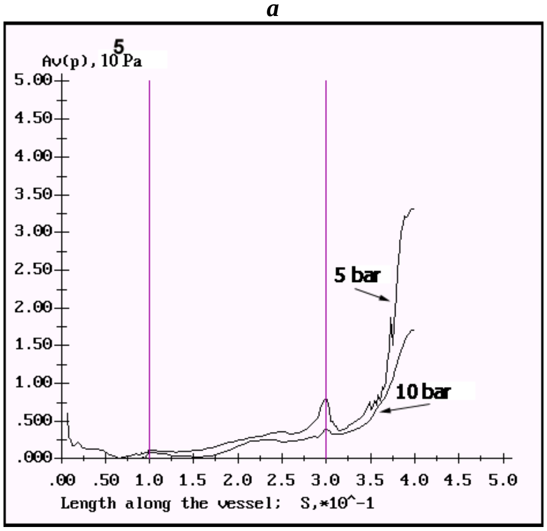

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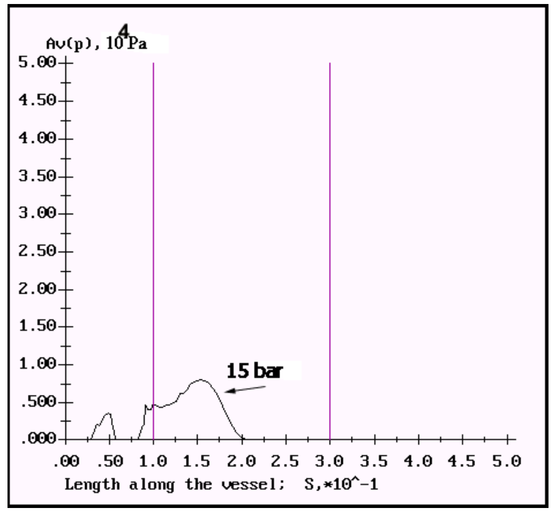

c

Fig. 9. 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.

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. 9c) 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.

CONCLUSIONS

- The effects of energy dissipation in hypervelocity collisions of particles with vessels filled in by compressible fluid 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.
- 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.

ACKNOWLEDGEMENTS

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