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THE INFLUENCE OF THERMOSTATTING TEMPERATURE ON THE IGNITION AND DEFORMATION DYNAMICS OF A CYLINDRICAL CHARGE IN A NOZZLELESS PROPULSION DEVICE

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Abstract. This article presents the results of numerical simulation of the transition to steady-state operation of a nozzle less propulsion device (NPD) with a cylindrical viscoelastic solid propellant charge. The study was performed in a two-dimensional axisymmetric formulation, taking into account the coupled interaction of viscous compressible combustion products and a deformable charge. The viscoelastic behavior of the propellant is described using Prony series and the Williams-Landel-Ferry temperature-time shift function. It was found that an increase in the initial thermostating temperature of the charge reduces its ignition time and decreases the initial shear modulus, which leads to a more than twofold increase in surface movement. It is shown that low initial temperatures lead to a decrease in propellant chamber pressure, while an increase in temperature by 115 °C increases the maximum pressure by 25 atm. The convergence of the numerical solution on three computational grids is assessed.

Keywords: nozzle less propulsion device, viscoelastic charge, ignition of the charge, coupled simulation.

1. Introduction

Nozzle less propulsion devices (NPD) are of considerable interest for use in the launch stages of integral rocket-ramjet systems due to their high reliability, structural simplicity, no need for detachable nozzle equipment, and reduced requirements for thermal protection [1–3]. Based on a simplified physical mathematical model proposed in [4] for analyzing the intra chamber processes of the NPD, the following was established. The outlet cylindrical shape section results in 14% momentum loss compared to classical propulsion device. At the same time, the formation of a conical outlet charge channel section can contribute to an increase in the efficiency of the NPD, on condition that the reduction in the active combustion surface area remains relatively small. The observed deformation of the solid propellant charge due to significant pressure differences in the channel during the initial section of the NPD operation creates a risk of instability in the functioning of the propulsion device due to the mutual influence of deformation and gas-dynamic processes. To ensure a reliable assessment of the design's performance, it is crucial to conduct coupled modeling of gas dynamics and stress-strain state.

The viscoelastic properties of modern mixed solid propellant (the time dependence of the shear and elastic modules) significantly influence the assessment of the stress-strain state of the charge. In [5], a modeling of

the dynamic response of the SP charge to the initial load from the pressure increase was carried out using a quasi-static elastic analysis; taking into account the viscoelastic properties of the HTPB (transient analysis).

It was found that the first method gives overestimated response values relative to the second. An analysis of a solid propellant charge viscoelastic behavior of an NPD under the action of a gas-dynamic load during the initial period of its operation under various thermostating conditions charge, assuming that the channel surface ignites instantly, was conducted in [6]. It was shown that an increase in the charge thermostating temperature of the solid propellant leads to a decrease in the maximum pressure in the NPD combustion chamber due to an increase in the cross-sectional area of the channel.

In the work [7-9] an analysis was carried out of the two-pulse solid rocket engine starting operation. The study is based on the joint solution of: a system of three-dimensional non-stationary equations for a viscous heat-conducting gas; a system of equations of the mechanics of deformable solids; the heat transport equation – for calculating the propellant surface temperature. It is shown that for a 0.9 m charge in length and a channel diameter of 0.08 m, in case of rigid fixation of the nozzle block, with an increase in pressure from 0.1 MPa to 23.6 MPa, the amplitude of longitudinal oscillations of the charge surface can reach 10 mm, and lateral – 3 mm. In the paper [10], a viscoelastic structural analysis was performed to evaluate the influence of the insert properties on the distribution of stresses and strains along the insert/fuel interface in a solid-propellant propulsion device. The analysis was conducted based on a simplified two-dimensional axisymmetric model using the Ansys software package. The results showed that during the initial period of engine operation, under the influence of a load caused by an increase in pressure, the stresses along the interface increase with an increase in the initial modulus of elasticity and decrease with an increase in its Poisson's ratio.

The aim of this work is to study the influence of thermostating conditions on the cylindrical viscoelastic charge of a solid propellant behavior under the action of a gas-dynamic load in NPD during the period when the engine reaches a steady-state operating mode, taking into account the gradual ignition of the solid propellant charge surface.

