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HEAT CONDUCTION AND HEAT EXCHANGE IN TECHNOLOGICAL PROCESSES

INFLUENCE OF THE PREHEATING OF A WORKING MEDIUM ON THE THERMODYNAMIC EFFICIENCY OF PULSE-DETONATION-ENGINE PROPULSION MODULES

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A theoretical substantiation of calculation of the thermodynamic cycle of engines with detonation fuel combustion, which is realized in propulsion modules of pulse detonation engines, has been given. A system of equations for calculation of the parameters of detonation combustion waves under different conditions of their excitation has been obtained. On their basis, investigations of the influence of different factors on the parameters of detonation combustion waves and accordingly on the cycle work, thermal efficiency, and specific parameters of pulse detonation engines have been performed. It has been established that the loss due to the irreversibility of the process of heat supply in detonation combustion waves is much lower when propulsion modules are installed in the heated-gas flow. It has been shown that the temperature of the working medium fed to propulsion modules is the determining factor influencing the thermodynamic efficiency of the detonation-fuel-combustion cycle. Generalized characteristics in the form of one-parameter dependences of the specific parameters of propulsion modules of pulse detonation engines on the temperature of the working medium fed to them have been obtained.

Keywords: *detonation, deflagration, heat of combustion, entropy, irreversibility, detonation combustion, pulse engine.*

Introduction. Recent years have seen numerous investigations, inventions, and patents in the field of pulse detonation engines (PDEs). There are publications, e.g., [1, 2], on schemes, principles of operation, and fields of application of such engines. However, in connection with the extremely complex physicochemical, thermal, and gasdynamic processes in them, the methods of calculating the specific parameters and characteristics of pulse detonation engines have yet to be adequately developed and described in the literature. At the same time, different conceptual investigations of such engines and their comparative evaluation with the existing gas-turbine engines (GTEs) have necessitated the development of the engineering method of calculating the specific parameters and characteristics of pulse detonation engines of various schemes. The difficulty in dealing with the task set was the great variety of the proposed schemes of detonation engines and the resulting complexity of allowing for their special features. Nonetheless, the physical principles of organization of their operating process have common thermodynamic foundations. This has precisely made it possible to develop the methods of approximate calculation of the basic characteristics of pulse detonation engines, which were already partially published in [3, 4].

To calculate the parameters of pulse detonation engines we have introduced the notion of the *thermodynamic cycle of an engine with detonation (knocking) fuel combustion* (detonation-fuel-combustion (DFC) cycle). Such a cycle (1–2–3–4–1) with the pressure of a working medium (WM) being preincreased before its feed to a propulsion module (PM) is presented in Fig. 1 in T–S coordinates (solid curves). The detonation-fuel-combustion cycle consists of four processes: 1–2) preliminary adiabatic increase in the pressure of a fuel-air mixture (FAM) before feeding it to the PM; 2–3) heat supply q_1 in the detonation combustion wave; 3–4) adiabatic expansion of combustion products to atmospheric pressure; and 4–1) heat removal q_2 to the surrounding atmosphere. The supplied heat q_1 is dependent on the calorific value of the utilized fuel H_u and the excess air coefficient α in the detonation combustion chamber; it is de-

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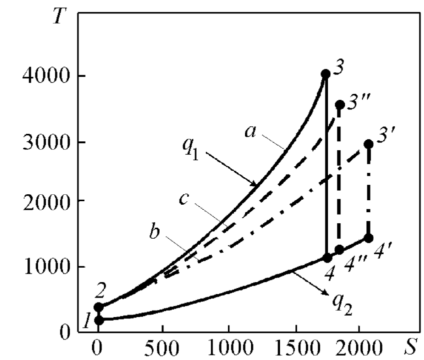


Fig. 1. Thermodynamic cycle of detonation fuel combustion (a) and its comparison to the Brighton (b) and Humphrey (c) cycles. T, K; S, J/(kg·K).

termined from the relation $q_1 = H_u/(\alpha L_0)$. The removed heat q_2, at $p_4 = p_1$, is found from the condition $q_2 = c_p(T_4 - T_1)$.

The author seeks to investigate, with a system of equations derived by him, the influence of the preincrease in the pressure and preheating of the working medium which has been fed to the PMs of pulse detonation engines on their thermodynamic efficiency.

Pulse-Detonation-Engine PMs. The term PM of a pulse detonation engine denotes a device in which a fuel-air mixture burns in a pulsating gas flow, and jet thrust is created due to the outflow of the combustion products through the nozzle. Pulsations can be induced artificially, i.e., in a forced manner, by, e.g., feeding discontinuosly a fuel (or a fuel-air mixture) or by using naturally occurring self-oscillatory processes. In the first case flow pulsations can be initiated by periodically recurring fuel-air-mixture flashes giving rise to shock waves which are accompanied by a considerable local increase in the pressure and temperature. If detonation burning occurs in these waves, such waves are called *detonation combustion waves* (DCWs). This character of the detonation-combustion process is ensured, e.g., in the well-known "classical" detonation tubes usually equipped with intake valves. The basic drawbacks of "tube" pulse detonation engines are large longitudinal dimensions and low pulsation frequencies leading to a decrease in the specific parameters and to a high level of noise.

Another type of PM is based on natural (spontaneously occurring) *self-oscillating processes* which are formed in certain gasdynamic systems. Flow of compressed air out of an annular nozzle to a half-open resonance cavity of special configuration provides an example. In shock-wave theory, this self-oscillatory process is known as the Hartmann–Sprenger effect. The nature of such pulsations is that shock waves occur on collision of supersonic radial air jets flowing out of the annular nozzle to the resonator cavity, and we have quite a considerable local increase in the pressure and temperature of this air in the central part of the resonator (at its "focus"). If a fuel-air mixture specially prepared for detonation combustion, not compressed air, is fed to the resonator cavity through the annular nozzle, self-ignition of the mixture at the resonator "focus" and its detonation combustion will occur under favorable conditions.

Preparation of the fuel-air mixture occurs in a *reactor*. In it, conversion of the fuel-air mixture, i.e., its decomposition into chemically active components, is effected due to exothermal reactions. This contributed to better combustion of such an activated fuel-air mixture in shock-wave structures periodically formed in the gasdynamic resonator.

The fuel-air mixture burns virtually instantaneously (explosively) in detonation waves with considerable increase in the temperature and pressure. But thereafter the detonation wave, once the fuel-air mixture has burned up in it, degenerates into a regular shock wave that moves to the resonator's nozzle device with a high supersonic velocity (approximately up to 2000 m/sec), carrying along the combustion products. They are discharged into the environment with a rate lower than the velocity of motion of the shock wave itself. The higher the outflow velocity and the larger the mass of these combustion products, the larger the thrust created by the PM.

On completion of the process of outflow (and emptying the resonance cavity), the inertia of the escaping gas produces a rarefaction wave, which moves in the opposite direction (toward the resonator's bottom cavity). Passing by the annular nozzle and having, behind the front, a pressure lower than that atmospheric, the rarefaction wave ensures the suction of a new portion of fresh fuel-air mixture. Next the cycle is repeated. Its duration is fractions of hundred of a second, whereas high pulsation frequencies diminish the noise level.

