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ABOUT "ADVANTAGES" OF DETONATION COMBUSTION AND REALIZATION OF STATIONARY FLOWS WITH DETONATION WAVE IN THE COMBUSTION CHAMBERS OF AIR-BREATHING JET ENGINE

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In connection with the assertions about the advantages of detonation combustion over the realized in air breathing jet engines (ABJE) slow (deflagration) combustion with constant pressure (according to the Brayton cycle), was performed an analysis of ramjet with slow combustion and ABJE with the Chapman-Jouguet detonation waves (DW) - pulsating, stationary and rotating (PDE, SDE and RDE). We consider SDE with deceleration of a supersonic flow in front of a direct detonation wave ($\mathrm{SDE}_{\psi>1}$) and without such deceleration before an oblique detonation wave ($\mathrm{SDE}_{\mathrm{ODW}}$) and an engine with deflagration combustion at a constant volume (according to the Humphrey cycle - ABJE*H*). The assertions about the advantages of combustion in a DW are based on comparisons of specific thrust and impulses determined by thermal efficiency by formulas that are valid only for ABJE, the flow in the path of which is stationary in inertial coordinates. Of these engines, these formulas are valid only for ramjet and SDE. According to mathematical models with the simplifications adopted in [1] and the calculations performed, the efficiency determined by the efficiency of the other ABJE is noticeably higher than their correct values. According non-stationary calculation, even with such PDE simplifications, they exceed the ramjet at specific thrust only with flight Mach numbers $\mathrm{M}_0 < 2.5$. The large losses in the RDE with rotating ("spin") DW in narrow annular combustion chambers are due to flow inhomogeneity in all coordinates, including the radial one. By virtue of what has been said, an increase in the ABJE by tens of percent during the transition to combustion in the DW is wrong. Even for subsonic and small supersonic M_0, on which, according to thrust characteristics, a ramjet is worse than PDE, which is obviously worse than a turbojet engine with deflagration combustion. The advantages of the ABJE with combustion in the detonation wave, if possible, then not according to the thrust characteristics, but for example, at a lower thermal tension in the engine ($\mathrm{SDE}_{\psi>1}$ at $\mathrm{M}_0 > 5$).

ABJE with stationary DW are possible if quasi-one-dimensional flows in “engine-like” channels with such DW are stable. It has been established that stationary flows with direct DW, which is possible only in an expanding channel, are unstable for any q^{o}. Investigation of the stability of quasi-one-dimensional flows with direct overdriven DW revealed stable regimes suitable for implementation, in particular, in $\mathrm{SDE}_{\psi>1}$.

Proponents of the widespread use of detonation combustion promise to improve the thrust characteristics of air-breathing jet engine (ABJE) by tens of percent, often with reference to the note by Ya.B. Zeldovich [2], who, allegedly, in 1940 showed the superiority of the ABJE with combustion in the detonation wave (DW) over the ramjet with deflagration combustion. The question arises: “Why did the ramjet, which was not then, become widespread, and the ABJE with detonation burning will not go through the stage of calculated and model research?” The answer to the question is already given by an appeal to Ya.B. Zeldovich, who writes in the same note: "The principally achievable efficiency of detonation-combustion cycle is only slightly larger (by 13% or less) than that of usual closed volume combustion, so it is rather unlikely that detonation combustion can be used in practice for energy production. ... Therefore, we believe that there are no prospects in searching for detonation-combustion cycles in a chase after a slightly larger theoretical efficiency. ... The losses in the detonation cycle decrease by a factor of two the thrust of the jet engine compared to the cycle with isentropic compression and constant-pressure combustion if one considers a rather high rocket speed equal to the propagation speed of detonation. ... The difficulty of carrying out and using the detonation with minimal losses makes the attempts of practical application of detonation combustion to energy production inadvisable. ... In a supersonic ABJE with continuous combustion, detonation combustion results (in absence of losses) in a lower thrust compared to the usual cycle." Ya. B. Zeldovich does not have any statements in support of DC in either this or other publications.

Following [1], the "ideal" characteristics of the air breathing jet engines are determined within the framework of the simplest mathematical model: air, combustible mixture and combustion products — perfect gases with constant heat capacities and their ratio — the adiabatic index $\gamma = c_p/c_v$; DW - the surface of discontinuity with the supply of fixed energy; deceleration of air in the air intake and flow of combustion products in supersonic parts of perfectly adjustable nozzles isentropic and stationary; the contribution of fuel to the total consumption is not taken into account; multi-chamber PDE valves open and close instantly, and DW initiates instantly and without energy consumption. The "ideal" characteristics of each engine defined within these assumptions are functions of the Mach number of flight M_0, $q^\circ = q/(c_pT_0)$ – the dimensionless calorific value of the combustible mixture (q – is the heat of reaction, T_0 – is the temperature of cold air) and γ.

