Experimental and numerical analysis of hydrogen jet autoignition in backward-facing-step-stabilized model scramjet combustor

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1 Introduction

Nowadays, scramjets are extensively studied as space high-speed transportation engines [1]. One of the most important problems in the development of scramjet technologies is the management of fuel mixing and ignition at a supersonic flow velocity at the inlet of the combustion chamber. At flight speed M=8-12, the flow Mach numbers at the entrance to the combustion chamber vary in the range 2.5 to 4. At such velocities, the residence time of the mixture in the combustion chamber is about 1 msec, which, in combination with relatively low static pressure (~ 0.05 MPa) leads to a drastic complication of the task of ignition and stable combustion.

To achieve fast and effective mixing of fuel and air, different schemes of fuel supply into the combustion chamber are actively investigated [2]. Transverse fuel supply from channel walls before the channel expansion is a simple and promising configuration to provide good penetration and mixing. From the other hand, such a scheme is accompanied by large total pressure losses due to strong shocks and can lead to channel choking. Therefore, the task of finding the optimal multi-jet fuel supply scheme, ensuring an efficient mixture of fuel and oxidant with the minimum loss of pressure is an actual task. The significant amount of studies has been done on jet interactions with supersonic crossflow, nevertheless the most of them is focused on the behavior of isolated jets.

Among other fuels, hydrogen has the desired ignition properties for supersonic combustion in a scramjet [3-5]. Due to the low temperature and incomplete mixing of fuel and air, there is a tendency for the flame to break. A backward facing step (BFS) and a cavity are often used as flame holder in supersonic flows [6-8]. The flow behind a BFS or inside a cavity is characterized by the presence of low-velocity recirculation zones, which increases the residence time of the mixture in the high-temperature region and forms a continuous source of mixture self-ignition.

In previous paper by the authors, various aspects of the scramjet-related process were investigated. The fundamentals of flows in a channel with a step and a cavity for various inlet Mach numbers were studied

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in [9, 10]. Injection of hydrogen and helium jets into variable-section channels under the conditions of a high-enthalpy turbulent flow was numerically simulated on the basis of two-dimensional RANS [11]. Verification of the computational technique is performed against available experimental results on jets injection in supersonic crossflow. Parametric studies show that an increase in the angle of inclination and the mass flow rate of the jet leads to an increase in the depth of jet penetration into the flow, but more intense separated flows and shock waves are observed in this case. The processes of ignition and flame stabilization for a hydrogen-air premixed mixture in a model combustor at supersonic flow velocities were studied numerically and experimentally in [12]. The influence of the configuration of the backward-facing step on the separation zone length, on the wave structure of the flow, and also on the process of ignition in the channel at the Mach number of 2.8 was considered. In recent papers [13, 14] the results of numerical and experimental investigations of hydrogen mixing and ignition processes in a supersonic combustion chamber with backward facing steps located on the channel walls are presented. The study deals with the investigation of a flow structure in the combustor taking into an account hydrogen multi-jet injection.

The present study is focused on determining the conditions for auto-ignition of hydrogen in the combustion chamber with the Mach number at the entrance equaled to 4. Another task consisted in determination the effective fuel supply model for auto-ignition, flame stabilization and prevention of the channel choking.

2 Experimental setup

The experimental investigations of reacting flows have been carried out in the impulse setup. As source of a high-enthalpy gas, the first prechamber of the hot-shot aerodynamic wind tunnel IT-302M [15] with a working time of 80 ÷ 150 ms was used. Peculiarity of this wind tunnel is that during the operation mode, the total pressure and total temperature are decreasing while Mach number remains constant.

The experimental model (Figure 1) consists of a profiled nozzle, isolator for flow stabilization and channel for modeling reacting flows, including multi-injector section with the BFS of $h = 25$ mm height and diverging section. On the upper and lower walls of the channel, the static pressure and heat flux gages are installed. The side walls of the working channel are equipped with the windows made of heat-resistance silica glass, which allows flow visualization.