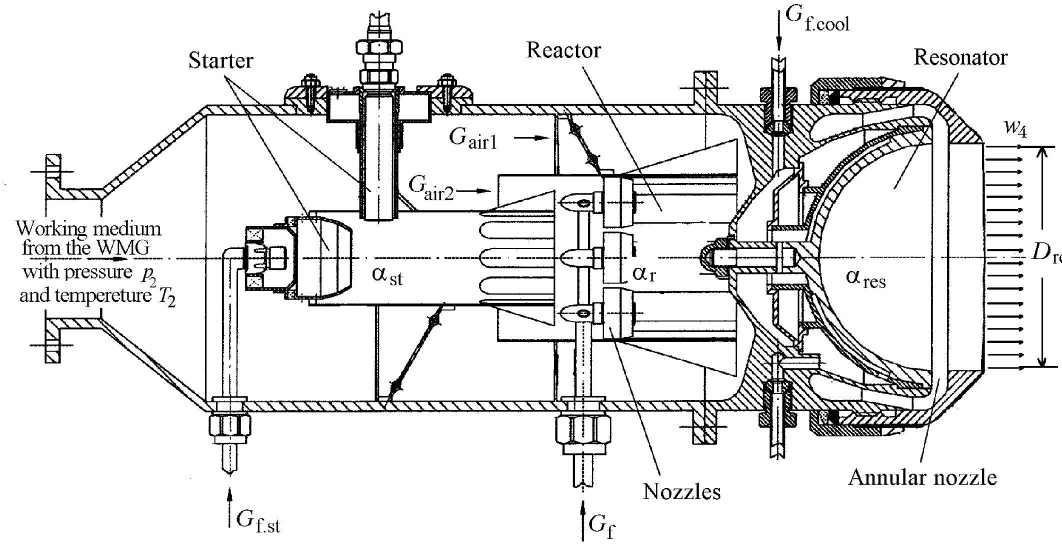


Fig. 2. Structural diagram of the pulse-detonation-engine PM.

The described scheme of a PM is original and unprecedented in the world. It was first patented in the USSR in 1991 by R. M. Pushkin and A. I. Tarasov [5] and was subsequently investigated on the basis of experimental test beds of a number of organizations, including the N. E. Zhukovskii Air-Force Engineering Academy and the "Saturn" Science and Production Association. A pulse detonation engine based on this scheme is distinguished by the absence of any mechanical valves and discontinuous igniters.

A structural diagram of one possible model of a pulse-detonation PM of this type is shown in Fig. 2. It consists of a starter, a reactor, an annular nozzle, and a resonator. The starter, to which a small amount of air (no more than 10%) is fed, is used for starting and primary heating of a working medium fed to the basic fuel-injection nozzles at the rate G_{air1}. The values of G_{air1} are selected so that the excess-air coefficient in the reactor of $\alpha_{\text{r}} = 0.3–0.4$, which is required for conversion of the fuel-air mixture, is ensured in feeding the entire flow rate of the fuel G_{f} through the nozzles. The entire remaining air at the rate G_{air2}, which is fed through the external duct, enters, via the annular nozzle, the resonator after mixing with the activated fuel-air mixture. The amount of the remaining air is selected so as to ensure a required α_{res} value (which is usually close to unity).

Small diametral dimensions of the resonators of pulse-detonation-engine PMs of this scheme are their characteristic feature. It has been established by experiment that for stable combustion, we must have $D_{\text{res}} = 70–90$ mm. Therefore, the thrust of one PM does not exceed 3000–5000 N. Higher thrusts require a group of PMs operated from one generator of working media.

The proposed method of calculation of detonation combustion waves (DCWs) takes no account of all subtleties of the actual process that are associated with the distinctive features of the arrangement of a PM but it quite objectively and reliably evaluates the fundamental process: formation and development of detonation combustion waves. Being identified from domestic and foreign experimental and calculated data, it ensures the acceptable accuracy of calculations in conceptual investigations of power units with PMs of any schemes.

Formulation of the Problem. The problem of calculation of the parameters and characteristics of pulse detonation engines is in determining the *cycle work* l_{cycle} and the *thermal efficiency* η_{t} which characterize the thermodynamic efficiency of a detonation-fuel-combustion cycle and are known to be expressed by the heats q_1 and q_2 as follows:

$$l_{\text{cycle}} = q_1 - q_2 , \quad \eta_{\text{t}} = 1 - \frac{q_2}{q_1} .$$

Since q_1 is always known for each utilized fuel, the problem of determination of the parameters of a detonation-fuel-combustion cycle is reduced to finding $q_2 = c_p T_1 (T_4 / T_1 - 1)$ and consequently to determining the temperature T_4/T_1. Then l_{cycle} and η_{t} are found from the formulas

$$l_{cycle} = q_1 \left[1 - \frac{c_p T_1}{q_1} \left(\frac{T_4}{T_1} - 1 \right) \right], \quad \eta_t = 1 - \frac{c_p T_1}{q_1} \left(\frac{T_4}{T_1} - 1 \right). \tag{1}$$

Figure 1 also shows in T–S coordinates the Brighton 1–2–3′–4′–1 (p = const) and Humphrey 1–2–3″–4″–1 (V = const) cycles for the equality of the supplied heat q_1 and the same values of the parameter $\pi = p_2/p_1$ characterizing the degree of preincrease in the pressure of the working medium before feeding it to the PM.

System of Equations for Calculation of the Parameters of Detonation Combustion Waves. To calculate the detonation-fuel-combustion cycle we must know the parameters and conditions of heat supply in process 2–3 — that of detonation fuel combustion. Calculation of this process is based on the use of thermogasdynamic relations for determination of the parameters of *detonation combustion waves,* which are used in shock-wave theory [6]. The parameters of detonation combustion waves are calculated with three conservation equations — mass, momentum, and energy equations. If, in accordance with Fig. 1, the parameters ahead of a detonation combustion wave are denoted by the subscripts 2 and the parameters behind it are denoted by the subscripts 3, the system of conservation equations for an ideal ($pV = RT$) gas is written as follows [6]:

(1) the mass equation

$$\rho_2 w_2 = \rho_3 w_3 \,; \tag{2}$$

(2) the momentum equation

$$p_2 + \rho_2 w_2^2 = p_3 + \rho_3 w_3^2 \,; \tag{3}$$

(3) the energy equation

$$q_1 = c_p (T_3 - T_2) + \frac{w_3^2 - w_2^2}{2} \,, \tag{4}$$

where ρ, p, w, and T are the density, pressure, velocity, and temperature of the gas at points 2 and 3 of the denotation-fuel-combustion cycle (Fig. 1).

Using relations (2)–(4), we derive a system of equations that is more convenient for calculation and analysis of the parameters of detonation combustion waves. Since we have $a^2 = kRT = kp/\rho = w^2/\mathrm{M}^2$ and $\rho w^2/p = k\mathrm{M}^2$, by simultaneous solution of Eqs. (2) and (3) we find

$$\frac{p_3}{p_2} = \frac{1 + k\mathrm{M}_2^2}{1 + k\mathrm{M}_3^2} \,. \tag{5}$$

Equation (2), at $\mathrm{M} = w/a$ and $pV = RT$, yields

$$\frac{T_3}{T_2} = \frac{\mathrm{M}_3^2}{\mathrm{M}_2^2} \left(\frac{1 + k\mathrm{M}_2^2}{1 + k\mathrm{M}_3^2} \right)^2 . \tag{6}$$

From Eq. (4), we obtain

$$\frac{q_1}{c_p T_2} + 1 = \frac{T_3}{T_2} + \frac{w_2^2}{2 c_p T_2} \left[\left(\frac{w_3}{w_2} \right)^2 - 1 \right],$$

where $w_2^2/T_2 = kR\mathrm{M}_2^2$. Next, using dependence (6), we find

$$\frac{q_1}{c_p T_2} + 1 + \frac{k-1}{2} \mathrm{M}_2^2 = \frac{\mathrm{M}_3^2 (1 + k\mathrm{M}_2^2)^2 \left(1 + \frac{k-1}{2} \mathrm{M}_3^2 \right)}{\mathrm{M}_2^2 (1 + k\mathrm{M}_3^2)} \,. \tag{7}$$