The coefficients for taking into account the non-isentropic of real supersonic flows in air intakes and nozzles and incompleteness of combustion introduced in [1] are quite arbitrary and cannot take into account the non-stationarity of flow in PDE combustion chambers and in the ABJE. In the present study, in the frame of the mathematical model developed in [3], calculations of nonstationary flows in the combustion chambers are performed. According to them, starting from small supersonic M_0, taking into account non-stationarity makes the specific thrust and impulses of these engines less than that of a ramjet for all values q°.

1. In the ABJE considered below, the combustion is usually preceded by compression in the air intake of the incoming air flow with velocity u_0 and always the expansion of combustion products in the nozzle. Following [1] in ideal models of all engines, air compression and expansion of combustion products in the nozzle to the incident flow pressure p_0 are stationary and isentropic. Under the conditions of isoenergeticity and isentropicity deceleration of air to a detonation wave (index "1") and expansion of combustion products behind the detonation wave (indexes "2" and "e"), are written in the form (a, ρ and ψ - sound speed, density and temperature ratio [1])

$$2a_1^2 + (\gamma-1)u_1^2 = 2a_0^2 + (\gamma-1)u_0^2, \quad 2a_e^2 + (\gamma-1)u_e^2 = 2a_2^2 + (\gamma-1)u_2^2, \tag{1.1}$$

$$\left(\frac{\rho_1}{\rho_0}\right)^{\gamma-1} = \left(\frac{p_1}{p_0}\right)^{1-1/\gamma} = \frac{a_1^2}{a_0^2} = \frac{T_1}{T_0} \equiv \psi \geq 1, \quad \frac{T_e}{T_2} = \left(\frac{p_e}{p_2}\right)^{1-1/\gamma} = \left(\frac{p_0}{p_2}\right)^{1-1/\gamma}, \tag{1.2}$$

According to the definition of ψ and the first equation (1.1) we have

$$\psi \equiv \frac{T_1}{T_0} = \frac{a_1^2}{a_0^2} = \frac{2+(\gamma-1)\mathrm{M}_0^2}{2+(\gamma-1)\mathrm{M}_1^2}. \tag{1.3}$$

For the studied ABJE air consumption $\dot{m}_0$ is much greater than fuel consumption $\dot{m}_f$. Therefore, equating the consumption of combustible mixture and consumption of combustion products, we write the parameters of the combustible mixture (with index "1") and combustion products (without index) in

$$h_1 = c_pT_1 + q = c_pT_0(\psi + \tilde{q}), \quad a_1^2 = \gamma RT_1, \quad q^\circ = q/(c_pT_0), \quad h = c_pT, \quad a^2 = \gamma p\omega = \gamma RT. \tag{1.4}$$

Here h and $\omega = 1/\rho$ are the specific enthalpy and volume, and $R = c_p - c_v$ is the gas constant. Although the values R, c_p, c_v and γ of air, mixtures and products of combustion differ and depend on temperature, when comparing the ABJE of different types, we take them the same and constant. Then, integrating the equation: $Tds = dh - \omega dp$, taking into account equation (1.4), we obtain the expressions for the increment of the specific entropy s at the transition (including with heat input and removal) from the state "a" to the state "b".

$$\frac{s_b - s_a}{c_p} = \ln\left[\frac{\omega_b}{\omega_a}\left(\frac{p_b}{p_a}\right)^{1/\gamma}\right] = \ln\left[\frac{T_b}{T_a}\left(\frac{p_a}{p_b}\right)^{1-1/\gamma}\right] = \frac{1}{\gamma}\ln\left[\frac{T_b}{T_a}\left(\frac{\omega_b}{\omega_a}\right)^{\gamma-1}\right]. \quad (1.5)$$

Combustion in ideal ramjet occurs at constant pressure in the mixture, when $M_1^2 << 2/(\gamma - 1)$. Ad hoc the formula (1.3) reduces to

$$\psi = 1 + (\gamma - 1)M_0^2/2. \quad (1.6)$$

Brighton cycles correspond to the combustion with constant p (Fig. 1*a*). In the diagram, the verticals"*0-1*" and "*2-e*" are the isentropes of air compression and expansion of combustion products, and the ("*1-2*") and ("*e-0*") curves for heat supply during combustion and removal from the jet stream are isobars $p = p_1$ and $p = p_e = p_0$. Under equation (1.5)

$$\frac{p_2}{p_0} = \frac{p_1}{p_0} = \left(\frac{T_1}{T_0}\right)^{\gamma/(\gamma-1)} = \psi^{\gamma/(\gamma-1)}, \quad \frac{T_e}{T_2} = \left(\frac{p_e}{p_2}\right)^{1-1/\gamma} = \left(\frac{p_0}{p_2}\right)^{1-1/\gamma} = \frac{1}{\psi}. \quad (1.7)$$

