Numerical modelling of combustion and electrization processes in a solid-fueled ramjet afterburning chamber

Yagodnikov D.A., Sukhov A.V., Bernikov V.V., Papyrin P.V. Bauman Moscow State Technical University

This work was supported by the Ministry of Science and Higher Education of the Russian Federation
(project No. 0705-2020-0044)

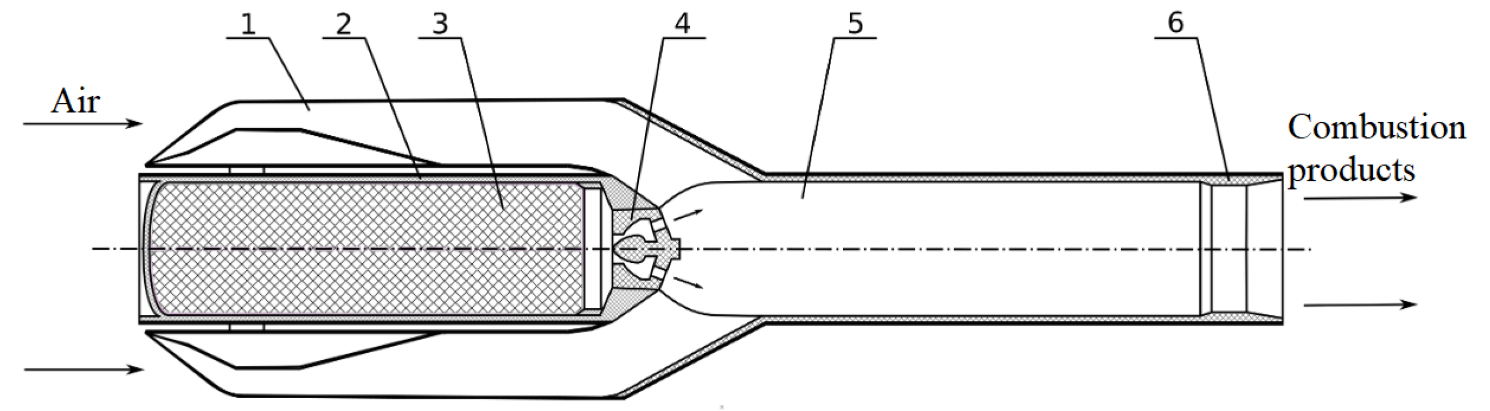


Figure 1 - Model ramjet
1 – air intake; 2 – gas generator; 3 - solid fuel; 4 – variable area nozzle of gas generator; 5 – afterburning chamber; 6 – main nozzle

The presence of chemically reacting condensed phase particles, along with the processes of high-enthalpy flows mixing, leads to a complex nature of gas-dynamic and electrophysical processes in the ramjet chamber, which consist in the formation of positive and negative ions, as well as the dispersed phase particles electrization

Basic equations of the mathematical model

The movement of the gas phase is described by the three-dimensional system of Navier-Stokes equations :

$$\frac{\partial}{\partial t}\int_{\Omega}\vec{W}d\Omega+\frac{\partial}{\partial t}\oint_{\partial\Omega}\left(\vec{F}_c-\vec{F}_V\right)dS=\int_{\Omega}\vec{Q}d\Omega$$

$$\vec{W}=\begin{bmatrix}\rho\\ \rho\cdot u\\ \rho\cdot v\\ \rho\cdot w\\ \rho\cdot E\\ \rho\cdot Y_1\\ \vdots\\ \rho\cdot Y_{N-1}\end{bmatrix};\quad \vec{F}_c=\begin{bmatrix}\rho\cdot V_n\\ \rho\cdot u\cdot V_n+n_x\cdot p\\ \rho\cdot v\cdot V_n+n_y\cdot p\\ \rho\cdot w\cdot V_n+n_z\cdot p\\ \rho\cdot H\cdot V_n\\ \rho\cdot Y_1\cdot V_n\\ \vdots\\ \rho\cdot Y_{N-1}\cdot V_n\end{bmatrix};\quad \vec{F}_V=\begin{bmatrix}0\\ n_x\cdot\tau_{xx}+n_y\cdot\tau_{xy}+n_z\cdot\tau_{xz}\\ n_x\cdot\tau_{yx}+n_y\cdot\tau_{yy}+n_z\cdot\tau_{yz}\\ n_x\cdot\tau_{zx}+n_y\cdot\tau_{zy}+n_z\cdot\tau_{zz}\\ n_x\cdot\Theta_x+n_y\cdot\Theta_y+n_z\cdot\Theta_z\\ n_x\cdot\Phi_{x,1}+n_y\cdot\Phi_{y,1}+n_z\cdot\Phi_{z,1}\\ \vdots\\ n_x\cdot\Phi_{x,N-1}+n_y\cdot\Phi_{y,N-1}+n_z\cdot\Phi_{z,N-1}\end{bmatrix};\quad \vec{Q}=\begin{bmatrix}Q_{p1}\\ \vdots\\ Q_{pN}\end{bmatrix}$$