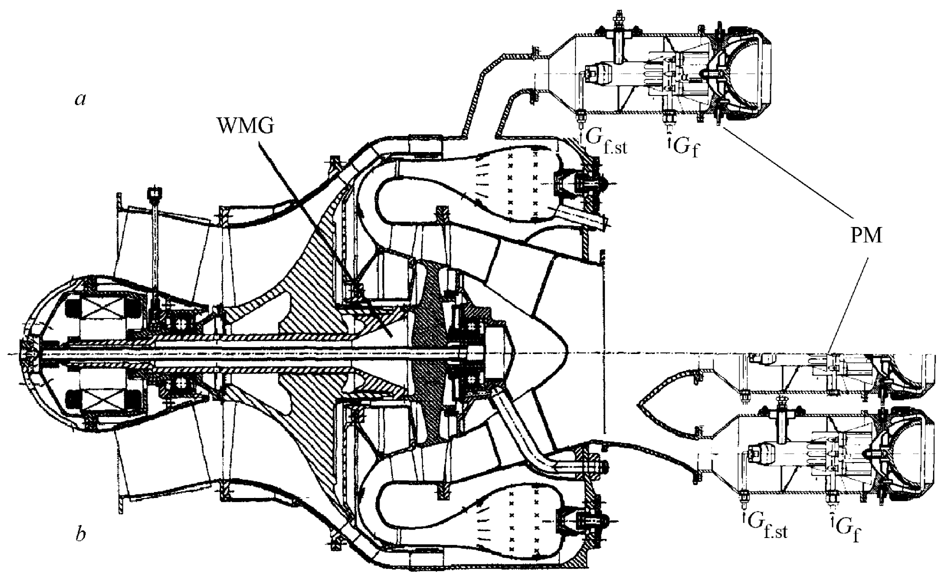


Fig. 3. Layout diagrams of the pulse-detonation-engine PM: behind the compressor (a) and at the turbine outlet (b).

The system of equations (5)–(7) for calculation of detonation combustion waves is convenient in that the sought gasdynamic parameters in it are represented as functions only of the Mach numbers M_2 ahead of the detonation combustion wave and M_3 behind it, which significantly simplifies all calculations of the characteristics of pulse detonation engines. This system enables us, in particular, for the prescribed parameters of the working medium ahead of the detonation combustion wave (at point 2, Fig. 1) and the known value of the supplied heat q_1, to determine the parameters behind the detonation combustion wave (in the already burnt fuel-air mixture, at point 3). The presence of this system of equations for detonation combustion waves with the known thermodynamic relations for the other processes of the detonation-fuel-combustion cycle (Fig. 1) makes it possible to find the temperature ratio T_4/T_1 and consequently to calculate the work and thermal efficiency of the cycle in question with formulas (1).

The influence of the mode of installation of PMs on their characteristics will be considered with the example of two structural diagrams (Fig. 3) of pulse detonation engines. Each of them consists of two elements: a working-medium generator (WMG) and a group of PMs. In Fig. 3a, PMs are installed at the compressor outlet; therefore, they are operated by clean air to which we supply the work $l_{\text{comp}} = c_p T_1(\pi_{\text{comp}}^{(k-1)/k} - 1)$ from the compressor of the working-medium generator; this work ensures the pressure $p_2 = p_1\pi_{\text{comp}}$ and the temperature $T_2 = T_1\pi_{\text{comp}}^{\frac{k-1}{k}}$ at the PM inlet. The temperature T_2 is comparatively low here. On the diagram in Fig. 3b, the parameters of the gas flow p_2 and T_2 at the PM inlet are the pressure and temperature of exhaust gases at the exit from the turbine of the working-medium generator. Therefore, the temperature T_2 is higher here. A comparison of the above diagrams makes it possible to elucidate the influence of the temperature T_2 of the gas flow at the PM inlet on the thermodynamic efficiency of the detonation-fuel-combustion cycle.

Calculation of the Characteristics of a Pulse Detonation Engine when the PM Is Installed behind the Compressor. The detonation combustion of a fuel-air mixture in the pulse-detonation-engine PM is excited by a shock wave. The velocity of propagation of a supersonic shock wave over the fuel-air mixture unburned as yet is characterized by the Mach number M_2. Due to the compression of the fuel mixture in the shock wave, which is accompanied by the increase in the pressure and the temperature, it is ignited and burns with a simultaneous decrease in the Mach number in the detonation combustion wave from M_2 to M_3. The *degree of reduction in the Mach number in the detonation combustion wave characterizes its intensity*. Figure 4 plots the basic parameters of the detonation combustion wave — the Mach number M_3 (Fig. 4a) and the ratios of the pressures p_3/p_2 (Fig. 4b), the temperatures T_3/T_2 (Fig. 4c), and the specific volumes V_3/V_2 (Fig. 4d) — as functions of the M_2 number (for different values of the parameter π_{comp}); the plots have been constructed with the system of equations (5)–(7). As is seen, all parameters of the

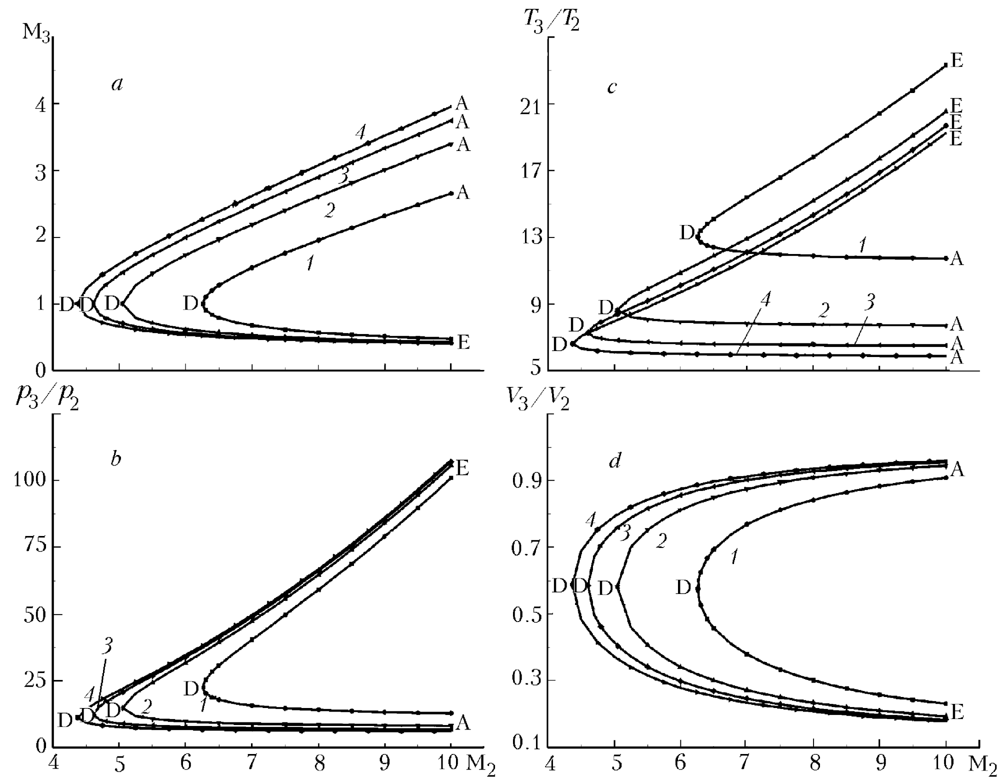


Fig. 4. Parameters of the detonation combustion wave vs. M_2 and π_{comp} at α = 1, M = 0, and H = 0 (the fuel is kerosene): 1) π_{comp} = 1, 2) 5, 3) 10, and 4) 15.

detonation combustion wave are presented, for different π (or π_{comp}), as functions only of the Mach numbers M_2 and M_3. These plots are characterized by the presence of two branches: DE and DA. On DE portions of the presented curves, we have $M_3 < 1$ for $M_2 > 1$, which ensures a considerable increase in the pressure and temperature (Fig. 4). Therefore, the detonation is strong here. *Such detonation combustion waves are called supercompressed*. On DA portions, the degree of deceleration of the gas flow in the detonation combustion wave becomes weaker as M_2 grows. Here we have $M_3 > 1$ for $M_2 > 1$, and increase in the pressure in the detonation combustion wave diminishes. *Such detonation combustion waves are called subcompressed*. Detonation becomes weak.

