Simulation of a supersonic flow around a body with a frontal gas-permeable insert by using a skeleton model of a highly porous cellular material

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Abstract. Numerical simulation of supersonic flow past a cylinder with a frontal gas-permeable insert is performed using the skeleton model of a highly porous cellular material. Numerical simulation was carried out within the framework of two-dimensional RANS equations written in an axisymmetric form. The skeleton model is a system of coaxial rings of different diameters, arranged in staggered order. The calculations were carried out in a wide range of determining parameters: Mach numbers $M_\infty = 3, 4.85$ and $7$, unit Reynolds numbers $Re_1 = 13.8 \times 10^5 ÷ 13.8 \times 10^6$ m$^{-1}$, the cylinder diameter $6 ÷ 40$ mm, the length of the porous insert $3 ÷ 45$ mm, the cell diameter of 1 and 3 mm. The results of the calculations are consistent with the available experimental data. The applicability of the skeleton model for the description of supersonic flow around axisymmetric bodies with front inserts from cellular-porous materials is shown.

1. Introduction

Gas-permeable porous materials in recent years have found application in promising methods of controlling supersonic aircraft [1-3]. Experimental studies in wind tunnels demonstrated the possibility of controlling supersonic flow and, in particular, controlling the aerodynamic drag of bodies by help of gas permeable highly porous cellular materials (HPCM) [1,4]. HPCM (Figure 1a) is formed when the foamed liquid metals solidify. The cellulars of the frozen foam form a spatial carcass from the partitions between the contacting cellulars. The porosity (the ratio of the total volume of the porous sample to the volume of the skeleton) of such a material lies in the range from 76% to 98%. The material ceases to be gas permeable with less porosity, and with greater porosity, a skeleton of the partitions is not formed. There are some recent applications of gas-permeable porous materials and in supersonic aerodynamics to suppress acoustic waves. In particular, it was possible to suppress acoustic disturbances in the shock layer on a plate in a nitrogen stream at $M = 21$ with the help of inserts of foamed nickel in experiments [5]. These phenomena are based on dissipation of the energy of acoustic disturbances, which are a dominating mode of instability of a hypersonic boundary layer, owing to friction in pores of the coating. It was shown in experiments [6] that the intensity of perturbations is attenuated by a sound-absorbing coating from the HPCM by 20% at the plate in the flow of vibrationally excited mixtures of CO$_2$ with air.

To increase the efficiency of the action of gas-permeable porous materials on a supersonic flow around various bodies and develop engineering methods for design of supersonic flying vehicles with porous control elements it is required to apply modern methods of numerical simulation of flow around bodies with porous inserts. At present, the main problem of numerical modeling is the optimal choice of the model of a gas permeable porous medium. Continuum models of a porous medium with a prescribed pressure gradient in the porous region as a function of the filtration rate in accordance with a certain law (e.g., the Darcy-Forchheimer law) are widely used for numerical simulations of the flow in a porous medium. Investigations [4,7] have demonstrated the results and the main difficulties in the use of continuum models of a porous medium during calculations. The fundamental problem of continuum models is that the scales of the structural elements of real porous materials (cell sizes) are comparable with the scale of porous inserts (the diameter of the model), but the continuum models are obtained for conditions of continuous media that do not have any structural elements inside themselves. Moreover, at supersonic velocities of the oncoming flow, there are drastic changes in the pressure gradient and filtration rate along the insert, which required the use of different filtration dependences along the porous insert.
The way out of the situation is a direct simulation of the skeleton of porous materials and the flow of gas in them. The results of such studies are described, for example in [8, 9], where a low-velocity gas flow was modeled through a porous-porous material. They chose a skeleton model in the form of intersecting spheres (Fig.1b), which most closely reflects the spatial structure of cellular-porous materials. However, this approach requires the use of a huge number of cells of the calculated grid (of the order of several tens of millions), which is time-consuming for parametric engineering calculations. The exact form of the spatial structure of the material does not play an important role in supersonic flow around a skeleton of a porous material. Here the leading role is played by the porosity coefficient and the scale (diameter) of the cells of the cellular-porous material. This creates a certain opportunity for constructing simpler model skeletons of cellular-porous materials.

![Figure 1. Enlarged image of a fragment of foamed nickel (a), computational skeleton model of the gas-permeable material of foamed nickel type (b), 3D image of the computational model of the gas-permeable insert (c) ![Figure 1. Enlarged image of a fragment of foamed nickel (a), computational skeleton model of the gas-permeable material of foamed nickel type (b), 3D image of the computational model of the gas-permeable insert (c)](Image)

In this paper, we solve the problem of the axisymmetric flow past a cylinder with a gas-permeable front insert made of LCPM by using a skeleton model of a highly porous cellular material.

