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Experimental Investigation of the Hydrogen Combustion Chamber and Its Complement with 2.5D CFD Data

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Abstract

Results of the experimental investigation of the hydrogen combustion chamber within the HEXAFLY-INT project are presented. Cross-sections of combustor have elliptic sections. Influence of different ways of hydrogen injection on pressure distribution along the combustor walls is studied experimentally. Experimental data are applied to validation of the new 2.5D method that had been proposed recently for approximate numerical simulation of duct flows. Achieved experimental results have been complemented to numerical ones.

Keywords: *combustion chamber, hydrogen, 2.5D approach, experiment, CFD.*

Nomenclature

Latin
M – Mach number
ER – equivalence ratio

At present time in many countries various concepts of high-speed vehicles for civil passenger transportation are developed for long distances with travel times much less than could be attained on the existing civil aircraft. In framework of the European project LAPCAT-II [1], several high-speed passenger vehicle concepts were studied on the basis of hydrogen fuelled air breathing engines. Aim of this work was to assess the technical feasibility of a high-speed vehicle for civil transportation that could fly to diametrically opposite points (e.g. from Brussels to Sydney) at speed ranging from Mach number M= 5 to 8. The claimed performances were verified on the basis of simulations and on-ground experiments. The next step is the verification by flight experiment which is one of the main goals of the international coordinated project HEXAFLY-INT.

Two concepts of the EFTV vehicle were proposed for study. A first concept is a glider vehicle, i.e. without any on-board propulsion. A second concept is a powered concept, i.e. with scramjet propulsion system. The first concept will evolve into in flight experiment while the second concept is studied numerically and experimentally on-ground by Russian entities such as TsAGI, CIAM, FRI and MIPT. Configuration of the EVTV powered concept having a length of L≈3 m developed by European Partners [2-4] is shown on the Fig. 1. The elliptical combustion chamber model which was created for the experimental tests is shown on Fig. 2 [5].

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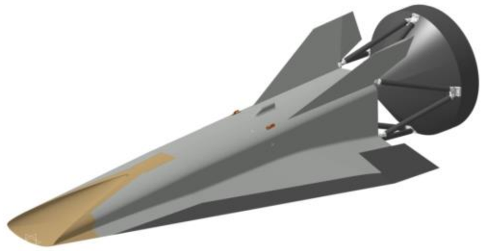


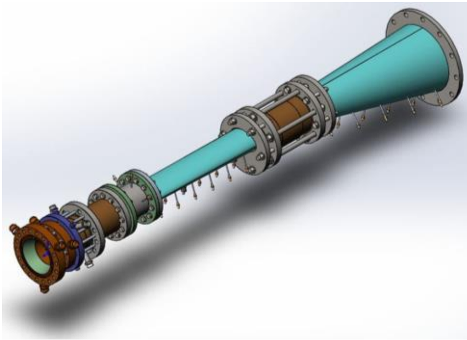


Fig. 1. Propelled concept HEXAFLY-INT

Fig. 2. Model of the combustion chamber

The tests of the combustion chamber are carried out on the connected-pipe T-131 facility of TsAGI (Fig. 3) that is intended to study:

- Operational processes in ramjet models;
- Various fuels carburation and burning processes in subsonic and supersonic flows;
- Thermal transformations of hydrocarbon fuel;
- Heat-shielding and structural materials;
- High speed air-feed jet engine models in free stream;
- Burning on the outer surfaces of flying vehicles;
- Air-feed jet engine air intakes.

