JOURNAL OF PROPULSION AND POWER
Vol. 17, No. 6, November–December 2001

Advancement of Scramjet Magnetohydrodynamic Concept

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A comparative thermodynamic analysis of several schemes of scramjets was performed. A conventional scheme and two alternative versions were considered. These versions differ by incorporation of magnetohydrodynamic (MHD) devices into the propulsion-system flow train. The first version relates to the earlier-developed AJAX concept, and a second one is a concept modification that represents a combination of MHD generator with downstream part of combustor. The cycles under study were composed of elementary thermodynamic processes. In numerical modeling of these processes, real air properties were used because of wide range of thermodynamic parameters variation. Engineering limitations on the maximum allowable values of static temperature in the flow train and velocity in the combustor were introduced. It was determined that under flight conditions chosen for the analysis the conventional design of the scramjet does not meet the limitations. Appropriate working regimes may be provided in the AJAX concept, but in that case dissipation losses increase significantly and the propulsion system specific thrust is reduced. A modification of the AJAX concept with the combustion heat bypassing from combustor into the nozzle allows obtaining high integral parameters of the cycle with compliance within imposed engineering constraints.

Nomenclature

F_r	=	specific thrust, m/s
h	=	enthalpy, kcal/kg
k_g	=	kinetic energy conversion factor for magnetohydrodynamic (MHD) generator
k_{sd}	=	kinetic energy conversion factor for supersonic diffuser
M	=	Mach number
N_a	=	electrical power input in MHD accelerator, kcal/kg
N_g	=	electrical power output in MHD generator, kcal/kg
p	=	pressure, atm
Q_c	=	specific fuel combustion heat, kcal/kg
Q_e	=	specific joule heat release, kcal/kg
R_{abs}	=	absolute gas constant, kcal/kmole · K
s	=	entropy, kcal/kg · K
T	=	temperature, K
u	=	velocity, m/s
W	=	kinetic energy, kcal/kg
η_e	=	electric efficiency factor
μ	=	molar mass, kg/kmole
ρ	=	density, kg/m^3
φ	=	angle between velocity vector and shock front, deg

Subscripts

a	=	after shock
b	=	before shock
c	=	combustor parameters
i	=	number of iterations in iterative process
k	=	number of shocks
0	=	stagnation parameters
1, 2, 2m, 3, 3p, 3t, 3m, 4m, 4	=	knot points of cycle diagrams

Received 19 August 2000; revision received 1 December 2000; accepted for publication 29 December 2000.

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Introduction

THE velocity of aircraft equipped with a ramjet engine (RAM) should rise with increase of flight altitude to compensate for a reduction of environmental air density. At flight altitude of about 30 km, the rated flight Mach number providing an airflow rate needed to maintain a specified value of the thrust is equal to 7–8. In spite of the high quality of modern supersonic diffusers, a deceleration of such flow down to subsonic velocity occurs with high shock wave losses sharply decreasing the propulsion system efficiency. Furthermore, deep deceleration of the hypersonic flow results in substantial increase of static temperature, which may achieve very high values (∼3500 K and higher). At these temperatures, the radiation component will dominate in a radiative–convective heat transfer, and the conditions of thermal resistance of the propulsion system design dictate a limitation on static temperature. This limitation in the flow train is partly met by increasing velocity. This approach can be used until the velocity in the combustor reaches the value at which stable combustion ceases. Thus, a new limitation on maximum flow velocity arises.

These problems may be lessened by application of a supersonic combustor operating at high velocity of motion of the reacting components. An overview of the main aspects and problems of physics of the supersonic combustion for application to the conventional design of a scramjet has been given in the classical work of Ferri.[1] Great attention has been given to this research. Nevertheless, to date only one flight experiment has been performed with Mach number $M = 5$ (Ref. 2). According to estimates, at $M > 8$, the kinetic energy of the freestream flow is so high that engineering constraints on static temperature after heat release in the combustor may be met only at very high flow velocity, whereby it is difficult to arrange an efficient combustion process. In so doing, the development of supersonic combustor for a scramjet of conventional design will require more considerable effort and time and as yet is problematic.

