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Hypersonic hydrocarbon fuel vehicle with M=6+

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Abstract

When analyzing the working process in the ramjet engine, complex consideration of all problems seems to be reasonable as their solution determines the efficiency of the engine. The main ones are: providing high combustion efficiency and minimal hydraulic losses, reliability of cooling of high-heat areas using cooling capacity of fuel and ensuring the strength of elements of motor channel with non-uniform thermal loads due to combustion fuel in complex gas-dynamic flow structures. The report examines the principal ways and approaches to solving mentioned problems, their novelty and advantages are proved and compared with traditional methods. Thus, to ensure high combustion efficiency and minimum hydraulic losses is proposed a method for organizing an intensive (pre-detonation) combustion regime with a smooth deceleration of the supersonic flow to the sonic speed with the use of a pulse-periodic gas-dynamic flow control. We propose a method for cooling high-heat areas that uses cooling resource of hydrocarbon fuel and includes the process of chemical conversion of kerosene (conversion) and nanocatalysts. The analysis showed that the high-heat design will work in elastoplastic area of behavior of construction materials, which is directly related to the resource engine operation. There are problems in reducing the strength of ramjet engine shells depending on deformations. Deformations also lead to a noticeable effect on the course of the working process in the combustion chamber and, naturally, on the heat transfer process and the catalysts operations (plastic and elastic deformations of bound shells).This paper gives some results illustrating the presence of mentioned problems. It is concluded that it is important to study both with the implementation in model experiments, and in carrying out theoretical and theoretical studies

Keywords: scramjet, combustion, ignition, active thermal protection

Nomenclature

M – Mach number

1. Ensuring a high completeness of fuel combustion and minimal hydraulic losses

A complex approach to the increase in the efficiency of a high-speed ramjet operating on a hydrocarbon fuel at the FV acceleration up to M=6+ is considered in the present work. A new approach is proposed to the solution of problems related to the arrangement of the engine operation regimes, combustor thermal protection, and ensuring the combustor strength.

The main problems of scramjet efficiency are ensuring the high completeness of fuel combustion, the minimal hydraulic losses, and the reliable ignition.

1.1. The high combustion completeness

High combustion completeness is ensured by the organization of intensive (predetonation) combustion conditions by affecting the process by thermal and gas-dynamic pulses produced by a special generator (GI). Below is an example of the implementation in case of hydrogen combustion in an axisymmetric combustion chamber (CC), the scheme of which and the test results are shown in Fig. 1.

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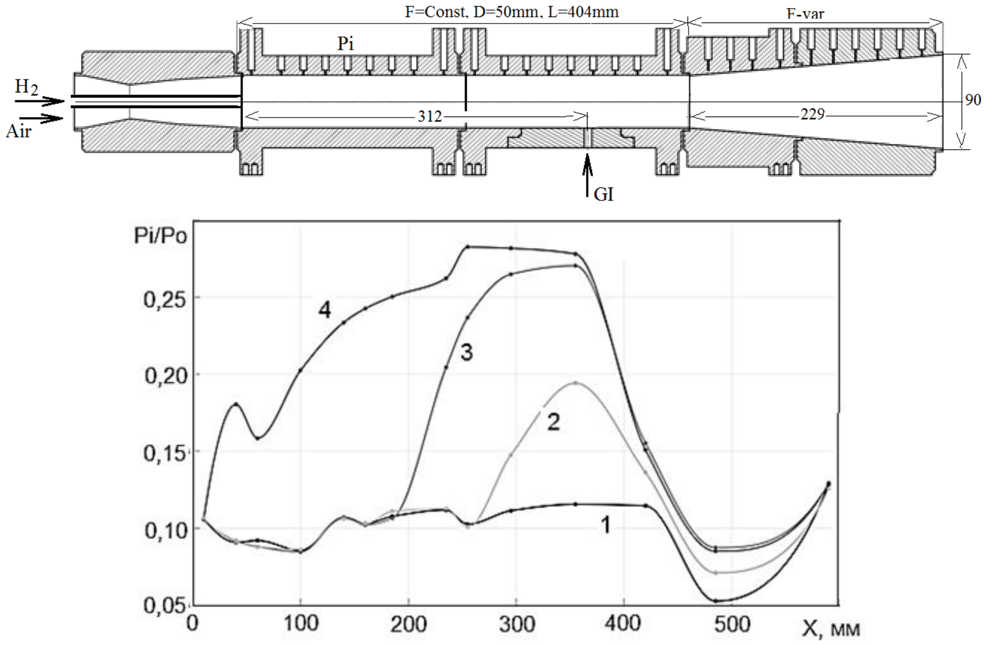

