2002ESASP.487...81R

RESEARCHES OF HYPERSONIC PROPULSION IN CENTRAL INSTITUTE OF AVIATION MOTORS

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ABSTRACT

Scientific research technologies and facility used in CIAM to study problems of hypersonic propulsion are described. Some results of application CFD researches, ground and flights experimental investigation of scramjet operation processes discussed. Some plans of test facility reconstruction, CFD methods improvement and future hypersonic flight test vehicle design and creation.

1. INTRODUCTION

Creation problems of supersonic combustion ramjet-scramjet-are studying in CIAM from fifties yeas. Firstly scramjet tract gas dynamic and possibility of combustion in supersonic flow were objects of theoretical and experimental researches. Seventies yeas beginning supersonic combustion was observe at some ground model experiment. The same time hypersonic flight test program was starting by CIAM. Eighties were yeas of intensification of worldwide hypersonic problem investigations and CIAM began to develop complex software for CFD hypersonic investigation, to create hypersonic ground facility for large scale experimental scramjet, to accelerate preparing scramjet hypersonic flight tests.

From 1991 CIAM as head of group of Russia and Kazakhstan firms is carrying out hypersonic flight tests of model scramjets this row of flight tests are the single in the world. Now CIAM has the largest in Europe ground hypersonic test facility to fire test of all interested fuels scramjets either free stream or connected pipe conditions, has highest level mathematics models and corresponded software for CFD investigations of scramjet operation processes, works to create Research hypersonic vehicle to test of hypersonic engines up to flight Much number 14. Special CIAM program is aimed to apply hydrocarbon fuel in scramjet. The important theaters of hypersonic propulsion investigations in CIAM is closely interaction of all aforementioned directions and scientific technologies.

We have shown scramjet cycle is real in real hypersonic flight and we have to show enough effectiveness of scramjet to apply at hypersonic vehicle and future space transportation systems.

2. RESULTS OF FLIGHT TESTS

Ground hypersonic test facility have principled distinctions of condition compared real flight that. The main distinction are: distortion of air composition during air heating, significant level of turbulence and other. These are very significant for fuel ignition, mixing, air intake performances and other. Thus hypersonic flight experiments are needed at early stage of scramjet investigation

The main aim of CIAM program of scramjet model flight tests was to check possibility to organize combustion in supersonic flow under condition of real flight.

Flight tests of axisimetric dual mode experimental scramjet were are carrying out on special hypersonic flying laboratory created on base of SA-5 surface-to-air missile. (Fig. 1) Cryogenic hydrogen tank, telemetric and control systems, coaxial combustion chamber and air intake replaced warhead of missile. (Fig. 2) The scramjet fired at flight Mach number equalled 3.5 and operated up to fuel used up. Due to rocket acceleration flight velocity continued increase, the scramjet overpass on supersonic combustion mode at flight Mach number 5. Designed maximum of flight Mach number was 6.0. For the last flight test the missile and the experimental scramjet were modified for 6.5 Mach number. More than two hundred parameters of the scramjet processes were transmitted to ground by telemetric system. The most part of that are pressure of air and hydrogen, temperature of walls and hydrogen in cooling jacket, before injectors and other tubes. Besides standard data of missile trajectory and velocities were used also. The scramjet was not separated from missile booster and we have now special equipment for scramjet saving after flight but as a role we find out the scramjets after landing. The scramjet structures had significant deformation after hard landing but could be used for analyses. (Fig.3 and 4)

In flight test of 1998 year we obtained the highest flight Much number (closely to 6.5) and the most duration of scramjet operation time (77 sec.). This test was carried out accordance NASA / CIAM contract. The main parameters of scramjet flight test are shown at Table 1.

Proc. 4th Europⁿ Symp. Aerothermodynamics for Space Applications, 15-18 Oct. 2001, Capua, Italy, ESA SP-487, March 2002

TABLE 1. The main parameters of flight tests.

Test dates	Nov. 27.1991	Nov. 17. 1992	March 1. 1995	Aug. 1. 1997	Feb. 12. 1998
Flight altitude max., km	35	22.4	30	33	27.1
Flight Mach number max.	5.6	5.35	5.8	6.2	6.5
Scramjet operation time, sec	27.5	41.5	-	-	77

3. GROUND EXPERIMENTS

In CIAM the tests of Scramjet mainly are carried out on the CIAM Research Test Centre C16 complex of test cells. This complex includes several compactly located experimental beds having the comon supply system of energy and other resources (Fig.5). The beds contain the installations for realisation of researches in various fields of study of processes in rocket and hypersonic engines. Series of small installations allow to operatively solve problems in research of operation processes in combustion chambers of engines with the help of use small-size models. Large beds are developed for researches of operation processes in large scale of combustion chambers or engine in a whole.

The C16VK test cell is specialised for experimental researches of the characteristics of large-scale models of Scramjet and their elements under either free jet or connected pipe conditions with simulation of flight Mach numbers M_f=4□7. (Scheme at Fig. 6) The test cell represents pressurised thermo-baro-chamber (TBC) with the built in gas-air contour (GAC), consisting of the aerodynamic nozzle (D_{exit}<600mm) and diffuser (D_{dif}=700mm). The C16VK test cell is equipped by the following systems:

- Supply of high pressure air (P□8Mpa, G□15kg/s);
- Combination of air heating - electrical heating (T□1000 a) and fire heating (T□2300 a);
- Exhaust system (P□1kPa, V□600m^3/s);
- Supply of gaseous combustible into an object (P□8MPa, G□1.5kg/s);
- Cryogenic cooling of object (consumption of a cooling agent G□3kg/s);
- Automated system of control of technological process and regime of object test;
- Automated system of acquisition and processing of experimental data;
- Thrust measurement system (F□10kN);
- Visualisation of a flow at an inlet of object;
- System of passivation and fire extinguishing in TBC.

1998 year C16VK vas used to test of exact copy of flight tested axisymmetric scramjet (Fig.7), 1999-2000 years experimental rectangular scramjet combustor was tested to study several variants of hydrogen injection strut. This year large scale experimental scramjet module is staying at C16VK to study operational processes. (Fig.8) Series of 6 tests was carried out July under condition of various fuel flow ratio and air total temperature. Next test series will be this year after change injector struts for that other structure.