In parallel, a search of new approaches to the scramjet operation organization is continuing to provide an acceptable efficiency of the propulsion system under the engineering constraints. One of them is the AJAX concept based on the application of magnetohydrodynamic (MHD) technology to bypass the kinetic energy from a supersonic diffuser into a nozzle.[3–6] According to this concept, the scramjet design incorporates an MHD generator located between the diffuser and the combustor and an MHD accelerator situated between the combustor and the nozzle. An MHD generator is used for the conversion of part of the flow kinetic energy into electrical energy that is transferred to an MHD accelerator for additional acceleration of combustion products. The concept authors supposed that the combined (geometric and MHD) method of flow deceleration in front of the combustor would allow reduction of the flow velocity to an acceptable value at lower dissipation losses and satisfy the corresponding constraints. The prospects for the concept depend on answers to two questions. The first question is concerned with the thermodynamic analysis of the scheme efficiency in comparison with conventional design of the scramjet. The second question refers to the feasibility of the concept proposed, that is, the possibility of arrangement of efficient operation of MHD devices at specific parameters of the working fluid in the scramjet duct and under existing mass and dimension constraints. It is evident that consideration of the second question depends on the first one having have a positive response.

The thermodynamic analysis of the scramjet scheme within the framework of the AJAX concept was the initial goal of the present work. However, in the process of performing the analysis, having revealed imperfections of the concept, a proposal to modify the concept was made to bypass the energy (both kinetic and thermal) directly from the combustor. It means a combination of combustor and MHD generator because an MHD energy conversion inside of the combustor is preferable from considerations of thermodynamic efficiency. An MHD accelerator may be combined with the nozzle, as well occupying some of its segment. The thermodynamic advantages of this scheme are determined by comparative analysis of the cycles described in the present work.

Note that a description of the ramjet cycles in terms of efficient values of nonideality of the processes of compression and expansion was given in Ref. 7, and general approaches to thermodynamic analysis of AJAX design were outlined in the recent work of Cole et al.,[8] where the perfect gas approximation was used and a constraint on stagnation temperature was applied to the propulsion system flow train. The design of the AJAX flow train has been studied in Ref. 9. The concept was improved by implementation of a two-plane shock system in the inlet diffuser. The computational technique was enhanced by introduction of turbulent viscous boundary layers of the train walls and chemical kinetics in supersonic flow expansion in the nozzle. These effects have been proved to be essential for the engine specific impulse evaluation. The conclusion was that there is a vehicle speed range where an MHD system is superior than that of a non-MHD system. This was conditioned by rather high electrical efficiency of MHD devices.

Cycle Configuration and Implied Assumptions

Let us consider the thermodynamic cycles of the three scramjet schemes just mentioned. Simplified block diagrams of the schemes are given in Figs. 1–3. For the initial point of the cycles, the parameters of airflow corresponding to flight altitude of about 30 km and

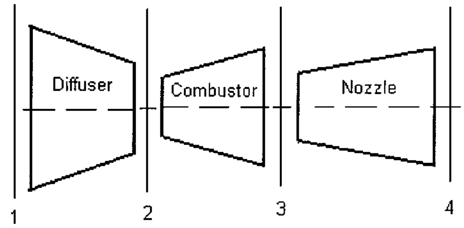

Fig. 1 Simplified block diagram of conventional scramjet scheme.

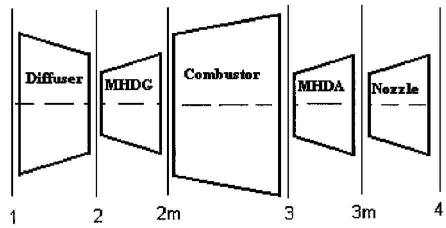

Fig. 2 Simplified block diagram of AJAX scheme.

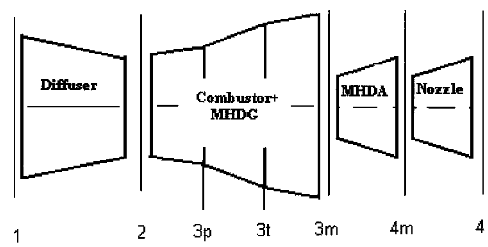

Fig. 3 Simplified block diagram of the RAM–MHD scheme.

Mach number $M_1 = 8$ are equal to the following values: pressure $p_1 = 0.012$ atm, temperature $T_1 = 230.3$ K, velocity $u_1 = 2436$ m/s, enthalpy $h_1 = 55$ kcal/kg, and entropy $s_1 = 1.97$ kcal/kg · K. The fuel combustion heat Q_c is taken as 826 kcal/kg, which approximately corresponds to hydrogen combustion in air. The range of variation of the static parameters in the scramjet flow train under intensive flow deceleration is very wide, and application of the perfect gas model leads to an error in the determination of the cycle parameters. In this connection, the analysis is performed for real air properties that were defined by diagrams of its thermodynamic functions.[10] The cycles are constructed in coordinates of static enthalpy h and entropy s.