Fig. 1 Geometry of the flow path and the influence of the energy of pulses produced by the generator (GI) on the pressure distribution along the length of the channel.
1 - combustion of hydrogen in the absence of pulses; 2-4 - the operation of the generator with increasing energy in the pulse

Test parameters: Mach number M = 2.2; total pressure P0 = 0.7 MPa; total temperature T0 = 1650 K; air excess factor α = 10.1; frequency of pulse-periodic action f = 20 Hz. The turning-on of the generator leads to an increase in pressure in the channel, which indicates an intensification of combustion. With increasing energy in the pulse, the region of intense combustion moves upstream. Estimates of heat generation have shown that curve 4 corresponds to the "predetonational" combustion mode, when the flow velocity at the end of a constant cross-section area is close to the speed of sound and hydrogen burns completely in the constant cross-section area of the CC.

If there is no energy effect or if the pulse frequency or power is insufficient, a diffusion low-intensity combustion mode is realized along the entire length of the CC.

1.2. The minimal losses of total pressure

Minimal losses of the total pressure are achieved due to the sustaining of supersonic speed at the entrance to the combustion chamber. The flow is decelerated to the speed of sound due to combustion in the constant cross-section area of the CC. In the insulator (before the CC) there is no pseudo-shock, in which the total pressure is lost as in a normal shock.

The decrease in the total pressure loss is confirmed by the total pressure measurement by a tube mounted on the axis of the output section of the CC. Below, Fig. 2 shows the change in the pressure recorded by the total-pressure tube when the combustion mode in the channel changes with time, depending on the absence or presence of the energy effect.

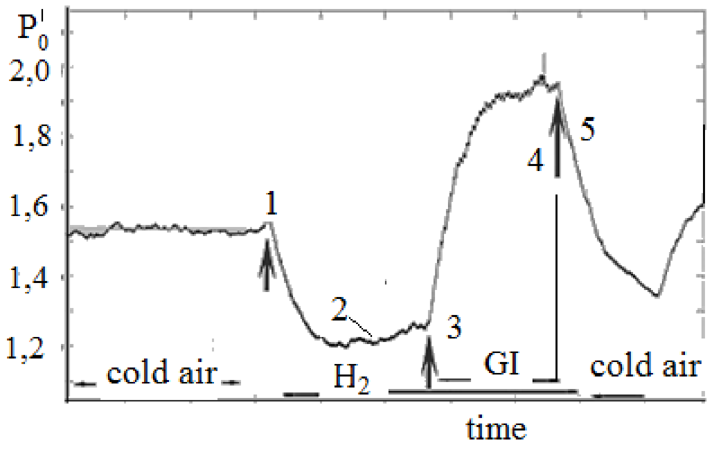

Fig. 2 Diagram illustrating the change in the total pressure in the output section of the CC.
1 – switching on the electric arc heater (EAH); 2 - supply of hydrogen; 3 - switching on the GI;
4 – switching off the GI; 5 – stopping the hydrogen supply and turning off the EAH.

When the generator is turned on, the pressure (P'0) increases by ≈ 56%. This indicates a decrease in the total pressure loss in the CC pathway.

