Effect of porous material heating on the drag force of a cylinder with gas-permeable porous inserts in a supersonic flow

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Abstract. The paper presents the results of an experimental investigation of supersonic flow around a solid cylinder with a gas-permeable porous insert on its front end and of supersonic flow around a hollow cylinder with internal porous inserts in the presence of heating of the porous material. The experiments were performed in a supersonic wind tunnel with Mach number 4.85 and 7 with porous inserts of cellular-porous nickel. The results of measurements on the filtration stand of the air filtration rate through the cellular-porous nickel when it is heated are also shown. For a number of experiments, numerical modeling based on the skeletal model of a cellular-porous material was carried out.

1. Introduction

In recent years work is underway to study the control of aerodynamic forces using gas-permeable porous inserts in the airframe of a supersonic aircraft [1-3]. The traditional aerodynamic control methods for the flow around supersonic aircraft do not always give the expected effect due to the appearance of the detachment phenomenon. The use of porous inserts makes it possible to eliminate undesirable effects and diversify the methods of flow control including using the thermal effect on flow in porous materials [4]. This approach allows to exclude mechanical movements of airframe elements or blowing of jets when creating a control action.

The paper presents the results of an experimental study of the effect of heating gas-permeable cellular-porous nickel on the air filtration rate on the filtration stand described in [5] were previously performed. It was studied the air flow in a tubular channel with a densely installed sample of a porous material with heating from the outside of a metal tubular channel and when the sample was heated in a thermally insulated dielectric tubular channel by passing an electric current through it. The temperature of the porous sample was not measured, but the temperature of the air passing through the sample was measured. This scheme was chosen from the considerations that it is the heating of air that causes the change in the filtration rate. The design of the stand allowed independently to vary the pressure drop across the sample of the porous material and the
Reynolds number calculated from the pore diameter and air filtration rate. Cell-porous nickel samples with a pore diameter \( d = 1, 2, 3 \) and \( 4 \) mm, a diameter of \( 15 \) mm and a length of \( 42 \) mm were used. The following data were determined in the experiments:

- dependences of the filtration rate on the pressure drop on a porous sample at a variation in the temperature of the air passing through the material for different pore diameters,
- dependences of the mass flow of air through a porous sample at a variation in the temperature of the air passing through the material for different pore diameters,
- dependences of the rate change of the filtration on the degree of heating of air from the Reynolds number \( \text{Re}_d^0 \) calculated from the pore diameter and the air filtration rate in the material without heating in the range of \( 30-600 \).

On the basis of these data, geometric characteristics of the skeleton model of porous-porous nickel were developed [5, 6], which was used in numerical simulations of supersonic flow around a cylinder with a front porous insert without heating [6] and with heating of the porous inserts in this work.

Experiments to study the effect of heating on the drag force of cylindrical models with porous inserts were performed in the supersonic wind tunnel T-327B of ITAM SB RAS at Mach numbers \( M_\infty = 4.85 \) and \( 7 \) and the corresponding unit Reynolds numbers \( \text{Re}_1^\infty = 2.7 \times 10^6 \) and \( 1.5 \times 10^6 \) m\(^{-1}\). The stagnation temperature of the flow was \( 294 \) K. The wind tunnel T-327B with the Eiffel chamber has a shock-running system and the possibility of the air outflowing into a large vacuum volume pumped out by high-performance vacuum pumps. The pressure in the working section of the wind tunnel before starting is \( 10^{-2} \) torr. The force of aerodynamic drag was measured by tenso-balance on which the models were mounted. Registration of electric signals of devices and sensors was carried out by a multichannel ADC National Instruments PX.

In the experiments at \( M_\infty = 4.85 \) the model [1] of a solid cylinder with a front porous insert equal in length to two cylinder diameters with pores diameter of \( 1 \) mm was used.

![Figure 1](image_url).

**Figure 1.** Scheme of the model heating: 1 – cylinder with front porous insert, 2 – retractable ohmic heater

On this model the influence of heating the porous material of the front insert on the aerodynamic drag of the model was studied. The diameter of the model was \( 15 \) mm, the total length of the model was \( 110 \) mm. The heating of the porous insert was carried out by the thermal radiation of the ohmic heater partially enclosing the front porous insert as shown in Fig. 1. The temperature of the porous insert was measured by a copper-constantan thermocouple at the insertion axis at a point half the length of the insert. When the maximum heating temperature of the insert is reached before the start of the wind tunnel the heater is taken out of the flow boundary. In the process of supersonic flow around the model, the temperature at the measurement point varied in the range from the maximum heating temperature before the wind tunnel was started up to the stagnation temperature.

In experiments at \( M_\infty = 7 \) a hollow thin-walled cylinder model with gas-permeable porous inserts was used (Fig. 2). The model consisted of two discs of cellular porous nickel (pore size \( 1 \) mm, \( 95\% \) porosity) \( 24 \) mm in diameter and \( 10 \) mm thick inserted in a thin \( 46 \)-mm-long fluoroplastic cylinder at a distance of \( 26 \) mm from each other. The cylinder was installed along the flow axis with the help of a
holder with a small cluttering of the flow. To create a glowing electric discharge between porous disks the disks were connected through the ballast resistance with a 600-volt power supply source.

