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NUMERICAL SIMULATION OF A SCRAMJET WITH PULSED PERIODIC ENERGY SUPPLY

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Abstract. Operation of a hydrogen-powered scramjet is restricted to flight Mach numbers $M_\infty = 7.0 \div 7.5$ owing to a significant decrease in combustion efficiency. This decrease in combustion efficiency is associated with two reasons: poor quality of mixing of high-velocity jets within a limited distance and the growth of static temperature of air at the combustor inlet. The energy supply to the air flow in a pulsed periodic mode inspires hope that it is possible to extend the range of flight Mach numbers wherein a straight flow channel can be used as part of a hybrid engine to increase the effective specific impulse.

Because of an essential decrease of combustion completeness, a ramjet operation on hydrogen is bounded by the flight Mach numbers: $M_\infty = 10 \div 12$. This decrease depends on two reasons: bad quality of mixing of supersonic streams at a confined and increase of a static air temperature at a combustion chamber inlet. Radiant energy supply to the air flow allows one to expect an extension of a range of the flight Mach numbers, that makes possible to use a ramjet channel as a part of a compound engine (e. g., as a part of the scramjet with MHD flow control [1]) for increasing of an efficient specific impulse. Therefore, a value of the radiant energy supplied can be larger than a value of the heat energy released by fuel burning.

The results of the numerical simulation of the unsteady flow in the channel simulating the ramjet element and consisting of constant and extending sections are presented in the paper. In contrast to the classic scheme, where the energy was supplied at the expense of a fuel burning in the combusting chamber, the radiant energy is continuously supplied in a pulse-periodic regime. To simulate this problem the Euler equations are numerically solved in a “channel” approximation for plane case [2]:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} = \mathbf{G}$$
$$\mathbf{U} = (\rho y, \rho u y, e y)$$
$$\mathbf{F} = \left(\rho u y, \left(p + \rho u^2\right) y, (p + e) u y\right)$$
$$\mathbf{G} = (0, p\, dy/dx, q y)$$

Here, the x - coordinate is directed along the channel and refers to its width *d* at the inlet, $y = y(x)$ is the dimensionless channel width (refers to d); time t refers to d/a_0, the gas velocity u and sonic speed a are to a_0, density ρ is to ρ_0; presser p is to p_0, the total energy of a unit of a gas volume e is to $\rho_0 a_0^2$; q is the power supplied to a unit of a gas volume and referred to the value $\rho_0 a_0^3/d$; p_0 and a_0 are dimensional pressure and sound speed in the flow at the channel inlet; the parameter ρ_0 is determined from the condition $p_0 = \rho_0 a_0^2$. For the model of gas considered

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

At the pulse-periodic energy supply the q - value is determined by expression

$$q = \Delta e(x) g(t), g(t) = \sum_i \delta(t - i \cdot \Delta t),$$

$\delta(t)$ is the pulse Dirack function, Δt is the period of energy supply, $\Delta e(x)$ is the energy supplied to a unit of a gas volume. Parameters of the undisturbed flow are given at the channel inlet, and a linear extrapolation is used at the channel outlet [2].

To solve this problem the Mac-Cormack method [3] with an artificial viscosity of the fourth order of smallness is applied in the interval between the time moments of the energy supply. Every time the pulse energy is supplied so quickly, that change of the gas density and its velocity for the corresponding very small interval of time is neglected. Therewith, density of the gas energy increases by

$$\Delta e(x) = \begin{cases} \Delta e, x_1 \le x \le x_2 \\ 0, x < x_1 \cup x > x_2 \end{cases}.$$

The Δe –value is determined from comparison of the power of the supplied energy and its continuous supply at a rate corresponding to the total hydrogen combustion. Power of the energy supplied is accepted equal

$$\int_{x_1}^{x_2} qy dx = \gamma M_1 Q, Q = \frac{k \cdot Hu}{a_0^2 L_0}.$$

Hu is the hydrogen calorific capacity, L_0 is the stoichometric coefficient, k is the assigned coefficient of increase of the energy supplied in the pulse periodic regime, M_1 is the Mach number of the flow at the channel inlet. This power is uniformly supplied at the extending channel part along x in the given range $[x_1, x_2]$, i.e. the qy value is assumed to be constant and equal to

$$qy = \frac{\gamma M_1 Q}{\Delta x}, \Delta x = x_2 - x_1.$$

At the pulse periodic regime the energy is supplied as follows

$$\Delta e = \frac{\gamma M_1 Q \Delta t}{\Delta x \cdot y}.$$

Table

M_∞	M_1	T_1	γ
6	2.4	835	1.35
8	3.0	1050	1.33
10	3.6	1300	1.32
12	4.0	1610	1.30
16	4.5	2375	1.23

