Influence of the relative momentum flux ratio on the mixing of hydrogen jets in an M=4 crossflow

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Abstract. The paper presents the results of numerical simulation of the 3D flows in a plane channel with the abrupt expansion. Sonic hydrogen jets are supplied from two circle orifices located opposite each other on the channel walls before the backward-facing step. The numerical simulations are carried out under the conditions of experiments performed at the hot-shot wind tunnel IT-302M ITAM SB RAS for the following flow parameters: Mach number at the entrance of the channel $M = 3.8$, the total temperature $T_0 = 1715$ K, and the total pressure $P_0 = 6.5$ MPa. Calculations were performed with a change in the jet supply pressure from 0.4 to 3.6 MPa, which ensures the variation in the jet-to-crossflow momentum flux ratio in the range of $J = 0.7 \div 6$. Mathematical modeling was performed in ANSYS Fluent based on the Reynolds-Averaged Navier-Stokes equations supplemented by the $k-\omega$ SST turbulence model. A comparison of the calculated and experimental data on the flow structure, as well as the static pressure distributions on the walls, indicates a satisfactory agreement. The calculated results made it possible to obtain a clearer understanding of the 3D flow structure in the channel and reveal the influence of the injection pressure on the level of mixing.

1. Introduction
Hydrogen is currently considered as one of the most suitable fuels for aircraft, since it is highly flammable, and has good net calorific value. Besides, it is widespread, and the process of burning is environmentally friendly [1]. One promising application of hydrogen fuel is hypersonic propulsion systems. Great efforts were made during the last decades to study the hydrogen jets supplying into supersonic crossflow both experimentally [2, 3] and numerically [4–12].

Transverse jet injection is significantly improving mixing [13]. The main parameter affecting the penetration depth of the jets into the transverse supersonic flow and the mixing of primary and injected gases is the jet-to-crossflow momentum flux ratio $J = (\rho U^2)_j / U^2 = (\gamma p M^2)_j / (\gamma p M^2)_f$.

Most researches were done for injection into open space for flows at moderately high Mach numbers $M = 1.0 \div 2.5$. Information on these studies is provided in extensive reviews containing data on the flow structure in the jet interaction region with the main flow [14]. At the same time, there is a more pressing problem of mixing intensification at Mach numbers at the combustion chamber inlet exceeding $M = 3$, for which only a few studies are known [15]. It should be noted that the flow pattern is substantially complicated in the presence of the channel walls, steps, and cavities, as well as in the case of multi-jet injection [16].

In previous papers by the authors [17–19], 2D and 3D numerical investigations of supersonic flows in channels with jet injections were performed employing in-house code and ANSYS Fluent on the
RANS-based approach. Computational results were compared with the experimental data of several authors. The results of calculations for 2D turbulent supersonic flows in channels have shown good agreement with the experimental data [17]. Several aspects of 3D flows were examined in [18, 19], namely, the effect of the jet injection angle on the flow structure and parameters behind the backward-facing step, control of mixture parameters in the channel, reduction of pressure losses; etc.

The current work presents the results of the comprehensive calculation and experimental study of the interaction of hydrogen jets with supersonic (M=3.84) crossflow. The numerical simulations are carried out under the conditions of experiments [20]. A feature of this work is the high Mach number and the stagnation parameters corresponding to the actual flight conditions. Experimental data verify the calculation results. The structure of 3D-dimensional non-reacting flows in a channel with the sudden expansion with transverse hydrogen injection is investigated. The degree of hydrogen mixing is evaluated lengthwise the combustion chamber in the wide $J$ range by computing the mass-averaged uniformity index of hydrogen mass fraction. These data are necessary to select the optimal fuel supply scheme for the scramjet combustion chamber.

2. Experimental setup and model

The experiments are performed at the hot-shot wind tunnel IT-302M ITAM SB RAS [21] in the connected pipeline mode. The channel consists of a supersonic nozzle, an insulator behind which the injection section is located with two backward-facing steps (BFS) of 25 mm height (Figure 1). Behind the injection section, there is the expanding part of 380 mm length with the walls inclined at 6° (not shown in the figure). Two injection orifices of 2.8 mm diameter are placed on the bottom and top walls of the channels with the centers located on the symmetry line 12.5 mm in front of the BFS.

