EXPERIMENTAL AND NUMERICAL SIMULATION REASERCH OF HYDROGEN BURNING AT THE DUCT

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Abstract

The effective scientific cooperation between Moscow aviation institute (MAI) and Central institute of aviation motors (CIAM) in experimental – computational methodology of physics research of hydrogen combustion in ducted flows applied to scramjet combustion chambers is established. The results of fundamental experimental researches of the mechanism of combustion of fuel in the supersonic flow conducted in MAI in 70-th years and permitted to verify the mathematical models and numerical methods of calculations are reviewed. Then the verified codes were used for the study of flow detailed structure. The outcomes of experimental researches of the combustion chambers of the different schemes verifying a reality and complexity of physical processes and interpretation of these results with the aid of numerical simulation are demonstrated.

Nomenclature

M_n – Mach number
P, T – static parameters
ER – equivalent ratio
S, R – separation and reattachment zone of boundary layer
x – longitudinal coordinate
R – radius of generator nozzle
F – area of combustion chamber at a cross section

Index:

g, n – gas parameters at the nozzle exit of generator and heater
* – stagnation parameters
j – jet parameters
en, ex – gas parameters at the entrance and exit cross section

The efficiency of ramjets to the greatest degree depends on efficiency of the combustion chamber in the supposition of sufficiency of knowledge about properties input and output equipment. The creation effective wide-range ramjets, having the high characteristics in wide change of flying speeds and trajectory conditions, is impossible without a profound knowledge of the mechanism of flame stabilization at different modes of its activity. Today it is well-known, that the mechanism of a working process in the scramjet combustion chamber differs by exclusive complexity: the positive longitudinal pressure gradient changes the characteristics of a boundary layer, provokes separated flows arising, creates strong wave structure effecting on the characteristics of diffusion combustion.

In MAI, the experimental researching of gas-dynamic flow pattern with combustion of fuel was conducted from the end of 60-s. The results of researches become the good basis for fruitful cooperation MAI with CIAM in the field of an experimentally – computational methodology of researches of the mechanism of combustion of fuel in ducted supersonic flows.

Not far to this moment the combustion chambers with burning in supersonic flow represented a “black box” with data satisfactorily defined in the inlet and outlet cross-sections and with virtually full uncertainty as to the gas dynamics inside these chambers.

More recently it has been made known from a limited number of sources that the processes of thermal and mechanical throttling (i.e., at heat addition [1],[2] and in a pseudoshock) are similar as to the external features, namely the distribution of static pressure measured on the channel wall. In spite of the differences in above physical processes, they can be approximated by single semi empirical relationship [3]. However, the absence of experimental data required for a substantiation of this statement was explained by the imperfection of investigation diagnostic methods.

Investigations [4] were realized at the experimental setup (Fig. 1). The air heater was supplied by supersonic axisymmetric contoured nozzle connected to the heater exit cross section. The parameters at the nozzle exit plane are as follows: stagnation temperature T* – up to 2300K, Mach number $M_n = 2.89$, static pressure $P_n = 0.5\times10^2$ KPa, oxygen content in the gas after heater is approximately 23% (by weight). The nozzle diameter is equal to 0.07 m. The combus-

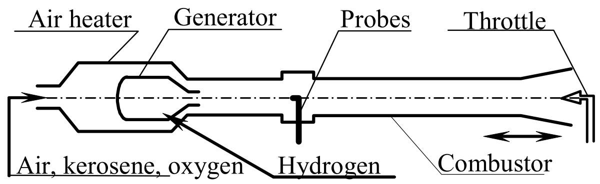


Fig. 1. Experimental setup

tion chamber, representing a cooled cylinder (0.07 m in diameter), is installed at the exit flange nozzle of heater. It is composed of modules and has maximal length equal to 1.09 m.

The fuel (gaseous hydrogen) is fed axially by means of a gas generator (placed in the plenum) into combustion chamber through a conical nozzle having 0.02 m in diameter at the exit plane. The nozzle parameters are: $T_g = 300$K, $M_g = 2.4$, $P_g = (0.4–0.75)\times10^2$ KPa. The range of fuel-to-air ratio variation at combustion chamber inlet is ER = 1.5–10. One of the 0.13 m long module servers for providing leak-proof, plane-parallel microprobe displacement in the cross-section to measure the total and static pressures. The module has lateral cavities for the removal measuring devices from the flow field.

