Original Article

Derivation Of Theoretical Calculations Of The Acoustic Problem With Experimental Data

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Abstract

This work presents the results of complex experimental and computational studies of the shock-wave and thermodynamic parameters of the collision of a particle with the wall of the pressurized compartment of a spacecraft, depending on the physical and mechanical characteristics of the impactor material and the impact velocity. The results of calculations of the parameters of the wall breakdown and air waves in the pressurized compartment of the spacecraft are compared with the data of experimental measurements.

Keywords: spacecraft, pressurized compartment, meteoroid particles, space debris, high-speed impact, breakdown, acoustic waves.

Introduction

The ever-increasing danger of a spacecraft (SC) colliding with space debris (SD) requires research into the processes of high-velocity impact and possible breakdown of the spacecraft body, which is important in the development of means of its protection, which include anti-meteoritic screens and equipment for the operational determination of the point of impact (breakdown), the operation of which is based on the use of an acoustic air wave inside the apparatus, which occurs when energy is released at the point of impact (breakdown).

The substance of space debris particles of natural origin, as a rule, is stone, iron, their mixture and ice with various inclusions.

The bulk of man-made space debris particles are particles consisting of fragments of aircraft structural materials, mainly aluminum and its alloys.

The problem under consideration plays an important role in determining the strength and durability of aircraft. The obtained theoretical results are compared with experimental data, which differ insignificantly.

Formulation of the problem

On the basis of light-gas gas-cumulative and electric-discharge guns, experimental studies of the breakdown of the pressure compartment wall, modeled by a 2-4 mm thick aluminum alloy plate, simulators of space debris microparticles, hereinafter referred to as "strikers", are carried out.

The impactors are made in the form of spheres, compact cylinders, ellipsoids with maximum dimensions from ~ 3 to 13.7 mm.

Tests are carried out in the speed range ~ 0.5÷6.5 km/s.

In the tests, the parameters of wall destruction are studied depending on the size, speed and material of the "striker" and, using pressure sensors, the parameters of the acoustic wave in the pressurized compartment are measured.

Since when accelerating a "striker" made of pure ice in the cannon barrel to a speed and higher, it is crushed before it leaves the barrel, in experiments, indestructible ice "strikers" are preliminarily reinforced with cotton fabric, which makes up to 40% of the total weight of the projectile.

Decisions and discussion of results

Let us consider a calculation scheme for analyzing the process of breakdown of the spacecraft wall by a particle of different materials thickness.

To do this, within the framework of the model of an absolutely inelastic particle impact on a thin flat screen, we write the equations for the conservation of mass, momentum, and energy in the form [1]:

$$m_{сг} = m_{сф} + m_{вэ}; \quad (1)$$

$$m_{сф}V_0 = (m_{сф} + m_{вэ})V_{сг}; \quad (2)$$

$$m_{сф}V_0^2/2 = m_{сг}V_{сг}^2/2 + E_в + A_S, \quad (3)$$

where $m_{сф}$, V_0 - the mass and velocity of the particle before impact with the protective screen, $m_{сг}$, $V_{сг}$ - the mass and velocity of the bunch (the particle together with the knocked-out part of the screen), $m_{вэ}$ - the mass of the knocked-out part of the screen, $E_в$ - the internal energy of the colliding bodies expended on breaking the screen, A_S - the work spent on breaking the screen.

First, preliminary analyzing the system of equations (1)-(3), we note that when taking into account the real values of the strength characteristics of the screen materials and the time of their resistance, i.e., time of flight of particles through a thin screen, the work of the resistance A_S forces does not exceed a few percent of the initial kinetic energy of the particle. Therefore, in the future, when performing calculations in equation (3), the value A_S can be neglected and considered as $A_S \approx 0$.