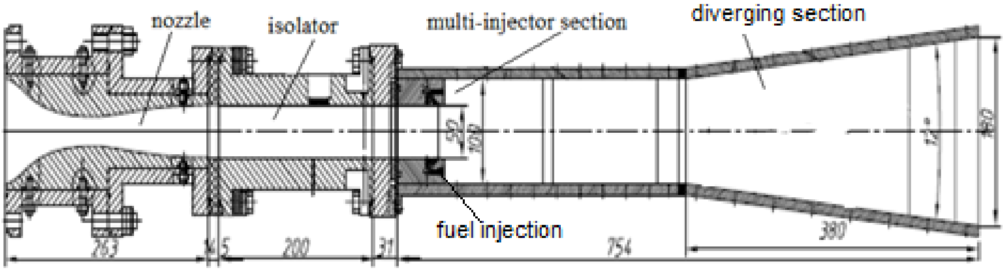


Figure 1. Scheme of experimental model

Model was tested at the following conditions at the combustor entrance: Mach number M_∞=3.83, total temperature $T0_\infty$=1500K ÷ 2400K, static pressure P_∞= 0.06÷0.25 MPa. Sonic hydrogen jets are supplied from eight orifices located on the bottom and top walls of the multi-injector section before the BFS. The diameter of the orifices is 2.8 mm, and the injection angles are 45^O and 90^O. The total pressure of jet supply $P0_j$ varies in the range of 2.2 ÷6.4 MPa that leads to changing of the fuel-air equivalence ratio (CE).

3 Numerical algorithm

The numerical 3D simulations are performed using the URANS-based approach closed by the $k-\omega$ SST turbulence model. Calculations are carried out with ANSYS CFD Fluent. The density-based solver is used, widely applied for modeling high-speed compressible flows. For modeling of hydrogen combustion, a detailed kinetic scheme [16] is implemented with 38 reactions for 8 species: H_2, O_2, H_2O, OH, H, O, HO_2, H_2O_2. Comparison of experimental and numerical data have shown [17], that this kinetic scheme correctly predicts the ignition delay time in the temperature range of $1000 < T < 2500K$.

Due to the symmetry of the problem, only quarter of the experimental channel is modeled. In the computations, the origin is set at the intersection of the external edge of the BFS with the central vertical plane of symmetry. At the inlet section, the profiles of static pressure and temperature, Mach number and turbulent parameters, obtained from the precursor calculation of a flat profiled nozzle are given. The results of calculations have shown that the turbulent boundary layer thickness at the inlet of injection section was 11 mm that agrees with the experimental measurements. The pressure-outlet conditions are set at the outlet section. On the solid walls, the no-slip and cold wall T_w=300 K conditions are assigned. The details of the computational model can be found in [14].

A structured multi-block grid with about 3.5 mio quadrilateral cells is constructed in the computational domain. Grid has the refinement toward the solid surfaces. During the calculations, the grid adaptation by y^+ values, density and temperature gradients is carried out, and the final grid has about 5.5 mio cells. The grid independence study is performed for the cold flow case for three meshes of different density, and the results are compared between themselves and with the experimental data on static pressure distributions on the wall as well. The presented simulation results are obtained on a medium-size grid contained about 5.5 mio cells.

