Use of MHD systems in hypersonic aircraft

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The possibilities of using magnetohydrodynamic (MHD) systems on hypersonic aircraft are discussed. The distinctive features of using MHD systems in the flow path of ramjet engines are examined. A quasi-one-dimensional mathematical model for the engine is presented which includes the MHD interaction with the flow. It is shown that the specific impulse of an engine system can be raised by using MHD systems. © *1998 American Institute of Physics.* [S1063-7842(98)00811-3]

Hypersonic flight in the atmosphere involves extreme force and thermal effects on the structure of an aircraft. Under certain flight conditions, a plasma ''shell'' can develop around an aircraft, leading to interactions of the aircraft with the surrounding medium which are fundamentally new compared to conventional aerodynamics. Under these conditions, a magneto-gasdynamic volume interaction with the high speed, ionizing flux can be effective for creating control torques, reducing thermal fluxes to the surface of the aircraft, and controlling the structure of the flow.[1] In this paper we examine some distinctive features of using MHD systems in the flow path of a scramjet engine[2] with a magneto-plasma-chemical (MPC) engine developed in the framework of the AJAX concept[3] as an example. The traditional scheme for a scramjet engine has a number of fundamental disadvantages which substantially limit its range of applicability. The complex flow structure in the flow path of a scramjet engine increases the probability of flow separation, which leads to blocking of the channel and makes it more difficult to ignite the fuel in the combustion chamber efficiently.[4] At flight speeds below the design speed, the air intake of a scramjet engine typically has a lower air feed efficiency and a lower degree of compression of the stream. When the speed of a hypersonic aircraft changes, there is a significant realignment of the flow structure in the flow path of the scramjet engine. Altogether, these problems mean that scramjet engines are efficient only within a small range of flight speeds.

In order to extend the domain of operation of scramjet engines, it is necessary to introduce an additional mechanism for acting on the stream which makes it possible to further compress the stream in the air intake, regulate the flow structure, and inhibit the development of separated flows. One of the most promising ways of acting additionally on super- and hypersonic flows in the flow path of ramjets is through a volume interaction using MHD systems. Figure 1 shows a simplified diagram of an MPC engine which implements these principles; it is essentially a scramjet engine with MHD systems inserted in its flow path. Let us examine briefly the functional purpose of the main subsystems of the MPC engine which distinguish it from a scramjet engine. An external MHD generator is used to control the flow profile, regulate the air feed rate in the flow path of the MPC engine, and increase the pressure. An internal MHD generator is used to raise the pressure and prevent the development of separated flows. An ionizer is used to create the required conductivity in the flow when the natural conductivity of the flow does not provide the required degree of MHD interaction. The electrical energy generated by the MHD generators is used to power the ionizer and on-board equipment and to provide further acceleration of the combustion products in the MHD accelerator.

Let us analyze an MPC engine scheme with an internal MHD generator and an MHD accelerator. For clarity we shall do this study with the simplest of assumptions. A quasi-one-dimensional approximation is used in a model of an inviscid, thermally nonconducting ideal gas with a constant specific heat. The MHD flows are described using an approach developed[5,6] for analyzing complex systems, including MHD systems. Let us examine the features of this approach briefly. Formally assuming that the pressure gradient in the MHD channel is proportional to the force exerted on the flow by the magnetic field, we introduce a proportionality coefficient ξ. For an ideally sectored Faraday MHD channel we assume that

$$\frac{dp}{dx} = \xi(x)(1-k)^2 \sigma B^2 v, \tag{1}$$

where p is the static pressure in the flow, v is the flow velocity, x is the longitudinal spatial coordinate, k is the load coefficient, σ is the conductivity of the flow, and B is the magnetic induction.

If we limit ourselves to the class of solutions for which ξ is constant, then, using Eq. (1), we can obtain simple analytical expressions for the parameters at the outlet of the MHD channel. The corresponding flow regime will be called the $\xi=$const flow regime. The changes in the flow parameters in the MHD channel are given by

$$\frac{T_2}{T_1} = 1 + \frac{1-k}{k}\left(1+\frac{\gamma-1}{2}M_1^2\right)(1+\xi)\,\eta,$$