After that, from the solution of the system of equations (1)-(3), in principle, it is possible to determine the velocity of the bunch mass $V_{сг}$, $m_{сг}$, and the internal energy of the colliding bodies $E_в$. However, for this, it is first necessary to calculate the mass value of the knocked-out part of the screen $m_{вэ}$ based on solving the problem of expanding a cylindrical cavity in the screen material or experimental measurement of this value and mathematically describe the shock-wave, thermodynamic components of internal energy $E_в$, taking into account the deformation and destruction of the particle materials, as well as the screen in high-speed impact testing.

Note that the internal energy $E_в$ of colliding bodies at impact velocities $V_0 = (5-8)\text{km/s}$ can be realized in the following forms [2]:

- energy of heating E_{iT} and microstructural transformations E_{id} (crushing of a particle and an embossed part of the screen);

- kinetic energy of the radial expansion of the fragments of fragmentation of the particle and the screen K_r.

Thus, the internal energy of the colliding bodies $E_в$ after the screen breakdown is mathematically written as

$$E_в = E_{iT} + E_{id} + K_r \quad (4)$$

where $E_{iT} = m_{сф}E_{iTcT}(\varepsilon,T) + m_{вч}E_{iTэT}(\varepsilon.T)$

$m_{вч}=\rho_{вч}V_{вч}$ ($V_{вч}$ - the volume of the embossed part of the screen), ε - volumetric deformation, T - temperature,

$E_{id} = m_{сф}E_{idсф} + m_{вч}E_{idэк}$; $K_r = (K_{r1}^{л.бок} + K_{r2}^{п.бок})$; $\varepsilon_{сфвчэ} = 1 - (\rho_{сфвчэ}/\rho_{сф})$; $\varepsilon_{вчэ} = 1 - (\rho_{0эк}/\rho_{вчэк})$; $m_{сфвчэ} = \rho_{сфвчэ} \times V_{сфвч}$;

$$K_{r1}^{л.бок} = K_{r2}^{п.бок} = (m_{сф} + m_{вэ})/2 \times V_{r,cr}^2/2; \quad (5)$$

where $V_{r,cr}$- the radial expansion velocity of fragments of fragmentation of the particle and the screen, which is directed perpendicular to the surface of the screen and is determined from the solution of the corresponding cylindrical problem of the propagation of a cylindrical plastic wave in the screen material in the radial direction under the action of a given load $P_0(t)$.

Therefore, based on the solution of the system of equations (1)-(5), the numerical values of the mass $m_{сг}$ and speed $V_{сг}$ are determined, including the internal energy $E_{в}$ expended on the breakdown of the barrier, depending on the impact speed V_0, which in turn serve as initial data for studying the dynamics of cloud movement particles in the pressure compartment of the spacecraft.

Here, it should be additionally noted that the initial parameters of the problem of collision of two bodies at $t=0$ in the case of heterogeneity of the materials of the particle and the screen are determined using the laws of conservation of mass, energy, and momentum at the fronts of the reflected and refracted waves propagating in their materials. In this case, the schematic picture of the problem has the form

