Choice of boundary conditions at the unsteady modeling of jets flowing into the supersonic flow

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Abstract. Numerical simulation of ignition of the gas mixture not mixed previously in the supersonic flow localized in a channel was performed. The ignition is initiated by the shock wave from the throttling jet, which results in significant changing of pressure difference between the main flow and the gas generator of the throttling jet. It is shown that applying boundary conditions similar to the breakdown of arbitrary discontinuity conditions, makes it possible to obtain the transonic mode observed in the experiment. The near-wall and axisymmetric supply of the gaseous fuel was considered.

1. Introduction

The application area of jets controlling supersonic flows is continuously expanding [1-14]. In particular, the throttling jet can operate similarly to a solid-state ledge under a sufficiently high pressure drop. This contributes to the formation of vortex zones, where ignition and combustion can occur. Using a throttling jet of compressed air to intensify the combustion in the ramjet combustion chamber when the fuel is supplied upstream was proposed in [1, 2]. However, as a result of the ignition of the mixture, the pressure near the jet slot can change so significantly that the outflow can become subsonic. In spite of this, the constant value of the inflow velocity of the jet is often used as a boundary condition in numerical modeling. It is supposed in numerical simulation [3] that the products of combustion flow from the reactor into the cavity with constant sonic velocity through the annular gap. The pressure in the reactor ranges from 0.5 to 2 MPa, in the cavity it is more than 0.1 MPa. In case of existing pressure drop, a question arises about the relevancy of using such a boundary condition at the jet inlet into the cavity.

When modeling the system similar to [1] by the authors [4] the constant value of the velocity in the throttling jet was also specified, despite the fact that the pressure increased sharply during ignition and subsequent combustion of the fuel. Therefore, the transonic mode which is observed in the experiments [1, 2] wasn’t formed, because despite a significant increase of pressure in the channel, the jet continued to flow at the constant speed. As a result, the flow became substantially subsonic.

In addition, the fuel not mixed previously supplied upstream of the throttling jet sometimes flows with a significantly lower pressure drop than between the throttling jet and the main stream. The
change in pressure drop as the result of ignition of the fuel can stop gas flowing. Thus, it becomes necessary to take this circumstance into account when choosing the boundary and initial conditions for the jets in case of significant pressure changes in the main flow. The use of constant stagnation pressure and temperature as a boundary condition for the jet [5, 6] allows us to obtain a greater variety of regimes and a flow pattern that is closer to reality. It is also shown that applying this boundary condition allows obtaining a numerically transonic regime.

The non-stationary numerical simulation of the system similar to [1, 2] for cases of near-wall and axisymmetric fuel supply were performed. It was shown that the use of boundary and initial conditions corresponding to the conditions of the breakdown of an arbitrary discontinuity conditions allows obtaining a flow structure in the channel that qualitatively coincides with the experimental one.

2. Time intervals and the dimension of problem.

The choice of the dimension of problem is determined by the objectives of the study and the duration of the simulated process.

The scheme of the experiment in [2] is given only for an axisymmetric channel; it is reproduced in Figure 1. However, the results are also presented for a similar planar channel with a length about 0.5 m with transverse dimensions of 3 and 4 cm. The Mach number of the unperturbed flow is \( M = 2 \). The ignition and combustion is initiated by gas-dynamic pulses (a stream of compressed air supplied periodically) created by a special generator (GI), see Figure 1. For an axisymmetric channel, hydrogen was supplied along the axis at the beginning of the expanding section; for a flat channel, the delivery method is not described. In case of energy impact in the section of constant cross section the structure of shock waves is formed, where hydrogen is burnt. The excess air coefficient is within 10 ÷ 11, the deceleration pressure is \( 7 \times 10^3 \) Pa, the stagnation temperature is 1700 K. As it is noted in [2], the gas-dynamic pulse frequency of 10 Hz is the threshold for the quasistationary gas-dynamic formation. When the frequency increases (to 20, 30 and 40 Hz) there is no significant change in the distribution of static pressure along the channel. The decrease in total pressure loss is confirmed by an experiment of recording the total pressure in the outlet section of the combustion chamber.

![Figure 1. The common scheme of fuel combustion [2].](image)

In the experiment [2] there are two time scales: the time for supplying one gas-dynamic jet pulse with duration of about ten milliseconds, and the period between two gas-dynamic jet pulses with a duration of at least 30 ms.

In numerical simulation at short time intervals, or in obtaining a stationary solution, as well as in the case when the geometry of the system allows creating a structured grid, 3D modeling is used [6-8]. A two-dimensional approximation is used [5, 9-13] at relatively large time intervals or due to difficulty to construct structured grids. The purpose of this study is a relatively large time interval, so a two-dimensional model is chosen.

3. The problem formulation

The studies were carried out for the flat and axisymmetric channels using non-stationary Reynolds-averaged Navier–Stokes equations with \( k-\omega \) SST or \( k-\varepsilon \) turbulence models, and simplified chemical
kinetics with one reaction. Numerical simulation was performed using the Ansys Fluent. Hydrogen-air and ethylene-air are considered as fuel mixtures not mixed previously. The Ansys Fluent values of the chemical constant values were used for modeling chemical reactions.