The method proposed by MAI for the complex study of supersonic flow with burning and throttling is based on using small-size measuring probes. Within the framework of a designed technique the group of new measuring means distinguished by mesh sizes was built. Small-size probes for the measurement of gas flow stagnation and static pressures are show in fig.2. T-shaped probe has an elliptic profile and is installed in the flow in such a manner that the major axis of ellipse coincides with the flow direction. Two holes of probes are connected with pressure gauges. The probe serves for the indication of gas motion direction near the wall. One of modules (0.32 m long) is used for the wall temperature measurement and T – shapes installation in 6 points at internal surface.

The insertion of probes into a reacting flow distorts insignificantly the pattern of pressure longitudinal distribution, displacing upstream by 0.4 of pipe diameter the characteristic

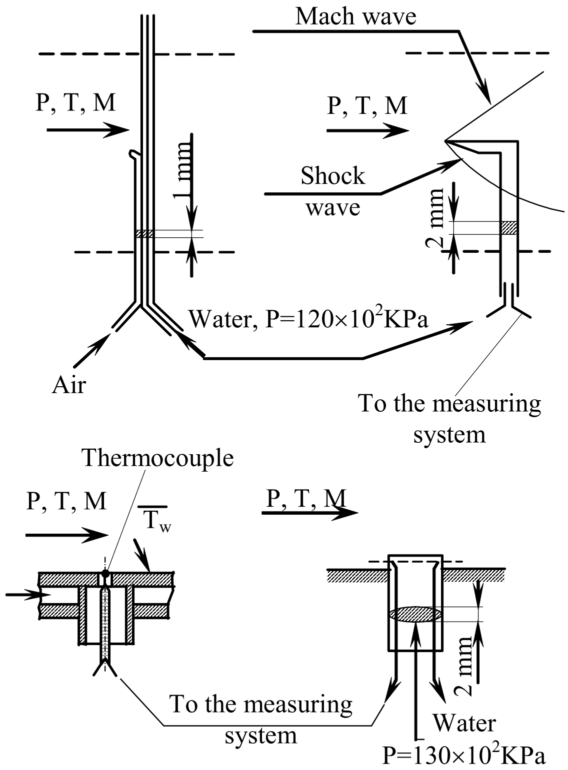


Fig. 2. Technical equipment

pressure wave that arises at the heat addition to a supersonic flow. An analogous influence of probes becomes apparent also in the investigation of pseudoshock.

All measuring devices have endured (without erosion) the test under flow temperature up to 2200K. The recording of parameters was performed continuously in the process of experiment. Induction gauges recorded the measured pressures.

The characteristic distribution of static pressure over the initial segment of the combustion chamber at the various values of heat addition and the mechanical throttling was investigated.

A resultant conclusion about the gas state at different regimes of throttling consists in the following.

In the separation zone, the longitudinal oscillations are revealed: the pulsation frequency = 20–24 1/s and amplitude amounts to 20% of the measured static pressure level in corresponding cross-section.

The knowledge of pressure wave motion permitted to determine the length of primary separation zone under the thermal throttling. This length was equal to 0.06 – 0.08 m. The separation zone in the pseudoshock region was 0.035 – 0.055 m long.

By results of researches, the distributions of relative temperature near the wall, and also full and static pressures in cross sections of the combustion chamber were obtained. On results last the fields of velocity in a channel for modes with combustion are constructed.

At the thermal throttling there can be two principal different schemes of flow:

1. The supersonic combustion, when wave structure does not render the essential influencing on efficiency of heat release;

2. The large longitudinal pressure gradient in a channel instigates a separation of flow on a wall and strong precombustion shock wave. Thus in cross section of the combustor there is a two-sheeted flow keeping subsonic and supersonic zones. The given mechanism is characterized by high performance of combustion process.

The analysis of experimental material presented allows to interpret qualitatively the physical model of the supersonic flow throttling (fig.3). In essence, it was the first and unique work where a flow model was based on experimental physical researching data [5].

