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MODELLING OF INTERNAL BALLISTICS PROCESSES IN SCRAMJET ENGINE DURING THE MOTION IN THE ATMOSPHERE

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Physical and mathematical model and results of modeling of the processes proceeding in the channel of a scramjet and in the surrounding atmosphere are presented for Mach numbers of 6.7–10. The mathematical model is based on the gas dynamics equations written in the two-dimensional approximation taking into account combustion of a gaseous fuel. Dependences of the total aerodynamic force projection onto the direction of scramjet motion on its speed and mass fuel supply rate are analyzed.

Keywords: scramjet, gas dynamic processes, gaseous fuel, combustion, total aerodynamic force, mathematical modeling.

Introduction

The application of scramjets is most optimal for motion in high layers of the atmosphere with high speeds and Mach numbers of incoming flow of 6–10 [1]. However, their development faces considerable technical difficulties caused by large thermal and dynamic loads on the scramjet body, unstable regimes of engine operation, and difficulties in fuel supply to achieve a high degree of fuel combustion in the supersonic air flow [2].

The schematic diagram of the scramjet model is shown in Fig. 1, and it was taken from [3]. The scramjet channel is converged at the inlet, has a constant cross section in its short part, and then is diverged at the rear part.

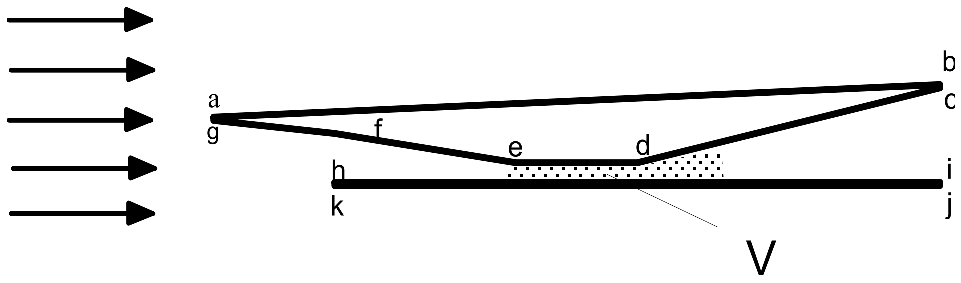

Fig. 1. Vertical cross section of the model scramjet

After the interaction of the incoming supersonic flow with the protrusive frontal part of the scramjet, an oblique shock wave is formed in air. A series of shock waves is formed inside of the scramjet channel. The temperature and pressure in the combustion region increase, and the flow diverges in the nozzle creating a thrust.

Problem formulation

The gas dynamics equations are used to model gas dynamics processes in the channel of the model scramjet and the incoming flow (Fig. 1). It is assumed that a proper amount of gaseous fuel ($G_{\Sigma H2}(kg/(s\cdot m))$) is injected into the volume V of the channel of width 1 m. The mass supply rate of the fuel is uniform throughout the volume. It is assumed that the times of fuel mixing and burning are much less than the time of air passage through the scramjet channel.

Taking into account the above assumptions, the system of gas dynamics equations in the 2D approximation has the form:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}=G_{H2} \tag{1}$$

$$\frac{\partial \rho u}{\partial t}+\frac{\partial\left(\rho u^2+p\right)}{\partial x}+\frac{\partial \rho u v}{\partial y}=0, \tag{2}$$

$$\frac{\partial \rho v}{\partial t}+\frac{\partial \rho u v}{\partial x}+\frac{\partial\left(\rho v^2+p\right)}{\partial y}=0, \tag{3}$$

$$\frac{\partial \rho E}{\partial t}+\frac{\partial\left(u \rho E+p u\right)}{\partial x}+\frac{\partial\left(v \rho E+p v\right)}{\partial y}=Q G_{H2}, \tag{4}$$

$$p=\rho R T, \quad E=e+u^2/2+v^2/2, \quad e=\frac{p}{\rho\left(k-1\right)}. \tag{5}$$

where x and y are coordinates, t is time, ρ is the gas density, u and v are components of the velocity vector, p is pressure, T is temperature, E is the total gas energy, e is the internal gas energy, G_{H2} is the mass supply rate of the fuel, Q is the specific heat of fuel combustion, k is the adiabatic exponent of air, and R is the gas constant. The system of equations consists of equations of continuity (1), motion (2) and (3), energy (4) and ideal gas (5).