2. Physical statement of the problem

Figure 1 shows a cutout of a model nozzleless engine. The engine consists of a cylindrical solid propellant charge 1 attached to the engine body 2, an igniter 3, and a combustion chamber 4, which is initially closed by a plug 5. The left end surface and the cylindrical surface 6 of the charge are the surfaces capable of combustion. The right end surface 7 is armored. Combustion products entering from the combustion surface flow out through the boundary 8 after the plug is opened.

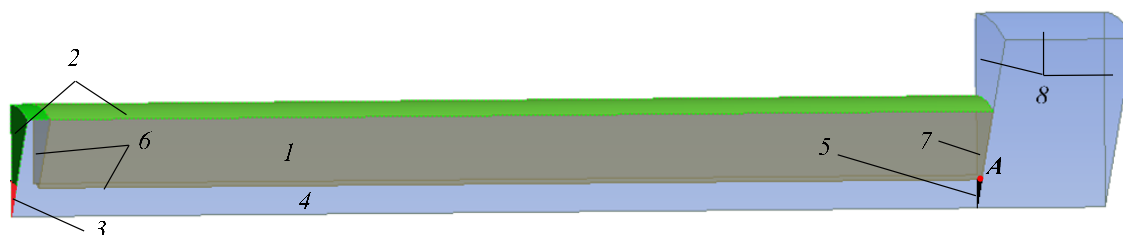


Fig.1. Sectional view of a model nozzleless engine: 1 – SP charge, 2 – housing, 3 – igniter device, 4 – combustion chamber, 5 – plug, 6 – combustion surface, 7 – inert surface, 8 – outlet boundary; A – control point

It is assumed that, at the initial moment, igniter 3 is triggered, the combustion products of which enter the combustion chamber filled with air and heat the surface of the charge 6 through convective, conductive, and radiant heat exchange. The igniter operates for a time t_{ig} , ensuring a mass flow equal to G_{ig} . After the charge surface temperature reaches the ignition temperature, mass and energy begin to flow from the combustion surface into the combustion chamber. After the pressure on the plug surface exceeds the breakdown pressure p_d , combustion products flow out of the combustion chamber.

The combustion products are assumed to be a three-component viscous compressible gas, with unsteady flow. The solid propellant charge is taken to be a visco-hyperelastic body, which is deformed under the action of the gas-dynamic load arising from the combustion products, altering the combustion surface. This, in turn, causes a change in the combustion chamber pressure, leading to a change in the charge's stress-strain state.

3. System of equations for the stress-strain state of a charge

To describe the effects of hyperelasticity, the Neo-Hooke model is used, and to describe the effects of viscoelasticity, the generalized Maxwell model is used, in which the relaxation modules of elasticity are approximated by Prony series [11].

Mass conservation equation

$$\frac{d\rho_s}{dt} + \rho_s \nabla_k V_{s,k} = 0, \quad (1)$$

Equation of motion for particle

$$\rho_s \frac{d^2 u_{s,i}}{dt^2} = \nabla_k \sigma_{s,ki}, \quad (2)$$

where $u_{s,i}$ – the movement of a particle in the medium; $V_{s,i} = \frac{du_{s,i}}{dt}$ – the velocity of the movement of the particles in the medium.

Finite strain tensor

$$\varepsilon_{s,ij} = \frac{1}{2} \nabla_i u_{s,j} + \nabla_j u_{s,i} + \nabla_i u_{s,k} \nabla_j u_{s,k}, \quad (3)$$

The relationship between stresses and strains for a visco-hyperelastic body is:

$$\sigma_{s,ij} = 2 \int_0^t G(t-\tau) \frac{d}{d\tau} \left(\frac{1}{J} F_{ik} \cdot \frac{\partial w_D(\bar{I}_1)}{\partial C_{kl}} \cdot F_{lj}^T \right) d\tau + \delta_{ij} \int_0^t K(t-\tau) \frac{d}{d\tau} \left(\frac{\partial w_V(J)}{\partial J} \right) d\tau, \quad (4)$$

$$w_D(\bar{I}_1) = \frac{\bar{I}_1 - 3}{2}, \quad (5)$$

$$w_V(J) = (J - 1)^2, \quad (6)$$

where $G(t)$ – is the relaxation shear modulus; $K(t)$ – is the relaxation volume modulus, $\bar{I}_1 = I_1/J^{2/3}$; $I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$; $\lambda_1^2, \lambda_2^2, \lambda_3^2$ – eigenvalues of matrices $C_{ij} = F_{ki} F_{kj}$, $F_{ij} = \partial x_i / \partial X_j$ – are the components of the strain gradient tensor, $J = \det(F_{ij})$.

