EVALUATION OF THE RAMJET PROPULSION AT A ENERGY PULSE SUPPLY

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An attempt to model a working process of ramjet was made. A radiant energy in a pulse periodical regime is supplied in contrast to the classical scheme, where the energy in a combustion chamber is supplied continuously by fuel burning. To simulate this problem the Euler equations in the "channel" approximation for a plane case are solved numerically [1]:

$$\partial \boldsymbol{U}/\partial t + \partial \boldsymbol{F}/\partial x = \boldsymbol{Q},$$

$$\boldsymbol{U} = (\rho y,\ \rho u y,\ e y),\ \boldsymbol{F} = (\rho u y,\ (p+\rho u^2)y,\ u(p+e)y),\ \boldsymbol{Q} = (0,\ p\,\mathrm{d}y/\mathrm{d}x,\ 0).$$

Here the coordinate x is directed along the channel and referred to its width d at the inlet, $y = y(x)$ is a dimensionless channel width (referred to d); time t is referred to d/a_0, velocity of gas u and a velocity of sound a are to a_0, density ρ is to ρ_0; pressure p and a full energy of a gas volume unit e were non-dimensionalized using values $\rho_0 a_0^2$; p_0 and a_0 are dimensional pressure and velocity of sound in a flow at the channel inlet (the corresponding gas density is equal to $\gamma\rho_0$). For the considered gas model

$$p = (\gamma - 1)\cdot(e - \rho u^2/2), \quad a^2 = \gamma p/\rho .$$

At the inlet of the energy supply channel, the parameters of undisturbed flow are set, and at the channel outlet a linear extrapolation is used [1]. Every time, energy is supplied so quick, that change of the gas density and its velocity for the corresponding period of time can be neglected. To solve this problem the MacKormak method [2] with an artificial voscosity of the forth order of smallness was applied. The calculations were performed for the Mach numbers of the flow at the engine inlet from 2 up to 5. It was obtained a complex picture of shock waves system changing in time, rarefaction waves and contact discontinuities. The establishment conditions of the quasi-stationary regime of the flow in dependence on the Mach number, on the energy source power, on its size and position, and on the angle of the widened channel section had been investigated.

The shock waves, propagating streamwise and upstream are arisen at the energy supply in a single impulse. The rarefaction waves (after inter-reflection) follow after them that are catch up with the shock waves and weaken them. If the shock wave propagating upstream has no time to come out from the channel to this moment of time, it is drifted downstream, and the disturbance area leaves the channel. Such picture can be seen in Fig. 1, which shows the pressure distribution p on the channel of constant section $d = 1$ for two moments of time: curve 1 is for $t = 0.1$, curve 2 is for $t = 0.2$ (at the channel inlet pressure $p = 1$, gas density is $\rho = 1.4$, the Mach number M = 5, the energy is released in region x from 0.4 up to 0.42, an initial pressure increasing by $\Delta p = 100$ corresponds to it).

In a widening channel at the periodical energy supply, a periodical flow regime arising is possible. Figure 2 presents the Mach number distribution on the channel for three moments of time $t = 1$, $t = 1.05$ and $t = 10$, the curves 1, 2 and 3 accordingly (the channel widening began at x equal to 0.8 and was of 20 %, the energy was supplied at x from 0.8 up to 0.82, a period of the energy supply was $\Delta t = 0.2$; the other parameters are the same as in Fig. 1). Distributions at

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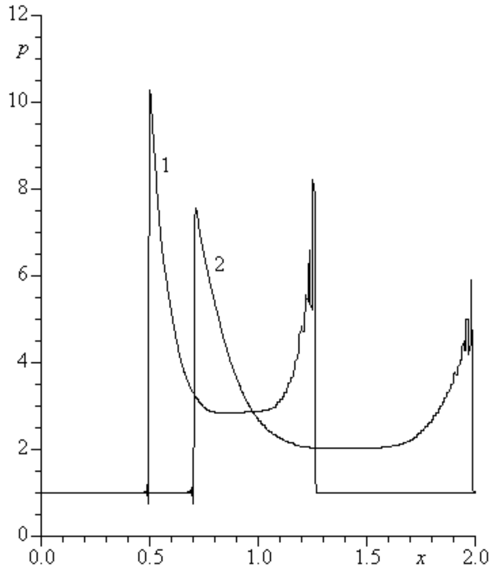


