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Hydrogen demonstrator of high-speed cruising ramjet for hypersonic flight speeds

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Annotation

The paper presents the results of numerical and experimental studies of a hydrogen demonstrator the high-speed ramjet for hypersonic flight with an engine ventral position and a flat air intake device (AID). Simulated bench fire altitude tests of the demonstrator. When simulating a ground-based experiment, the geometry and operation mode of the stand on which the tests were carried out as part of the HEXAFLY-INT project were repeated closely. The flow parameters in the combustion chamber and the nozzle of the model were calculated for different values of the oxidizer excess ratio and combustion efficiency. The total flow pulse at the nozzle section and the total force acting on the model (effective thrust) were determined. The range of parameters with the positive air-jet balance is estimated.

Keywords: *high-speed ramjet, hydrogen demonstrator, numerical simulation, air intake device.*

List of abbreviations and notation

ER - excess fuel ratio
p^* - full pressure
T^* - total temperature
F_x - effective thrust
AID - air intake device
HA – hypersonic aircraft
PPP – power propulsion plant
T_w – wall temperature
CC -combustion chamber
TV – test vehicle

Introduction

Modern developments in the field of civilian hypersonic aircraft (HA) are carried out in many countries [1,2]. The most important component of such aircraft is the power propulsion plant (PPP) integrated with the airframe, which, as a rule, at such high flight speeds, is usually considered a ramjet engine, or using its combined PPP. One of the first projects of an aerospace system with a hypersonic aircraft with a ramjet engine was the "Spiral" being developed in the USSR [3]. Civilian-like aircraft of this type were designed for low-Earth orbit flights (NASP (USA) [4], SKYLON (Great Britain) [5], JASP (Japan) [6], Hyperplane (India) [7], ASP-carrier (China) [8], Zanger (Germany) [9], STS-2000 (France) [10], Tu-2000, MAKS [11]) or passenger transportation (ZEHST [12], HEXAFLY-INT [13], JAXA [14]).

Of great interest are civilian hypersonic aircraft. From an economic point of view, a hypersonic civil aircraft with flight Mach numbers M = 5–8 has an advantage over supersonic passenger aircraft such as the "Tu-144" and "Concord" in that it can make a direct and reverse transcontinental flight in one day. In the present research the current stage,

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numerical and experimental studies of the working process efficiency in the internal flow path of the propulsion power plant, aerodynamics of the aircraft are carried out, the efficiency of the air intake device (AID) is addressed, and the characteristics of heat-resistant materials are studied. As an example, in fig. 1 shows a diagram of a typical hypersonic aircraft designed by SKYLON. The HA length is more than 80 m, the maximum weight is about 275 tons. It will take a bit more than a few equatorial orbit. Mach number M ≤ 16, while the Ramjet works up to the Mach number M = 5.5.

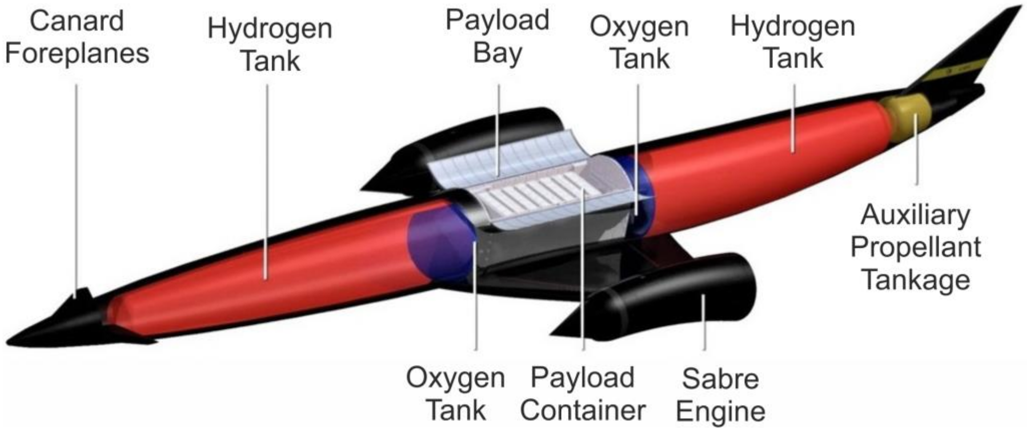


Figure 1. The scheme of HA "SKYLON" [5]

For the first time in the world, flight tests of an axisymmetric high-speed Ramjet on hydrogen fuel were carried out in Russia in 1991 using the "KHOLOD" hypersonic flying laboratory (HFL) [14]. Then, from 1992 to 1998, together with France, and then the United States, (see Fig. 2), another 4 flight tests of the axisymmetric high-speed Ramjet demonstrator were carried out. In these flight tests, the engine-demonstrator was not separated from the booster. The possibility of realizing an efficient working process in a combustion chamber at supersonic flow rates at the inlet under real hypersonic flight conditions has been practically investigated.