The dependence of relaxation modules on time is approximated by Prony series [11]:

$$G(t) = G_0 g(t), \quad K(t) = \frac{2(1+\nu)}{3(1-2\nu)} G_0 g(t) \quad (7)$$

$$g(t) = \alpha_0 + \sum_{i=1}^n \alpha_i \exp\left(-\frac{t}{a(T)\tau_i}\right), \quad (8)$$

where α_i and τ_i – are the coefficients of the Prony series; $a(T)$ – is the temperature-time shift function; G_0 – is the initial shear modulus; ν – is the Poisson's ratio, $g(t)$ – is the relative relaxation modulus.

The temperature-time shift function $a(T)$ according to the Williams-Landel-Ferry model [12] has the form:

$$\log a(T) = \frac{a_1(T - T_0)}{a_2 + T - T_0}, \quad (9)$$

4. System of equations for the viscous compressible gas flow

To describe the flow of combustion products in the combustion chamber, the Navier-Stokes equations for a multi-component compressible heat-conducting gas are used.

Continuity equation

$$\frac{\partial \rho_g}{\partial t} + \frac{\partial \rho_g V_{g,k}}{\partial x_k} = S_p, \quad (10)$$

Mass conservation equation of ignition gas

$$\frac{\partial \rho_g \xi_{ig}}{\partial t} + \frac{\partial \rho_g \xi_{ig} V_{g,k}}{\partial x_k} = \frac{\partial}{\partial x_k} \left(\rho_g D_{ig} \frac{\partial \xi_{ig}}{\partial x_k} \right), \quad (11)$$

Mass conservation equation of propellant gas

$$\frac{\partial \rho_g \xi_{pr}}{\partial t} + \frac{\partial \rho_g \xi_{pr} V_{g,k}}{\partial x_k} = \frac{\partial}{\partial x_k} \left(\rho_g D_{pr} \frac{\partial \xi_{pr}}{\partial x_k} \right) + S_p, \quad (12)$$

Mass fractions conservation equation

$$\xi_{ig} + \xi_{pr} + \xi_{air} = 1, \quad (13)$$

Momentum equation

$$\frac{\partial \rho_g V_{g,i}}{\partial t} + \frac{\partial \rho_g V_{g,i} V_{g,k}}{\partial x_k} = - \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{g,ik}}{\partial x_k}, \quad (14)$$

Energy conservation equation

$$\frac{\partial \rho_g e_g}{\partial t} + \frac{\partial \rho_g V_{g,k} h_g}{\partial x_k} = \frac{\partial}{\partial x_k} \left(\lambda_g \frac{\partial T_g}{\partial x_k} + \tau_{g,ik} V_{g,i} \right) + a \int_0^{4\pi} I(r_i, s_i) d\Omega - 4a\sigma T_g^k + S_E, \quad (15)$$

Radiative intensity transfer equation

$$\frac{\partial I(r_i, s_i) s_k}{\partial x_k} + (a + \sigma_s) I(r_i, s_i) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(r_i, s_i) d\Omega, \quad (16)$$

where $e_g = \frac{1}{k-1} \frac{p}{\rho_g} + \frac{V_g^2}{2}$ – the total internal energy of the gas; $h_g = e_g + \frac{p}{\rho_g}$ – the total enthalpy of the gas;

$V_g^2 = \sum_{k=1}^3 V_{g,k}^2$ – the square of the velocity vector; $\tau_{g,ik}$ – the viscous stress tensor, $\mu_g \left(\frac{\partial V_{g,i}}{\partial x_k} + \frac{\partial V_{g,k}}{\partial x_i} - \frac{2}{3} \delta_{ik} \frac{\partial V_{g,j}}{\partial x_j} \right)$; t – time; x – the spatial coordinate; p – the pressure; V – the velocity; k – the specific heat ratio at constant pressure to the specific heat capacity at constant volume for a gas mixture; ξ_{ig} – ignition gas mass fraction, is the mass fraction of the fuel gas, ξ_{air} – the mass fraction of air, a – the radiation absorption coefficient, σ – the Stefan-Boltzmann constant, $5.67 \cdot 10^{-8} \text{W}/(\text{m}^2 \text{K}^4)$, σ_s – the scattering coefficient, n – the refractive index, s_i – the components of the radiation direction vector, r_i – the components of the position vector, Ω – the solid angle, S_p , S_E – the specific mass gain and energy gain due to propellant combustion, respectively.