1.3. A reliable ignition

A reliable ignition is created by the technology of starting the ramjet after the accelerator separates from the flying vehicle. No deceleration of the supersonic flow in the combustor down to subsonic velocities is required at the start by using the other gas-dynamic or physical-chemical means of action on the process. The technique uses the fact that the fuel for the start is supplied to the first zone of the interval of constant cross section of the combustor, and a quasi-stationary pulsatile, pre-detonation combustion regime from the thermal and gas-dynamic impulses of the generator is initiated. After the quasi-stationary pulsatile, pre-detonation combustion regime has been established, the fuel combustion is arranged in the combustor part of a variable cross section in the amount specified by the air excess coefficient.

The stationary combustion regime in the combustor is preserved at the generator switch-off. Such a technology has been confirmed in the model experiment. At the hydrogen supply to the part of the duct of a constant cross section (the supply to the 1st zone), a diffusion combustion regime (a low level of the pressure increase in the duct) is realized. After the generator switch-on, the combustion process becomes intense (pre-detonation) - the pressure in the duct grows. The hydrogen supply to the second zone (to the combustor expanding part) leads to a general pressure increase at the expense of heat supply from combustion. At a generator switch-off, the pressure level does not change. A steady combustion regime in the combustor has been realized.

Experiments with the combustion of ethylene, performed in a flat CC, confirmed the results obtained with the combustion of hydrogen. This is evidenced by the pressure distribution along the length of the channel at different times in accordance with the experimental cyclogram (see Fig. 3). The peculiarity of the experiment was that hydrogen was used to simplify the organization of combustion in the expanding channel.

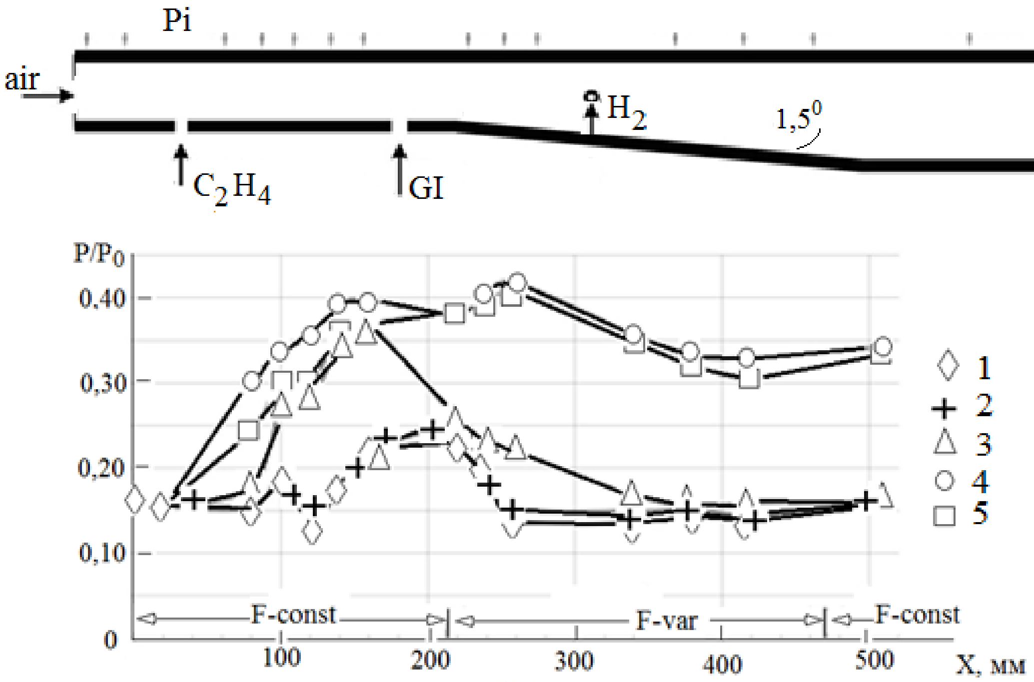

Fig. 3 The scheme of the channel and the static pressure distribution along it
1 - before fuel supply; 2 - when ethylene is fed into a constant cross-section area; 3 - after the turning on the GTI; 4 - after the start of hydrogen injection into the expanding part of the channel and 5 - after turning off the GTI with the retaining of the fuel supply to both belts.