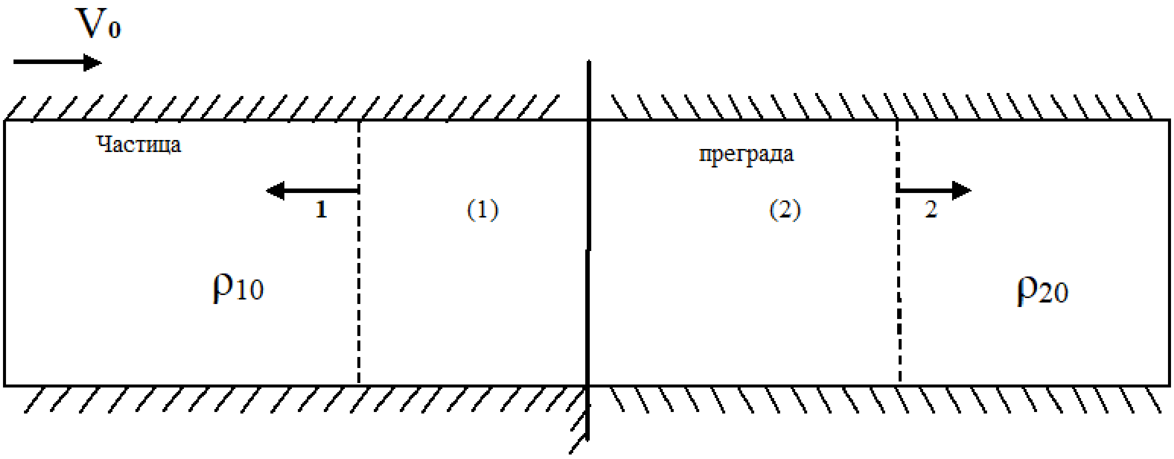

Fig. 1

Let us write the above conservation laws on wave fronts in the form [4]:

In the drummer material:

$$\begin{aligned} &\dot{u}_1 = \varepsilon_1^* \dot{R}_1, \\ &P_1^* - P_{10} = \rho_{10} \dot{u}_1 \dot{R}_1, \\ &\frac{\left(P_1^* - P_{10}\right)}{\rho_{10}} \left(1 - \frac{\rho_{10}}{\rho_1}\right) = E_1^* - E_{10}; \end{aligned} \qquad (6)$$

where $\varepsilon_1^* = 1 - \dfrac{\rho_{10}}{\rho_1}$ - volumetric deformation, $\dot{u}_1$ - mass velocity, $\dot{R}_1$ - shock wave velocity, $P_{10} \approx 0$, P_1^* - pressure, E_1^* - energy density in the particle material.

In the target material, i.e., flat barriers:

$$\begin{aligned} &\dot{u}_2 = \varepsilon_2^* \dot{R}_2, \\ &P_2^* - P_{20} = \rho_{20} \dot{u}_2 \dot{R}_2, \\ &\frac{\left(P_2^* - P_{20}\right)}{\rho_{20}} \left(1 - \frac{\rho_{20}}{\rho_2}\right) = E_2^* - E_{20}; \end{aligned} \qquad (7)$$

where $\varepsilon_2^* = 1 - \dfrac{\rho_{20}}{\rho_2}$ - volumetric deformation, $\dot{u}_2$ - mass velocity, $\dot{R}_2$ - shock wave velocity, $P_{20} \approx 0$, P_2^* - pressure, E_2^* - energy density in the particle material.

In addition, at the contact of two media consisting of a particle and a flat barrier, we have the following conditions of the problem:

$$P_1^* = P_2^* = P_s,$$
$$\dot{u}_1^* + \dot{u}_2^* = V_0, \quad (8)$$

where V_0 - particle impact speed.

Further, to determine the initial parameters of the above problem of the collision of bodies, it is necessary to supplement the system of equations (6)-(8) with the equations of state of the media experimentally determined at high pressure levels, which in general have the form [5]:

$$P_1(\varepsilon,T) = P_{1\Pi}(\varepsilon) + P_{1T}(\varepsilon,T),$$
$$E_1(\varepsilon,T) = E_{1\Pi}(\varepsilon) + E_{1T}(\varepsilon,T); \quad (9)$$

$$P_2(\varepsilon,T) = P_{2\Pi}(\varepsilon) + P_{2T}(\varepsilon,T),$$
$$E_2(\varepsilon,T) = E_{2\Pi}(\varepsilon) + E_{2T}(\varepsilon,T); \quad (10)$$

where

$$E_{i\Pi}(\varepsilon) = \int_{\rho_{i0}}^{\rho_i} \frac{P_{i\Pi}(\varepsilon)}{\rho_i^2} d\rho_i + E_{i0} \quad (11)$$

$P_{i\Pi}$ - potential pressure in i -environment, $i = 1{,}2$.

E_{i0} - the additive energy constant, in this case it is assumed $E_{i0} = 0$.

Thus, the problem under consideration of determining the parameters of collision of heterogeneous space debris particles (SM) with a flat barrier is reduced to finding a solution to the system of nonlinear equations (6) - (11).