The known gas-dynamic model of pseudoshock is illustrated in fig.3 (a). The flow structure at regime of weak thermal throttling (when the influence of shock wave on the development of the process is insignificant) is shown in the fig.3 (b). A typical example of the thermal choking is given in fig.3 (c) where the active heat release is determined by the effects of local "quasydetonation" stabilized by shock waves ("precombustion shocks"). Separated zones, in their turn, initiate their shock waves. The position of these zones depends on the value of longitudinal pressure gradient. Thus, the flow physical model at thermal throttling of supersonic flow is based on a feedback

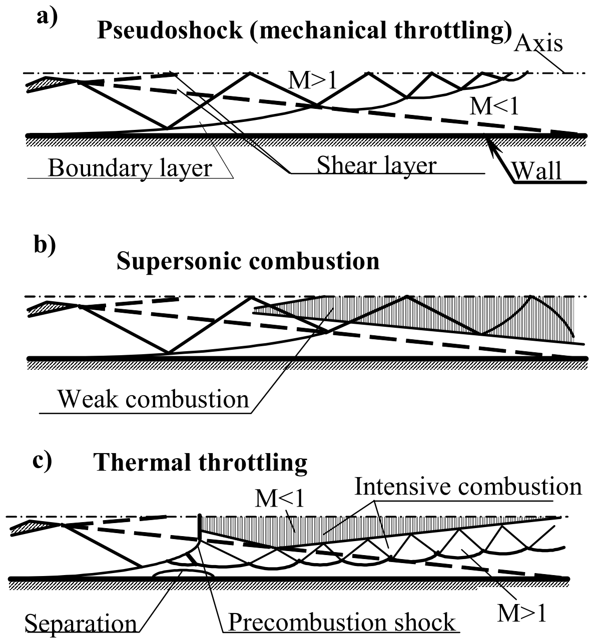


Fig. 3. Physical model of mechanical and heat throttling of supersonic flow

mechanism, i.e. the heat release results in a positive longitudinal static pressure gradient and, in turn, it defines shock structure intensity.

In 1990th years, the active work concerning the numerical simulation of scramjet operational process was began in CIAM. One of the central points of this activity was the numerical simulation concerning the combustion process in supersonic flow. The system of codes was developed for this purpose [6]. One of the most important problems is the experimental verification of mathematical models and numerical tools. Additional requirement to the experimental verification is the simple geometry of the combustor and not very complicated system of injection because in opposite case the special simplifications of these elements are needed for the numerical simulations due to capabilities of real computer systems. This is especially important in the case of complex gasdynamic flow structure. Unfortunately, it is difficult task to find adequately documented publications with conditions of experimental research of ducted flow simulating combustor operation for practically important regimes. One of the experimental researches, which have been used in CIAM [7], [8] for the numerical tool verification, was the MAI experiment on the model cylindrical combustor. The important feature of the MAI data [4] was the additional information concerning structure of the flow inside the combustor. As the rule, only pressure distribution along the wall is available from the experiments. This numerical simulation and experimental research have allowed to point out some important features of the typical gas-dynamic flow structures, which are generated due to combustion, and to associate these flow structures with the pressure distributions along the duct wall.

The following test case was considered. The axial hydrogen jet is injected into air stream in the tube of constant cross-section area with some expansion in the exit part. The main flow parameters and duct geometry were chosen on the base of published experimental data. Some additional cases out of scope of experimental research were considered in the numerical simulation to explain the change of the flow structure due to the influence of dimensionless parameter, characterizing the heat released into the flow due to combustion. This parameter is the ratio of the heat released at the combustion and the total enthalpy flow of the air stream at the combustor entrance. The base regime was chosen in accordance with CIAM authors understanding taking into account the MAI published data. Hydrogen jet parameters are given as follows: pressure p_j=0.94 bar, Mach number M_j=2.4, temperature T_j=133 K, diameter of the jet injection tube d_j=20 mm. The tube diameter is equal to 70 mm. Three considered cases differ by some air stream parameters. The pressure p_e=0.94 bar and temperature T_e=1150 K are identical in all these cases. It is necessary to note that temperature in the calculations was chosen higher then in experiment to provide the self-ignition as in the experiment. At the air stream temperature corresponding to experimental one the self-ignition was not realized in computations. The problem of combustor starting was numerically solved only recently. However, this