It was supposed that the compression process in the supersonic diffuser is adiabatic and goes along a curve approximating a system of three oblique shocks and a following normal shock wave of equal stagnation pressure ratio. It was assumed that the working fluid expansion in a nozzle is isentropic, and the processes in the MHD devices are isothermal. The other assumptions are common hypotheses used for the thermodynamic analysis. An aircraft velocity, freestream parameters, fuel combustion heat, and integral efficiency factor of MHD devices are assumed as fixed parameters for all calculations. A comparison of different schemes was performed in terms of the specific thrust of the propulsion system taking into account engineering constraints on maximum allowable static temperature and velocity in the combustor.

To describe the technique of the cycle construction and particular assumptions used for the cycle models development, let us consider each of the schemes.

Conventional Scramjet Design

Conventional scramjet design (Fig. 1) falls into the family of Brayton cycles and consists of two adiabatic processes, compression in the supersonic diffuser (points 1 and 2 in Fig. 1) and expansion in the nozzle (points 3 and 4), and two isobaric processes, heating in combustor (points 2 and 3) and heat rejection into atmosphere (points 4 and 1).

The flow kinetic energy $W_2 = u_2^2/2$ at the diffuser outlet (completion of compression process corresponds to point 2) was defined by a factor $k_{sd} = W_2/W_1$, which was varied from 0.01 to 0.75. It was assumed that the compression process in the diffuser up to velocity u_2 occurs along the curve approximating, in h–s coordinates, a system of three oblique shocks and a following normal shock wave. Relative losses of stagnation pressure for each of the shocks were predetermined as roughly $p_{0k}/p_{0k+1} \approx 2$, which for a fixed number of shocks provides integral shock wave losses in the supersonic diffuser close to minimum value. As made in Refs. 11 and 12, corrections of Oswatitsch's results (see Ref. 13) are not critical for the goals of the present study.

Application of graphic diagrams of air thermodynamic functions notably complicates the task of description of the shock waves system. To solve this problem, an iterative algorithm has been developed based on expressions for pressure and enthalpy after the shock wave:

$$p_a = p_b + \rho_b u_{nb}^2 (1 - u_{na}/u_{nb}) \tag{1}$$

$$h_a = h_b + 0.5u_{nb}^2 \left(1 - u_{na}^2 \big/ u_{nb}^2\right) \tag{2}$$

The expressions follow from the conservation equations for the shock wave written in terms of velocity component u_n normal to the shock front. The value u_{nb} is defined by an angle φ between the velocity vector and the shock wave front: $u_{nb} = u_b \sin\varphi$. The value of angle φ is assigned to provide the given ratio p_{0k}/p_{0k+1}.

The iterative process is constructed in the following way. By the use of the value u_{na}^i obtained in the previous iteration ($u_{na}^0 = 0$ may be used as an initial approximation for u_{na}), the new values of p_a^{i+1} and h_a^{i+1} are calculated; then temperature and molar mass after the shock wave are determined from diagrams,[9]

$$T_a^{i+1} = T\left(h_a^{i+1}, p_a^{i+1}\right), \qquad \mu_a^{i+1} = \mu\left(h_a^{i+1}, p_a^{i+1}\right) \tag{3}$$

The new density value is determined from the thermal equation of state:

$$\rho_a^{i+1} = \frac{p_a^{i+1}\mu_a^{i+1}}{R_{\text{abs}} \times T_a^{i+1}} \tag{4}$$

Finally, from the equation of flow mass conservation, the new value of velocity u_{na}^{i+1} is calculated,

$$u_{na}^{i+1} = u_{nb} \times \rho_b \big/ \rho_a^{i+1} \tag{5}$$

The process is finished when $|1 - u_{na}^{i+1}/u_{na}^i| \leq \varepsilon = 10^{-3}$. For complete convergence, as a rule, it is enough to perform 5–6 iterations. If it is needed, the value of φ is corrected, and the process is repeated to the extent of assigned ratio p_{0k}/p_{0k+1}. With this algorithm, the flow parameters after each shock wave were obtained, and the deceleration curve was plotted with the outlet velocity $u_2 = 243$ m/s. The compression process completion in the diffuser at the specified value of k_{sd} (point 2 in h–s diagram) is defined by the intersection of the deceleration curve and the isoenthalpy line $h = h_2 = h_{01} - u_2^2/2 = \text{const}$.

