3 Workshop "Thermochemical processes in plasma aerodynamics"

Analysis of Scramjet with MHD bypass

E.G. Sheikin, A.L. Kuranov

Hypersonic Systems Research Institute,

St. Petersburg, Russia, e-mail: ajax@comset.net

The propositions to use the MHD systems to control flow in a scramjet channel were put forward in development of the "AJAX" concept. The paper [1], in which the basic principles for the MHD control in a scramjet were described for the first time in detail, was published in 1998. The main emphasis in the paper was put on analyzing the scramjet scheme with the control system composed of the MHD generator located upstream of the combustion chamber and the MHD accelerator located downstream of the combustion chamber, see the Fig.1. The "Magneto Plasma Chemical Engine" title was used in the paper for designation of the engine. At present the title "Scramjet with MHD bypass" is frequently used for the engine designation. Perhaps the title is more obvious met to the scheme. It was shown in the paper [1] that the MHD bypass in a scramjet allows one to increase the scramjet specific impulse. In addition the functional relation which determines requirements for the engine subsystems, at which the MHD bypass leads to increasing the scramjet specific impulse, is obtained in the paper [1]. In the subsequent papers [2-5] the propulsion was analyzed in more complicated physical model taking into account the problems of creation of nonequilibrium conductivity of flow in the MHD generator channel. In the papers the requirements for parameters of the magnetic system, the ionizer, the MHD generator and the scramjet, at which the MHD bypass increases the scramjet specific impulse, are formulated. Despite of the considerable progress in investigation of the propulsion the results obtained in [1-5] don't establish clearly the reason which is responsible for increase the scramjet specific impulse due to the MHD control. Probably the not full clarity of results obtained in the papers [1-5] is caused in the first place by the non-traditional approach [6], which is very useful for the system analysis but does not give the clearness of the results obtained, was used for the MHD systems description. And in the second place the total pressure losses in the key subsystems of the propulsion investigated was not compared in the cases with and without the MHD bypass.

The paper offered now is aimed to clarify the main reasons which are responsible for increasing the specific impulse of the scramjet with the MHD bypass in analyzing the elementary model approach. The scheme of the scramjet with the MHD bypass shown in Fig.1 is considered.

In the scheme the MHD generator disposed upstream of the combustion chamber transforms part of the flow enthalpy to electric power. The electric power produced by the MHD generator is transferred to the MHD accelerator disposed downstream of the combustion chamber. In the scheme the power redistribution decreases the total enthalpy of the flow at the entry of the combustion chamber. The power spending on the creation of the flow conductivity in the MHD generator channel is not taken into account in the model. Quasi-onedimensional approach is used for flow description. The specific heat for the flow is supposed to be constant. The combustion chamber is supposed to be working in a mode with a constant static pressure. Typically the fuel mass flow in the combustion chamber is noticeably less than the air mass flow. So we consider the combustion as a heat release in neglecting a mass of the fuel injected. The nozzle is supposed to be isentropic. MHD systems are considered in using conventional 1D set of MHD equations. The specific impulse I_{sp} is assumed as the basic characteristic for the propulsion.

It is easy to show that, in the approach considered, the scramjet specific impulse is uniquely depends on the integral recovery coefficient of the total pressure σ in all the system at any fixed heat release in the combustion chamber and at given nozzle geometry. In particular, if we consider the design nozzle, for which the static pressure at the nozzle exit is equal to the static pressure in the free stream p_0, the specific impulse I_{sp} is defined by the relation:

$$I_{sp}=\frac{\alpha_F L_0}{g}\left(\sqrt{2\left(\frac{H_u}{\alpha_F L_0+1}+c_p T_0\left(1+\frac{\gamma-1}{2}M_0^2\right)\right)\left(1-\frac{(1/\sigma)^{1-1/\gamma}}{1+\frac{\gamma-1}{2}M_0^2}\right)}-M_0\sqrt{(\gamma-1)c_p T_0}\right)$$

where M_0 and T_0 are the Mach number and the static pressure for the free stream, c_p is the specific heat at constant pressure, γ is the specific heats ratio, H_u is the fuel calorific value, L_0 is the stochiometric coefficient, α_F is the excess air factor, g is the acceleration of gravity.