$$\frac{v_2}{v_1} = \sqrt{1-\frac{1+\xi(1-k)}{k}G\,\eta},$$

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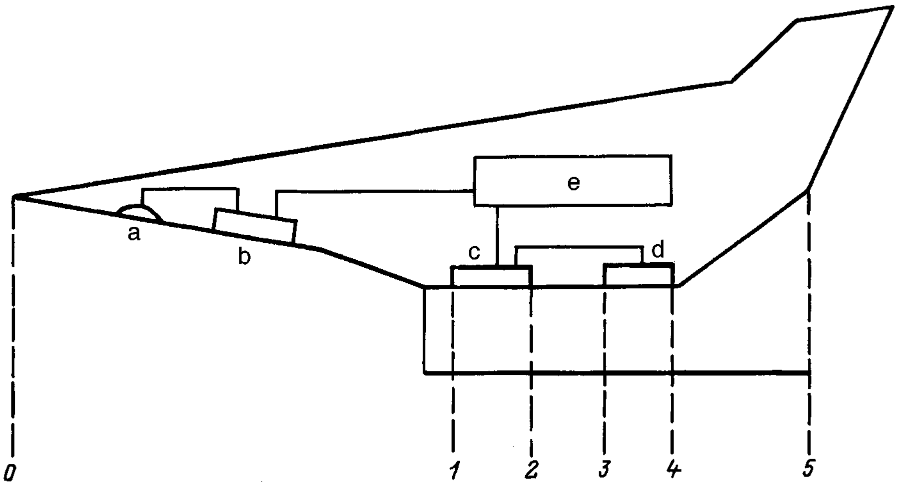

FIG. 1. Simplified sketch of a magneto-plasma-chemical engine: (*0–1*) air intake, (*1–2*,c) internal MHD generator, (*2–3*) combustion chamber, (*3–4*, d) MHD accelerator, (a) ionizer, (b) external MHD generator, (e) onboard systems.

$$\frac{p_2}{p_1}=\left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}\frac{\xi}{\xi+1}},\quad G=\frac{2+(\gamma-1)M_1^2}{(\gamma-1)M_1^2}. \tag{2}$$

Here T is the temperature, M is the Mach number, γ is the adiabatic index, η is the coefficient of conversion of the enthalpy of the flow into electrical energy, and the subscripts 1 and 2 label the parameters at the inlet and outlet of the MHD channel, respectively. The $\xi=\text{const}$ flow regime includes, as a special case, the often examined flow regimes that are characterized by conservation of one of the flow parameters. The values of ξ corresponding to these regimes are listed in Table I.

In analyzing an MPC engine with an internal MHD generator, we shall use the following subscripts to denote the parameters at various locations: 0 in the incident flow, 1 at the entrance to the MHD generator, 2 at the entrance to the combustion chamber, 3 at the entrance to the MHD accelerator, 4 at the entrance to the jet nozzle, and 5 at the outlet of the nozzle. (Naturally, the outlet parameters of a subsystem are the inlet parameters of the subsystem located after it.)

In this paper we limit ourselves to examining the case in which conductivity of the flow is achieved without the use of an ionizer. We examine the subsystems of an MPC engine and determine the relationships among the parameters at the inlet and outlet of the system.

The air intake includes an external part, which compresses the entering flow in a system of oblique shocks, and an internal part (isolator), which provides for a return and further compression of the flow. The following characteristics are used: N, the number of shocks in the external part, Θ_N, the net return flux in the air intake, and σ_{in}, the coefficient of restitution of the total pressure in the air intake. If the temperature at the outlet of the air intake (the inlet of the MHD generator) is T_1, then the changes in the pressure and velocity in this subsystem are determined by the following equations:

$$\frac{p_1}{p_0}=\sigma_{\text{in}}\left(\frac{T_1}{T_0}\right)^{\frac{\gamma}{\gamma-1}},\quad \frac{v_0^2}{2}+c_pT_0=\frac{v_1^2}{2}+c_pT_1, \tag{3}$$

where c_p is the specific heat of air.

The MHD generator is characterized by the parameters ξ_1 and k_1 and the enthalpy conversion coefficient η. The changes in the flow parameters in the channel of the MHD generator are determined by

$$\frac{T_2}{T_1}=1+\frac{1-k_1}{k_1}\left(1+\frac{\gamma-1}{2}M_1^2\right)(1+\xi_1)\,\eta,$$

$$\frac{p_2}{p_1}=\left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}\frac{\xi_1}{\xi_1+1}}. \tag{4}$$

We consider a combustion chamber operating at constant pressure. Since the mass feed rate of fuel is usually much lower than that of air, we shall treat the delivery of fuel to the combustion chamber as heat release without mass input. Then the changes in the flow parameters in the combustion chamber have the simpler form[2]

$$T_3=T_2+\Delta T,\quad p_3=p_2,$$

$$\Delta T=\frac{H_u}{c_p(\alpha L_0+1)}, \tag{5}$$

where H_u is the calorific value of the fuel, L_0 is the stoichiometric coefficient, and α is the excess air factor.

