AERODYNAMIC CHARACTERISTICS OF CYLINDRICAL BODIES IN SUPERSONIC FLOW: NUMERICAL/EXPERIMENTAL STUDIES AND FLOW VISUALIZATION

V.I. Kornilov, I.N. Kavun
Khristianovich Institute of Theoretical and Applied Mechanics, SB RAS
630090, Novosibirsk, Russia

Introduction

On the modern spacecrafts are often used for special purposes capsules with radionuclide or reactor source on board [1]. In the event of an emergency capsule should autonomously return to Earth on a ballistic trajectory. During the descent in lower atmosphere the internal structure of capsule should not be subjected to the damaging effects of external heat fluxes and aerodynamic forces. This problem is solved by applying a temperature-resistant capsule and heat-shielding materials, and by the judicious selection of the ballistic parameter, which depends on the weight of capsule, its external shape and area of the midsection. In such a situation, it is also possible intentional orientation of capsule at the optimum angle of attack for the given aspect ratio, which is achieved by appropriate setting-off of capsule or special stabilizing devices [2].

Due to a number of specific features and design requirements, such a capsule should be possible of a simple geometric shape, usually a relatively small aspect ratio. In this regard, of particular interest is the configuration of a smooth flat-face circular cylinder. The similar configuration can have different shapes of rounded front faces, due to the requirements of reducing the loss of heat-shielding coating at the corners. Capsule of cylindrical shape is technological, beneficial in a constructive, layout and strength relations. However, for the weight optimization and selection of the most advantageous ballistic parameter necessary to know the influence of both angle of attack and aspect ratio on the aerodynamic characteristics of the capsule and, first all, on the drag coefficient. Important practical interest is the gasdynamic flow characteristics of the capsule, in particular, the position of shock waves, rarefaction waves, separation regions and other features of the flow.

Experiment conditions, techniques and procedure of numerical computation

All experiments were performed in a supersonic wind tunnel T-313 ITAM SB RAS [3], which is a blowdown facility of gas holder-type with air exhaust into the atmosphere. The test section of the T-313 is of square section with dimensions 0.6 × 0.6 m² length 2 m which installed in the pressure chamber. The wind tunnel is equipped by four component aerodynamic balance of the mechanical type with a multiple range measuring elements such as the rider. Operating range of Mach numbers $M_\infty$ is 1.75–7.0 (in increments of 0.25 to $M_\infty = 4$ and then in increments of 1).

The experiments were performed at a Mach number range of the incoming flow $M_\infty = 2.02–5.92$ and unit Reynolds number $Re_1$ from $12 \times 10^6$ to $50 \times 10^6$ m⁻¹ in the range of angles of attack $\alpha = 0°-90°$. As objects of research the models of a right circular cylinder of diameter $D = 80$ mm, made of alloy D16T, were used.

Mounting of the model on the tail sting, which in turn is fixed to the scimitar balance strut, was implemented with the help of a special seating nest, whose axis in the plane of the angle of attack forms with the longitudinal axis of the cylinder a given variable angle $\alpha_z$. Using this method, which has hitherto been known as a method of successive given angles, caused by the need to cover the entire investigated range of angles of attack, because the angle of turning of the sting is limited by the $\alpha_z$-balance mechanism. For this reason, for the study of aerodynamic characteristics of a cylinder with various aspect ratio several similar models were used, differing by the angle $\alpha_z$. Step changes in the angle of attack $\alpha$ during testing was mainly 5°. Moreover, the maximum angle $\alpha$ does not exceed 90°. The presence of symmetry of the model allows us to extend the results of
experiments on the angle $\alpha > 90^\circ$ and thereby obtain the circular aerodynamic characteristics of the cylindrical bodies.

When determining the aerodynamic coefficients $C_x$ and $C_y$ the measured aerodynamic forces $X$ and $Y$ (drag and lift) refers to a value $q_\infty \cdot \pi D^2/4$, where $q_\infty$ is dynamic velocity of the incoming flow. Angle of attack, in which the longitudinal axis of the model coincides with the velocity vector of the incoming flow, taken as zero ($\alpha = 0$).

Statistical treatment of 7-fold measurements of aerodynamic characteristics of one of the models was shown that tolerance limits represented an interval in which the probability $P = 0.95$ are 95% of the sampled results are as follows

$$\Delta C_x = \pm 0.015; \Delta C_y = \pm 0.015.$$

Visualization of the flow picture in the vicinity of the test models was carried out using an optical shadow device Toepler IAB-451. In some cases, the method of limiting imaging surface streamlines on the base of a mixture consisting of the transformer oil with kerosene and a pigment in the form of carbon black was used.

