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Study of gas dynamics of the intersecting jets in a semi-open channel

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Abstract. The subject of the study is axisymmetric channel with a hemispherical bottom. The compressed air flows into the channel through the holes located on the surface of the hemispherical bottom. The ratio of all holes area to the outlet area of the channel is equal to 0.25. The experimental and numerical study of jets intersecting at a single point is performed. The countermoving jets and the focused jets are investigated. The distribution of pressure over the surface of the channel and the total pressure at the output of the channel are obtained. The main experimental result is as follows: the total pressure recovery coefficient for the focused jets is twice more than that for the countermoving jets.

1. Introduction

Slot nozzles are of practical interest as an alternative use of the Laval nozzle [1]. The gas dynamics of separate off-design supersonic jet is studied extensively [2-8], but interaction of multiple jets is a more complex problem. The gas dynamics structure of the flow has a significant impact on the processes of fuels ignition and combustion. Therefore, the gas dynamic structure formed by the multiple jets deserves additional study. Some of the results of the effusion of the jets from the holes of a few millimeters are presented in [1]. The area of all the holes of the channels from [1] is tenfold smaller than the outlet area of the channel. This work is dedicated to the effusion of intersecting jets from the holes, which total area is fourfold smaller than the area of the channel. The paper presents the results of the experimental and numerical study of jets gas dynamics. The semi-open channels are characterized by sufficiently thick walls to create directional jets. The compressed air flows from the prechamber through the holes. The jets are focused at a single point on the axis of the channel. It is shown that the direction of the jets has a significant effect on the total pressure recovery coefficient.

2. Results and Discussion

The shadow scheme with a circular knife was applied for registering the flow structure. There were fluctuations of the gas dynamics parameters at low pressures in the prechamber $p_f$. The supersonic mode is established when the pressure in the prechamber is greater than a certain critical value.

Numerical modeling was carried out basing on unsteady three-dimensional Euler equations. Experimental data and calculation results are given in Table 1 and Table 2 for the countermoving jets.
and focused jets respectively. The pressure at the test points, the total pressure $p_0$ and static pressure $p_S$ on the axis in the outlet section of channel, and the Mach number are presented in these tables. The total pressure for a direct shock wave and static pressure were measured in the experiment to obtain the Mach number and the total pressure on the axis at the outlet section of the channel. The total pressure for a shock wave, and all other values were obtained in the calculation process for the case of numerical modeling.

Let us consider the case of the countermoving jets. The compressed air flows to the channel through four holes located opposite each other in pairs in two mutually perpendicular planes. The test points for measuring the pressure and the pressures values in these points are shown in Figure 1a and Figure 1b respectively.

![Figure 1](image)

**Figure 1.** The case of the countermoving jets: (a) – the model with countermoving jets; (b) – the experimental dependences of the pressure for the test points from the prechamber pressure.

The plane with the test points is located between the planes containing the opposite holes at the same distance from each other. Table 1 contains the data for two values of the pressure in the prechamber. The graphs in Figure 1b indicate the linear character of the static pressure dependences on the walls under the following conditions: the value of the pressure in the prechamber must be more than some certain value. We named this type of solution an automodel solution. The main features of this automodel solution are following: the constant Mach number, the linear character of the dependences of static pressure on the walls as function of the pressure in the prechamber. The unsteady subsonic flow is formed at low pressures in the prechamber. While the pressure of the prechamber achieves some critical value, the supersonic flow is formed. The data in Table 1 are averaged with respect to time. There are fluctuations of flow parameters in the experiment as well as in the numerical simulation. The maximum fluctuation during calculation does not exceed 20%. It should be noted a good agreement of the experimental data and calculation results.

The difference between the results of measurements at the point $p_2$, $p_3$, $p_4$ and the data of three-dimensional calculations is shown in Table 2. This difference is within the range of the fluctuations. The Mach number is also practically independent on the pressure in the prechamber and coincides with the value obtained in the experiment.