Table presents the values of the flight Mach number M_∞ (static temperature T_∞=218 K) and the data obtained from the thermodynamic calculations: the Mach number M_1, temperature T_1, and specific heat ratio γ in front of the combustion chamber. In the given paper a numerical simulation was carried out for the Mach number $M_1 = 2.4, 3, 4$ and 4.5. The corresponding values of Q are 11.11, 8.83, 5.76 and 3.19. The specific heat ratio $\gamma = 1.33$ (for the last Mach number $\gamma = 1.23$). For all this variants the presser at the channel inlet was assigned equal to $p = 1$, the gas density is $\rho = \gamma$.

Figure 1 shows the channel configuration.

Due to calculations of the supersonic flow in the channel with the pulse periodic energy supply, a complex picture of the system of the shock waves, rarefaction waves and contact discontinuities is obtained. The condition of the flow coming out to a periodic regime in dependence of the Mach number of the flow, power of the energy sours, its size and position and on divergence angle of the extending channel part.

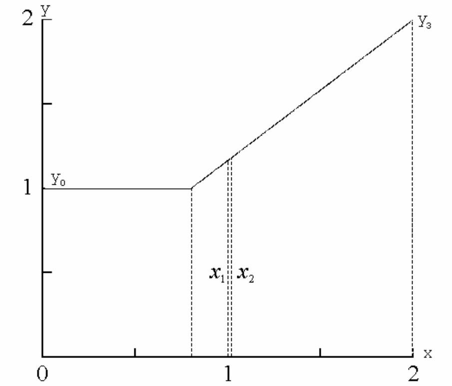

Fig. 1. Channel configuration ($x_1 < x < x_2$ is the energy supply zone)

At input of an energy single impulse in the some local zone, shock wave propagating downstream and upstream appeared. Then rarefaction waves follow. After inter reflection they catch up with the shock waves and attenuate them. In the shock wave propagating upstream does not have time to come out from the channel up to this moment of time, it is swept downstream and the region of disturbance leaves the channel.

In the extending channel at the periodic energy supply a periodic flow regime can be established. Figure 2 demonstrates distribution of the pressure and Mach number along the channel length at moment of time $t = 10$ for $M_1 = 2.4$ at the pulse periodic energy supply in zone ($x_1 = 1.61, x_2 = 1.62$); a period of the energy supply is $\Delta t = 10^{-3}$.

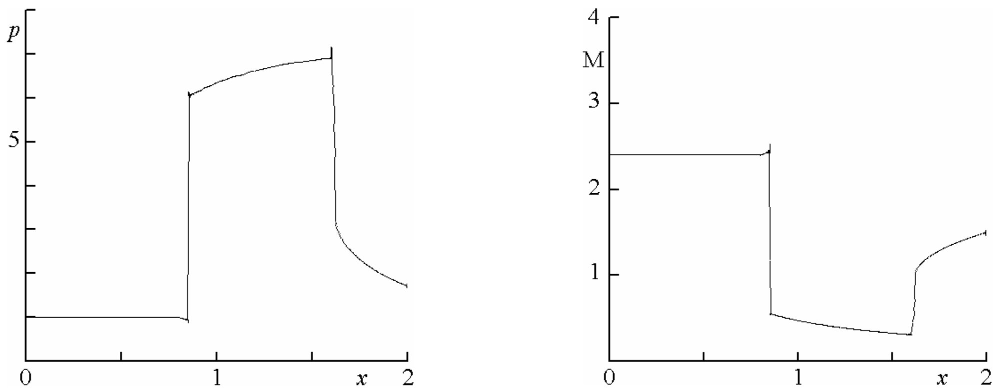

Fig. 2. Distribution of the pressure and Mach number along the channel length for the moment of time $t = 10$ at the pulse periodic energy supply ($M_1 = 2.4$, $\Delta t = 0.001$).

To the moment of time considered a periodic flow regime is established. Resulting to the energy supply a shock wave propagating upstream is developed, that it stopped in front of the narrow channel section. A subsonic flow is behind the shock wave. It accelerates in the narrow zone of the energy supply and becomes a supersonic one.