Later on, the methodology for conducting such flight tests was applied by Australian scientists (HyShot [16]) to study the workflow in the Ramjet model combustion chambers and was used in flight tests in India [17].

Flight experiments with hydrogen engines were also implemented in projects X-43 (Mach numbers M=6.8 and 9.6) [18] and HIFiRE (M=7, without a ramjet engine) [19]. A large series of ground fire tests were also conducted in different countries outside and in Russia. The HA X-43A scheme is presented in Fig. 3 [18]. In two launches, during the first, at the flight Mach number M=6.8, during the second M=9.6, the stated engine thrust was demonstrated. Hydrogen was used as a fuel, but combustion was initiated using Silane, which indicates problems with self-ignition of the fuel in this engine. The propulsion power plant (PPP) when flying at a speed corresponding to the Mach number M = 10, worked for no more than 10 seconds, so it can be argued that the issues of the cooling system and the resource work of the high-speed Ramjet demonstrator in this work were also not achieved, and the goal was to demonstrate the possibility engine operation at such flight speeds.


Figure 2. Hypersonic flying laboratory "KHOLOD" at the launch position (a) and at the stand (b)

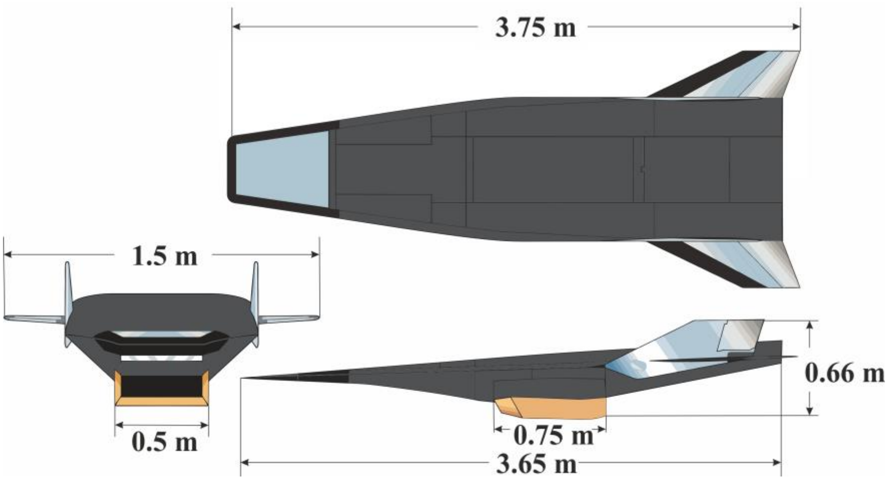
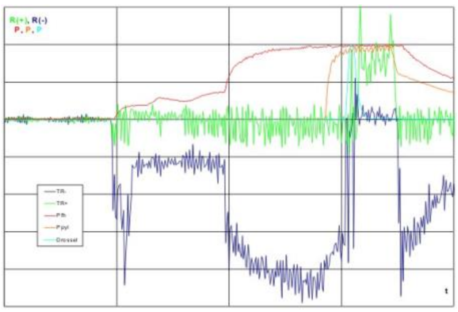


Figure 3. The hypersonic hydrogen fuel aircraft X-43A overview

A large series of ground fire tests were also conducted abroad and in Russia. Thus, at the TsIAM's Ts-16VK stand for the X-2000 bench model with "small" hypersonic Mach numbers, the positive effective thrust created by the model engine-demonstrator in integration with the experimental HA (Fig. 4) was registered for the first time at the stand. During the test, the sensors for recording the longitudinal force first showed the resistance of the experimental object (Fig. 4b). After the fuel supply and the implementation the combustion process, an excess of the force created by the engine-demonstrator in integration with the experimental HA over the resistance of the experimental object was recorded. In tests, gaseous hydrogen and natural gas were used as fuel. The presented experimental data convincingly confirm the thrust efficiency of the Ramjet integrated with the aircraft on "small" hypersonic Mach numbers.

a) Experimental object X-2000 in the working part of the stand Ts16VK



б) Sensors recording the longitudinal force at the high-altitude experiments of the tested vehicle

Figure 4. Model engine in integration with experimental HA

In European Union, the main program in the field of civil hypersonic technology is the "HEXAFLY-INT" program, within which comprehensive aircraft research with a high-speed ramjet engine running on hydrogen fuel is conducted. The model itself (Fig. 5) differs from the well-known developments of the type "waverider" by the dorsal arrangement of the AID and the two-belt fuel injection system. The propulsion system is a supersonic combustion chamber of elliptical section, which passes into a nozzle, expanding first in one plane, then in two.