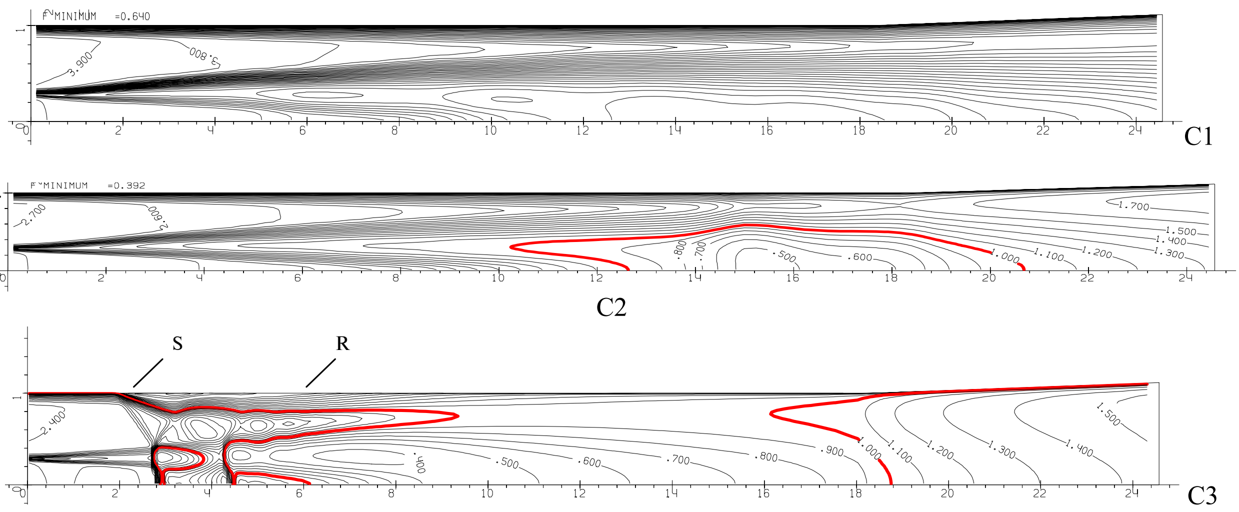


Fig. 4. Mach number fields

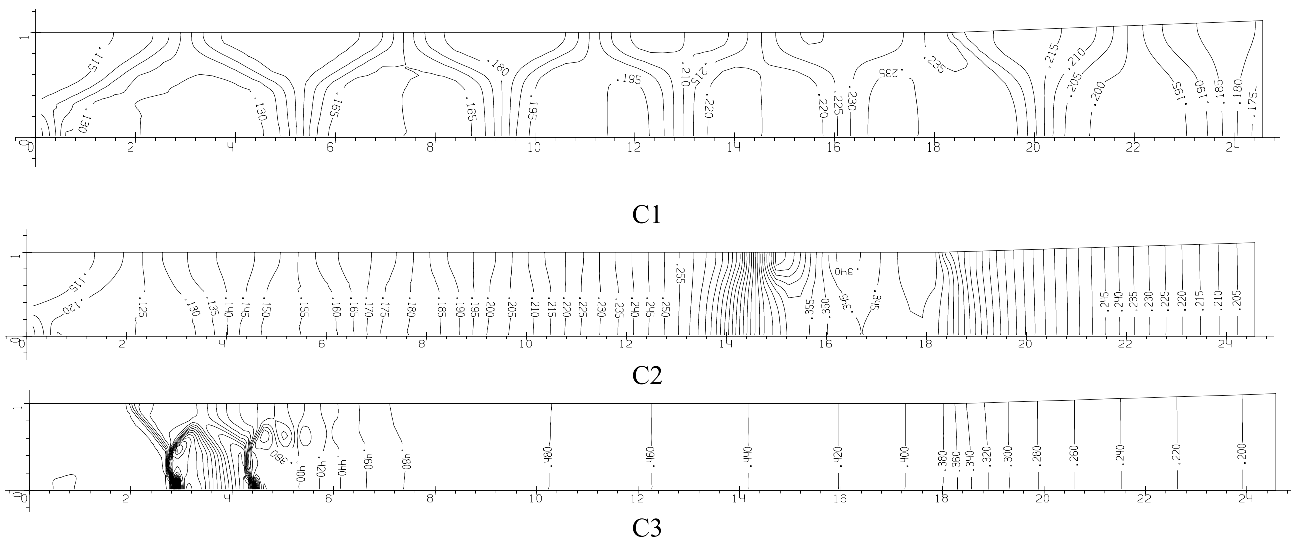


Fig. 5. Pressure fields

process of combustor starting was not taken into account at the beginning of the work on verification [7],[8]. It is necessary to note that the method of air heating at the combustor entrance could provide the mechanism of self-ignition and combustor starting. Mach number M_e was varied in computations. Three cases are presented here, corresponding to 3.9, 2.8 and 2.5 (cases C1, C2 and C3 correspondingly). The hydrogen is diluted by the nitrogen in order to provide the equal pressures in the jet and air stream. The air-to-fuel equivalence ratio value α is equal to 6.5, 4.6 and 4.07 for the cases C1, C2 and C3 accordingly. Both the boundary layer on duct wall and the boundary layers on injector walls were taken into account at the combustor entry.