Assumptions used at the construction of the combustion process (curve 2–3) are typical for thermodynamic analysis: The mass flow rate increase due to fuel injection was neglected, and an absence of momentum losses due to skin friction and heat losses was assumed. The latter assumption means that due to the isobaric condition the flow velocity at this part of the cycle is constant, and variations of static and total enthalpy are equidistant. Thus, the completion of this process (point 3) corresponds to the intersection of isobaric curve $p = p_2$ and isoenthalpy line $h = h_3 = h_2 + Q_c$.

Dissipative losses in the nozzle were neglected on the assumption that they have an equal relative influence in the comparative analysis carried out. Thus, the nozzle expansion process is assumed to be isentropic and in the h–s diagram represents the vertical line segment from point 3 to the intersection with isobar curve $p = p_1$ (point 4). The cycle is closed by this isobaric curve. Of course, the assumption on the isentropic expansion process in the nozzle must be revised in the quantitative analysis of the specific design.

For the comparative analysis the following values of k_{sd} were chosen: 0.01, 0.25, 0.5, and 0.75. The effect of shock wave losses in the diffuser on efficiency of a conventional scramjet scheme at different k_{sd} was discovered by a comparison of the cycles constructed with application of the technique described (case B) and with an assumption that the compression process in diffuser is isentropic (ideal) (case A).

AJAX Concept

As already noted, the AJAX concept (Fig. 2) differs from the conventional scramjet design in particular by a presence of additional devices in the propulsion system: MHD generator (MHDG) and MHD accelerator (MHDA).

The MHDG is installed between supersonic diffuser and combustor, and the MHDA is located between combustor and nozzle. Accordingly, the cycles constructed for this design include additional processes: 2–2m, MHD energy generation, and 3–3m, MHD flow acceleration.

In the analysis, it was assumed that these processes are isothermal when the flow kinetic energy is mainly converted into electrical energy. It corresponds to the basic idea of the authors of the AJAX concept: to bypass the kinetic energy from the diffuser to the nozzle, which will allow lower velocity in the combustor with the possible reduction of total dissipative losses. Moreover, this velocity reduction does not result in an increase of static temperature at the combustor inlet.

Description of MHD processes is completed by setting the factor $k_g = W_{2m}/W_2$, governing the conversion of kinetic energy in MHDG, equality $N_g = N_a$, where specific electrical power output in MHDG $N_g = h_{02} - h_{02m}$, electrical power input in MHDA $N_a = h_{03m} - h_{03}$, and integral electric efficiency factors $\eta_{eg} = N_g/(N_g + Q_{eg})$ for MHDG and $\eta_{ea} = (N_a - Q_{ea})/N_a$ for MHDA.[14] In the calculations, the factors η_{eg} and η_{ea} were set as constant values of 0.8. From the authors' experience in the development of stationary and pulse MHD devices,[15,16] these values of η_e provide a rather efficient process of the MHD energy conversion. The feasibility of this process depends mainly on whether needed values of electrical conductivity of the working fluid and magnetic field induction in scramjet MHD devices are achieved. This problem is of special consideration (for instance, see Ref. 17, where possibilities of electron beam ionization in hypersonic MHD channels are analyzed) and is beyond the scope of this work.

The determination of the wall skin-friction momentum and heat losses in the flow train is also outside the thermodynamic analysis conducted because this demands specification of design parameters of the system.

The entropy s_{2m} and static enthalpy h_{2m} are related by

$$h_{2m} = h_{02} - W_{2m} - (s_{2m} - s_2)\eta_{eg} T_2/(1 - \eta_{eg}) \tag{6}$$

following from the relationships for $s_{2m} = s_2 + Q_{eg}/T_2 = s_2 + [(1 - \eta_{eg})/\eta_{eg}]N_g/T_2$ and $N_g = h_{02} - (h_{2m} + W_{2m})$. Thus, the process in MHDG is completed at the point of intersection of the isothermal curve $T = T_2$ and the straight line $h(s) = h_{02} - W_{2m} - (s - s_2)\eta_{eg} T_2/(1 - \eta_{eg})$.