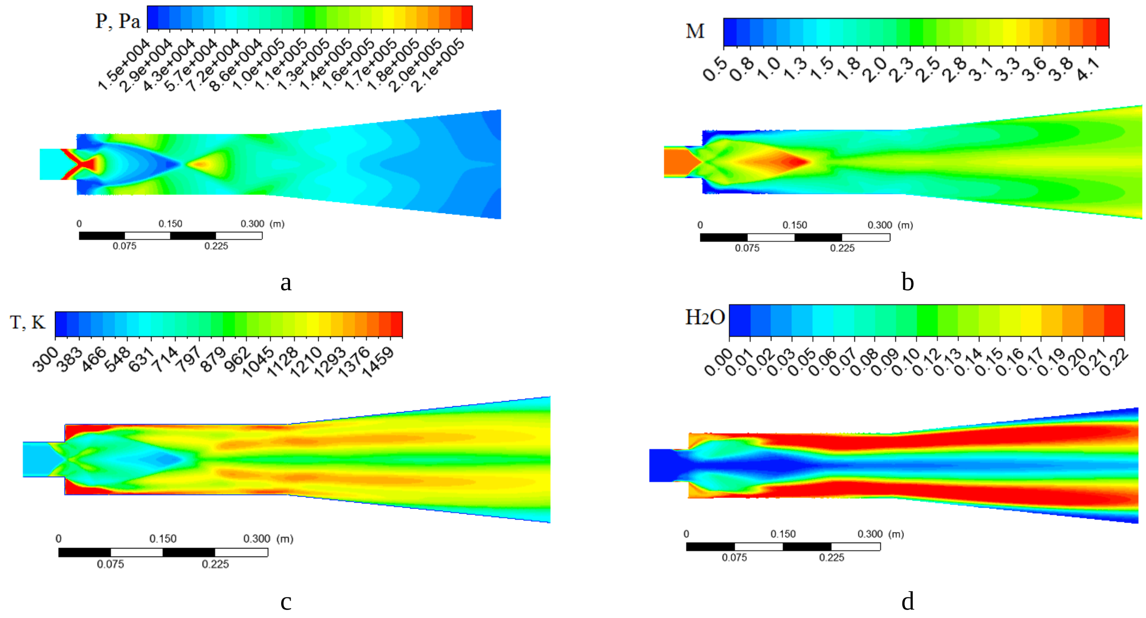
4 Results and discussions

The experiments are focused on studying the mechanism of auto-ignition and effective control of the combustion process. It is shown that combustion stabilization process is realized in three stages. The first stage with small pressure increase corresponds to local combustion in the separation zones formed at the channel walls due to action of jet-induced shocks reflected from the opposite wall. At the second stage, intensive combustion and pressure increase over all combustion chamber is observed owing to flame propagation upstream and essential expansion of near-wall burning layer which thickness exceeds a thickness of a boundary layer and BFS height. The increase in a heat release leads to an intensification of mixing and the further upstream flame propagation. The third stage of process is characterized by steady combustion and high level of pressure in all the combustion chamber while the flow core remains supersonic. The recirculation area behind the backward facing step is not a flame holder and, especially, its source. Rather, the role of this area is mostly to prevent the transmission of disturbances upstream (into the isolator) and choking the channel.

As a result of the performed experimental investigations, two scenarios for the development of the hydrogen ignition process have been found, without and with channel choking [13]. These are confirmed by measurements of pressure, heat fluxes, shadow visualization of the flow structure and registration of flame propagation in the channel. To evaluate independently the effect of various parameters on the mixture auto-ignition, the intensity of burning and the channel choking, for each injection angle, CE is varied from 0.51 to 1.1. It is found that when the fuel is supplied at 90^O angle, a mode with channel choking is realized at some late moment of the experimental run in the entire range of CE, whereas in a case of 45^O injection, a regime of supersonic combustion during the whole run is achieved by reducing the CE value.

Two cases corresponding to different angles of hydrogen supply are selected for numerical analysis, which are discussed below. Computations are carried out at M_∞=3.83 under the flow parameters chosen within the experimental range and correspond to some moment of the experimental runs. The first case is for the hydrogen injection angle 90^o with channel total pressure $P0_\infty$=8.83 MPa, total temperature $T0_\infty$= 1900K and CE=0.8. The second case is for the injection angle of 45^o, $P0_\infty$=8.5 MPa, $T0_\infty$= 2100K and CE=0.6. As it was already mentioned, in all the performed experiments with the 90^o injection scheme, the channel choking is observed at some time moment. The inlet data for the case 1 correspond to some early time moment at which the channel choking шs not occurred yet.

Numerical simulation helps us to investigate in detail the structure of the flow and the ignition processes that occur in the combustion chamber. In Figures 2, 3 the results of computations are shown in the symmetry plane for the case 1 (Fig. 2) and case 2 (Fig. 3). The static pressure field (Fig. 2, a) shows the wave structure in the channel. The shock associated with jet injection exists in a short part of the channel and then it disappears due to the interaction with the expansion fan and a low-density recirculation zone after the BFS. Further increase of pressure is associated with the tail shock formed at the reattachment zone. The next pressure rise is due to the action of the tail shock that comes from the opposite wall. The Mach number field (Fig. 2, b) shows the three layer flow pattern at the outlet with a high speed flow ($M \approx 3$) in the near-wall and central regions and two combustion zones with $M \approx 2.5$ flow. The combustion occupies the whole recirculation zone and then it weakens due to the action of the expansion fan.



