The influence of nozzle geometry on the gas-dynamic structure of the supersonic nonisobaric jet

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Abstract. The paper presents the investigation results of the flow structure of cold supersonic jets flowing out of model nozzles with a Mach number on the exit $M_a = 3.5$: an axisymmetric nozzle, a nozzle with a rectangular critical section, a beveled nozzle with a rectangular critical section. Flow schlieren images and transverse measured total pressure profiles in the flow are presented. The influence of the critical section shape and the beveled exit section on the shock-wave structure of the flow is described.

1. Introduction

In the development of promising space reentry vehicles the usage of multi-jet systems for vehicle deceleration in the final part of the landing trajectory is currently proposed. The flow structure near the reentry vehicle surface and the study of its aerodynamic characteristics during deceleration are presented in [1]. Supply conduit technical features and the requirement for an aerodynamically

Figure 1. The geometry of the studied nozzles. (a) - nozzle 1, (b) - nozzle 2, (c) - nozzle 3
“clean” external surface of the apparatus when the nozzle section does not go beyond the vehicle profile
make the goal of studying the influence of supersonic nozzles geometry on the outflowing jets gas-
dynamic structure relevant.

The work was carried out at the AT-326 wind tunnel and the Vertical Jet Unit (VJU) of the ITAM SB RAS. Detailed descriptions of equipment and research methods are given in [2] and [3].

The purpose of the work is to determine the influence of the shape of the critical section of the nozzle
and the beveled cut of the exit section on the gas-dynamic structure of the flow of a supersonic jet
flowing out of nozzles with a geometric Mach number in the exit section $M_a = 3.5$.

Supersonic jets flowing out of three nozzles with the Mach number on the cut $M_a = 3.5$ and the output
diameter $D_a = 20$ mm are studied. The nozzles geometry is shown in figure 1. To perform experiments
to estimate the influence of the critical section shape on the supersonic jet, we used a pair of nozzles 1
and 2 with different geometry and equal critical section area (figure 1, (a), (b)). To estimate the effect
of the beveled cut, we studied a nozzle 3 with $M_a = 3.5$, $D_a = 20$ mm, similar to nozzle 2 with the beveled
cut with an angle $\theta = 24^\circ 20'$, shown in figure 1 c. The research was performed for cold jets with the
total pressure ratio in the prechamber of the wind tunnel to the ambient pressure $Npr = 91.5$.

2. Flow visualization
Flow schlieren visualization was carried out using a shadow device IAB-451 and a digital CCD camera
with a resolution of 1400 × 1000. Figure 2 shows representative schlieren images of the studied
supersonic jets initial part in the symmetry plane. Exposure time is 4 ms.

![Schlieren images](image)

**Figure 2.** Schlieren images of the investigated jets. Vertical plane. $D_a = 20$ mm, $Npr = 91.5$.
Exposure 4 ms. Horizontal knife. (a) - nozzle 1, (b) - nozzle 2, (c) - nozzle 3
The complex flow shock-wave structure is clearly registered. The groove presence in the critical section of nozzle 1 (figure 2, (a)) leads to the nozzle shock appearance. The observed additional shock is formed due to the microstep presence in each of the nozzles divergent part, leading to an abrupt expansion of the channel.

The rectangular shape of the nozzle 2 critical section (figure 2, (b)) leads to the additional shock waves formation and jet elongation along the vertical axis.

The beveled exit section of nozzle 3 (figure 2, (c)) leads to a distortion of the flow shock-wave structure and a deviation of the jet axis from the nozzle axis. For the presented mode, the deviation occurs towards the external normal to the nozzle exit.

3. Pitot pressure probe measurements

Figure 3 shows the transverse profiles of the pitot pressure in the section $x/Ra = 4$ in the vertical ($y$-var) and horizontal ($z$-var) planes.

The recorded profiles in the perpendicular planes coincide in the case of the axisymmetric nozzle (figure 3, (a)).

For the nozzle with rectangular critical section (figure 3, (b)), the vertical profile ($y$-var) is elongated along the abscissa according to the outer mixing layers position, which is explained by the influence of

![Figure 3](image_url)

Figure 3. Transverse profiles of the jet pitot pressure with varying $y$ and $z$. (a) - nozzle 1, (b) - nozzle 2, (c) - nozzle 3
the rectangular critical section. On the \( y \) axis, the pressure maximum is displaced, and the position of local pressure minima on the profile is not symmetrical with respect to the origin \( (y/R_a = -0.35 \text{ and } y/R_a = 0.7) \). Such pressure distribution pattern along the \( y \) axis is caused by an inaccuracy in the nozzle 2 manufacture along the critical section long side (along \( y \) axis).

For the beveled nozzle (figure 3, (c)), the horizontal distribution (\( z \)-var) is symmetrical and qualitatively corresponds to that recorded for the case of the nozzle with the normal cut (figure 3, (b)). The vertical profile (\( y \)-var) has an asymmetric appearance with a significantly more developed external mixing layer from the side of positive \( y \) values. This distribution pattern is explained by the nozzle beveled cut, which leads to the shock waves asymmetric position in the jet flow field.

Figure 4 presents the results of a comparative analysis of the pitot pressure transverse profiles in characteristic sections of supersonic jets \( M_a = 3.5 \) \( Npr = 91.5 \).

![Figure 4. Transverse profiles of the pitot pressure in the symmetry plane. (a) - section \( x/R_a = 4 \), (b) - section \( x/R_a = 20 \), (c) - section \( x/R_a = 45 \)](image)

Near the nozzle exit section (figure 4, (a)), insignificant deviations in the local pressure maxima region \( y/R_a = \pm 0.5 \) are recorded both for the pair of nozzles 1 and 2, and for 2 and 3. Pitot pressure differences in the mixing layer for positive \( y \) values between nozzles 2 and 3 are explained by the beveled cut of the nozzle 3. Differences increase with distance from the nozzle exit (figure 4, (b)). At a large distance from the nozzle exit (figure 4, (c)) for the nozzle with rectangular critical section (2) the high intensity of dissipative processes caused by a more complex shock-wave structure leads to an accelerated decrease in the measured pitot pressure. For instance, at a distance of \( x/R_a = 45 \), the
difference reaches 1.5 times. For the beveled nozzle (3), the pitot pressure in the jet downstream decreases even faster due to more intensive mixing with the environment. It reaches 1.8 times at a distance of $x/R_a = 45$.

4. Conclusion
New data were obtained on the structure of supersonic jets flowing out of nozzles $M_a = 3.5$ with the rectangular critical section and the beveled exit section. It is shown that near the nozzle exit, a change in the critical section shape and the presence of the beveled exit do not significantly affect the parameters distribution in the supersonic stream. Downstream, the rectangular shape of the critical section leads to the dissipative processes intensification caused by a more complex shock-wave structure. This entails a decrease in the measured pitot pressure with increasing distance from the nozzle exit. It is shown that the beveled cut of the nozzle additionally enhances the jet energy dissipation due to more intensive mixing with the environment. This leads to a more rapid decrease in total pressure in the jet downstream.

References
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