Equation of state

$$p = \rho_g T_g \sum_{j=1}^3 \xi_j R_j, \quad (17)$$

where $R_j = R_y / M_j$, R_y – the universal gas constant; M_j – the molar mass of the j th component.

In this formulation of the problem, the burning surface is replaced by a solid wall, and the mass gain and energy gain of gases is modeled through source terms in the continuity equation (10), in the propellant gas mass conservation equation (12), and in the energy conservation equation (15) [13]: $S_p = \rho_T u_{01} p^{v_1} \delta(x_k; R_k)$, $S_E = c_{p,pr} T_p S_p$, where R_k – the function describing the combustion surface; $c_{p,pr}$ – the specific heat capacity of the propellant gas at constant pressure, ρ_T – the fuel density. $u_{01} = u_0 \exp(\beta T_{g,0})$ – the fuel combustion rate at 1 atm [14], u_0 – the pre-exponential factor, β – the coefficient of sensitivity of the combustion rate to the initial temperature $T_{g,0}$, $v_1 = v_{ref} + k_v(T_{g,0} - T_{ref})$ – the exponent in the combustion rate law, k_v – the temperature coefficient, v_{ref} , T_{ref} – the reference values of the exponent and the initial temperature, T_p – the propellant combustion temperature, $\delta(x_k; R_k)$ – Dirac delta function.

4. Boundary conditions

For a solid body: plane of symmetry: $u_{s,nn} = 0$ – equality to zero of normal displacements; condition of fixing: $u_{s,i} = 0$ – displacements in all directions are equal to zero.

For gas: non-deformable solid wall: $V_{g,k} = 0$; igniter: $\rho_g V_{g,n} = G_{ig} \eta t_{ig} - t$, $T = T_{ig}$, $\xi_{ig} = 1$, $\xi_{pr} = 0$ where ηt – Heaviside function; deformable solid wall, propellant: $\rho_g V_{g,n} = G_{ig} \eta t_{ig} - t$, $T = T_{ig}$, $\xi_{ig} = 1$, $\xi_{pr} = 0$; channel outlet: $p = p_n$ – at subsonic flow the pressure is equal to the environmental pressure; plane of symmetry: $V_{g,n} = 0$, $\frac{\partial \phi}{\partial n} = 0$, $\phi = \rho_g, \xi_{ig}, \xi_{pr}, V_{g,\tau_1}, V_{g,\tau_2}, p$. The interface between the surface of a solid and a gas:

$\sigma_{s,nn} = -p + \tau_{g,nn}$ – equality of normal stresses in propellant and gas; $\sigma_{s,n\tau_1} = \tau_{g,n\tau_1}$, $\sigma_{s,n\tau_2} = \tau_{g,n\tau_2}$ – equality of shear stresses in propellant and gas; $V_{s,i} = V_{g,i}$ – equality of the movement speeds of propellant and gas particles. $I = \frac{1}{\pi} \left[n^2 \varepsilon_w \sigma T_w^4 - (1 - \varepsilon_w) \int_0^{4\pi} I \cdot s_n d\Omega \right]$, where ε_w – wall emissivity.

