Investigation of the interaction of conical bodies with an supersonic flow at low angles of attack

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Abstract. The study of the interaction of conical bodies with an incident supersonic flow is carried out. In the presented theoretical and experimental studies, the parameters of the incident flow near the investigated bodies were determined at different Mach numbers. Experimental studies were carried out using a supersonic atmospheric-vacuum tube of the aerodynamic laboratory of the Mozhaysky Military Space Academy. The theoretical study is based on the model of a viscous perfect gas described by the Navier-Stokes equations.

1. Introduction
In the last decade, there has been a steady trend towards the use of computer automated systems for gas dynamic calculations. The most effective is the use of numerical research methods in combination with experimental ones, which are a means of verifying the calculation results. Therefore, when comparing the results of numerical studies with the results of data obtained experimentally, it is important to correctly determine the adequacy of the mathematical models used in the calculations, which determine the accuracy of the results obtained. The article presents the results of studying the gas-dynamic parameters of a supersonic flow near conical bodies, which are common structural elements used in rocket and space technology.

2. Numerical simulation
Numerical calculations of the gas-dynamic parameters of a supersonic flow near conical bodies are carried out at various Mach numbers (M∞ = 1.5–3.5) and an angle between the body axis and the normal of the incident flow (α) in the range from 0 to 10°.

The following objects of study were selected: "Model 1" - a cone blunt over a sphere with a spherical bluntness radius r = 4.71 × 10^-3 m, a length of l = 3.4 × 10^-2 m, a half angle at the apex of the conical part θ = 9 and a diameter at the base d = 1.8 × 10^-2 m (Figure 1 (a, c)) and "Model 2" - a sharp cone with a length l = 3.4 × 10^-2 m, a semi-angle at the apex of the conical part θ = 16 and diameter at the base d = 1.8 × 10^-2 m (Figure 1 (b, d)).
Numerical calculations with the adiabatic exponent \((k = 1.4)\) were carried out on a difference grid with dimensions: model No. 1 - \(5.4 \times 10^6\) elements and model No. 2 - \(5.7 \times 10^6\) elements. As a turbulence model that closes the Reynolds-averaged Navier-Stokes equations, Menter’s shear stress transfer model was used [1-3]. To solve the system of equations, an implicit scheme on a tetrahedral structured grid was used (Figure 2). The normalized distance values are \(y^+ \approx 20\).

The choice of the form of the computational domain is due to the formation of a bow shock wave in front of the body in a supersonic flow. The boundaries of the outer computational domain cover the entire disturbed flow region near the models; at the same time, to reduce the computing power of the used server station, the minimum permissible number of cells has been determined.

On the outer boundary of the computational domain, a uniform incident flow \((p_\infty = 10^5\ \text{Pa})\) is specified (the degree of turbulence is 5%). At the outlet boundary, the condition for smooth flow continuation. On the surface of the model there is a non-leakage condition (Figure 3)
Calculation options are presented in table 1.

| №  | Model | $M_\infty$ | $Re_\infty$ | $\alpha$, deg |
|----|-------|------------|-------------|---------------|
| 1  | 1.5; 2.5; 3.5 | $6.4 \times 10^5$; $1.07 \times 10^6$; $1.51 \times 10^6$ | 0 |
| 2  | 1.5; 2.5; 3.5 | $6.4 \times 10^5$; $1.07 \times 10^6$; $1.51 \times 10^6$ | 5 |
| 3  | 1.5; 2.5; 3.5 | $6.4 \times 10^5$; $1.07 \times 10^6$; $1.51 \times 10^6$ | 10 |
| 4  | 1.5; 2.5; 3.5 | $6.4 \times 10^5$; $1.07 \times 10^6$; $1.51 \times 10^6$ | 0 |
| 5  | 1.5; 2.5; 3.5 | $6.4 \times 10^5$; $1.07 \times 10^6$; $1.51 \times 10^6$ | 5 |
| 6  | 1.5; 2.5; 3.5 | $6.4 \times 10^5$; $1.07 \times 10^6$; $1.51 \times 10^6$ | 10 |