2. **Skeleton model of a gas-permeable porous medium**

The challenge of the present activities was to perform numerical simulations of a supersonic flow around a streamwise aligned cylinder with a frontal porous insert without empirical data used in the computations. Mironov et al. [4] found that the main effect on the air flow in insert material pores is produced by the inertial term of the quadratic dependence responsible for flow interaction with partitions of the porous skeleton, i.e., for aerodynamics of the flow past pore partitions. This fact gives grounds to consider the flow around a cylinder with a porous insert as the flow around an integrated model consisting of the porous insert skeleton and the cylinder. In this approach, the porous medium is presented as a three-dimensional system of discrete elements modeling the skeleton of a real porous material. Further we term it as the skeleton model of a porous medium to distinguish it from traditional continuum models.

In this case, it is important to choose an appropriate geometry of the porous material skeleton, which would be consistent with conditions of a high-velocity air flow in the porous insert. In addition to the cell size and porosity value, one more criterion of a correct choice of the skeleton geometry is the correspondence of the predicted structure of the external flow field and the magnitude of wave drag reduction to experimental data.

A fairly simple geometry of the HPCM skeleton consisting of staggered elements with a square cross section (Figure 1c) was successfully applied for modeling the absorption of acoustic disturbances in a hypersonic flow past a flat plate with a porous insert [5,10]. A similar model of the skeleton of HPCM in the form of square or rectangular elements, twisted about the longitudinal axis, is proposed in this paper for solving of the task of axisymmetric flow around a cylinder with a gas-permeable front insert. Thus, the proposed skeleton model is a system of coaxial rings of different diameters arranged in staggered order (Figure 1d). One can ignore the azimuthal motion of the gas for axisymmetric inserts in flows at zero angle of attack and construct a model skeleton from ring elements without radial baffles, taking into account the absence of radial baffles in the characteristics of the ring elements and their arrangement. Some correction of such a model structure can be done by comparison with the data of the tube experiment. The shape and size of the elements of the HPCM skeleton were chosen from the condition of correspondence to the material porosity coefficient of 0.95, i.e., the total volume of the skeleton elements was only 5% of
the porous insert volume. The distance between the skeleton elements in the axial directions was equal to the pore diameter $d$. In the radial direction, the distance between the elements was smaller than $d$ to compensate for the absence of radial partitions of the model skeleton. The value of this difference was determined in a series of computations with variations of the distance between the elements and the shape of the elements themselves. Additional characteristics of the HPCM are the random arrangement of the skeleton elements and the length of material non-transparency. Therefore, the vertical row of elements was gradually shifted in the computational model to ensure the correspondence to the length of real HPCM non-transparency. This fact is illustrated in the image of the model porous insert in Fig. 1c as a periodically repeated step on the external boundary of the insert.

3. Experimental data
The investigations of the flow around a cylinder with a frontal porous insert made of cellular-porous nickel were performed in a T-327B supersonic blowdown wind tunnel based at ITAM SB RAS [4]. The model of the cylinder with the frontal gas-permeable porous insert made of the HPCM has the diameter $D=14.5$ mm, the porous insert length was varied from zero to 45 mm, and the total length of the model was $L=100$ mm. The length of the porous insert $\Delta x$ normalized to the cylinder diameter $D$ ($\Delta x/D$) was varied within $0.2 \div 3.1$ with the use of a moving thin-walled tube closely adjacent to the cylinder. The model was mounted on a three-component strain-gauge balance, which measured the drag force generated by the model.

4. Numerical simulation
The problem of the axisymmetric flow past a cylinder with a gas-permeable front insert was solved within the framework of the two-dimensional RANS equations written in an axisymmetric form. The calculations were carried out using the $k$-$\omega$ SST turbulence model. The space derivatives were approximated by means of implicit schemes of the second order of accuracy. Convective fluxes were approximated by the Roe-FDS method of splitting with a TVD limiter for retaining solution monotonicity near discontinuities and local extremes of the flow. Integration with respect to time was performed by the third-order TVD Runge-Kutta scheme. The flow around the cylinder with model inserts was numerically simulated by the commercial package ANSYS Fluent.

The projection of the computational domain onto a plane is a rectangle, and its lower boundary coincides with the axis of symmetry of the cylinder. The computational domain consisted of several subdomains (region ahead of the body, region of the porous insert, and region behind the porous insert) in order to provide grid refinement near the bow SW and the cylinder surface and to minimize the number of cells in the computational domain. The porous subdomain was covered by a uniform rectangular computational grid. Up to ten processors of the Information-Computational Center of the Novosibirsk State University and the Siberian Supercomputer Center were used in the computations.