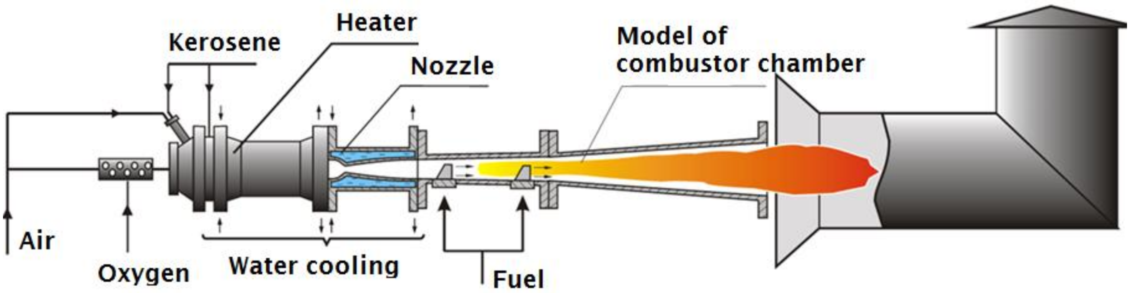


Fig. 3. Scheme of the T-131 facility of TsAGI

The combustion chamber is composed of the seven separate sections (Fig. 4): an intermediate part of the direct air heater, a critical insert, a part of the supersonic nozzle, a pre-injector section with two semi-struts, a section of combustion chamber with full-strut, a section of the 2D-nozzle and a section of the 3D-nozzle. All the sections are interconnected through the connecting flanges.

The CC is attached to the T-131 connected pipe facility through the cooled conic adaptor that is located at TsAGI test bench. For this purpose, the ring that is made of the heat-resistant steel is placed into the flange cylindrical groove.

The mock-up has three ports for hydrogen injection and eight ports of water supply to cool the intermediate part of the heater and the critical section. There are two rows for the fuel injection inside the model.

The fuel pylon-injector, so called semi-strut, (Fig. 5) has an arrow-shaped geometry with the leading edge radius of R_1=2 mm and the trailing edge radius of R_2=0.3 mm. The pylon is made of the heat-resistant steel. The injector exit diameter is 5 mm and the duct diameter is 4 mm. The pylons are located in such a way that the fuel is supplied into the inner pipe of chamber under the given angle of 60° relative to the air stream. The hydrogen supply to the pylon is performed through the M14 threaded connector.

The central fuel pylon, so called full-strut, (Fig. 6) has an arrow-shaped geometry with the leading edge radius of R_1=2 mm and the trailing edge radius of R_2=0.2 mm. The pylon is made of the heat-resistant steel. The pylon has four holes of diameter 1.4 mm. The holes are located on two wedge surfaces (angle of 34.2°) in such a way that the fuel supply is provided as downstream. The duct diameter is 4 mm. The fuel supply to the pylon is performed through the M14 threaded connector.

