Investigation of gas dynamic parameters of the conical nozzle block functioning in the Hypersonic Aerodynamic Shock Tube

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Abstract The results of investigations of the conical nozzle block of the hypersonic shock aerodynamic tube (HAST) [1–4] of the Laboratory of Radiative Gas Dynamics of the Institute for Problems in Mechanics RAS are presented. The efficiency of short conical nozzle is calculated. The gas dynamic flow parameters were measured experimentally at different distances from the nozzle exit. The design pressure values are compared with the measurements at the nozzle outlet. Comparison of numerical calculation and experimental results shows that the nozzle is started, successfully worked and it is possible to obtain a uniform flow at Mach numbers \( M = 5...7 \).

1. Introduction
Experimental studies in the Hypersonic Aerodynamic Shock Tube (HAST) of the Laboratory of Radiative Gas Dynamics at the Institute for Problems in Mechanics RAS are continuing. The investigated gas flows are formatting by using the short conic nozzle and oncoming onto models of high speed aircraft primitives [1–4]. The flow quality should be investigated at several distances from the nozzle exit to ensure the flow uniformity. A direct numerical study of gas-dynamic processes in the complete configuration of HAST involves overcoming a number of problems.

The main problem is connected with the necessity of non stationary calculation of the large number of interacting gas-dynamic discontinuities taking into account viscous phenomena on very detailed computational grids. The latter is due to the large length of the impact tube (15 m) [1], limited by the possibility of using 1D calculations, the presence of an additional diaphragm in the nozzle throat and the need to resolve the boundary layers in the tube sections and in the nozzle block.

In this paper, at first, a simplified mathematical modeling was carried out, in which numerical calculations can be divided into two stages. At the first stage non stationary processes in the shock tube sections (driver and driven tubes) after opening the diaphragm are considered. At the second, the quasi-stationary gas flow through the nozzle block and the formation of the near-to-nozzle field of gas-dynamic parameters in the jet incoming to the vacuum chamber are calculated. The questions of the first stage were considered in the [2, 3], and the parameters are experimentally refined, so let's use them.

2. Conical nozzle block scheme in the HAST facility
The HAST experimental setup, 15 m of length, is shown in diagram (figure 1).
Figure 1. The HAST scheme.

The HAST scheme shows the following: high-pressure chamber (1), cylindrical channel / driven tube (2), vacuum chamber (3) and installed in it hypersonic nozzle (4) with a critical section (5), pressure gauge (6), high-speed solenoid valve (7), second membrane unit (8), high-frequency dynamic pressure sensors (9), (10), (11), (12), observation windows (13), model holders (14) with models, analog-to-digital converters (15), PC (16), high-speed video camera (17). High-vacuum pumps (pumping stations), gas mixing and filling systems are not shown. View of the HAST part with the nozzle block inlet and the vacuum camera is shown in the photo of figure 2.

Figure 2. Photo of the shock tube section and aerodynamic part of the HAST facility.

The short conical nozzle in the aerodynamic block of the HAST, in front of which the model is mounted, is shown in figure 3.

The nozzle block inlet with critical section is located in the shock tube driven section. It has a built-in part for mounting the membrane before entering the nozzle. A sketch of the simplified conical nozzle for the calculations below is shown in figure 4. Here: \( r^* \) - the radius of the nozzle critical cut, \( R \) – the radius of the nozzle output section, \( L \) – the length of the nozzle, \( \theta \) – the half angle of the nozzle supersonic part.
3. Quasi-stationary calculation of the HAST nozzle block

The base of the nozzle block used in HAST experiments equipped with a conical nozzle with the radius of the critical cross-section \( r^* = 4 \) mm and the radius of output section \( R = 43.5 \) mm, the half-angle of the supersonic cone part \( \theta = 13.4^\circ \), the length of the supersonic part \( L = 168 \) mm. the geometric degree of the nozzle expansion is:

\[
\left( \frac{R}{r^*} \right)^2 = 118.266
\]