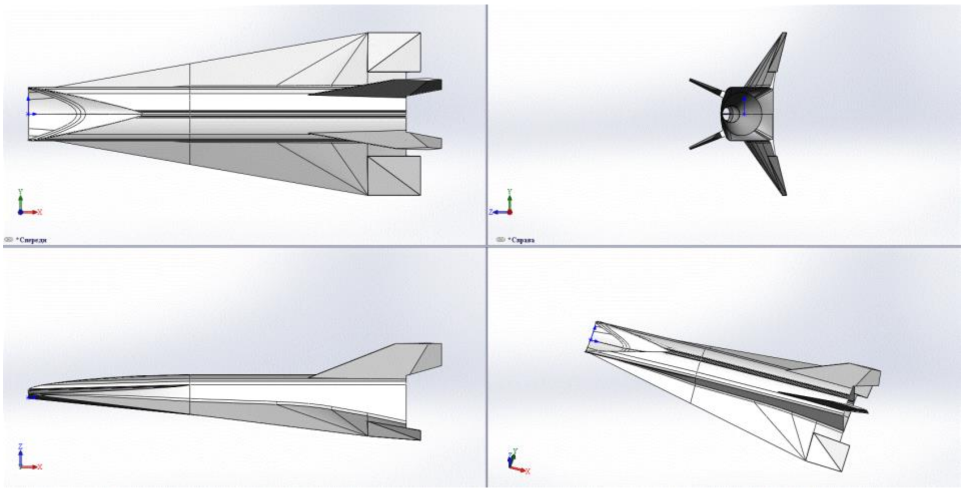


Figure 5. The appearance of the aircraft (in the framework of the project HEXAFLY-INT)

Research in the framework of the "HEXAFLY-INT" project

In the framework of the international project "HEXAFLY-INT", with participation of TsAGI, ESA, CIAM, MIPT, and others, computational and experimental studies of a high-speed ramjet engine demonstrator running on hydrogen fuel are carried out. The Central Institute of Aviation Motors (CIAM, Moscow, Russia,) participates in this project in part of the preparation, conduct and analysis of ground tests of the bench module. A stand module was created [20-23] (Fig. 6). It is a SCRAMJET integrated with AID, and mounted on a power pylon. At the same time there are no external aerodynamic surfaces (wings, elevons and ailerons). Tests of this module were carried out with imitation of altitude conditions of flight with the Mach number of the incident flow M=7.5. Hydrogen was chosen as a fuel, since it has a high calorific value, a large cold resource and a short ignition delay, which is necessary with a short residence time of fuel particles in the combustion chamber (CC) of the SCRAMJET.