The propellant surface temperature is determined from the solution of an ordinary differential equation obtained by the method of integral relations using an approximation of the temperature profile inside the propellant by a third-order parabola [15]

$$\frac{dT_w}{dt} = \frac{4}{3} \frac{q_w^2}{\lambda_T \rho_T c_T} \frac{(T_g - T_w)}{(T_w - T_{wn})(2T_g - T_w - T_{wn})}, \quad (18)$$

with the initial condition: $T_w|_{t=0} = T_{wn}$, where q_w – the heat flow from the gas to the propellant surface, λ_T – the propellant thermal conductivity coefficient, c_T – the propellant specific heat capacity coefficient

5. Numerical technique

The computational domain is a sector of a cylindrical domain, fig. 1, in which the angle between the section planes drawn along the axis is 10° . For the numerical solution of the system equations (1)–(9) describing the stress-strain state of the charge, the finite element method with linear shape functions for eight-point hexagonal elements was used. The numerical solution of the system equations describing the flow of

combustion products (10)–(17) was performed using the Patankar method on a grid with hexagonal cells using an implicit upwind scheme of second-order accuracy in spatial variables for the convective terms of the equations and first-order accuracy in time. The implementation of these methods was carried out in the Ansys computing package in the Workbench environment using the Transient Structural and Fluent modules, respectively, data exchange between them was carried out using the System Coupling module. At each time step, 20 iterations were performed solving the system of hydrodynamic equations. At each stage of load-displacement coupling, 5 iterations were performed. The time step size was chosen to be 10^{-5} s, and the end time was 0.1 s. The ordinary differential equation (18) was solved using Euler's method.

6. The discussion of the results

For the numerical solution of the problem, the following parameter values were adopted. The charge length is 125 cm, web thickness is 7 cm, the charge channel radius is 4 cm, the gap width between the left ends of the combustion chamber and the charge is 1 cm, the width and height of the areas to the right of the charge are 19 cm and 21 cm, respectively. The thermophysical parameters of the combustion products are given in Table 1, the characteristics of the solid propellant are given in Table 2, the Prony series coefficients for the model propellant at a temperature of 20°C are given in Table 3 [16], the initial shear modules depending on temperature and Poisson's ratio are given in Table 4, the coefficients of the temperature-time shift function are given in Table 5 [17].

Table 1. Thermophysical properties.

Properties	Air	Gas from solid propellant	Gas from the ignition device
Specific heat, J/(kg·K)	1006	1900	800
Molar weight, kg/kmol	29	24	55
Dynamic viscosity, Pa·c	$1.79 \cdot 10^{-5}$	$8 \cdot 10^{-5}$	$4 \cdot 10^{-5}$
Thermal conductivity, W/(m·K)	0.0242	0.25	0.1

Table 2. Solid propellant properties.

Pre-exponential factor, u_0 , mm/s	2.309	Combustion temperature, K	2900
Sensitivity coefficient, β , K ⁻¹	$2.972 \cdot 10^{-3}$	Propellant density, kg/m ³	1700
Temperature coefficient, k_T , K ⁻¹	$-1.5 \cdot 10^{-4}$	Thermal conductivity, W/(m·K)	0.6
Reference indicator, v_{ref}	0.41	Specific heat capacity, J/(kg·K)	1400
Reference initial temperature, T_{ref} , K	343	Ignition temperature, K	600

Table 3. Prony series coefficients for propellant.

i	α_i	τ_i , C
0	0.0486666	
1	0.0114570	$5 \cdot 10^{-6}$
2	0.0055763	$5 \cdot 10^{-5}$
3	0.2436390	$1 \cdot 10^{-4}$
4	0.2486060	$2.5 \cdot 10^{-4}$
5	0.1022000	$5 \cdot 10^{-4}$
6	0.1285610	$1 \cdot 10^{-3}$
7	0.0833416	$2.5 \cdot 10^{-3}$
8	0.0551554	$5 \cdot 10^{-3}$
9	0.0537361	$1.5 \cdot 10^{-2}$
10	0.0190610	$5 \cdot 10^{-2}$

Table 4. Initial values of the shear modulus and Poisson's ratio.

T , °C	G_0 , MPa	ν
-45	90	0.4999
20	50	
70	30	

Table 5. Coefficients of the function $a(T)$, equation (9).

a_1 , [-]	-5.4
a_2 , K	770.27
T_0 , K	293

The absorption coefficient of gas mixture radiation was taken to be 80 m^{-1} [18]. As estimates show [6], by the time of 0.1 s the relative shear modulus reaches its lowest value of ~ 0.0487 , (equation (8)), which is practically independent of the propellant temperature in the range from -45°C to $+70^\circ\text{C}$. Therefore, further calculations were carried out up to the specified time.

