Parameters of the air flow formed by the interchangeable nozzles with the transformed critical part

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Abstract. The results of studies of the nozzle block functioning with interchangeable nozzles at the hypersonic aerodynamic shock tube (HAST) are presented. Air flow parameters from the elongated nozzle and of variety of critical cross-sections of the inlet of the nozzle were calculated. The dependence of the influence of the nozzle critical section size on the uniformity of incoming flow and speed was shown. The calculated pressure values were compared with those measured experimentally at the nozzle exit cut and at different distances from it.

1. Introduction

The numerical and experimental investigation in the Hypersonic Aerodynamic Shock Tube (HAST) Research Resource Center at the Ishlinsky Institute for Problems in Mechanics RAS on the high speed flow around aircraft models and gas flows at hypersonic speeds is ongoing [1, 2]. The standard conical hypersonic nozzle investigated in [3] is used in experiments. The idea of nozzle elongation is caused both by a decrease the boundary layer [4] and by the possibility of observing shock-wave structures on the nozzle section in the vacuum unit window.

The new elongated hypersonic conical nozzle is formed by a regular nozzle with a removable bell, which continues the internal conical geometry of the nozzle without flaws that could disrupt the stream line. The length and diameter of the outlet section of the new nozzle changed at the same angle of the solution cone, and studies were conducted with the transformed critical part of the nozzle. This is required new computational and experimental studies of the operation of this development.

In the same way as in work [5], a simplified mathematical simulation was carried out in this study. Quasi-stationary gas flows and formation of gas-dynamic parameters behind the nozzle section were considered.

The HAST photo is shown in figure 1. Conical short and elongated nozzles are shown in figure 2 and figure 3, respectively. The transformed critical parts of the nozzles are shown in figure 4. A sketch of the simplified conical nozzle for the calculations below is shown in figure 5.
Figure 1. The HAST facility.

Figure 2. Regular conical nozzle.

Figure 3. Elongated conical nozzle.

Figure 4. The transformed critical parts of the nozzles.
Figure 5. The sketch of the simplified elongated conical nozzle.

Here: $R$ – the radius of the nozzle output section, $R = 87.5$ mm; $L$ – the length of the nozzle, $L = 350$ mm; $\theta$ – the half angle of the nozzle supersonic part, $\theta = 13^\circ$, 40; $r^*$ – the radius of the nozzle critical cut, $r^*_4 = 4$ mm; $r^*_2 = 2$ mm, $r^*_1 = 1$ mm.

2. Quasi-stationary calculation of the elongated conical nozzle flow field

A numerical simulation of the stationary flow of a viscous gas in an axisymmetric elongated nozzle and jet was presented. The system of two-dimensional (axisymmetric) nonstationary Navier-Stokes equations written in divergent form and supplemented by the equations of state of the ideal gas and boundary conditions at the boundaries of the computational domain was solved. At the boundaries corresponding to the solid walls, the adhesion conditions was setting. At the nozzle inlet, the total pressure and total temperature were settled on the axis of symmetry – the non-flow condition, at remote boundaries – the conditions of absence of reflection. The terms describing convective transport in this system were approximated by a modified Godunov scheme of high order of accuracy [6]. The terms of the equations describing the diffusion (viscous) transfer were approximated by the control volume scheme. Promotion timing was performed using the method of Runge-Kutta of the third order [6–8].

The geometric degree of the nozzle expansion and the ratio of specific heat capacities for the gas environment – air are equal to:

$$\left( \frac{R}{r^*} \right)^2 = N$$

$$\gamma = \frac{c_p}{c_v} = 1.4$$

The Reynolds number, characterizing the flow of viscous gas in the nozzle, $Re = 6 \times 10^4$ was calculated by the parameters in the critical section of the nozzle and $r^*$. The gas temperature at the nozzle inlet was $T_k = 820$ K. The constant pressure in the space surrounding nozzle (in the vacuum chamber) was 0.1 Pa.

2.1. Calculation of the nozzle flow field with replaceable critical radius

The radiuses of the nozzle critical cut were: $r^*_4 = 4$ mm, $r^*_2 = 2$ mm, $r^*_1 = 1$ mm. The results of calculations for the stationary flow regimes in the elongated conical nozzle in the coordinates normalized to the critical radius are presented in figures 6–8.

