Influence of flow conditions on compression surfaces of hypersonic inlet on characteristics of boundary layer bleed

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Abstract. The paper presents the results of analytical and experimental study of the bleed coefficient at flight Mach numbers from 3 to 7. For the calculation, a calculation model with a fixed exit in the supercritical bleed mode was used, which allows varying the bleed air mass depending on flow conditions and parameter of the bleed system. The measurement of the bleed flow coefficients were performed for three bleed configurations in a wind tunnel at local Mach numbers in front of the bleed area from 2.5 to 5.96. The model had a long forebody, so that before the bleed area there was a thick boundary layer. As a result, new experimental data on bleed coefficient and its general dependence on the Mach number of up to 6 and the bleed angles of 90° and 45° were obtained. It is revealed that at an increase in the local Mach number, the tendency towards a decrease in the bleed coefficient is observed, and this tendency becomes more intensive with a decrease in the bleed channel inclination. These data were used to evaluate known analytical calculation method to determine the characteristics of bleed systems at hypersonic flow velocity.

1. Introduction.
One of the most effective approaches to controlling the flow in the inlets is the bleed of the boundary layer that helps to prevent the separation of the boundary layer and choking the channel [1]. Usually boundary layer bleed is realized through a system of perforated (porous) areas on the inlet surfaces near the channel entrance or in the areas of interaction of shock waves with the boundary layer. Perforation, as a rule, is presented by the round holes with a diameter much smaller than the scale of the air inlet. The meaning of this process is to remove the low-pressure near-wall part of the boundary layer and thereby reduce losses, prevent the boundary layer separation and excludes unstart of inlet.

Currently, there is extensive experience in the study and application of flow control at the entrance to the channel for inlets of various types (two-dimension, axisymmetric, mixed compression) [2, 3]. At the initial stage of research, the efforts were focused on studying the general characteristics of bleed systems and their influence on the flow structure and the inlet start [4]. Analysis of the known studies shows that the development of air bleed systems for inlets is based on experimental data and empirical dependences, which play a crucial role in the process of modeling such flows [5-7]. As a result of these studies, it was shown that at development of the boundary layer bleed on the inlet compression surfaces, designers encounter difficult tasks. Their solution has to allow the achievement of the necessary mass flow rate of bleed air and inlet efficiency.

Usually the task is to determine the bleed flow coefficient ($C_d$) depending on the diameter of the bleed holes or total area of the bleed and the ratio of the total pressures on the outer edge of the
boundary layer and in the bleed chamber \((P_{\text{blch}}/P_t)\) [5]. Another important geometrical parameter is the inclination angle of the bleed channel. A decrease in the channel inclination angle from 90° to 20° leads to an increase in \(C_d\) in the range of Mach of 1.25–2.46 [6]. Together with the obvious geometric and gas-dynamic parameters at determining \(C_d\), it is necessary to take into account the flow structure in front of the bleed hole or bleed area, the relative channel length, and the packing density of the bleed holes [7]. In addition, the efficiency of the bleed is influenced by the ratio of the hole diameter to the displacement thickness of the boundary layer \(d/\delta^*\), which affects the formation of separation zones in the bleed channel and leads to reduction of the air mass flow via bleed channel [8]. A similar effect is exerted by the relative length of the bleed channel \(d/L\).

For the calculation of bleed systems, various semi-empirical models are used, which are based on numerous experimental data. A large amount of such data allows developing and verification of various analytical approaches [9] and, at the same time, is the reason for the contradictory character of some results due to the multi-parameter nature of the problem. Recently, together with experimental studies and analytical models, numerical simulation methods have been widely used [10]. As a result, it is possible not only to predict the effect of boundary layer bleed on the characteristics of the inlet, but also to determine the flow structure, flow velocity, effective area of the bleed channel, and the dependence of these parameters on the flow conditions on the compression surfaces. The application of CFD methods allows us to understand more deeply the fine structure of the flow in the bleed channels, what is not always possible in scope of experiment, and choose the methods of flow control.

Most of the above-mentioned researches of boundary layer bleed, like many others not named here, are focused on the study of the flows in the air inlets with a flight Mach number from 0.8 to 3.5. Along with this, some data have been published, which demonstrate that with increasing Mach number, one can expect the growth of bleed air due to the increased need to remove a part of the boundary layer and prevent its separation, as well as to ensure stable engine operation [11]. However, these studies indicate so far only trends and require experimental testing in a wind tunnel.

The purpose of this work was to study the boundary layer bleed on the compression surface of the hypersonic inlet and to assess the feasibility of using known models and analytical relationships at expanding flight Mach numbers to 7. At the same time, the task consisted in determination of the effect of the air bleed system on the characteristics and start conditions of the inlet.

2. Model and methodology
To study the porous bleed properties, 2-shock inlet model with a design Mach number of 8 was used. The model had a removable cowl that allowed modeling the interaction of shock wave with boundary layer. A bleed area was placed in front of the channel entrance. In the tests, the boundary layer bleed was carried out via changeable inserts with one or two rows of holes with diameter \(d=4\) mm (figure 1).