Figure 2 shows the effect of the initial temperature on the ignition front propagation across the charge surface. Increasing the initial temperature leads to a decrease in the ignition time of the charge surface, with

complete ignition of the end surface occurring much later than that of the cylindrical surface. The increase in the slope of the ignition curve for the end surface, fig. 2b, is due to the trapping of relatively cold gas at the dead end of the gap, resulting in an increase in the time it takes for the charge surface to warm up to ignition temperature. It should be noted that the thermal error in calculating the ignition time, which was due to the time step used in solving equation (18), amounted to approximately 3 ms.

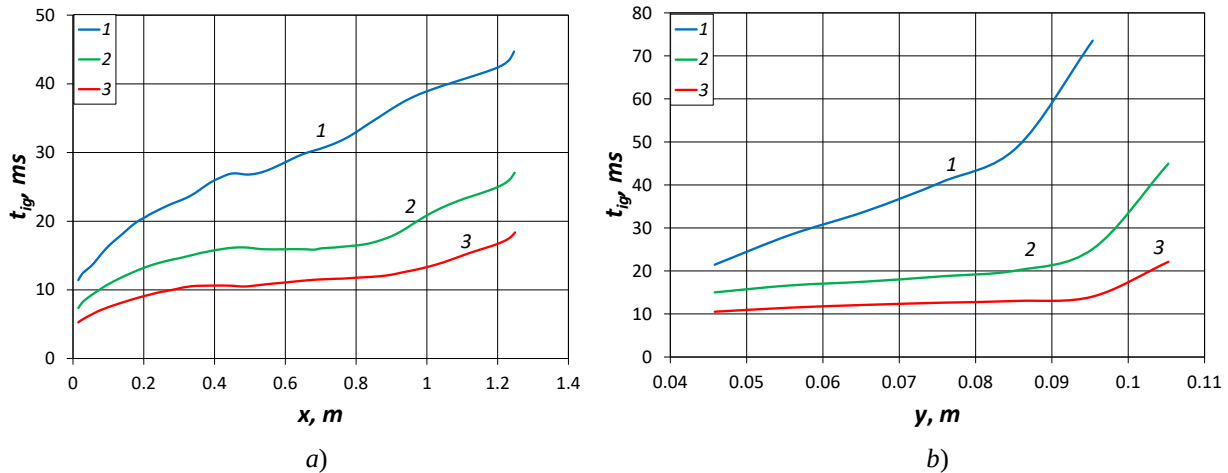


Fig.2. Dependence of surface ignition time on coordinate: *a* – cylindrical surface, *b* – end surface;
1 – $T_0 = -45^\circ\text{C}$, 2 – $T_0 = 20^\circ\text{C}$, 3 – $T_0 = 70^\circ\text{C}$.

Low initial shear modulus values, typical for propellants with high thermostating temperatures, lead to large displacements of the propellant surface, fig. 3. Reducing the shear modulus from 90 MPa to 30 MPa caused by high thermostating temperatures resulted in a more than twofold increase in the displacement of point A from the equilibrium position, both axially and radially. The non-monotonic behavior of the curves up to the 20–30 ms time point is due to the operation of the igniter and the failure of the plug, which lead to significantly non-stationary processes in the combustion chamber.