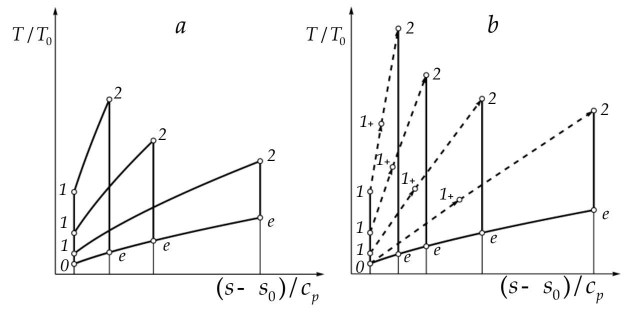

Figure 1. *s-T* phase diagram of Brighton (*a*) and PDE (*b*) cycles

The heat $q_{add} = q$, supplied during combustion, set, and removed from the jet q_{rej} is such that the decrease in entropy $s_0 - s_e$ is equal to its growth $s_2 - s_1$. When $p = p_1$ and $p = p_e = p_0$ it gives

$$T_e/T_0 = T_2/T_1 = 1 + q^\circ/\psi. \quad (1.8)$$

The consequence of equalities (1.6) and (1.8) – are formulas for the thermal efficiency of the ideal Brayton cycle

$$\eta_{th} = \frac{q_{add} - q_{rej}}{q_{add}} = 1 - \frac{q_{rej}}{q_{add}} = 1 - \frac{1}{\psi} = \frac{(\gamma-1)M_0^2}{2+(\gamma-1)M_0^2}. \quad (1.9)$$

By virtue of conservation of the total enthalpy and formulas (1.4), (1.6)-(1.8) with stationary isentropic expansion of the combustion products in the nozzle to $p_e = p_0$ the velocity at the nozzle exit

$$u_e^2 = u_0^2(1 + q^\circ/\psi). \quad (1.10)$$

The same formula is obtained by substituting into the expression for u_e from [1]

$$u_e^2 = u_0^2 + 2\eta_{th}q_{add} = u_0^2(1 + 2\eta_{th}q^\circ/(\gamma - 1)M_0^2) \quad (1.11)$$

η_{th} from (1.9) and M_0^2 from (1.6). According to the ratio u_e/u_0, found by the formula (1.10) and (1.11), the specific thrust $F/\dot{m}_0$ and impulse I_{sp} can be determined from the equation (g – is the gravitational acceleration)

$$\frac{F/\dot{m}_0}{u_0}=\frac{u_e}{u_0}-1,\ \ I_{sp}=\frac{F}{\dot{m}_f g},\ \ \frac{u_e^2}{u_0^2}=1+2\eta_{th}q_{add}/u_0^2=1+q^\circ/\psi. \tag{1.12}$$

Replacing the isobars "*1-2*" in figure 1*a* with isochoric: $\omega=\omega_1=\omega_0\psi^{-1/(\gamma-1)}$ we obtain the ideal Humphrey cycle with combustion at a constant volume with thermal efficiency:

$$\eta_{th}=1+\frac{1}{q^\circ}-\frac{1}{q^\circ}\left(\frac{\psi+\gamma q^\circ}{\psi}\right)^{1/\gamma}. \tag{1.13}$$

If then, as in [1], for the velocity u_e, use the formula (1.11) with η_{th} from (1.13) and M_0^2 from (1.6), we will get

$$\frac{u_e^2}{u_0^2}=1+\frac{2\eta_{th}q^\circ}{(\gamma-1)M_0^2}=\frac{\psi+q^\circ}{\psi-1}-\frac{1}{\psi-1}\left(\frac{\psi+\gamma q^\circ}{\psi}\right)^{1/\gamma}. \tag{1.14}$$

For the calculated u_e/u_0 the specific thrust $F/\dot{m}_0$ and the impulse I_{SP} are determined by formulas (1.12). However, the velocity equation (1.14) – is a consequence of the constancy of the total enthalpy that is valid only for a stationary outflow from section "*1*" with h_1 from equation (1.4) to the nozzle section, which is not preserved during non-stationarity outflow from the combustion chamber. Therefore, formula (1.14) and the results of its substitution into equations (1.12) are incorrect.