Small hypersonic beds of C16 are used for experimental study of supersonic combustion behind single fuel injector and single injector strut. Several other beds are used to test decomposition endothermic liquid fuels and combustion of decomposition products.

4. CFD IN SUPERSONIC COMBUSTION INVESTIGATIONS

The system of mathematical models and computer codes for numerical simulation of supersonic combustion applied to scramjet was developed. Its capabilities were substantially extended to include strut system, wall boundary layers, 3D effects, strut base face and separation region behind it. The system of codes is based on the numerical solution of parabolized or full Navier-Stokes equations supplemented by turbulent viscosity equation and by detailed chemical kinetics schemes for hydrogen and air mixtures. (Fig. 9)

The method of special design of micro-nozzles for hydrogen injection, which provides the hydrogen jet decay on two jets of smaller size is proposed. This results in twofold decrease of the combustor length at the special choosing of the position and number of struts, and the number of hydrogen nozzles and their location on each strut. It is shown that the proposed method of mixing enhancement provides also the appreciable increase of combustion efficiency. The direct comparison of numerical results with data of special experiment at test facility C-16 of CIAM Research Test Center was made. This experiment was carried out to check the existence of jet dividing effect for injector with nozzle having elliptical exit cross-section. Numerical simulation of the experimental chamber with single strut and elliptical injector nozzle was performed using different codes on the base of parabolized and full Navier-Stokes equations. In the case of full Navier-Stokes equations, the influence of strut base face on flow fields and mixing efficiency was estimated. Good qualitative agreement of numerical and experimental results, obtained in test case of supersonic heated air jet injected into supersonic air stream, is observed. This agreement occurs in the shape of the jet, in the jet dividing into two smaller jets at the experimental conditions, and in the flow wave structure. The experimental research performed on CIAM test facility C-16 confirmed the decay effect (detected at the numerical simulation) of jet injected from specially designed elliptical nozzle. (Fig. 10)

The possibility to enhance the mixing and combustion process by special strut afterbody design was studied numerically. The special strut design provides: first, the fuel jet injection at an angle to the main supersonic air stream due to injection nozzle inclination; second, intensive air flow into the region between fuel jets due to special recesses made on lateral sides of the strut. It is shown that secondary air flow induced by special recesses on lateral sides of strut afterbody makes the essential contribution into mixing enhancement. The comparison of numerical results with experimental data obtained in ITAM for flow path of model engine was performed. The special strut was installed in the duct of model engine. The reasonable qualitative and satisfactory quantitative agreement is observed for the stagnation temperature fields in control cross-sections of the duct. (Fig. 11)

The analysis of existing experimental data and numerical investigations show that two different combustion regimes can be realized in the duct at the combustion at the supersonic conditions at the entrance of the combustor. This difference in the flow structure is caused by different value of heat released into the air stream at the combustion relative to own total enthalpy flow of air stream. For conditions corresponding to high flight Mach number the supersonic diffusion combustion regime is observed. The combustion in the regime of shock train system is realized at the conditions corresponding to small hypersonic flight Mach number. It is just this combustion regime which was realized in model scramjet engines tested on ground test facilities at conditions corresponding to flight Mach number M_f=6. For the shock train system combustion regime the role of wall boundary layer and its interaction with shocks system in the duct is of primary importance at the development of flow structure. The mathematical model requires the full Navier-Stokes equations application for the flow description. The special experiments were used for the mathematical model and numerical method verification. The model axisymmetric combustor consists of cylindrical duct of constant cross-section area and trailing slightly expanding section. Numerical investigations were carried out to examine the influence of wall thermal conditions of model axisymmetric combustor on the flow structure in the case of "pseudoshock" combustion regime. The "pseudoshock" combustion regime is characterized by transition from supersonic flow to subsonic one in the shock train system which interacts with wall boundary layer. The inverse transition through the sound velocity in the flowpath is realized at the entrance to expanding duct. It is shown that:

a) the position of the head of shock train system strongly depends on wall temperature;

b) the combustion process enhancement is observed in the subsonic regions in comparison with supersonic zones. (Fig. 12)

The possibility of ignition and flame stabilization in the base region is investigated, using numerical solution of full Navier-Stokes equations with detailed chemical kinetics scheme for hydrogen-air in quasi-laminar approach, on the example of model problem. The axisymmetric supersonic hydrogen jet is injected into supersonic coflowing air stream. The thickness of injector lip was varied. Two different situation were considered. In the first of them, the self-ignition takes place on the small distance from the injector. It is shown that the increase of the lip thickness and hydrogen heating do not allow to achieve the combustion just behind the base face of the lip for the considered conditions. In the second situation, the self ignition is not achieved on the considered length for all analyzed lip thickness. Therefore the operation of sparking plug was also simulated. It is shown that chemical reactions with radicals OH production begin just behind the lip base face. However, the combustion terminates as the fresh air and hydrogen mix into wake with OH radicals. The length of the OH tongue increases as the lip thickness increases. At some lip thickness, the combustion is initiated in the base region and is spread into the main stream. (Fig. 13)

5. FUTURE FLIGHT TEST ACTIVITY

1992 CIAM together with Russia Flight Research Institute and other firms began development Experimental Hypersonic Flight Vehicles, known as IGLA (from Russian abbreviation _ZbW), for flight experiments to study scramjet and many other problems of hypersonic flight up to $M_f = 15$. These hypersonic gliders will be accelerate by ballistic missile. During separate flight experimental scramjet will be fired in time of needed velocity and altitude. All data of flight parameters and scramjet operation will be transmit to Earth surface and record on airborne recorder to analyze after landing.

Photo of full size mock of IGLA variant and the main that parameters are given at Fig. 14. IGLA Program have support of ROSAVIAKOSMOS as part of state Space Program of Russia. We are study now the main problems of IGLA structure, aerodynamics, thermal protection and other. Ground test of rectangle scramjet module (see chapter 3 of this paper) is part of IGLA program also.Nearest year we are hope to carry out technology flight test of IGLA version.