Further, taking into account that the shock-wave process in the target occurs much faster than the thermodynamic one, and the thermal component of pressure P_T at temperatures $T < 10^6 K$ is much less than the potential component of pressure P_Π [3], those $P_T << P_\Pi$ the above systems of equations (6)-(8) are solved by the method of successive approximations. In this case, as a first approximation, the shock-wave problem is solved with the involvement of the first two equations of the system (6) and (7), as well as equations (8) without taking into account the thermal component of pressure $P_T(\varepsilon,T)$. In the second approximation, based on the known dynamic parameters of the problem $P_{i\Pi}$, $\dot{u}_i$, ε_i^*, $R_i(i = 1{,}2)$ the thermal components of the internal energy and temperature of the particle and target materials $E_{iT}(\varepsilon_i, T_i)$ and T_i are determined using the energy equations, and specific, experimentally established expressions $P_T(\varepsilon,T)$ and $E_T(\varepsilon,T)$.

In the course of calculations for the expressions $P_\Pi(\varepsilon)$, $E_\Pi(\varepsilon)$ and $P_T(\varepsilon,T)$, $E_T(\varepsilon,T)$ the experimental data of works [4, 5] are used, which are valid for pressures of the order of magnitude $10^6 kg/sm^2$ and take into account the influence of the temperature factor on the wave process.

From conditions (11), taking into account the first two equations of system (6) and (7), after some transformations, we obtain:

$$\dot{R}_1 = \frac{V_0\left(1 \pm \sqrt{\dfrac{\rho_{10}\varepsilon_2^*}{\rho_{20}\varepsilon_1^*}}\right)}{\left(\varepsilon_1^* - \dfrac{\rho_{10}}{\rho_{20}}\varepsilon_2^*\right)}, \quad \dot{R}_2 = \frac{V_0 - \varepsilon_1^* \dot{R}_1}{\varepsilon_2^*}; \quad (12)$$

Then, from the second equations of system (6) and (7) (for $P_{10} = P_{20} = 0$), taking into account (12), we obtain systems of two equations with respect to ε_1 and ε_2 in the form:

$$P_{1\Pi}^{*}\left(\varepsilon_1^{*}\right)=\frac{\rho_{10}\varepsilon_1^{*}V_0^2\left(1\pm\sqrt{\dfrac{\rho_{10}\varepsilon_2^{*}}{\rho_{20}\varepsilon_1^{*}}}\right)^2}{\left(\varepsilon_1^{*}-\dfrac{\rho_{10}}{\rho_{20}}\varepsilon_2^{*}\right)^2},\quad P_{2\Pi}^{*}\left(\varepsilon_2^{*}\right)=\frac{\rho_{20}\varepsilon_2^{*}V_0^2\left(\dfrac{\rho_{10}}{\rho_{20}}\pm\dfrac{\varepsilon_1^{*}}{\varepsilon_2^{*}}\sqrt{\dfrac{\rho_{10}\varepsilon_2^{*}}{\rho_{20}\varepsilon_1^{*}}}\right)^2}{\left(\varepsilon_1^{*}-\dfrac{\rho_{10}}{\rho_{20}}\varepsilon_2^{*}\right)^2} \quad (13)$$

Considering that the adiabatic equations for the materials of a particle and a flat barrier $P_{1\Pi}\left(\varepsilon_1\right)$ and $P_{2\Pi}\left(\varepsilon_2\right)$ are experimentally known, the system of equations (13), as a system of two nonlinear algebraic equations with respect to ε_1 and ε_2, is solved numerically.

Experimental and calculated materials obtained by processing the test results are shown in tables 1 and 2.

Table 1 Results of experimental studies.