The ideal PDE in the *sT* phase diagram, as in [1], corresponds figure 1*b*. Its difference from figure. 1*a* – arrows on the graph giving parameters on shock waves in the combustible mixture ("1-1_+") and the combustion zone ("1_+-2"). In the ω-p coordinate plane, the combustion zone corresponds to a segment of the "line of Rayleigh – Michelson" [4]. As in [1] let us assume that in an ideal PDE, the DW is self-sustaining ("Chapman – Jouget" - DW $_{CJ}$), direct and burns a fixed combustible mixture. Behind the direct detonation wave, the gas velocity in the coordinate system moving with the detonation wave is equal to the speed of sound, which for equations (1.4) gives:

$$M_{CJ}^2\equiv\frac{D_{CJ}^2}{a_1^2}=1+\frac{\gamma+1}{\psi}q^\circ+\sqrt{\left(1+\frac{\gamma+1}{\psi}q^\circ\right)^2-1},\ \ \frac{p_2}{p_1}=\frac{1+\gamma M_{CJ}^2}{\gamma+1},\ \ \frac{T_2}{T_1}=\frac{\left(1+\gamma M_{CJ}^2\right)^2}{(\gamma+1)^2M_{CJ}^2}. \tag{1.15}$$

Here D_{CJ} – is the speed of the detonation wave in the motionless gas in front of it. Proceeding further, as in the case of the Brighton cycle, for η_{th} PDE we obtain

$$\eta_{th}=1+\frac{1}{q^\circ}-\frac{1}{q^\circ M_{CJ}^2}\left(\frac{1+\gamma M_{CJ}^2}{\gamma+1}\right)^{1+1/\gamma}. \tag{1.16}$$

If again to determine u_e/u_0 following [1] we use the equation (1.11), then after substituting into it the η_{th} from (1.16) we come to the expression

$$\frac{u_e^2}{u_0^2}=1+\frac{2\eta_{th}q^\circ}{(\gamma-1)M_0^2}=\frac{\psi+q^\circ}{\psi-1}-\frac{1}{(\psi-1)M_{CJ}^2}\left(\frac{1+\gamma M_{CJ}^2}{\gamma+1}\right)^{1+1/\gamma}. \tag{1.17}$$

Such an expression for u_e/u_0 – is a consequence of the condition of constancy of the total enthalpy from a gas in front of a DW $_{CJ}$ to the initial section of the nozzle. Despite the fact that nothing at least remotely resembling a stationary process between sections "2" and "*e*" in the PDE is impossible in principle.

Air breathing jet engines with combustion in stationary DW $_{CJ}$ without pre-compression of the air ($SDE_{\psi=1}$) was first considered by Ya.B. Zeldovich [2]. Here, ψ = 1, and the point "*1*" and "*0*" in figure 1*b* match up, and the Mach number M_{CJ} standing at the entrance to the engine of the detonation wave is equal to the Mach number of flight:

$$M_0^2=M_{CJ}^2=1+(\gamma+1)q^\circ+\sqrt{[1+(\gamma+1)q^\circ]^2-1}. \tag{1.18}$$

The formulas for efficiency η_{th} and u_e/u_0 for $SDE_{\psi=1}$ are

$$\eta_{th} = 1 + \frac{1}{q^{\circ}} - \frac{1}{q^{\circ}M_{CJ}^2}\left(\frac{1+\gamma M_{CJ}^2}{\gamma+1}\right)^{1+1/\gamma}, \quad \frac{u_e^2}{u_0^2} = 1 + \frac{2}{\gamma-1}\left[\frac{1+q^{\circ}}{M_0^2} - \frac{1}{M_0^4}\left(\frac{1+\gamma M_0^2}{\gamma+1}\right)^{1+1/\gamma}\right] \tag{1.19}$$

The flow in the entire path of $SDE_{\psi=1}$, as in ramjet, is stationary. Therefore, the use of the formula for u_e/u_0 from (1.19) and the consequences of its substitution in the expressions from (1.12) is correct here.
When the flight speed is greater than the $M_0 > M_{CJ}$ is possible air breathing jet engines ($SDE_{\psi>1}$) with air compression in front of the DW_{CJ}. In his ideal model, the flow is permanently isentropically inhibited until $M_1 = M_{CJ} < M_0$ with

$$\psi = 2/(\gamma+1) + \left\{M_0^2 - 2q^{\circ} - \sqrt{2[2+(\gamma-1)M_0^2 + 2q^{\circ}]q^{\circ}}\right\}(\gamma-1)/(\gamma+1).$$

With this ψ value of M_{CJ}^2 determines the formula (1.15), η_{th} and u_e/u_0 depending on M_{CJ}^2 by formula (1.16) and (1.17). Flow in $SDE_{\psi>1}$ stationary, and unlike PDE, the use of these formulas is legal. Another type of engines SDE is air breathing jet engines with ψ = 1 and oblique DW_{CJ} (SDE_{ODW}).The velocity vector in front of the detonation wave has a constant normal component, such that $M_{n0}^2 = M_{CJ}^2$ with M_{CJ}^2, defined by formula (1.18). Thus η_{th} SDE_{ODW} does not depend on M_0, and u_e/u_0 with growth of M_0 monotonously decreases.