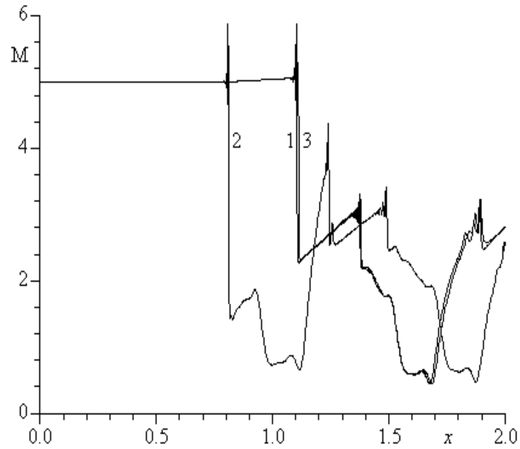


Fig. 2.

Fig. 1.

the moments of time which are divisible to the energy supply period (curves 1 and 3) are practically coincided.

Force, averaged for the period and effected on the channel walls is equal to

$$F = ((p + \rho u^2)S)_2 - ((p + \rho u^2)S)_1,$$

where S is a square of the channel section, ρ and u are the gas density and velocity of the gas flow correspondingly, indexes 1 and 2 are referred to the inlet and outlet sections. Figure 3 shows a specific force of the considered engine model in dependence on time

$$f = F/\rho_1 u_1 S_1.$$

At increasing of the energy supply frequency, the mentioned flow regime is failed: disturbances introduced by a quickened energy supply do not have time to leave the channel. At this, a significantly stronger shock wave irrepressibly moving forward to the inlet section is formed. Behind it, the flow is essentially sub-sonic. It also has a oscillating character, but an

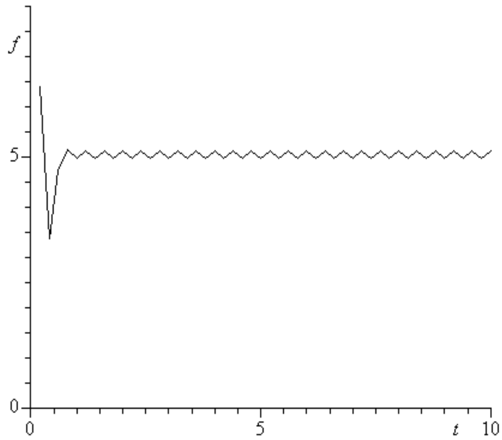


Fig. 3.

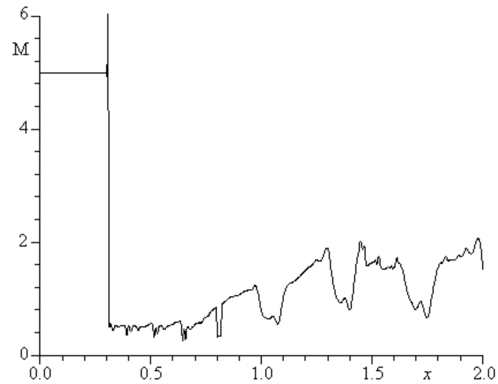
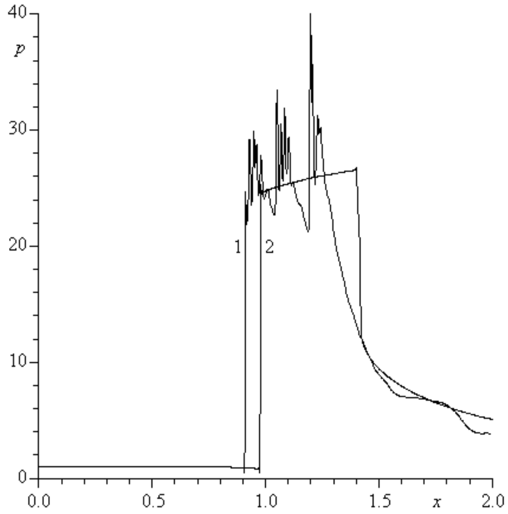


Fig. 4.