The boundary conditions specified at the inlet to the calculation area have the incoming flow parameters:

$$p(0,y,t)=p_{at},\ \rho(0,y,t)=\rho_{at},\ u\left(0,y,t\right)=U_0,\ v\left(0,y,t\right)=0,\ 0\le y\le L_y .$$

At the rear of the calculation area, the boundary conditions for the supersonic air outflow are not assigned; for the subsonic air outflow, one boundary condition is assigned:

$$p(L_x,y,t)=p_{at},$$

where L_x is the length of the calculation area and L_y is its height. Here L_x and L_y values were chosen so that the boundary conditions from below ($y=0$) and from above ($y=L_y$) of the calculation area did not influence the parameters of the flow surrounding the scramjet, and conditions of non-flow were specified.

System of equations (1)–(5) was solved numerically by the S. K. Godunov method [3] on the grid adjusted to the scramjet contour; it was solved numerically till establishment of a stationary flow in the scramjet channel and in the surrounding space.

In calculations it was assumed that the scramjet moved at an altitude of 30 km above the Earth's surface. The parameters of the standard atmosphere (incoming flow) at this altitude were taken in accordance with GOST 4401-81: $p_{at}=1616\,Pa$, $\rho_{at}=0.0251\,kg/m^3$, the incoming flow velocity varied in the limits $U_0=2000\div3000\,m/s$ (the Mach numbers $M=6.67\div10$ for the incoming flow). Hydrogen was chosen as a fuel; its minimum specific heat of combustion was $Q=121.55\cdot10^6\ J/kg$, and the mass supply rate of the fuel was in the range $0.01\le G_{\Sigma H2}\le 0.0875\,кг/\left(с\cdot м\right)$.

Results and discussion

Results of calculations are shown in Figs. 2(a-d). Figure 2 shows the fields of the state parameters for air and combustion products in the scramjet channel. In the process of interaction of the incoming flow with the protruding inlet of the scramjet, the flow decelerated at its front part (*a–g*), and a normal shock wave was formed. Below it an oblique shock wave was formed which interacted with the oblique shock wave propagating from the *h–k* region of the lower flat part of the scramjet body.