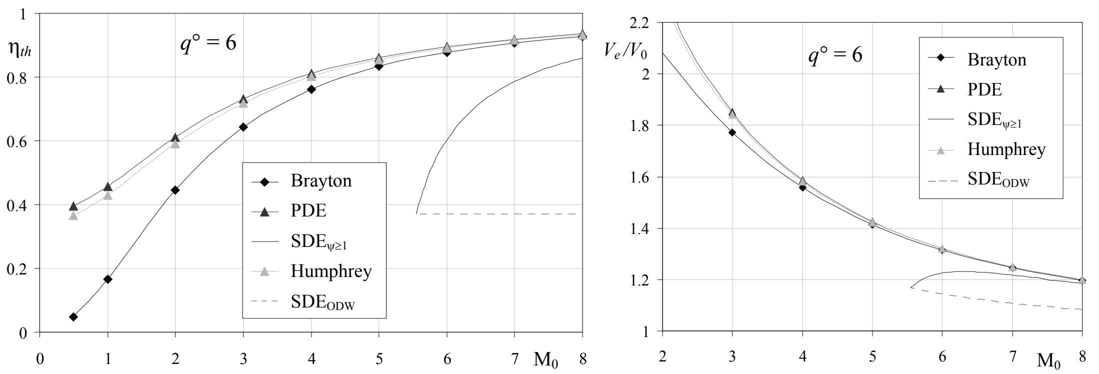

Figure 2. Ideal thermal efficiency (a) and ratios u_e/u_0 (b) for ABJE with slow and detonation combustion

The dependencies on the M_0 of ideal efficiencies and the u_e/u_0 determined by them for the considered engines with q° = 6 are presented in figure 2. Here and everywhere in the calculations γ = 1.4. For a given q° $SDE_{\psi=1}$ possible with one M_0, which in figure 2 correspond to the intersection points of the curves for $SDE_{\psi>1}$ and SDE_{ODW}. In terms of efficiency η_{th} and speed ratio u_e/u_0, and consequently, in terms of thrust characteristics SDE_{ODW} and $SDE_{\psi=1}$ are worse than all engines considered. With subsonic and small supersonic Mach numbers M_0 the ramjet is much worse than PDE both in thermal efficiency and their thrust characteristics (wrongful for PDE). However, with increase in M_0 the superiority of PDE over ramjet virtually disappears.

2. The effects of unsteadiness make it illegal to determine the ratio of velocities , and the thrust characteristics of PDE and ABJE using the ratio, through their thermal efficiency according to the formula (1.11). Accounting of the effects was carried out in the approximation of inviscid and non-heat-conducting gas. The PDE had $n \geq 2$ pairs of cylindrical detonation chambers with instantly opening and closing inlets at the left ends (at x = 0, flow from left to right). The valve was opened when the pressure at x = 0 and the average pressure in the chamber became less than the mixture pressure before the bundle of chambers. When the inlet to the chamber is open, the chamber received a perfectly mixed fuel mixture, and DW_{CJ} was initiated instantly and without additional energy at one of their ends. The right end of the chambers (x = L) is the section of the suddenly tapering part of the nozzle with a given ratio f of the sectional of the open

critical section to the chamber area. The Mach number of combustion products < 1 at x = L is constant and known for a given f < 1 and always assumed supercritical difference. The DW$_{CJ}$ initiated at one end of the chamber, is reflected from the partially open right or closed left end as a shock wave (SW). These and SW, which are associated at the further reflections, are sources of entropy growth, which are not included in the determination of ideal characteristics of PDE. However, the chamber-averaged total enthalpy of combustion products decreases during the flow in the absence of SW too, in contrast to the diagram sT Fig. 1b, where the products of combustion isentropically expand from defined by the formulas (1.15) parameters behind DW$_{CJ}$.