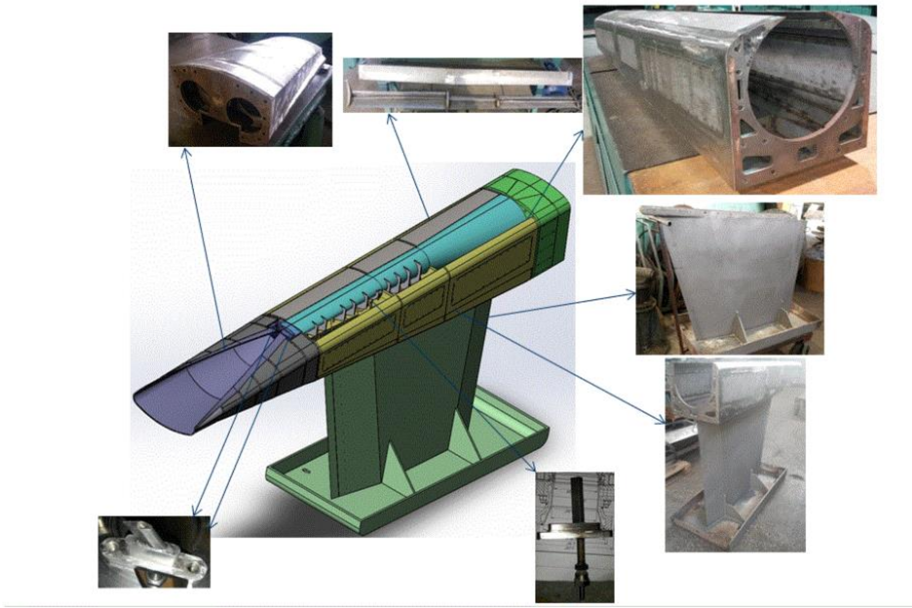


Figure 6. Stand module HEXAFLY-INT

The bench module was installed on the force load measuring device - a torque platform, which allows determining the traction and economic characteristics of the bench module. The module is equipped with static pressure sensors for analyzing the workflow inside the module flow path. For the start, in which a positive aero-propulsion balance was registered, in fig.7 shows the dependence of the force acting on the bench module integrated with the power pylon. For this point, the total pressure in the fired heater was 6.4 MPa, and the total temperature was 2310 K. The jump in the thrust sensor readings at time t=12.5 s corresponds to the start of the AID. Fuel is supplied to the CC when the pressure in the OP reaches a constant value, that is, it can be assumed that no changes in the input parameters occur during the CC process. During fuel supply to the CC (t=17-18.5 s), a steady workflow was demonstrated, providing a positive air-jet balance of the "bench module + power pylon" system, average force value F_x = 85.4 N. Average value of aerodynamic drag during testing X = - 360 N.

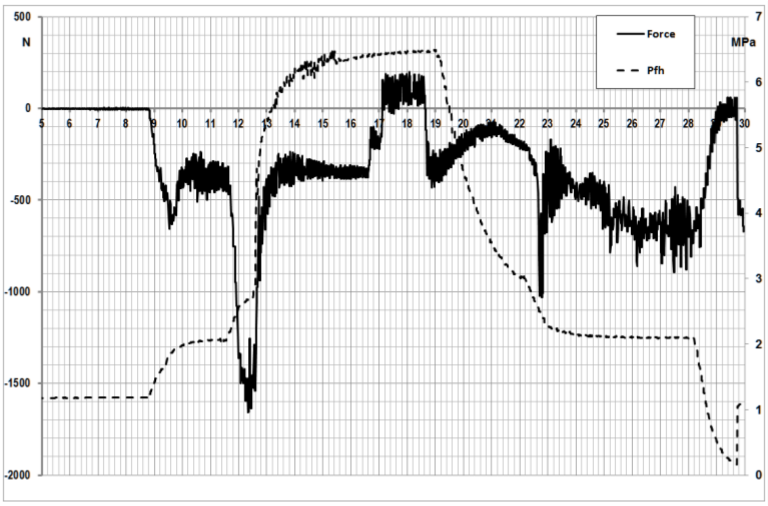


Figure 7. The total force (Force, N) acting on the device depending on the time and the total pressure in the TV (Pfh, MPa)

Numerical studies of the hydrogen demonstrator of a high-speed cruising ramjet for hypersonic flight speeds

According to the "HEXAFLY-INT" program the aircraft has the spatial configuration of air intake, but in this project the classical AID was considered as the alternative configuration. The basis for selecting the configuration of the AID upon the principle of obtaining mass air flow and thrust required to ensure a positive aerodynamic balance, and the achievement of the maximum recovery coefficient of the total pressure σ_u. Two variants of calculated AIDs were considered, based on a criterion similar to the Osvatich criterion, and described in [24, 25] to obtain a close to maximum recovery ratio of the total pressure σ_{AID}: with two and three external compression panels. In this case, the maximum value of σ_{AID}, provided that the flow velocity in the throat is directed parallel to the sidewall and corresponds to the specified Mach number in the throat with a system of oblique shock waves with the same degrees of external compression and with the same degrees of internal compression. Preliminary estimates in a one-dimensional formulation using the ratios of flow parameters at oblique shock waves showed that the maximum value of σ_{AID} for the version with three panels is 30% higher than this value for the version with two panels. However, the presence of three compression panels suggests a much longer length of the AID. (The assessments made showed that within the limits of the given dimensional limitations, it is possible to create an AID with three compression panels.) Then, based on the one-dimensional calculations described above, a two-dimensional version of the flat AID with three external compression panels was constructed (Fig. 8).