The calculations were carried out in a wide range of determining parameters: Mach numbers $M_\infty = 3$, 4.85 and 7, unit Reynolds numbers $Re_1 \infty = 13.8 \times 10^5 \div 13.8 \times 10^6$ m$^{-1}$, the cylinder diameter $D=6 \div 40$ mm, the length of the porous insert $\Delta x=3 \div 45$ mm, the cell diameter of HPCM $d=1$ and 3 mm.

Solving the problem, we obtained all gas-dynamic variables of the flow both outside the model and inside the porous material. The drag coefficient of the model was calculated as $C_d = F/\left(0.5 \cdot \rho_{\infty} \cdot u_{\infty}^2 \cdot S_m\right)$, where $\rho_{\infty}$, $u_{\infty}$ are the free-stream density and velocity, $S_m$ is the area of the model mid-section, and $F$ is the aerodynamic force including the pressure force, the friction force, and the wave drag force. In this work, the force $F$ was calculated from the difference in the total momentum of the flow ahead of the bow SW and in the plane of the rear end face of the cylinder (integral characteristics). Thus, we calculated the drag coefficients $C_d$ of the cylinder with the frontal porous insert and $C_{d0}$ of the solid cylinder.

5. Results
The computed pressure fields of flow past a solid cylinder and a cylinder with a porous insert located in front of it are shown in Figure 2a,b. The transition from the arc-shaped bow shock wave on the solid cylinder (Figure 2a) to the oblique shock (Figure 2b) on the cylinder with a gas permeable porous insert is clearly visible. The bow SW becomes “seated” onto the frontal plane of the cellular porous insert practically. The weaker oblique jumps caused by the outflow of air jets from the pores are arisen behind the
bow shock. The fields of the streamlines for the flow around a solid cylinder and a cylinder with the frontal porous insert are in Figure 2 c,d. It is seen that the streamlines on cylinder with the frontal porous insert have a flux reversal angle less than on a solid cylinder. This leads to a weakening of bow shock wave and the appearance behind it of a sequence of weak shock waves on the trickle of flowing current. This gas flow redistribution in the cellular porous body leads to formation of a flow similar to the flow around a pointed body, resulting drag reduction of model in the supersonic flow.

The experimental and computed normalized drag coefficients of the model \( C_d/C_{d0} \) are plotted in Figure 3a as functions of the normalized length of the porous insert \( \Delta x/D \). Figure 3 shows the experimental data [1] for two pore diameters \( d = 1 \) and 3 mm. The results of computations based on the skeleton model of a porous medium are shown in Figure 3a by the dashed curves. The solid curve illustrates the results for the flow computed by the two-zone continuum model for the pore diameter \( d = 3 \) mm [9]. It is seen significant (within 35%) drag reduction for large lengths of the gas-permeable porous insert (\( \Delta x/D \geq 1.5 \)).

![Figure 2](image1)

**Figure 2.** The computed pressure fields and the fields of the streamlines \( M_{\infty} = 4.85, p_{\infty}=186\text{Pa}, T_{\infty}=51\text{K}, \text{Re}_{\infty} = 2.7 \times 10^6\text{m}^{-1} \); (a,c) – solid cylinder; (b,d) – cylinder with a frontal porous insert \( \Delta x/D = 2 \), \( D=14.5\text{mm}, d=1\text{mm}, L=100\text{mm} \).

The experimental and computed normalized drag coefficients of the model \( C_d/C_{d0} \) as functions of the Reynolds number \( \text{Re}_{\infty} \) based on the free-stream parameters and the cylinder diameter \( D \) are compared in Figure 3b. The change of Reynolds number in the calculations was made by changing the static pressure of the oncoming flow calculated from the values of the stagnation pressure in the experiment. The results show a significant (within 11%) change in the aerodynamic drag at \( \text{Re}_{\infty}<0.4\times 10^5 \), where viscosity effects are likely to manifest themselves. The change of the drag coefficients of the model is insignificant in the rest of the Reynolds number range (\( \text{Re}_{\infty}\geq0.4\times 10^5 \)). This indicates a weak dependence of the task on viscosity and the predominance of the process of inviscid flow inside a porous material in the creation of drag of the entire model as a whole.

![Figure 3](image2)
**Figure 3.** Experimental (1,2) and computed (3,4,5) normalized drag coefficient of the model versus the normalized length of the porous insert for $Re_{1∞} = 2.7 \times 10^6$ m$^{-1}$ (a) and versus the Reynolds number $Re_0$ for $\Delta x/D = 2.0$ (b): 1, 5 – $d=1$mm; 2,3,4 – $d=3$mm; 3 – continuum model [9]; 4,5 – skeleton model. $M_∞ = 4.85$, $p_∞=186\text{Pa}$, $T_0=51\text{K}$.