The prime objective of calculation of the detonation-fuel-combustion cycle is determination of the quantities l_{cycle} and η_t. The cycle work l_{cycle} characterizes the *propulsive efficiency* of the detonation-fuel-combustion cycle, whereas its thermal efficiency η_t evaluates the loss and characterizes the economical operation. The quantities l_{cycle} and η_t are determined using the system of equations (5)–(7) as follows. To determine them we must know the temperature ratio T_4/T_1, as is seen from (1). However we can represent T_4/T_1 as the product of three factors: $T_4/T_1 = T_4/T_3 \times T_3/T_2 \times T_2/T_1$. For the adiabatic processes 1–2 and 3–4 at $p_1 = p_4$, we have the product $\frac{T_4}{T_3}\times\frac{T_2}{T_1} = \left(\frac{p_2}{p_3}\right)^{\frac{k-1}{k}}$ and consequently $\frac{T_4}{T_1} = \frac{T_3}{T_2}\left(\frac{p_2}{p_3}\right)^{\frac{k-1}{k}}$. Hence with Eqs. (5) and (6) we obtain

$$\frac{T_4}{T_1} = \frac{M_3^2}{M_2^2}\left(\frac{1 + kM_2^2}{1 + kM_3^2}\right)^{\frac{k+1}{k}} . \tag{8}$$

As is seen, the temperature ratio T_4/T_1 is a function only of the M_2 and M_3 numbers here, too. This equation makes it possible to calculate the quantities l_{cycle} and η_t; the minimum of the temperature ratio T_4/T_1 must correspond to the of l_{cycle} and η_t maxima.

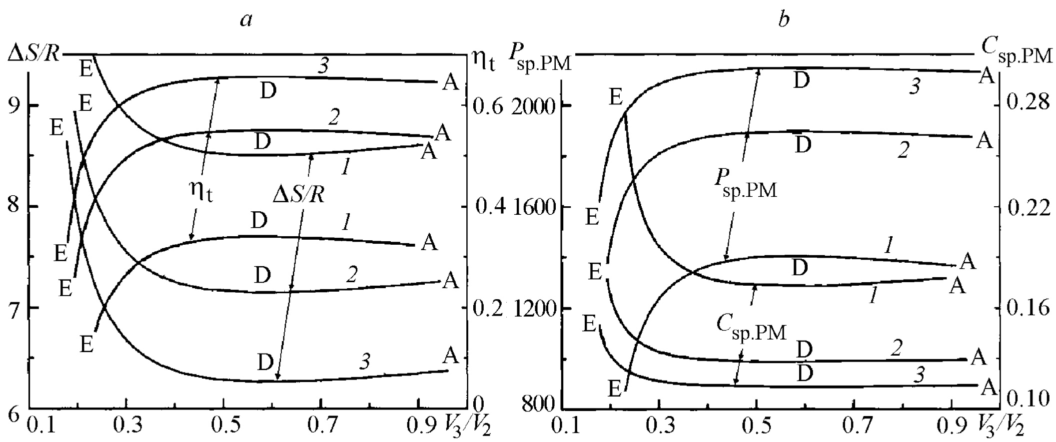


Fig. 5. Quantities $\Delta S/R$ and η_t (a), $P_{sp.PM}$ and $P_{sp.PM}$ (b) vs. V_3/V_2 and π_{comp}: 1) π_{comp} = 1, 2) 5, and 3) 10.

To more clearly visualize the parameters of the detonation-fuel-combustion cycle physically, we analyze them, representing them as functions of the ratio of specific volumes V_3/V_2 evaluating the *intensity* of detonation combustion waves. Values of V_3/V_2 lower than those at points D correspond to *supercompressed* detonation waves, whereas higher values correspond to *subcompressed* detonation combustion waves. Figure 5 plots the thermal efficiency of the detonation-fuel-combustion cycle, the entropy increment $\Delta S/R$, and the specific parameters of the pulse-detonation-engine PM as functions V_3/V_2. As is seen, the maximum values of η_t (and consequently of l_{cycle}) are attained at points D of the presented curves. It is seen that the minima of the $\Delta S/R$ values correspond to points D, too.

Entropy Analysis of the Detonation-Fuel-Combustion Cycle. We apply entropy analysis to evaluation of the influence of the loss on the efficiency of the detonation-fuel-combustion cycle. A distinctive feature of the detonation-fuel-combustion cycle is that it is *irreversible* because of the presence of compression shock waves; irreversibility is unique to process 2–3 of heat supply in detonation combustion waves. However, as is known from thermodynamics, the degree of irreversibility of the process of heat supply is characterized by the entropy increment in this process; the change in the entropy is a function only of the change in the state of the gas flow regardless of the process in which this state has been attained. In our case, at point 2 of process 2–3, the state of the gas flow (p_2 and T_2) is known. The gas state at point 3 (p_3 and T_3) is found from solution of the presented system of equations (5)–(7), if the quantity of the supplied heat q_1 is prescribed. In this case the change in the entropy in process 2–3 ($\Delta S = S_3 - S_2$), since it is a function only of the gas state at points 2 and 3, is determined (as is shown in [6]) from the formula

$$\Delta S = c_p \ln (T_3/T_2) - R \ln (p_3/p_2) , \tag{9}$$

where c_p is the specific heat of the working medium, which is averaged over process 2–3.

Formula (9) yields the overall increase in the entropy in a detonation combustion wave. It is made up of the reversible and irreversible components: $\Delta S = \Delta S_{rev} + \Delta S_{irrev}$. The reversible part is due to the increase in the temperature in the process of combustion of the fuel, whereas the irreversible part is related mainly to the decrease in the total pressure in the detonation combustion wave in which the fuel combustion is effected. The quantity ΔS_{rev} (for the adopted q_1 value and specified inlet conditions) is virtually a constant; therefore, $\Delta S = S_3 - S_2$ (or the dimensionless parameter $\Delta S/R$) changes only due to the change in ΔS_{irrev}, and $\Delta S/R$ minima attained at points D must correspond to the minimum ΔS_{irrev} values and maximum η_t values. This is confirmed by calculations whose results are presented in Fig. 5a.

If the quantities l_{cycle} and l_{comp} are known, we can determine the specific parameters of the pulse-detonation-engine PM. Since the works l_{cycle} and l_{comp} are transformed to the increment in the kinetic gas-flow energy, we have $w_4^2 - V_{fl}^2 = 2(l_{cycle} + l_{comp})$. From the outflow velocity w_4, we find $P_{sp.PM} = w_4 - V_{fl}$, and the quantities $P_{sp.PM}$ and $C_{sp.PM}$ are determined from the formulas

$$P_{\mathrm{sp.PM}} = \sqrt{2(l_{\mathrm{cycle}} + l_{\mathrm{comp}}) + V_{\mathrm{fl}}^2} - V_{\mathrm{fl}}\,, \quad C_{\mathrm{sp.PM}} = \frac{3600}{\alpha L_0 P_{\mathrm{sp.PM}}}\,, \tag{10}$$

where w_4 is the time-averaged value of the velocity of flow of the working medium out of the PM. The $P_{\mathrm{sp.PM}}$ and $C_{\mathrm{sp.PM}}$ values calculated by the above method as functions of V_3/V_2 are presented in Fig. 5b for different values of the parameter π_{comp}. Here, too, the most advantageous specific parameters of the PM are attained at points D.

