Effect of porous inserts on aerodynamics of flying vehicles

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Abstract. Experimental and numerical investigations of a supersonic flow around a cylindrical model with a porous frontal insert made of a high-porosity cellular material performed at the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences are briefly reviewed. New data on the influence of the angle of attack on the flow around a cylinder with a porous frontal insert are reported. Methods of using high-porosity cellular materials for controlling supersonic flows around axisymmetric bodies are demonstrated.

1. Introduction

One of the methods used to control the wave drag and friction drag of flying vehicles is the use of porous materials. Application of inserts made of porous materials allows one to affect the laminar-turbulent transition and shock wave-boundary layer interaction, prevent flow separation, withdraw some part of the incoming flow with the help of the porous frontal insert and organize its bypass to the base region of the vehicle, etc. In turn, the presence of the gas-permeable frontal insert may lead to redistributing of viscous friction due to friction in pores and to air overflow in the transverse direction. These processes may be particularly effective in high-porosity cellular materials (HPCM). HPCM interaction with a supersonic flow can significantly alter the flow around the vehicle and affect the aerodynamic characteristics of the latter.

The present paper describes experimental and numerical investigations of a supersonic flow around a cylindrical model with a gas-permeable frontal insert made of HPCM aligned at a zero angle of attack, which were performed at the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences (ITAM SB RAS). Wind tunnel experiments with cylindrical models having a porous frontal insert and calculations performed with the continuum and skeleton models of the porous material revealed significant reduction of the wave drag. Mechanisms of drag reduction in supersonic flows are described. Various methods of HPCM applications for creating systems for control of supersonic flows around axisymmetric bodies are discussed. New data on the influence of the angle of attack on the flow around a cylinder with a frontal insert made of HPCM are presented. The data were obtained in wind tunnel experiments and in computations with the use of new three-dimensional skeleton models of the porous material.
2. Review of investigations of a supersonic flow around a cylindrical model with a gas-permeable frontal insert made of HPCM aligned at a zero angle of attack performed at ITAM SB RAS

ITAM SB RAS is a leader in studying of gas-permeable porous materials application for control of supersonic flows around flying vehicles. Many comprehensive investigations combining experimental and numerical studies were performed at ITAM SB RAS for the last decade.

Experimental investigations were performed with a simple model, which was a cylinder with a cylindrical gas-permeable porous frontal insert made of HPCM. The experiments were conducted in wind tunnel based at ITAM SB RAS in the ranges of flow Mach numbers $M_\infty = 5 \div 21$ and unit Reynolds numbers $Re_\infty = (0.6 \div 13.5) \times 10^6$ m$^{-1}$. The drag force of the model was measured in the experiments for different values of the porous insert length $\Delta x$, pore diameter $d$ in the HPCM, and cylinder diameter $D$. The force measurements were supplemented with the Schlieren visualization of the flow field around the model. Already the first experimental investigations [1] revealed a significant decrease in the drag force of the cylinder with a porous frontal insert made of HPCM in a supersonic flow.

The first numerical investigations of a supersonic flow with a gas-permeable frontal porous insert [2, 3] were performed with the use of the continuum model of a porous medium based on the Darcy-Forchheimer filtration law. The computations revealed that it is rather difficult to apply the continuum model of filtration in numerical simulations of a supersonic flow around bodies with porous inserts. The reason for problems involved in using continuum models for supersonic flows is significant nonuniformity of the flow in the porous material in terms of both velocity and density. As a result, the coefficients in the Darcy-Forchheimer law are variable quantities depending on the position of the flow region in the porous material. They have to be obtained for each region of the frontal insert in wind tunnel experiments or in measurements in filtration test rigs [4]. Thus, the porous insert was divided in [3] into two domains (with high and low velocities of the air flow in pores) with different values of the coefficients in the Darcy-Forchheimer filtration law.

Nevertheless, numerical simulations of a supersonic flow around a cylinder with a porous frontal insert with the continuum model made it possible to clarify the physical aspects of the drag reduction phenomenon. It was demonstrated that, because of the difference in the hydraulic drag of the central and peripheral layers of the porous material of the frontal insert, the shape of the streamlines corresponds to the flow around an effective pointed body whose drag is smaller than that of the cylinder without the porous insert (Fig. 1). It was also shown that the flow field in the porous material and, correspondingly, the drag of the cylinder with a porous frontal insert is determined by the inertial (quadratic) term in the Darcy-Forchheimer law, while the friction in the pores is low.

The continuum approach requires empirical data to be obtained in wind tunnel experiments and measurements in filtration test rigs. Therefore, another approach was used in further numerical simulations: direct modeling of the gas flow in the porous material skeleton. Its advantage is the use of data only on the spatial geometry of the porous material skeleton without involving additional empirical data on its filtration properties. In this approach, the porous medium is presented as a spatial system of discrete elements (2D skeleton model of the porous medium).