The pressure at the nozzle inlet, according to preliminary estimates and experimental data, was set at three levels: \( Pk = 0.5, 1.9, 2.3 \) atm. The gas inlet temperature \( Tk = 297 \) K. The pressure in the space surrounding nozzle (in the vacuum chamber) \( Ph = 0.1 \) Pa. The ratio of specific heat capacities for the gas environment - air is equal to:

\[
\gamma = \frac{c_p}{c_v} = 1.4
\]

The temperature dependence of the viscous transfer coefficient is described by the Sutherland formula:

\[
\mu = \mu_0 \frac{T_0 + C \left( \frac{T}{T_0} \right)^{\frac{2}{7}}}{T + C \left( \frac{T}{T_0} \right)^{\frac{2}{7}}},
\]

here:

\( \mu \) – dynamic viscosity in (Pa\*s) at a given temperature \( T \),

Figure 3. Photo of the short conical nozzle output in the vacuum chamber.

Figure 4. The sketch of the simplified short conical nozzle.
\( \mu_0 \) – control viscosity in (Pa\( \cdot \)s) at control temperature \( T_0 \),

\( T \) – set temperature in Kelvin,

\( T_0 \) – control temperature in Kelvin,

\( C \) – Sutherland constant.

The calculation area is the space inside the nozzle, including the subsonic part, the area of the vacuum chamber above the nozzle, the area adjacent to the nozzle section and covering the near field of the jet flow. A regular calculation grid adapted to the boundaries of the computational domain is generated in the region. The thickening of the grid was carried out near the solid walls of the nozzle, in the area of the critical section and near of the output section of the nozzle.

In this numerical study, the steady flow of viscous gas in axisymmetric nozzle and jet was calculated. The system of two-dimensional (axisymmetric) nonstationary Navier-Stokes equations written in divergent form and supplemented by thermal and caloric equations of ideal gas state and boundary conditions at the boundaries of the computational domain is solved numerically.

Only molecular (laminar) viscosity was taken into account. On the boundaries corresponding to solid walls, the adhesion conditions were set. At the nozzle inlet, the enthalpy and entropy calculated for the total pressure and the stagnation temperature on the axis of symmetry were preserved - the condition for the absence of motion. At the remote boundary, the conditions for the absence of reflection were set. The terms in the system of equations describing the convective transfer were approximated by means of a modified high-order Godunov scheme [5-8]; the terms of the equations describing the diffusion (viscous) transfer were approximated by a finite volume scheme. The calculation process developing in time was carried out using the Runge-Kutta method of the second order [6].

The results of calculations for the stationary flow regimes in the conical nozzle in the coordinates normalized to the critical radius are presented in figures 5-10. Here one can see the Mach number field and the distribution of Mach numbers along the axis of the nozzle symmetry. The results of calculations for the inlet pressure values are presented: \( P_k = 0.5 \) atm in figures 5 and 6; \( P_k = 1.9 \) atm in figures 7 and 8, \( P_k = 2.3 \) atm in figures 9 and 10.

**Figure 5.** Field of Mach numbers. Conical nozzle, \( P_k = 0.5 \) atm, \( r^* = 4 \) mm.

**Figure 6.** The distribution of Mach number along the nozzle axis. Conical nozzle, \( P_k = 0.5 \) atm, \( r^* = 4 \) mm.
Figure 7. Field of Mach numbers. Conical nozzle, $P_k = 1.9$ atm, $r^* = 4$ mm.

Figure 8. The distribution of Mach number along the nozzle axis. Conical nozzle, $P_k = 1.9$ atm, $r^* = 4$ mm.

Figure 9. Field of Mach numbers. Conical nozzle, $P_k = 2.3$ atm, $r^* = 4$ mm.

Figure 10. The distribution of Mach number along the nozzle axis. Conical nozzle, $P_k = 2.3$ atm, $r^* = 4$ mm.

