MHD-control of gas flow in the tract hypersonic ramjet engine.

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Nowadays in leading countries of the world active research has been conducted on developing the perspective hypersonic aerospace aircraft. One of the key directions of research on this problem is the development highly efficient hypersonic ramjet engine (HRE). It is known that the efficiency of HRE with supersonic flow velocities in the combustion chamber decreases with the increasing of flight velocities. The basic losses take place in the combustion chamber as firstly the relative losses of working capacity of gas is considerably increasing at the heat supply, secondly because of high speed of the flow the quality of fuel confusion with the air on the bounded length considerably deteriorates and the completeness of combustion declines. The remarks of estimates demonstrate that for this reason the application of HRE is bounded evidently with the Mach numbers of flight that doesn't exceed 11-12. At the same time the thermodynamic estimates demonstrate the considerable reserve on the specific characteristics. This reserve can partly be realized by the reconstruction of the structure of the current using MHD-interaction.

In the Institute of Computational Modelling and Institute of Theoretical and Applied Mechanics a principle of MHD-control of gas flow in the channel HRE has been worked up. It is based on the creation of local plasma areas with temperature 10^4 K in the flow that would interact with an external magnetic field so as to increase the specific characteristics of engine [1]. The use of the effect of T-layer in HRE would also allow to get the electric energy on the board of an aircraft. Some part of this energy would be used in the initialization of T-layers and creation of the magnetic field, another part for the useful energy.

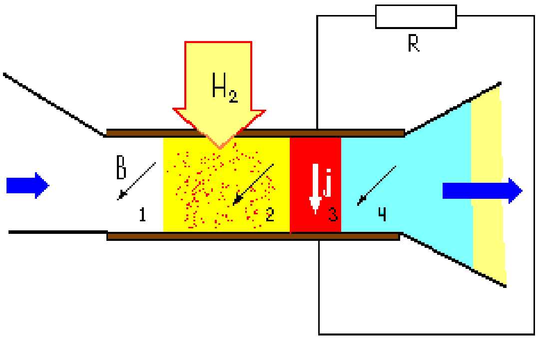

Fig.1. The scheme of hypersonic ramjet engine and the structure of the stream.

The principle of MHD-control of the gas flow is based on the following physical processes (Fig.1). The filling current is broken and contracted in the air intake whereupon it proceeds to the entrance of the combustion chamber, constructively combined with MHD - channel. Here the system of initialization with the high-voltage break-down of gas creates periodically the high-temperature current layers. The mode of MHD interaction is selected so, that the Joule dissipation would compensate the power losses and the mode of the self-sustaining T- layer is installed. The self-sustaining T - layer in a flow of gas is the peculiar plasma's piston to which the braking electromagnetic force reconstructing the structure of the current in the combustion chamber of HRE is applied. When the T-layer brakes in the HRE channel the non-stationary structure of the flow is formed, consisting of the following zones: 1- undisturbed gas current, 2 - shock compressed gas, 3 - T- layer, 4 - area of the wave of exhaustion. Changing the specific characteristics of MHD-interaction (*K*-load factor, *B*- induction of the magnetic field) we may control the value of the electromagnetic force applied to the T-layer, the extension of the zones and the value of their physical parameters. We offer to conduct the combustion of the fuel in the area of shock compressed gas which is characterized with higher pressure, and the velocity of the flow is considerably lower than that at the input that promotes the more effective burning of fuel. Moreover the combustion of the fuel in this area is profitable for thermodynamics as the average temperature of the heat supply increases while the average temperature of the flow stays unchanged. In the nozzle part the gas flow accelerates, creating the propulsion impulse.

In the works [2,3] the structure of the current in the HRE channel with one T-layer has been investigated on the basis of solution of the one-dimensional system of equations of gas dynamics in Lagrange coordinates with the regard of the heat of fuel combustion in the area of shock-compressed gas. The calculation of structure of current was added with the definition of balances of energy and impulse for all zones of the flow and general efficiency of MHD-process. With the help of functional mathematical model the specific propulsion characteristics of the engine for each zone of a gas flow were estimated, and then the average characteristics during a running cycle (the flight time of T-layer) were found. The given estimates have shown, that the application of MHD-control with a T-layer can increase the value of the specific HRE impulse up to 50 %.

The estimates have shown the basic opportunity of the use of MHD-control with a T-layer for the extension of range of work of the engine on Mach's numbers and the improvement of specific propulsion characteristics. To define of an opportunity of practical use of MHD-control it is necessary to solve a set of various problems, including the research of periodic mode of work.