A skeleton model as a set of coaxial ring-shaped elements with a quadratic cross section was proposed and successfully implemented for numerical simulations of the flow around a cylinder with a porous insert for the first time in [5, 6]. It should be noted that the proposed skeleton model does not represent the real structure of the porous material used (foamed nickel). Therefore, HPCM skeleton construction is based on two assumptions. First, the governing parameters of the model are the porosity coefficient and the HPCM pore size. Second, in an axisymmetric flow around the HPCM sample, air basically moves only in the streamwise and radial directions, while the air velocity in the azimuthal direction is negligibly small because of the random arrangement of the pore walls in the real material and the absence of azimuthal pressure difference at a zero angle of attack.
Validation of the proposed approach showed that these assumptions were correct. The calculated data on the filtration dependences [7], bow shock wave (SW) position, and drag coefficients are in good agreement with the test rig and wind tunnel experiments [8 , 9]. Significant (55%) drag reduction was obtained for long porous inserts (Δx/D ≥ 1.5). For short inserts (Δx/D ≤ 0.2), the minimum degree of drag reduction was observed. It was shown that the drag reduction mechanism for a cylinder with a gas-permeable porous frontal insert in a supersonic flow includes attenuation of the bow SW and formation of a system of weaker waves in the external flow behind the bow SW (Fig. 2). It is this redistribution of the gas flow that is responsible for the formation of a flow similar to the flow around a pointed body whose drag is smaller than that of the cylinder without the gas-permeable insert.

Figure 2. Computed isolines of Mach number (ring-shaped skeleton model) M_∞=7.

It was shown [9, 10] that an increase in the Mach number leads to an increase in the normalized drag coefficient both for cylinders with a porous frontal insert and for cylinders with an aerospike. As the cylinder diameter increases, the normalized drag coefficient also increases, whereas an increase in the pore diameter, vice versa, leads to a decrease in the drag coefficient. The analysis of data obtained in [1,8,9,10] made it possible to derive a similarity criterion (D/d)^1/2M_∞^{-2/3} in the problem of a supersonic flow around a cylinder with a frontal HPCM insert aligned at a zero angle of attack. Based on all experimental and computed data, the drag coefficient is found to be a linear function of this criterion.

Based on the results and their analysis, various methods of using HPCM for control of supersonic flows around axisymmetric bodies were developed: variation of the porous insert length [9], symmetric and asymmetric heating of the porous insert [11-14], and variation of the base pressure by means of directing some part of the impinging flow to the base region through the porous material. The absence of moving elements in the model structure including the porous frontal insert makes HPCM attractive for creating flight control systems.

Further development of research of supersonic flows around bodies with gas-permeable porous inserts implies developing a three-dimensional skeleton model of the porous medium and performing experiments and numerical simulations of the flow around a cylinder with a porous frontal insert aligned at nonzero angles of attack. The goal of the study is to find the specific features of the flow at an angle of attack and a similarity criterion for the coefficients of aerodynamic forces similar to that derived previously in studying the model behavior at a zero angle of attack.

### 3. Development of a three-dimensional skeleton model of a porous medium

A three-dimensional model of a skeletal or a cellular-porous material is developed for problems of modeling flows around bodies with porous inserts at nonzero angles of attack. In the present study, we use two three-dimensional skeleton models of a porous medium consisting of a set of intersecting hollow spheres. These models differ by the spatial arrangement of the neighboring spheres. In both skeleton models, the basic figure for skeleton construction is a pyramid with the spheres placed at the vertices. The pyramid based is a square in the first model and equilateral triangle in the second model (Fig. 3a,d). In the first model, the skeleton in the first model is constructed by means of parallel shifting of the quadrangular pyramid in all directions by a distance equal to the distance between the sphere centers at the pyramid base (Fig. 3b). In the second model, the skeleton is designed by means of superimposing the faces of the neighboring triangular pyramids (Fig. 3e). As a result, the number
Figure 3. Figures for skeleton formation (a,d); model elements made of HPCM consisting of quadrangular (b) and triangular (e) pyramids; sphere modeling an individual HPCM pore for the skeleton model based on quadrangular (c) and triangular (f) pyramids.

and size of holes corresponding to intersection of the neighboring spheres are different for spheres modeling individual pores of the high-porosity cellular material (Fig. 3c,f). It should be noted that both skeleton models are able to reproduce the correct pore diameter $d$ and HPCM porosity $k$ (ratio of the void volume to the total volume of the porous material).

Figure 4. Predicted density fields for a cylinder with a porous frontal insert $d=2$ mm, $M_{\infty}=7$, $Re_{1\infty}=1.5 \times 10^6$ m$^{-1}$: (а) $\alpha=0$ and (b) $\alpha=15^\circ$ (skeleton model composed of quadrangular pyramids).