№эксп	Мат-л уд.	Форма снаряда	V_0, км/с	$\varepsilon_{1нач}$	$\varepsilon_{2нач}$	$P_{нач}$ атм	$\dot{u}_{1нач}$ м/с	$\dot{R}_{1нач}$ м/с	$\Delta E_{1нач}$ Дж/кг	$\dot{u}_{2нач}$ м/с	$\dot{R}_{2нач}$ м/с	$\Delta E_{2нач}$ Дж/кг
1385	ПНД	Цилиндр со сфер. прит ∅ 13,72 мм	6,14	0,74	0,33	266010	4320	5809	932920	1820	5535	1657000
1383	ПНД	Цилиндр со сфер. прит ∅ 13,72 мм	5,9	0,73	0,31	251080	4173	5684	870770	1726	5515	1491000
1384	ПНД	Цилиндр со сфер. прит ∅ 13,72 мм	6,05	0,74	0,32	260090	4265	5765	909710	1784	5533	1592300
1386	ПНД	Цилиндр со сфер. прит ∅ 13,72 мм	5,97	0,74	0,32	255690	4215	5719	888610	1754	5518	1538800
1101	ПНД		0,9	0,25	0,031	23030	735	2946	270140	165	5270	13607
1098	лед		1,03	0,27	0,033	24568	854	3121	364780	175	5265	15462
1099	лед		1,14	0,28	0,038	28305	936	3303	438830	203	5290	20639
1100	лед		1,0	0,27	0,032	23477	831	3073	345860	168	5275	14162
1102	лед		1,0	0,27	0,032	23477	831	3073	345860	168	5275	14162
1103	лед		0,76	0,24	0,021	15646	647	2648	209540	112	5288	6343
1104	лед		0,8	0,25	0,023	16907	678	2722	230190	121	5282	7379
1387	база-льт	Овал 10,5х7,7х6,2	5,84	0,41	0,52	490640	2744	6629	3766900	3095	5985	4790200

		мм										
1388	Квар-цит	Овал ∅ 13,7 мм	5,92	0,41	0,52	497760	2777	6693	3856000	3142	6003	4939000
1371	Al	Шар ∅ 6,74 мм	5,89	0,50	0,50	498700	2934	5883	4304000	2934	5883	4304000
1372	Al	Шар ∅ 6,74 мм	5,8	0,49	0,49	454160	2889	5866	4173400	2889	5000	4304000
1374	Al	Шар ∅ 6,74 мм	5,65	0,48	0,48	440330	2814	5836	3960400	2814	5836	3960400
1375	Al	Шар ∅ 6,74 мм	5,75	0,49	0,49	489100	2885	5900	4163900	2885	5900	4163900
1376	Al	Шар ∅ 6,74 мм	6,12	0,51	0,51	514300	3071	5972	4717100	3071	5972	4717100

Let us now present the rationale for simulating an ice particle made of polyethylene, which is important for high impact velocities.

Let us estimate the values of the kinetic energy of a particle made of polyethylene ice (HDPE) at impact velocities $V_0 = (0{,}76 \div 1{,}14) km/s$ (see Table 1). In this case, an ice particle weighing 0.3 g has an energy

$$\varepsilon_k = m_0 \frac{V_0^2}{2} = (116 \div 174) J; \quad (14)$$

where $m_0 = 0{,}3g$- all particles from ice.

PND particle weighing 0.28 g at $V_0 = 0{,}9 km/s$ has energy

$\varepsilon_k = 116\ J$ (15)

According to the criterion of K.P. Stanyukovich [2], the specific crushing energy $\bar{\varepsilon}_k = 100\ J/g$ of the AMG-6 target material with respect to 1 g of aluminum at high-speed impact is

$\bar{\varepsilon}_k = 100 J/g$ (16)

Comparing (13) and (14) with condition (15), we note that at the above speeds of impact of particles from ice and HDPE in the material of a thin-walled (H $= 2mm$) aluminum target, fragmentation and spall fracture occur that are close in mechanical and thermodynamic parameters.

Table 2 Results of calculated and measured punch holes.