One of major factors influencing the structure of the current in HRE channel with MHD-control are the shock waves and waves of underpressure, that are formed in the interaction of a T-layer with a magnetic field. Here the wave disturbances cooperate with each other and with T-layers, created in periods by the system of initialization, and, thus, they influence considerably on the structure of a T-layer and the characteristics of the current in the HRE channel.

The numerical modeling of the structure of the non-stationary gas dynamic current in HRE channel was conducted on the basis of the solution of the system of non-stationary equations of gas dynamics in the Euler coordinates.

$$\frac{\partial \rho F}{\partial t}+\frac{\partial \rho u F}{\partial x}=0, \qquad (1)$$

$$\frac{\partial \rho u F}{\partial t}+\frac{\partial \rho u^2 F}{\partial x}+\frac{\partial p F}{\partial x}=jBF+p\frac{\partial F}{\partial x}, \qquad (2)$$

$$\frac{\partial \rho F\left(e+\frac{u^2}{2}\right)}{\partial t}+\frac{\partial \rho u F\left(e+\frac{u^2}{2}\right)}{\partial x}+\frac{\partial p u F}{\partial x}= \qquad (3)$$

$$=(jE+q_{in}+q_f-q_R)F\ ,$$

$$j=\sigma E, \quad E=(1-K)uB, \qquad (4)$$

$$p=R\rho T, \quad E=c_V T. \qquad (5)$$

Here j - current density, F(x))- the section of the channel, t- time, x-coordinates, p – pressure, e –internal energy, E - electric field tension, q_{in} - the power of heat apportionment of the initialization, q_R - radiation energy losses, q_f - specific heat of combustion of fuel, σ - electroconductivity, T - temperature, ρ - gas density.

The boundary condition on the entrance are the parameters corresponding to the parameters on the exit from the air intake, that were preliminarily estimated with the regard of irreversible losses on the oblique leaps, and the boundary condition on the exit corresponds to the free departure as the derivative parameters are set as zero. The initial condition is the hypersonic undisturbed current of gas.

The value of radiation losses of energy was defined in the approximation of the volumetrical radiator in the form $q_R = 2\sigma_R \varepsilon(T, p, \delta)T^4/\delta$. Here σ_R - the Hermann-Boltzman constant, ε - the blackness factor of the flat emanating layer, δ - the sickness of the emanating layer. The thermophysical and radiation properties of the gas were calculated with the help of software package MONSTR [4] and were entered into the program in the tabular form $\sigma(T, p)$, $\varepsilon(T, p, \delta)$, $\mu(T, p)$, $\gamma(T, p)$.

The system of equations (1.1-1.5) was solved with the obvious method of MacCormack [5]. Due to the fact that the current contains the areas with the large gradients of parameters (T-layers and shock waves) the method of the flow correction FCT [6] was used to eliminate oscillations and to increase of the precision of the estimates.

In the figure below the results of the modeling of the current are introduced with the following parameters on the entrance of the hypersonic flow to the combustion chamber: T=600K, p=$4.5\cdot10^4$ Pa, u=1500m/s. The parameters of MHD-interaction are: K=0.8, B=2T. In the course of the numerical modeling the periodical mode of work was investigated, when the T-layers are initialized in the entrance to the combustion chamber with the frequency of 500 Hz.

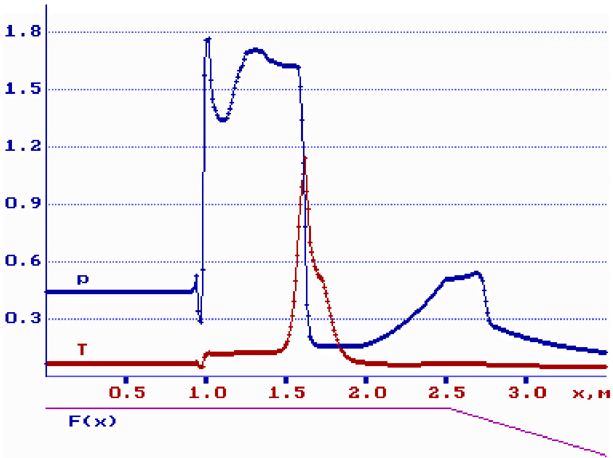

Fig.2. Distribution of temperature (scale 10^4 K) and pressure (10^5 Pa) in the channel at the moment of time $t = 10^{-3}$ s.

The non-stationary process starts at the initial moment of time with the initialization of the first T- layer, which is simulated by the setting of q in the form of sinusoidal impulse with duration of 10^{-4} seconds on the entrance to the channel. The power of thermal apportionment is set so that, that for this time the temperature in a local area of the flow would achieve 10^4 K, which is accompanied by the corresponding increase of the pressure. At the same time the electroconducting gas starts to interact with the magnetic field, so the shock wave goes up the flow while the wave of the rarefaction goes down (Fig.2).