As a result of the calculations performed, the coefficients of the drag force ($C_x$) were obtained for models No. 1 and No. 2 at different numbers $M_\infty$ and angle $\alpha$ (Figure 4). Dependencies of $C_x$ at angles $\alpha \leq 10^\circ$ for models No. 1 and 2 are practically linear.
The distribution of static pressure and density along the parabolic generatrix of the surface of model No. 1 at various numbers $M_\infty$ is shown in Figure 5. For model No. 2, the distribution of static pressure and density over the surface is shown in Figure 6.

**Figure 5.** Distribution of pressure (in Pa) (a, b, c) and density (in kg/m$^3$) (d, e, f) over the surface of model No. 1 at $\alpha = 0^\circ$ (a, d), $\alpha = 5^\circ$ (b, e) and $\alpha = 10^\circ$ (c, f). $M_\infty = 1.5; 2.5$ and $3.5$.

**Figure 6.** Distribution of pressure (in Pa) (a, b, c) and density (in kg/m$^3$) (d, e, f) over the surface of model No. 2 at $\alpha = 0^\circ$ (a, d), $\alpha = 5^\circ$ (b, e) and $\alpha = 10^\circ$ (c, f). $M_\infty = 1.5; 2.5$ and $3.5$.

### 3. Experimental results

To verify the numerical and physical models of the flow, we used the data obtained experimentally on the atmospheric-vacuum wind tunnel (AT ST-4) (Figure 7 (a, b)), developed and created by the staff of the Mozhaisky Military Space Academy [4].

Experiments in AT ST-4 were carried out at $M_\infty = 1.5; 2.5$ and $3.5$. The angle between the axis of the body and the normal of the incident flow varied from 0 to $10^\circ$. The working gas is air. Models of the investigated bodies are made of ABS plastic using additive 3D printing technologies (Figure 7 (c, d)).
Figure 7. Photos of AT ST-4. (a) general view, (b) working part, (c) fastening model No. 1 in the working part, (d) fastening model No. 2 in the working part.

Figure 8. Shadow patterns of the flow around the body model (Model no. 1). (a) steady state \( M_\infty = 1.5 \) and \( Re_\infty = 6.4 \times 10^5 \); (b) steady state \( M_\infty = 2.5 \) and \( Re_\infty = 1.07 \times 10^6 \), (c) \( M_\infty = 3.5 \) and \( Re_\infty = 1.51 \times 10^6 \).

To visualize the flow process, an IAB-451 schlieren-shadow device with laser and LED illuminators (wavelength 535 nm) and a SONY RX100M4 digital video camera (shooting frequency - 1000 frames/s, frame resolution - 1244 × 420 pixels) were used.

To convert elastic deformations of sensitive elements, proportional to the forces acting on the model, into electrical signals with subsequent registration, a three-component aerodynamic balance is used.

The results of experimental studies with the values of gas-dynamic parameters and shadow patterns are presented in Figures 8 and 9.

Figure 8 shows that the image of model 1 is deformed. The reason for the distortion is the strong refraction of light in the shock layer in front of the model; the aft area is distorted much less. It is impossible to measure the departure of the bow shock wave across the width of the visible shock layer. This is one of the disadvantages of the shadow method. For pointed bodies, the bow shock wave is much weaker and the distortion is less, which can be seen in the images of the flow around model No. 2 (Figure 9) obtained by the same method.
Figure 9. Shadow patterns of the flow around the body model (Model No. 2).
(a) steady state ($M_\infty = 1.5$ and $Re_\infty = 6.4 \times 10^5$) (b) steady state ($M_\infty = 2.5$ and $Re_\infty = 1.07 \times 10^6$; (c) steady-state mode ($M_\infty = 3.5$ and $Re_\infty = 1.51 \times 10^6$).