Force averaging over the period and affected on the channel walls is computed from formula

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

were indexes 1 and 2 refer to the inlet and outlet sections. Specific force is equal to

$$f = F/(\rho u y)_1$$

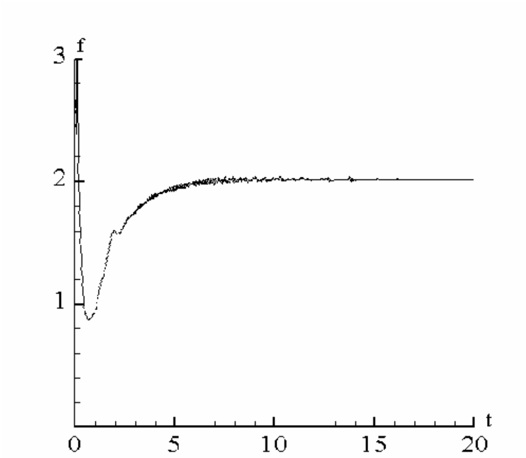

Fig. 3. Specific force at the pulse periodic energy supply (M_1=2.4)).

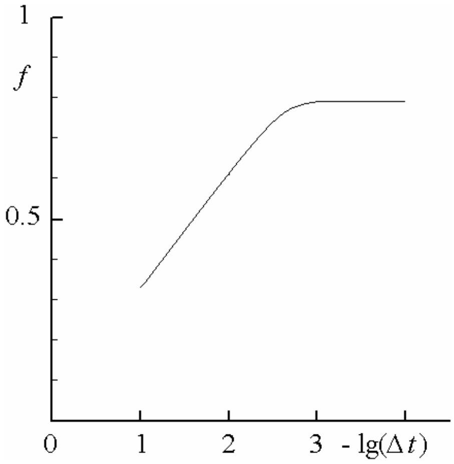

Fig 4. Dependence of the specific force on a period of the energy supply ($M_1 = 4, x_1 = 1, x_2 = 1.02$).

The results presented in Fig. 3 demonstrate that at the pulse periodic energy supply a stationary value of a specific force is established (the flow parameters are the same in Fig. 2). The specific force value is significantly depends on frequency of the energy supply. Figure 4 illustrates dependence of the specific force on the period Δt ($M_1 = 4, x_1 = 1, x_2 = 1.02$).

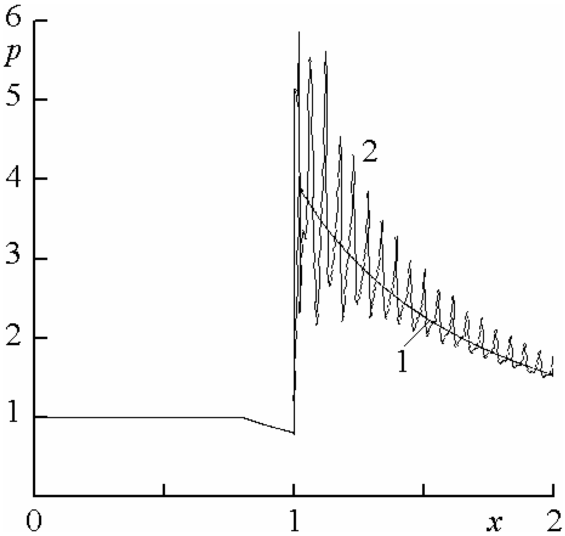

Fig. 5. Pressure distribution along the channel length ($M_1 = 4,\ 1 - \Delta t = 10^{-3}, 2 - \Delta t = 10^{-1}$)

Decrease of a specific force at decrease of frequency of the energy supply (increase of Δt) is to increase of an impulse loss in series of more strong shock waves appeared at a lower frequency of the energy supply (see the pressure distribution in Fig. 5), because more energy is supplied for one tact.

Influence of a position of the energy supply zone on the specific force is relatively weak: at $M_1 = 4$ transfer to of this zone to the side of the narrow channel (x_1 decreases from 1.4 up to 0.9) leads to increase of f by 13%.

Character of change of the specific force with the Mach number at the channel inlet is shown in Fig.6. It is necessary to note that the specific force is normalized to the velocity of sound in the initial channel section.

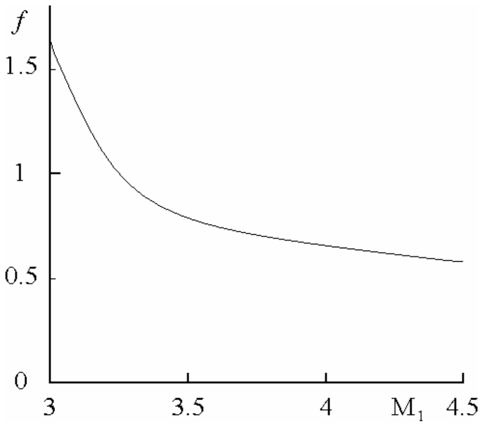

Fig. 6. Dependence of specific force on the Mach number at the channel inlet

At the pulse periodic energy supply the specific force can be increased by means of supply of more energy than at the complete energy combustion for the same air consumption (in a supersonic flow at the channel inlet a combustion completeness is significantly smaller than a unit).