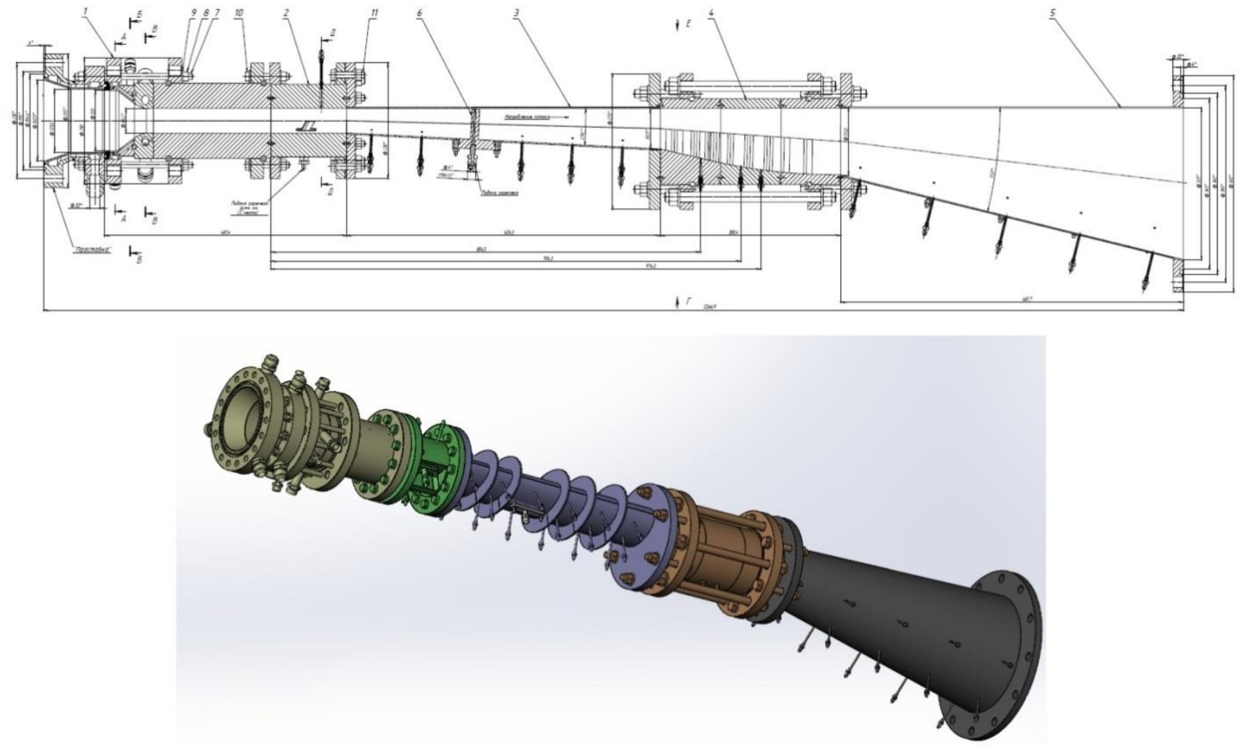


Fig. 4. Combustion chamber mock-up

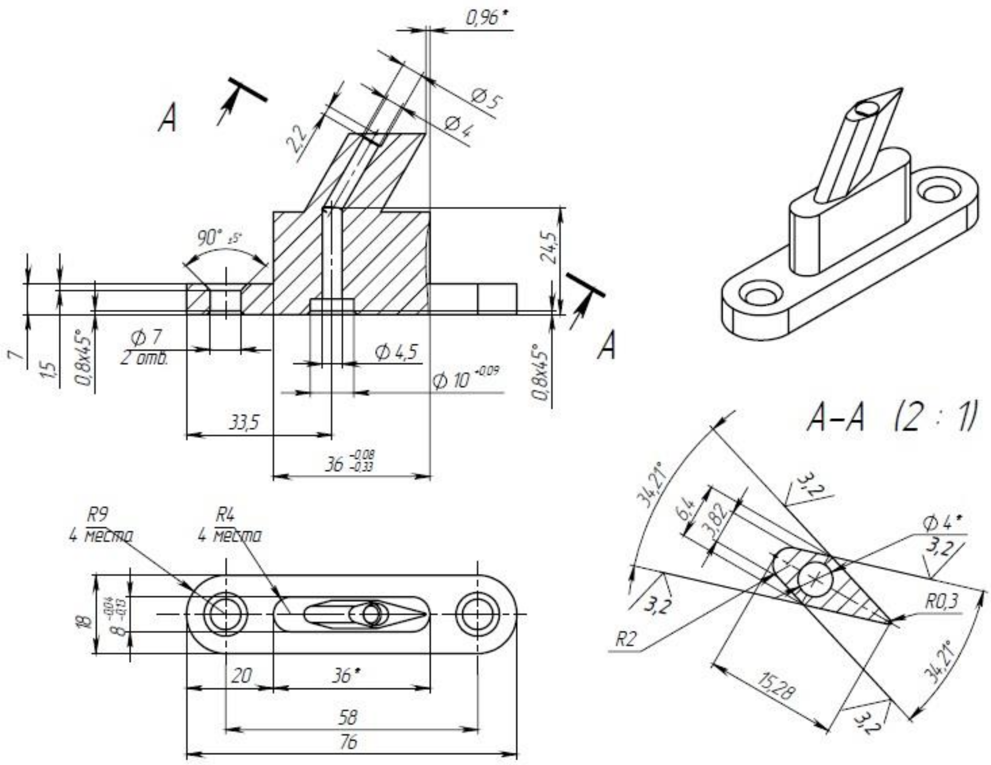


Fig. 5. Semi-strut

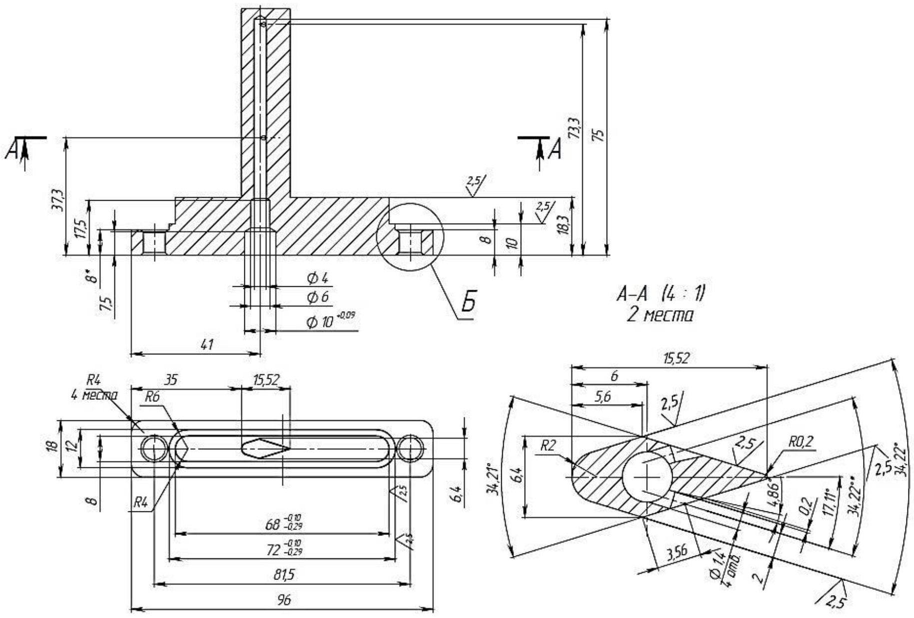


Fig. 6. Full-strut

Experimental investigation of the high-speed combustion chamber at the flow conditions at the duct entry corresponding to Mach numbers M=6; 7; 7.4 was performed. Typical static pressure distribution along the duct is shown on Fig. 7.