Test parameters: Mach number M = 1.89; total pressure P0 = 0.67 MPa; total temperature T0≈1700 K; frequency of pulse-periodic action f = 30 Hz. The experiment confirmed the persistence of intense combustion in the CC when the GTI was shut down.

2. Active thermal protection

Critical problems at hypersonic flight speeds include: cooling of the heat-stressed parts of the airframe's liner and combustion chamber, as well as the organization of stable ignition and consistent combustion of fuel in the supersonic air flow in the combustion chamber of the scramjet.

Active thermal protection of HFV, developed at JSC "Hypersonic Systems Research Enterprise" [1, 2], is based on thermochemical transformation of the initial hydrocarbon fuel by means of utilization of heat losses associated with aerodynamic heating of the apparatus and the operation of the powerplant. This conversion is carried out in catalytic thermochemical reactors, placed in the heat-stressed parts of the apparatus. It makes possible to:

– increase the cold-resource of the initial fuel by means of its physico-chemical transformations to provide effective cooling of the structure of the apparatus;

– obtain a hydrogen-containing fuel mixture directed to the combustion chamber and improving the characteristics of the combustion process.

According to the estimates of a number of authors, summarized by Lander [3], the value of the necessary cooling resource depending on the Mach number of the flight for devices of different design and purpose form an area bounded by two curves (Fig.4). The lower curve refers to unmanned vehicles, and the upper one refers to manned vehicles.

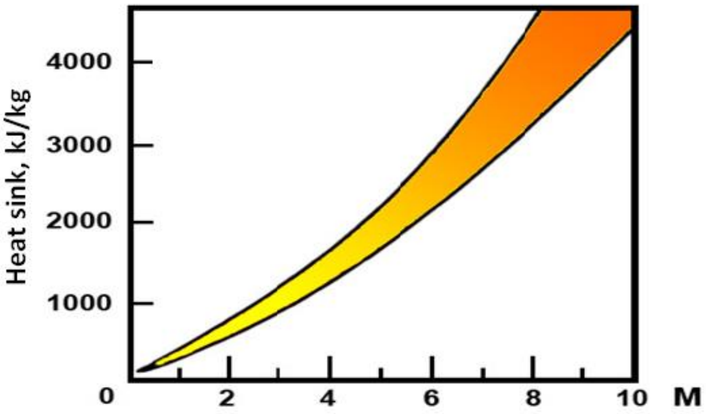

Fig. 4 Heat-sink requirement as a function of flight speed

Physical and chemical fuel transformations on board an HFVX. Steam conversion and cracking are most often considered in the literature as fuel transformation processes on board an HFV. Estimates [4] show that the use of steam conversion on board of PEM compared with cracking increases the cooling capacity of hydrocarbon fuel by 2-3 times and allows to provide heat protection of apparatus up to M = 8-9.

The reactions of steam conversion and cracking of hydrocarbons differ considerably as regards the output product composition. In the case of cracking of hydrocarbons, mainly C–C bond rupture and, more rarely, more energy-strong C–H bond rupture take place; therefore, the products of liquid fuel conversion consist mainly of low-molecular hydrocarbons C1–C4 and a small amount of hydrogen (<10% with respect to the volume), whereas with steam conversion the amount of the produced hydrogen exceeds 70% in volume.

It is known that the main disadvantage of hydrocarbon fuels is the large ignition delay time (τ_{delay} > 10 ms), as compared to hydrogen (τ_{delay} ~ 0.1 ms), which results in a too long supersonic combustion chamber. Mixing a certain amount of hydrogen with kerosene, however, reduces τdelay and, as a consequence, the length of the combustion chamber [5]. Estimates show that not all the kerosene can undergo endothermal steam conversion, its main mass goes directly to the combustion chamber, and a large amount of hydrogen produced from the converted part of the fuel makes it possible to achieve permanent kerosene ignition for stable operation of the scramjet.