№ эксп.	Материал ударника	$d_{отв}^{расч}$, мм	$d_{отв}^{экс}$, мм
1385	ПНД	23,36	22x24
1101	ПНД	12,97	10,5
1102	Лед	12,98	7
1388	Кварцит	20,19	16,2x15,8
1376	A1	21,50	21,5

Measurement of the pressure $\Delta P_{акуст}$ at the fronts of acoustic waves in experiments with an electric discharge gun shows that at an impact velocity of about 1 km/s a particle made of reinforced ice and a particle of the same mass made of polyethylene at an impact velocity of ~ 0.9 km/s, the value of $\Delta P_{акуст}$ is practically the same , so at a distance R = 1.2 m from the breakdown point $\Delta P_{акуст}$ ~ 350Pa in both cases.

At impact velocities ~ 6 km/s (experiment with a light gas gun) at a distance R= 1.2 m from the impact point, a pressure $\Delta P_{акуст} \sim 1{,}7 \cdot 10^5$ Pa was recorded.

Hence it follows that the particle impact velocity significantly affects the intensity of the acoustic wave in the pressurized compartment of the spacecraft, and in the case of particle impacts from HDPE and ice, the difference in pressure values at the front of the acoustic wave is insignificant. If the mass of the impactor particle increases by a factor of 4, which corresponds to a twofold expansion of the contact area of the particle with the barrier, then the pressure value at the acoustic wave front at the corresponding point in the pressurized compartment atmosphere also increases by a factor of two.

At the same time, based on the analysis of the results of a series of numerical calculations of the parameters of a high-speed collision of two bodies, it should be noted that if the particle density is less than the barrier density, i.e. $\rho_{10} < \rho_{20}$, then the mass velocity of the particle $\dot{u}_{1нач}$ has a value greater than the mass velocity of the obstacle $\dot{u}_{2нач}$ ($\dot{u}_{1нач} > \dot{u}_{2нач}$), which is in accordance with the results of the above experiments.

Further, comparing the results of experiments obtained for the cases $\rho_{10} < \rho_{20}$ and $\rho_{10} = \rho_{20}$ using an AMg-6 barrier, we note that in the first case, an acoustic wave of higher intensity arises in the SC pressurized compartment at a distance of R= 1.2 m. This is due to the fact that a basalt particle is heavier than an aluminum particle and, at the same impact velocities V_0, it has a relatively larger amount of motion $m_{сф}V_0$ and, accordingly, a large kinetic energy $m_{сф}{V_0}^2/2$, where $m_{сф}$ is the mass of the particle.

To estimate the parameters of the acoustic wave in the atmosphere of the pressurized compartment, the following calculation scheme is proposed below.

Preliminarily, it is necessary to determine all parameters of the breakdown in the collision of a particle with a flat barrier, i.e., parameters of the medium behind the front of a high-intensity plane compression wave, taking into account thermal processes and various materials of the particle at the moment of barrier breakdown. These shock-wave and thermodynamic parameters of the medium behind the front of a plane compression wave upon impact with a particle of space debris serve as the initial data for determining the initial values of pressure and other thermodynamic parameters of the air shock wave (ASW) propagating in the atmosphere of the spacecraft pressurized compartment.

The wave pattern of this problem is schematically represented as:

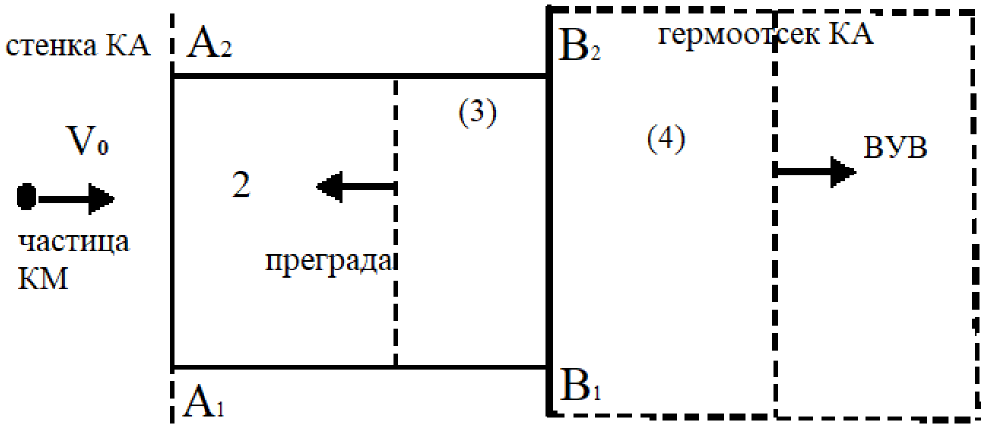

Fig. 2

To determine the ASW parameters in region (4), it is necessary to solve the contact problem for regions (3) and (4) with known values of the wave parameters in region (2) in the spacecraft wall material (see Fig. 2), which were previously determined in the previous research.