Basic equations of the particle ignition and combustion

particle ignition stage

$$\frac{dr_{\text{к}}}{dt}=a_{Al}\cdot\frac{\nu\cdot\rho_{air}}{\rho_{Al}}\cdot K\cdot n_{O_2}\cdot e^{-\frac{E_1}{R_\mu\cdot T_p}}+a_B\cdot\left(1{,}44\cdot10^{-11}\cdot T_p^2\cdot n_{O_2}\cdot\frac{\rho_{air}}{\rho_B\cdot\delta_p}\cdot e^{-\frac{E_2}{R_\mu\cdot T_p}}\right)\quad(1)$$

$$\frac{d\delta_{Al_2O_3}}{dt}=K\cdot\frac{\rho_{air}.n_{O_2}}{\rho_{Al_2O_3}\cdot\beta}\cdot\delta_{Al}\cdot a_{Al}\cdot e^{-\frac{E_1}{R_\mu\cdot T_p}}\quad(2)$$

$$\frac{d\delta_{B_2O_3}}{dt}=\frac{1}{\rho_{B_2O_3}}a_B\left[4{,}636\cdot10^{-11}T_p^2n_{O_2}\frac{\rho_{air}}{\delta_p}e^{-\frac{E_2}{R_\mu\cdot T_{\text{к}}}}-I_{B_2O_3}^v\left(1+\frac{\delta_{B_2O_3}}{r_p}\right)^2\right]\quad(3)$$

$$\frac{dT_p}{dt}=\left(\rho_p\frac{dr_p}{dt}\Delta H_{AlB_2}+Q_\lambda+Q_R-Q_v\right)\frac{3}{c_{p\_p}\cdot r_p\cdot\rho_p}\quad(4)$$

When one of the conditions is met: $T_p > 2400$ K or $\delta_{B_2O_3} < 1$ nm, the calculation is performed for the **particles combustion stage**

$$\frac{dr_p}{dt}=a_{Al}\cdot\frac{n_{O_2}\cdot T_{ign}^{0,2}}{69\cdot10^3\cdot r_p^{0,5}}+a_B\cdot0{,}676\cdot\left(I_{B_2O_2}+I_{BO}\right)\cdot n_{O_2}\cdot\frac{\rho_{air}}{\rho_B}\quad(5)$$

$$\frac{dT_p}{dt}=\left(\rho_p\frac{dr_p}{dt}\Delta H_{AlB_2}+Q_\lambda+Q_R\right)\frac{3}{c_{p\_p}\cdot r_p\cdot\rho_p}\quad(6)$$

Interaction of condensed and gas phases

Source terms for the gas phase:
Mass conservation equations:

$$Q_\rho=\dot{N}\cdot\left(\Delta m_{B_2O_3}+\Delta m_{Al_2O_3}-\Delta m_{O_2}\right);\ Q_{O_2}=-\dot{N}\cdot\Delta m_{\ O_2},$$

$$\dot{N}=\frac{m_p}{m_{p0}}.$$

Momentum conservation equations:

$$Q_{\rho u}=-\dot{N}\cdot\left(m_{p1}\cdot u_{p1}-m_{p0}\cdot u_{p0}\right)$$

$$Q_{\rho v}=-\dot{N}\cdot\left(m_{p1}\cdot v_{p1}-m_{p0}\cdot v_{p0}\right)$$

$$Q_{\rho w}=-\dot{N}\cdot\left(m_{p1}\cdot w_{p1}-m_{p0}\cdot w_{p0}\right)$$

Energy conservation equation:

$$Q_{\rho E}=N\cdot\left(\Delta H-\alpha\cdot\left(T-T_p\right)\cdot F_p\right)$$