The considered processes of cracking and steam conversion of hydrocarbons are not alternative to each other. Each of them occupies its niche, as regards cooling capacity and the amount of hydrogen produced. Depending on the design of a particular vehicle, its velocity, trajectory, and flight duration, it is necessary to consider different variants of thermal protection and managing the burning process in the engine using particular endothermal processes.

On-board reactors and catalysts. Application of heterogeneous catalysis for heat regeneration in objects of aerospace equipment required a new approach to the development of catalysts and thermochemical reactors (TCRs) based on them. Thermochemical reactors should be light and firm, should have various shapes, and should possess low hydraulic resistance.

On-board catalysts, along with traditional requirements to the activity, selectivity, and operation life, should satisfy a number of specific requirements; namely, they should represent one whole with the heat transferring surface. They should possess high heat conductivity, thermocyclic strength, and chemical heat resistance, as well as stability to impact loading and vibration. They should operate in the conditions of high temporally variable heat fluxes. In [6] where the problem of application of steam conversion of methane for thermal protection of heated surfaces was considered, it was demonstrated numerically and analytically that it is possible to remove the thermal flux $q \sim 10^6$ W/m^2 from the reactor wall if it is covered by a porous coating with the pore diameter 10^{-4}–10^{-6} mm, a thickness of about 10^{-2} mm, and an effective heat conductivity of not less than 1 W/(m·K).

Experimental studies. In this study, we consider the element of thermal protection under the action of moderate thermal fluxes ($q \cdot 10^5$ W/m^2). It represents a thermochemical reactor for steam conversion of methane as the basic component of gasification of liquid hydrocarbons. The thermochemical reactor (Fig. 5) consisted of two channels: channel 1 with a length of 590 mm, a width of 60 mm, and a height of 4 mm, forming the cooling jacket of the central channel 2, along which the nitrogen plasma jet heating the inner walls of the reactor flows.

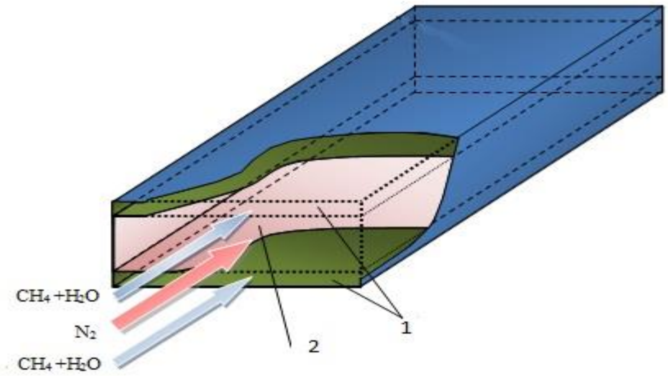

Fig. 5 Schematic diagram of the thermochemical reactor

The first series of experiments was performed in the reactor with smooth metallic walls with natural catalytic activity. For the steam-methane mixture flowrate G = 0.7 g/s and the average temperature of the inner reactor walls t_w = 1050°C, the methane conversion level did not exceed 6% (Fig. 6). The reduction of the mixture flowrate to 0.2 g/s resulted in the growth of the conversion level to 36% due to the longer time spent by the reagents in the reactor.