The MHD accelerator is characterized by the parameters ξ_3 and k_3. It is assumed that all the energy produced by the MHD generator is transferred to the MHD accelerator. The changes in the flow parameters in the MHD accelerator channel are determined by

TABLE I.

Flow regime	Value of ξ corresponding to the given flow regime
$\rho=\text{const}$	$\xi=\gamma-1$
$p=\text{const}$	$\xi=0$
$T=\text{const}$	$\xi=-1$
$M=\text{const}$	$\xi=-\left[1+\frac{2}{(1-k)(\gamma-1)M_1^2}\right]\frac{1}{G}$
$v=\text{const}$	$\xi=-1/(1-k)$

$$\frac{T_4}{T_3}=1+\frac{k_3-1}{k_3}\left(1+\frac{\gamma-1}{2}M_1^2\right)\frac{T_1}{T_3}(1+\xi_3)\eta,$$

$$\frac{p_4}{p_3}=\left(\frac{T_4}{T_3}\right)^{\frac{\gamma}{\gamma-1}\frac{\xi_3}{\xi_3+1}}. \qquad (6)$$

We assume that the flow in the nozzle is isentropic. Then the relative change in the flow pressure is related to the relative temperature change by

$$\frac{p_5}{p_4}=\left(\frac{T_5}{T_4}\right)^{\frac{\gamma}{\gamma-1}}. \qquad (7)$$

At the design efflux from the nozzle, the system of Eqs. (3)–(7) can be closed by assuming that the pressure at the nozzle exit is the same as in the surrounding medium, i.e., $p_5=p_0$. Given this relationship, the system of Eqs. (3)–(7) yields the following formula for calculating the flow temperature at the nozzle exit:

$$T_5=\frac{T_4}{\sigma_{\text{in}}^{(1-1/\gamma)}\left[\frac{T_1}{T_0}\left(\frac{T_2}{T_1}\right)^{\frac{\xi_1}{\xi_1+1}}\left(\frac{T_4}{T_3}\right)^{\frac{\xi_3}{\xi_3+1}}\right]}. \qquad (8)$$

The efflux velocity of the gas from the nozzle is determined in terms of the temperature T_5 using the conservation of energy,

$$v_5=\sqrt{v_0^2+2c_p(T_0+\Delta T-T_5)}. \qquad (9)$$

These formulas can be used to determine the specific impulse I_{sp} of the MPC engine. Neglecting the mass feed rate of fuel compared to that of air, we obtain[7]

$$I_{\text{sp}}=\frac{\alpha L_0}{g}(\varphi v_5-v_0), \qquad (10)$$

where g is the acceleration of gravity and φ is a coefficient which takes the nonideality of the nozzle into account.

In those cases where it is not specially noted otherwise, we shall set $\varphi=1$.

The set of Eqs. (3)–(10) can be used to calculate the specific impulse of the MPC engine for given parameters of the air intake, MHD system, and combustion chamber. Here the specific impulse depends on a large number of parameters: α, L_0, M_0, T_1, σ_{in}, k_1, ξ_1, η, k_3, and ξ_3. T_1 and σ_{in} are defined in terms of the air intake parameters N and Θ_N and a computational technique similar to that described in Ref. 8 was used, with posterior averaging of the parameters in the outlet section of the air intake. We have determined the range of variation of the parameters of the subsystems of an MPC engine within which the use of an MHD system makes it possible to increase the specific impulse of the engine system. We use the obvious functional relationship