REFERENCES

1. Roudakov A., Schikhman Y., Semenov V., Novely Ph. Flight Testing an Axisymmetric Scramjet ... IAF -93-S.4.485.
2. Roudakov A., Semenov V., Kopchenov V., Hicks J. Future Flight Test of an Axisymmetric Hydrogen-Fuelled Sxramjet Engine on the Hypersonic Flying Laboratory. AIAA-96-4572.-
3. Roudakov A., Semenov V., Hicks J. Resent Flight Test Results of the CIAM-NASA Mach 6.5 Scramjet Flight Program. AIAA-98-1643.
4. Sosounov V.A., Roudakov A.S.,Semenov V.L., Kopchenov V.I., Lanshin A.I, Romankov O.N. Two generations of Russian SCRAM flying test beds. XII ISABE Symposium, 11-15 September, 1995, Melborne, Australia.
5. A.Roudakov. Some problems of Scramjet propulsion for Aerospaceplanes. Part II. Scramjet: development and test problems. AGARD Lecture Series, 194, 1993.
6. C. McClinton, A.Roudakov, V.Semenov, V.Kopchenov. Comparative flow Patrh Aanaalysis and Design Assessment of an Axisymmetric Hydrogen Fueled Scramjet Flight Test Engine at a Mach Number of 6.5. AIAA Paper 96-4571, 1996.
7. V.Yu.Alexandrov, S.A.Belykh, A.N.Prokhorov, G.K.Vedeshkin. Investigation Laboratory of CIAM Research Test Center to Test Large-Scale Propulsion System Models and Their Components for Aerospace Systems. Proceedings of Seventh International Conference on the Methods of Aerophysical Research, Novosibirsk, Aug. 22-26, 1994- Novosibirsk 1994. - Pt. II, pp. 35-40.
8. V.Yu.Alexandrov, A.N.Prokhorov, A.S.Roudakov. Capabilities of Flight Conditions Simulation on Ground Test Facilities. Proceedings of Seventh International Conference on the Methods of Aerophysical Research, Novosibirsk, Aug. 22-26, 1994- Novosibirsk 1994. - Pt. I, pp. 9-17
9. Application of CFD methods in scramjet investigations and design. Ed. By V.I. Kopchenov. In «Scientific Input into Aviation Engines Development», V.1, Moscow, Mashinostroyeniye, 2000, p.251-272.
10. L.Bezgin, A.Ganzhelo, O.Gouskov, V.Kopchenov, I.Laskin, K.Lomkov. Numerical simulation of supersonic flows applied to scramjet duct. ISABE 95-7082, 1995, p.895-905.
11. L.V. Bezgin, A.N. Ganzhelo, V.I. Kopchenov. Influence of the integration effects on the characteristics of the scramjet. High Speed Aerodynamics, 1997, V.1, N 1, p.93-103.
12. V.I. Kopchenov, K.E. Lomkov. The enhancement of the mixing and combustion processes applied to scramjet engine. AIAA Paper, 92-3428, 1992.
13. V.I. Kopchenov, K.E. Lomkov. 3D numerical simulation of the supersonic combustion enhancement and scramjet combustor design with account of nonequilibrium chemical reactions. High Speed Aerodynamics, 1997, V.1, N 1, p.43-53.
14. O.V. Gouskov, V.I. Kopchenov, K.E. Lomkov, Yu.S. Mnatsakanyan, A.N. Prokhorov, A.A. Shutov. Numerical and experimental investigation of supersonic mixing and combustion. AIAA Paper, 2001-1821, 2001.
15. A.M. Kharitonov, A.V. Lokotko, A.V. Tchernyshyev, V.I. Kopchenov, K.E. Lomkov, A.S. Roudakov. Mixing processes of supersonic flows in a model duct of rocket scramjet engine. AIAA 2000-0559, 2000.
16. O. Gouskov, V. Kopchenov. Numerical simulation of duct flows at supersonic entry conditions. VIII International Conference on the Methods of Aerophysical Research, Proceedings, P.3, 1996, Novosibirsk, p.84-89.
17. L.V. Bezgin, A.N. Ganzhelo, O.V. Gouskov, V.I. Kopchenov. Numerical simulation of viscous non-equilibrium flows in scramjet elements. ISABE 97-7131, 1997, p.976-986.
18. O.V. Gouskov, V.I. Kopchenov. Investigation of influence of pylon back face on mixing and ignition process of hydrogen jet. X International Conference on the Methods of Aerophysical Research, Proceedings, P.3, 2000, Novosibirsk, p.57-62.

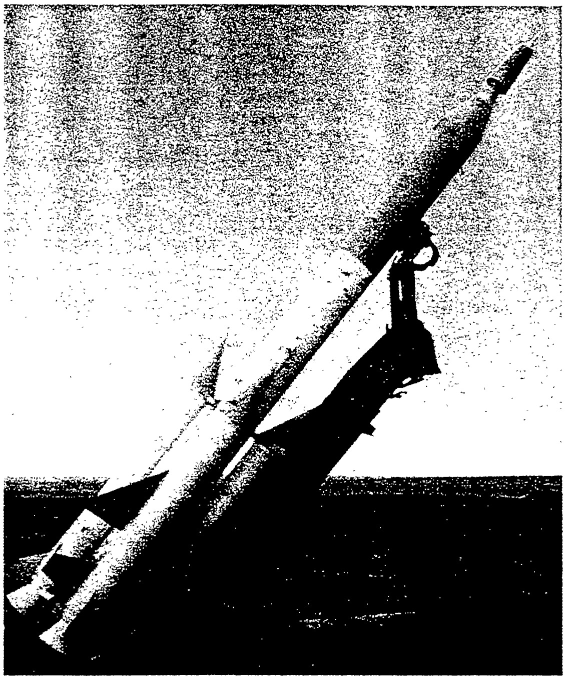

Fig. 1. Experimental scramjet on missile before flight test.

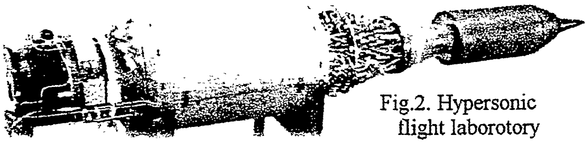

Fig.2. Hypersonic flight laborotory

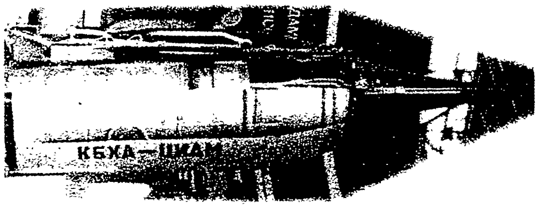

Fig. 3. Experimental scramjet show example

Fig. 4. Experimental scramjet after flight test.

