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Abstract. The article presents the results of the development of methodology for the calculation of non-stationary gas dynamics processes occurring in gas dynamic paths of rocket engines and environment at the launch of rockets. The method takes into account the change of geometry of solid fuel combustion surface during the operation of the engine and the change in the geometry of the computational domain taking into account the dynamics of rocket launch. Numerical simulation of gas-dynamic processes of the launch of model solid-fuel rocket was done. The unsteady gas-dynamic flow pattern was investigated. The pressure curve in the solid propellant rocket engine combustion chamber, the speed of movement and overload were determined.

1. Introduction

Investigation of the processes of aerogasdynamics at rocket launch and the development of calculation methods are among of current interest. This complex scientific and technical problems arising in the process of development, creation and operation of rocket complexes [1]. A number of problems that arise in the development of advanced launch boosters with solid rocket engine are caused by the non-stationary force effect of combustion products on the design elements of the rocket (combustion chamber housing, nozzle block, external rocket housing, and gas rudders) and the launch platform. This impact is largely determined by the rocket gas dynamic schemes, which are characterized by a significant variety of shapes, dimensions and functional features. Non-stationary gas dynamic processes characteristic of the period when solid rocket engine reaches the nominal regime of work (ejection of a nozzle plug, the height of solid propellant charge, etc.) affect the dynamics of motion, an unsteady spatial gas dynamic picture of flow and, in the general case, determine the gas dynamic loads acting on structural elements of rocket engines and launch surface [2].

Carrying out physical modeling for these purposes is associated with high material costs, especially in terms of carrying out natural experiments at the initial design stage. Therefore, one of the approaches to solving indicated problems is to use the methods of mathematical modeling. This allows reducing the cost of design and the development time of solid propellant rocket motors by replacing a significant part of the experiments with mathematical modeling on computer using modern specialized high-performance software systems [3].

Recently, the work related to the interaction of jets with oblique obstacles passing along the jet has been gaining popularity. Thus, in [4], the results of mathematical modeling of the effect of a jet on an inclined surface at an angle of 45^0 for an inviscid gas are presented. The calculations were carried out within the framework of a nonstationary setting, but without taking into account the distance of the jet

source from the interaction surface. The work [5] presents the results of the interaction of the jet with the obstacle at different distances, as well as the angle of inclination of the obstacle. The calculation results were carried out in the absence of motion of the jet source. The work [6] is devoted to the effect of a jet on an inclined obstacle without movement of the jet source. Three-dimensional results of mathematical modeling are presented. Thus, the works where the change of the charge geometry and the process of vehicle movement are taken into account are not known to the authors.

This paper presents the results of the development of calculation method of unsteady gas dynamic processes in gas dynamic paths of the rocket and the outer regions during rocket launch including: combustion chamber with variable in the process the height of the filler geometry, nozzle unit, supersonic jet interacting with streamlined surface of rocket and launch surface.

2. Research methods

The paper considers the gas dynamics of the rocket launch in non-stationary operation modes of solid propellant rocket engines, taking into account the change in the combustion surface and the force interaction of supersonic jets of combustion products with the launch surface and rocket's elements. The operation of large solid propellant rocket motors is characterized by uneven burnout of the charge along the channel length. This leads, in the case of studying non-stationary processes, to take into account the change in the charge geometry.

It is taken into account that the rocket is under the influence of gas dynamic forces (thrust forces, aerodynamic drag) and gravity. The exhaust jet of combustion products interacts with the stationary launch surface and the moving elements of rocket.

The scheme of computation domain is shown in figure 1 and includes: 1 – outer rocket body; 2 – charge of solid propellant; 3 – gas dynamic path; 4 – charge burning surface of solid propellant; 5 – combustion chamber housing; 6 – nozzle unit; 7 – axis of symmetry; 8-9 – outer boundaries of computational domain; 10 – impervious start surface; 11 – environment.
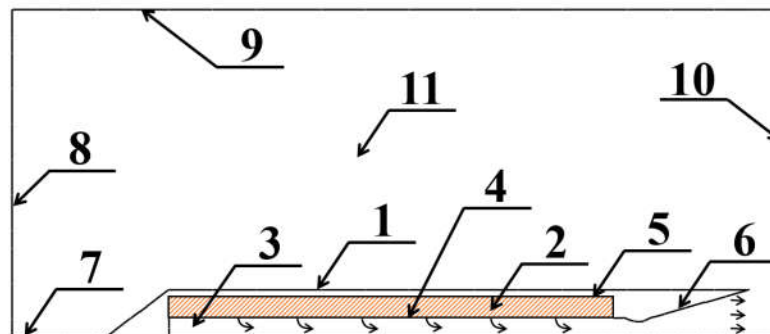

Figure 1. Scheme of computation domain.