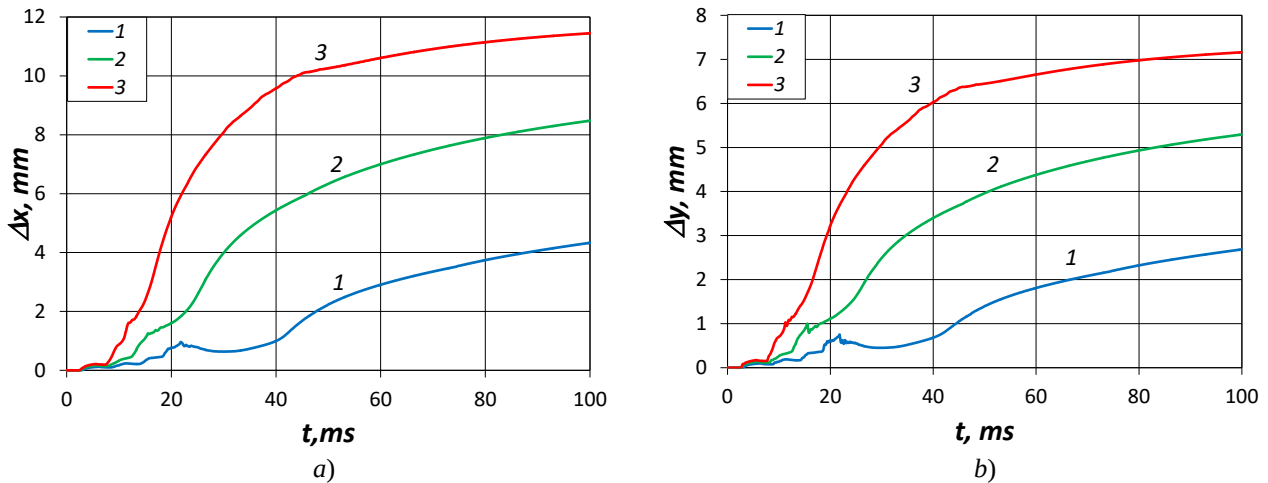


Fig.3. Dependence of the control point movement on time: *a* – longitudinal coordinate, *b* – radial coordinate;
1 – $T_0 = -45^\circ\text{C}$, 2 – $T_0 = 20^\circ\text{C}$, 3 – $T_0 = 70^\circ\text{C}$.

Low initial charge temperatures lead to low pressures in the combustion chamber. Increasing the initial temperature by 115 degrees increases the maximum pressure by 25 atm, which is associated with an increase in the propellant combustion rate with increasing initial temperature. The dependence of the combustion rate on the initial temperature has a greater influence on the increase in pressure in the combustion chamber than the dependence of the elastic modulus on the initial temperature, when lower values of the elastic modulus lead to an increase in the cross-sectional area of the channel and a subsequent decrease in pressure [6].

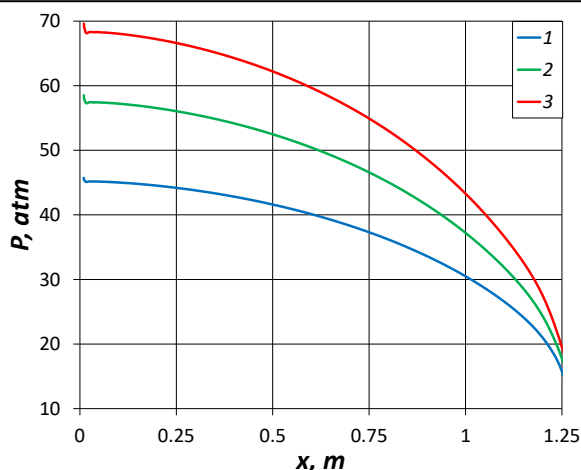


Fig.4. Pressure distribution on the combustion surface at the time of 0.1 s:
 1 – $T_0 = -45^\circ\text{C}$, 2 – $T_0 = 20^\circ\text{C}$, 3 – $T_0 = 70^\circ\text{C}$.

To study the convergence of the numerical solution, calculations were performed on three meshes, the parameters of which are given in Table 6. The number of elements and cells in the rotational direction was equal to 1, which corresponds to an axisymmetric approximation. The calculations were performed with a time step of 10^{-5} s.

Table 6. Mesh parameters for convergence study.

Mesh name	Cell size along the x-axis and y-axis, mm	Number of cells in the gas region	Number of elements in the charge region
Mesh №1	10	1074	875
Mesh №2	5	4296	3500
Mesh №3	2.5	17184	14000

Convergence of the numerical solution is verified using the L_2 norm $\|\vec{x}\| = \sqrt{\frac{1}{n} \sum_{i=1}^n x_i^2}$. The convergence condition requires satisfying the inequality

$$\|\vec{u}_{h/2} - \vec{u}_{h/4}\| < \|\vec{u}_h - \vec{u}_{h/2}\|, \quad (19)$$

where $\vec{u}_h$ is the numerical solution vector obtained on the mesh 1 with step size h , $\vec{u}_{h/2}$ is that on the mesh 2, and $\vec{u}_{h/4}$ is that on the mesh 3. Table 7 presents the norms of the differences between solutions obtained on successive meshes for the pressure distribution along the channel axis at $t = 100$ ms, the dependence of the cylindrical surface ignition time on the longitudinal coordinate, and the radial displacement of point A over time. As the table shows, the convergence condition (19) is satisfied for all key parameters.

