Effect of the structure of skeleton models of cellular materials on the drag of a cylinder with a frontal gas-permeable insert in a supersonic flow

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Abstract. The paper presents the results of the numerical simulation of the supersonic \((M_\infty = 7)\) flow around the cylinder with the front gas-permeable porous insert at different angles of attack. The numerical simulation involves the comparative analysis of a number of skeleton models of high-porous cellular materials of the front insert: from the set of coaxial rings of different diameters, and the set of hollow spheres with different spatial resolution. The calculated data of the drag coefficient have been compared with the wind tunnel experiment results.

1. Introduction

The tasks of control of the flow around bodies which are important for practical applications can be divided into two groups: the tasks related with the inhibition of the disturbances caused by developing acoustic waves [1-5] in hypersonic boundary layers, and the tasks of control of the mean flow characteristics [6-8]. Use of gas-permeable high porous materials in supersonic aerodynamics permits controlling the air drag for aircrafts [7-20]. Experimental and numerical results showed the high efficiency of the control of the air drag for a cylinder with a front porous insert made from cellular-porous nickel with the high porosity value. The blunt cylinder model located along the flow was chosen in order to show up the higher effect of porosity on the model drag reduction. A ring skeleton model from a high-porous cellular material (HPCM) was chosen for the conditions of the cylinder flow at the zero angle of attack [8, 14-16, 1-20].

Practical needs of supersonic aerodynamics call for experimental and numerical investigations of the flow around bodies with gas-permeable inserts under angles of attack. The transition from the axisymmetric flow task to the 3D task suggests the development of new models of the porous medium and approximation of its spatial structure to the real HPCM carcass. Today, there are no investigations in the literature devoted to the effect of the structure of gas-permeable porous materials on air drag characteristics of bodies.

This paper presents the early results of experimental and numerical investigations in this direction. The paper presents two 3D models with the different HPCM spatial structure: the ring skeleton model...
for the non-symmetric flow around the cylinder with the front porous insert and the skeleton model from hollow spheres. The results of these models construction and utilization are presented experimental and numerical aerodynamic coefficients of the cylinder with the front porous insert are obtained for different angles of attack, the data are compared to each other.

2. Experimental model and wind-tunnel measurements of aerodynamic forces

The model presenting a solid cylinder 14.5 mm in diameter, in which a thin tube moves with no gap (see figure 1a) is used in the experimental researches. The tube purpose is to keep the gas-permeable porous insert on the cylinder leading end-face, plus to change the insert length in the flow. The general model length \( L \) was constant (100 mm). The model photo and schematic are given in [8-10, 12, 13, 18-20, 21]. In the experiment, the porous inserts with the porosity value \( k = 0.95 \) and pore cell diameter \( d \) of 1; 2, 3 and 4 mm were used.

The experiments with the model were carried out in the supersonic wind tunnel T-327B ITAM SB RAS at the Mach number \( M_\infty = 7 \) and unit Reynolds number \( Re_\infty = 1.5 \times 10^6 \text{ m}^{-1} \). The aerodynamic forces measurements were performed with the aid of three-component strain gage balance. The model was fixed to the balance with a holder which permits changing the angle of attack by the model [21]. The aerodynamic forces were measured as the model angle of attack was varied within the limits \( \alpha = 0 - 15^\circ \), and the relative length of the porous insert variation \( \Delta x/D = 0 - 2 \).

![Figure 1](image)

**Figure 1.** Experimental model of the cylinder with the front porous insert (a); cylinder model under in the numerical simulation: with the 2D-skeleton of the front porous insert (b) and with the 3D-skeleton from coaxial rings (c); with the 3D-skeleton from the set of hollow spheres (d). \( L = 100 \text{ mm}, D = 14.5 \text{ mm}, \Delta x = 28 \text{ mm}, k = 0.95, d = 2 \text{ mm} \).

