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Control of transsonic combustion of the hydrocarbon fuel by means of hydrogen and air side jets

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Received January 18, 2024
Revised March 14, 2024
Accepted March 19, 2024

The present numerical study deals with a possibility of ensuring hydrocarbon fuel combustion in a high-speed flow in a short axisymmetric channel by means of hydrogen and air side (annular) jets eliminating shock waves, which are the main source of total pressure losses. The Reynolds-averaged Navier−Stokes equations with the $(k-\varepsilon)$ turbulence model are solved. A stable transonic mode is obtained in the first section. A pulsating mode of hydrogen burning with destruction of the shock wave structure of the flow is obtained in the second section. The physical mechanisms of the observed processes are studied.

Keywords: hydrocarbon fuel, hydrogen, combustion, throttle jet, transonic mode.

DOI: 10.61011/TPL.2024.07.58715.19867

Various methods are proposed to ensure combustion in a high-speed flow localized in a channel with a variable cross-section (see, e.g., [1–3]). The method proposed in [4,5] allows one to solve simultaneously such problems as minimizing of the stagnation pressure losses and mixing of the fuel mixture followed by its ignition. This method is based on the principle of minimization of entropy increasing during the combustion process. According to this principle, when fuel burning takes place in the first part of the channel with a constant cross section, the flow initially characterized by the Mach number $M > 1$ should be decelerated to a value corresponding to the velocity of sound and preserve this value when burning arises in the expanding part of the channel. The first stage was realized in the experiments [5] by using a package of heat-gas-dynamic pulses and the second fuel supply line in front of the channel expansion. A transonic combustion mode in the first section was obtained in the calculations [6]. Nonlinear effects of impulse energy sources acting on the external flow around bodies were also revealed in [7]. These effects ensured fuel ignition in short channels [6]. This paper deals with problems related to fuel supply in front of the channel expansion, such as combustion of this fuel, control of this process, and its influence on the transonic mode in the narrow part of the channel. The great difference in the molecule weights of the gas in the main flow and the fuel supplied as an annular jet is a key point.

The problem is solved in an axisymmetric formulation. The channel consists of the nozzle block with an axial fuel injector and two sections characterized by almost the same length and the diameter ratio $d_2/d_1 = 1.8$. The high-speed flow in the first section is generated by the Laval nozzle with the following parameters in the prechamber: pressure $p_0 = 0.7\,\text{MPa}$ and temperature of $1700\,\text{K}$ (the static pressure in the flow is $p = 0.065\,\text{MPa}$). Then the fuel characterized by the effective chemical formula $C_{12}H_{23}$ is supplied through the axial injector. The process in the channel is controlled by means of jets injected through an annular gap (hereinafter referred to as the side jets): gas-dynamic impulses (GIs), which are supplied in the first section of the channel at a point localized at a distance of one fifth of the length from the end of this section, as well as additional fuel (hydrogen or $C_{12}H_{23}$) supplied near the end of the first section, and air supply in the second section. The fuel supplied along the axis does not burn without throttling of the flow. Gas-dynamic impulses, which are pulsating air jets with the amplitude of $0.4-0.6\,\text{MPa}$, are supplied for fuel ignition. Three impulses are sufficient for development of intensive burning. The static pressure behind the combustion front reaches $0.2-0.25\,\text{MPa}$. The fuel amount is determined from the requirement to form a transonic mode. As was shown in [6], by using GIs, the entire amount of the fuel can be burned in the first section. However, not all the oxygen in the channel is consumed. Then side supply of hydrogen or the $C_{12}H_{23}$ fuel at a pressure of $0.3\,\text{MPa}$ and temperature of $300\,\text{K}$ is ensured directly in front of the second section. Further, an air jet in the second section is used to control the combustion process. The pictures with parameter distributions presented below provide an idea about the model scheme. The x and y coordinates, as well as all sizes of the model are normalized to the doubled length of the first section. The 2D unsteady Reynolds-averaged Navier−Stokes equations with the $k-\varepsilon$ turbulence model, simplified chemical kinetics, and ideal-gas model for the mixture components are solved similar to that done in [6]. The stagnation pressure and temperature as well as the static pressure are set at the inlets to the fuel injectors and branch pipes. An explicit scheme with the time step constrained according to the threshold value of the Courant