The flow parameters are as follows: Mach number at the entrance of the injection section is $M=3.84$, the total temperature $T_0 = 1715$ K, and the total pressure $P_0 = 6.5$ MPa. Nitrogen was used as the main gas to prevent the hydrogen self-ignition. In the experiments, the static pressure distribution on the walls, and the flow rate of the primary and injected gases are measured. High-speed shadow visualization is used to determine the structure of the flow.

![Figure 1](image1.png)

Figure 1. Schematic diagram of the injection section of the experimental model: (a) front and (b) top view.

3. Mathematical models and numerical methods

Mathematical modeling is performed using ANSYS Fluent based on the Reynolds-Averaged Navier-Stokes equations for multicomponent gas mixture supplemented by the $k-\omega$ SST turbulence model. The 3D computational domain includes the injector part, the expanding duct, and takes into account the symmetry of the channel (Figure 2). The problem is computed in a steady-state approach using the density-based Fluent solver. The AUSM second-order scheme is used for the convective fluxes.

In the computational domain, the multiblock structured hexa-grid containing 6.5 million cells with a refinement to the channel walls is constructed. The adapted grid used in most of the computations consists of 10 million cells and provides the resolution of the laminar sublayer ($y^+ = 2 ÷ 5$). The grid convergence studies were performed for the case of the flow without jets [19].
On the solid walls, the no-slip velocity conditions and temperature of $T_w=300$ K are prescribed. The symmetry conditions are used on the side and top boundaries of the computational domain. At the inlet section, the profiles of the gas-dynamic and turbulent parameters are set, accounting for the boundary layer of 11 mm thickness on the walls. At the injection orifice, pressure far-field conditions are set with Mach number $M=1$, jet static temperature of 240 K, and various static pressure values. A series of calculations have been performed with multiple jet supply pressure varying from 0.4 to 3.6 MPa, which ensures the variation in the jet-to-freestream momentum flux ratio in the range of $J = 0.7 \div 6$.

4. Results and discussions

The flow structure in the channel with the injection can be restored by scanning the pressure fields at the boundaries of the computational domain. Figure 3 shows that the flow pattern is three-dimensional and differs significantly in the longitudinal sections.

In the front symmetry plane (Fig. 3, c), in which the center of the injection orifice is located, a $\lambda$-configuration of shock waves is observed, formed by the bow and separation shocks. The horseshoe-shaped trace of the bow shock can be seen on the upper symmetry plane (Fig. 3, b) and the bottom wall (Fig. 3, d). On the sidewall (Fig. 3, a), the bow shock is revealed as a local increase in pressure near the top symmetry plane. The bow shock reflected from the top symmetry plane interacts with a hydrogen jet, and the shock wave is reflected from the low-density mixing layer by the rarefaction wave (Fig. 3, c). Therefore, the high-pressure region formed by the jet does not extend into the channel part behind the BFS. An increase in pressure behind the BFS is associated with the formation of a tail shock closing the separation region. Further, a system of compression and rarefaction waves is observed, which propagates downstream and reflects from the channel walls.

For validation, the results of calculations and experiments are compared by the flow structure and the distribution of static pressure on the channel walls. In Figure 4, the calculated and experimental schlieren patterns are analyzed in the vicinity of injection for the cases $J = 3$ and 6. The flow is from left to right. The numerical schlieren is constructed by averaging the density gradient fields in three longitudinal sections.

The jet injected into the supersonic transverse flow generates a complex shock-wave and vortex structure described in many papers [2, 14-16]. The red lines in the experimental pictures show the bow shock waves generated by the jet injections from the upper and lower walls of the channel. The blue lines mark a barrel-shaped structure, which is typical for an underexpanded jet. Similar structures in the calculated picture are visible. The inclination of the shock waves coincides, as well as the shape and position of the "barrels." The figure shows that with $J$ increasing, the wave structure shifts upstream, and the size of the "barrels" increases, which is consistent with the data [20].

Figure 2. Computational domain and boundary zones.

Inlet, outlet, injection orifice, top symmetry plane, bottom wall, front symmetry plane.
Figure 3. Computed pressure fields for the $J=6$ case at the boundaries of the computational domain: (a) back wall; (b) top symmetry plane, (c) front symmetry plane, and (d) bottom wall.