Fig.2 shows the dependencies of the scramjet specific impulse upon the factor σ for two configurations of nozzle: the design nozzle (dashed line) and the nozzle with the exit area A_5 which is equal to the scramjet entrance area A_0 (solid line). One can see that the scramjet specific impulse is essentially depends on the total pressure recovery coefficient in the range of real losses of the total pressure in a scramjet (σ<0.3). It is evident that increasing the integral recovery coefficient of the total pressure in the system is the only way to increase the scramjet specific impulse. Fig.3 demonstrates what increment for the scramjet specific impulse is obtained when the factor σ increase is equal to 10%. The adduced results demonstrate the evident fact - the worse the initial system the greater positive effect is caused by the total pressure increasing. In particular the increment of a scramjet specific impulse for the scramjet with off-design nozzle is greater than one for the scramjet with design nozzle.

The integral coefficient σ for the scramjet with MHD bypass can be determined by means of the total pressure recovery coefficients for the propulsion subsystems by the ratio: $\sigma=\sigma_{in}\sigma_{gen}\sigma_{com}\sigma_{ac}\sigma_{noz}$, where co-factors in the right-hand side of the relation determine the total pressure recovery coefficients in the inlet, the MHD generator, the combustion chamber, the MHD accelerator and the nozzle correspondingly. In the model under consideration $\sigma_{noz}=1$ (isentropic nozzle), moreover at given inlet geometry and given flight Mach number the factor σ_{in} by no means depend on the MHD interaction. Thus the only way to vary the integral coefficient σ consists in changing the complex $\sigma_{MHDcom}=\sigma_{gen}\sigma_{com}\sigma_{ac}$. Hence, to investigate the role of MHD bypass on the scramjet performance one can analyze only part of the propulsion composed of the MHD generator, the combustion chamber and the MHD accelerator. The complex stated above can be concisely titled as the combustion chamber with MHD bypass.

At first we examine how the MHD generator influences on the total pressure recovery coefficient in the combustion chamber by changing the flow parameters at the combustor entrance. The MHD generator working in a mode with a constant temperature is considered. Level of MHD bypass is characterized by the enthalpy extraction ratio η. Fig.4 shows the total pressure recovery coefficient in the combustion chamber depending on the relative temperature increase at various levels of MHD bypass. Here M_1 and T_1 are, correspondingly, the Mach number and the temperature at the combustor entrance, ΔT is the temperature increase in the combustion chamber. It is evident from Fig.4, the greater level of the MHD bypass the smaller losses of the total pressure in the combustor at given heat supply. It is consequence of decrease of the total enthalpy of a flow at the combustor entrance due to the MHD bypass. Hence one can say that the MHD bypass leads to increasing the total pressure recovery coefficient σ_{com} in the scramjet combustion chamber. In accordance with Fig.5 the effect depends on the MHD flow regime. In particular the MHD generator with a constant cross-sectional area is more effective than the MHD generator with a constant pressure along the channel length. Therefore, the following analysis of the combustion chamber with MHD bypass is carried out in using the MHD generator with a constant cross-sectional area. The MHD accelerator working in a mode with a constant pressure is considered. Dependencies of the total pressure recovery coefficients in subsystems of the combustion chamber with the MHD bypass are shown in Fig.6. According to Fig.6 the MHD bypass decreases the total pressure in the MHD generator and increases the total pressure both in the combustion chamber and in the MHD accelerator. The integral recovery coefficient for the total pressure in the combustion chamber with the MHD bypass

