INTRODUCTION

One of the avenues for aeronautical technology evolution is the creation of hydrocarbon-fueled hypersonic flight vehicle (HFV) capable of sustained cruise flight in the atmosphere. The quest for flight altitude increase up to 30-40 km leads to velocities exceeding Mach 6.0. Such conditions of flight enable realization of many scientific, economic, military, and other tasks for which neither modern-day aeronautics nor astronautics present necessary solutions. Besides, combat HFV (airplanes, cruise missiles) would be highly invulnerable under such flight conditions.

Extensive research on HFV is carried on by the USA, France, Russia and other countries. In 2003 a new joint Defense Advanced Research Projects Agency (DARPA)/United States Air Force (USAF) program dubbed “FALCON” [1,2] for Force Application and Launch from ConUS was initiated - a continuation of a well-known HyTech (for Hypersonic Technology) program. The final objective of FALCON program is to provide the US Armed Forces by 2025 with the reusable vehicle capable of achieving hypersonic velocities of Mach 6 and above, thus ensuring rapid delivery of any pay-load to any point of the globe within $\leq 2$ hours. Hypersonic cruise vehicle is designed for aircraft-like operations from existing airfields. An important contribution of FALCON program to future, apart from power and efficiency enhancement of the USA Armed Forces, would be commercial flights between Washington and Singapore or suchlike.

The program FALCON has several stages. Hypersonic technology vehicles (HTV) will be the first to come into play to demonstrate novel technologies in various fields of aircraft construction (aerothermodynamics, high-temperature materials and structures, combined cycle engines and different fuels, navigation, plasma communication, etc.). The first flights of HTVs are planned for May and October of 2009. X-51A [3] will be among the first endothermically fueled vehicles. It is the flight demonstrator of a hydrocarbon-fueled scramjet made within HyTech program realization that underwent successful engine ground tests. The true viability of X-51A propelled by a JP-7 kerosene using catalytic pyrolysis will be demonstrated in a series of 4 flight tests beginning in August 2009.

The French program [4] dubbed LEA resembles in many aspects the American counterpart, only a bit legging in time. The first ramjet-powered HFV flights will be conducted within 2010-2011 time frame. It has been already announced that methane-hydrogen mixture and synthetic hydrocarbon fuel undergoing pyrolysis will serve as a fuel.

The concept of hypersonic flight vehicle under development at the Leninetz holding company under the name Ajax [5, 6] is based on the active energy interaction of the system with the air flow past it. HFV of the Ajax concept is an open aerothermodynamic system. Kinetic energy of hypersonic air stream assimilated by HFV sub-systems is transformed into wide spectrum of useful activities. Such an approach lends an opportunity to crucially remodel all aspects of further development of the aeronautical and aerospace technologies. Active structure cooling should be realized using steam reforming of the regular hydrocarbon aviation fuel which in itself is the basic energy carrier. The resulting (after hydrocarbon decomposition) hydrogen is used for improvement of fuel mixture parameters. Hydrogen production and MHD systems application for air flow stagnation and acceleration opens up the way for creation of scramjet. Power achieved in the process exceeds significantly that of the existing systems. Electric energy produced can be used in plasma flow-over systems for increasing HFV’ aerodynamic efficiency.

Within the framework of Ajax conception new technologies aimed at mastering hypersonic flight velocities have been suggested [7]. Their application could enable creation of:
- HFV active thermal protection and fuel conversion system based on chemical heat regeneration;
- Magnetoplasmachemical engine magnetohydrodynamic exerting power effect on hypersonic flow and using steam hydrocarbon reforming yields;
- Plasma setup acting on aerodynamic performances of HFV.

Schematic of Ajax concept HFV is shown in Fig.1.

**Fig.1 Schematic diagram of Ajax concept HFV**

1. **Active thermal protection and fuel conversion**

   Active thermal protection system is one of the energy transfer channels [8, 9]. It represents itself an aggregate of recuperative heat exchangers – thermochemical reactors (TCR) placed in the most heat-stressed parts of airframe and engine structures, wherein various physical and chemical processes occur ranging from elementary heating of coolants and up to endothermic catalytic reactions. One of the coolants and a reagent is a hydrocarbon fuel – aviation kerosene, and an energy source for realization of physical and chemical transformation is utilized heat from aerodynamic heating and from power plant. Thermal protection system under consideration fulfills not only traditional function providing for normal temperature conditions of the vehicle structure but serves simultaneously as a preparation system for the new modified fuel comprising molecular hydrogen.