2.1. Basic equation

It is assumed that, at the initial moment of time, the combustion front spread over the entire surface of the solid propellant charge. Combustion products are non-viscous compressible ideal gas. The unsteady system of Euler equations describing the spatial flows of an ideal gas has the form [7]:

$$\frac{d}{dt}\left(\iiint_{G} \rho \, dG\right) + \oint_{S} \rho \mathbf{v} \cdot d\mathbf{S} = 0; \tag{1}$$

$$\frac{d}{dt}\left(\iiint_{G} \rho \mathbf{v} \, dG\right) + \oint_{S} \left(\rho \mathbf{v}\mathbf{v} + p\hat{\mathbf{I}}\right) \cdot d\mathbf{S} = 0; \tag{2}$$

$$\frac{d}{dt}\left(\iiint\limits_{G} e\,dG\right) + \oint\limits_{S}(e+p)\mathbf{v}\cdot d\mathbf{S} = 0, \tag{3}$$

where G – finite area in three-dimensional space; $dG = dx\,dy\,dz$ – volume element; S – surface bounding the region G; $d\mathbf{S} = \mathbf{n}\,dS$ – oriented surface element S; $\mathbf{n}$ – external normal to S, and dS – element of area; t – time; ρ – density; p – pressure; $\mathbf{v} = [u,v,w]^{\mathrm{T}}$ – velocity vector of gas flow; ε – specific internal energy, $e = \rho\varepsilon + \rho\left(u^2 + v^2 + w^2\right)/2$ – total energy per unit volume; $\hat{\mathbf{I}} = \mathrm{diag}\,[1,1,1]$ – unit tensor of dimension 3×3; $\mathbf{a}\cdot\mathbf{b}$ – scalar multiplication of two vectors.

System of equations (1)-(3) is closed by equation of state of an ideal gas:

$$\varepsilon = \frac{p}{(k-1)\rho} \tag{4}$$

2.2. Numerical approach

For numerical solution of equations (1)-(4) the Godunov's scheme is used, adapted to an arbitrary number of faces in the calculation cell. The finite volume method is used to construct difference scheme. The entire computational domain is covered by discrete cells consisting of arbitrary convex finite polyhedra with volumes G_i, where $i = 1, 2, \ldots$ – the number of such volume, and the number of faces $m = m(i)$. Each face has an area S_j, where $j = 1, 2, \ldots, m(i)$. Then the integral equations in each polytope G_i are approximated as follows:

$$G_i\frac{\rho_i^{k+1} - \rho_i^k}{\Delta t} + \sum_{j=1}^{m(i)} R_j\left(\mathbf{V}_j\cdot\mathbf{S}_j\right) = 0; \tag{5}$$

$$G_i\frac{(\rho\mathbf{v})_i^{k+1} - (\rho\mathbf{v})_i^k}{\Delta t} + \sum_{j=1}^{m(i)}\left(R_j\mathbf{V}_j\right)\left(\mathbf{V}_j\cdot\mathbf{S}_j\right) + \sum_{j=1}^{m(i)} P_j\mathbf{S}_j = 0; \tag{6}$$

$$G_i\frac{e_i^{k+1} - e_i^k}{\Delta t} + \sum_{j=1}^{m(i)}\left(E_j + P_j\right)\left(\mathbf{V}_j\cdot\mathbf{S}_j\right) = 0. \tag{7}$$

As a result, we obtain Godunov's scheme [8] for an arbitrary computational grid. Here $\mathbf{S}_j = \mathbf{n}_j S_j$, and Δt – time step. Lower whole index i denotes the values of functions assigned to the center of mass i polyhedrons, and the lower whole index j denotes the values assigned to the center j faces of a discrete cell. Upper whole index k indicates the time step number. Large value R, $\mathbf{V}$, P, E denote, respectively, density, velocity, pressure, and total energy on the faces of discrete grid cell. These values are determined from the solution of the Riemann problem [8] in the direction of the external normal. Other methods based on approximate solutions of the Riemann problem can be used to calculate flows: ROE, Osher, HLL, HLLC, HLLE, etc. Scheme (5)-(7) easily generalizes to two-dimensional and axisymmetric approximations.