At the expense of the inducted electric field the current starts to flow in the gas, that compensates the radiation losses of the energy and provides the mode of self-sustaining T-layer. Behind the front of the shock wave the apportionment of the heat in the combustion of the fuel is simulated. The apportionment of the heat raises the temperature of the gas in the area of shock-compressed gas up to 1150K, and the extension of this area increases approximately on 50 % and to some insignificant extent it leads to the increase of the pressure and speed of T-layer. For the moment of time 10^{-3} s the T-layer forms the stabilized structure, i.e. its' parameters stay further constant before the exit in the nozzle part. At an entrance of a T-layer in the nozzle temperature of gas in it declines (Fig. 3.), but this of mass of gas accelerates. The application of effect of T-layer in HRE has its' positive side in comparison to the pure generator process, as in this case energy spent on initialization, isn't lost, and contributes considerably to the propulsion impulse of the engine.

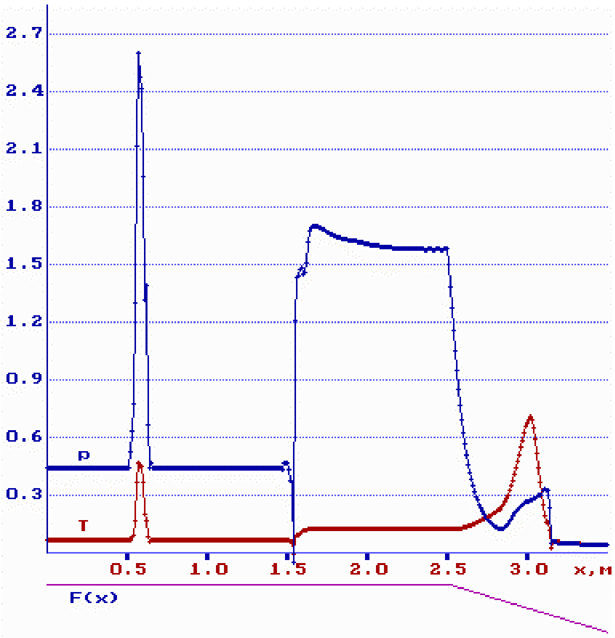

Fig. 3. Distribution of temperature (scale 10^4 K) and pressure (10^5 Pa) in the channel at the moment of time t =2.05 10^{-3} s.

At the moment of the entrance of a T-layer in the nozzle part the initialization of the subsequent T-layer occurs (fig.3). Here in the combustion chamber still remains shock -wave disturbance, that goes up along the flow and at the certain parameters of MHD-interaction the front of this shock wave can achieve the newly initialized T-layer within the limits of the chamber of combustion, changing radically its' power balance. In this case the radiation losses of the energy increase in the direct proportion of pressure, and speed of gas with the corresponding Joule heat apportionment decrease, that leads as a result in to the fast loss of electroconductivity, the stopping of MHD-interaction and break of the mode of the engine work. This effect is the feature of a periodical mode and it is necessary to be considered. For the elimination of the disintegration of a T-layer it is necessary to select parameters of MHD-process excluding interaction of a T-layer with a shock wave. This condition imposes the additional restrictions in comparison with process with an isolate T-layer [3].

In the considered periodical mode there is an interaction of a shock wave with the wave of rarefaction departing from the new T-layer, but there is no interaction of a T-layer with the shock wave, as it has time to be brought out from the combustion chamber (Fig. 4.).

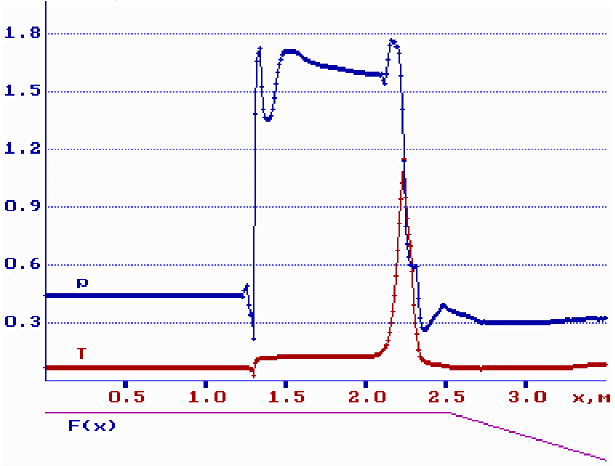

Fig. 4. Distribution of temperature (scale 10^4 K) and pressure (10^5 Pa) in the channel at the moment of time t =3.8·10^{-3} s.