   Among the multitude of existing endothermic reactions [10] we consider, first of all, steam hydrocarbon reforming. The estimates show [8,9] that as to available cooling resource, hydrocarbon + water composition, subjected to steam reforming process, is approaching the version of liquid hydrogen cooling.

   It should be noted, that catalytic steam hydrocarbon conversion, as to its thermal effect and hydrogen amount produced, by several times surpasses non-catalytic endothermic processes such as pyrolysis, cracking and depolymerization of hydrocarbons. The problem lies in the creation of the extended catalytic surface of heat exchange and maintenance of its properties throughout all period of product operation.

   A specific type of hydrocarbon steam conversion reaction depends on the process conditions (temperature, pressure, hydrocarbon-water ratio, and so on). For example, at high temperatures (T > 1200 K) the reactions proceed practically till formation only H₂ and CO (high temperature conversion):

   \[a C_n H_m + b H_2 O \rightarrow f H_2 + g CO\]  \hspace{1cm} (1)

   At low temperatures (T < 700 K) product output is shifted considerably toward formation of CH₄ and CO₂ and resulting reaction of gasification can be presented as follows (low temperature conversion):

   \[a C_n H_m + b H_2 O \rightarrow d CH_4 + e CO_2\]  \hspace{1cm} (2)

   As a general case, both reactions (1) and (2) are accompanied by two more independent reversible reactions which determine equilibrium composition of the converted gas:

   \[CH_4 + H_2 O \leftrightarrow CO + 3H_2\]  \hspace{1cm} (3)

   \[CO + H_2 O \leftrightarrow CO_2 + H_2\]  \hspace{1cm} (4)

   Unfortunately, the process of hydrocarbon decomposition is complicated by undesirable reactions of free carbon (coke) formation. Two-stage steam conversion of liquid hydrocarbons (Fig.2) is one of the ways to decrease coke formation in the components of thermal protection system [8,9].

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From Fig. 2, the scheme of the two-stage process becomes simplified turning into one-stage if, first, methane is the original fuel and, second, the duration of setup operation is not too long allowing to neglect the coke formation process – the fact proven by experiments [11]. It is expedient in both cases to conduct at once the high temperature steam reforming.

To study the process of hydrocarbon fuel transformation, TCR of various configurations have been used. One of TCR’s fragments is shown in Fig. 3.

Fig. 3 Fragment of cylindrical TCR (not to scale)

The reactor itself represented a cavity formed by two coaxial cylinders with 500 mm length and clearance width d=2.0 mm between them. Inner surface of this cavity was coated with Ni-Cr catalyst and methane was to act as one of the reagents. Schematic of the setup for methane reforming is presented in Fig. 4. The water was heated and evaporated in water evaporator (1). Heating of the steam and methane from the cylinder was done in electric heaters (2) and (3) respectively. Then came blending of reagents and their supply at ∼ 550°C to TCR (4) where chemical endothermic reaction proceeded. Heat input to the steam-methane mixture was realized through inner wall of the reactor. The high-temperature nitrogen jet from plasmatron (5) served as a heating source. The TCR inner wall temperature was taken by thermocouples (6). Samples for analysis of the reaction yields composition were taken with the help of samplers (7).

Fig. 5 shows a typical profile of the reactor’s wall temperature distribution. The initial part of the curve corresponds basically to the mixture convective warm-up to the temperature of reaction.
Then gradual deceleration of wall temperature increase starts followed by its drop caused by intensive heat extraction for endothermic reaction of steam reforming. When feeding neutral gas nitrogen to the reactor, this phenomenon is not observed; convective warm-up of the mixture (dotted line) lengthwise of the reactor goes on instead.

![Temperature distribution on TCR wall](image1)

![Distribution of methane and hydrogen concentrations lengthwise of TCR](image2)

Fig.5 Temperature distribution on TCR wall  
Fig.6 Distribution of methane and hydrogen concentrations lengthwise of TCR

Fig.6 shows distributions of methane and hydrogen concentration lengthwise of the reactor that bear witness of the chemical reaction inside the reactor.