The process completion in MHDA (point 3m) corresponds to the intersection of the isotherm curve $T = T_3$ and isentropic line $s = s_{3m}$, where $s_{3m} = s_3 + (1 - \eta_{ea}) \times N_a/T_3$, $N_a = N_g$. The construction algorithm of the cycle for other parts of the AJAX concept is analogous to algorithm described earlier for the conventional scramjet design. It is clear that within the framework of the accepted technique the velocity at the combustor inlet is determined by multiplication of factors $k_{sd}k_g = W_{2m}/W_1 = u_{2m}^2/u_1^2$.

In the analysis of the cycles of the AJAX scheme (case C), four sets of factors k_{sd} and k_g were used: cycle 1, $k_{sd} = 0.5$, $k_g = 0.5$; cycle 2, $k_{sd} = 0.5$, $k_g = 0.02$; cycle 3, $k_{sd} = 0.75$, $k_g = 0{,}67$; and cycle 4, $k_{sd} = 0{,}75$, $k_g = 0.33$.

Modification of AJAX Concept (RAM–MHD Scheme)

The modification of the AJAX concept (RAM–MHD scheme) proposed in the present paper is an attempt to meet the engineering limitations on velocity and static temperature in the combustor with retention of high efficiency of the propulsion system. The basic idea of the modification is to bypass both kinetic and thermal energy of flow from the combustor to the nozzle, for which purpose MHD devices are combined (totally or partially) with combustor, nozzle, or other components of the engine. In the present paper a variant of RAM–MHD scheme is considered (Fig. 3), where the combustor is partitioned into three sections: the first one is isobaric and the two others are isothermal.

In the first section, combustion proceeds at the constant pressure and velocity. When the limiting static temperature $T_{\rm lim}$ for the combustor is achieved, the flow enters the second section of the combustor, where the duct geometry provides isothermal combustion process at $T = T_{\rm lim}$. In this case, the flow velocity increases, and at the point corresponding to velocity $u = u_{\rm lim}$, the third section of combustor starts where combustion proceeds concurrently with MHD power generation. It is assumed that this combined process in the third section is arranged in such a way that constant temperature and velocity are maintained simultaneously: $T = T_{\rm lim}$ and $u = u_{\rm lim}$. This is possible because of the combustion heat release in this section.

The isobaric combustion process in the first combustor section is completed at the point of intersection of curves $p = p_2$ and $T = T_{\rm lim}$ (point $3p$). All earlier assumptions for the description of the combustor of conventional scramjet design are valid for this process, and so the fraction of combustion heat Q_{cp}, released in the first section of the chamber, is defined as the difference of static enthalpies at the beginning and the end of the process: $Q_{cp} = h_{3p} - h_2$.

Condition $T = T_{\rm lim}$ is fulfilled in the second section of the combustor due to flow acceleration from the velocity $u_{3p} = u_2$ up to the velocity $u_{3t} = u_{\rm lim}$. The combustion process in this section continues up to point $3t$. At this point, the stagnation enthalpy is equal to $h_{03t} = h_{3t} + 0.5u_{\rm lim}^2 = h_{03p} + Q_{ct}$, where Q_{ct} is combustion heat release in the second section ($3p - 3t$) of the combustor. Because in the isothermal process Q_{ct} is equal to $T_{\rm lim}(s_{3t} - s_{3p})$, an equation

$$h_{3t} + 0.5u_{\rm lim}^2 = h_{03p} + T_{\rm lim}(s_{3t} - s_{3p}) \tag{7}$$

defines implicitly the value s_{3t}. This equation was solved using graphs in the h–s diagram. The straight line $h - h_{03p} = T_{\rm lim}(s - s_{3p})$ is drawn, through the point with coordinates $\{s_{3p}, h_{03p}\}$, corresponding to stagnation parameters of the beginning of the process under consideration. After that, a value of entropy s_{3t} was defined, for which a distance between the drawn straight line and isothermal curve $T = T_{\rm lim}$ is equal to the kinetic energy at the end of this section $W_{3t} = u_{\rm lim}^2/2$.

In so doing, the heat Q_{cm} released in the third section of combustor is determined as $Q_{cm} = Q_c - Q_{ct} - Q_{cp}$. An entropy increment in this section is equal to $s_{3m} - s_{3p} = (Q_{cm} + Q_{eg})/T_{\rm lim}$. As in the case of the AJAX scheme, joule heat release in MHDG, Q_{eg}, is related to electrical power N_g by the relationship $Q_{eg} = [(1 - \eta_{eg})/\eta_{eg}] \times N_g$. The value of N_g was defined as $N_g = Q_{cm} - (h_{3m} - h_{3t})$. The electric efficiency factor is specified as $\eta_{eg} = 0.8$.