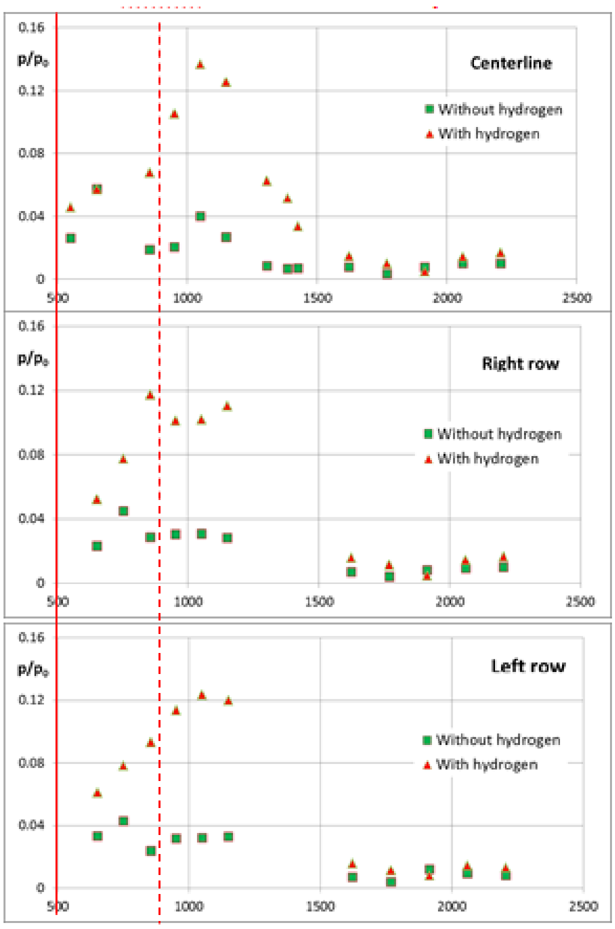


Fig. 7. Typical static pressure distribution

In tests simulated free-steam Mach number M=7; 7.4 full-strut has been destroyed, so most of the tests were conducted in case of fuel supplying only from the semi-struts in wide range of ER coefficient. Besides these tests, some tests with imitator-strut installed instead of the full-strut were done. This imitator was made from high heat-resistance material with protective coating of the external surface. Imitator had thickness and fillet close to full-strut geometry but it hadn't duct and holes for hydrogen supply.

Self-ignition of the hydrogen was achieved at all investigated conditions but at the conditions corresponding to free-steam Mach number M=7.4 and low values of the ER coefficient burning wasn't stabilized. When hydrogen was injected through semi-struts, it was increasing of the static pressure inside the model 2.5-3 times in comparison with regime without hydrogen supply and peak of the static pressure was located nearby full-strut.

Some investigation of the influence of the imitator-strut presence on the hydrogen burning inside the model was carried out. It could be stated that burning was obtained in both cases with and without imitator-strut. However presence of the imitator-strut increased maximum value of the static pressure in the model's duct and shifted its peak a little bit upstream. When fuel is injected through semi-struts and full-strut, static pressure was increased 3-5 times in comparison with 'cold' regime and increasing of the static pressure wasn't almost propagated to 2D and 3D nozzle sections.

Regimes at which increasing of the static pressure propagates so high upstream that could influence on the static pressure in supersonic part of the aerodynamic nozzle were defined. Such regimes are very dangerous for propulsion because could lead to buzzing of the intake.

In order to achieve more information about the model it was necessary to conduct some CFD tests which have complemented experimental results.

As a rule, turbulent flows of a viscid gas in aircraft power plants are complex multi-scale phenomena. Computation of so complex flows on the basis of 3D Reynolds-averaged Navier-Stokes equations (RANS) can require huge computer resources even in the case of multi-processor parallel computations. Therefore, multiple parametrical calculations, which are necessary at the stage of engine design, cannot be performed on the basis of 3D RANS. Even nowadays, semi-empirical quasi-1D calculations are used for this purpose. But quasi-1D calculations cannot take into account the details of fuel mixing with air and finite-rate chemical processes that are strongly determined by local structure of the flow. In 2014, new 2.5D approach [6] has been proposed in TsAGI to increase the accuracy and informativeness of approximate parametrical calculations on the stage of engine design. 2.5D approximation replaces the real 3D flow in a duct by a flow with parameters that are constant alongside coordinate axis. It may be treated as a result of 3D flow averaging alongside coordinate axis. Calculation is performed in a plane, but variable width of duct in side direction is taken into account.

In Fig. 8 the typical flow structure in model combustor is demonstrated. It corresponds to flight Mach number M=7 and integral equivalence ratio ER=0.935. Injection scheme is 43.4%-43.4%-13.2% (it means than 43/4% of total mass-flow rate of hydrogen is injected from each of two semi-struts and the rest 13.2% - from the central full-strut). In this regime, average Mach number at the entrance in the inviscid core is close to M=2.7. Only part of the duct is shown, and the scale along the duct width is increased. It is shown that oblique shock waves arise ahead of the fuel jets, injected from the semi-struts. In the place of their interaction with wall, small separation of boundary layer arises. Field of temperature shows that in the supersonic jets from semi-struts a weak heat release proceeds initially only on the surfaces of the jets (because of low temperature of injected hydrogen – 163 K).

