Investigation of gasdynamic parameters of a supersonic flow near a body at various Mach numbers

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Abstract. Interaction of a body with an incident supersonic flow is considered. By using numerical and experimental methods, gas-dynamic parameters of the supersonic flow near the body are determined for various Mach numbers. Theoretical calculations of the supersonic flow around a body are carried. The mathematical models used in the calculations are verified by the results of experimental studies performed in the IT-1M hypersonic impulse tube of the aerodynamic laboratory of the Mozhaysky Military Space Academy.

1. Introduction

Studies of supersonic flows around blunt bodies as elements of aircraft is one of the vital tasks of external aerodynamics. The article presents results of the study of gas-dynamic parameters of the incident flow near a body obtained on the basis of numerical and experimental modeling of supersonic flows. The application of mathematical modeling methods at early stages of the design process for the tasks of this class can significantly reduce the need for a physical experiment and allows a preliminary parametric optimization necessary for a proper choice of the design parameters. At the same time, a decrease in the need for a physical experiment in no way reduces its value as the main criterion for verifying the results of numerical modeling.

2. Numerical simulation results

In this article the gas-dynamic parameters of the supersonic flow near the body were calculated numerically at various Mach numbers (\(M_\infty=8 – 17\)).

The body used as an object of our studies was a cone blunted in a sphere with a radius of spherical blunting \(r\) (11.9\(\times10^{-3}\) m), length \(l\) (8\(\times10^{-2}\) m), half-angle at the apex of the conical part \(\theta = 9^\circ\), and diameter of the y base \(d\) (4\(\times10^{-2}\) m) (Figure 1).

A numerical calculation of the gas flow with an adiabatic index (\(k = 1.4\)) was carried out on a mesh with a dimension of 2.2\(\times10^6\) elements. The research was based on the model of a viscous perfect gas described by the Navier – Stokes equations [1,3]. In the calculations, the standard Spalart-Allmares turbulence model was employed. To solve the system of equations, an implicit scheme was used on a hexagonal structured mesh (Figure 2) [4,5]. The normalized distance \(y^+\) was from 15 to 20.
Figure 1. Model of the body under investigation: (a) orthogonal projection, (b) isometric view.

The factor responsible for the choice of the shape of the computational domain was the formation of a head shock wave in front of the body during the supersonic flow. The external computational domain included the perturbed flow region and the head shock wave. To reduce the computational power, the minimum allowable number of cells was specified.

Figure 2. Computational mesh (a) side view, (b) isometric view.

The boundary conditions were as follows: (i) a uniform incident flow at the external boundary of the computational domain (the degree of turbulence is 5%), (ii) a smooth continuation of the flow at the exit boundary, and (iii) a non-leakage condition on the surface of the body (Figure 3).

The calculations of the flow around the body were performed for $M_\infty=8–17$, at $p_\infty$, $\rho_\infty$ and $T_\infty$ corresponding to the parameters listed in Table 1.
Figure 3. Boundary conditions.

Table 1. Initial data for the calculations.

| №  | H, km | p∞, Pa  | ρ∞, kg/m³ | M∞ | Re∞ | T∞, K |
|----|-------|---------|-----------|-----|-----|-------|
| 1  | 30    | 1197    | 1.8×10⁻²  | 8   | 1.2×10⁻⁶ | 226.5 |
| 2  | 30    | 1197    | 1.8×10⁻²  | 10  | 1.5×10⁻⁶ | 226.5 |
| 3  | 30    | 1197    | 1.8×10⁻²  | 12  | 1.8×10⁻⁶ | 226.5 |
| 4  | 30    | 1197    | 1.8×10⁻²  | 14  | 2.1×10⁻⁶ | 226.5 |
| 5  | 30    | 1197    | 1.8×10⁻²  | 17  | 2.5×10⁻⁶ | 226.5 |
| 6  | 50    | 79.77   | 9.77×10⁻⁴ | 8   | 6.0×10⁻⁴ | 270.6 |
| 7  | 50    | 79.77   | 9.77×10⁻⁴ | 10  | 7.5×10⁻⁴ | 270.6 |
| 8  | 50    | 79.77   | 9.77×10⁻⁴ | 12  | 9.0×10⁻⁴ | 270.6 |
| 9  | 50    | 79.77   | 9.77×10⁻⁴ | 14  | 1.0×10⁻⁵ | 270.6 |
| 10 | 50    | 79.77   | 9.77×10⁻⁴ | 17  | 1.2×10⁻⁵ | 270.6 |
| 11 | 60    | 21.95   | 3.09×10⁻⁴ | 8   | 1.9×10⁻⁴ | 247  |
| 12 | 60    | 21.95   | 3.09×10⁻⁴ | 10  | 2.4×10⁻⁴ | 247  |
| 13 | 60    | 21.95   | 3.09×10⁻⁴ | 12  | 2.9×10⁻⁴ | 247  |
| 14 | 60    | 21.95   | 3.09×10⁻⁴ | 14  | 3.4×10⁻⁴ | 247  |
| 15 | 60    | 21.95   | 3.09×10⁻⁴ | 17  | 4.1×10⁻⁴ | 247  |

