Study of the flow structure in boundary layer bleed channel at the hypersonic speed of external flow

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Abstract. The paper presents the study of the flow structure in a boundary layer bleed channel and calculation of the mass flow rate under the conditions of thick boundary layer incoming. The flow at Mach numbers of M = 3, 4, 6 and angle of attack 6° has been considered. In the framework of the problem, the Reynolds-averaged Navier-Stokes equations added with the k–ω SST turbulence model have been solved. Numerical simulation of the flow in the channel has been carried out using the Roe implicit scheme of the second order of accuracy. Pressure and temperature profiles at the outlet boundary obtained at the simulation of the flow around the inlet forebody have been used to specify the inlet boundary conditions for simulation of the flow through the boundary layer bleed hole. The pressure distribution obtained at numerical simulation of a flow in the boundary layer bleed channel has shown that there is a large high-pressure area caused by the presence of so-called “barrier shock” near the channel back wall. Thus here is a supercritical pressure drop which ensures a sonic flow in the bleed hole. This conclusion has been confirmed by the experimental data obtained for small supersonic speeds. Calculation of the mass-flow rate through exit cross-section of the cylindrical bleed channel has shown that the mass flow rate coefficient decreases 2.5 – 3 times with the Mach number increasing from 3 to 6. The mass flow coefficient also decreases by about 10% due to the change of conditions in the 3D flow before the bleed hole with the moving off from the symmetry plane.

1. Introduction

Recently, a large number of studies have been conducted in respect to the hypersonic vehicle development. The main object of the studies is a hypersonic ramjet engine that seems to be the most effective one in providing the hypersonic flight. The aim is to increase the engine efficiency, namely, to ensure the maximum air flow through the inlet, implementing the design flow regime and the total pressure loss reducing in a wide range of flight conditions.

The boundary layer separation is a serious problem that leads to instability in the inlet operation and the deterioration of its characteristics. One of the solution methods is to implement the distributed boundary layer bleeding in order to remove partly the low-pressure part of it through the perforated areas on the compression surfaces before entering the inlet channel. The boundary-layer bleed decreases the mass flow to the engine, mitigates the effects of adverse pressure gradients, and reduces the boundary-layer thickness. The method effectiveness is confirmed for supersonic inlets by the Mach number free flow of up to 2.5. For the inlets with the flight range of the Mach number from 3 to 12, this problem is much more complicated due to the significant change of the external flow conditions.
2. Problem statement
The present paper is devoted to the numerical simulation of the boundary layer bleeding through the perforated region on the ramp. The statement of the problem and the computational domain are determined by the test model and conditions studied at testing. Experiments have been carried out in the wind tunnel ITAM SO RAN T-313. Test section sizes are 0.6x0.6x2 m. Operating conditions of the wind tunnel: the Mach number range is from 2 to 7, the Reynolds number per unit length is from 8 to 54 million at temperatures of 285 – 415K. The model consists of an inlet forebody and a two-shock inlet with the boundary layer bleed (BLB) (figure 1).

Figure 1. Experimental model: 1- hypersonic inlet forebody, 2-cowl, 3 - boundary layer bleeding surface.

Perforation on the ramp is a system of round holes with a diameter of 4 mm, spaced 13 mm apart (figure 2, a). The inclination of the orifice channels to the compression surface is of 90°. At this stage of the study, under consideration is the single BLB channel located in the symmetry plane of the ramp and 13, 26, or 39 mm away from it (figure 2, b). Air flows through the hole in the surface and then through the outlet channel.

Figure 2. BLB system schematic: a) General view of the porous region with multiple bleed holes, all dimensions are given in mm, b) Bleed plenum: 1 - boundary layer bleed holes, 2- exit channel

The aim of the present work is to study the flow structure and define the mass flow rate characteristics in a single BLB channel at the free flow Mach numbers varying from 3 to 6 at the angle of attack equal to 6°.