$$\left.\frac{\partial I_{\text{sp}}}{\partial\eta}\right|_{\eta\to 0}>0.$$

Equations (9) and (10) imply that this condition is equivalent to the condition

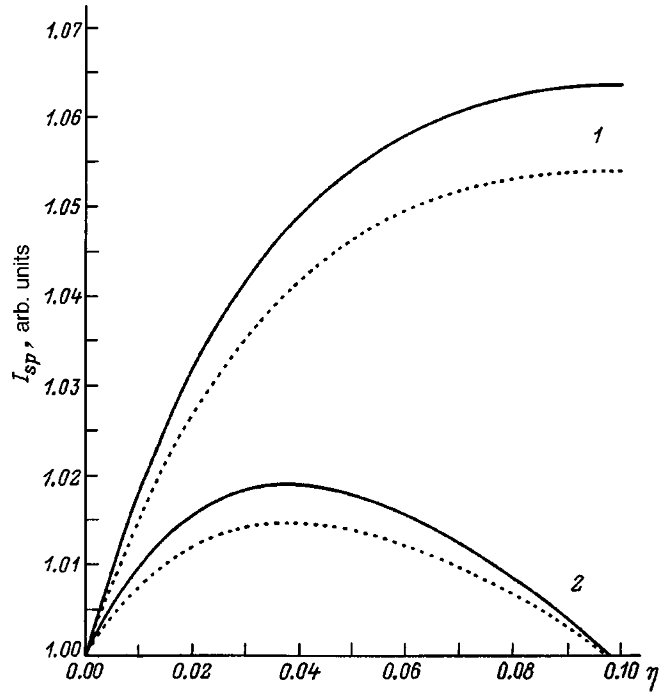

FIG. 2. Specific impulse of a magneto-plasma-chemical engine as a function of the conversion efficiency of flow enthalpy into electrical energy: $\Theta_N=0.2$ rad, $k_1=0.5$, $k_3=2$; $M_0=6$ (*1*), 8 (*2*); smooth curves $\varphi=0.95$, dotted curve $\varphi=1$.

$$\left.\frac{\partial T_5}{\partial\eta}\right|_{\eta\to 0}<0.$$

After the required transformations, we obtain the following inequality:

$$\xi_1>\frac{T_1}{\Delta T}\frac{1-k_1/k_3}{1-k_1}. \qquad (11)$$

Since the load coefficient for the MHD generator is $0<k_1<1$ and for the MHD accelerator $k_3>1$, the specific impulse of an MPC engine in this configuration increases for positive ξ_1, which, according to Eq. (1), corresponds to an MHD generator operating with an elevated pressure along the channel length. The requirements on the magnitude of the pressure drop are less at higher ΔT and lower T_1. Figure 2 shows the specific impulse of the MPC engine as a function of the coefficient of conversion of the enthalpy of the flow to electrical energy for different values of the Mach number of the incident flow for ideal and nonideal nozzles. A value $\eta=0$ corresponds to a scramjet engine. All these curves are normalized to the specific impulse of a scramjet engine. (The curves of Figs. 2–5 are for $\xi_1=\xi_3=\alpha=1$ and $N=2$.)

In all the calculated variants, MHD energy conversion in the flow path of the engine system leads to an increase in the specific impulse, and for a nonideal nozzle the positive effect is more significant. The relative increase in the specific impulse of the MPC engine in this variant is more significant for lower Mach numbers.

The dependence of the specific impulse on the load coefficient of the MHD generator shown in Fig. 3 is nonmono-

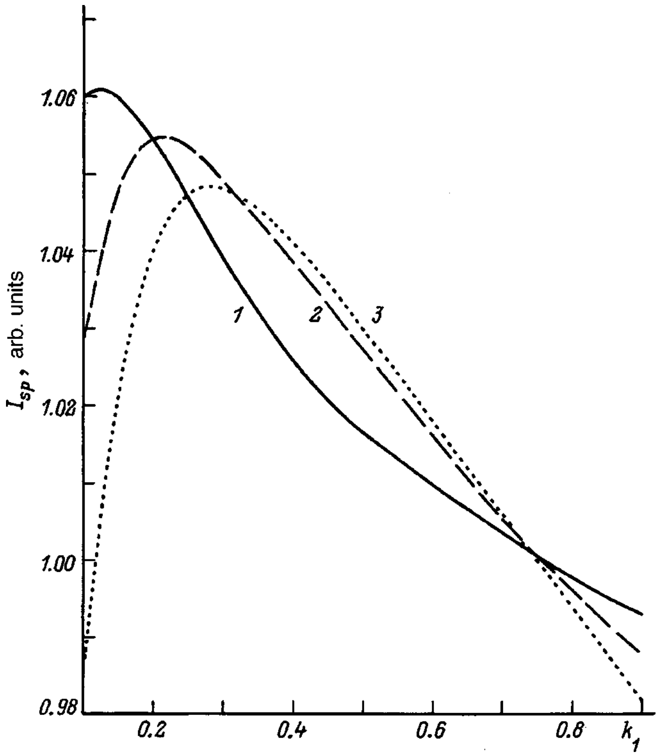

FIG. 3. Specific impulse of a magneto-plasma-chemical engine as a function of the load coefficient of the MHD generator: $M_0=6$, $\Theta_N=0.2$ rad, $k_3=2$; $\eta=0.05$ (*1*), 0.1 (*2*), 0.15 (*3*).