We should take into account that weak detonation is unrealizable as a rule. Therefore, the data calculated for subcompressed detonation combustion waves are arbitrary in character. Also, it is well to bear in mind that the detonation-fuel-combustion cycle in question is not ideal, since the basic loss due to the irreversibility of heat supply to the detonation combustion wave has already been allowed for in its calculation. In the actual detonation-fuel-combustion cycle, just as in all existing gas-turbine engines, there is the hydraulic loss in the elements and the loss due to the incompleteness of fuel combustion. This calls for correction of the results of calculation according to the available experimental data. As has been shown in [7], the correction is reduced to applying comparatively small corrections to the calculated data.

The main conclusion to be drawn from consideration of the presented plot is that the *optimum operating regimes of the pulse-detonation-engine PM are attained for the detonation intensity corresponding to points* D of the presented curves (Fig. 5). Reduction in η_t with deviation from these regimes, particularly toward supercompressed detonation combustion waves, is seen to be related to the considerable increase in the loss due to the irreversibility of the process of heat supply in detonation combustion waves of the detonation-fuel-combustion cycle. The *use of supercompressed detonation combustion waves does not ensure the improvement of the parameters* of pulse-detonation-engine PMs. Points D on the resulting curves, for which we have $M_3 = 1$, correspond to Chapman–Jouget (CJ) detonation regimes well known from gas dynamics and described in [6] in detail.

Calculation of the Parameters of the Pulse-Detonation-Engine Cycle for Chapman–Jouget Detonation. In gas dynamics, it is proved that CJ detonation is the most stable form of detonation, since stabilization of the detonation combustion wave due to the occurrence of thermal crisis is attained at exit from the detonation combustion chamber at $M_3 = 1$ [6]. The procedure of calculation of the parameters and characteristics of pulse detonation engines for this case was given in [3] as early as 2002. The use of the system of equations (5)–(7) makes it possible to substantially simplify derivation of all computational formulas used in this procedure. In particular, from formula (7), on condition that $M_3 = 1$, we find the number $M_2 = M_{\mathrm{CJ}}$:

$$M_{\mathrm{CJ}} = \sqrt{\frac{k^2-1}{2}\frac{q_1}{a_2^2} + a_2^2} + \sqrt{\frac{k^2-1}{2}\frac{q_1}{a_2^2}}\,, \tag{11}$$

where $a_2^2 = kRT_2 = kRT_1\pi^{\frac{k-1}{k}}$ is the velocity of sound in the fuel mixture prior to its ignition (at point 2, Fig. 1). From formula (8), at $M_3 = 1$, we determine the temperature ratio T_4/T_1:

$$\frac{T_4}{T_1} = \frac{1}{M_{\mathrm{CJ}}^2}\left(\frac{1 + kM_{\mathrm{CJ}}^2}{k+1}\right)^{\frac{k+1}{k}}. \tag{12}$$

From the found T_4/T_1 value, we compute the thermal efficiency and the cycle work

$$\eta_t = 1 - \frac{c_p T_1}{q_1}\left[\frac{1}{M_{\mathrm{CJ}}^2}\left(\frac{1 + kM_{\mathrm{CJ}}^2}{k+1}\right)^{\frac{k+1}{k}} - 1\right], \quad l_{\mathrm{cycle}} = q_1\eta_t\,, \tag{13}$$

whereas the specific parameters are determined from the same formulas (10).

Fuel Consumption by the Working-Medium Generator. The working-medium generator itself (Fig. 3a) does not produce jet thrust in the design regime. It only makes the working medium available for all PMs. However, it becomes necessary to calculate the amount of fuel consumed by the working-medium generator. The specific hourly rate

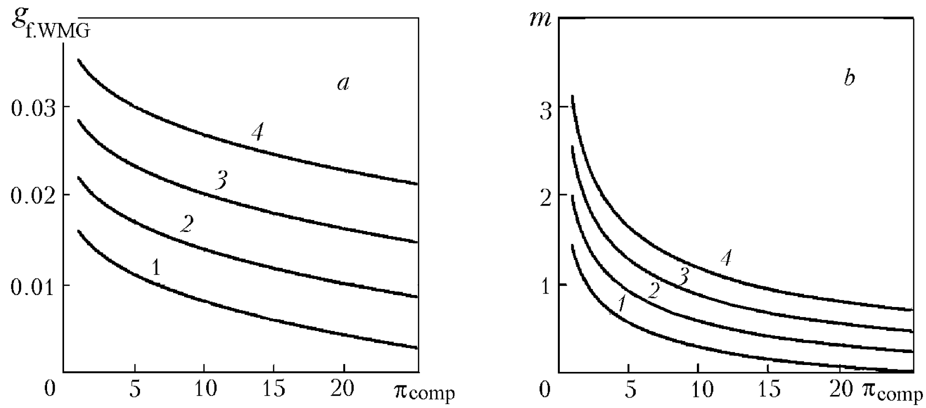


Fig. 6. Quantities $g_{\text{f.WMG}}$ (a) and m (b) vs. working-medium-generator parameters π_{comp} and T_{g} at $V_{\text{fl}} = 0$ and $H = 0$: 1) $T_{\text{g}} = 900$, 2) 1100, 3) 1300, and 4) 1500 K.

of fuel flow in the working-medium generator per 1 N of thrust created by the PM (since P_{WMG} is assumed to be equal to 0) is determined from the condition

$$C_{\text{sp.WMG}} = \frac{3600 G_{\text{f.WMG}}}{P_{\text{PM}}},$$

where $P_{\text{PM}} = G_{\text{airPM}} P_{\text{sp.PM}}$.

The air flow tapped off the compressor and entering the PM for the working-medium generator (Fig. 3a) is determined with allowance for the fact that $G_{\text{air}\Sigma} = G_{\text{airPM}} + G_{\text{air,c.ch}}$, where $G_{\text{air,c.ch}}$ is the flow rate of air entering the combustion chamber of the working-medium generator. To calculate the relative flow rate of air entering the PM, we introduce the parameter $m = G_{\text{airPM}}/G_{\text{air,c.ch}}$. When the value of m is known, the overall rate of air flow through the working-medium generator (Fig. 3a) is equal to $G_{\text{air}\Sigma} = [(m+1)/m]G_{\text{airPM}}$. The relative rate of fuel flow in the working-medium generator per 1 kg/sec of air entering the combustion chamber of the working-medium generator is equal to $g_{\text{f.WMG}} = G_{\text{f.WMG}}/G_{\text{air,c.ch}}$. To determine it, we use the condition of heat balance of the working-medium generator $G_{\text{f.WMG}} H_{\text{u}} \eta_{\text{c}} = Q G_{\text{air,c.ch}}$, where $Q = c_p(T_{\text{g}} - T_{\text{comp}})$ is the heat expended in heating the gas from the temperature $T_{\text{comp}} = T_2$ behind the compressor to the temperature T_{g} ahead of the turbine. Then we have

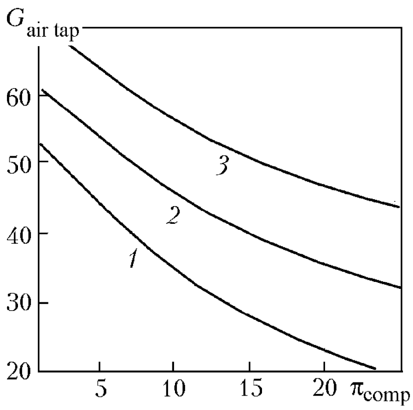
$$g_{\text{f.WMG}} = \frac{c_p\,(T_{\text{gas}} - T_{\text{comp}})}{\eta_{\text{c}} H_{\text{cycle}}},$$

where η_{c} is the coefficient of completeness of fuel combustion in the working-medium generator and c_p is the average specific heat of the gas in the temperature interval $T_{\text{comp}} - T_{\text{g}}$. With allowance for the found values of m and $g_{\text{f.WMG}}$ we determine $C_{\text{sp.WMG}}$:

$$C_{\text{sp.WMG}} = \frac{3600 g_{\text{f.WMG}}}{m P_{\text{sp.PM}}}. \tag{14}$$

