Influence of surface permeability on gas-dynamic characteristics of high-speed flight

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Abstract. This paper covers the use of gas-permeable materials as the outer surface of a high-speed aircraft. The gas-dynamic structures of supersonic flows are compared in the presence of blowing from the body surface and in its absence. The influence of the blowing speed on the structure of the formed gas-dynamic discontinuities is determined

1. Introduction

The most important parameters of high-speed flight are good mobility and thermal protection. Currently, there are various ways to control drag and aerodynamic performance, as well as various methods of thermal protection. Research in this scientific field of next-generation high-speed aircraft design has led to the possibility of controlling their aerodynamic characteristics by using gas-permeable surfaces. The application of gas-permeable surfaces in the head of a high-speed aircraft [1] and as inserts on the inlet channel of a supersonic air intake [2] can influence significantly on heat fluxes on the surface of the aircraft and the drag force in general.

Research of possible applications of gas permeable coatings has been going on for several decades. The transpiration cooling method [3] was used in chambers with very high heat flux densities into the wall (liquid-propellant rocket engine on high-energy fuels with high pressure, gas-phase, nuclear rocket engines). The essence of this method of thermal protection is the use of a fine porous material through which the coolant passes to the required area of the wall. This method has a number of advantages that make it possible to increase the efficiency of the chamber; however, the possibility of this method of cooling is limited by difficulties in material science and actual level technology.

Another example of the use of gas-permeable surfaces is the project of the German Center for Aviation and Cosmonautics SHEFEX [4]. The experimental suborbital unmanned high-speed rocket plane, the prototype of the SHEFEX II aerospace systems, has a special coating of the ribbed nose made of porous carbon fiber reinforced ceramics. This allows, upon entry into the atmosphere, to release gas from the nose, which envelops the front of the aircraft and cools it. It is assumed that this method minimizes material carryover, which will make it possible to re-use it [4]. Russian inventions (patents RU 2559193 C1, 08.10.2015 [5] and RU 2621195 C1, 06.01.2017 [6]) also describe a method for controlling the flow around a supersonic aircraft based on gas-permeable surfaces. In the works of the Khristianovich Institute of Theoretical and Applied Mechanics [1, 7-9] the efficiency of a porous cellular sound-absorbing insert on the surface of a plate was studied, the application of highly porous cellular materials to control supersonic flows around axisymmetric bodies was considered. The
authors of studies [1, 7-9] obtained both numerical and experimental research. It was shown that the use of gas-permeable absorbing inserts leads to an improvement in flight characteristics.

In this work, a numerical simulation of a high-speed flow around a body in dense layers of the atmosphere with a gas-permeable surface is obtained. Due to presence of gas-permeable coating, gas is blown out into the incident flow. Simulation is performed in a flat two-dimensional approximation, which allows further qualitative theoretical analysis using the methods of optimization of shock-wave systems and structures developed in the last 10-15 years [10-12]. The calculated flowfields and shock-wave structures are compared with the results of calculating the flow around an impenetrable solid body of identical shape.

2. Model and methods

Numerical simulation of a gas permeable surface was carried out in the ANSYS engineering analysis software package using the Fluent computational fluid dynamics module. The mathematical model of high-speed flow around an article with permeable surfaces consists of a system of two-dimensional differential Reynolds-averaged Navier-Stokes equations with a high-Reynolds closing k-ε model of turbulence. The associated “Density-Based” solver is selected for the solver settings. Equation discretization schemes was as it follows: “Implicit” – implicit iterative solver, Roe-FDS numerical scheme, “Green-Gauss Cell Based” method for gradient approximation and second order of discretization of all other equations. The design area around the body is constructed in such a way that the head shock wave that forms at the leading edge does not interact with the inlet and side boundaries. Boundary conditions of adhesion and impermeability, and adiabaticity, are set on the wall of the body [13]. The computational mesh was refined near the body walls to improve the quality of computations in areas with large gradients of flow parameters. Computational mesh was also adapted to the pressure gradients resulting during computations (see Figure 1) to obtain more reliable results.

![Figure 1. Computational area.](image)

The computational grid has about 400 thousand cells. Each refined layer of cells has a cell size 4 times smaller than before refinement on previous level of refinement. The half-angle of the wedge in the head part is 20°; that corresponds to the formation of an attached shock at flow around an impenetrable solid (in particular, at the Mach number M = 5, the maximum flow deflection angle at the attached shock wave is 41.118°, and the flow deflection angle corresponding to the critical flow velocity behind the shock wave is equal to 41.109°).