Figs.7 and 8 present dependencies of methane conversion degree $X$ and average density of heat flux lengthwise of the reactor $q_{av}$ on steam-methane mixture velocity at the reactor inlet.

![Methane conversion degree](image3)

![Average heat flux density](image4)

Fig.7 Methane conversion degree  
Fig.8 Average heat flux density

Summarizing application results of the steam methane reforming under standard (industrial) conditions and laboratory investigation of the process at the unlimited heat supply, one can draw a conclusion on the possibility of thermochemical transformation of the primary fuel in the system of reactors with various degree of conversion ($10 – 100 \%$) at the heat utilization in a wide range of heat loads ($0.05 – 1$ MW/m$^2$).

2. Use of MHD Systems for scramjet performance control

Schematic of a scramjet with additional subsystems is shown in Fig.9 [12-14]. The external MHD generator allows one to control a flow field and to regulate the air mass flow rate in a scramjet. The flow compression in MHD controlled inlet is a result of joint actions of multishock gas-dynamic compression and additional MHD compression. The internal MHD generator is used for increasing the static pressure and for preventing of flow separation. External and internal MHD generators located upstream the combustion chamber transform a part of the flow enthalpy into the electric power. Part of produced electric power is spent on flow ionization. The rest of the power is transferred to MHD accelerator located downstream the combustion chamber, for additional acceleration of combustion products and to power onboard systems. The degree of MHD influence on a flow in MHD generator channel depends on a magnetic induction value and the flow
conductivity. The use of MHD systems in a scramjet allows one to increase effectiveness of a propulsion system thermodynamic cycle and to increase its specific impulse and thrust.

![MPCE schematic](image)

**Fig.9** MPCE schematic: 0-1 – air inlet; 1-2,c – internal MHD generator; 2-3 – combustor; 3-4,d – MHD accelerator; 4-5 – nozzle; a – ionizer; b – external MHD generator; e – onboard systems.

To evaluate effect of MHD-controlled inlet on the scramjet performance, numerical computations of propulsion scheme have been carried out wherein all power produced by MHD generator located in the air inlet is transferred to the accelerator located downstream of the combustion chamber. Typical characteristics of this propulsion are presented in Table1 in a relative form, where $B$ – value of magnetic induction, $M$ – Mach number, $I_{sp}$ – specific impulse, $\varphi$ – air mass flow rate, $\pi$ – relative pressure.

<table>
<thead>
<tr>
<th>$M_\infty$</th>
<th>$B$, T</th>
<th>MHD-controlled inlet</th>
<th>Scramjet with MHD accelerator</th>
<th>Scramjet without MHD accelerator</th>
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<tr>
<td></td>
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<td>$\pi/\pi_0$</td>
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3. **Plasma Method of Aerodynamics Control**

The energy produced by MHD generator can be used for creation of artificial plasma formations whereby control over aerodynamic characteristics of HFV becomes possible [6, 7]. By the addition of energy in the shock wave region and variation of flow parameters in boundary layer it is possible to decrease drag, prevent flow separation phenomenon, and increase lift.

The use of aerodynamics plasma control has a number of advantages as compared to the traditional methods [15]. These control systems are non-inertial ones; they have no need for mechanical devices and can be used in hypersonic flights under heavy thermal and mechanical loads.

In Figs.10-13, presented are schemes and the results of some our model experiments favoring the fact that by application of the developed techniques and apparatus the essential rearrangement of flow in the boundary layer near aerodynamic body is possible as well as variation of pressure on the streamlined surface.
Conclusion

The AJAX conception is the most integral one from power realization point of view. Linked organically together, here are different scientific and technical approaches:

- Usage of heat losses for converting hydrocarbon fuel into hydrogenous mixture for scramjet combustion;
- MHD control of ionized air flow in the engine to improve its performance and transform part of the air kinetic energy into electric power;
- Local energy effect on the ram airflow to ensure control over vehicle aerodynamics.

REFERENCES

2. St. Walker et al. Falcon HTV-3X – A Reusable Hypersonic Test Bed. AIAA 2008-2544