If we denote the parameters of the media in regions (3) and (4) by indices 3 and 4, then to determine them from equations (9) - (14) when replacing indices 1 and 2, respectively, with indices 3 and 4, we have a similar system of equations.

In this case, at the contact B_1B_2 of two media (see Fig. 2), the following boundary conditions take place

$$P_3^* = P_4^* = P_{0s}^*,$$

$$\dot{u}_3^* + \dot{u}_4^* = \dot{u}_2^*, \quad (17)$$

where $\dot{u}_2^*$ is the known mass velocity of the obstacle in the region (2), P_{0s}^* is the contact pressure on the line B_1B_2.

In contrast to equations (10), which are valid for the spacecraft wall material, in the area (4) for pressure $P_4(\varepsilon, T)$ and energy $E_4(\varepsilon, T)$ in the pressurized compartment atmosphere, we use the following formulas [3]:

$$P_4{}^*(\varepsilon, T) = P_{04}(\frac{\rho_4}{\rho_{04}})^\gamma = P_{04}(\frac{1}{1-\varepsilon_4})^\gamma, E_4{}^*(\varepsilon, T) = c_v T, \quad (18)$$

where $\varepsilon_4 = 1 - \frac{\rho_{04}}{\rho_4}$, $P_{04} \approx 1\ atm, \gamma = c_p/c_v$ - adiabatic constant, c_v - heat capacity of air.

Taking into account that the above air coefficients γ and c_v weakly depend on temperature [3, 7], in the future, when carrying out numerical calculations on a PC, we consider them to be constant and temperature-independent values.

Subsequently, using the previously calculated initial values of pressure, mass velocity, temperature, and velocity of the shock wave of air in the pressurized compartment near the breakdown section of the spacecraft wall, all the above parameters of the ASW in the atmosphere of the pressurized spacecraft depending on the distance r are determined. For this, the model of a point explosion by L.I. Sedov [5].

In the future, the results of these theoretical calculations within the framework of solving this acoustic problem, i.e. far from the place of breakdown of the spacecraft wall are compared with the experimental measurement data.

Analysis of the results of calculations based on formulas (9)-(18), taking into account the initial parameters of experiments given in tables 2 and 3, shows that at particle impact velocities $V_0 = (5{,}75; 6{,}12)$ km/s, shock-wave and thermodynamic the parameters of the barrier and the air in the pressurized compartment near the breakdown zone have the values given in tables 4 and 5.

Table 4

V_0, km/s	$P_{3П}$, kg/sm^2	P_{3T}, kg/sm^2	$P_3 = P_{3П} + P_{3T}$, kg/sm^2	$E_{3П}$, kJ/kg	E_{3T}, kJ/kg	$E_3 = E_{3П} + E_{3T}$, kJ/kg	$\dot{u}_3, m/s$	$\dot{R}_3, m/s$	T_3, K
5,75	$447 \cdot 10^3$	$18{,}77 \cdot 10^3$	$466 \cdot 10^3$	3602	531	4134	2875	5897	1155
6,12	$482 \cdot 10^3$	$24{,}1 \cdot 10^3$	$506 \cdot 10^3$	4031	650	4680	3060	5969	1412

Table 5

V_0, km/s	$P_4^{в}$, kg/sm^2	E_4^{B}, kJ/kg	$\dot{u}_4, m/s$	$\dot{R}_4, m/s$
5,75	$109 \cdot 10^3$	4130	2874	2980
6,12	$124 \cdot 10^3$	4679	3059	3160