Numerical simulation of the problem has been carried out using ANSYS commercial package (the academic version). The stationary Reynolds-averaged Navier-Stokes equations have been solved for the turbulent flow. The turbulence model k-ω SST has been used. In the framework of the problem, a 'density-based' solver has been exploited for an implicit second-order accuracy scheme of Roe.

The BLB characteristic definition is divided in two stages. At the first stage, the flow around the inlet forebody before the BLB holes has been modeled. At the second stage, the flow in the bleed hole is
simulated. Detailed description of the first modeling stage is given in [1]. In the present paper, the main attention is paid to the second stage, i.e. to the simulation of the flow through the BLB channel.

Figure 3, a shows the computational domain and the boundary condition assignment scheme for the simulation of the flow through the BLB cylindrical channel. The domain for the flow calculating is a thick plate with a hole bounded by rectangular flow regions above and below. The type of the boundary conditions 'pressure inlet' are set at the input boundaries, i.e. the static pressure $p$, the total pressure $P_0$ and the total temperature $T_0$. Above the plate (the input boundary 1), these values have been obtained at the simulation of the flow around the inlet forebody, since the plate on top, in fact, is a continuation of the compression ramp of the inlet. Under the plate (the inlet boundary 2), the conditions assigned are the same as in BLB plenum used in the experiments. The non-slip boundary condition 'wall' with heat flux equal to zero is used on the surfaces of the plate and the hole. The boundary condition 'pressure outlet' is set at the output borders, i.e. the static pressure $p$ and the total temperature $T_0$ are assigned (figure 3, a). At the lateral boundaries, the flow symmetry condition is used. The meshes have been built using the ANSYS ICEM CFD application. The mesh for calculating the flow through the bleed hole consists of about 2.2 million elements.

Figure 3. a) Computational domain for the flow simulation through the BLB channel and the boundary conditions schematic; b) General view of the mesh

Flow parameters are given in table 1.

| $M$ | $p_0$, Pa | $P_0$, Pa | $T_0$, K | $\alpha_x$, $^\circ$ |
|-----|-----------|-----------|-----------|------------------|
| 3.037 | 10855.96 | 422078.2 | 284.5 | 6 |
| 4.03 | 6527.61 | 1031488.5 | 280 | 6 |
| 6.06 | 522.145 | 876461.25 | 376.5 | 6 |

3. Results of the flow around the inlet forebody modeling and transfer of parameter profiles

In paper [1], it is shown that a stepwise increase of the pressure takes place at the compression ramps at the flow around the inlet forebody, and the pressure increases significantly with the increasing Mach number (figure 4).

The profiles of the flow parameters behind the shock wave at the end of the last compression ramp obtained at this stage of the flow simulation have been taken as the calculation parameters and for the initial conditions assignment for the flow problem through a single BLB channel. Geometrically, the input boundary for the modeling through the BLB channel is part of the output boundary of the domain.
Figure 4. Pressure distribution along the plane of symmetry of the inlet forebody.

Figure 5. Transfer of parameters from one computational grid to another: a) scheme; b) static pressure profile: 1 – the profile obtained from the calculation of the flow around the inlet forebody, 2 – profile after interpolation.

for simulation of the flow around the inlet forebody (figure 5, a). And yet, these are borders with different computational grids. To transfer the parameter profiles from one grid to another, cubic splines with defect 1 have been used. These splines are widely used because of their relative simplicity and the fact that they are quite sufficient to keep the continuity of the second derivative functions.

Using the known parameter values on the first grid, the parameters on the second grid have been calculated by the spline interpolation. Figure 5 presents schematically the transfer of the pressure profile as the input parameter for simulation of the BLB through the hole located in the symmetry plane of the perforated bleeding area. Figure 5, b shows the initial profile and the profile after interpolation with different location and number of nodes. One can see that there is very good agreement between the results with the exception of very small areas in the vicinity of a sharp change of parameters (figure 5, b). This phenomenon is typical for the cubic splines, but no attempts have been made to correct this defect in the work, because we assume that the parameter profiles are slightly distorted, and it cannot fundamentally change the flow flowing to the BLB channel.