3. Numerical simulation of the axisymmetric flow around the cylinder with the front porous insert (2D ring skeleton model)

To simulate the flow in the front HPCM gas-permeable porous insert on the leading end-face of the cylinder flown at the zero angle of attack, the skeleton model with a simple spatial structure from coaxial rings of different diameters is suggested. In the axial cross section plane, this ring system presents a set of impermeable chequered square elements (figure 1b).

This model was previously used to construct the skeletons of the front porous insert, the pore diameters are \( d = 1 \text{ mm} \) and 3 mm. The paper models the skeleton of the HPCM front porous insert, \( d = 2 \text{ mm} \). Figure 2 shows the density fields at the flow around the solid cylinder and the cylinder with the front porous insert (the length \( \Delta x = 28 \text{ mm} \) at the Mach number \( M_\infty = 7 \) and zero angle of attack. Table 1 demonstrates that the resulting computational data by the cylinder drag coefficients and the value of drag reduction coincide with the experiment within the measurement accuracy limits.
Figure 2. Density fields at the flow around the cylinder $D = 14.5$ mm: the solid cylinder (a) and cylinder with the front porous insert $\Delta x = 28$ mm, $k = 0.95$, $d = 2$ mm (b). $M_\infty = 7$, $Re_1 = 1.5 \times 10^6$ m/s.

Table 1. Cylinder drag coefficients

| $M_\infty = 7$ $Re_1 = 1.5 \times 10^6$ m/s | $C_\alpha$ | $C_\alpha$ | $C_\alpha/ C_\alpha$ |
|-------------------------------------------|----------|-----------|------------------|
| Experiment                                | 1.83±0.015 | 1.304±0.015 | 0.712             |
| CFD                                       | 1.8429    | 1.3084    | 0.71              |

4. Numerical simulation of the flow around the cylinder with the front porous insert at the angle of attack

4.1. The solid cylinder

To determine the effect of the front porous insert in the cylinder flown by a supersonic flow at the angle of attack, the flow around the solid cylinder should be calculated. The task of the non-symmetric flow around the cylinder was solved within the framework of Reynolds-averaged 3D Navier Stocke equations, with the aid of the ANSYS Fluent package.

Figure 3a-3d show the computational density fields on the solid cylinder flown by the supersonic ($M_\infty = 7$) flow at different angles of attack. It is evident that at every angle of attack, the separating arched shock wave forms ahead of the leading end-face of the cylinder. As the angle of attack rises, the head shock wave presses to the cylinder surface windward, and distances from the surface leeward. The obtained calculated values of the drag coefficient (the curves) are presented in figure 4 for different angles of attack in comparison with the experimental findings (the symbols) obtained in the wind tunnel T-327B ITAM SB RAS (see Chapter 2). The data difference does not exceed 4%.

The computational code was verified also by means of comparison with the experimental data found in the wind tunnel T-313 ITAM SB RAS [22] for the solid cylinder at $M_\infty = 4$, $Re_1 = 50 \times 10^6$ m/s (see figure 4). It is obvious that the scatter of the calculated and experimental data does not exceed 4% either.

Figure 4 also shows that the drag coefficients rise along with the angle of attack growth. The reason is that, as the angle of attack rises, the asymmetric flow around the cylinder increases the size of the body interacting with the flow.

4.2. 3D skeleton ring model

The 2D ring HPCM skeleton model has shown good results in the calculations of the axisymmetric flow around the cylinder with the front porous insert. That is why the ring model (figure 1c) constructed in the same way as the 2D ring skeleton model has been chosen as the first 3D model. The 3D model also features only three parameters (the porosity value $k$, pore diameter $d$, and HPCM transparency length), which are easily found by direct measurements.

Figure 3e-3h presents the calculated density fields on the cylinder with the front porous insert flown by the supersonic ($M_\infty = 7$) flow at different angles of attack. Evident that at every angle of attack, the head shock wave attaches to the leading end-face of the model, and the angle of the head shock wave inclination toward the flow reduces. Moreover it is obvious that the intensity of the head shock wave leeward the model is much lower than it is during the flow around the solid cylinder.
Figure 3. Calculated density fields $M_\infty = 7$, $Re_\infty = 1.5 \times 10^6$ m$^{-1}$ during the flow around the solid cylinder (a-d) and the cylinder with the front porous insert $\Delta x = 29$ mm, $k = 0.95$, $d = 2$ mm (e-h) at different angles of attack: (a,e) - $\alpha = 0$; (b,f) - $\alpha = 5^\circ$; (c,g) - $\alpha = 10^\circ$; (d,h) - $\alpha = 15^\circ$.