Figure 7 shows for M_1=4 the specific force at the pulse periodic energy supply (Δt =0.001) equal to a continuous supply k = 1 (curve 1), at k =1.5 (curve 2), k =1.7 (curve 3) and k =2 (curve 4). In the last variant an area of the channel section at the outlet was increased up to 2.5.

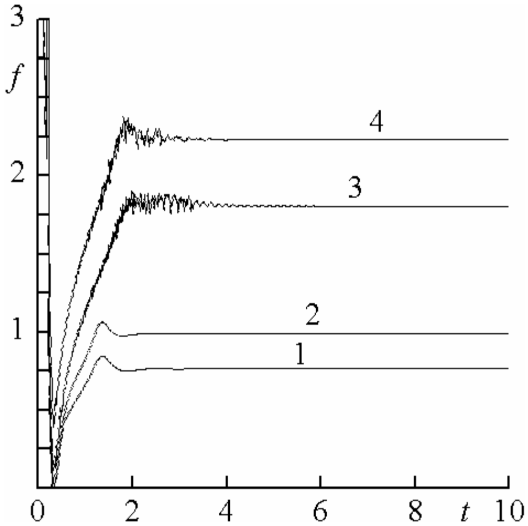

Fig. 7. Comparison of the specific force at different level of the energy supply: 1 – 1.0Q, 2 – 1.5Q, 3 – 1.7Q, 4 – 2Q, M_1=4, Δt =0.001.

At supply of a relatively small energy in the narrow zone the shock wave developed does not move far from the energy supply zone, it is close to it. The gas flow is decelerated in the shock wave and energy supply region, but remains supersonic (curve 1 in Fig. 8). Then, this flow accelerates in the extending channel part. At increase of the energy supply the gas flow is greatly decelerated. When the energy supply increases up to the some critical degree a gas velocity reaches a value equal to a local speed of sound at the end of the energy supply zone. Phenomena similar to a denotation wave in a combustible mixture [4]. Then the flow is again accelerated (curves 2 in Fig. 8). In the result of further increase of the energy supplied, the shock wave is separated from the energy supply zone.

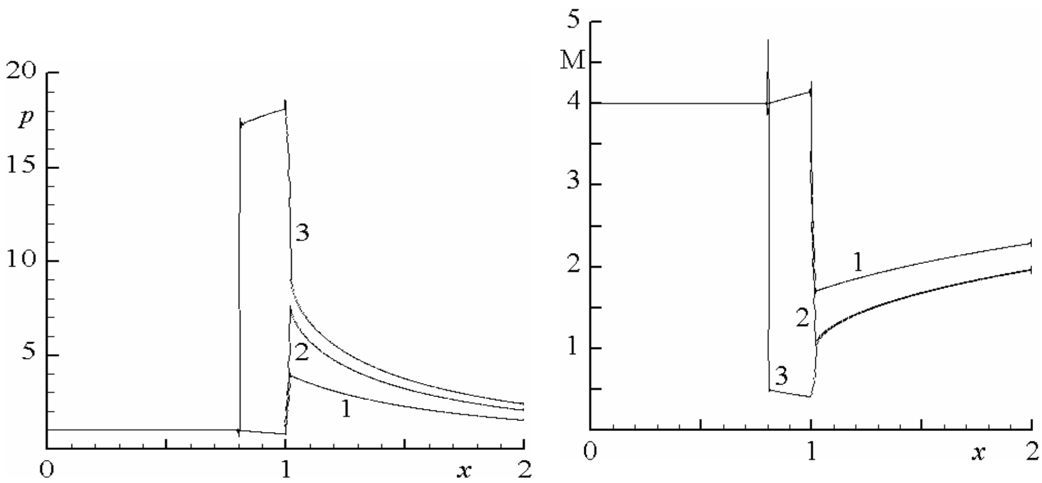

Fig. 8. Distribution of the pressure and the Mach number along the channel length at the pulse periodical energy supply:
1 – Q, 2 – 1.5Q, 3 – 1.7Q, M_1=4, Δt =0.001, x_1=1, x_2=1.02

Position of the wave front is stabilized in a more narrow channel part. The energy is supplied into the subsonic flow, which then accelerated up to the sonic speed at the end of the energy supply zone, after that it is accelerated in the extending channel section (Curve 3 in Fig. 8). Therefore, distributions of the Mach numbers after energy supply zone coincide for the two last variants.

Thus, the simulating results presented demonstrate that application of the pulse periodic energy supply to the air flow makes possible to increase the flight Mach numbers and to use the ram channel as a part of a compound engine for increasing of an efficient specific impulse.

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