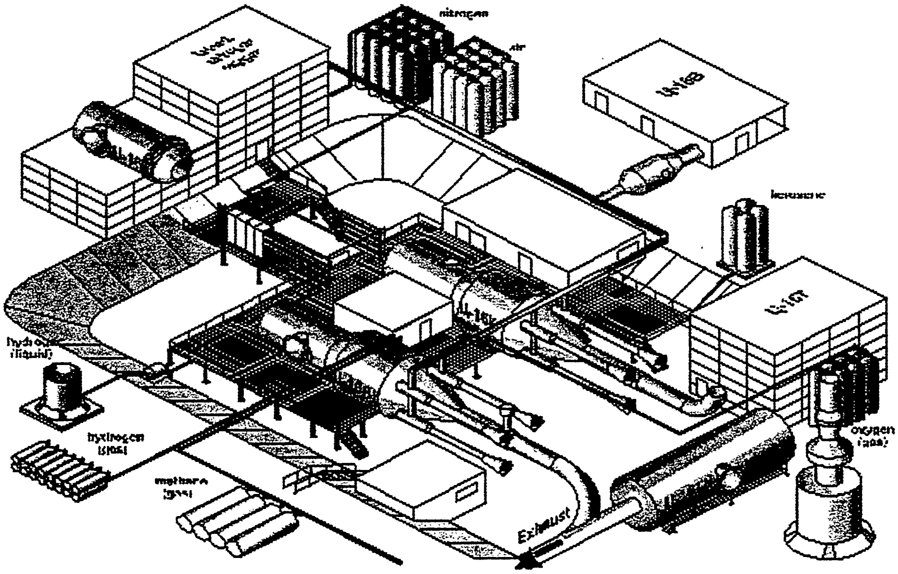

Fig. 5. C16 test facility complex of CIAM.

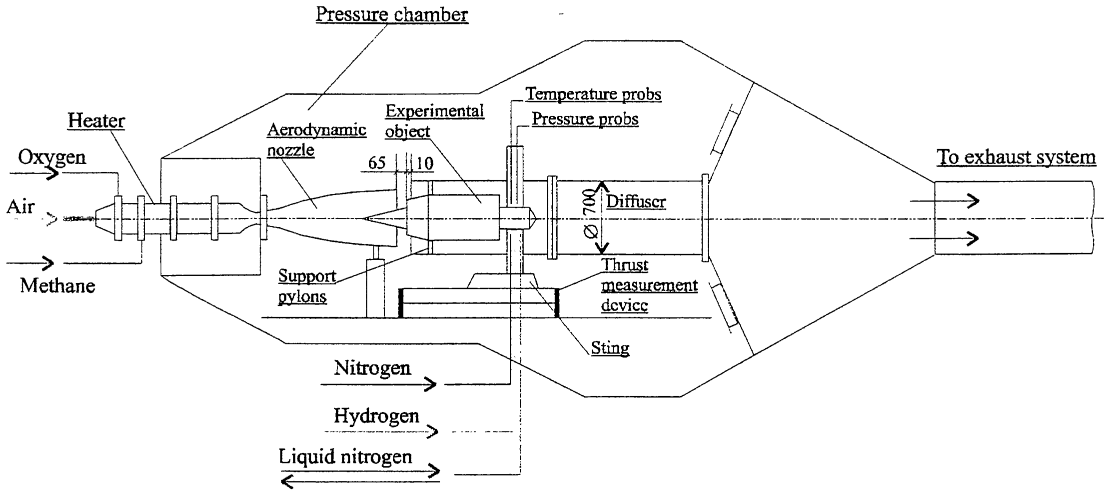

Fig. 6. Scheme of C16VK test facility.

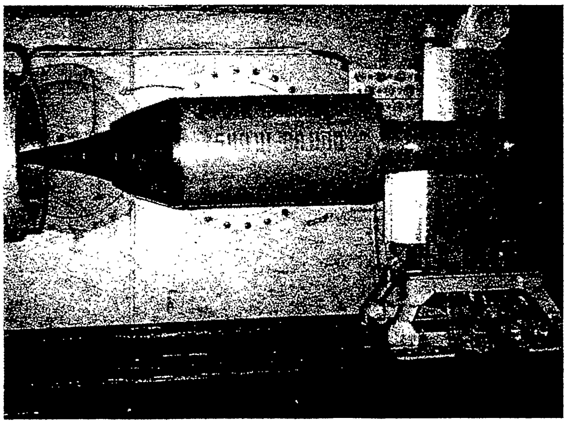

Fig. 7. Axisimmetric scramjet at C16VK.