More intensive shock wave is formed ahead the blunted leading edge of the central full-strut. Its interaction with boundary layers on the duct walls leads to formation of separation zones of higher size. Oblique shocks, produced by these separations, intersect with leading shock wave from central full-strut in the region of passage of jets from two semi-struts, with lower Mach number. As a result, these shocks intersect irregularly, with formation of Mach disks, curved due to the flow inhomogeneity in the hydrogen jets. Behind the Mach disks, there are regions of subsonic flow. Growth of pressure and of temperature in shock-wave structures accelerates the reaction, and decrease of velocity in this region lead to longer residence of fuel in the reaction zone. Downstream from the central full-strut, combustion proceeds in regions of subsonic or transonic flow. Curved leading shock wave ahead of the central pylon and curved Mach disks, and also boundary layer separations generate vortices and become strong generators of turbulence. Growth of turbulence helps to combustion downstream from the central full-strut through the transport of heat from combustion zones to cold flow regions and through the transport of reagents to combustion zones. In the separations on the walls there is no combustion because of the absence of fuel. Combustion practically stops at considerable distance upstream from the section, where the duct width begins to grow. This effect is mainly due to the fact that here the duct area starts to grow (the width of the duct is still constant, but its height starts to increase along *x* axis). Stopping of the heat release and growth of the duct area lead to growth of the Mach number.

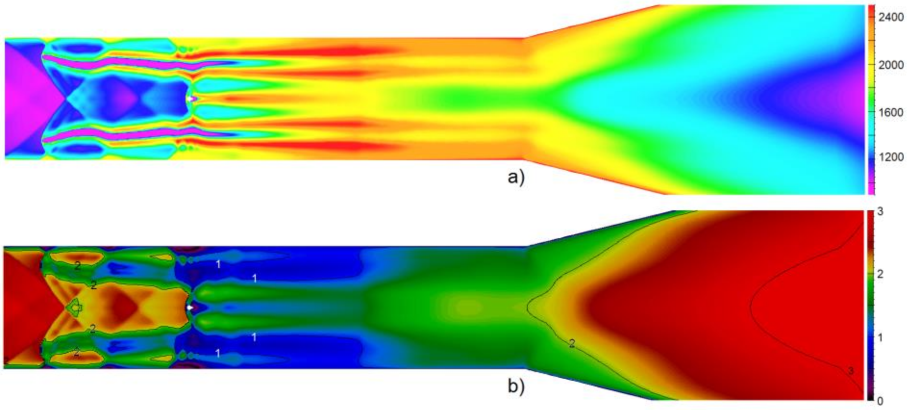


Fig. 8. Typical flow structure (M=7, ER=0.935, injection scheme 43.4%-43.4%-13.2%): a) field of static temperature [K]; b) field and isolines of Mach number

Experimental validation of the new 2.5D method for approximate calculation of duct flows has shown that this method allows predicting the most important physical features of the flow and provides engineering accuracy in prediction of loads on duct walls. This accuracy is enough for multiple parametric calculations at the stage of the engine design. This approach may become good alternative to quasi-1D calculations, which are still used for estimation of the engine characteristics at the stage of its preliminary design.

Nevertheless, 2.5D approach is approximate way of flow analysis. It cannot reproduce all details of 3D flows. It may be recommended for use at the stage of preliminary design of combustion chambers. 2.5D calculations allow to make preliminary choice of most valuable variants of geometry and of flow regime and to diminish essentially the quantity of expensive and prolonged 3D calculations. But at the final stage of the engine design, when detailed flow structure shown be taken into account and thin adjustments are applied, both 3D calculations and experiments are of course necessary.

Also 2.5D approach could be effective in revealing flow phenomena that difficult to measure in the connected-pipe tests.

During the first test series it was shown that the full-strut is located in the place with the maximum value of the static pressure in the model duct, which led to its burnout at parameters corresponding to the flight Mach number M = 7. Therefore, a new section was designed and manufactured in which the main fuel supply pylon was moved upstream as far as possible, based on the design limitations of the model (Fig. 9).