When M_0, q^o, f and the parameters of the mixture before the coupling of the chambers, including the nonzero Mach number (such that $(\gamma-1)M^2 << 2$), are given, the unsteady flow in the chamber is calculated by integrating the equations of one-dimensional gas dynamics by an explicit monotonic decay difference scheme of the second (on smooth solutions) order in x-coordinate and t-time with a through account of SW and contact discontinuities. The exceptions are the time intervals of burning (they are small compared to the period of operation of the camera, but non-zero for PDE and zero at instant, although "slow" combustion in Humphrey cycle). At these intervals, DW$_{CJ}$ and the adjacent centered rarefaction wave were calculated using the formulas (1.15) and taking into account the nonzero velocity of the mixture before DW. The parameters on the cut of perfectly adjustable nozzles ($p_e = p_0$) ($p_e = p_0$) were determined by the flow parameters at $x = L$ by one-dimensional formulas with M = 1 in minimal sections.. Average u_e/u_0 for the period were calculated at entering the periodic regime, and thrust characteristics, taking into account the unsteadiness of the flow and SW, were determined using the average u_e/u_0 for the period.

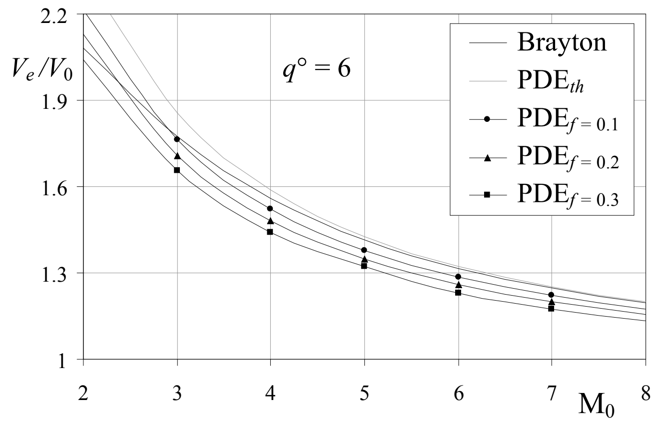

Figure 3. Comparison ratio u_e/u_0 for ramjet, PDE_{th} and $PDE_{f=0.1,0.2,0.3}$

The curves u_e/u_0 for PDE with DW$_{CJ}$, which is initiated at $x = L$, at $q^o = 6$ and $f = 0.1$, 0.2 and 0.3 are shown in figure 3. The curves are calculated within the non-stationary model ($PDE_{f=0.1,0.2,0.3}$), by thermal efficiency (PDE_{th}) and for ramjet. The consideration of non-stationarity limits the advantage of the PDE over the ramjet at a moderate supersonic Mach numbers (at $q^o = 6$ $M_0 < 2.4$ for $f = 0.2$ and $M_0 < 2.9$ for $f = 0.1$). Calculations for PDE with DW$_{CJ}$, which is initiated at $x = 0$, gave slightly smaller values, and for ABJE$_H$ slightly larger. Mutual arrangement of the curves is the same at the other q^o.

3. Recently, special attention is paid to RDE, which are engines with rotating DW. One explanation for this is the steady flow in the DW$_{CJ}$ -rotating coordinate system, and the reasoning about the total enthalpy remaining in the steady flow. At the same time, however, they forget that full enthalpy H is not stored in the rotating non-inertial coordinates along the path lines, and H is a different value. So, if u, v and w are components of velocity **V** in fixed coordinates x, r, φ, then entropy is preserved (between shock waves) and $H' = h + (V'^2 - r^2\omega^2)/2 = H - \frac{r^2\omega^2}{2}$ in the flow which is stationary in rotating with angular velocity ω coordinates x, r, and $\varphi' = \varphi - \omega t$, $\frac{r d\varphi'}{w'} = \frac{dx}{u} = \frac{dr}{v}$, along the path lines, where $w' = w - \omega r$ is the

circumferential component of velocity in rotating coordinates. The mass flow of the axial moment of the amount of motion, which is determined by $\Gamma = r\,w$, is zero and remains so in the chamber and nozzle at the axial flow at the entrance to the chamber. Zero flow does not mean the smallness of the circumferential velocity w, behind DW w is the value of the order of the velocity DW. Therefore, the alternating component w, and the maximums $|r\,w\,\omega|$ are values of the order of the square of the speed DW at the same order of the inhomogeneity H'.