The main results illustrating the flow structure are presented in the following figures. Mach number and static pressure fields are shown in fig.4,5. The sonic lines in the Mach number fields are marked by bold lines. Pressure ratio distributions along the axis and wall of the duct are shown in fig.6. It was obtained that self-ignition takes place on some distance downstream from initial cross-section in all considered cases. In the first case, the flow remains supersonic in the major part of the channel. The structure which consists of alternating compression and expansion regions is realized. The level of pressure, averaged over the cross-section, increases in the cylindrical part of the channel in downstream direction. In the second case, we can see large closed subsonic region in the flow core near the axis of symmetry. This corresponds to the experimental fact [4] that the subsonic region arises near the axis of the duct. The flow is supersonic in the layer between embedded subsonic region in the core and subsonic part of the wall boundary layer. The appreciable rise of the pressure level is detected in the duct section, containing local subsonic region, in comparison with previous case. In the third case, the system of shocks and separation region are generated in the vicinity of the ignition point. It is necessary to note, that transition from supersonic to subsonic flow occurs and the flow remains subsonic in the major part of the cylindrical duct. The inverse, sub- to supersonic flow transition, is realized at the entry to the expansion part of the channel. The pressure distribution along the wall is strongly different in comparison with this one corresponding to first case. In this, third case, the pressure along the wall increases in the initial part of the cylindrical duct and then slowly decreases in the second part of the cylindrical channel. This pressure distribution in the cylindrical duct is in

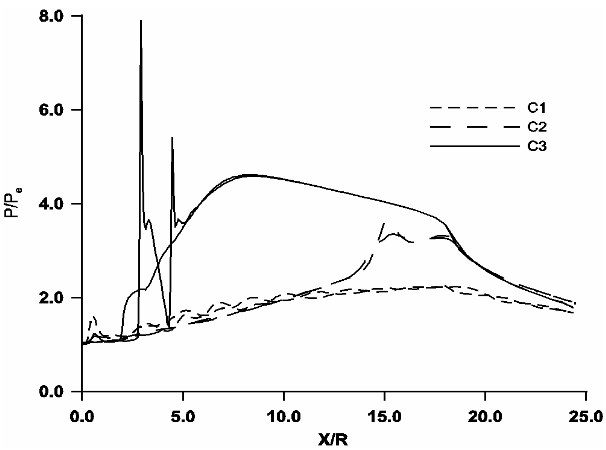


Fig. 6. Pressure ratio distribution along the duct

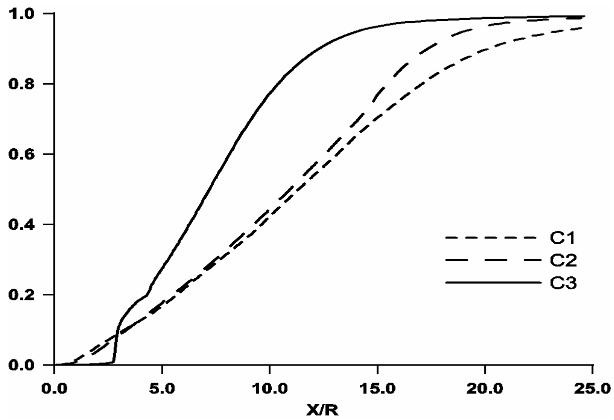


Fig. 7. Combustion efficiency

good qualitative and adequate quantitative agreement with experimental results. The pressure is practically uniform in normal direction in the region of subsonic flow. The pressure distribution along the wall is comparatively smooth and along the axis of symmetry it is strongly nonmonotone in the head of the formed structure due to strong shock system (see fig.6). The dependence of combustion efficiency versus longitudinal distance for all three cases is shown in fig.7. It is necessary to point out the tendency toward combustion enhancement in subsonic regions.