Construction of the cycles of the RAM–MHD scheme (case D) is completed by description of the processes of acceleration of combustion products in MHDA that was performed in the same manner as for the AJAX scheme.

Results and Discussion

Comparison of the different schemes of the propulsion system was performed in terms of values of specific thrust, that is, the difference of velocities $u_4 - u_1$ with regard to specified constraints on the maximum allowable values of static temperature in the flow train $T_{\rm lim} = 3000$ K and velocity in the combustor $u_{\rm lim} = 1700$ m/s.

Figure 4 shows four cycles constructed for the conventional scramjet design with the assumption of isentropic process of flow deceleration in the diffuser (case A). The cycles differ by a factor of kinetic energy conservation $k_{\rm sd}$ (cycle 1, $k_{\rm sd} = 0.01$; cycle 2, $k_{\rm sd} = 0.25$, cycle 3, $k_{\rm sd} = 0.5$, and cycle 4, $k_{\rm sd} = 0.75$). Combustor parameters pressure p_c, velocity u_c, and maximum temperature $T_{c\,\rm max}$ corresponding to each of these cycles are listed in Table 1. The value of $T_{c\,\rm max}$ corresponds to the completion of the combustion process. Specific thrust of propulsion system F_r is given in the Table 1 as well.

Table 1 Characteristic parameters of scramjet ideal Brayton cycles (case A)

Parameter	Value			
Factor $k_{\rm sd}$	0.01	0.25	0.50	0.75
Combustion pressure p_c, atm	190	60	14	2.2
Velocity in combustor u_c, m/s	243	1215	1710	2104
Maximum combustion temperature $T_{c\,\rm max}$, K	4500	4070	3600	3160
Specific thrust F_r, m/s	1083	1050	995	896

Table 2 Characteristic parameters of reference scramjet cycles (case B)

Parameter	Value			
Factor $k_{\rm sd}$	0.01	0.25	0.50	0.75
Combustion pressure p_c, atm	17.5	9	2.5	0.8
Velocity in combustor u_c, m/s	243	1215	1710	2104
Maximum combustion temperature $T_{c\,\rm max}$, K	4150	3800	3450	3075
Specific thrust F_r, m/s	896	858	801	741

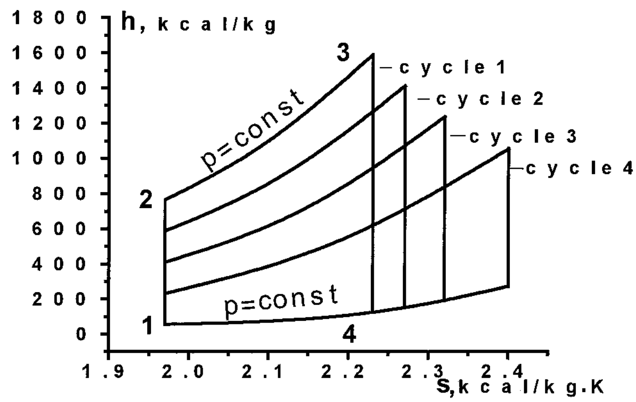

Fig. 4 Scramjet ideal Brayton cycles (case A): cycle 1, $k_{\rm sd}$ = 0.01; cycle 2, $k_{\rm sd}$ = 0.25; cycle 3, $k_{\rm sd}$ = 0.5; and cycle 4, $k_{\rm sd}$ = 0.75 (initial and final points of the processes are numbered for first cycle only).

As follows from Table 1, velocity increase in the combustor leads to the significant reduction of p_c and $T_{c\,\rm max}$ that is especially notable in the pressure. Nevertheless, note that the specified constraints on velocity and static temperature in the combustor are met simultaneously in none of the cycles. Moreover, even for $u_c = 2104$ m/s $>$ $u_{\rm lim}(k_{\rm sd} = 0.75)$, $T_{c\,\rm max}$ is significantly higher than $T_{\rm lim}$. We notice as well that, with velocity increase in the combustor, there is a sharp deterioration of the cycle integral parameters due to the rise of dissipation losses (entropy increment $s_3 - s_2$) in the combustor with reduction of temperature.