The results of calculations for the stationary flow regimes in the elongated conical nozzle in the coordinates normalized to the critical radius $r^* = 4$ mm, 2 mm, 1 mm are presented in figures 9–11.
Figure 6. The Mach number field in a long conical nozzle, \( P_k = 1.9 \) atm., \( r^* = 4 \) mm.

Figure 7. The Mach number field in a long conical nozzle, \( P_k = 1.9 \) atm., \( r^* = 2 \) mm.

Figure 8. The Mach number field in a long conical nozzle, \( P_k = 1.9 \) atm., \( r^* = 1 \) mm.
The Mach number increases if the radius of the nozzle critical section decreases and the degree of expansion of the nozzle decreases. However, as the critical section of the nozzle decreases, the boundary layer grows (figures 6–8). Also, due to the large length of the supersonic part of the nozzle,
a large boundary layer is growing on the inner wall, which "pushes" the flow from the wall and thus makes it more "one-dimensional", but constantly accelerating along the direction of the x-axis.

2.2. Calculation of the flow field parameter in the elongated conical nozzle
The main flow parameters in the elongated nozzle are calculated. Parameters of density, velocity, Mach number and temperature were calculated. Results are shown in figures 12–15.

The flow speed graph behind of the elongated nozzle.

\[ P_{cr} = 3.88 \text{ atm} \]

![Figure 12. Graph of flow speed.](image)

Mach graph of the elongated nozzle.

\[ P_{cr} = 3.88 \text{ atm} \]

![Figure 13. Graph of flow Mach number.](image)
2.3. Calculation of the nozzle flow field at different pressure at the critical nozzle section

The calculated pressures at the elongated nozzle outlet, according to preliminary estimates, were set as following: $P_k = 1.9, 3.0, 3.3, 3.8$ atm, $r^* = 4$mm. Graphs of flow rates in a long nozzle ($r^* = 4$mm) and at distance behind the nozzle section are shown in figure 16.
3. Experimental verification of the calculation of pressures behind the elongated nozzle cut
The calculations behind the section of the elongated nozzle for the critical radius of 4mm and pressures of 1.9 atm and 3.88 atm at different distances from it were experimentally verified. Here the graphs of pressures at different distances from the nozzle section are presented. As expected, the pressure behind the cut of the elongated nozzle is greater at a higher pressure at the critical nozzle section and a shorter distance from the nozzle cut. Experimental confirmation of the calculated pressure at \( r^* = 4 \) mm and \( P_k = 1.9 \) and 3.88 atm is given in [5]. The comparison of calculation with experiment at \( P_{cr} = 1.9 \) atm and \( P_{cr} = 3.88 \) atm at distance from the nozzle exit is on figure 17.

![Graph of stagnation pressure depending on distance behind the nozzle section. (Calculation)](image1)

**Figure 16.** The calculated pressure at the elongated nozzle outlet.

![Comparison of calculation with experiment](image2)

**Figure 17.** Comparison of calculated values (C) with experiment (E).

Experimental verification of the calculation of pressures of the elongated nozzle at \( r^* = 1 \) mm showed underestimated results. This is due to the fact that in the shock tube before the critical section
of the nozzle the pressure of the incident and reflected shock waves do not allow the flow to pass through such a small nozzle inlet. Therefore, \( r^* = 4 \) mm is the smallest real radius of the critical section of the nozzle, no matter what the advantages of calculations of its reduction may give.

**Conclusion**

The calculated parameters of pressures, velocity, Mach, temperature and density for different critical sections of the nozzle showed the following. With a decrease in the critical section of the nozzle, the Mach number increases, the boundary layer increases. This makes the flow more uniform and prevents it from expanding when it flows out of the conical nozzle. Experimental verification of the calculation of pressures of the elongated nozzle at \( r^* = 1 \) mm showed underestimated results. The calculated parameters at \( r^* = 4 \) mm of the pressures behind the section of the elongated nozzle satisfy the experimentally determined ones.

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