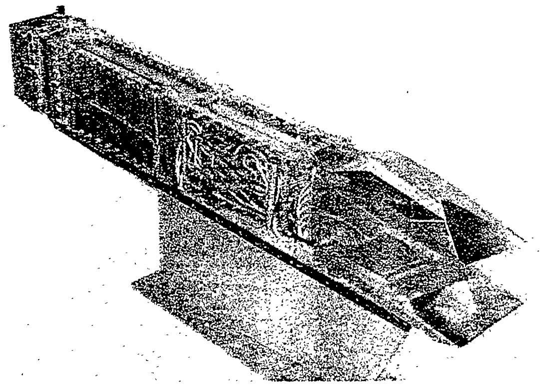

Fig. 8 Ground tested scramjet module

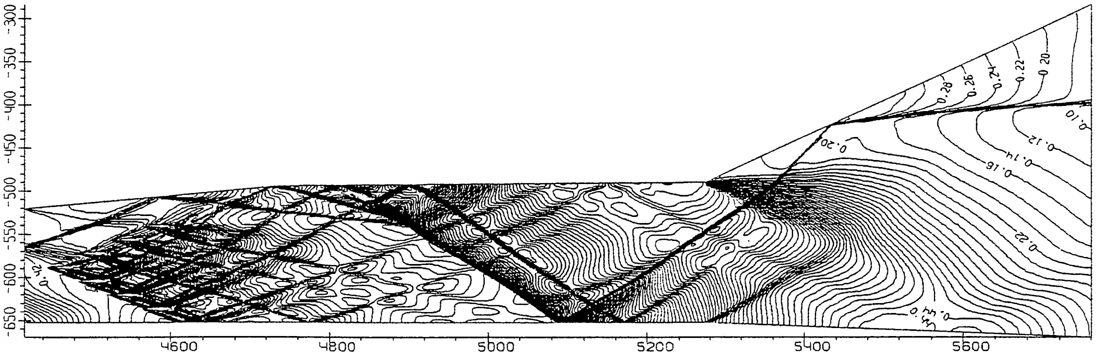

Fig.9w. Pressure field

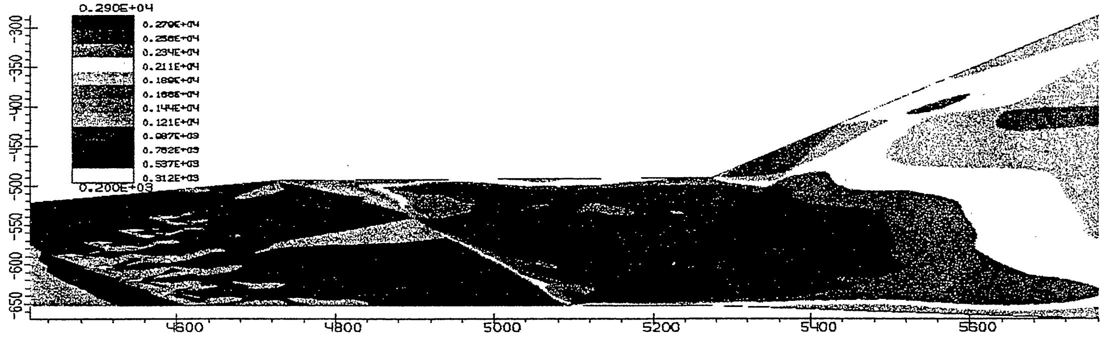

Fig. 9b. Temperature field (K)

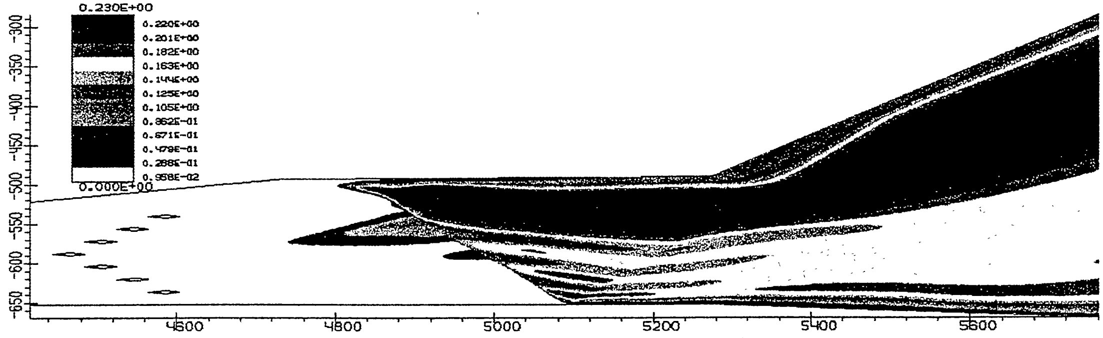

Fig.9c. Water mass fraction field

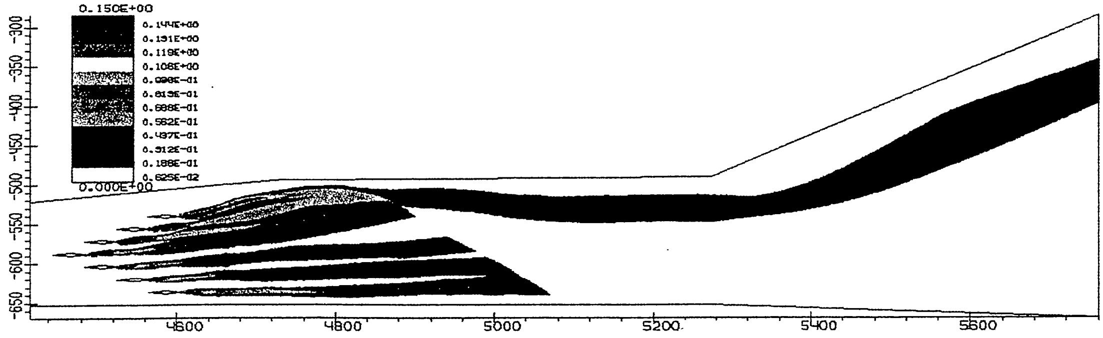

Fig.9d. Hydrogen mass fraction field.

Fig. 9. Flow fields in the duct of model scramjet integrated with HFL vehicle

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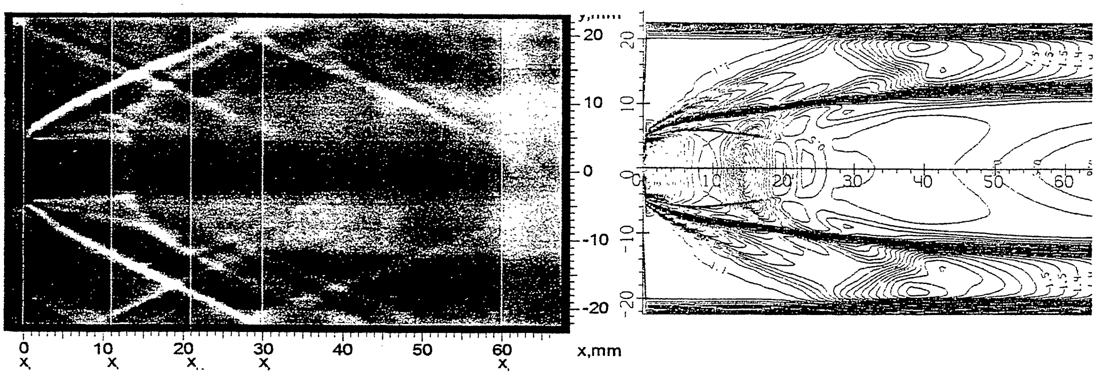
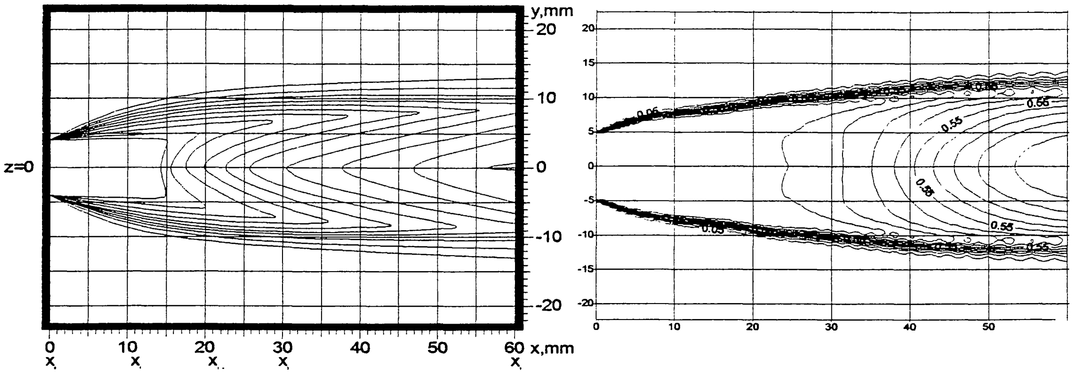