Figure 8. General scheme of AID with three compression panels

It should be noted that the launch of such AIDs with the design system of oblique shock waves with increasing aircraft speed to the design one, as a rule, does not occur. This can be shown using the Kantrowitz criterion for launching a supersonic AID [20]. Therefore, the throat of the AID has been expanded to improve the performance of the launch. When building a three-dimensional model of the AID, the shape of the nose of the aircraft was chosen in such a way as to ensure maximum air flow. Along the edges of the third external compression panel, partitions were added to reduce the spreading of air. Taking into account the increase in the thickness of the boundary layer along the engine path, the transition channel of the AID is made with a slight expansion. This version of the AID differs from the AID of the demonstrator of the HEXAFLY project by a simpler flat and complex spatial geometry. The general scheme of the flow path of the engine is shown in Fig.9.

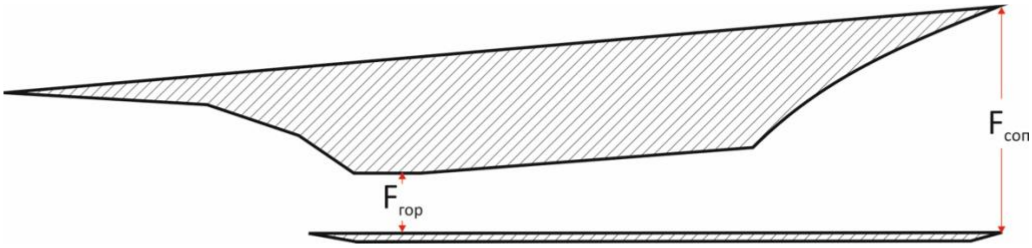


Figure 9. The general scheme of the flow path of the engine

Numerical simulation of high-altitude fire bench tests

Calculation of the flow without fuel supply to the CC HA.

This chapter is devoted to numerical simulation of the flow around a three-dimensional model of the Ts-16VK TsIAM test bench with the HA prototype demonstrator installed in it.

The operational parameters of the tests correspond to those specified during the tests in the framework of the HEXAFLY project [22], and are listed in Table 1.

Table 1. Test parameters

M	angle of attack, deg	p_{on}*, MPa	T_{on}*, K	T_w, K
7,5	8	6,4	2310	1000

On the constructed grids, a complete set of Favre-averaged Navier-Stokes equations for compressible gas with variable thermophysical properties with closure using the Spalart-Allmaras one-parameter turbulence model was solved. For the working gas, the dependence of it's specific heat at constant pressure on the temperature was set, corresponding to the combustion products in this operating mode of the stand.

Due to the installation of the TV with zero yaw angles and roll, the computational area consisted of the intra-bench space and flow path of the model bounded by the surfaces washed by the combustion products and the plane of symmetry on which the corresponding boundary condition (BC) was set. Sticking conditions were set on all walls, as well as a constant temperature T_w. For a subsonic PG at the entrance to the bench nozzle, the pressure p_{op}*, temperature T_{op} *, resulting in the output section of the OP, were set. In the output section, the static pressure was set at p = 0.02 bar. Data for the values specified in the BC are given in Table 1.

The stated boundary value problem was solved numerically using the Roe FDS method of implicit second order accuracy. The fields of the initial conditions (IC) in all calculations were uniform: speed V=0 m/s, static temperature T=300 K, static pressure p=0.02 bar. All the presented calculations have been brought to the exit of expenses through the flow areas of the stand to constant, consistent values.

Figure 10 presents the field of distribution of Mach numbers in the plane of symmetry (passes through the vertical pylon). Table 2 shows the values of the averaged flow parameters in the throat of the AID.