The quantities m and $g_{\text{f.WMG}}$ appearing in (14) are functions of the parameters π_{comp} and T_{g} of the working-medium generator. To determine m we use the equation of balance of the capacities of the compressor and turbine of the working-medium generator $G_{\text{air}\Sigma} l_{\text{comp}} = G_{\text{g}} l_{\text{turb}}$ and the equation of balances of the flow rates of air $G_{\text{air}\Sigma} = G_{\text{air,c.ch}}(1 + m)$ and the gas $G_{\text{g}} = G_{\text{air,c.ch}}\,(1 + g_{\text{f}})$, from which we find the interrelation of the quantities m and $g_{\text{f.WMG}}$:

$$(1+m)\, l_{\text{comp}} = (1 + g_{\text{f.WMG}})\, l_{\text{turb}}. \tag{15}$$



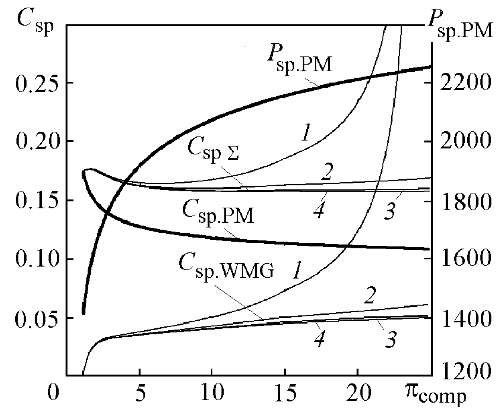


Fig. 7. Quantity $G_{\text{air tap}}$ vs. working-medium-generator parameters π_{comp} and $T_g \left(G_{\text{air tap}} = \frac{m}{m+1} G_{\text{air}\Sigma} \right)$: 1) T_g = 1100, 2) 1300, and 3) 1500 K. $G_{\text{air tap}}$, %.

Fig. 8. Quantities $P_{\text{sp.PM}}$ and C_{sp}. vs. working-medium-generator parameters π_{comp} and T_g for CJ detonation at $\alpha_\Sigma = 1$ (the fuel is kerosene): 1) T_g = 900, 2) 1100, 3) 1300, and 4) 1500 K. C_{sp}, kg/(N·h); $P_{\text{sp.PM}}$, N·sec/kg.

Here the compressor work l_{comp} in the working-medium generator is determined from a prescribed π_{comp} value, whereas the turbine work l_{turb} can be found at a prescribed at temperature T_g from the fact that in the working-medium generator (Fig. 3a) (at $P_{\text{WMG}} = 0$) we have $\pi_{\text{turb}} \approx \pi_{\text{comp}}$, since the gas flow in the turbine is expanded to atmospheric pressure. Figure 6 plots m and $g_{\text{f.WMG}}$ as functions of π_{comp} and $T_{\text{g.WMG}}$. The amount of air that can be tapped off the working-medium generator compressor (Fig. 3a) is also dependent on the design parameters of the working-medium generator π_{comp} and T_g (Fi. 7). It is seen that for moderate values of the temperature T_g (of the order of 1300 K) and for $\pi_{\text{comp}} \approx 5$–10, the amount of air tapped off the working-medium generator amounts to about 50% of $G_{\text{air}\Sigma}$.

The specific parameters of a pulse detonation engine as functions of $\pi = \pi_{\text{comp.WMG}}$ are plotted in Fig. 8 for different values of T_g of the working-medium generator. Here $P_{\text{sp.PM}}$ values increase with $\pi_{\text{comp.WMG}}$, whereas $C_{\text{sp.PM}}$ values diminish, which is due to the improvement of utilization of the supplied heat q_1 in the detonation-fuel-combustion cycle with growth in π_{comp}. However, $C_{\text{sp.WMG}}$ increases with π_{comp} and the plot of $C_{\text{sp}\Sigma}$ as a function of π_{comp} levels out. The $C_{\text{sp}\Sigma}$ minimum is attained for $\pi_{\text{comp.WMG}} \approx 5$–8 and is weakly dependent on the temperature $T_{\text{g.WMG}}$. Consequently, a working-medium generator of this scheme does not require high parameters of the operating process, which are characteristic of today's gas-turbine engines. For example, if the diametral dimension of the working-medium generator is not determining, the acceptable data are ensured by a working-medium generator with a single-stage centrifugal compressor and an uncooled single-stage gas-turbine (Fig. 3). However, the fuel expenditure in actuating the working-medium generator is as large as 30% of $C_{\text{sp.PM}}$ and is allowed for by formula (14).

Calculation of the Characteristics of a Pulse Detonation Engine when the PM Is Installed behind the Turbine. Since in this case the detonation-fuel-combustion cycle is open, it is more correct to calculate the detonation combustion wave directly from prescribed parameters p_2 and T_2 of the gas flow at the PM inlet [8] rather than in terms of the cycle work. We find the velocity of sound $a_2 = \sqrt{kRT_2}$ from these parameters and the mach number $M_2 = M_{CJ}$ from formula (11). Next, from formulas (5) and (6), we determine the ratios of the pressures p_3/p_2 and the temperatures T_3/T_2 at $M_3 = 1.0$. We determine the parameters at point 3 from a prescribed p_2 and compute the velocity of gas flow w_4 out of the PM (on expansion of combustion products from the pressure p_3 to the pressure $p_4 = p_1$) from the equation $w_4 = \sqrt{2c_pT_3[1-(p_1/p_3)^{(k_g-1)/k_g}]}$ and the PM specific thrust $P_{\text{sp.PM}} = w_4 - V_{\text{fl}}$ from the parameters at point 3 of process 2–3. Here the averaged values of c_p and k in the temperature range T_3–T_4 are taken as these quantities.

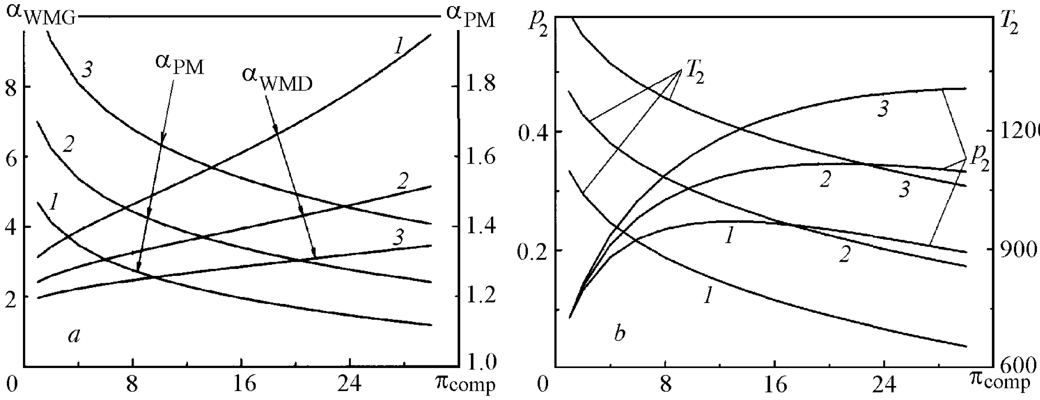


Fig. 9. Quantities α_{PM}, α_{WMG} (a) and p_2, T_2 (b) of the working-medium-generator design parameters π_{comp} and T_g: 1) T_g = 1100, 2) 1300, and 3) 1500 K. p_2, MPa; T_2, K.