The cycles of case B (conventional scramjet design with regard to shock wave losses in diffuser) are given in Fig. 5. The flow deceleration process in the diffuser was determined with the same values of factor $k_{\rm sd}$. Recall that completion of this process was defined with application of a deceleration curve, the technique of its construction was described earlier. Numerical parameters of the cycles constructed are given in Table 2. We note that these cycles are considered as reference ones because comparisons with them are used for evaluation of cases C and D.

Analysis of Figs. 4 and 5 shows that the total entropy increment in cycles A is much lower than in the reference cycles, although the entropy increment in the combustor is nearly the same. Consequently, in the conventional scramjet scheme, dissipation losses

Table 3 Characteristic parameters of the AJAX cycles (case C)

Parameter	Value			
Factor k_{sd}	0.50	0.50	0.75	0.75
k_g	0.50	0.02	0.67	0.33
Combustion pressure p_c, atm	2.1	1.1	0.38	0.15
Velocity in combustor u_c, m/s	1215	243	1710	1215
Maximum combustion temperature $T_{c\,max}$, K	3400	3375	3000	2950
Specific thrust F_r, m/s	725	649	601	377

Table 4 Characteristic parameters of RAM–MHD cycles (case D)

Parameter	Value			
Factor k_{sd}	0.01	0.125	0.25	0.50
Combustion pressure p_c, atm	17	12	7	2.5
Minimum velocity in combustor u_c, m/s	243	862	1215	1710
Maximum combustion temperature $T_{c\,max}$, K	3000	3000	3000	3000
Specific thrust F_r, m/s	743	738	731	720

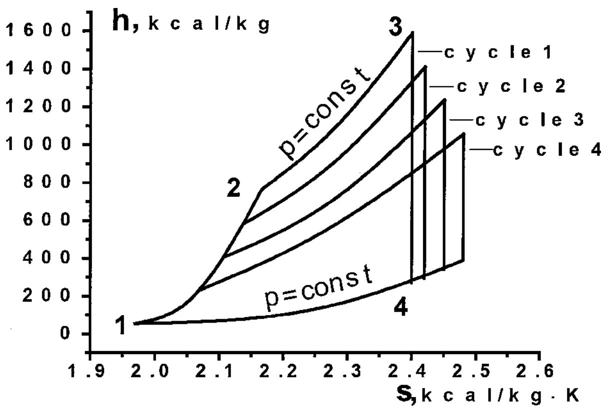

Fig. 5 Reference scramjet cycles (case B): cycle 1, k_{sd} = 0.01; cycle 2, k_{sd} = 0.25; cycle 3, k_{sd} = 0.5; and cycle 4, k_{sd} = 0.75 (initial and final points of the processes are numbered for first cycle only).

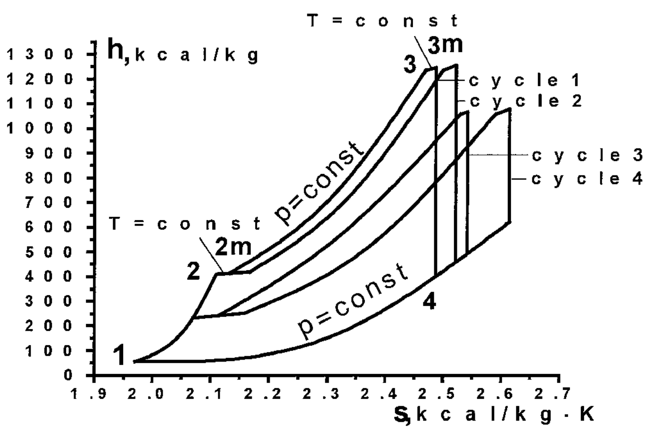

Fig. 6 AJAX cycles (case C): cycle 1, k_{sd} = 0.5, k_g = 0.5; cycle 2, k_{sd} = 0.5, k_g = 0.02; cycle 3, k_{sd} = 0.75, k_g = 0.67; and cycle 4, k_{sd} = 0.75, k_g = 0.33 (initial and final points of the processes are numbered for first cycle only).