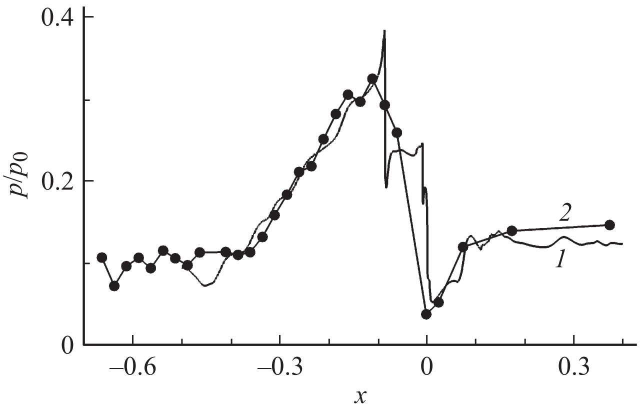

Figure 1. Comparison between the calculated (*1*) and experimental (*2*) pressure distributions alone the channel wall.

number of 0.9 as well as the AUSM scheme [8] with the MUSCL-reconstruction of third order for the convective streams are used in the calculations. The cells of the computational grid are shaped as quadrangles. The ratio between maximum and minimum step lengths is 64, and the total number of cells is equal to 810 000. The grid is refined near the jets and the channel walls. The calculations were first performed for the experimental conditions [5] to verify the computational model used. The dimensionless pressure distributions along the channel wall are compared in Fig. 1. The calculated data (curve *1*) are averaged according to the algorithm [6]. The vertices of the broken line 2 correspond to the experimental data.

The calculation results in the case with hydrogen supply before the beginning of flow throttling in the second section are presented in Fig. 2. The pressure along the channel wall as a function of the axial coordinate x and the system of isolines for the quasi-steady pressure field with the Mach number isoline of $\mathrm{M} = 1$ (bold line) on the background the distributions of the H_2O mass fraction distributions are presented in Fig. 2, *a*. Two isolines with the Mach number $\mathrm{M} = 1$ start from the narrow section. The Mach number in the region between them satisfies the condition $\mathrm{M} > 1$. A rarefaction wave caused by the flow around the step makes the accelerating flow turn to the wall of the second section. An oblique shock wave is formed in the flow characterized by uniform physical properties under the condition of its reflection from the wall. The flow downstream from this shock wave has a direction parallel to the wall. In the problem solved, the flow in the rarefaction wave interacts with the layer of hydrogen whose molecular weight is smaller than that of air by an order of magnitude; as a consequence, the velocity of sound is significantly greater. The flow downstream from the step turns to the direction parallel to the wall in the layer containing hydrogen and its combustion products where the Mach number $\mathrm{M} < 1$, and no shock wave is formed. Meanwhile, a considerable mass of air and $C_{12}H_{23}$ combustion products move with the Mach number $\mathrm{M} > 1$ from the first section without contacting this layer. This flow decelerates in the hanging shock wave reflecting from the axis of symmetry. The pressure increases behind this shock wave. The pressure becomes more uniform in the subsonic layer near the wall: isolines 4-7 located above the Mach shock configuration are almost perpendicular to the wall (Fig. 2, *a*). As a result, the pressure in the vorticity zone behind the step increases, as can be seen from Fig. 2, *a* (upper fragment), where the dimensionless pressures p/p_0 on the wall are compared for different cases: after the GIs action and then after the side supply of H_2 or $C_{12}H_{23}$ (curves *1*–*3*, respectively). The channel expansion is located at $x = 0.5$. An abrupt pressure drop at $x \approx 0.49$ corresponds to the position behind the fuel jet; the top and bottom segments of the curves correspond to the side walls of the first and second channel sections, respectively. The pressure on the wall behind the channel expansion becomes significantly lower (by an order of magnitude). However, the pressure is greater more than twice in the case with hydrogen supply (curve *2*) as compared to the case without hydrogen supply (curve *1*).