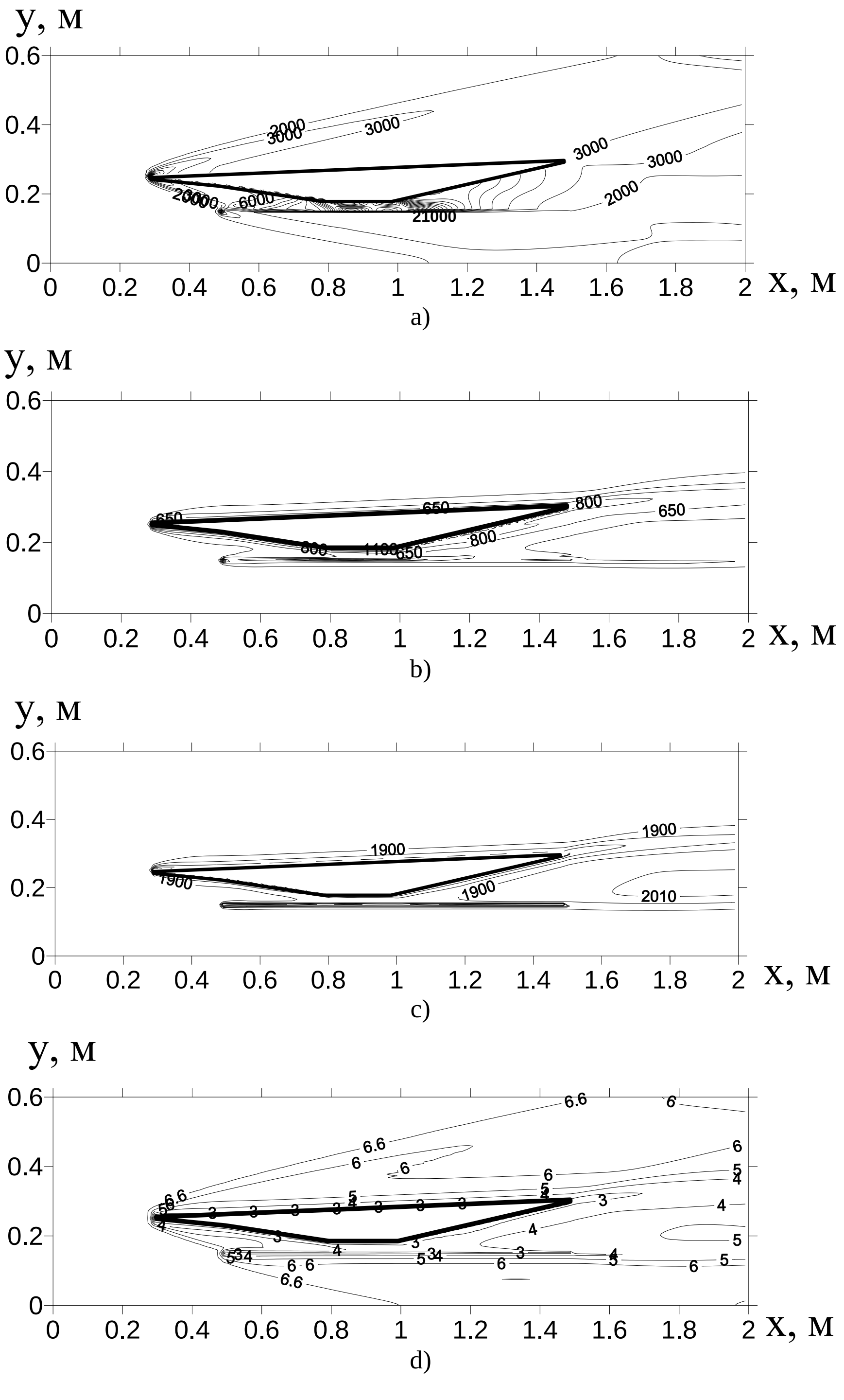

Fig. 2. Fields of pressure, in *pa* (a), temperature (*K*) (b), horizontal velocity(*m/s*)(c), and the Mach numbers (d) in the flow of air and combustion products in the scramjet channel. The incoming flow velocity was *U0 = 2000 m/s*, and the mass supply rate of the fuel (hydrogen) was *GΣH2 = 0.01 kg/(s·m)*.

Their interaction led to the formation of oblique shock waves in the air flow in the scramjet channel (Fig. 2a). As a result, the incoming supersonic flow decelerated in the converging part of the scramjet channel, remaining supersonic one.

A gaseous fuel (hydrogen) is injected into a part of the channel located between 0.8 and 1.2 m. In this region the temperature and pressure of the air flow increase. When the mixture of air with combustion products entered into the diverging part of the scramjet channel, it accelerated and produced excessive pressure on the walls of the diverging part of the scramjet channel thereby creating a positive scramjet thrust.

The following special features of the air flow in the scramjet channel should be noted. After air has passed through the shock wave at the scramjet inlet (regions *a–g* and *h–k* in Fig. 1), its temperature considerably increases. After shock compression, the high-temperature air passes along the channel surface and scramjet body and creates high temperature regions near its surfaces. If fuel is injected in these regions, the temperature increases after the fuel combustion, thereby leading to an increase in the heat flux toward the walls of the scramjet channel and their overheating. Therefore, the fuel is injected in the region V shown in Fig. 1 that is spaced at a certain distance from the walls of the scramjet body. When the fuel burns in the air flow, its temperature increases, and the Much number decreases. Therefore, the Much number at the nozzle output is smaller and the velocity of air motion at the output is somewhat greater than the incoming flow velocity (Figs. 2c and 2d).