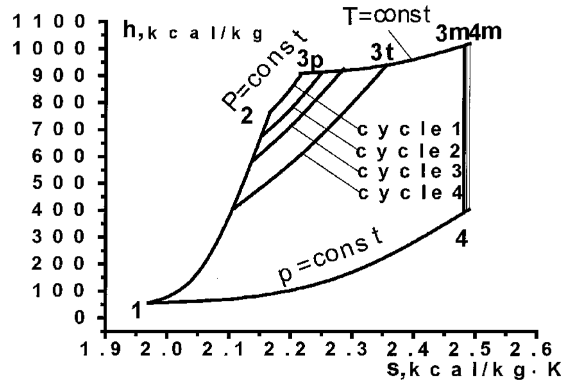

Fig. 7 RAM–MHD cycles (case D): cycle 1, k_{sd} = 0.01; cycle 2, k_{sd} = 0.125; cycle 3, k_{sd} = 0.25; and cycle 4, k_{sd} = 0.5 (initial and final points of the processes are numbered for first cycle only).

in the supersonic diffuser and combustor are practically additive. As is seen from Table 2, the consideration of shock wave losses in the diffuser leads primarily to sharp reduction of pressure in the combustor at slight temperature reduction. The propulsion system thrust decrease caused by shock wave losses in the diffuser is very high. Although in the reference cycles the combustor temperature is less than in cycles A, its maximum value remains higher than the maximum allowed temperature. That is, in the conventional scramjet design, the problem of temperature reduction to allowable level cannot be solved, obviously, only by increase of flow velocity in the combustor.

Four cycles corresponding to the AJAX design (case C) are shown in Fig. 6. The values of factors k_{sd} and k_g defining the cycle characteristics and parameters p_c, u_c, $T_{c\,max}$, and F_r are given in Table 3.

One can see from comparison of Figs. 5 and 6 that dissipation losses in cycles C are substantially greater than in the reference cycles. Also, with increase of bypassed energy determined by factor k_g, entropy increment increases and the specific thrust falls. This entropy increase is caused, on the one hand, by low temperature at which joule heat release occurs in MHDG, and on the other hand, by notable reduction of average temperature of fuel burning in the combustor in comparison with the reference cycles. At the same time (see Table 3), the energy bypassing within the frames of the AJAX design, in general, allows reduction of the combustor temperature down to an allowable level with the fulfillment of condition $u_c < u_{\lim}$ (cycle 3); however, in this case the cycle integral parameters are significantly impaired.

The cycles of case D for the proposed RAM–MHD scheme are shown in Fig. 7. For their construction, values of factor k_{sd} of 0.01, 0.125, 0.25, and 0.5 were used (at higher k_{sd}, velocity in the combustor exceeds $u_{\lim}$). Calculated results for these four cycles are given in Table 4.

Recall that in this scheme the processes in the second section of the combustor as well as in the MHDG (the third section of the combustor) and MHDA proceed at the same temperature, that is, follow one continuous isotherm $T = T_{\lim} = 3000$ K. As seen from Fig. 7 and Table 4, specific thrust achieves comparatively high values and has weak dependence on the intensity of flow deceleration in the diffuser. Improvement of integral parameters in comparison with case C is connected both with the increase of temperature in the inlet part of the combustor, that is, fuel burning temperature in this section, and with temperature increase at which joule heat release occurs in the MHDG. In this case, both temperature and pressure in the MHDG channel are higher than those in the case of the AJAX scheme. Note that effective operation of MHD devices at $T = T_{\lim}$ is much more realistic than in the case of the AJAX scheme.

Conclusions

The comparative thermodynamic analysis of the considered scramjet schemes leads to the following conclusions.

1) At flight velocities corresponding to Mach number >8 with application of fuel of heat caloric value >800 kcal/kg in the conventional ramjet scheme, the flow static temperature in a combustor may significantly exceed the maximum allowed values.

2) The MHD energy bypassing from the supersonic multishock diffuser to the nozzle in principle allows reduction of the combustor temperature down to an allowable level; however, in this case the propulsion system thrust falls significantly.

3) A principal capability exists to arrange the cycle with the MHD bypassing the flow energy from the combustor to the nozzle, while keeping the static temperature and the velocity at allowable levels in the engine flow train. The thermodynamic analysis shows that in this case the integral dissipative losses are minimized, which results in higher values of specific thrust.

The general idea that led to the introduction of the RAM–MHD cycle is to conduct the dissipative processes at as high as possible temperatures and velocities. MHD energy bypassing offers the unique possibility to perform combustion at maximum allowable temperature and velocity. In this case the engine cycle becomes the most efficient.

The combination of combustor and MHDG in one unit poses a new technical problem. There is no practically data on high velocity combustion in a strong magnetic field. The accumulation of these data is the key problem in the development of this line of research. The accompanied problems of MHD bypassing such as providing of high values of electrical conductivity and magnetic field are to be solved as well.

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