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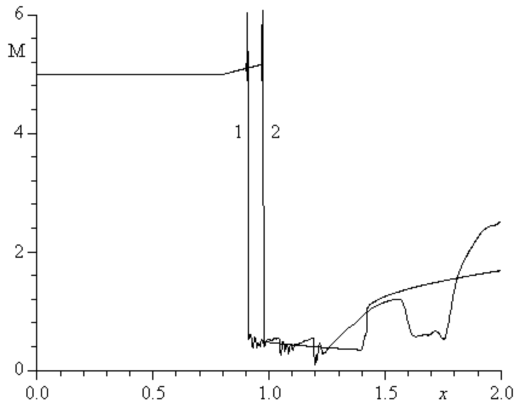

Fig. 6.

oscillations wavelength becomes significantly less. Figure 4 shows the distribution of the Mach number along the channel length at the moment of time $t = 10$ at the energy supply frequency $\nu = \Delta t^{-1} = 10$ (the other parameters values are the same as in Fig. 2). Increase of the channel opening angle can again stabilize the flow regime.

It is interesting to compare the results obtained at a pulse and continuous energy supply of one and the same energy.

Hydrogen caloric value is equal to $1.2 \cdot 10^8$ J/kg. In account on 1 kg of air in a process of the hydrogen burning, the energy of $3.5 \cdot 10^6$ J is released. In a dimensionless form the energy $q = 30 \cdot M_\infty$ will be supplied per a unit of time, where M_∞ is the flow Mach number at the channel inlet. This energy was supplied in the widening channel part equally along x. The calculations were made for the channel that length was equal to 2. The channel widening began from $x = 0.8$, its section area was two times increased. The energy was supplied at x from 1.4 up to 1.42. At a pulse regime the energy was supplied in an interval $\Delta t = 0.1$. Figures 5 and 6 represent distributions of the pressure and the Mach numbers along the channel length, when the periodical flow regime at the pulse energy supply (curves 1) and a stationary flow regime at a continuous energysupply (curves 2) were set.

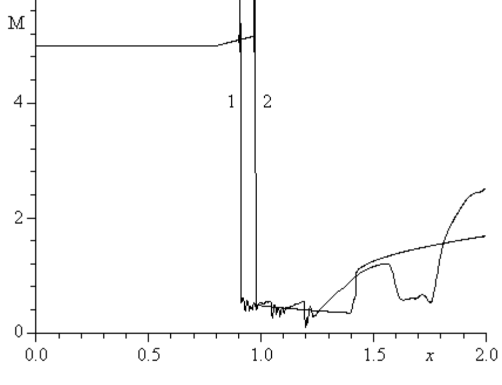

Figure 7 shows a comparison of the specific force values affected the channel walls for these two regimes. It is also presented the specific force values with a period $\Delta t = 10^{-2}$ and 10^{-3} (curves 3 and 4). At the periodical energy supply the specific force can be increased by supply of a greater energy for the same air consumption. Figure 7 represents the curve 5 obtained at the energy supply 1.2 times higher, than at continuous energy supply (the other parameters have the same values as for curve 4).

Fig. 7.

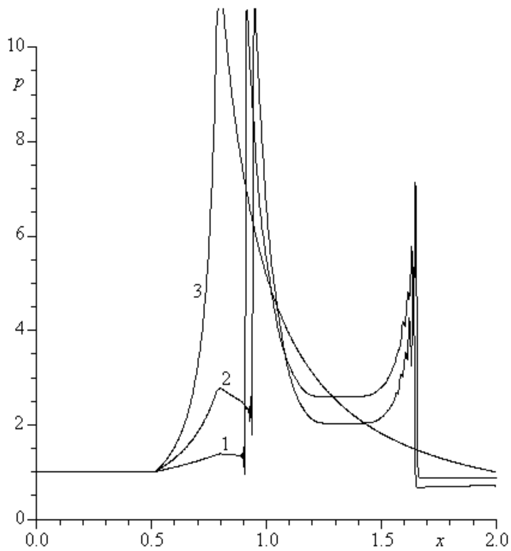

Fig. 8.