4. Result of the flow in the BLB channel modeling

Figure 6 shows the pressure distribution and streamlines inside the BLB channel. The flow pattern schematic is shown in figure 6, a [2]. In figure 6, b, one can see flow pattern in the BLB channel. The arrow conventionally shows the direction of the flow flowing into the hole at the speed $V$.

First of all, the high degree of the flow non-uniformity in the channel should be noted in both the longitudinal and transverse directions.

The calculation results indicate a complex flow pattern with two zones with higher and lower velocities (to the left and right of the channel symmetry axis). An extensive high-pressure region is visible near the rear wall. Its appearance is caused by the presence of the so-called “barrier” shock [2]. These data also show that the “barrier” shock does not cause the flow separation on the compression
ramp. This is due to the fact that the shock is inside the cylindrical channel, as is seen in figure 6. This conclusion is confirmed by the experimental data obtained for small supersonic speeds (M = 1.27) [3]. The increased-pressure area on the leeward side contributes to the reversal of the flow along the longitudinal axis of the channel and the formation of an extensive circulation region (figure 6, b), which prevents the flow increase. As a result, the main air flow passes through the area to the right of the symmetry axis, at the rear wall. It is also confirmed by the output jet structure analysis. The result is in qualitative agreement with the flow schematic presented in figure 6, a.

![Flow pattern schematic](image)

**Figure 6.** Flow pattern in a single BLB channel at M = 4 in front of the bleeding channel: a) flow pattern schematic [2]; b) pressure distribution of and streamlines in the channel symmetry plane.

Bleed configurations are often characterized by the sonic flow coefficient (Q), which is defined as:

\[ Q = \frac{w}{w_i^*}. \]

Here, the numerator is the calculated mass-flow rate at the hole exit and the denominator is the ideal mass-flow rate under the choked conditions. The perfect mass-flow rate can be defined by formula (1) at Mach number M=1 [4]:

\[ w_i^* = P_{06} \cdot AM \left( \frac{\gamma}{RT_{06}} \right)^{\frac{1}{2}} \left( 1 + \frac{\gamma-1}{2} M^2 \right)^{\frac{\gamma+1}{2(\gamma-1)}}, \]

where \( A \) is the channel cross-sectional area, \( M \) is Mach number, \( P_{06} \) is the stagnation pressure, and \( T_{06} \) is the stagnation temperature at the boundary layer edge.

In the framework of this problem, the sonic flow coefficient has been located for the orifices in the symmetry plane of the compression ramp and at the distances of 13, 26, and 39 mm from the symmetry plane at the free flow Mach numbers from 3 to 6.

![Normalized flow coefficient](image)

**Figure 7.** Normalized flow coefficient depending on the distance between a hole and the symmetry plane (M= 3, 4 and 6).
Figure 7 shows the dependence of the sonic flow coefficient on the distance from the symmetry plane for Mach numbers 3, 4 and 6. The data are normalized using the sonic flow coefficient for the orifice located in the plane of symmetry ($Q_{sym}$). It has been found that the sonic flow coefficient decreases more significantly as the Mach number increases. The coefficient decreases for the BLB holes located at some distance from the symmetry plane.

The coefficient decreases by 10% at the Mach number 3, and by 13% at the Mach flow equal to 4. Evident that the sonic flow coefficient decreases by about 39% for the hole located at the distance of 39 mm from the symmetry plane at the Mach number of 6.

5. Conclusions
As a result of the numerical modeling, the flow structure in a single BLB channel has been defined, and the sonic flow coefficient has been calculated versus the Mach number and the hole position relative to the symmetry plane. The main conclusions that can be drawn from the numerical simulation are the following:

- It has been found that a complex three-dimensional flow structure with separation zones and a high level of pressure non-uniformity realizes in a small cylindrical BLB channel at a supersonic external flow velocity. That leads to the BLB channel flow coefficient decreasing.
- The sonic flow coefficient through the BLB channel decreases at the free flow Mach number increasing.
- The flow coefficient decreases within the distance from the symmetry plane increasing. The higher the Mach number, the greater degree of the flow coefficient decrease.

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