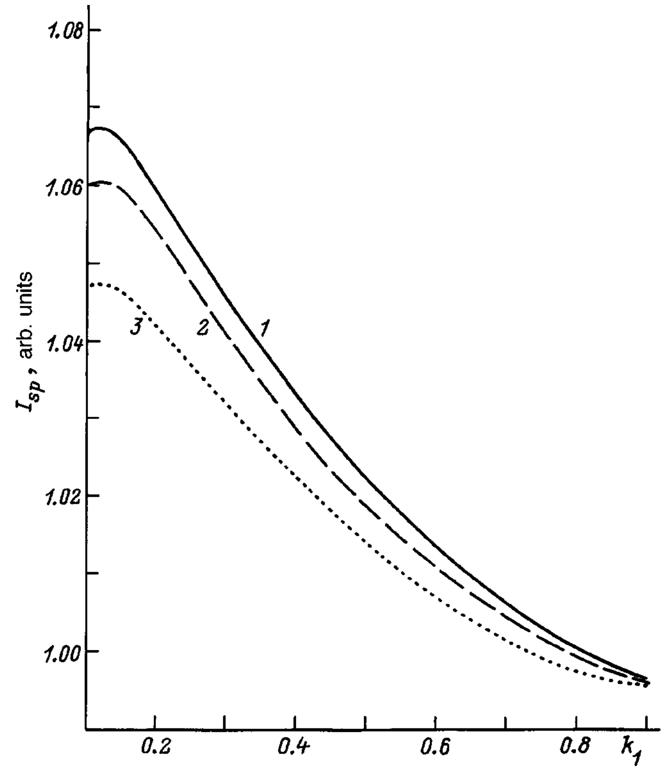

FIG. 5. As in Fig 3, for $M_0=6$, $k_3=2$, $\eta=0.05$; $\Theta_N=0.1$ (*1*), 0.2 (*2*), 0.3 rad (*3*).

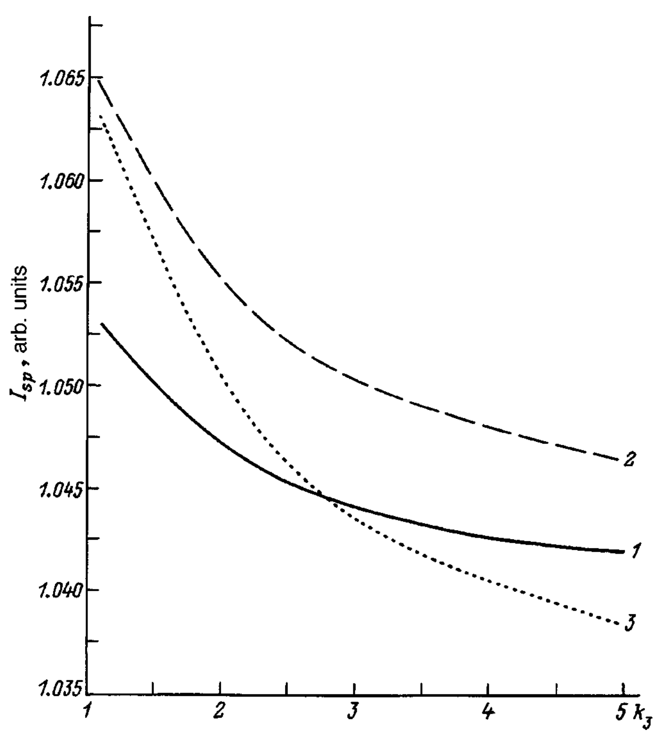

FIG. 4. Specific impulse of a magneto-plasma-chemical engine as a function of the coefficient k_3: $M_0=6$, $\Theta_N=0.2$ rad, $k_1=0.25$, $\alpha=1$, $\eta=0.05$ (*1*), 0.1 (*2*), 0.15 (*3*).

tonic, with a distinct extremum. The magnitude and location of the extremum depend on the conversion coefficient of flow enthalpy into electrical energy. With increasing η the extremum shifts toward larger k_1, while its magnitude decreases. Figure 4 shows that the specific impulse of an MPC engine falls off monotonically with rising k_3. With increasing η the dependence of the specific impulse on the load coefficient k_3 becomes more pronounced. The results shown in Fig. 5 imply that the relative increase in the specific impulse is maximum for an MPC engine with an air intake characterized by a minimum turn angle for the flow.

These calculations show that using MHD systems in the flow path of a scramjet engine with a suitable choice of parameters makes it possible to increase the specific impulse of the engine system. We have found the limits on the range of variation in the parameters of the MPC engine subsystems that will ensure enhanced specific impulse for the system. In later papers we shall examine the possibility of using MHD interactions for controlling the flow structure and study the characteristics of MPC engines in a two-dimensional Euler approximation.

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