Numerical solution of the problem of the flow over cylindrical bodies was performed using a commercial software package ANSYS Fluent. The three-dimensional Reynolds equations using $k$-$\omega$ SST turbulence model were solved. As a working medium is a viscous heat-conducting perfect gas. It is assumed that the thermodynamic state of the gas is described by Mendeleev – Clapeyron. The heat capacity of the gas is considered to be constant. The dynamic viscosity of the gas is a function of temperature and is given by Sutherland. The dependence of the thermal conductivity on temperature is calculated from the kinetic theory of gases in accordance with the formula Aiken. Heat transfer between the wall and the air flow is absent.

The geometry of the computational domain is a cylindrical area with diameter $10D$ and length $10L$, in the center of which is located the tested aerodynamic model. For a given task the value of the coefficients of drag and lift forces depend primarily on the ratio of the pressure on the windward and leeward sides of the model. For this reason the boundary layer in the calculation is not resolved in detail. Dimensionless parameter characterizing the boundary layer height $y^+ = (\rho v \sqrt{\tau_w} / \rho_\infty) / \mu$ was $10^0–10^2$. Computational grid on the model surface was set approximately uniform, namely of shape of the hexagonal cells. The number of cells along the radius of the cylinder, the circumference and on its length is 100, 400 and 200, respectively. In free flow computational grid is made with some of the tenuity from the model surface to the outer surface of the computational domain. The number of cells in the surrounding space model in the direction of the surface of the model to the outer boundary of 100 in all directions. The total number of cells in the computational domain is of 14 million.

Main results

**Aerodynamic characteristics.** The experimental and calculated data were revealed a number of important properties and peculiarities of flow around cylindrical bodies. In particular, in the investigated range of aspect ratio $\lambda$ the drag coefficient $C_x$ of the cylinder when $\alpha = 0^\circ$ is actually independent on the magnitude $\lambda$. It is clear that in this case the skin friction value is extremely small in the overall balance of aerodynamic drag of such bodies, so the value of $C_x$ is almost completely determined by the component of the wave drag caused by intense shock wave in front of the cylinder face. On the contrary, in a crosswise flow ($\alpha = 90^\circ$) the effect of aspect ratio on $C_x$, as one would expect, reaches a maximum value. This confirms also Fig. 1, in which the dependences of $C_x = f(\lambda)$ of cylindrical model in the range of aspect ratios from 0.6 to 12.0 and sampled values of the angle of attack $\alpha = 0, 10^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ, 70^\circ, 80^\circ$ и $90^\circ$ are shown. One can be seen, in particular, that at the flow around the cylinder with aspect ratio $\lambda = 1.1$ the influence of the angle of attack on the drag coefficient is practically absent. Thus, if for the cylinder $\lambda > 1.1$ the distinguishing capacity is growth $C_x$ with increasing angle of attack, so for the cylinder $\lambda < 1.1$ is a decrease.
Fig. 1. Variations of the drag coefficient of cylindrical body with the cylinder aspect ratio at sampled values of the angle of attack $\alpha$.

In this case also attention paid to a number of peculiarities in the behavior of the drag coefficient of the cylinder as a function of aspect ratio at variation of the model angle of attack. It is easy, in particular, be noted that the change in $C_x = f(\lambda)$ of cylindrical model in the range of aspect ratio of 0.6 to 12.0 for the angles of attack $\alpha$ of 0 to 90° has a character close to linear. In this case, the growth rate of the value of $C_x$ with increasing $\lambda$ directly proportional to the angle of attack.

These and some other features of flow allow present all the experimental data in the form of a simple generalization relationship:

$$C_x = 1.685\{1 + (\lambda - 1.1)[(\alpha\,90^\circ)^{1.5} - (\text{Sin}4\alpha)/10.6]\},$$

which is convenient in terms of practical use, because it allows easy to determine the drag coefficient of the cylindrical body in the flow coordinate system, knowing its aspect ratio and angle of attack. As an example, in Fig. 2 for the case of a flow around the cylinder $\lambda = 2.0$ the comparison of experimental results (circles) and calculated (dashed line) data obtained using the above relationship (1) is given.