The same result was obtained in the experiment [5] (little circles on the curves). This effect provides a possibility of using hydrogen supply in front of the step to hold the transonic mode in the narrow section after GI interruption. The values of the pressure in curves *1* and *3* behind the step are practically the same, which suggests that side supply of the heavy $C_{12}H_{23}$ fuel is ineffective. In the calculations, the amount of burned hydrogen is below 7% and practically does not affect the pressure field. The fuel combustion completeness is determined by the amount of the oxidizer and by the degree of mixing with it. The H_2 mass fraction with isolines of the absolute values of flow vorticity ω is shown in Fig. 2, *b*. The jet of supplied hydrogen spreads along the wall after its fragmentation. Almost all hydrogen enters the region with large values of vorticity. However, this subsonic region without abrupt changes in structure contain practically no O_2, and so H_2 does not burn.

In the subsequent calculations, a jet of compressed air is supplied to the second section to improve hydrogen combustion. The results for the pressure $p = 0.2\,\mathrm{MPa}$ and temperature $T = 300\,\mathrm{K}$ (cold stream) are presented in Fig. 3. There are obvious changes in the flow structure. A turbulent vortex sheet is shed from the step when this jet is supplied. Vortex clots break away from its end due to its instability. These vortex structures are shown by the isolines of the absolute values of vorticity $\omega = 0.05$ and $0.1\,\mathrm{MHz}$ on the background of the mass fraction of hydrogen in Fig. 3, *a*. The amount of hydrogen has decreased significantly, as can be seen from the comparison with Fig. 2, *b*. The character of the vorticity distribution in the case of side air jet supply changes significantly: powerful vortex structures are formed. The distribution of hydrogen with forming clots (spots) is a result of their formation. A pulsating mode of hydrogen combustion arises in the second section. The calculation shows that approximately 50% of the hydrogen flow rate