For general case of movement spatial discrete cell, the following scheme is used [7]:

$$\frac{(\rho G)_i^{k+1} - (\rho G)_i^k}{\Delta t} + \sum_{j=1}^{m(i)} R_j\left([\mathbf{V} - \mathbf{D}]\cdot\mathbf{S}^{k+1/2}\right)_j = 0; \tag{8}$$

$$\frac{(\rho \mathbf{v} G)_i^{k+1} - (\rho \mathbf{v} G)_i^{k}}{\Delta t} + \sum_{j=1}^{m(i)} (R\mathbf{V})_j \left([\mathbf{V} - \mathbf{D}] \cdot \mathbf{S}^{k+1/2}\right)_j + \sum_{j=1}^{m(i)} P_j \mathbf{S}_j^{k+1/2} = 0;$$ (9)

$$\frac{(eG)_i^{k+1} - (eG)_i^{k}}{\Delta t} + \sum_{j=1}^{m(i)} E_j \left([\mathbf{V} - \mathbf{D}] \cdot \mathbf{S}^{k+1/2}\right)_j + \sum_{j=1}^{m(i)} P_j \mathbf{S}_j^{k+1/2} = 0;$$ (10)

$$\frac{G_i^{k+1} - G_i^{k}}{\Delta t} - \sum_{j=1}^{m(t)} \left(\mathbf{D} \cdot \mathbf{S}^{k+1/2}\right)_j = 0.$$ (11)

Here $\mathbf{D}_j$ – speed of center j faces of discrete cell. Half-integer superscripts $k+1/2$ denote the values of corresponding values at time $t+1/2\Delta t$. Equation (11) there is an equation for changing volume of discrete cell G_i. The calculations used Cartesian coordinate system associated with rocket. The change in position of the tops of calculated cells in the problem under consideration occurs due to the change in the surface of solid propellant charge during combustion and movement of the launch rocket to launch surface under the action of gas dynamic forces.

2.3. Solid fuel charge burnout simulation
To simulate the process of burnout of solid propellant charge, the technique [9] is used, based on approximation of the shape of charge channel by set of faces of unit cells located in the vicinity of the combustion surface. To determine the new position of combustion surface and local gas entry, the power law of combustion is used:

$$u_v = u_0 p_v^{v},$$ (12)

where u_v – local burning rate in the vicinity of moving edge apex at current time step; p_v – local pressure in vicinity of apex of movable face; u_0, v – burning rate constants.

The new position of the cell vertices on combustion surface is calculated as follows:

$$\mathbf{x}^{k+1} = \mathbf{x}^k + \mathbf{n}_x u_v \Delta t,$$ (13)

where $\mathbf{x}$ – coordinates of the vertex of the movable edge of cell; $\mathbf{n}_x$ – the unit vector of the internal normal to combustion surface at point $\mathbf{x}$.

Calculation of local gas flow m from the edge of computational cell lying on combustion surface can be carried out using the following relation:

$$m = \rho_f u_e S_e,$$ (14)

where u_e – local burning rate at center of face of computational cell; ρ_f – density of solid propellant; S_e – computational cell face area.

However, to fulfill the law of conservation of mass of combustion products coming from combustion surface, taking into account the change in cell volume, the following relation was used in the work:

$$m = \rho_f \Delta G^k / \Delta t,$$ (15)

where ΔG^k – change in cell volume at current time step.

The calculation algorithm taking into account the rebuilding of computational grid near the combustion surface at the current time step is constructed as follows:

1.   By the known value of the pressure in center of cell, the local pressure near the vertices of its movable face is determined.

2.   Using (12) the local combustion rate near the top of movable face is determined.

3.   The unit vector of the internal normal to combustion surface at the top of moving face is determined as: $\mathbf{n}_x = (\mathbf{n}_l + \mathbf{n}_r)/2$, where $\mathbf{n}_l$ and $\mathbf{n}_r$ – unit vectors of the outer normal of computational faces lying on the combustion surface and having common vertex x.

4.   Using (13) new coordinates of the vertices of movable faces of the cells are determined.

5.   For all movable cells, the geometric parameters are recalculated (cell volume and face area).

6.   Using (15) the local gas entry through the faces of the computational grid lying on the combustion surface is determined.

2.4. Modeling the movement of a launch vehicle

To determine the characteristics of carrier rocket movement, the following calculation algorithm is used:

1.   Based on the known distribution of gas dynamic parameters at the current time step, the resultant of gas-dynamic forces acting on the rocket surface is determined:

$$\mathbf{F} = \iint_s p\mathbf{n}dS \qquad (16)$$

where S – surface of internal and external elements of rocket, $\mathbf{n}$ – unit normal vector to an elementary area dS.

2.   The mass of the rocket at the current time step is calculated as: $m_{roc}^k = m_{roc}^{k-1} - m_f^k$, where m_{roc}^{k-1} – the mass of the rocket in the previous time step, m_f^k – mass of fuel burned at the current time step, equal to the total gas entry from the combustion surface.