Figure 4. Drag coefficients $C_x$, $C_y$ of the solid cylinder versus the angle of attack: 1-2 – calculated data $C_x$; 3 - calculated data $C_y$; 4, 6 – experimental data (T-327B); 1, 3, 4, 6 - $M_\infty = 7$, $Re_\infty = 1.5 \times 10^6$ m$^{-1}$; 2, 5 - $M_\infty = 4$, $Re_\infty = 50 \times 10^6$ m$^{-1}$; 5 - experimental data $C_x$ (T-313 ITAM SB RAS) [22].
Figure 5. Drag coefficients $C_x$, $C_y$ of the cylinder with the front porous insert $\Delta x = 29$ mm, $k = 0.95$, $d = 2$ mm versus the angle of attack: 1, 3 – calculated data $C_x$, $C_y$; 2, 4 - experimental data obtained in the wind tunnel T-327B ITAM SB RAS; $M_\infty = 7$, $Re_{1\infty} = 1.5 \times 10^6$ m$^{-1}$.

The found calculated data of the drag coefficient values (the curves) on the cylinder with the front porous insert are shown in figure 5 for different angles of attack in comparison with the experimental data (the symbols) obtained in the wind tunnel T-327B ITAM SB RAS (see Chapter 2). The maximal difference is 10%. Here, similarly to the solid cylinder (figure 4), the drag coefficients rise along with the angle of attack growth.

4.3. 3D skeleton model from hollow spheres (spherical)

Another 3D skeleton model in appearance is more similar to the cellular structure of the HPCM; it presents the set of hollow spheres with the diameter equal to the HPCM pore diameter $d$. The sphere position is such that the sphere centers are in octahedron apexes, the octahedron rib length is $a$ and $b = \sqrt{3}a/2$ (figure 6a). The gas passes through the holes in the hollow spheres. The distance between the sphere centers can be either smaller than the sphere diameter $d$ – the crossing spheres (figure 6b), or bigger than $d$ – the non-crossing spheres (figure 6c). In the second case, to provide the gas passage through the spheres, the cylindrical channels of the radii $R_1$ and $R_2$, respectively, are cut along the octahedron ribs $a$ and $b$ (see 6a). The values of these radii correspond to the certain value of material permeability $q$. Here, $q$ is the ratio of the sum of the though-holes projection areas to the full area of the material projection toward the flow. The radii $R_1$ and $R_2$ were chosen in such a way to preserve the material skeleton unbroken. Figure 6b,c demonstrates the elementary volumes of the skeleton model for the cases of the crossing and non-crossing spheres. Green indicates the edges of contact with neighboring elementary volumes, grey shows the hollow sphere boundaries, red and violet show the internal surfaces of the respective cylindrical channels.

Figure 6. (a) – Scheme of the spatial position of the closely located spheres as an octahedron; (b) the elementary volume of the skeleton model from the hollow crossing spheres; (c) the elementary volume of the skeleton model from the hollow non-crossing spheres.

Figure 7 presents the projection of the skeleton model from the set of hollow spheres on the plane ($y$, $z$) for different parameters $k$, $a$, and $q$. For these variants, the calculations were carried out to clarify the influence of the structure on the drag coefficient $C_t$ (see table 2).
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According to Table 2, the coefficients $C_r$ obtained for the used set of parameters of the spherical model turned out to be higher than the values obtained for the ring model and in the experiment. However, the wide range of variation of the coefficient $C_r$ (from 1.55 to 1.72) permits in future, varying the spherical model parameters, having the data in agreement with the experiment. Furthermore, the variants of octahedron turn in order to increase the parameter $q$ were beyond the consideration in the current structure of the spherical model.