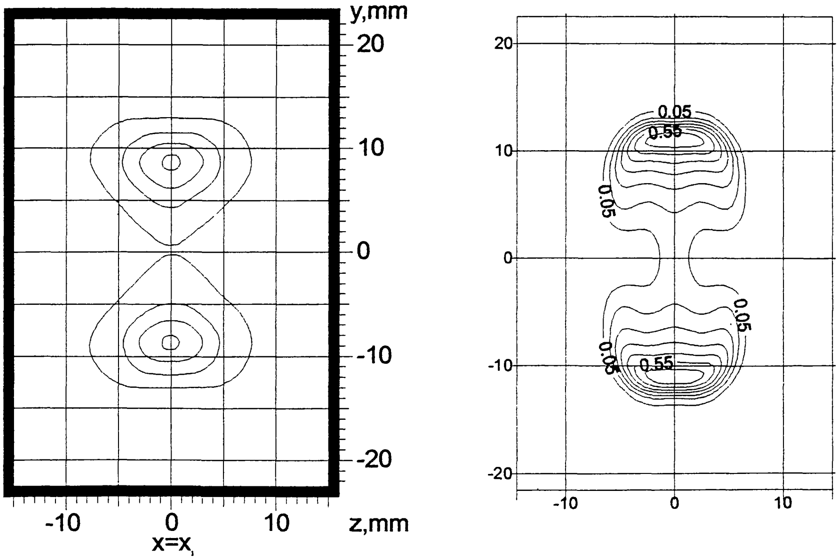
a) Shadow picture (experiment)

b) Density field (calculation)



c) Temperature field (experiment)

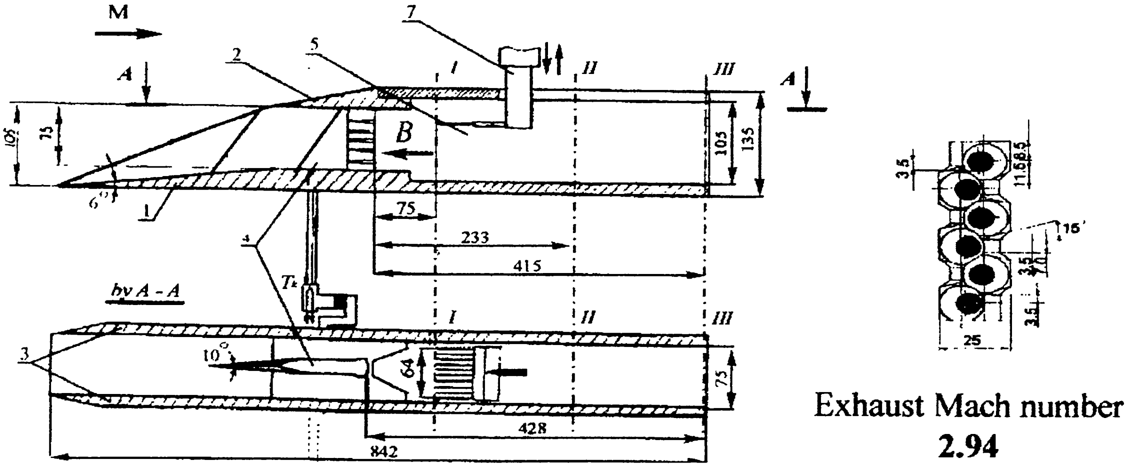
d) Temperature field (calculation)



e) Temperature field (experiment)

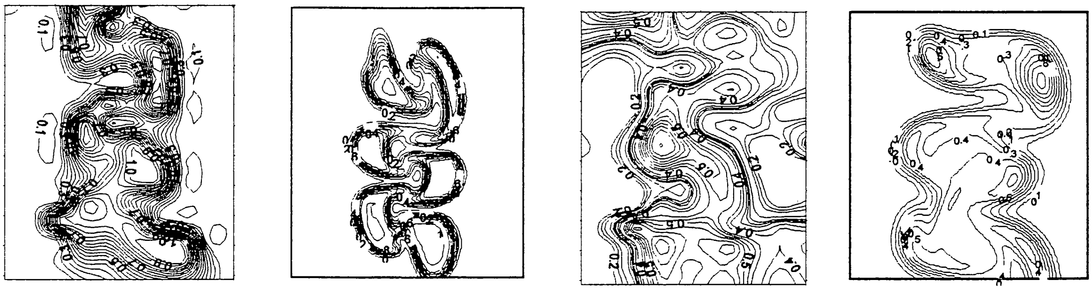
f) Temperature field (calculation)