Modeling of dispersed phase evolution in the flow path of the ramjet (taking into account electrification)

The equation of motion for a single particle:

$$m_p\frac{d\overrightarrow{v_p}}{dt}=\sum_{j=1}^{N_F}\overrightarrow{F_j},$$

m_p – particle mass; $\overrightarrow{v_p}$ – particle velocity vector;
$\sum\overrightarrow{F_j}$ – the sum of the forces affecting on a particle

Aerodynamic force affecting on a particle:

$$F_{aer,i}=\frac{C_xF_{pm}|v_i-v_{p,i}|(v_i-v_{p,i})}{2},$$

C_x – drag coefficient;
F_{pm} – particle cross-section area;
v_i – gas velocity; $v_{p,i}$ – particle velocity;

Variation in particle charge depending on time:

$$\frac{dZ_p}{dt}=\sum_{j=1}^{N_I}I_j$$

Z_p – atomic number of a particle;
I_j – flow of charged particles absorbed or emitted by a particle

Fluxes of ions and electrons on the particle surface:

$$I_i=4\pi r^2\left[n_i\mu_i\frac{d\phi}{dr}+D_i\frac{dn_i}{dr}\right],\ I_e=-4\pi r^2\left[n_e\mu_e\frac{d\phi}{dr}-D_e\frac{dn_e}{dr}\right],$$

ϕ – electric potential in the surroundings of a particle;
$\mu_{i(e)}$ and $D_{i(e)}$ – mobility and diffusion coefficient of ions and electrons, respectively

Thermionic emission flux:

$$I_{th}=\frac{(4\pi rTk)^2m_ee}{h^3}\exp\left(-\frac{W}{kT}\right),$$

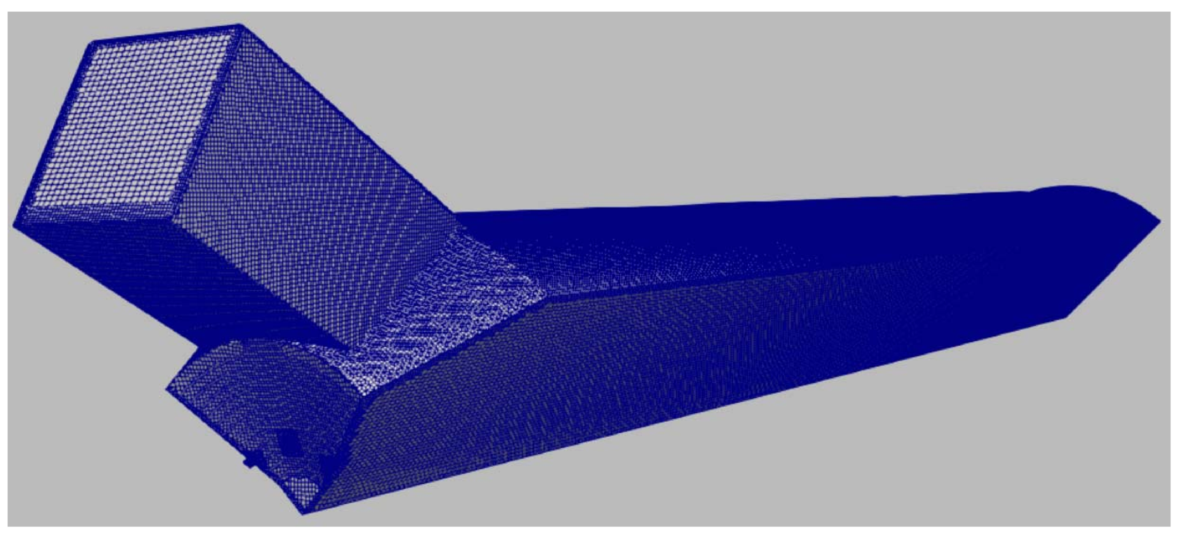
m_e – electron mass; h – Planck's constant
W – work function of an electron from a surface of a particle