Due to the non-flow conditions on the walls of narrow cylindrical channels $v \approx 0$, and the flow equations take the form

$$(r\rho u)_x + (\rho w')_{\varphi'} = 0, \;\; [r(\rho u^2 + p)]_x + (\rho w' u)_{\varphi'} = 0, \;\; p_r = \rho w^2/r, \qquad (3.1)$$

$$(r\rho u\Gamma)_x + (\rho w'\Gamma + rp)_{\varphi'} = 0, \qquad (r\rho u H')_x + (\rho w' H')_{\varphi'} = 0.$$

They usually consider the two-dimensional subsystem without the third equation to the pathlines $r d\varphi'/w' = dx/u$ on a cylindrical surface r = const. Along such lines, the value $h + (V'^2 - r^2\omega^2)/2$ is stored with $v = 0$, which is equivalent to preserving the total enthalpy $h + V'^2/2$, which is determined by the gas velocity in the rotating coordinates. The said about the subsystem of four equations (3.1) is known. However, contrary to this, due to the third equation (3.1) in those subdomains of narrow cylindrical RDE chambers, where the module w is of the order of the DW velocity, the radial non-uniformity of the pressure is of the order of unity. So, even in such chambers at almost zero radial velocity, the flow is spatial with large irregularities of the parameters in all variables. Large irregularities are accompanied by large losses of thrust. When the radius of the annular chamber RDE is tens of cm and product ωr is equal to the DW velocity, the value of ω is so large that due to the value H' saving and slight Γ change, the specific impulse of the RDE I_{SP} with tapering central body and the cylindrical external contour of the nozzle may significantly decrease. An additional increase of entropy in the RDE also takes place in shock waves, although weaker than in PDE.

4. $SDE_{\psi i\,1}$ are possible if one-dimensional steady flows in engine-like channels of variable area with combustion in straight DW are stable. According to [5], the shifted DW, which remains to be DW_{CJ}, will continue to shift in the same direction, demonstrating the instability of such flows. In fact, however, the perturbation of the DW_{CJ} makes it over-compressed with a large module velocity, which is directed against the flow, and the DW will again be able to take its stationary position. We show that, despite this, such flows are always unstable.

Behind DW_{CJ} $M_2 = 1$, and in a stationary stream, DW can be stable only in an expanding channel. The supersonic flow at $M_0 > M_J$ in the air intake is slowed down to $M < M_J$ in a minimum cross section, and then accelerates in the expanding part with an increase in the Mach number M_1 and decrease in ψ. According to (1.15) M_J is growing, but (see below) slower than M_1. Therefore, in some section $x = x_1$ of the expanding channel equality $M_J = M_1$ will be valid, and it is possible to put DW_{CJ} there . Analysis of the stability of this flow will begin, assuming after [5], that DW remains to be DW_{CJ} at the displacement $x_1 = x_1(t)$ from the stationary position. Due to formulas (1.3) and (1.15) we have $M_J^2 = M_J^2(M_1^2)$ and

$$\frac{dx_1}{dt} = a(M - M_J) = a\,\frac{M^2 - M_J^2}{M + M_J} \approx \lambda x_1, \;\; \lambda = \frac{a_1}{2M_1}\left(1 - \frac{dM_J^2}{dM_1^2}\right)\frac{dM_1^2}{dx}.$$

In the considered flow M_1 is an increasing function of x and the λ sign determines the difference in parenthesis. After performing simple calculations, we get

$$\frac{dM_J^2}{dM_1^2} = \frac{(\gamma-1)M_J^2}{\left[2+(\gamma-1)M_J^2\right]\sqrt{1+2\psi/[(\gamma+1)q^\circ]}} < 1. \qquad (4.1)$$

At the different adiabatic exponents before and after DW_{CJ}, the inequality is preserved.

So, $\lambda > 0$ and the stationary flow with the DW_{CJ} are unstable. Perturbed $ДВ_{CJ}$, becoming a over-compressed, with the same parameters of the incident flow has a greater speed than DW_{CJ}. The movement of the over-compressed detonation wave to the right can change the instability conclusion. On the contrary, when the detonation wave is shifted to the left, the high velocity of the over-compressed detonation wave will confirm the correctness of this conclusion, which is quite enough. When the detonation wave moves to the left, the high velocity of the over-compressed detonation wave will confirm the correctness of this conclusion, which is quite enough. By the way, precisely because of inequality (4.1) M_J changes more slowly than M_1.

Since it is impossible to realize $SDE_{\psi i\ 1}$ with DW_{CJ}, it is natural to find out whether similar stationary flows with over-compressed detonation wave are stable. For $M_0 = 4.11$, $M_1 = 2.44$, $M_2 = 0.8$, $\psi = 2$ and $q^o = 5$ the contours of a flat channel with such a four-inlet air inlet and a Laval nozzle with a sudden narrowing part are shown in fig. 4*a*. In fig. 4*b* shows the stationary distributions of *p* and M on the *x* axis for $x < 1.75$ and average over the cross section (from a one-dimensional calculation) for $1.75 \le x \le 3.5$. In the one-dimensional approximation in the minimum section of the nozzle M = 1.