Fig10. Elliptical nozzle



Exhaust Mach number
2.94

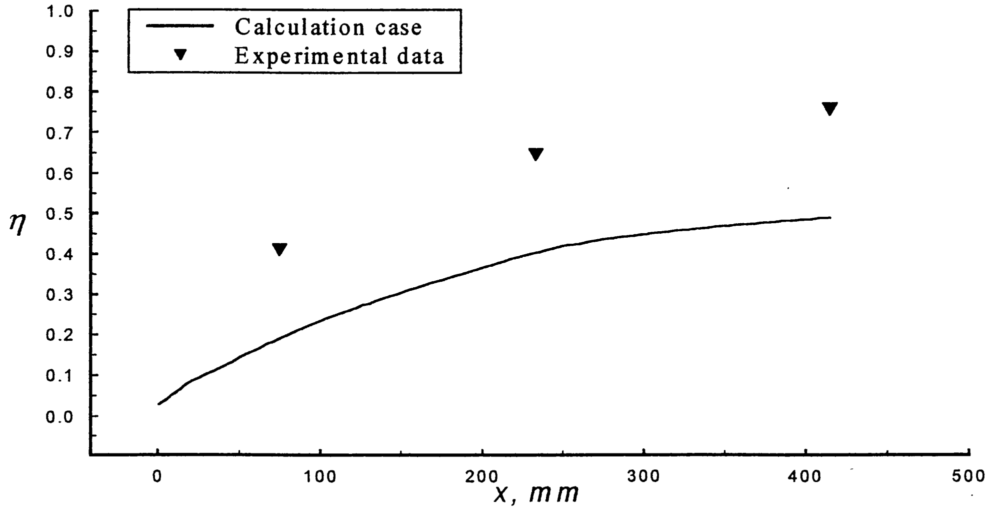
a) Sketch of the model



experiment calculation
Section I

experiment calculation
Section III

b) Relative total temperature fields.



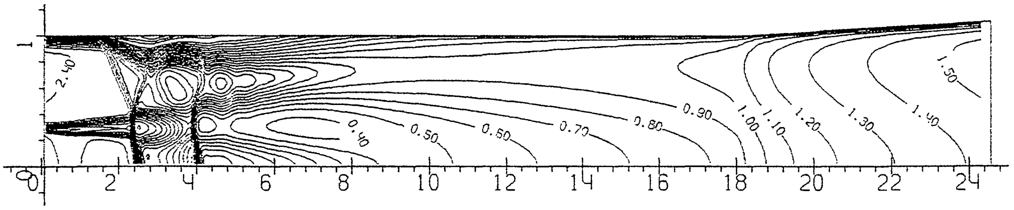
d) Mixing efficiency

Fig.11.

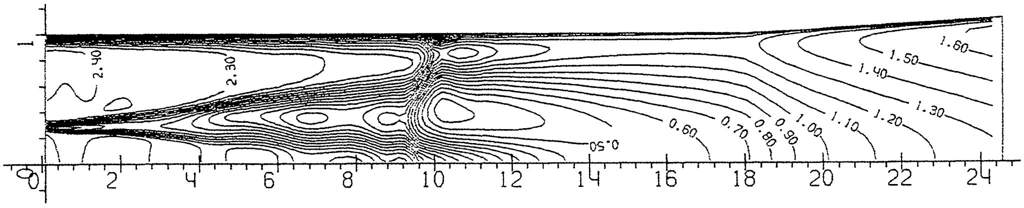
COMBUSTION IN THE DUCT (Supersonic flow at the entry)