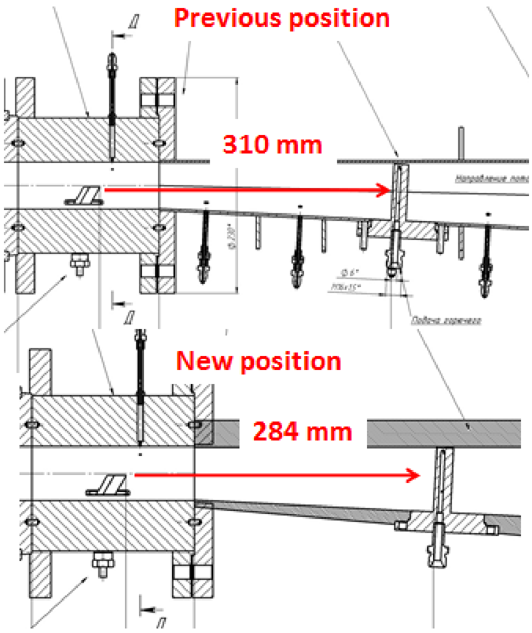
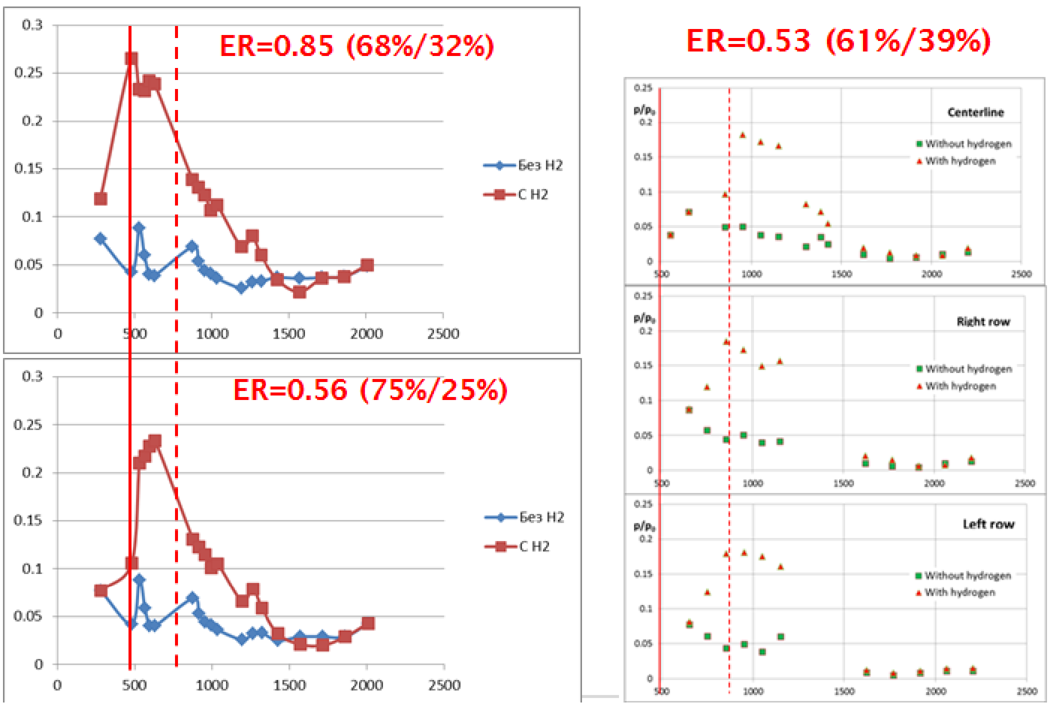


Fig. 9. New full-strut position

Tests of the new section were carried out as part of the previous model of the combustion chamber in the facility T-131 TsAGI.