**Table 1.** Pressure ($10^5$ Pa) at the test points and the Mach number for the countermoving jets.

|          | $p_1$ | $p_2$ | $p_3$ | $p_4$ | $p_5$ | $p_6$ | $p_9$ | $p_0$ | $p_5$ | $M$  |
|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|
| Experiment | 15    | 4.8   | 4.38  | 3.6   | 2     | 1.07  | 4.38  | 5.61  | -     | 1.65 |
The case of the focused jets: (a) – the model with focused jets; (b) – the experimental dependences of the pressure for the test points from the prechamber pressure.

The plane with the test points is located between the planes containing the opposite holes on the same distance from each other. The graphs in Figure 2 indicate the linear character of the static pressure dependences on the walls under the following conditions: the value of the pressure in the prechamber must be more than a certain value. The unsteady subsonic flow is formed at low pressures in the prechamber. While the pressure of the prechamber achieves some critical value, the supersonic flow is formed. We can point out that the experimental data as well as the calculation ones have the same properties as in the case of countermoving jets. We can also name automodel the solution for the focused jets. The data in Table 2 are averaged with respect to time. The fluctuation of the parameters is less than for the case of countermoving jets: their value consists of 10\% for the value of the pressure \( p_f = 15 \) atm and the fluctuations of parameters are small to negligible for the pressure \( p_f = 24 \) atm. As we can see from Figure 1b and Figure 2b, the supersonic mode formation takes place at the pressure values in the prechamber, which are less than the ones for the countermoving jets.

Table 2. Pressure (10^6 Pa) at the test points and the Mach number for the focused jets.

|       | \( p_r \) | \( p_5 \) | \( p_8 \) | \( p_9 \) | \( p_0 \) | \( p_3 \) | M     |
|-------|----------|----------|----------|----------|----------|----------|-------|
| **Experiment** | 1.5      | 1.77     | 1.62     | 1.0      | 5.54     | 7.52     | -     | 2.05  |
| **3D simulation** | 1.5      | 1.41     | 2.03     | 1.3      | 4.4      | 5.8      | 0.84  | 1.92  |
| **Experiment** | 2.4      | 2.77     | 2.46     | 1.46     | 9.15     | 13.6     | -     | 2.05  |
| **3D simulation** | 2.4      | 2.61     | 1.88     | 2.06     | 7.31     | 10.4     | 1.24  | 2.07  |

The difference between the experimental and the calculation results consists of 25\% with exeption of the Mach number. The coinciding of experimental and calculation value of the Mach number is very good.

As we can see from Figure 3, the experimental values of the loss of total pressure in the case of the focused jets are almost twice less than for the countermoving jets. We should point out that the
calculation values of the loss of total pressure differs from the experimental values in 25%: loss of total pressure in the case of the focused jets is almost 1.5 fold less than for the countermoving jets. This difference must be investigated in detail in the future, but we can suppose some reasons for this phenomenon. The main of them is the heterogeneous distribution of the flow parameters values.

![Graph showing the total pressure recovery coefficient](image1)

**Figure 3.** The dependences of the total pressure recovery coefficient $\sigma = \frac{p_0}{p_f}$ from the prechamber pressure for the focused holes (blue line) and the opposite holes (red line).

![Distributions for focused jets](image2)

**Figure 4.** The distributions for the focused jets at the prechamber pressure $p_f=2.4$ MPa in the plane of measurements: (a) – the Mach number; (b) – the pressure.
The calculations results shown in Figure 4 are distribution of the Mach number (Figure 4a) and the pressure in the plane of measurements (Figure 4b) at pressure in the prechamber $p_f = 2.4 \text{ MPa}$. We can see that the flow is sufficiently heterogeneous.

The distribution of the Mach number, static pressure and total pressure along the diameter of the output section of the channel is presented in Figure 5 for the case considered. We can see from Figure 5 that the flow at the nozzle is fully supersonic, but the maximum difference between parameters consists of 15%.

![Figure 5. The distribution of the Mach number (1), total pressure (2) and static pressure (3) along the diameter of the output section of the channel.](image)

3. Conclusion
Data analysis indicates that semi-open channel can be used as a supersonic nozzle. The loss of total pressure depends considerably on the process of jets mixing. This process is determined by the ratio of area of all the holes to the output area of the channel as well as location and direction of the jets.

The total pressure recovery coefficient for the focused jets is twice more than the same parameter for the countermoving jets according to the experimental estimation, but for the case of numerical simulation the difference is about 1.5 fold.

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