Flow: air, P= 0.94 bar, T=1150 K, D=70mm., M_e=2.5

Jet: hydrogen+nitrogen, P=0.94 bar, M_j=2.4, T=133 K, d=20mm, α=4.07

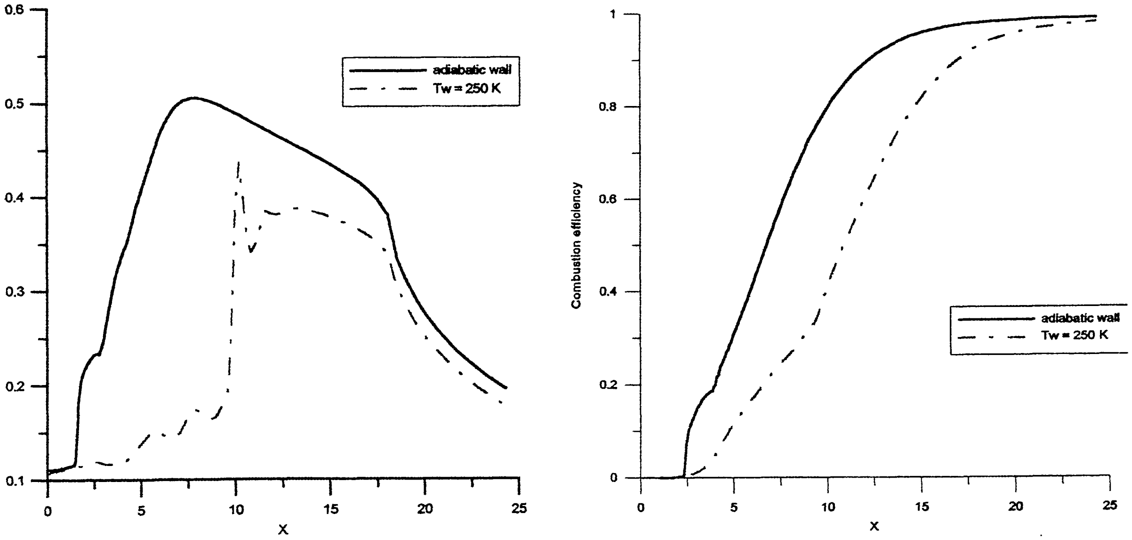


adiabatic wall



T_w=250 K

Mach number fields



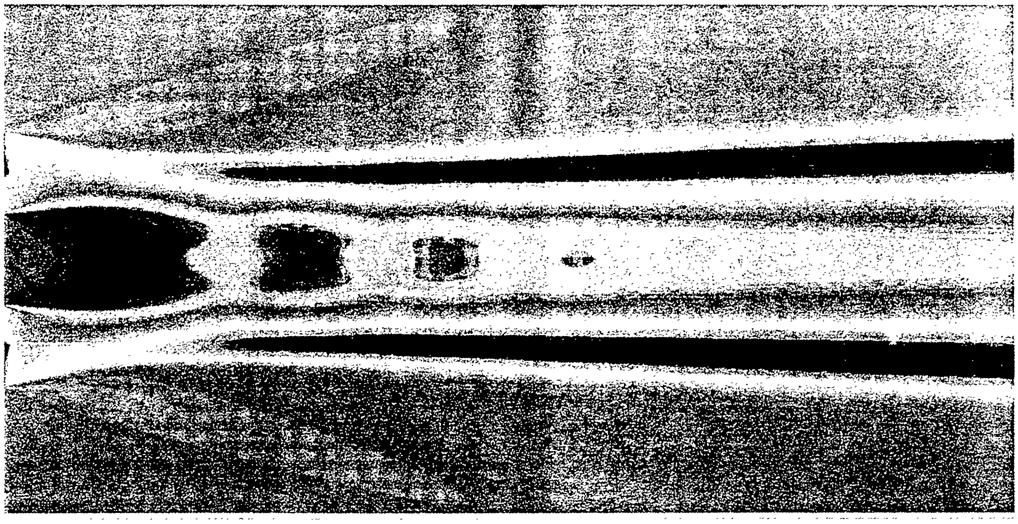
Wall pressure distributions

Combustion efficiency

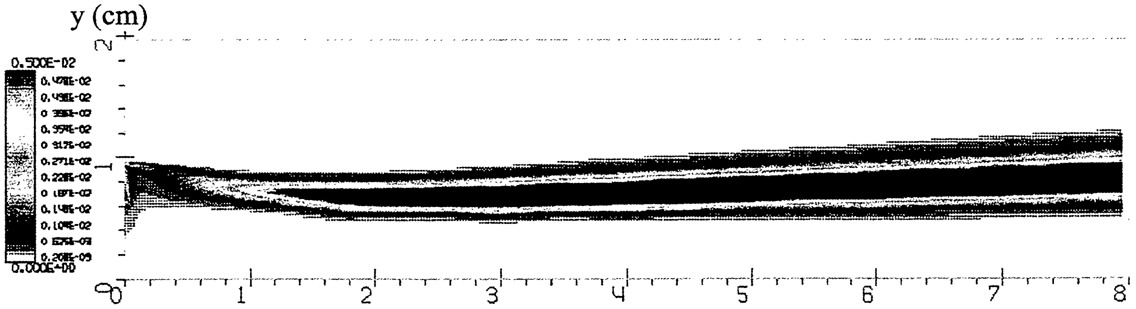
Fig.12.

IGNITION BEHIND THE BASE FACE

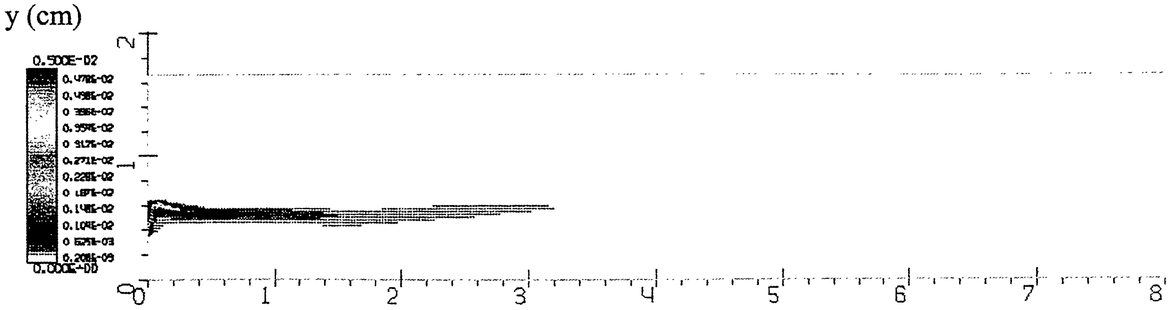
Air flow:	M=2.5,	T= 900 K,	P=0.1 MPa
Hydrogen jet:	M=2.0,	T= 500 K,	P=0.1 MPa.



a) Temperature field
Injector lip thickness h = 0.6 cm.



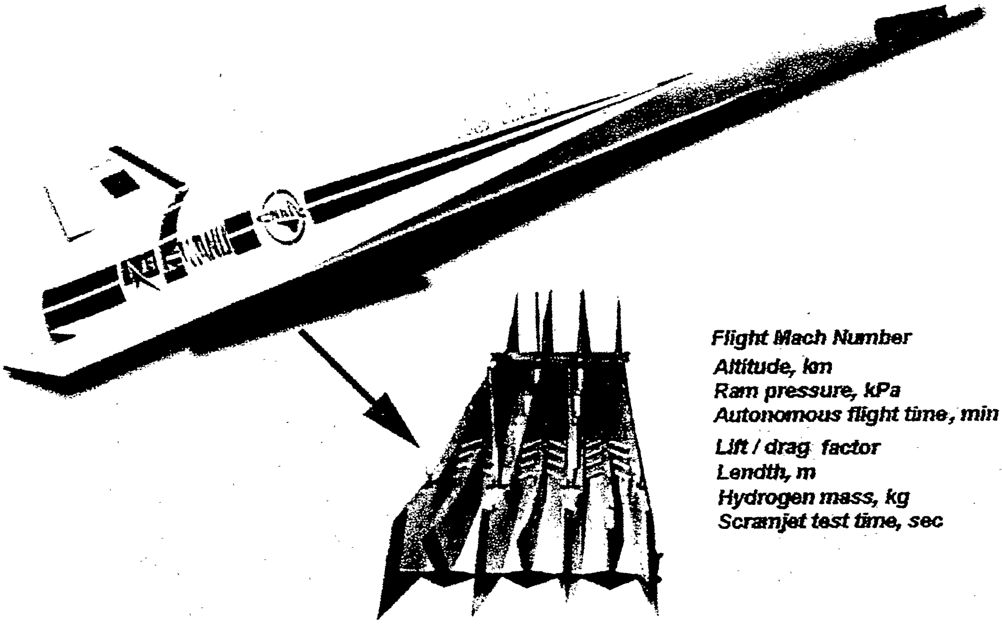
b) OH mass fraction field
Injector lip thickness h = 0.6 cm.



c) OH mass fraction field
Injector lip thickness h = 0.3 cm.

Fig.13.

HYPERSONIC RESEARCH FLIGHT VEHICLE



Flight Mach Number	*3.6 ... 14.0*
Altitude, km	*26 ... 50*
Ram pressure, kPa	*2 ... 70*
Autonomous flight time, min	*7 ... 12*
Lift / drag factor	*3.1*
Lendth, m	*8.0*
Hydrogen mass, kg	*18*
Scramjet test time, sec	*50*

Fig. 14