The front disk served as the cathode, the rear disk as the anode. The discharge power was regulated by the ballast resistance in the range from 40 to 190 W. In the wake of the cylinder, on its axis and near the rear porous disk, there was a copper-constantan thermocouple used to measure the temperature of air passing through the porous disks. The temperature of the passing air served as an indicator of the heating of the porous material and the efficiency of heat exchange between of the porous material and the incoming air flow. During the operation of the wind tunnel the temperature of the air passing through the model increased with time and the growth rate of the temperature was depended on the power of the glow discharge. Measures have been taken to minimize the effect of the thermocouple and the electrical wires on the balance readings. During operation of the wind tunnel, the current in the discharge circuit, electric signals of the thermocouple and the balance were recorded. The output data of the measurements was the dependence of the drag force of the model on temperature of the air passing through the model. In addition the dependences of the air temperature behind the model on the discharge burning time and its power were determined. This model is ideologically close to the model of work [2], where the reduction in drag is based on the flow of part of the incident air flow into the rear region through the conical gas permeable front porous insert. In the model on Fig. 2 the flow of a portion of the incident airflow into the rear region behind the cylinder is controlled by heating the porous disks.

Preliminary experiments on the selection of modes of electric glow discharge, the distance between gas permeable porous disks and the pore diameter were carried out within the framework of studies of the excitation of gas micro-jets that outflow into low-pressure space.

### 3. Results and discussion

The main results of measurements at the filtration stand are set forth in [5]. In particular a significant increase in hydraulic resistance and a drop in the filtration rate in cellular-porous nickel was shown with an increase in the temperature of the air passing through the porous material for all pore diameters. With an equal heating temperature of the porous materials, the influence of heating on the hydraulic resistance is the greater, the smaller the pore diameter and the smaller the Reynolds number of \( \text{Re}_d^0 \), calculated from the pore diameter and the air filtration rate without heating the material. The processing of the measurement results gave an empirical dependence of the coefficient of reduction of the filtration rate on the degree of air heating \( \gamma \text{[m/(s·grad)]} \) from \( \text{Re}_d^0 \) and \( d \):

\[
\gamma = \frac{1}{A - B/\sqrt{\text{Re}_d^0}}, \quad A = 19.12 + 0.303 \cdot d^2, \quad B = 80.53 - 0.41 \cdot d.
\]
Based on these data, experiments in the wind tunnel were performed on models with porous inserts with a pore diameter of 1 mm where the greatest effect of heating on the drag force was expected.

In Fig. 3 shows the results of measurements and calculation of the dependence of the normalized coefficient of drag force of the cylinder with the front porous insert on the temperature of the porous insert at the measuring point $T_{\text{ins}}$ for $M_\infty = 4.85$ (Fig. 1). The normalization was made on the drag coefficient at the insertion temperature of 294 K. Measurements were made only in the temperature range of 300-400 K since the metal model intensively reflected the thermal radiation of the heater and the radiation was came out along the ends and into the cutting of the heater (see, Fig. 1). Numerical modeling within the framework of the skeleton model of a porous insert [5, 6] made it possible to obtain the dependence of the coefficient of drag force in over a wider range of temperatures. It can be seen that when the temperature of the porous insert is increased by 400 degrees, then an increase in the coefficient of aerodynamic resistance by $\pm 12\%$ can be achieved. Calculations have shown that the increase in drag force is associated with the growth of viscous friction in the heated front layers of the porous insert. This leads to an increase in the angle of inclination of the head shock wave to the direction of the flow and to an increase in the momentum loss of the flow on the shock wave.

The obtained data allow to change the control scheme of the drag force of such model for the case of real flight in the atmosphere. In a real flight due to the high stagnation temperature the front porous insert will be heated to a temperature of more than 1000 K. In this case, when the insert is cooled with the liquid (for example, the fuel for aircraft engine), the drag force coefficient will decrease. In addition it is possible to additionally obtain a useful effect of the fuel pyrolysis into the gaseous state and increase the efficiency of the engine.

In Fig. 4 shows the results of measurements of the coefficient of drag force with variation of the temperature of the air transmitted through the model $T_g$, obtained for the model on Fig. 2. The results of measurements are presented in the form of increase in the coefficient of drag force in percents. The value of the coefficient of drag force is normalized to the coefficient of drag force at a temperature of 294 K. The graph shows the data obtained in different experiments, with different glow discharge.
power and at different temperatures of the air passing through the model. The graph also shows the linear and quadratic approximations of the experimental data. It can be seen that when the air in porous inserts is heated to 700 K, the drag force of the model can be increased by 5% and a further increase in temperature $T_g$ will only slightly increase this value. Most likely, this is due to the weak influence of pressure in the trailing edge of the model on drag force.

### 4. Conclusions

Experiments have been carried out to investigate the effect of heating of cellular-porous nickel on the hydrodynamic characteristics of a porous material with a one-dimensional flow of air through it. In experiments in a supersonic wind tunnel the effect of heating a porous material on the drag force of the cylinder with a front porous insert and on the drag force of the hollow cylinder with two porous inserts was studied.

It is shown that at an equal temperature of heating the porous material, its hydraulic resistance is the greater, the smaller the pore diameter and the smaller the Reynolds number calculated from the pore diameter and the air filtration rate without heating the material. An empirical relationship for the coefficient of proportionality between the filtration rate and the temperature of the air passing through the material as function of the Reynolds number is obtained.

For the solid cylinder with a front porous insert the experimental and calculated dependences of the normalized coefficient of drag force on the insert temperature are obtained.

For the hollow cylinder with porous inserts an experimental dependence of the increase in the normalized coefficient of drag force on the temperature of the air passing through the inserts was obtained. It is shown that the effect of heating on the drag force for this model is lower than for a cylinder with a front porous insert.

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