![Fig. 2. Comparison of experimental values (circles) of drag coefficient of cylinder with those predicted by relationship (1) (dashed line) for $\lambda = 2.0$.](image)

![Fig. 3. Drag coefficient of cylinder as function of its aspect ratio at $\alpha = 90^\circ$.](image)

Note also important regularity in the behavior of the drag coefficient of the cylinder depending on $\lambda$ when $\alpha = 90^\circ$. This can be seen from Fig. 3, which shows the results of measurement $C_x$ in a wide range of the model aspect ratio $\lambda = 0.6; 1.0; 1.3; 1.5; 2.0; 2.6; 3.0; 4.4; 8.0; 12.0$. It turned out
that the drag force normalized by the dynamic velocity and area of the longitudinal section of the cylinder $DL = D^2 \lambda$ leads to the constant value of 1.24 in drag coefficient $C_D$ with an error not greater than $\pm$ 3%. All this suggests that the drag of form makes proportional to the length of the model contribution to the total balance of aerodynamic drag, and the role of the cylinder faces is the same for all tested aspect ratios. Some deviation $C_D$ from constant value of 1.24 at small $\lambda$, possibly due to the arising in these cases, interference by the flow around closely spaced faces of the model. This means that when $\lambda \leq 1$ the linearity of this dependence is likely to be observed will not.

Interesting features in the behavior of the aerodynamic characteristics $C_t$, $C_n$ of cylindrical body in the model coordinate system are revealed. In particular, the variation of the normal force coefficient $C_n = f(\lambda)$ in the range of $\alpha = 0 \rightarrow 90^\circ$ has a character close to the linear (Fig. 4), which is consistent with a modified Newtonian theory. This case is confirmed by the known fact that the coefficient of tangential force $C_t$ does not depend on the aspect ratio of the cylinder. Indeed, Fig. 5, in which the value of $\lambda$ selected as a parameter, is proof of that.

![Fig. 4. Variations of the normal force coefficient with the cylinder aspect ratio in the range of angles of attack $\alpha = 0 \rightarrow 90^\circ$.](image1)

![Fig. 5. Comparison of experimental values of the tangential force coefficient (symbols) with those predicted by relationship (2) (line) in the range of angles of attack $\alpha = 0 \rightarrow 90^\circ$.](image2)

Marked features enabled with satisfactory accuracy for practice to generalize the available experimental data in the form of a simple empirical relationship, which is a function of only the angle of attack model

$$C_t = 1.685[(\cos \alpha)^{1.65(\alpha^90^\circ)}]$$

(2).

It should be noted that the obtained experimental results are confirmed by the corresponding numerical calculations. As an example the Table shows the comparison of the experimental and calculated values of the drag coefficient of the cylinder $\lambda = 2$ at the different Mach numbers and angles of attack.

<table>
<thead>
<tr>
<th>$M_\infty$</th>
<th>2.02</th>
<th>2.98</th>
<th>4.04</th>
<th>5.02</th>
<th>5.92</th>
<th>4.04</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha^\circ$</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>32</td>
<td>58</td>
<td>90</td>
</tr>
<tr>
<td>$C_{t,\text{exp}}$</td>
<td>1.644</td>
<td>1.695</td>
<td>1.685</td>
<td>1.644</td>
<td>1.664</td>
<td>1.685</td>
</tr>
<tr>
<td>$C_{t,\text{comp}}$</td>
<td>1.626</td>
<td>1.686</td>
<td>1.678</td>
<td>–</td>
<td>–</td>
<td>1.678</td>
</tr>
</tbody>
</table>

As can be seen, the maximum difference between them is less than 1%. In fairness, we note that some variability of the experimental values for $C_t$ at different Mach numbers might be due to the fact that the Reynolds number is not able to sustain the same for all $M_\infty$. 

4
Experimental and computer visualization

Within the framework of the Navier – Stokes equations for the flow parameters occurring in the experiment, the gasdynamic flow structure in the vicinity of a cylindrical body with the help of a software package Fluent was computed. As an example, Fig. 6 shows the shock-wave structure around the cylinder $\lambda = 2$ at $\alpha = 0^\circ$ and Mach number $M_e = 2$ (a); 3 (b); 4 (c). In general, the main gasdynamic peculiarities are about the same. With increasing Mach number the departure of the bow shock from the cylinder face is decreased. At the same time shock inclination (flattening) along $x$ coordinate is increased, which is quite natural. Region of flow separation, especially when $M_e = 2$, and oblique shock formation at the point of attachment of the boundary layer behind the leading corner point clearly visible. The turning flow after passing a fan of expansion waves from the trailing corner point creates a convergent fan of compression waves.