3.   According to the known resultant of gas dynamic forces and gravity, the velocity and acceleration of the launch vehicle at the current time step is determined.

Taking into account the known parameters of the rocket movement, the computational grid near the launch surface is rebuilt using the following algorithm:

1.   Determine the unit vector of the internal normal to the launch surface at vertex of moving face.

2.   The new coordinates of the vertices of movable faces of cells are defined as: $\mathbf{x}^{k+1} = \mathbf{x}^k + \mathbf{n}_x u_{roc} \Delta t$, where u_{roc} – rocket speed at current time step.

3.   Verify is carried out to ensure that the specified limit on geometric characteristics of computational cell is achieved near the launch surface, upon reaching which cell is split into two.

4.   The geometric parameters of the moving cells are recalculated (the volume of cell and the area of faces), the speeds of movement of faces are determined.

Based on the described methodology a software package has been developed that allows calculating unsteady flows of combustion products in gas dynamic paths of rocket engine and environment.

2.5. Initial conditions and mesh description

The following characteristics of model rocket are taken into account in calculations: rocket length L_{roc}=20.5 m; the length of nozzle unit L_n=4.3 m; diameter of rocket – 3 m; radius of nozzle inlet section 0.6 m; the radius of nozzle throat R^*=0.5 m; the radius of nozzle exit R_a=1.5 m. A model cylindrical single-chamber charge of internal combustion of solid propellant is considered characteristic of launch booster. The length of solid propellant charge L_f=14.2 m; radius of internal surface of solid propellant charge R_f=0.6 m; the weight of booster (including charge of solid propellant) 187000 kg; density of solid propellant $\rho_f = 2200$ kg/m³; temperature of combustion products 3400 K; equilibrium adiabatic index of gaseous mixture of two-phase combustion products

1.16; constants in the law of burning rate of solid propellant: $u_0 = 0.006$ m/s, $v = 0.3$. The distance from the nozzle exit to launch surface at initial moment of time is 1 m.

As initial conditions in the computational domain 12 (figure 1) conditions of an undisturbed environment at the Earth's surface were accepted: $P_a = 101325$ Pa, $T_a = 300$ K. At the boundary 1, 5, 6 and 11 boundary conditions of non-flow were set; at the boundary 8 – the symmetry conditions; on the edges of cells lying on combustion surface (boundary 4) – local gas entry; at the boundary 9 – parameters of the incident flow of corresponding rocket velocity at current time step; at the boundary 10 – soft boundary conditions.

The calculations were carried out in an axisymmetric setting. The block-structured computational grid constructed using the algorithm given in [10] was used. At the initial time, the size of calculated grid in free volume of combustion chamber was 200×10 cells, in the nozzle unit – 60×20 cells.

The calculation was made up to the moment of time $t = 2.9$ s, which corresponds to the output of rocket to the nominal mode of operation and removal of it from the launch surface at distance equal to $4L$ booster. In a typical calculation, the total number of cells at time $t = 0$ s was 1×104, and at time t=2.9 s – 8×10^4.

3. Results and discussion

Numerical studies of the gas dynamics of launch of model axisymmetric solid propellant booster are carried out. In figure 2 the distribution of Mach numbers is shown at various moments of time. At a time $t = 0.02$ s the intermediate moment of the engine performance which is determined by a sharp change of combustion products movement in the gas dynamic path is shown. In figure 2(b) the flow is shown at the moment of time $t = 0.1$ s, corresponding to the beginning of the main section of the engine operation ($P = 45$ bar). On figure 2(c) it is shown the moment when the rocket motor reaches the values of the thrust force required for takeoff from surface ($P = 54$ MN). Figure 2 (d)-(f) illustrates the process of jet distribution while the rocket moves away from the starting surface. It can be seen that with the distance a complex gas-dynamic flow pattern formed in the jet. The Mach number is dynamically changed inside the jet with the Mach barrel formation. The jet structure is in good agreement with the results of [11] for a static computational domain.
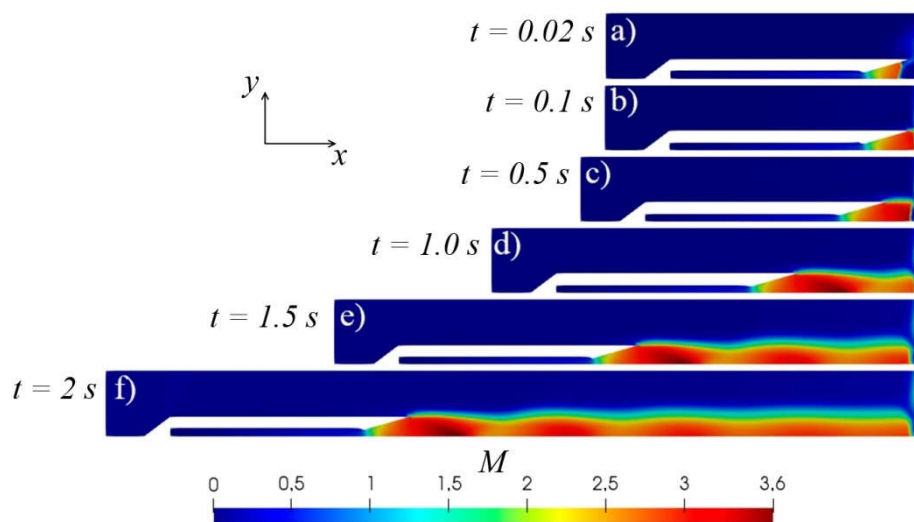