Figure 4. Computed (top) and experimental (bottom) schlieren pictures for $J = 3$ (a) and 6 (b).
A quantitative comparison of the experimental and numerical data is presented in Figs. 5, 6. Figure 5 shows the experimental and calculated normalized pressure distributions along the bottom wall behind the BFS \((x = 0)\). Figure 6 displays the maximum and minimum values of the normalized static pressure on the walls versus \(J\).

In the absence of jets, the graph shows typical pressure behavior behind the BFS, namely, a sharp decrease in pressure in the base region and pressure recovery in the tail shock closing the recirculation region. The pressure decrease at \(x > 0.2\) m is associated with the arrival of the rarefaction wave generated as a result of bow shock interaction with the jet supplied from the opposite wall, and the pressure increase at \(x > 0.4\) occurs under the influence of the tail shock. The action of the jets manifests itself in an increase in the base pressure, a slight increase in the pressure maximum in the tail shock, and the upstream shift of the system of compression and rarefaction waves. An additional local pressure maximum in the expanding part of the channel is due to the action of the head shock reflected from the sidewall of the channel (Fig. 3, d). The calculations correctly reproduce the growth trend of the maximum and minimum pressure values with increasing \(J\), although the maxima are underpredicted in the calculations by 5–8%.

**Figure 5.** Computed (lines) and experimental (symbols) static pressure distributions along the central line on the bottom wall.

Calculations provide data on the concentration of hydrogen over the entire channel, which is not available in the experiment. Figure 7 shows the fields of mass concentration of hydrogen (in logarithmic scale) in the symmetry plane and bottom wall for \(J = 6\). At this highest studied value of \(J\), the jet penetrates high and reaches the upper plane of symmetry. Nonzero values of hydrogen concentration are visible in the separation region before the jet, and in the separation region after the BFS.

After reflection from the upper symmetry plane, the jet descends to the bottom wall, then rises again and spreads downstream while expanding. In the front symmetry plane, the distribution of hydrogen concentration near the exit is quite uniform, however low values of hydrogen concentration are observed in the internal angle region between the channel walls (Fig. 7, b).

To evaluate the degree of mixing of hydrogen with nitrogen, a mass-average uniformity index \(\gamma_m\):

\[
\bar{\phi}_m = \frac{\sum_i \phi_i |\rho_i U_i|}{\sum_i |\rho_i U_i|}, \quad \gamma_m = 1 - \frac{\sum_i (|\phi_i - \bar{\phi}_m|) |\rho_i U_i|}{2 |\bar{\phi}_m| \sum_i |\rho_i U_i|}
\]

is calculated in several cross-sections along the channel. Here \(\phi_i\) is the H\(_2\) mass concentration in an \(i\)-th cell; \(\rho_i U_i\) is the mass flow rate through the section of \(i\)-th cell; \(A_i\) stands for a cross-sectional area of the cell, and \(\bar{\phi}_m\) is the mass-average H\(_2\) mass concentration.

In Figure 8, the plots of the hydrogen uniformity index along the channel are presented for various \(J\) values, which show that with \(J\) increasing, the degree of gas mixing is also rising. Nevertheless, the degree of mixing is somewhat low even for the highest \(J\) value studied, and the uniformity index is
significantly smaller than that for the argon jets at the same $J$ [22]. The insufficient degree of mixing and the presence of regions with low hydrogen concentrations can be explained by the fact that in this model problem, only one injection orifice is located along the channel width. In actual combustion chamber configurations, the degree of mixing is increased with the aid of multi-injection schemes [14].

**Figure 7.** Computed H$_2$ mass fraction fields for $J = 6$ at the front symmetry plane (a) and the bottom wall (b).

**Figure 8.** Computed mass-weighted H$_2$ uniformity index along the channel for various $J$.

**Conclusions**
The comprehensive calculation and experimental study of the non-reactive supersonic (M=3.84) flow in a channel interacted with transversal hydrogen jets is presented for a wide range of the jet-to-crossflow momentum flux ratio. The calculation results are verified by experimental data of the flow structure in the vicinity of injection and static pressure distributions on the wall. The calculations correctly reproduce the growth trend of the maximum and minimum pressure values with increasing $J$, although the maxima are underpredicted in the calculations by 5 – 8%. The degree of hydrogen mixing is evaluated lengthwise in the combusting chamber by computing the mass-averaged uniformity index of hydrogen mass fraction. The data on hydrogen concentration in the channel is obtained, which is necessary to select the optimal fuel supply scheme for the scramjet combustion chamber.
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