Table 7. Norms of the differences between numerical solutions on successive grids

$\vec{u}_h$	$\ \vec{u}_h - \vec{u}_{h/2}\ $	$\ \vec{u}_{h/2} - \vec{u}_{h/4}\ $
P , atm	0.705	0.297
t_{ign} , ms	4.185	2.365
Δy , mm	0.319	0.197

The pressure distribution along the charge combustion surface at a time of 100 ms is shown in fig. 5. Curve 1 corresponds to mesh №1, curve 2 – mesh №2, and curve 3 – mesh №3.

Fig. 6 shows the effect of the computational mesh on the dependence of the ignition time of a cylindrical charge surface on the longitudinal coordinate for propellant with an initial shear modulus of 70 MPa ($T_0 = 20^\circ\text{C}$).

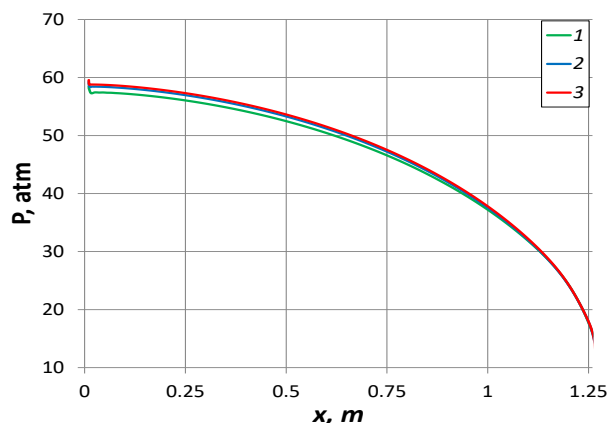


Fig.5. The effect of the mesh on the pressure distribution along the channel axis:

1 – mesh №1, 2 – №2, 3 – №3; $T_0 = 20^\circ\text{C}$.

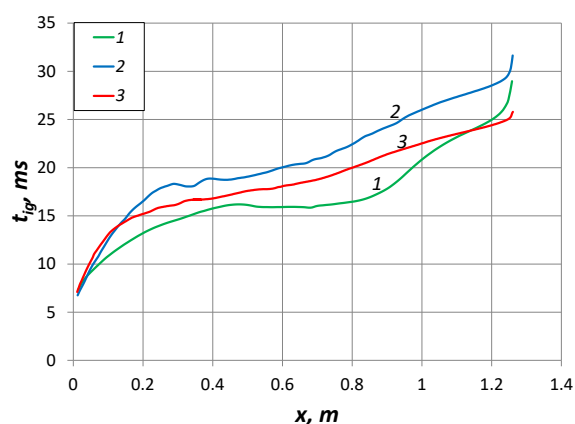


Fig.6. The effect of the mesh on the dependence of the ignition time on the longitudinal coordinate:

1 – mesh №1, 2 – №2, 3 – №3; $T_0 = 20^\circ\text{C}$

7. Conclusions

The conducted study demonstrates the critical dependence of the dynamics of the NPD reaching a steady-state mode on the initial temperature of charge thermostating. Increasing the temperature accelerates surface ignition but significantly reduces the propellant's shear modulus, which causes deformations (axial and radial) to more than double. This creates a risk of engine instability due to changes in the channel geometry. The two competitive effects determine combustion chamber pressure: an increase in the combustion rate as the propellant heats up (increasing pressure) and an increase in the flow area due to material softening (decreasing pressure). Practical NPD design requires considering not only the gas dynamics but also the viscoelastic properties of the propellant over a wide temperature range (from -45°C to $+70^\circ\text{C}$). The obtained results can be used to optimize operating conditions and improve the reliability of nozzleless propulsion devices.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRedit author statement

Minkov L.L.: Conceptualization, Methodology; ; **A.Gimayeva N.R.:** Investigation, Data Curation, Writing Original Draft. The final manuscript was read and approved by all authors.

Statement on the use of Artificial Intelligence.

The authors declare that no artificial intelligence tools were used to generate scientific content, results, or conclusions of this article.

Data Availability Statement

The data are available upon reasonable request from the authors.

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