The stability of the flow was studied numerically. At $t = 0$, the same relative perturbations *p*, ρ and *u* (pressure disturbance Δp is shown in fig. 4b) were introduced in the subsonic channel. The development of perturbations at $t > 0$ was calculated by the calculation scheme applied in section 2. The difference of the algorithm is in the selection of a moving DW - the left boundary of the calculated flow and in a uniformly moving *x* differential grid with a fixed right border $x = 3.5$ - the coordinate of the sudden narrowing of the nozzle. In fig. 5 are shown Δp for $t \le 7.77$. The time *t* is related to L/u_0, where 4*L* – is the incomplete length shown in fig. 4*a* SDE. In this example, the initial disturbance after reflections from the cross section of a sudden narrowing part of the channel and the DW then increases noticeably at t $t \approx 7$ to t = 7.77 and almost completely disappears, demonstrating the stability of the flow under study.

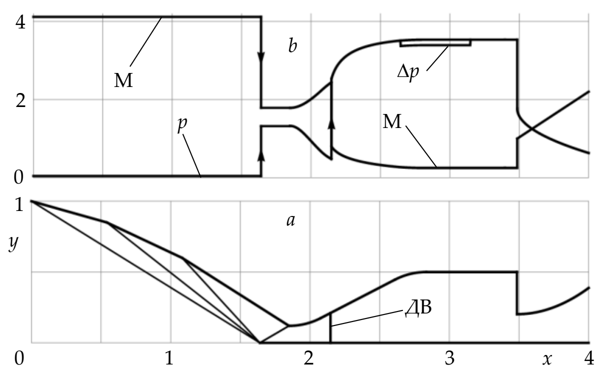

Figure 4. SDE with over-compressed DW (*a*) and pressure and Mach number distributions in it (*b*)

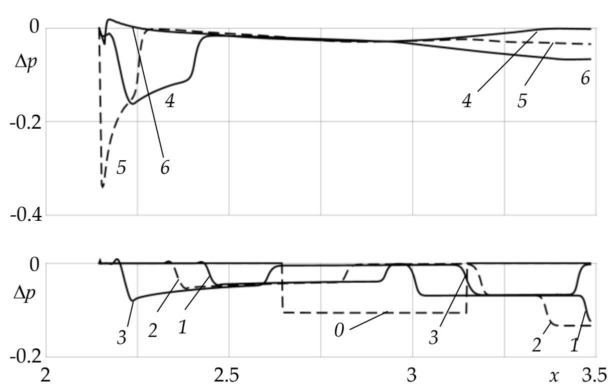

Figure 5. Pressure perturbations between the DW and the minimum nozzle section at $t = 0$ (*0*), 0.82 (*1*), 1.23 (*2*), 2.06 (*3*), 6.16 (*4*), 6.97 (*5*), 7.77 (*6*)

In also numerical studies of the stability of flows from a straight [6] or close to straight [7] over-compressed detonation wave, the reflection of disturbances from the output cross sections of the channels was less intense than from the sudden narrowing of the SDE nozzle, figure 4. Taking this phenomenon into account, examples of stable stationary flows in engine-like channels with combustion in a compressed detonation wave given in this paper serve as an additional stimulus for further study of such flows.

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ЭНЕРГОЕМКИЕ НАНОУГЛЕРОДНЫЕ МАТЕРИАЛЫ

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Введение

Металл-органические каркасные структуры (MOFs) – одно из интересных направлений в широкой области применения, в том числе для энергоемких материалов. Пористая кристаллическая структура привликает все большее внимание из-за ее высокой удельной поверхности и возможности улучшения их физико-химических свойства путем внедрения металлических центров. Однако способ получения этих объемных полимеров являются дорогостоящим и многоступенчатым процессом. В связи с этим представляет интерес поиск альтернативных методов получения объемных материалов на основе многослойных графенов [1-4].

Использование графен оксидных структур в качестве энергоемких добавок может стать одним из перспективных способов для повышения эффективности высокоэнергетических ракетных топлив. Представляет интерес использования двухслойных и многослойных графеновых структур в качестве таких добавок. Перспективным, простым и экономически эффективным путем является получение многослойных графенов из рисовой шелухи (РШ) и скорлупы грецкого ореха (СГО). В институте проблем горения разработан метод синтеза многослойных графен оксидных структур (graphene oxide frameworks (GOFs)) из растительных отходов таких как рисовая шелуха или скорлупа грецкого ореха [5-10].