The projection of the force onto the x axis of interaction of the air flow with the scramjet body (the projection of the total aerodynamic force) was calculated from the formula:

$$F = \int_{S_1} p_s dS_n + \int_{S_2} p_s dS_n \ ,$$

where *ps* is the pressure on the scramjet body walls, *dSn* is the projection of the element of the scramjet body surface area onto the plane perpendicular to the *x* axis, and *S1* and *S2* are the areas of the *a–b–c–d–e–f–g* and *h–i–j–k* surfaces of the scramjet body (Fig. 1) of width 1 m. The drug was not considered here.

Fig.3 shows the dependence of the projection F of the total aerodynamic force onto the x axis for the indicated mass supply rate of the fuel on the incoming flow velocity.

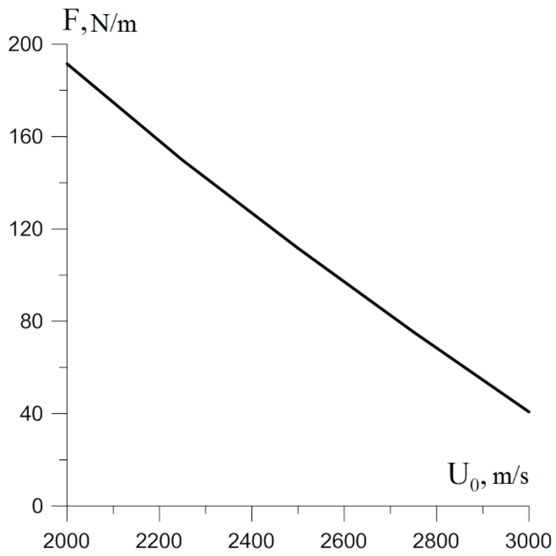

Fig. 3. Dependence of the projection of the total aerodynamic force onto the x axis on the velocity of the scramjet motion in the atmosphere for *GΣH2 = 0.01 kg/(s · m)*.

When fuel burns, the flow of air and combustion products has increased temperature and pressure at the output from the diverging part of the scramjet channel thereby creating a positive resultant force under the action of which the scramjet will be accelerated. The plot in Fig. 3 shows that when the incoming flow rate (the velocity of scramjet motion) increases the projection of the total aerodynamic force onto the *x* axis decreases. For a preset fuel supply rate, the scramjet is accelerated and moves uniformly with a velocity of ~3200 *m/s*.

Conclusion

Thus, based on the developed physical and mathematical model of gas dynamics processes arising in the process of scramjet motion in the atmosphere, calculations of the gas dynamics flow parameters for regions including the supersonic flow, scramjet channel and out of it were performed for scramjet motion with the velocities corresponding to the Mach numbers 6.7–10. The dependences of the total aerodynamic force projection onto the direction of scramjet motion on the velocity of its motion and the fuel mass flow rate were obtained. When the incoming flow rate (the velocity of scramjet motion) increases, the projection of the total aerodynamic force onto the x axis decreases. For a preset fuel supply rate, the scramjet is accelerated and moves uniformly with a velocity of ~3200 m/s.

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REFERENCES

1. Aleksandrov V. N., Bytskevich V. M., Verkholomov V. K. et al. *Integrated Scramjet Engines on Solid Fuels . Principles of Theory and Calculation.* (in Russian), Moscow , Akademkniga Publishing and Bookselling Center, 2006.
2. Baev V. K., Golovichev V. I., Tret'yakov P. K. et al. *Combustion in a Supersonic Flow* (in Russian). Novosibirsk, Nauka, 1984.
3. Fomin V.M., Gun'ko Ju.P., Majul' I.I. *Jet plane of the future*. Available at: http://www.paralay.com/rusgiper.html.
4. Godunov S. K., Zabrodin A. V., Ivanov M. Ya. Et al. *Numerical Solution of Multidimensional Gas Dynamics Problems* (in Russian), Moscow, Nauka, 1976.

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