Thus the following features, which correlate with experimental data analysis, were obtained in the computational research [7],[8]. The increase of the relative heat throttling due to combustion provides the principal variation of the gas-dynamic flow structure in the duct. The regions of subsonic flow arise in this duct at the combustion in the core of the flow, near the duct axis. At the strong heat throttling the transition to the combustion with large subsonic regions take place. Moreover, the transition to subsonic flow can take place with the thermal choking of the duct and with inverse transition to the sonic conditions at the entrance to the expanding section of the duct. The shock waves and boundary layer interaction with separation region arising play important role in this flow structure formation.

In MAI the experimental activities were conducted with the wide-range combustion chamber together with MAI and Aerospaciale (France) [9].

Research works of combustion process were conducted at the test-bench with using reattached air-channel scheme.

Air preheater, which is cooled by water, has a Laval nozzle, and the rectangular combustion chamber was attached to it.

For a heating of air the incineration of kerosene with previously oxygenation air was made. The high efficiency of combustion allows ensuring the minimum influencing of combustion products on a working process in the combustion chamber. For an estimation of efficiency of combustion of kerosene, the gas extraction from hot flow with their subsequent chemical analysis were conducted, and also computational estimations of combustion efficiency with taking into account heat looses to the cooling water and a pressure measurement before the supersonic nozzle.

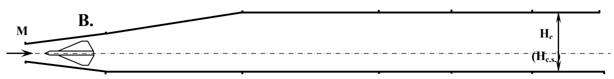
Total temperature of a model flow was determined by a computational way. The technique of calculation parameters of preheated flow allows selecting oxygen flow rate and kerosene for obtaining given temperature of a model flow. During debugging a preheater, with the high temperature thermocouple the measurements of a field of temperature at the exit of a nozzle and comparison of results of the tests with calculations were conducted. The good correlation was obtained.

During experiment the control of a preheater is conducted manually. The accuracy of maintenance of a given level T_0 is not worse than ±40°K.

To the exit of a nozzle of a preheater (generator of a model flow) the model combustion chamber of rectangular cross-section was adjoined. The walls of the chamber are cooled by water. The fuel (hydrogen) is supplied in a gaseous kind (with temperature 20–25°C) from bottles.

Combustion chamber design allows to change the angles of install of the upper wall modules of a channel, concerning a horizontal axis both in "+", and in "-". And it is possible to change angle of install of panels without change of general expansion ratio of combustion chamber (F_{ex}/F_{en}).

The geometry of the chamber channel was varied, if necessary, in set-up time between of experiments. The fuel was injected into the



$M_f = 6.0$	$T_0 = 1660K$	$H_{ch} = 90$ mm	$H_{st} = 0$ mm	Supersonic burning.
$M_\infty = 2.5$	$P_0 = 15$ Bar	$H_{c.s.} = 90$ mm	Fuel: H_2	

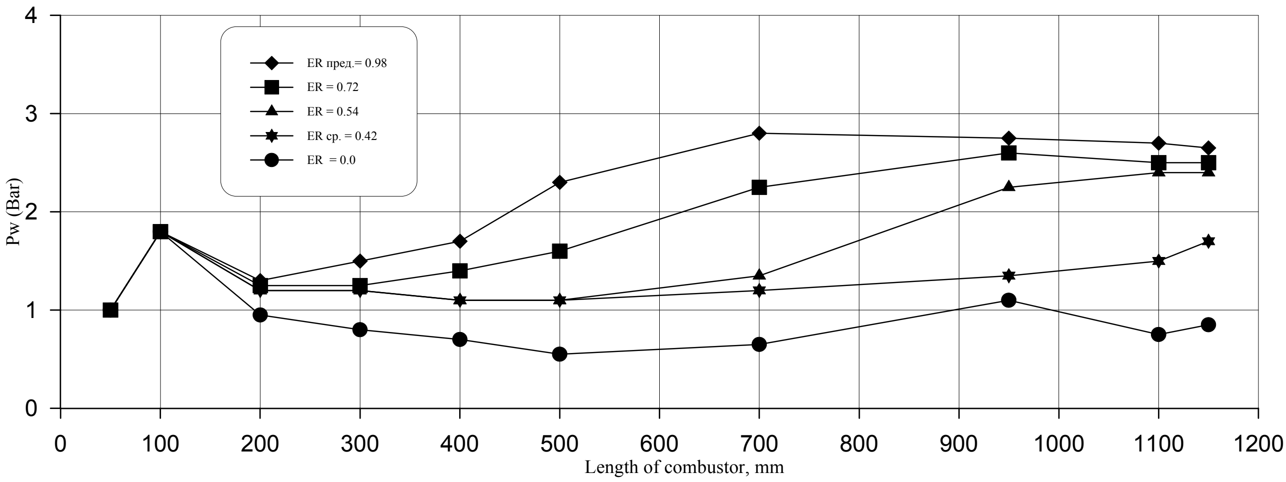


Fig. 8. Testing of model "PROTOTYPE" in scramjet regime

chamber through a special pylon. The nose part of a pylon body was cooled by water. The tail part of a pylon was cooled either by air, or fuel, given to the chamber.