Figure 2. Distribution of Mach numbers at various moments of time.

The paper investigates the thrust characteristics of non-stationary operation mode of solid propellant rocket motor. In figure 3 the change in the x-components of thrust vector and pressure averaged over chamber volume are shown. At a time $t = 0.25$ s the engine goes to nominal mode. The

curves of pressure and thrust are progressive. This is due to the cylindrical shape of the propellant charge and the increase of the combustion surface area over time. Figure 4 shows the characteristics of the speed and acceleration of the rocket during launch as a function of time. The acceleration curve has similar dynamics to the pressure and thrust and at the end of solution is 2.5g. The speed of the rocket changes linearly and at $t = 2.9$ s reaches the value 21 m/s.
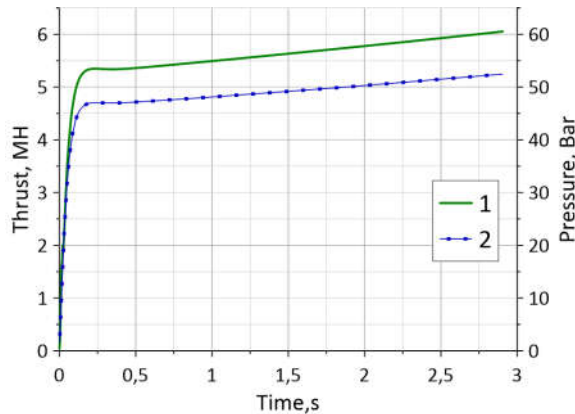

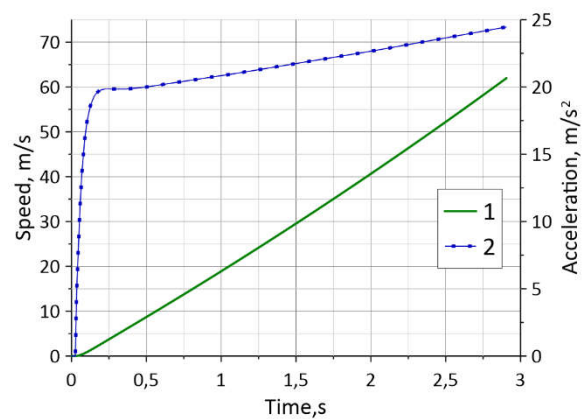**Figure 3.** Thrust (1) and pressure (2) in combustion chamber.

Figure 4. Speed (1) and acceleration (2) of the rocket.

4. Conclusion

The paper presents the results of numerical simulation of solid propellant rocket motor motion from the moment of start to reaching the nominal operating mode. The main gas-dynamic characteristics that determine the operation of solid propellant rocket motors are presented. The unsteady process of jet propagation and its interaction with the ground surface is shown.

The work is based on the methodology developed by the authors of the calculation of the rocket motor gas dynamics at the start and the thrust characteristics of solid propellant rocket motors in non-stationary operating modes. The presented methodology and calculation program make it possible to investigate the dynamic processes characteristic of the launch vehicle. The program is taking into account the change in the geometry of the combustion surface of the solid fuel charge during the launch and exit of the motor in the nominal operating mode and the changes in the geometry of the computational domain due to the movement of the vehicle within a single gas-dynamic calculation in the combustion chamber, nozzle block and exhausting jet.

The implemented method makes it possible to simulate rather complex designs of the launch vehicle, combustion chamber and configurations of solid propellant charges with a high filling factor. The method makes it possible to effectively evaluate the energy-thrust characteristics of various configurations of the solid propellant charge, which provide a given pressure curve over time, for subsequent use in prototypes.

Acknowledgments

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