The averaged values of gas-dynamic parameters and shadow patterns obtained from the results of a series of experimental studies are presented in Tables 2, 3 and in Figure 12.

Table 2. Values of gas-dynamic parameters obtained experimentally for models No. 1.

| Parameter | Values | Unit |
|-----------|--------|------|
| $P$       | 200    | Pa   |
| $p_\infty$ | $1.02 \times 10^5$ | $1.02 \times 10^5$ | $1.02 \times 10^5$ |
| $M_\infty$ | 1.5; 2.5; 3.5 | 1.5; 2.5; 3.5 | 1.5; 2.5; 3.5 |
| $\alpha$ | 0      | 5    | 10   |
| $P_0$     | $1.025 \times 10^5$; $1.037 \times 10^5$; $1.025 \times 10^5$; $1.037 \times 10^5$; $1.025 \times 10^5$; $1.037 \times 10^5$ | $1.052 \times 10^5$ | $1.054 \times 10^5$ |
| $C_x$     | 0.53; 0.48; 0.46 | 0.55; 0.47; 0.45 | 0.54; 0.49; 0.45 | 0.45 |

Table 3. Values of gas-dynamic parameters obtained experimentally for model No. 2.

| Parameter | Values | Unit |
|-----------|--------|------|
| $P$       | 200    | Pa   |
| $p_\infty$ | $1.02 \times 10^5$ | $1.02 \times 10^5$ | $1.02 \times 10^5$ |
| $M_\infty$ | 1.5; 2.5; 3.5 | 1.5; 2.5; 3.5 | 1.5; 2.5; 3.5 |
| $\alpha$ | 0      | 5    | 10   |
| $P_0$     | $1.021 \times 10^5$; $1.023 \times 10^5$; $1.021 \times 10^5$; $1.023 \times 10^5$; $1.021 \times 10^5$; $1.023 \times 10^5$ | $1.026 \times 10^5$ | $1.025 \times 10^5$ |
| $C_x$     | 0.66; 0.54; 0.42 | 0.6; 0.51; 0.43 | 0.67; 0.52; 0.45 | 0.45 |

When comparing the results of numerical and experimental studies of the gas-dynamic parameters of the flow near the body at supersonic speeds, we used the criteria of geometric and dynamic similarity (in terms of the number $M_\infty$ and $Re_\infty$ for an unperturbed flow).

The data obtained are in agreement with each other with a high degree of reliability. The results of comparing the shadow patterns of the flow around the body (calculation and experiment) indicate their good correlation with each other (structures of the same type) (Figure 10).
4. Conclusion
In the range $1.5 \leq M_\infty \leq 3.5$ and $0 ^\circ \leq \alpha \leq 10 ^\circ$, a supersonic flow around conical bodies with cone half-angles $\theta = 9$ and $16 ^\circ$ is investigated. The obtained research results showed that the used mathematical models of supersonic flow around bodies at low angles of attack are in good agreement with the results of experimental studies carried out at the AT ST-4 aerodynamic tube of Mozhaysky Military Space Academy (the difference in values for $C_x \approx 5\%$ and $p_0 \approx 10.2\%$). It shows that used codes are reliable for the obtaining of the aerodynamic characteristics of the rocket and space technology with the corresponding ranges of numbers $M_\infty$ and $\alpha$.

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References
[1] Raymond Brun 2009 *Shock Tubes and Shock Tunnels: Design and Experiments* (RTO-EN-AVT-162 lecture series, von Karman Institute)
[2] F R Menter P F Galpin T Esch M Kuntz C Berner 2004 *Paper ICAS 2004–2.4.1*
[3] Liou M S Steffen C J 1993 *Journal of Computational Physics* **107**
[4] N P Savishenko et al 2018 *J. Phys.: Conf. Ser.* **1135** 012099