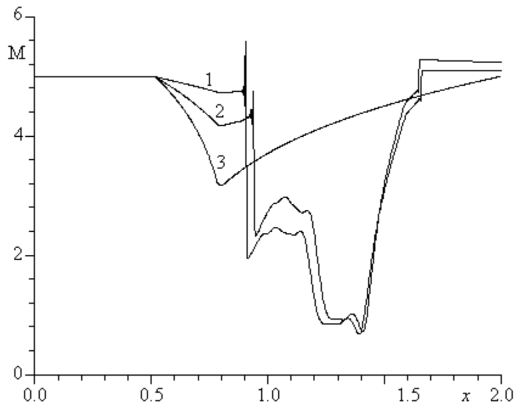

Fig. 9.

Calculations for the channel ending with a Laval nozzle were performed in the work

For a single energy impulse ($\Delta p = 100$) distributions of the pressure and the Mach numbers are presented in Figs. 8 and 9 (critical section was posed at $x = 0.8$, the section area was equal to 0.8, 0.5 and 0.2, the curves 1, 2 and 3 corresponded to them; the energy was supplied just behind the nozzle throat at x from 0.8 up to 0.82). At small narrowing of the channel (curve 1), a super-sonic flow is dragged adiabatically before the nozzle throat. In the widening channel section the shock waves propagating up- and downstream and drifted to the channel outlet are observed. At decreasing of the critical section area, a powerful reflected shock wave is formed (curve 3).

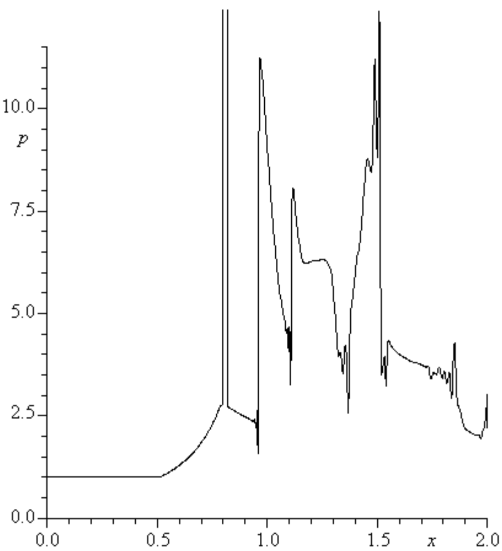

Fig. 10.

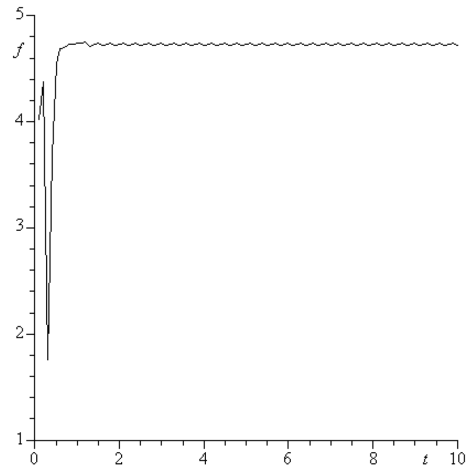

Fig. 11.

Resulting from a periodical energy supply, a complex system of the shock waves propagating both upstream and downstream, the rarefaction waves and the contact discontinuities are arisen. It is seen from Fig. 10 (the energy is supplied just behind the nozzle throat at x from 0.8 up to 0.82 in an interval of time Δt = 0.1, pressure increasing in Δp = 100 corresponds to the energy supply, in a critical section y =0.5). The pressure distribution is presented for two moments of time t =1 and t =10. These moments of time are divisible to the energy supply period Δt, and the curves are practically interflowed. It indicated that a periodical character of the flow regime was set. Figure shows a pressure peak caused by a next energy supply.

The force, effecting the channel walls conducts itself in accordance with the established flow regime. Figure 11 shows a dependence of the averaged for a period of the specific force f on time.

Application of the pulse periodical energy supply gives a possibility to increase a thrust of the ramjet.

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