At the beginning of the test series, the runs were carried out at the parameters at the entrance of the model corresponding to the flight Mach number M = 6 with a fuel strategy similar to that in the previous series of tests (Fig. 10). In addition, tests with ER=0.85 were carried out with a larger amount of fuel (35%) injected through the full-strut. In this case the amount of the fuel was closed to the maximum value without knocking the flow into the aerodynamic nozzle of the facility. It is shown that in the investigated regimes the maximum value of the static pressure is between the fuel supply rows, closer to the semi-struts. At these conditions, in the case of more fuel being supplied through the full-strut, the efficiency of the working process is increased, which indicates the need for fuel combustion in the expanding part of the model duct.



New full-strut position Previous full-strut position

Fig. 10. Results at conditions correspond to the flight Mach number M=6

In the tests with flow parameters at the entrance of the model corresponding to the flight Mach number M = 7, the full-strut was not destroyed (Fig. 11), which indicates a decrease in the thermal load on the strut and a shifting of the maximum value of the static pressure displacement to the semi-struts.

Fig. 11. Full-strut after tests

In the course of the tests, it was found that even at ER = 1.18, no knocking into the aerodynamic nozzle occurs. With decreasing ER to 0.74 (with constant correlation between two fuel supplying rows) the static pressure rose inside the model insignificantly (Fig. 12). At ER = 1 level of the static pressure inside the model was rose with increasing the amount of the fuel injected from the semi-struts. So, it is necessary to supply more fuel through the semi-struts, i.e. it is necessary to burn more fuel in a section with a constant cross section.

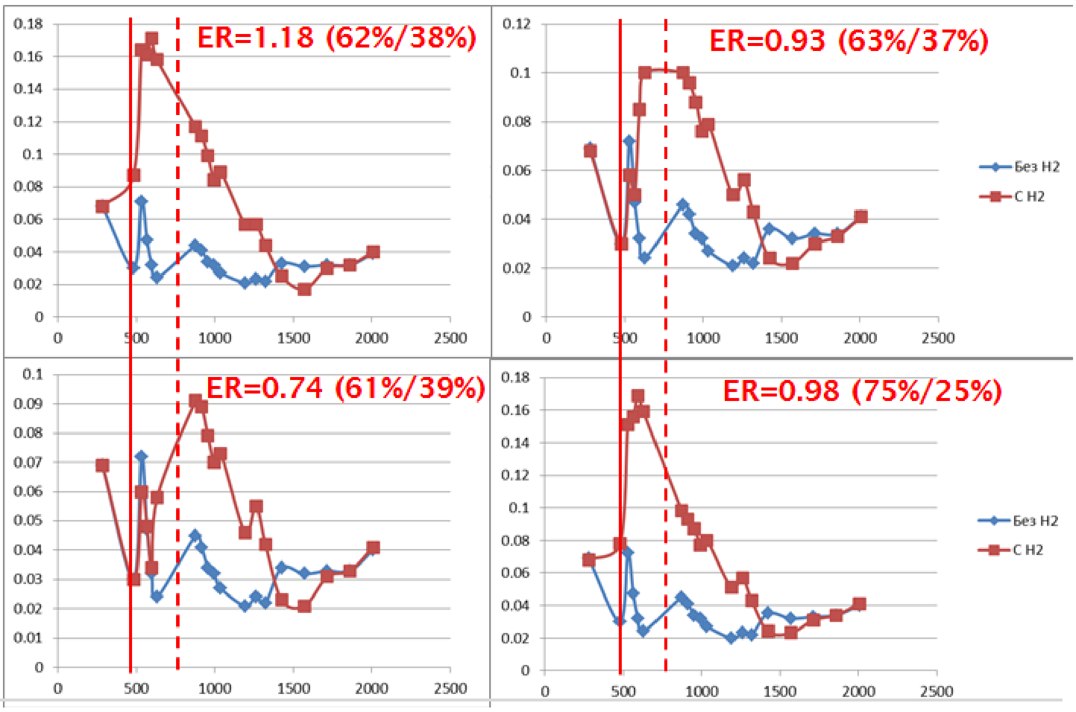


Fig. 12. Results at conditions correspond to the flight Mach number M=7

Acknowledgments

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