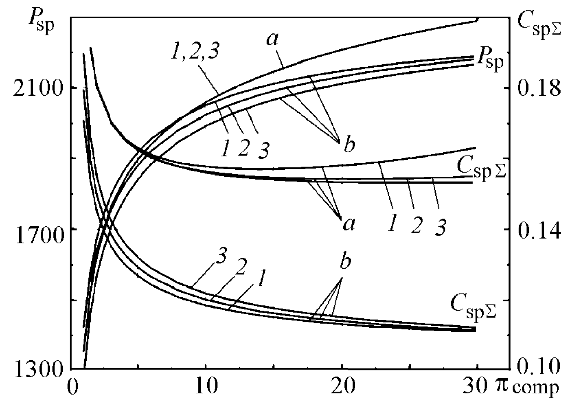


Fig. 10. Comparison of P_{sp} and $C_{sp\Sigma}$ for pulse detonation engines (Fig. 3) for different working-medium-generator parameters π_{comp} and T_g with allowance for the fuel consumption by the working-medium-generator: 1) T_g = 1100, 2) 1300, and 3) 1500 K. P_{sp}, N·sec/kg; $C_{sp\Sigma}$, kg/(N·h).

Determination of the heat q_{1PM} supplied to the PM gas is of importance. Partial combustion of the fuel in the working-medium generator (Fig. 3b) influences the excess-air coefficient α_{PM} in the PM and the stoichiometric coefficient L_{0PM}. The reason is that the same air participates in fuel combustion twice: first in the working-medium generator and then in the PM. Therefore, in the case of complete utilization of air by fuel combustion, i.e., when $\alpha_\Sigma = 1$, we cannot obtain $\alpha_{PM} = 1$. The quantity α_{PM} in these cases turns out to be more than unity.

The total quantity of supplied heat (per 1 kg of the working medium) is $q_\Sigma = q_{WMG} + q_{PM}$; therefore, we obtain $\dfrac{1}{\alpha_\Sigma L_{0\Sigma}} = \dfrac{1}{\alpha_{WMG} L_{0WMG}} + \dfrac{1}{\alpha_{PM} L_{0PM}}$; the quantity α_{WMG} is dependent on π_{comp} and T_g of the working-medium generator. The plots of α_{WMG} and α_{PM} (at $\alpha_\Sigma = 1$) as functions of π_{comp} and T_g, which have been calculated from these considerations, are presented in Fig. 9a. For the PM, it is desirable to have as large air excesses as possible in the combustion chamber of the working-medium generator with the aim of obtaining α_{PM} minima in the PM combustion chamber and of increasing the fraction of heat supplied to it. As is seen, the α_{PM} minima (close to unity) correspond to low T_g and high π_{comp}. The parameters of the gas flow (p_2 and T_2) entering the PM in this case as functions of T_g and π_{comp} of the working-medium generator are given in Fig. 9b. Here the level of temperatures T_2 is quite significant, but the possibilities of obtaining high pressures p_2 are limited.

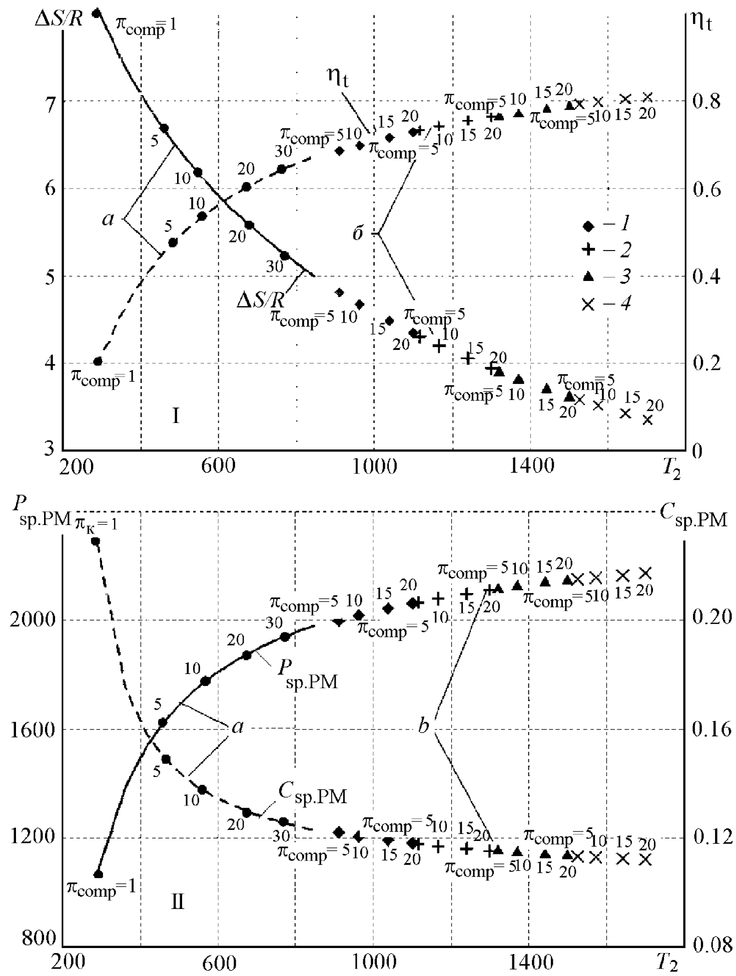


Fig. 11. Generalized dependences of $\Delta S/R$ and η_t (I), $P_{sp.PM}$ and $C_{sp.PM}$ (II) on T_2 for different working-medium-generator parameters π_{comp} and T_g at α_Σ = 1, M = 0, and H = 0 (the fuel is kerosene) (a and b, see Fig. 3): 1) 1100, 2) 1300, 3) 1500, and 4) 1700 K. $P_{sp.PM}$, N·sec/kg; $C_{sp.PM}$, kg/(N·h); T, K.

From the parameters found at point 2 ahead of the detonation combustion wave and from formulas (5) and (6) at M_3 = 1 we determine the parameters p_3 and T_3 at point 3 behind the detonation combustion wave (Fig. 1) and then find P_{sp} and $C_{sp\Sigma}$. These quantities as functions of T_g and π_{comp} for $\alpha_\Sigma = 1$ on condition that M = 0 and H = 0 are given in Fig. 10. As is seen, the efficiency at utilization of the supplied heat q_1 is improved with growth in π_{comp}. Figure 10 also shows the quantities $P_{sp.PM}$ and $C_{sp\Sigma}$ found earlier for Fig. 3a (when the PM is installed behind the compressor). It is clear that *installation of the PM behind the turbine is more advantageous*, since it gives a considerable gain in $C_{sp\Sigma}$ values (up to 30–40%) (with allowance for the differences in fuel consumptions by the working-medium generator). The main reason for such a considerable improvement of the economical operation of the pulse-detonation-engine PM (Fig. 3b compared to Fig. 3a) is that *increase in the temperature T_2 at the PM inlet substantially improves the efficiency of the detonation-fuel-combustion cycle*. This is due to the favorable influence of the increase in the temperature T_2 on the specific parameters of the pulse-detonation engine PM.

Generalized Characteristics of Pulse-Detonation Engine PMs. Temperature T_2 is the determining factor evaluating the thermodynamic efficiency of a pulse-detonation engine PM. This follows from an analysis of the system of equations that has been obtained for calculation of the parameters of detonation combustion waves. The analysis shows that the basic parameters evaluating the thermodynamic efficiency of the detonation-fuel-combustion cycle, such as the cycle work, thermal efficiency, specific thrust, and specific fuel flow rate of the pulse-detonation

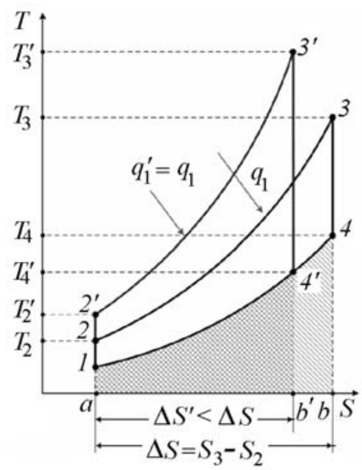


Fig. 12. Comparison of detonation-fuel-combustion cycles in T–S coordinates at different working-medium temperatures T_2 at the PM inlet ($T_2' > T_2$).

engine PM are one-parameter dependences on the temperature T_2 of the working medium (air, gas, or fuel-air mixture) entering the PM.