4. Effect of the angle of attack on the flow around a cylinder with a frontal HPCM insert
The numerical simulations of a supersonic flow around a cylinder with a gas-permeable frontal insert were performed by solving three-dimensional Reynolds-averaged Navier-Stokes equations with the use of the ANSYS Fluent CFD software system. A three-dimensional skeleton model was used for modeling the flow in the pores. The solution of the problem provided all gas-dynamic variables of the flow both outside the model and inside the porous material (Fig. 4).

The experimental investigations were performed in the T-327A supersonic wind tunnel based at ITAM SB RAS. The drag and lift coefficients of the cylinder with the frontal insert made of cellular-porous nickel were measured under the following free-stream conditions: $M_{\infty}=7$ and $Re_{1\infty}=1.5 \times 10^6$ m$^{-1}$. The model cylinder diameter $D$ was 14.8 mm, the angle of attack $\alpha$ was varied from zero to 20$^\circ$, and the normalized length of the porous insert $\Delta x/D$ was varied from zero to 2.7, whereas the total length of the model was fixed at 100 mm. The porous insert was made of a cellular material with a porosity coefficient of 0.95 and pore diameter $d=1$, 2, 3, and 4 mm. Probing of the flow field at the nozzle exit showed that the model was located in a sufficiently uniform flow in the range of the angle of attack $\alpha$ from zero to 25$^\circ$.

The aerodynamic forces were measured by a three-component strain-gauge balance. The angle of attack of the model was varied by means of changing the angle of balance positioning (Fig. 5a).
The forces measured in the balance-fixed system $F'_x$ and $F'_y$ were recalculated to the flow-fixed coordinate system $F_x$ and $F_y$ by the formulas

$$F_x = F'_x \cos \alpha + F'_y \sin \alpha \quad F_y = -F'_x \sin \alpha + F'_y \cos \alpha$$

For obtaining the drag coefficient $C_x$ and lift coefficient $C_y$, the forces $F_x$ and $F_y$ were normalized to one half of the free-stream dynamic pressure per cross-sectional area of the cylinder. To check the validity of balance measurements with changes in the angle of balance positioning, we also performed a series of measurements with the use of a special sting of the model with a varied angle of cylinder positioning, i.e., without changing the angle of balance positioning (Fig. 5b). In this case, the forces are directly measured in the flow-fixed coordinate system. The results of both procedures of force measurements coincided with each other.

Figure 6 illustrates the behavior of the drag coefficient $C_x$ and lift coefficient $C_y$ of the cylinder with a frontal HPCM insert. As the porous insert length increases, the drag of the model is seen to decrease for all angles of attack. Moreover, drag reduction becomes even slightly more intense as the angle of

![Figure 6](image6.png)

Figure 6. Aerodynamic coefficients versus the normalized length of the porous insert for different angles of attack of the model; $d = 2$ mm.

![Figure 7](image7.png)

Figure 7. Computed and experimental normalized drag coefficient for a cylinder with a porous frontal insert versus the similarity parameter: the straight line is the generalized dependence.
attack increases. On the other hand, the value of $C_y$ increases with increasing porous insert length and tends to a constant value reached at $\Delta x/D > 1$. The trends discussed here were observed for all pore diameters of the frontal insert material. The negative values of $C_y$ at $\alpha < 15^\circ$ and $\Delta x/D < 0.5$ can be attributed to the fact that the cylinder model with the porous insert aligned at an angle of attack actually becomes sharper because the lower part of the frontal face moves forward, while the upper part of the frontal face moves backward when the model is arranged at an angle of attack. In this case, the model in the supersonic flow is actually a cylinder with a slanted frontal face rather than a cylinder with a straight frontal face as in the situation with $\alpha = 0$. As the frontal face is slanted, the flow is deflected asymmetrically and a transverse force in the opposite direction to shifting of the model face due to an increase in the angle of attack is formed. As a result, negative values of $C_y$ are observed (see Fig. 6). At $\alpha \geq 15^\circ$, the model generates a lift force greater than the force generated by the slanted frontal face, and the values of $C_y$ become positive.

The summary plot of all computed and experimental results, including those for the cylinder at an angle of attack (red symbols), is shown in Fig. 7. It is seen that the drag coefficients for the angles of attack $\alpha \leq 15^\circ$ follow the similarity criterion derived previously for $\alpha = 0$ [9]. At high angles of attack $\alpha > 15^\circ$, the experimental data deviate from the generalized dependence (straight line).

Conclusions
A brief review of comprehensive experimental and numerical studies of a supersonic flow around a cylinder model with a gas-permeable frontal insert made of a high-porosity cellular material performed at ITAM SB RAS is presented. Three-dimensional skeleton models of HPCM are proposed. New data on the influence of the angle of attack on the aerodynamic coefficients of the model are reported.

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