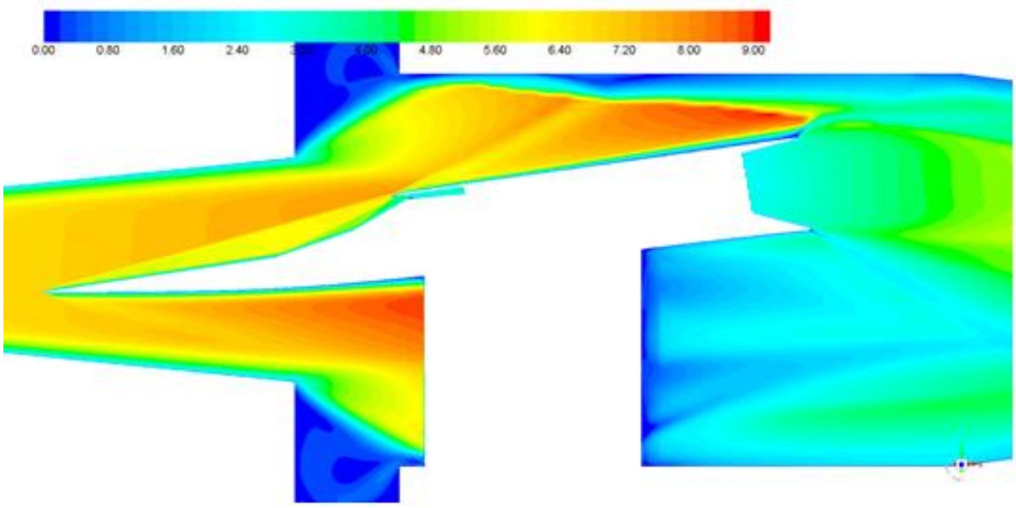


Figure 10. The field of Mach numbers in the plane of symmetry

Table 2. Averaged parameters of the flow in the throat of the AID

Flow rate through OP $G_{facility}$, kg/s	10,52
Flowrate through AID G_{throat}, kg/s	2,392
Wall temperature T_w, K	1000
Temperature T_{th}, K	1340
Pressure p_{th}, bar	0,369
Total pressure p_{th}*, bar	8,602
Mach number M_{th}	2,63
Velocity $V_{x\ th}$, m/s	1818
Recovery ratio σ	0,134
Resistance Force X, kgf	193,57
Lift Force Y, kgf	93,8

From Fig.10 it is seen that in the process of numerical simulation the AID starts up with the establishment of supersonic flow in the flow path of the TV. The gas, entering the thermal-pressure chamber (TPC), accelerates in the rarefaction wave adjacent to the wall at the CC cut, then the flow turns in the SW, and then it moves parallel to the wall of the diffuser. This SW from the wall of the diffuser comes to the side of the engine and the fuselage of the TV. Thus, the aerodynamic forces listed in the table differ from those that would act on the TV in a uniform free flow.

Assessment of the thrust and economic characteristics of the prototype demonstrator in bench test conditions

Evaluation of aerodynamic forces acting on the TV when starting with the fuel supply to the CC. The evaluation of aerodynamic forces on the mode with fuel supply to the CC TV was carried out in several stages. In the first, the X and Y components of the integral vector of pressure and friction forces acting on the bench pylon and the TV surfaces were calculated using data from a three-dimensional calculation of the flow in the stand, except for the surfaces bounding the flow path region between the throat cross section of the inlet pipe and the nozzle section. Also, in the section of the throat of the AID, the integrals of conservative quantities were calculated: mass flow rate, the components of the vector of the total momentum of the flow, and the flow of total enthalpy. At the second stage, it was assumed that the flow in the CC and the nozzle is one-dimensional, and all velocities are parallel to the axis Ox of the associated coordinate system. Based on the obtained Gr, Ir and hr*, the flow parameters given in the table were calculated averaged over the cross section, taking into account the conservation laws. As was assumed in this one-dimensional calculation, the fuel, for which hydrogen was used, was supplied to the CC in a gaseous state at the speed of sound.

The chemical composition and thermodynamic parameters of the combustion products were considered equilibrium, but the completeness of the combustion of the fuel along the path changed according to the burnout curve [25]. For their calculation, a system of equations was solved on the basis of integral conservation laws for the reacting mixture of fuel and oxidizer. The thermodynamic properties and the equilibrium composition of the products of combustion were calculated using the program created in CIAM. The mixture consisted of the following elements: H, O, C, N, H2, O2, N2, OH, H2O, NH3, NO, CH4, CO, CO2, NO2.

Finally, based on the data obtained at the previous stages, integral calculations of aerodynamic forces acting on the TV were made. Figure 11 shows the values of the longitudinal component of the aerodynamic force acting on the TV and the bench pylon at different fuel combustion rates at the end of the combustion chamber.