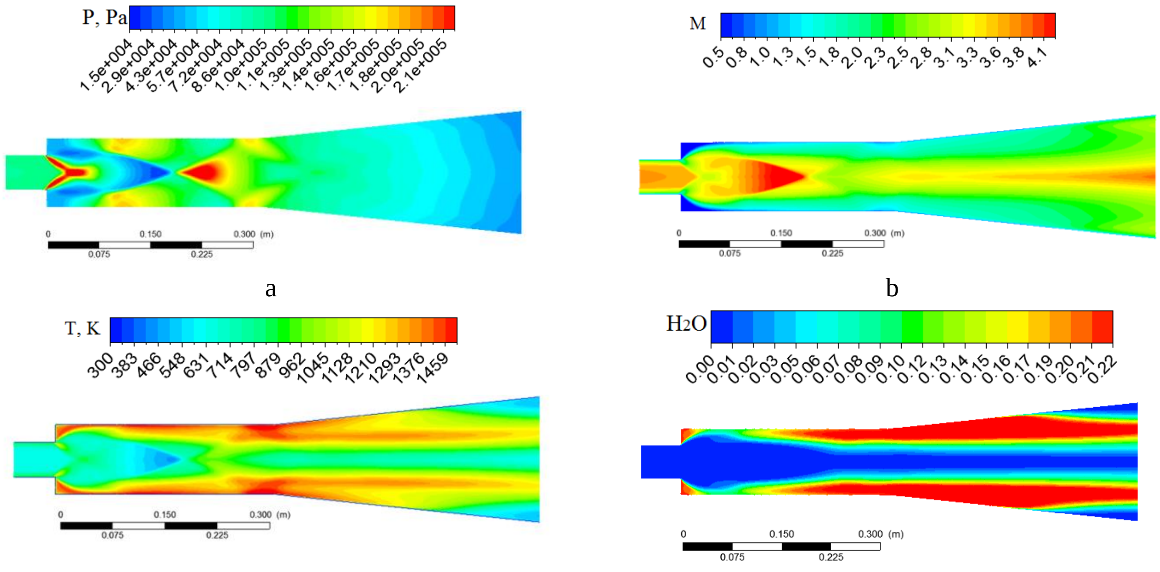
a b

c d

Figure 2. Computed fields of static pressure (a), Mach number (b), static temperature (c) and mass fractions of H_2O (d) for $\alpha = 90°$, $\beta = 0.8$

The pressure field for the case 2 (Fig. 3, a) shows that the flow structure does not change significantly in the constant area section at decreasing the jet injection angle. The local combustion is observed in the recirculation zone after BFS. The combustion intensification occurs behind the tail shock, and then the combustion spreads along the channel walls. Low temperature and absence of H_2O in the center of the channel testifies to the absence of the combustion in this region. In the diverging part of channel, the zones of combustion are detached from the walls near the outlet (Fig. 3, d).

Figure 4 presents the experimental and computed pressure distributions along the walls in the symmetry plane. Despite the qualitative agreement, in both cases, the pressure level is overpredicted in the computations at 0.1 m < x < 0.2 m. Besides the turbulence modeling issues, the possible reason for this disagreement is the steady-state approach and the constant inlet parameters used in the computations while in the experiments, the main flow parameters are changing during the run, and the transient behavior of the flow structure and combustion process have been revealed.



a b

c d

Figure 3. Computed fields of static pressure (a), Mach number (b), static temperature (c) and mass fractions of H2O (d) for $\alpha = 45°$

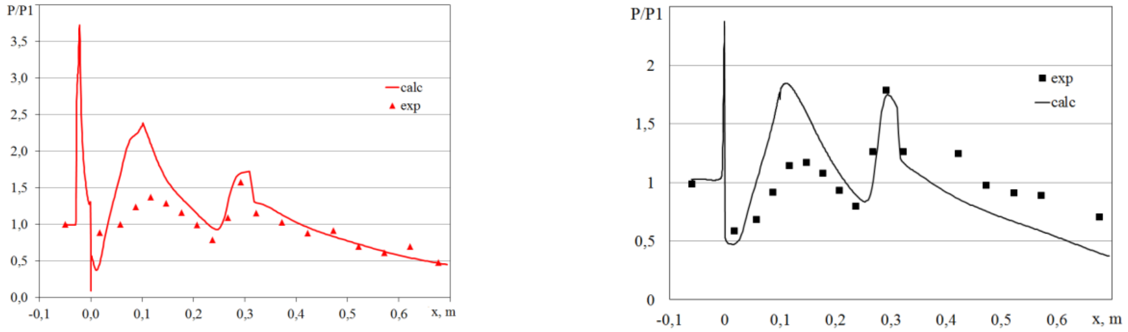


Figure 4. Relative static pressure distributions along the wall for $\alpha = 90°$ (left) and $\alpha = 45°$ (right)

Generally, the computations confirm the observations of the experiment. Combustion in the near-wall region has a determining effect on the flame holding and flame propagation through the entire channel up to BFS. It is shown that a change of the fuel injection pressure and angle of injection can be an effective means of controlling the position of the initiation of combustion and its intensity, as well as by method of preventing the transition to subsonic combustion and to choking of channel. The further computational work will be aimed on the implementation of the transient simulation and using the advanced turbulence approach as well.

Acknowledgments

The work was supported by the Russian Foundation for Basic Research, Grant №17-08-01158 A).

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