The calculations were made of the flow past a cylinder with a porous gas-permeable insert of a large length ($\Delta x/D = 2$) with a pore diameter of 1 mm diameter model $D = 14.5$ mm that to determine the influence of Mach number on the decreasing of the drag coefficient. The flow parameters are as follows: stagnation pressure $P_0=1\text{atm}$, stagnation temperature $T_0=290\text{K}$, Reynolds number $Re_0= 4.0 \times 10^5$. The results of these investigations in comparison with the experimental data are given in Table 1. It is seen that normalized coefficient of resistance of the model varies slightly (within 6%) with an increase in the Mach number from 3 to 7. Such a weak dependence is probably associated with a small thickness of the boundary layer growing on the elements of a porous material at such Mach numbers. This means that the flow in the pores is not blocked and the flow freely expires from the porous zone.

**Table 1.** Computed and experimental data of normalized drag coefficient of the cylinder with a frontal porous insert $\Delta x/D = 2$ for different Mach numbers.

| $C_d/C_{d0}$ | $M_∞=3$ | $M_∞=4.85$ | $M_∞=7$ | $M_∞=7$ |
|--------------|----------|------------|----------|----------|
| $Re_{1∞} = 2.7 \times 10^6$ m$^{-1}$ | $Re_{1∞} = 2.7 \times 10^6$ m$^{-1}$ | $Re_{1∞} = 2.7 \times 10^6$ m$^{-1}$ | $Re_{1∞} = 1.5 \times 10^6$ m$^{-1}$ |
| Experiment | – | 0.739±0.025 | – | 0.83±0.025 |
| CFD | 0.733 | 0.737 | 0.778 | 0.818 |
Figure 4. The fields of the streamlines on flow around cylinder with a frontal porous insert $\Delta x/D = 2$, $d=1\text{mm}$, $M_\infty = 7$, $p_\infty=42.4\text{Pa}$, $T_\infty=26.85\text{K}$, $Re_\infty = 2.7 \times 10^6\text{m}^{-1}$. (a) - $D=6\text{mm}$, (b) - $D=14.5\text{mm}$, (c) - $D=20\text{mm}$.

Figure 4 shows the fields of the streamlines for flow around cylinders of different diameters $D = 6$, 14.5 and 20 mm with a porous front insert $\Delta x/D = 2$, $d=1\text{mm}$ at $M_\infty = 7$. It is seen that if the diameter of the model grows, the angle of deflection of the current lines from the model surface increases, which is associated with a more intensive outflow of gas from a porous zone of larger diameter. This leads to increasing of the angle of inclination of the bow shock to the direction of flow and, as a result, to increasing of the momentum loss of the oncoming stream. Therefore, the efficiency of the porous insert decreases with increasing of the model diameter and the aerodynamic drag increases.

Figure 5. Computed and experimental data of normalized drag coefficient of the cylinder with a frontal porous insert $\Delta x/D = 2$ versus the ratio of the diameter of the model to the pore diameter:

1 – experimental data
2 – numerical data
3 – generalizing dependence (1) for $M_\infty=7$.

Figure 5 shows the calculated and experimental data of the normalized drag coefficient of a cylinder with a porous insert $\Delta x/D = 2$ for Mach number 7 versus the ratio of the model diameter to the pores diameter of the insert $D/d$. It is seen that the values of aerodynamic drag coefficient are approximated by a unified dependence

$$C_x/C_x0 = 1 - 0.6879/\sqrt{D/d}$$  \hspace{1cm} (1)

and therefore, the parameter $D/d$ can be considered a geometric similarity parameter for the aerodynamic drag coefficient of bodies with frontal porous inserts.

6. Conclusions
Numerical simulation of supersonic flow past a cylinder with a front insert from the HPCM using skeleton model of a porous medium over a wide range of Reynolds numbers, Mach numbers, lengths of the porous insert, pore diameters and the ratio of the model diameter to the pores diameter of the porous material is carried out.
It is shown that the skeleton model in the form of a system of coaxial rings of different diameters, located in a staggered order, makes it possible to obtain results consistent with the experimental data on the weight measurements of the aerodynamic drag.

In the parametric calculations, a weak dependence of aerodynamic drag coefficient of the cylinder with the front insert from the HPCM on the Mach numbers in the range 3-7 and on the unit Reynolds numbers in the range $13.8 \times 10^5 \div 13.8 \times 10^6$ m$^{-1}$. The influence of the ratio of the model diameter to the pores diameter (the geometric similarity criterion) on the aerodynamic drag coefficient is shown.

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