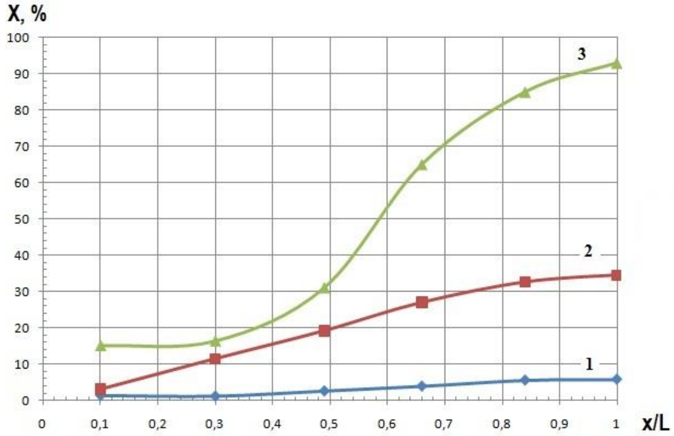

Fig. 6 Methane conversion level along the reactor length
(1) G = 0.7 g/s, smooth wall; (2) G = 0.2 g/s, smooth wall; (3) G = 0.7 g/s, framework catalyst

The situation changed quantitatively in the series of experiments with the framework nichrome catalyst in the form of a pressed wire filling the reactor volume with good thermal contact with its walls. In this case for the flowrate G = 0.7 g/s, the methane conversion level increased to 92% and the hydrogen production was 45% with respect to the volume (see Fig. 7). When the reactor wall temperature increased to 1250°C, the hydrogen concentration in conversion products increased to 65 volume %.

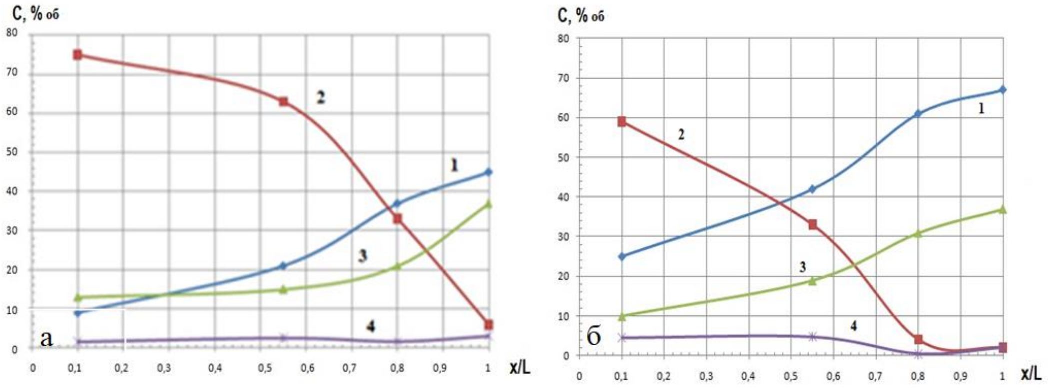

Fig. 7 Concentration of reaction components along the reactor length for (a) t_w = 1050 °C and (b) t_w = 1250°C. (1) H_2, (2) CH_4, (3) CO, and (4) CO_2.

The analysis of the experiments showed that the degree of conversion of hydrocarbon fuel and the amount of absorbed heat flux in TCR is influenced by the design of the catalytic reaction space and the catalyst quality, the flowrate of the chemically reacting mixture, and the catalyst surface temperature.

3. Ensuring the of the combustion chamber durability

The important problem is associated with the formation of rational schemes and design elaboration, ensuring the implementation of the above workflows. the heat-stressed structure will work in the elastic-plastic region of the behavior, which is directly related to the life of the engine. There are problems of the influence of plastic and elastic deformations of bound shells on the joint work with nanocatalysts. As shown by studies of 2014-2015, there are problems strength reduction in the scramjet shells and changes in the working process in supersonic combustion chambers, depending on the large deformations of the shells.

To solve the problem of the scramjet thermal state, it's relevant to use structures with regenerative cooling of cases. In 2008-2010, research was carried out on the calculation of generators (Fig. 8), which supplied the model gas mixture to a test bench for the scramjet research, various design options and cooling systems for scramjet chambers (see Fig. 9). The generators were developed at the Federal State Unitary Enterprise "TsIAM" and they supply a model with gas mixture to a test bench for the scramjet. The combustion chambers had different geometric shapes and regenerative cooling systems.