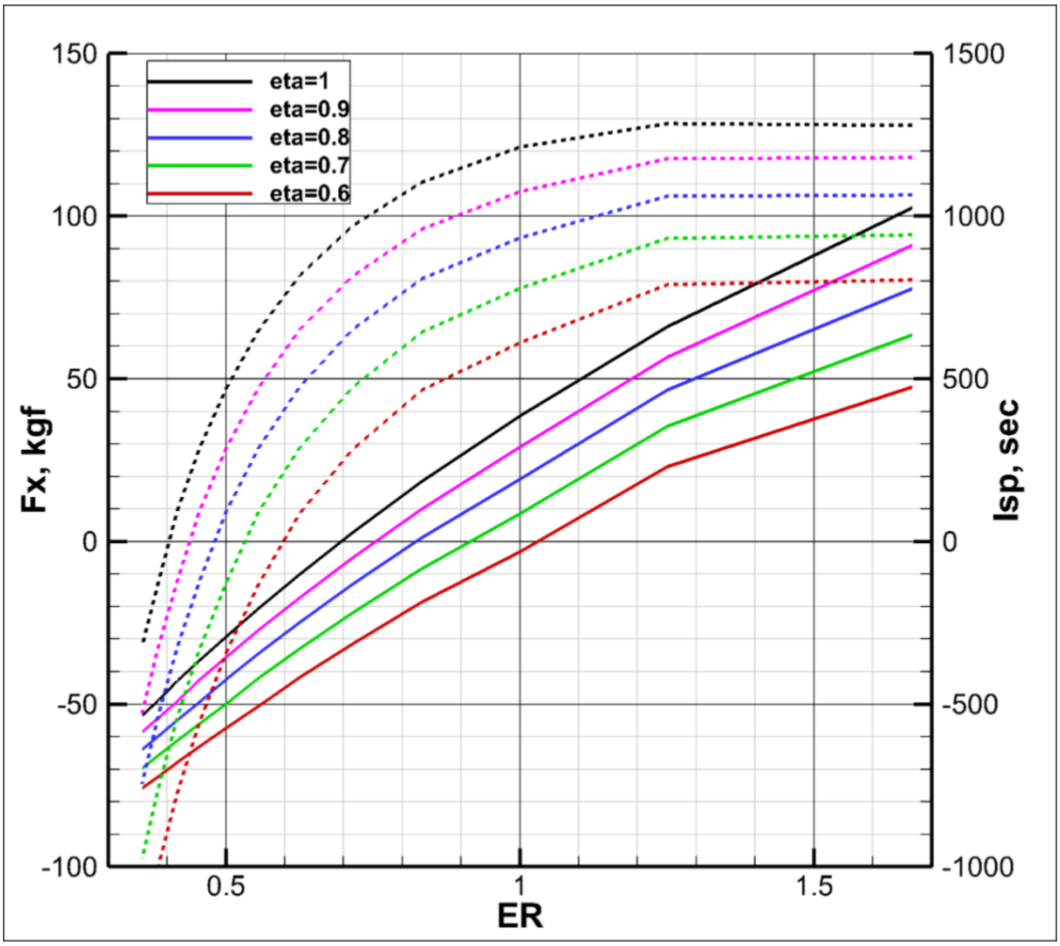


Figure 11. The longitudinal component of the aerodynamic force acting on the TV and the bench pylon (left axis, solid lines) and specific impulse (right axis, dotted lines) at different fuel combustion rates at the end of the combustion chamber depending on the fuel excess ratio

It can be seen that in the conditions of bench tests a positive aero-propulsion balance can be obtained, in this area there are also maximum values of specific impulse

Perspective aerospace systems

In addition to projects to create hypersonic civil airplanes, combined propulsion systems with a direct-flow contour are considered for use as part of reusable aircraft for outputting payloads into orbit (Fig. 12). So in [26] proposed a turbo-rocket-ramjet engine having two circuits and 4 modes of operation. In the first mode, the TRE circuit works, accelerates the aircraft to the flight Mach number M = 3, then the second circuit is turned on and the engine operates as an Ramjet and accelerates the aircraft from M = 4 to M = 5-6, then due to the geometric changes of the flow path, the direct-flow ramjet goes in the scramjet mode of operation and accelerates the aircraft to a flight Mach number M = 8, and finally, the last mode is the operation of a ramjet as a rocket engine nozzle and acceleration to M = 10.

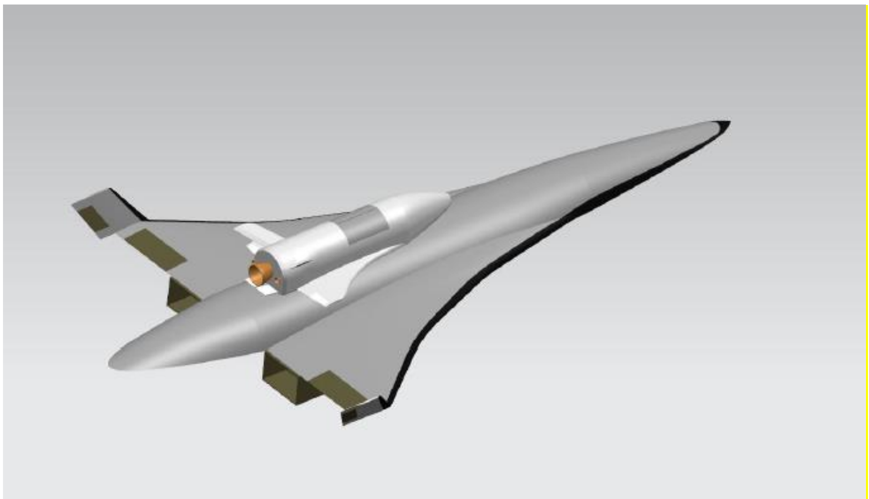


Figure 12. A two-step system to put a payload to orbit.