| Skeleton model | $k$ | $a$, mm | $q$ | $C_r$ | $C_r/C_{\infty}$ |
|----------------|-----|---------|-----|-------|------------------|
| Ring           | 0.95| -       | -   | 1.39  | 0.75             |
| Spherical      | Figure 7(a) | 0.95 | 0.98 | 0.59 | 1.72 | 0.922 |
| Spherical      | Figure 7(b) | 0.98 | 0.95 | 0.81 | 1.57 | 0.842 |
| Spherical      | Figure 7(c) | 0.98 | 0.98 | 0.81 | 1.547 | 0.829 |
| Spherical      | Figure 7(d) | 0.95 | 1.05 | 0.61 | 1.686 | 0.9 |

5. Conclusion
The effect of the structure of the high-porous cellular-materials skeleton models on the drag of the cylinder with the front gas-permeable insert has been numerically simulated in the supersonic flow. It is demonstrated that the parameters of the model porous material impose the essential influence of the drag coefficients of the flow around the cylinder with the front porous insert.

References
[1] Fedorov A V, Shiplyuk A N, Maslov A A et al. 2003 J. Fluid Mech. 479 99-124
[2] Maslov A A, Kudryavtsev A N, Mironov S G et al. 2007 J. Appl. Mech. Tech. Phys. 48 368-74
[3] Maslov A A, Mironov S G, Kudryavtsev A N et al. 2010 J. Fluid Mech. 650 81-118
[4] Maslov A A, Mironov S G, Poplavskaya T V et al. 2012 J. Appl. Mech. Tech. Phys. 53 162-72
[5] Tsyryulnikov I S, Maslov A A, Mironov S G et al. 2015 Tech. Phys. Lett. 41 184–86
[6] Maslov A A, Mironov S G, Poplavskaya T V, et al. 1999 European Journal of Mech. B/Fluids 18(2) 213-26
[7] Mironov S G, Maslov A A, Poplavskaya T V et al. 2015 J.Appl. Mech. Tech. Phys. 56 549–57
[8] Maslov A A, Mironov S G, Poplavskaya T V et al. 2019 J. Fluid Mech. 867 611-32
[9] Fomin V M, Mironov S G and Serdyuk K M 2009 Tech. Phys. Lett. 35 117-19
[10] Bedarev I A, Mironov S G, Serdyuk K M et al. 2011 J. Appl. Mech. Tech. Phys. 52 9-17
[11] Mironov S G, Maslov A A and Tsyryulnikov I S 2014 Tech. Phys. Lett. 40 888-90
[12] Mironov S G, Maslov A A and Tsyryulnikov I S 2015 Method of control over supersonic aircraft
overflow. Pat. 2559193 C1 RU
[13] Mironov S G, Kolotilov V A and Maslov A A 2015 Thermophysics and Aeromechanics 22 599-607
[14] Poplavskaya T V, Kirilovski S V and Mironov S G 2016 AIP Conf. Proc. 1770 030067
[15] Poplavskaya T V, Kirilovski S V and Mironov S G 2017 J. Phys.: Conf. Series 894 012074
[16] Poplavskaya T V, Kirilovski S V, Mironov S G et al. 2017 AIP Conf. Proc. 1893 030155
[17] Mironov S G, Poplavskaya T V and Kirilovski S V 2017 AIP Conf. Proc. 1893 030151
[18] Mironov S G, Poplavskaya T V and Kirilovski S V 2017 Thermophysics and Aeromechanics 24 629-32
[19] Kirilovski S V, Maslov A A, Mironov S G et al. 2018 Fluid Dynamics 53 409–16
[20] Mironov S G, Poplavskaya T V, Kirilovski S V et al. A A 2018 Tech. Phys. Lett 44 225-8
[21] Maslov A A, Mironov S G, Poplavskaya T V et al. 2019 J. Phys. Conf. Series (in press)
[22] Kornilov V I and Lysenko V I 2011 NSU Newsletter. Series: Physics 6 16-24