$\sigma_{MHDcom}=\sigma_{gen}\sigma_{com}\sigma_{ac}$ increases at given conditions. It follows from Fig.7 that efficiency of the MHD bypass depends on the load factors for the MHD generator k_1 and the MHD accelerator k_3. In order to estimate how the MHD bypass influences on the scramjet performance at various flight velocities we consider the scramjet with two-shock inlet which is characterized by the design Mach number M_d=10, the total turning angle θ_N=15° and relative value of the inlet throat F_{th}=0.1. According to Fig.8 the total pressure recovery coefficient for the combustion chamber with the MHD bypass significantly depends on the flight Mach number. When $M_0=M_d=10$ the MHD bypass decreases the integral recovery coefficient for the total pressure. When $M_0<M_d$ the MHD bypass increases σ_{MHDcom}. The more the flight Mach number differs from the design Mach number the greater increment of the total pressure due to the MHD bypass occurs. The results shown in Fig.9 demonstrate that increment of the scramjet specific impulse due to the MHD bypass is increased too while increasing the divergence between the flight Mach number and design Mach number. The effect of the MHD control on the scramjet specific impulse significantly increases in using the off-design nozzle.

References

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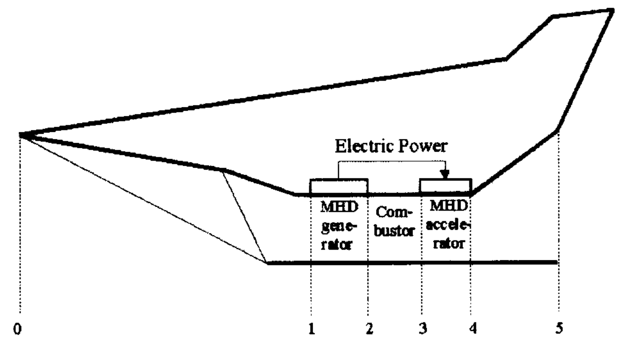

Fig.1 The sketch for the scramjet with MHD bypass

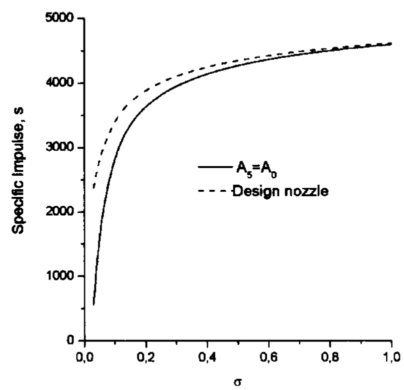

Fig.2 Specific impulse for scramjet depending on the total pressure recovery coefficient at the nozzle exit, M_0=6, the fuel – H_2, α_F=2.

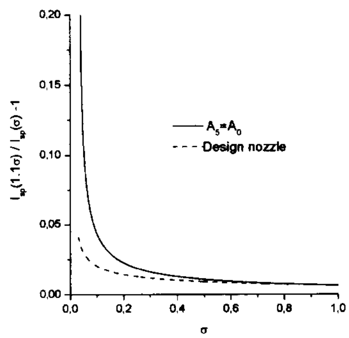

Fig.3 Relative increase for scramjet specific impulse caused by 10% increment of the total pressure recovery coefficient, M_0=6, the fuel – H_2, α_F=2.

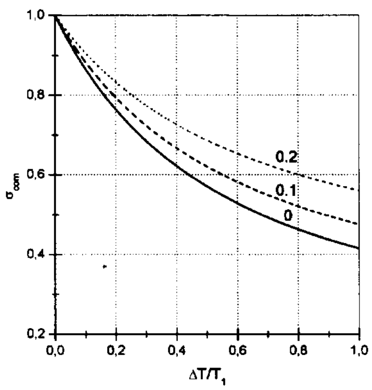

Fig.4 The total pressure recovery coefficient in the supersonic combustion chamber at various levels of MHD bypass (working mode for the MHD generator is T– constant), M_1=2, k_1=0.5.