![Fig. 6. Shock-wave structure around cylinder $\lambda = 2$ at $\alpha = 0^\circ$ and Mach number $M_e = 2$ (a); 3 (b); 4 (c).](image)

Another example of the computation of the gas-dynamic flow structure is shown in Fig. 7 when the angle of attack $\alpha$ is varied. It can be seen that the flow pattern becomes more complex when $\alpha$ grows (Fig. 7b, 7c, 7d). On the leeward side of the model the flow separation with the formation of an oblique shock at the point of attachment of the boundary layer is implemented. When $\alpha = 58^\circ$ (Fig. 7d) possible secondary separation with the flow attachment and the formation of additional oblique shock is implemented. On the windward side the pronounced (within the length of the model) moving the shock wave to the side wall of the cylinder is observed. Closing supersonic zones in the wake of the cylinder base at $\alpha = 17^\circ$ и $32^\circ$ (Fig. 7b, 7c) initiates here a new shock wave.

In Fig. 8a gasdynamic flow structure in the vicinity of the longitudinally streamlined circular cylinder ($\alpha = 0$) is also given, as the areas of equal values of flow density. In Fig. 8b the areas of equal values of Mach numbers are shown with wearing on their background streamlines (arrows).

The bow shock 1 in front of the body, the expansion waves 2 and 3 in the region of flow separation behind the leading corner point and trailing corner point, respectively, attached shock wave 4 behind the region of flow separation, detached shock wave 5, which is formed as a result of turning the flow field in the wake region, and also the wake itself 6 behind the body clearly visible.

Figure 9 shows the comparison of the computed (top) and experimental (bottom) gasdynamic flow structure, formed in the vicinity of the longitudinally streamlined cylinder. (Here the knife-edge systems for schlieren photography is horizontal, making the images above and below the antisymmetric.) It is easy to notice almost complete identity in the position of the bow shock and its shape. It is not surprising, therefore, that the computed when $\alpha = 0$ value of the cylinder drag coefficient $C_x$ differs little from the experimental result.
As it follows from foregoing, a satisfactory agreement between the computational data and the experimental results has been obtained also when changing the Mach number and angle of attack of the cylindrical body.

**Brief conclusions**

The analysis of aerodynamic characteristics of cylindrical bodies with the aspect ratio λ = 0.6÷12.0 in the range of angles of attack α = 0÷90° and Mach number range $M_\infty = 2.02$–5.92 was performed. The findings lead to the following conclusions.
1. The drag coefficient $C_s$ of the cylinder in the investigated range of $\lambda$ when $\alpha = 0$ is actually independent of the aspect ratio of the latter. On the contrary, in a crosswise flow ($\alpha = 90^\circ$) the effect of the aspect ratio on $C_s$ reaches its maximum value. The dependence $C_s=f(\lambda)$ in the range of angles of attack $\alpha = 0^\circ$– $90^\circ$ has a character close to the linear. These and some other features of flow over the tested cylinders allowed to be presented the experimental data in the form of a simple empirical relationship.

2. The important regularity in the behavior of the drag coefficient of the tested cylinders at $\alpha = 90^\circ$ was revealed. The essence of this is that drag force normalized by the dynamic velocity and area of the longitudinal section of the cylinder leads to the constant value of 1.24 in the drag coefficient with an error not exceeding ± 3%.

3. The valuable features in the behavior of the aerodynamic characteristics of the tested cylindrical bodies in the model coordinate system were revealed. In particular, the variation of the normal force coefficient with the cylinder aspect ratio in the range of $\alpha = 0 \div 90^\circ$ has a character close to the linear, which agrees with Newton's shock theory. In this case the known fact is confirmed that the coefficient tangential force does not depend on the cylinder aspect ratio. Marked features enable with satisfactory accuracy for practice to generalize the available experimental data in the form of a simple empirical relationship, which is a function of only the angle of attack.

4. Computation results of gasdynamic flow structure in the vicinity of a cylindrical body, in particular, the position of the shock wave in front of the body, its shape and other flow parameters obtained within the framework of the Navier – Stokes equations are in satisfactory agreement with the data of flow structure visualization by shadowgraph. As a consequence, the computed values of the drag coefficient of the circular cylinder at various angles of attack differ from the experimental ones less than 1%.

REFERENCES