The Mach number of the supersonic undisturbed flow in the channel is $M = 2$. Fuel is supplied through a slot (rectangular shape for a flat channel and ring shape for an axisymmetric channel). The combustion of hydrogen-air mixtures in the flat channel with a temperature in the prechamber of 1000 K and 1700 K and ethylene-air mixtures in the axisymmetric channel with a temperature in the prechamber of 1700 K were investigated. In the case of hydrogen burning, the fuel is always supplied at subsonic rate. The velocity range for ethylene is constricted by subsonic and sound values. The pressure difference between the gas generator of the throttling jet and the main flow in the channel is selected in such a way, that when there is no burning in the channel, the flow rate is close to the velocity of sound. The combustion in the channel increases the pressure, as a result the pressure drop decreases, the outflow becomes subsonic. The total pressure in the prechamber for the main flow in all cases is 7 atm. For both of jets (throttling and gaseous fuel jets), the total and static pressure are set as the boundary conditions as in [5, 6]. In the gas generator for gaseous fuel in the case of hydrogen, the total pressure is 2 atm, for the case of ethylene it is 6 atm, in the gas generator of the throttling jet in both cases it is 4 atm, the stagnation temperature is 300 K. The characteristic dimensions of the channels are the following: the supersonic nozzle with Mach number $M = 2$ at the inlet; section length of constant section is about 10 calibers of critical cross section; for a section of constant cross section, the transverse size for a flat channel is 3 cm; for the axisymmetric diameter, it is 5 cm. The parameters of the simulated system approximately correspond to the same values of experiments [2].

4. **Hydrogen burning in a flat channel**

In numerical simulation the solution is stationary at the reference time. The nozzle at the inlet is not ideal, which causes formation spatial inhomogeneities of the flow up to 10%. The inflowing gaseous fuel practically does not burn until it meets a shock wave from the throttling jet. After that the burning process moves upstream near the wall.

The channel with 2D temperature distribution is shown in Figure 2 ($a, b$ – for the prechamber pressure 1000 K and 1700 K respectively). The main stream is a mixture of nitrogen and oxygen in proportions close to atmospheric air. In numerical simulation, the SST k-ω turbulence model is used. The intensity of turbulence at the inlet for the main stream and the air stream in CFD modeling is 0.1%. Hydrogen jets have a fairly high turbulence intensity of 5%. The results of numerical simulation of the interaction of a throttling jet with a boundary layer in the channel in the absence of fuel supply and comparison with experiment [14] are presented in [13].

The dimension of the combustion areas and the range of pressure fluctuations rise simultaneously with increasing temperature, as shown in Figure 2. The transonic mode forms in the both cases. There is satisfactory agreement with the experiment, as shown in [11]. The pulsation period is 0.1–0.2 ms (the corresponding frequency is 5–10 kHz). Large amplitudes of parameter oscillations are caused by low pressure differences between the fuel supply reservoir and the main flow in the channel, which is not desirable, since it creates prerequisites for the development of vibrations in the channel.

5. **Ethylene combustion in axisymmetric channel**

In contrast to the previous case, the fuel is supplied along the channel axis. This allows simulating low fuel consumption at high flow rates by reducing the diameter of the nozzle. In the case of a side annular slot for the same consumption, its width must be small enough not to allow forming the shock wave due to the viscosity effects. Due to the large pressure differential, the amplitudes of oscillations of the parameters become significantly smaller. Three consequential moments for the temperature distribution (the time increases from top to bottom) after the throttling near-wall jet is applied to the of axisymmetric ethylene flow are shown in Figure 3.
Figure 2. The temperature distribution: $a$, $b$ – for the prechamber pressure 1000 K and 1700 K respectively.

6. Ethylene combustion in axisymmetric channel
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increases from the top to the bottom: $t = 2.26$ ms, 4.08 ms, 6.53 ms)

The resulting transonic mode with Mach numbers 0.7 – 0.8 is obtained. As we can see from the Figure 3, the amplitudes of oscillation of parameters are small. The distributions of the main gas-dynamic parameters along the channel are presented in Figure 4 (a – c): $a$ – is the initial stage, $b$ – is the quasistationary transonic mode, $c$ – is the distribution of several characteristics at one time point.

![Graphs showing pressure distributions and parameter oscillations.]

**Figure 4.** The distributions of the main gas-dynamic parameters along the channel: $a$ – pressure distribution: 1 – $t = 2.26$ ms, 2 – $t = 2.51$ ms, 3 – $t = 2.84$ ms, 4 – $t = 3.65$ ms, $b$ – pressure distribution: 1 – $t = 3.24$ ms, 2 – $t = 3.65$ ms, 3 – $t = 4.08$ ms, 4 – $t = 6.31$ ms, $c$ – distributions of several parameters at $t = 6.53$ ms: 1 – pressure, 2 – temperature, 3 – the mass fraction of $O_2$, 4 – the mass fraction of $C_2H_4$, 5 – the mass fraction of $CO_2$, 6 – the mass fraction of $H_2O$.

The process of oscillation of parameters near the jets (throttling and fuel) is shown in Figure 5, where consumption and pressure fluctuations in the vicinity of the jets inflow into the channel are shown. Parameter fluctuations show negative pressure feedback presented in [11] (when pressure into the channel increases, the jet consumption decreases as we can see in Figure 5).

![Graphs showing oscillations of pressure and consumption.]

**Figure 5.** Oscillations of pressure and consumption near the fuel or throttling jet: $a$ – ethylene burning: 1, 3 pressure and 2, 4 consumption near the fuel and throttling jet subsequently; $b$ – 1, 2 pressure and consumption near the throttling jet respectively [11].
7. Conclusion
Thus, we showed numerically the possibility of a flow deceleration with Mach number \( M = 2 \) to transonic speeds in channels with a cross section of about 30 – 50 mm in the range of stagnation temperatures from 1000 K to 1700 K. An increase of temperature results in increasing the amplitude of pulsations, while the Mach numbers increase for about 10%. The parameters fluctuations decrease with an increase of the pressure difference between the fuel tank and the main flow. The most general regularities do not depend on the method of fuel supply (axisymmetric or near-wall). However, the axisymmetric method of fuel supplying causes decreasing of pulsation amplitude.

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