Numerical calculations

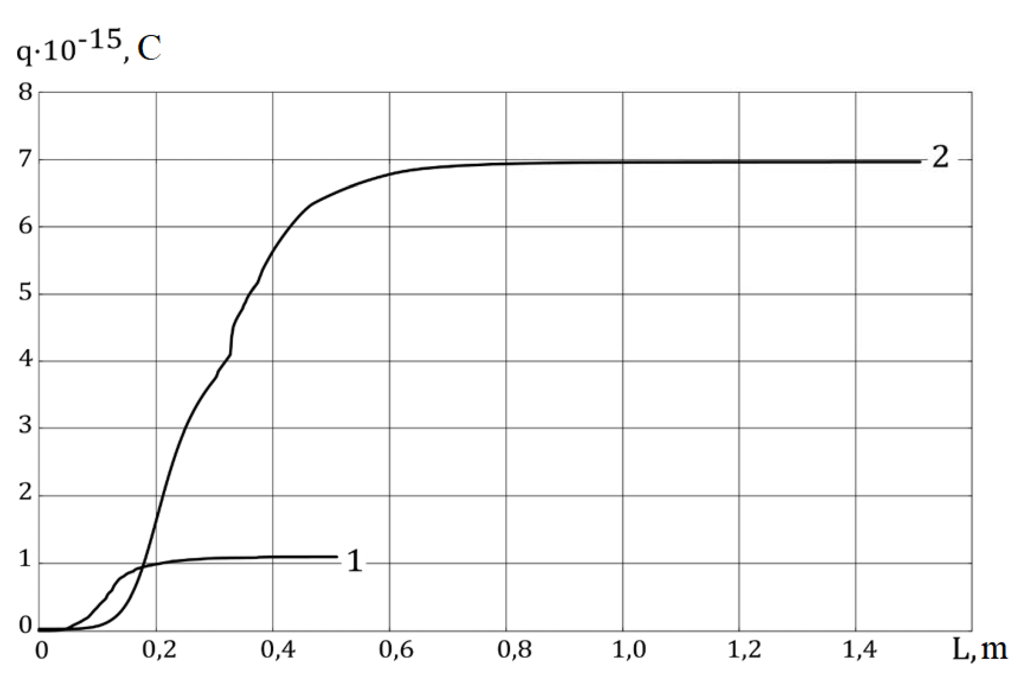
On the left boundary of the gas generator side, the generation products from two holes enter the computational domain with the mass flow rate of 0.06 kg / s and the equilibrium temperature of 1900 K, calculated by the ASTRA-4 software package for the fuel formula N2.273O9.029C16.246H32.967B48.104Cl2.127 (total enthalpy ΔH298.15 = -73.621 kJ / kg, pressure of 0.8 MPa)

From the air intake side, air is supplied with a mass flow rate of 2.35 kg / s and a total temperature of 700 K. The walls of the chamber were assumed to be adiabatic. On the planes of symmetry, assumpted the condition of impermeability and equality to zero of the gradients of the variables.

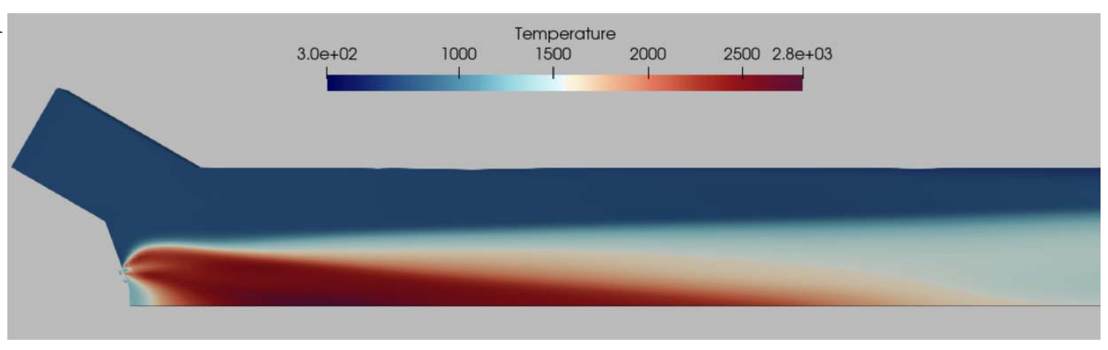
Typical dimensions of the model: diameter of the afterburner - 300 mm, length of the afterburner - 2500 mm, diameter of the cylindrical nozzle hole of the gas producer - 10 mm