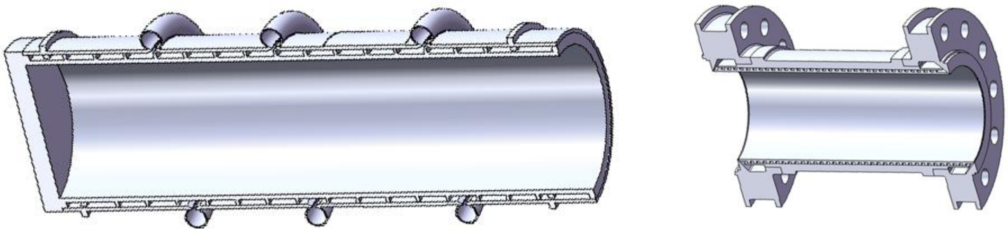

Fig. 8 The structural scheme of the flame tube FSUE "TsIAM"

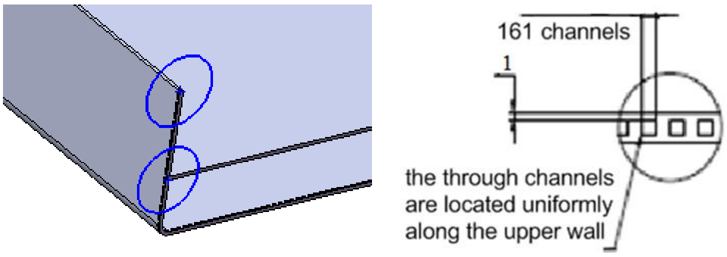

Fig. 9 One of the studied variants of the scramjet combustion chamber design proposed by FSUE "TsIAM"

Similar constructions work in the elastic-plastic region of material behavior. By that time, only the calculation method for the plane stress state was used for assessing the bearing capacity of the bonded shells, that are providing regenerative cooling of structures [7]. In 2008, a methodology for calculating the carrying capacity for the three-dimensional case was proposed [8]. It is based on consistently meeting the strength conditions of both shells for strength and deformation criteria. This technique is applicable to solving the problem of calculating the strength when combined bonded shells with nanocatalysts that are in the channels.

Another problem is the effect of deformation of the shells of supersonic scramjet chambers on the joint change in the workflow and the strength of the combustion chamber. Calculations showed that in large-sized chambers there is the largest deformation of the inner shell (Fig. 10).

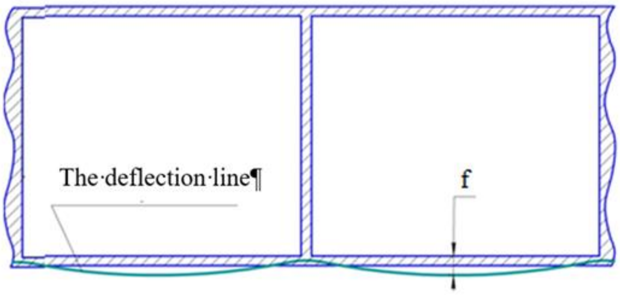

Fig. 10 Deformation of the combustion chamber inner shell section

To study these effects, experimental studies were carried out on the stands of the MAI (Fig. 11) and ITAM SB RAS (Fig. 12).

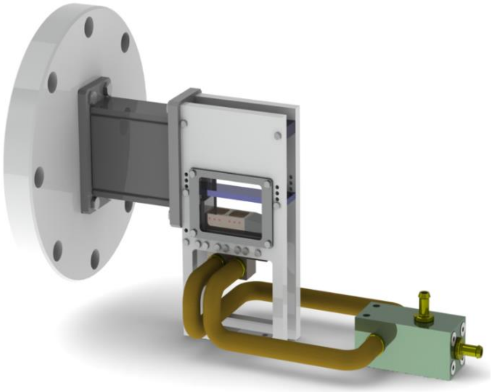

Fig. 11 Experimental installation of the MAI for testing deformed models of the scramjet camera