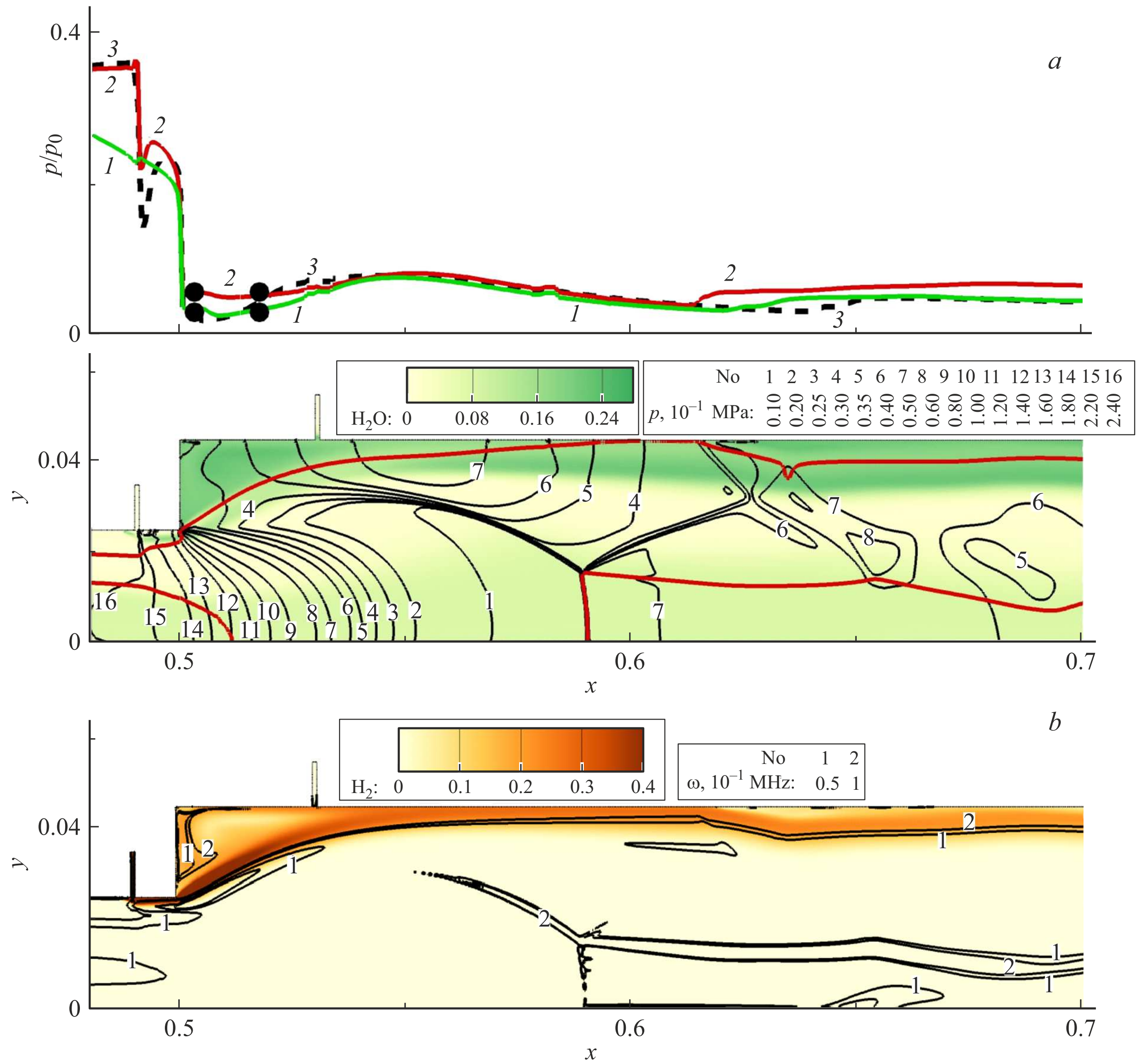

Figure 2. a) The bottom fragment shows the pressure isoline p and the Mach number isoline $M = 1$ on the background of the distribution of the H_2O mass fraction (the color palette of the mass fraction of H_2O and the pressure values for isolines 1–16 are shown above the solution domain); the top fragment shows the dimensionless pressures p/p_0 along the wall (*1* — before side fuel supply, *2* — during H_2 supply, and *3* — during $C_{12}H_{23}$ supply; the dots on curves *1* and *2* correspond to the experiment [5]); b) — field of the H_2 mass fraction with flow vorticity isolines.

burn down. Oxygen contained in the jet has been almost completely used, and oxygen leaving the first section is partially used (it can be seen from Fig. 3, *b*, which shows the field of the mass fraction of O_2 with the Mach number isolines). It can be seen that oxygen is localized only in the annular region up to the end of the channel. When the jet supply pressure is doubled, 63% of hydrogen burn down. Jet heating up to the 1000 K at the pressure 0.2 MPa results in reduction of the O_2 amount in it, disappearance of the pulsating mode, and reduction of the hydrogen combustion fraction.

The pressure in the vorticity region behind the step increases considerably under the action of the throttling jet. As a result, the combustion front in the first section is shifted to the axial injector. An important consequence is the destruction of the shock waves arising during the outflow from the first section to the second one (Fig. 2). The loss of the stagnation pressure occurs precisely in these shock waves. The resultant distributions of the Mach number and static pressure are shown in Fig. 3, *b* and *c*. The first of these figures shows that the transonic mode is preserved, and the second one (like Fig. 3, *a*) shows the destruction of the Mach structure of the shock waves. Combustion failure is not revealed in the first section in the case with additional air supply (the combustion front has approached the axial injector and stopped). The pressure isolines plotted on the