Figure 4 shows graphs of the distribution of pressure (Figure 4 a, c, e) and density (Figure 4 b, d, f) along the parabolic generatrix of the body surface at various numbers M∞ for atmospheric parameters corresponding to altitudes H∞ = 30, 50 and 60 km. The static pressure calculated for the lateral surface of the body was divided to the pressure of the unperturbed flow p∞. It was found that the greatest increase in pressure on the body surface (critical point) occurred at H∞ = 30 km and M∞ = 17 and its value increased relative to p∞ by 410 times (Figure 4a).
Figure 4. Pressure (a, c, e) and density (b, d, f) distributions on the body surface as various $M_\infty$.

The heights are: $H_\infty=30$ km (a, b), $H_\infty=50$ km (c, d), $H_\infty=60$ km (e, f).

Figure 5 shows the fields of gas-dynamic variables (pressure and density) in the plane of symmetry of the flow near the body ($H_\infty=30$-60 km, $M_\infty=17$). The structure of the fields of the gas-dynamic variables is rather pronounced. The blunting radius forms a disconnected head shock wave in front of the body.

3. Results

To validate numerical results, we used the data obtained experimentally at a pulsed wind tunnel IT-1M (Figure 6a) [2]. The difference between this hypersonic pulsed wind tunnel and classical installations was the use of a high-voltage electric discharge in the chamber in front of the nozzle for heating gas.

The experiments at a pulsed wind tunnel were performed at $M_\infty=17$ and $Re_\infty=1.2\times10^5$. The working gas was nitrogen. The body model was made from the ABS plastic by using 3D printing technology (Figure 6b).
Figure 5. Pressure (a, c, e) and density (b, d, f) distributions in symmetry plane of the body ($M_\infty=17$).
(a,b) $H_\infty=30$ km, $Re_\infty=2.5\times10^{-6}$; (c,d) $H_\infty=50$ km, $Re_\infty=1.2\times10^{-5}$; (e,f) $H_\infty=60$ km, $Re_\infty=4.1\times10^{-4}$.

Figure 6. (a) Photo of pulsed wind tunnel IT-1M, (b) model mounting on the holder.
To visualize the flow process, an IAB-451 schlieren-shadow device with a laser and LED illuminator (with a wavelength of 535 nm) and the a SONY RX100M4 digital video camera (shooting frequency - 1000 frames/s, frame resolution - 1244×420 pixels) were used.

The results of experimental studies with values of gas-dynamic parameters and schlieren patterns are presented in Figure 7 and Table 2.

![Schlieren patterns of the flow over the body](image)

**Figure 7.** Schlieren patterns of the flow over the body. The frames are made in the steady-state regime: (a) \( \tau = 33 \) ms, (b) \( \tau = 36 \) ms, (c) \( \tau = 39 \) ms.

**Table 2.** Experimental parameters.

| Parameter                                      | Value          | Unit |
|------------------------------------------------|----------------|------|
| Static pressure                                | 200            | Pa   |
| Stagnation pressure                            | \( 25.3 \times 10^3 \) | Pa   |
| Pressure in discharge chamber after discharge ignition | \( 93.0 \times 10^6 \) | Pa   |
| Mach number of the flow                        | 17.1           | –    |
| Drag force                                     | 8.1            | N    |
| Drag force coefficient                         | 0.274          |      |

When comparing the results of numerical and experimental studies of the gas-dynamic parameters of the flow near the body at supersonic speeds, the criteria of geometric and dynamic similarity were used (according to the Mach and Reynolds numbers for the unperturbed flow).

The experimental and numerical simulation data were found to be highly consistent with each other (Table 3).

**Table 3.** Experimental and calculated gas-dynamics parameters.

| Physical parameter                              | Experimental values | Calculated values | Unit |
|------------------------------------------------|---------------------|-------------------|------|
| Stagnation pressure                            | \( 25.3 \times 10^3 \) | \( 27.9 \times 10^3 \) | Pa   |
| Mach number of the flow                        | 17.1                | 17                | –    |
| Drag force                                     | 8.1                 | 8.7               | N    |

A comparison of the schlieren patterns of the body flow (calculation and experiment) shows a good qualitative agreement between them (structures of the same type) (Figure 8).
4. Conclusions
This article presents the results obtained in the studies of the gas-dynamic parameters of a supersonic flow near the body at various Mach numbers. It has been found that the results of numerical simulation using the selected mathematical model of supersonic flow around the body is in good agreement with the experimental results obtained at the IT-1M hypersonic impulse tube of the aerodynamic laboratory of the Mozhaysky Military Space Academy. The discrepancies in the parameters obtained in the numerical simulation and the experiment were \( \Delta M \approx 0.8\% \) for the Mach number and \( \Delta p \approx 11.2\% \) for stagnation pressure.

The results obtained allow one to use the mathematical model as a basis for determining gas-dynamic parameters near bodies of various configurations.

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