Therefore, from the calculation results of Table 4, we note that at $V_0 = (5{,}75; 6{,}12)$ for the pressure and energy components of the material - barriers, the inequalities $P_{3T} \ll P_{3П}$ (within 5%) and $E_{3T} < E_{3П}$ (within 20 %). This means that in this case, in the problem of a collision of two bodies with a breakdown of an obstacle, the shock-wave parameters play a decisive role and, according to the energy criterion of K.P. Stanyukovich [3], the target materials and particles are in a molten-liquid state, because the melting temperature of aluminum under normal conditions is T_m=933°K [8].

In addition, the results of calculations according to the formula of L.I. Sedov [5], taking into account Table 5, show that the air pressure in the containment compartment of the spacecraft drops rapidly with increasing distance r from the barrier breakdown site, and at a distance $r \geq 21{,}2$ m, the shock wave in the air degenerates into an acoustic wave. In this case, the calculated values of acoustic pressure with an accuracy of (10-20) % are in satisfactory agreement with the data of experimental measurements (see Fig. 1).

The mass of the knocked-out part of the wall $m_{вэ}$ was calculated from the experimental value of the diameter of the breakdown hole $d_{отв}^{эксп}$, from the system of equations (1)-(3) m_{cr}, the velocity V_{cr} and the internal energy E_{cr} of the bunch were determined.

Analyzing these results, it should be noted that the main share of the energy ~ (70-90) % of the initial kinetic energy of the particle E_1 is the kinetic energy of the cloud of dispersed particles E_{cr} formed during breakdown (without taking into account the thermal component of the energy of the cloud E_{Tcr}).

If we take into account E_{Tcr} of the cloud, then, based on the analysis of the calculation results, it is shown that 8.57% of the kinetic energy of the particle is spent on the thermal component of the internal energy of the barrier wall breakdown, and 81.43% of the particle energy is spent on the shock-wave process of destruction of the materials of the particle and the barrier during breakdown with the formation of a mixture cloud.

Summarizing the above, we note that when an aluminum particle collides with an AMg-6 barrier, the destruction of the particle and the target material occurs at impact velocities $V_0 = (1{,}8 - 2)$ km/s, and at $V_0 = (5 - 8)$ km/s the materials of the particle and the obstacle are in a liquid-melted state and the inequalities $P_T \ll P_П$ and $E_T <$

$E_П$ take place, where P_T, E_T are thermal and $P_П$, $E_П$ are shock-wave (potential, i.e. cold) components of pressure P and internal energy E.

Conclusion

1. Analysis of the calculated and measured sizes of punch holes (table 2) shows that the results of calculations and experiments are in satisfactory agreement within 10-20%.

2. As a result of the breakdown of the spacecraft wall by the high-speed “impactor”, partial evaporation of the colliding materials occurs and the impact products are carried out through the punch hole in the pressurized compartment, as a result of which a strong shock wave arises in the atmosphere of the pressurized compartment, which, as it moves away from the point of breakdown, degenerates into a sound wave.

3. As a result of an impact without breakdown, an acoustic wave arises due to the momentum transfer of the moving wall of the spacecraft in the atmosphere of the pressurized compartment (“drum” effect) [9].

4. Thus, in the work, complex experimental and computational studies of the shock-wave and thermodynamic parameters of the collision of a particle with the wall of the pressurized compartment of the spacecraft were carried out depending on the physical and mechanical characteristics of the impactor material and the impact velocity, the values of the thermal and kinetic energy of the impact products and their ratio were estimated, The maximum values of pressure near the target during the breakdown (impact) of the SC containment wall and in the containment far from the location of breakdown were calculated, and the calculation results were compared with experimental measurement data.

5. The results of the above experimental and theoretical studies can be useful for predicting the breakdown parameters and the propagation of shock-wave effects in the pressurized compartment of the spacecraft and for optimizing the parameters of the breakdown simulator in the MCS measuring complex in order to determine the coordinates of the spacecraft wall breakdown site.

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