The examples below consider air flow around a rhomboid body at an incident flow velocity corresponding to the Mach number M = 5. When analysing the flow with the blowing out of the gas flow, it is assumed that the front part of the rhomboid streamlined body has a permeable surface; when calculating the flow without blowing, the front part is considered to be a solid impermeable wall. The
rest of the boundaries of the body under consideration are considered impenetrable in all cases. The atmospheric parameters correspond to the values indicated in the Russian State Standard GOST 4401-81 “Standard Atmosphere” for an altitude of 15 km. The air stream which flows out of the penetrable body surface is also considered to be a perfect gas with a temperature equal to 300 K, and its flow velocities are equal to 0 m/s, 25 m/s and 50 m/s in each case under consideration, respectively.

3. Results and discussion
Figures 2-4 show the fields of static pressure, temperature, density and Mach numbers for three different conditions (degrees of permeability of the streamlined head): a completely impermeable surface (Figure 2), a permeable front part of the streamlined body with an outflow velocity equal to 25 m/s (Figure 3) and the permeable front part of the product with an outflow velocity equal to 50 m/s into the ambient space (Figure 4).

Figure 2. Distributions of static pressure (a), temperature (b), density (c) and Mach number (d) for completely impermeable surfaces.
Figure 3. Distributions of static pressure (a), temperature (b), density (c) and Mach number (d) at a gas normal velocity from the head equal to 25 m/s.
An attached oblique shock wave forms in front of a body without permeable surfaces. At a large distance from the body, under the influence of subsequent overtaking rarefaction waves [14, 15], the shock wave weakens and gradually degenerates into weak discontinuity. The disintegration of the discontinuity of the flow parameters at the trailing edge leads to the formation of two attached tail shock waves [16], and the stern wake is located immediately downstream of the trailing edge. The gas density ratio when passing through an oblique shock wave is limited, although the density in the shock layer is much higher than in the undisturbed flow. Gas outflow from the head with a normal speed of 25 m/s generates a new jump in density (as well as static temperature and flow Mach number) at the contact discontinuity (slipstream) between the stream that flows from the ambient and gas that is blown out from body surface. A shock wave break is formed at the leading edge, which nevertheless remains attached. With an increase in the normal blowing speed up to 50 meters per second, a detached curvilinear shock wave forms in front of the body. In this case, there is a region of increased pressure in front of the body, and the leading edge actually plays the role of a stagnation point. After passing through the nasal region, the gas undergoes rapid expansion with a more (or less) long transient process. In the flow region between the lateral surface of the body and the detached bow shock wave, large gradients of enthalpy, entropy, and density take place. In this compressed high-entropy layer, the gas has a higher temperature and density, which are noticeably higher than the analogous values immediately behind the bow shock. However, due to the total pressure loss at the head shock, these values are significantly inferior to the parameters of free stream deceleration (deceleration pressure 64 atm, deceleration density 17.195 kg/m$^3$ at static pressure 12.112 kPa, density 0.195 kg/m$^3$). In the presence of blowing out of unheated gas, the temperature near the product decreases significantly, which leads to a weakening of thermal loads on an object flying at high supersonic speed to safe values.

Thus, the presence of blowing out the air flow from the penetrable surface of the streamlined body can radically change the structure of the flow (including reducing the thermal loads on the aircraft). By changing the area and intensity of the blowing, it becomes possible to control the aerodynamic characteristics of the streamlined body, as well as to change the direction of its movement, creating a kind of gas rudders. The presence of gas-permeable surfaces can partially suppress the acoustic field and reduce the friction forces that negatively affect the boundary layer of the aircraft [17].

4. Conclusion
Interest to application of permeable materials as the outer coating of aircraft has appeared relatively recently, and it opens up great opportunities for researching this subject and consequent design of
supersonic aircraft. However, it is possible to find various fields of application of porous inserts on the surface of high-speed aircraft: they can be effective in suppressing aerodynamic noise and reducing friction forces, in reducing heat loads to the surface of an aircraft and in correcting the flowfield features, including directions of some streamlines, due to injection or blowing.

The results obtained indicate that a region with a low temperature forms in front of the body due to blowing out the cold working gas. Since blowing stream is studied as normal to the surface, it interacts with the incoming flow on the walls of the aircraft, thereby reducing friction (the blowing region is clearly visible in the flow patterns, and it does not mix with the incoming flow). It is also necessary to take into account that with an increase in the blowing speed, the attached shock transforms into a detached one with a corresponding increase in the gradient of thermodynamic parameters.

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