At decrease of factor of loading up to 0.7 and other parameters of process being constant the interaction of a T-layer with a shock wave occurs already within the limits of the combustion chamber at the moment of time t=3.2·10^{-3} s, and further the temperature, the electroconductivity of gas and the overfall of pressure in a T-layer decrease, and the MHD-interaction practically stops.

One of the major characteristics of MHD-process is the efficiency of transformation enthalpy, which is defined as the ratio of useful power selected in the loading, to the thermal power of the flow, brought in through entrance section, of combustion chamber. For the considered mode the value η_N=17% (when q_f=0 η_N=15%). Taking into account in the definition of, that in the chamber of combustion the heat content of the flow is increased at the expense of heat of combustion of fuel, we set the value η_N=7.5 of %. The major requirement for organization of a periodical mode is the reproduction of electrical energy powerful enough for the initialization of T-layers. In this case to initiate one T-layer $1.6{\cdot}10^5$ J were spent on one unit of the cross section of the channel, and for flight time one T-layer produces $2.4{\cdot}10^5$ J/m^2 of the useful energy. Thus it is necessary to note, that the parameters of MHD-interaction were not optimized on the production of useful energy.

The basic criterion of the efficiency of the engine are specific propulsion - $\boldsymbol{R_{ud}}$ and specific impulse - I_{ud}. Proceeding from this, the optimization of parameters of MHD-interaction was carried out with the purpose of increase of the value I_{ud}.

$$I_{ud}=\alpha L_0(\varphi \upsilon_5-\upsilon)/g \qquad (6)$$

Here: I_{ud} - specific impulse, α-excess air coefficient, L_0 –stochiometric coefficient, g – gravitational acceleration, φ - the coefficient considering imperfection of nozzle, υ - velocity of approach flow.

As we can see from the formula (6), the value of specific impulse is directly connected to υ_5 - the value of speed of a flow of gas on an exit from the nozzle. The value of speed υ_5 depends on the value of electromagnetic force applied to a T-layer. Under the action of electromagnetic force, there is the increase of temperature and pressure of gas in the chamber of combustion therefore at an exit in nozzle part the flow receives acceleration, that allows to increase considerably the value υ_5.

In the estimates of periodic power setting, basic efforts were are directed on the search of optimum values of parameters of an external magnetic field B and the load factor K and also on the selection of optimum frequency of initialization of T-layers, at which the front of shock wave disturbance extending up the flow doesn’t achieve the newly initialized T-layer within the limits of the combustion chamber. Otherwise there is a disintegration of a T-layer owing to the change of its’ power balance and the stopping of MHD-interaction.

In figure 5 the diagrams of dependence of a specific impulse of the engine from the Mach’s number of flight are given with the optimum values of frequency of initialization of T-layers, and as the values of an external magnetic field B and the loading K. For the comparison the values I_{ud} for ramjet engine without MHD-control are given.

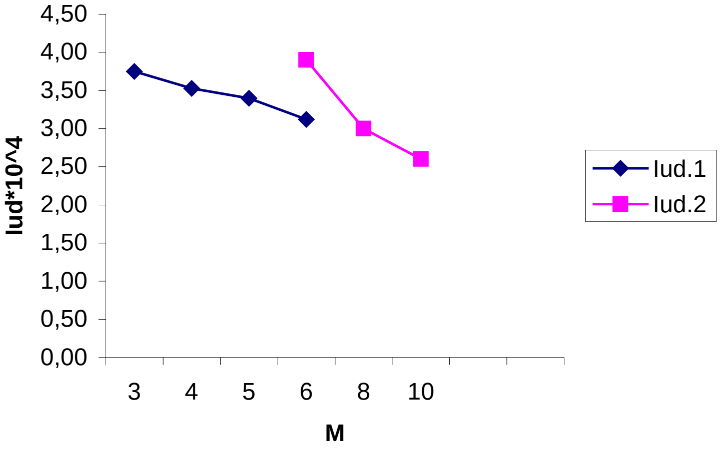

Fig. 5. I_{ud1} is specific propulsive impulse for ramjet, I_{ud2} is specific propulsive impulse for HRE with MHD – control.

From the diagram we can see, that the use of MHD-control of a gas flow allows to increase the value I_{ud} on 15-25 of % in the area of Mach's numbers order 6 in comparison with the traditional circuits of ramjet engines and to advance in the area with Mach's numbers of flight 6-10.

The further increase of the efficiency of an engine is possible at the expense of selection of values of frequency of the initialization of T-layers, and also variations of parameters of MHD-interaction.

LITERATURE

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