A similar research project is SpaceLiner - the concept of a suborbital hypersonic passenger spaceplane, developed since 2005 in the German Aviation and Cosmonautics Center (German: Deutsches Zentrum für Luft- und Raumfahrt DLR). The spaceplane of the vertical take-off, unconventional for passenger vehicles, is a two-stage aerospace system consisting of an unmanned (automatic) launch stage accelerator and a passenger suborbital stage designed for 50 passengers. Total power plant includes eleven liquid rocket engines (9 of them are installed at the starting stage, 2 - at the suborbital stage), working on cryogenic fuel - liquid oxygen (LOX) and liquid hydrogen (LH2). After the rocket engines are turned off, the suborbital stage is capable of covering large intercontinental distances in the planning flight for the shortest time. Depending on the route, flight heights of up to 80 km and speeds corresponding to a Mach number above 20 can be reached. The duration of the flight on the Australia-Europe route is 90 minutes, and on the Europe-California route - no more than 60 minutes.

According to the results of the analysis of the performance of various configurations of hydrogen Ramjets, further elaboration of the Multifunctional Hypersonic Aircraft (MHA) Project with an integrated hydrogen-jet propulsion system for carrying out transcontinental passenger traffic and launching spacecraft to near-Earth orbit seems advisable. The project is being developed at the Moscow Institute of Physics and Technology (MIPT) in the Laboratory of hypersonic and plasma technologies (LHPT). The aim of this project is to solve fundamental and applied scientific problems of aeroplasma dynamics, heat and mass transfer and combustion, to develop a technical look and technological solutions to ensure the creation of a multifunctional hypersonic aircraft with an integrated hydrogen jet propulsion system for transcontinental passenger traffic and the launch of spacecraft to near-Earth orbit To achieve this goal, the project plans to solve the following tasks:

1. Research of various concepts of reusable horizontal launch and landing space transportation systems. The formation of options for the technical appearance of the MHA with the hydrogen fuel power unit.

2. Refinement of existing and development of new physical and mathematical models of processes of aero-reacting flow dynamics, heat and mass transfer as applied to the hypersonic flow around bodies of various configurations, as well as gas dynamic flow and turbulent combustion of various fuel mixtures in subsonic and supersonic flows in channels of constant and variable cross-sections.

3. Development and implementation of a computational module (including in commercial software systems and open source software systems) for conducting numerical

simulation of flows in an integrated jet propulsion system on hydrogen fuel and the external flow of the HA.

4. Development and creation of a large-scale bench model for validation of physical and mathematical approaches for software and hardware for simulation of aerodynamics, heat and mass transfer and combustion for MHA, as well as establishing new patterns of physico-chemical and plasma processes on the surface of the MHA and in the flow path of the engine in wide range of speeds and flight altitudes. Adaptation of the complex stand and the creation on its basis of an experimental setup for testing a large-scale validation model. Tests of a large-scale validation model.

5. Computational and experimental studies of the specific features of gas-dynamic, plasma, and thermal effects in the case of hypersonic flow around various versions of MHA. Predictive assessment of the effectiveness of various options and the choice of the basic technical appearance of the MHA. The formation of the flow path of the engine and its integration with the fuselage MHA. Development of technologies to ensure proper aerodynamic characteristics of MHA, a highly efficient engine workflow and the efficiency of an integrated engine + MHA system for the required service life.

6. Development of requirements for systems and technical proposals for solving problems of navigation and telemetry transmission at hypersonic flight speed of MHA.

7. Analysis the results of computational-experimental research and development of proposals for the creation and layout of MHA based on the existing scientific and technical background, existing and promising technologies and materials, industrial design. Preparation of proposals for the organization of full-scale work aimed at developing an MHA flight demonstrator with an integrated jet propulsion system on hydrogen fuel, taking into account the possible cooperation of leading domestic and foreign scientific centers, as well as industrial enterprises.

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