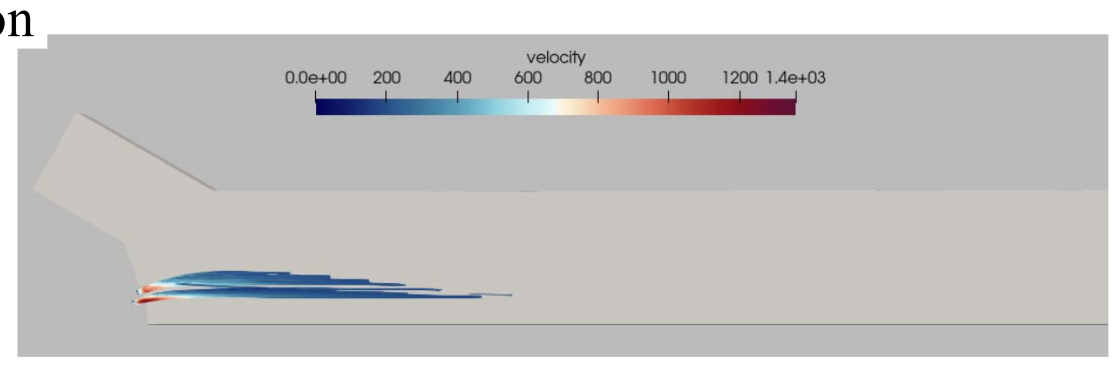
Mesh - 1/4 model ramjet by axis symmetry
(Number of cells ~1.5*10^6)



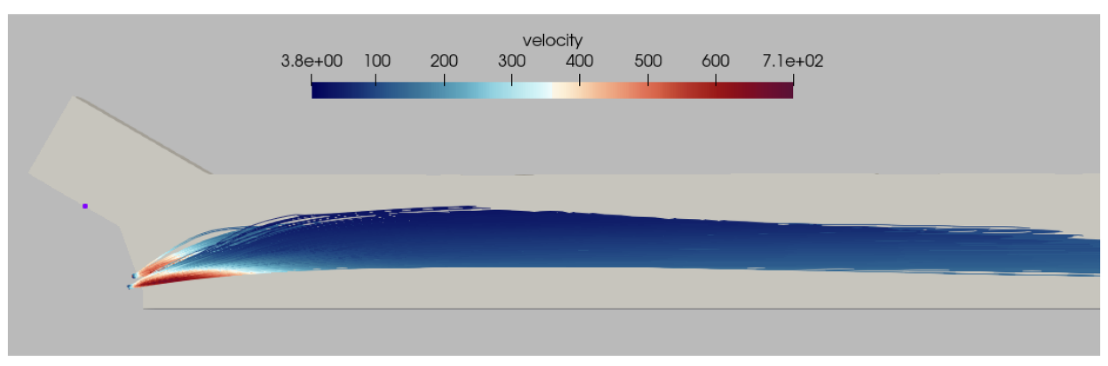
Change in the averaged charge of dispersed phase particles while moving in the flow path of the afterburning chamber: 1 - d = 2.311 μm, 2 - d = 11 μm



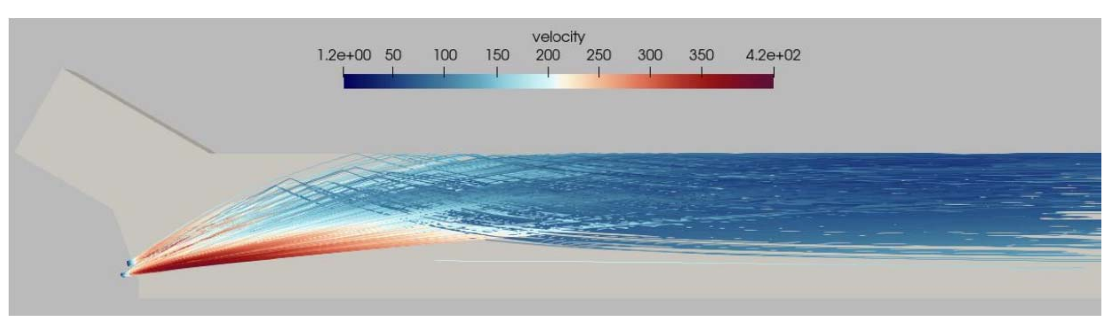
Temperature field of gaseous combustion products



Particle trajectories with a diameter of 2.311 μm



Particle trajectories with a diameter of 11 μm



Particle trajectories with a diameter of 31 μm