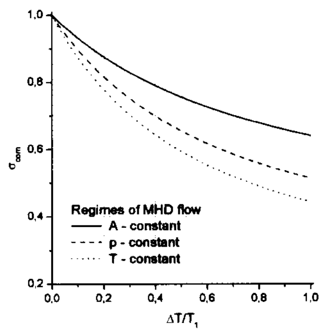

Fig.5 The total pressure recovery coefficient in the supersonic combustion chamber (p – constant) at various regimes of MHD flow in the MHD generator (The MHD bypass level is η=0.05), M_1=2, k_1=0.5.

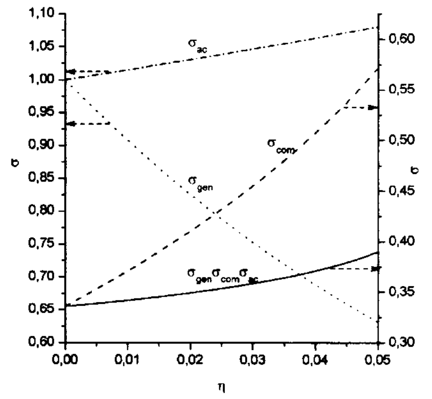

Fig.6 The total pressure recovery coefficient both in the combustion chamber with the MHD bypass and in its subsystems. M_1=2, k_1=0.5, k_3=1.2, $\Delta T/T_1$=1.5.

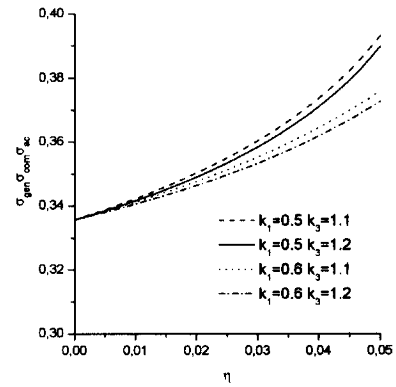

Fig.7 The total pressure recovery coefficient in the combustion chamber with the MHD bypass. M_1=2, $\Delta T/T_1$=1.5.

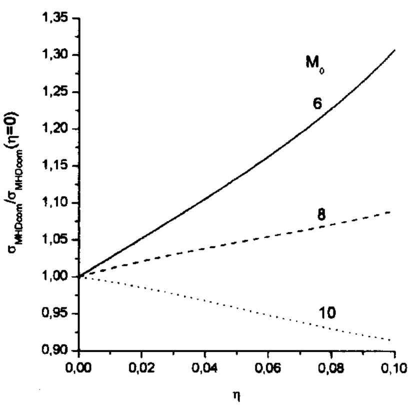

Fig.8 Relative values for the total pressure recovery coefficient in the combustion chamber with the MHD bypass in the scramjet for various flight Mach numbers. M_d=10, θ_N=15°, F_{th}=0.1, the fuel - H_2, α_F=1.5, k_1=0.5, k_3=1.2.

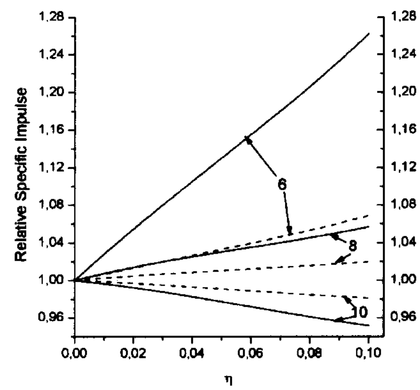

Fig.9 Relative values of specific impulse for the scramjet with the MHD bypass at various flight Mach numbers. Dashed lines for the design nozzle, solid lines for the off-design nozzle with A_5/A_1=1. M_d=10, θ_N=15°, F_{th}=0.1, the fuel – H_2, α_F=1.5, k_1=0.5, k_3=1.2.