Indeed, if the temperature T_2 is prescribed, we find, from (11), the quantity $M_2 = M_{CJ}$ for the known values of the supplied heat q_1 and the adiabatic exponent k and determine, from (12), the temperature ratio T_4/T_1 according to which l_{cycle} and η_t are determined from (1). The PM specific thrust is unambiguously found from l_{cycle}. For example, under test-bed conditions, we have $P_{sp.PM} = \sqrt{2q_1 l_{cycle}}$, whereas the quantity $C_{sp.PM}$ is determined in terms of $P_{sp.PM}$ from relation (10). The dependences $\Delta S/R$ are single-valued foundations of the temperature T_2, too, since in accordance with relation (9), they are dependent, under the conditions in question, only on the parameters p_3/p_2 and T_3/T_2 which are functions only of M_2 and consequently the temperature T_2 at $M_3 = 1$.

The validity of this analysis is fully confirmed by the calculated data, which are presented in Fig. 11. These calculations have been performed for the entire set of pressures p_2 and temperatures T_2 (Fig. 9b) when the PM is installed in the hot-gas flow (Fig. 3b) and for all p_2 and T_2 values determined earlier when the PM is installed in the cold-air flow (Fig. 3a). As is seen, the calculated points corresponding to each investigated parameter (η_t, $P_{sp.PM}$, $C_{sp.PM}$, and $\Delta S/R$) fall on its single curve for all values of the parameters of the operating process of the working-medium generator, i.e., π_{comp} and T_g, and in different modes of installation of the PM. They are independent of the pressure p_2 (within its permissible values), the number of PMs, and their dimensions. This points to the *universality of the obtained dependences*.

From these generalized dependences, it is clear that as the temperature T_2 increases, the loss due to the irreversibility of the process of heat supply in the detonation combustion wave substantially diminishes, the thermal efficiency η_t (and consequently the cycle work l_{cycle}) improves, $P_{sp.PM}$ grows, and $C_{sp.PM}$ decreases. In particular, as follows from Fig. 11, the increase from 500 to 1500 K in T_2 causes η_t to increase by approximately 60%; the value of $P_{sp.PM}$ increases, whereas $C_{sp.PM}$ diminishes by nearly 25% under test-bed conditions. Also, we emphasize that the generalized PM characteristics obtained for $M = 0$ and $H = 0$ are easily recalculated for different flight conditions, which substantially simplifies calculation of the altitude-speed characteristics of power units with pulse detonation engines.

Physical Reasons for the Favorable Influence of the Temperature T_2 on the Thermodynamic Efficiency of the Detonation-Fuel-Combustion Cycle. They are clearly illustrated by Fig. 12. It compares the thermodynamic cycles of detonation fuel combustion in T–S coordinates. The comparison is performed under identical external conditions (equality of the pressures p_1 and temperatures T_1) and the same values of supplied heat ($q_1 = q_1'$). The only difference is that the temperature T_2' of the fuel-air mixture at the PM inlet is higher than the temperature T_2. The condition $q_1 = q_1'$ in Fig. 12 corresponds to the equality of the areas of ducts a–1–2–3–4–b and a–1–2′–3′–4′–b'. The removed heat q_2 and q_2' are equivalent to the areas of ducts a–1–4–b and a–1—4′–b'. As is seen, the quantity of removed heat decreases with increase in the temperature T_2, which corresponds to the condition $q_2' < q_2$. As a result of growth in the temperature T_2, the maximum cycle temperature increases $T_3' > T_3$), whereas the exhaust-gas temperature diminishes ($T_4' > T_4$). The process 2–3 itself of detonation fuel combustion shifts to the region of higher pressures and temperatures, which precisely ensures $q_2' < q_2$. Decrease in the quantity of removed heat leads to a growth in the cycle work and thermal efficiency, since $l_{cycle} = q_1 - q_2$ and $\eta_t = 1 - q_2/q_1$, and to a decrease in the entropy increments ($\Delta S' < \Delta S$), i.e., to a reduction in the irreversibility loss by the process of heat supply to the detonation combustion wave.

CONCLUSIONS

1. On the basis of the obtained system of equations (5)–(7) and the established notion of the thermodynamic cycle of detonation-fuel-combustion engines (detonation-fuel-combustion cycle), we have developed an engineering method for the calculation of the parameters of detonation combustion waves and the propulsion-economical characteristics of pulse detonation engines.

2. It has been shown that the maximum values of the cycle works and thermal efficiencies of engines using the detonation-fuel-combustion cycle, and hence the most advantageous specific parameters of them, are attained for a detonation intensity corresponding to Chapman–Jouget conditions. The use of supercompressed detonation combustion waves does not ensure the improvement of the specific parameters of pulse-deformation-engine PMs.

3. By the method developed we have performed a comparative analysis of two different structural diagrams of pulse detonation engines, which differ by the mode of PM installation. The determining influence of the heating of a working medium supplied to the PMs of pulse detonation engines on their thermodynamic efficiency has been shown. On this basis, we have established a substantial advantage of economical operation (to 30–40%) of the pulse-detonation-engine scheme in which detonation combustion chambers are installed in the hot-gas flow at the turbine outlet compared to their installation in the flow of relatively cold air tapped off the compressor.

4. We have obtained the generalized dependences for calculation of the parameters and characteristics of pulse-detonation-engine PMs. They are one-parameter dependences of the thermal efficiency, cycle work, and specific parameters of a PM on the temperature T_2 of the working medium entering the PM. These regularities are universal, since they hold for PMs of different dimensions and with different modes of their installation and for working-medium generators of different schemes having different design parameters of the operating process.

NOTATION

a, velocity of sound, m/sec; c_p, average specific heat of the gas (air), J/(kg·K); C_{sp}, specific rate of fuel flow, kg/(N·h); D_{res}, resonator diameter, mm; G_{air}, air flow rate, kg/sec; G_g, gas flow rate, kg/sec; G_f, fuel flow rate, kg/sec; $g_{f.WMG}$, relative rate of fuel flow in the working-medium generator; H, flight altitude, m; H_u, low calorific value of the fuel, J/kg; k, adiabatic exponent; L_0, stoichiometric coefficient; l_{comp}, compressor work, J/kg; l_{turb}, turbine work, J/kg; l_{cycle}, cycle work, J/kg; M, Mach number; m, bypass ratio of the working-medium generator; P, jet thrust, N; P_{sp}, specific thrust, N·sec/kg; p, pressure, Pa and MPa; Q, quantity of heat, J/kg; q_1, supplied heat, J/kg; q_2, removed heat, J/kg; R, gas constant, J/(kg·K); S, entropy, J/(kg·K); $\Delta S/R$, entropy increment; T, temperature, K; T_g, gas temperature ahead of the turbine, K; T_{comp}, air temperature behind the compressor, K; V, specific volume, m^3/kg; V_{fl}, flying speed, m/sec and km/h; w, gas velocity, m/sec; α, excess-air coefficient; η_c, coefficient of completeness of fuel combustion; η_t, thermal efficiency; π_{comp}; degree of increase in the air pressure in the compressor; π_{turb}, degree of reduction in the gas pressure in the turbine; ρ, density, kg/m^3. Subscripts: air, air; g, gas; comp, compressor; c.ch, combustion chamber; irrev, irreversible; rev, reversible; tap, tapping; cool, cooling; fl, flight; st, starting; r, reactor; res, resonator; f, fuel; turb, turbine; sp, specific; cycle, cycle; Σ, overall, total; t, thermal; 1, 2, 3, and 4, cross sections along the engine duct (Fig. 1).

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