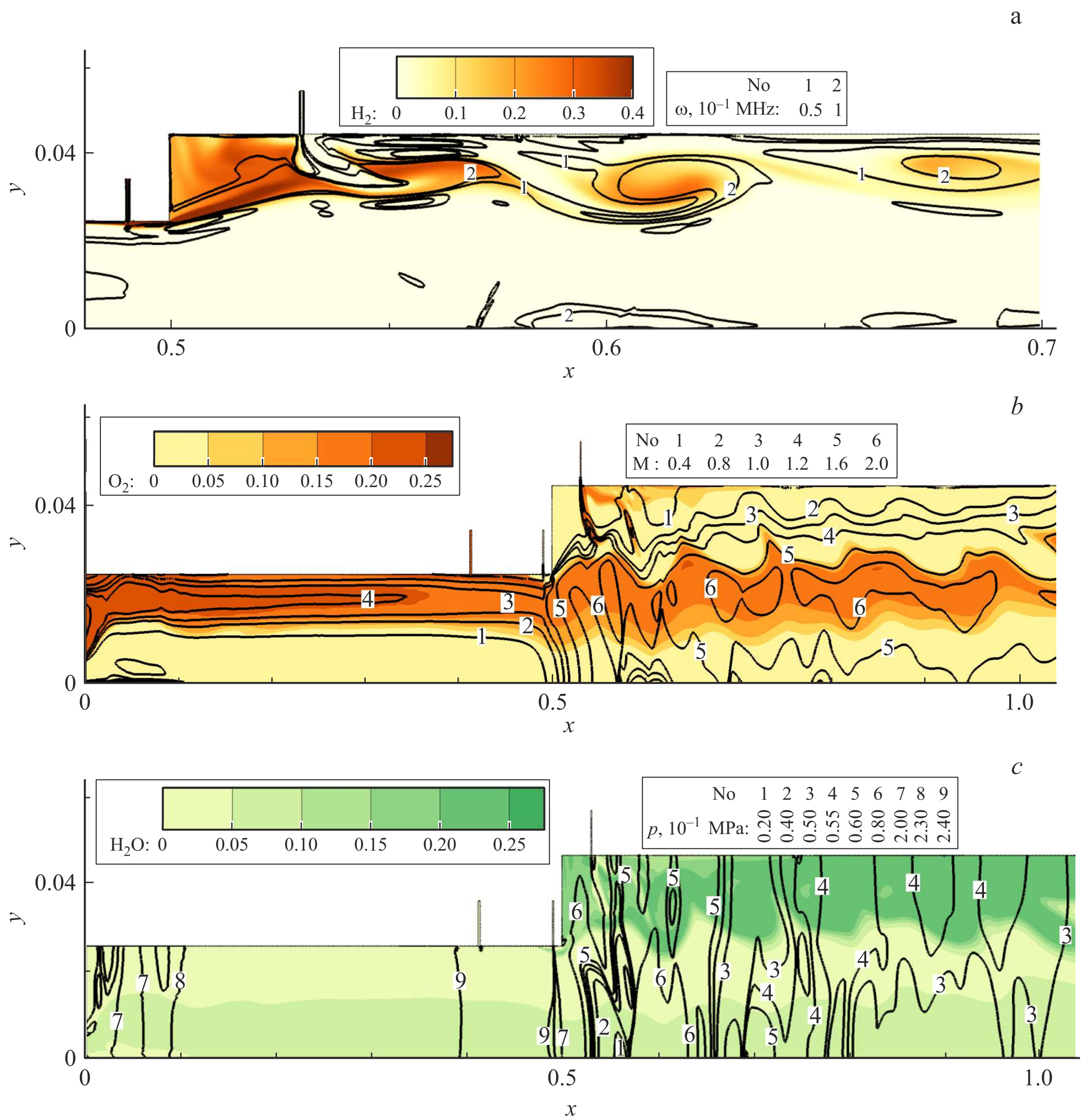

Figure 3. Fragment of the field of the H_2 mass fraction with isolines of the flow vorticity (a), field of the O_2 mass fraction with a system of isolines of the Mach numbers (b) and of H_2O with static pressure isolines (c) under the condition of side supply of H_2 with flow throttling taken into consideration.

field of the mass fraction of water vapor are presented in Fig. 3. The H_2O region has increased as compared to Fig. 2, which is due to more complete combustion of H_2.

Thus, it is numerically demonstrated that side hydrogen supply localized at the place of sudden expansion of the channel makes it possible to maintain the transonic combustion mode of the hydrocarbon fuel in the narrow part of the channel with a constant cross section, which is important for solving the problem of minimizing stagnation pressure losses. It is found that using a side jet of compressed air makes it possible to destroy the shock-wave structure of the flow behind the channel expansion, which is also important for total pressure loss reduction. The reason for these effects is established: it is the large difference in the molecular weights of the fuel (hydrogen) and oxidizer (air). A pulsating combustion mode of hydrogen supplied through a side injector ahead of the channel expansion is detected.

Funding

This study was carried out under the state assignment of the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences.

Conflict of interest

The authors declare that they have no conflict of interest.

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