The velocity field at a pressure of $P_k = 1.9$ atm was constructed for the flow regime studied in the experiment (figure 11).
Figure 11. The velocity field. Short conical nozzle, $P_k = 1.9$ atm., $r^* = 4$ mm.

Increasing the inlet pressure leads to an increase in static pressure and flow density inside the nozzle, that is, an increase in the Reynolds numbers and decrease in the thickness of the boundary layer on the wall.

It can be seen from the graphs that the field of flow parameters is rather uneven both along the x-axis and the y-axis (figure 5, 7, 9), with increasing the thickness of the boundary layer in the nozzle, there is a tendency both to a certain increase in the “one-dimensional” flow and to a slight decrease in the average cross-section value of the Mach number. So for $P_k = 0.5$ atm the flow at the nozzle section has a Mach number $M = 6.5$, $P_k = 1.9$ atm – $M = 6.8$. The current lines behind the nozzle section have smaller slopes than in the conical section, the Mach number grows more slowly with increasing spatial coordinates along the nozzle axis, for example, in figure 5 and figure 10. Thus, the growth of the boundary layer leads to the fact that the flow becomes more uniform in the area of influence of the nozzle cut parameters.

The flow parameters along the nozzle axis were evaluated. The calculated data of stagnation pressure at different distances from the nozzle exit are obtained for comparison with experimental data obtained at the HAST.

4. Experimental study of the HAST nozzle block
On the axis of the short conical nozzle, instead of the model (figure 3) certified dynamic pressure sensor PCB 113B28 was installed in the position of the Pitot tube. Sensor readings and calculated values of stagnation pressure at different distances from the nozzle exit are given in the table 1.

Table 1. Experimental and calculated values of stagnation pressure at distances from the nozzle exit.

| Distance from the nozzle exit, mm | $P_{pitot}$ - stagnation pressure (Pitot), Pa. | $P_t$ - stagnation pressure (Pitot), mV. |
|----------------------------------|-----------------------------------|-------------------------------------|
| 0                                | 0.35642E+04                       | 54                                  |
| 49                               | 0.26669 E+04                      | 41.4                                |
| 100                              | 0.18369E+04                       | 27.7                                |
| 144                              | 0.13498E+04                       | 21                                  |
| 193                              | 0.10452E+04                       | 15.5                                |
The stagnation pressure (Pitot) in the numerical study was calculated by the ratio:

\[ p_{\text{pitot}} = p \left[ \frac{2\gamma}{\gamma + 1} M^2 - \frac{\gamma - 1}{\gamma + 1} \right] \left[ \frac{4\gamma}{(\gamma + 1)^2} - \frac{2(\gamma - 1)}{(\gamma + 1)^2 M^2} \right]^{\frac{\gamma}{\gamma - 1}}, \]

where \( p \) is the static pressure at a given point.

Taking into account the transmission coefficient \( C = 15 \text{ mV/kPa} \) of dynamic pressure sensor PCB 113B28, comparison of the calculated and experimental values of the stagnation pressure is shown in the graph (figure 12).

![Figure 12. Flow stagnation pressure. Comparison of calculation and experiment.](image)

It can be seen that the calculated data are satisfactory reproduce the experimental results (error less than 4%).

**Conclusion**

Calculated-experimental researches of the HAST nozzle block at the Laboratory of Radiative Gas Dynamics at the IPMech RAS showed that the short conical nozzle suitable for supersonic flow for Mach number range \( M = 5..7 \). The calculations of the real conical nozzle of the experimental facility and of the formation of gas flows are made for real parameters in experiments.

The structure of the gas-dynamic flow near the conical nozzle section of the experimental unit is studied numerically. The calculated flow fields are compared with the nozzle outlet pressures measured experimentally at Mach numbers \( M = 5..7 \), which showed a satisfactory coincidence.
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