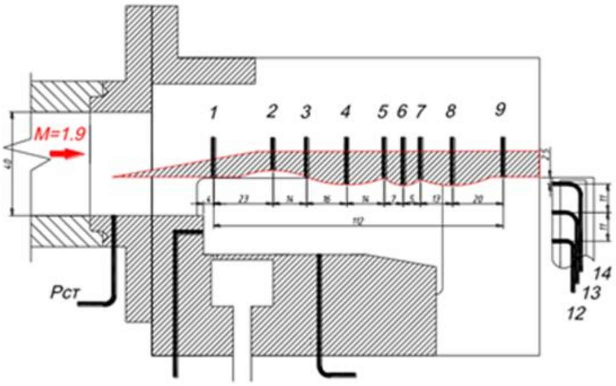

Fig. 12 Experimental installation of ITAM SB RAS for testing deformed models of a scramjet chamber

Plates with curvilinear surfaces equivalent to the deformed forms of the supersonic combustion chambers inner shell were tested under various engine operating conditions. In Fig. 13 shows one of the variants of the tested model design.

Fig. 13 Model of the deformed casing of the scramjet combustion chamber

The results of the experiments showed a significant change in the structure of the gas flow (Fig. 14) compared with an undeformed body (Fig. 15).

Fig. 14 The structure of the flow of burning hydrogen in the air flow in the path with a deformed body

Fig. 15 The structure of the flow in the path with a non-deformed body

There are areas of pressure concentration on the surface of the inner shell in the deformed tract. There is a change in the flow structure and the combustion process in the separation zone behind the step.

Calculations show that this effect leads to a decrease in the shell strength by 30 ... 50%. This almost completely compensates for the specified safety factor n_v = 1.3 ... 1.5. The neglect of this effect can lead to the destruction of the structure.

The method of digital processing of shadow images that was developed in MAI [9-10] allows a detailed analysis of the distribution of gas-dynamic parameters in a supersonic gas stream. It's based on a comparison of the results of digital processing of image intensity in discrete areas of the image with the characteristics of the gas flow: pressure, velocity and gas density gradient. The correspondence is based on experimental correlation functions between the numerical values of the indicated parameters.

Of interest is the distribution of intensity of the image in the area of the ledge (Fig. 14, 15), where the combustion process is organized. The presence of an oscillatory process recorded in both the longitudinal and vertical directions is obtained. In Fig. 16 shows the change in the image intensity in the longitudinal section 1 for the structure of the supersonic gas flow shown in Fig. 15.

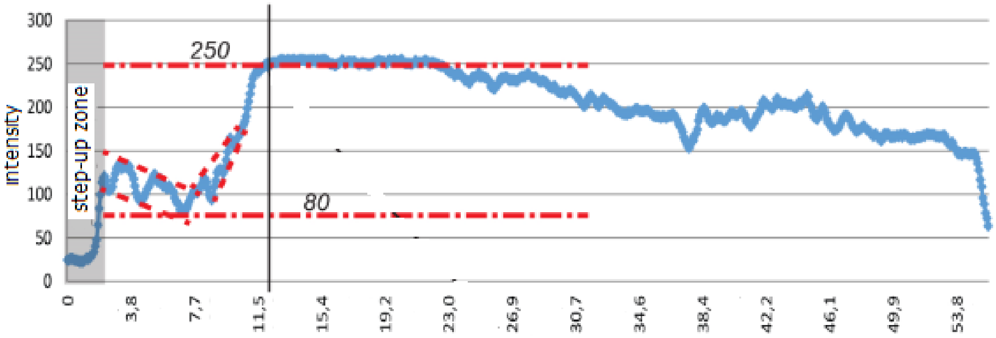

Fig. 16 The change in the intensity of the image in the longitudinal section of the path with a non-deformed body

In the ledge, the amplitude of oscillations diminishes as it moves away from its wall. This process ends immediately before the shock wave (image intensity = 250). A linear relationship between the image intensity and the gas pressure was obtained. The magnitude of the correlation is in the range of 0.81 ... 0.94.

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