During experiments the measurements of static pressure along the upper wall of the chamber were conducted. In a number of experiments, the measurement of stagnation pressure field at the exit of combustion chamber was conducted by water-cooled rib of Pitot tubes.

Some results of tests in a view of static pressure distribution along of channel of the chamber are adduced on fig. 8. On the same figure in the main specifications are presented the parameters of model flow, the sizes of a channel and propellant consumption.

The numerical simulation of the combustion process in this combustor was performed. The peculiarities of the combustion process and flow field structure in this were made at the numerical simulation. The complicated pylon system for fuel supply with longitudinal and normal fuel injection was simulated by one slot injector. Moreover, duct with rectangular cross-section was considered as 2D. The results for different values of ER were obtained. The pressure combustor were studied. Some simplifications distributions along the lower combustor wall are shown in fig. 9. The change of combustion regimes and wall pressure distributions with the increase of relative heat release is analogous to this one for model combustor discussed earlier. It is necessary to note

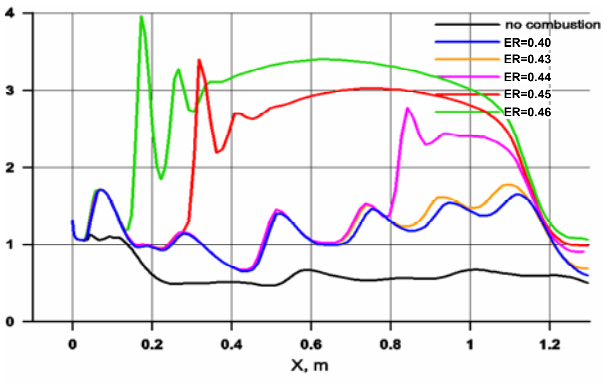


Fig. 9. Pressure distribution along the duct wall for different ER value

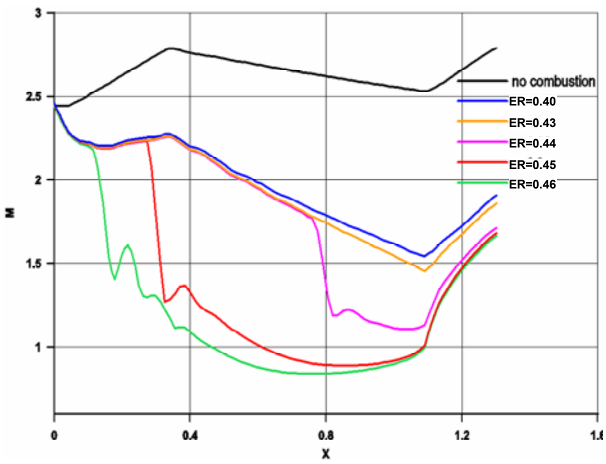


Fig. 10. Averaged over cross-section Mach number as function of longitudinal direction for different ER value

that different types of pressure distributions are obtained in this case. Some of them correspond to equivalent 1D supersonic flow and some to transition from supersonic to subsonic one with inverse transition to supersonic conditions at the entrance to expanding exit duct section. This fact is illustrated by the data in fig.10, where the averaged over cross-section Mach number is shown as function of longitudinal coordinate. Some regimes are transient. For example, it is difficult task to interpret the regime corresponding to ER=0.44 as subsonic or supersonic using the pressure distribution along the wall and 1D flow model with heat release.

It is necessary to note that these results are in qualitative agreement with experimental results as to the regime change with relative heat release rise. At some conditions, when transition to subsonic conditions inside the duct takes place, the maximal pressure rise with increase of the heat release does not change seriously. However, the length of the region with pressure rise increases and the head of this structure shifts in upstream direction with head stabilization in the expanding combustor section.

It is possible to conclude that joint experimental and computational research allows to establish the correspondence between the typical wall pressure distribution and gas-dynamic flow structure in the duct at the combustion in the case of supersonic flow at the entrance.

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