![Figure 1. Schemes of porous bleed model. All dimensions in mm.](image)

![Figure 2. Bleed chamber and measuring nozzle. 1 – pressure tap.](image)
In each row, the holes were located at distance of 13 mm from each other that excluded their mutual influence. In both cases, the experiments were carried out at the angles of inclination of the bleed holes of 90° and 45°. To assess the effect of the bleed on the start and characteristics of the inlet, dense package of 147 bleed holes with 45° inclination in a staggered order was used (figure 1, left). The bleed flow entered the common bleed chamber and then outflowed through the common exit channel, which had a fixed critical section area (figure 2). The size of the exit area varied depending on the total area of the bleed holes. To determine the air mass flow rate, the pressure in the bleed chamber and in the nozzle throat was measured. Experiments have shown that in all test modes, a critical or supercritical outflow regime was realized, which is due to sufficient level of pressure increase already at Mach number of 3 even at zero angle of attack.

To calculate the parameters of the porous bleed, the model for the bleed system with a fixed area of the exit section, proposed in [12], was used. It is assumed that the balance of air mass flow through the holes in the bleed area (m_{bl}) and the mass flow rate through exit nozzle of the bleed chamber (m_{ex}) remain constant, i.e. m_{bl} = m_{ex} and bleed flow coefficient can be determined by the ratio
\[ C_d A_{bl} U_{ch} = C_{ex} A_{ex}^* U_{ex}^*, \]  
(1)

where \( C_d, A_{bl}, U_{ch} \) are the total flow bleed coefficient, the area and speed in the bleed channels, \( C_{ex}, A_{ex}^*, U_{ex}^* \) are the bleed coefficient, the critical section area and the speed in the critical section of the exit nozzle of the bleed chamber, correspondingly. The basic assumption is that the bleed coefficient of the bleed holes \( C_d \) is common to the whole bleed area and is estimated based on empirical data processing for flows on a flat plate with single channels or porous bleed areas. Since the Mach number in the bleed chamber is very small, the total pressure in the chamber is equal to the static pressure and the total temperature is equal to the total temperature in the flow core in the bleed area. The area of the nozzle exit is determined by the conditions of critical flow at the exit of bleed chamber (\( M = 1 \)), which was confirmed by the calibration results of the measuring channel. The bleed coefficient of the nozzle \( C_{nz} \) depends on the flow conditions and the exit geometry, and is a known value. The bleed model involves continuous bleed throughout the area without identifying each hole. The boundary conditions are set for all points of the surface in the area of bleed and take into account the turning of the flow in the front wall of the bleed hole in the Prandtl-Meyer flow as suggested in [13].

Experimental studies of the boundary layer bleed were performed in the wind tunnel T-313 of ITAM SB RAS [14] with free stream Mach number from 3 to 7, which corresponded to a local Mach number in front of the bleed area from 2.85 to 5.96. The experiments were carried out in the range of total pressures of 0.2–1.2 MPa, total temperatures of 270–420 K, and Reynolds numbers of (18–56) 10^6 1/m. The Pitot pressure was measured in three cross sections in front of the bleed area to determine the parameters of the boundary layer. On the long forebody of the model, a boundary layer with a thickness from 6.2 mm to 12.8 mm was realized in front of the bleed area [17]. Measurements showed that, due to three-dimensional flow, the layer thickness decreased to the side edges by about 10–18%, depending on the Mach number. Under these conditions, the ratio diameter of the bleed channels to the displacement thickness (\( d/\delta^* \)), depending on the flow conditions, varied in the range from 1.0 to 3.2. At performing experiments, the pressure distribution on the forebody of the model was measured in the longitudinal and transverse directions in front of the bleed area and behind one. At testing the inlet, the start was determined and the mass flow rate and total pressure recovery were measured to assess the effect of the boundary layer bleed on the inlet characteristics.

3. Results

The effectiveness of the boundary layer bleed system depends on how well the low-energy part of the boundary layer is removed. This is determined by the bleed flow coefficient, which is defined as the ratio of the actual mass flow to the maximum mass flow at an ideal sonic velocity through the bleed channel. The change in the bleed coefficient depends mainly on the Mach number, inclination angle of the bleed channel and relative pressure in the bleed chamber, \( P_{blch}/P_t \). The value \( P_{blch}/P_t \) determines the outflow mode, namely, subcritical (\( M < 1 \)), critical (\( M = 1 \)) and supercritical (\( M > 1 \)) ones. In addition,
other flow properties, such as the diameter and shape of the hole, the relative length of the channel, the distance between the holes and the size of the bleed chamber, and others, affect the $C_d$ value. However, their influence, as shown by experiments [5], is not so significant. Under such conditions, the generalizing and analysis of data are extremely difficult and requires performing the large amount of experiments. Therefore, the influence of the determining parameters, for which a sufficient amount of empirical data is available, is discussed here.

To obtain the bleed coefficient for large Mach numbers, pressure measurements were carried out on the compression surfaces before the bleed area and at the exit of the bleed channel. It was found that for all test conditions at $M > 3$, the supercritical pressure drop $P_{blch}/P_t < 0.528$ was realized, at which the maximum flow rate was reached for the fixed Mach number. To determine the bleed coefficient, the method proposed in [13] was applied. The measured pressure in front of the bleed channels and in the critical section of the exit nozzle was used as the initial data. The flow rate of the exit nozzle was assumed to be known from the results of the calibration of nozzles of various sizes. As a result of the calculations performed, data were obtained on the effect of the Mach number and the angle of bleed inclination channel on the change in the bleed coefficient. Figure 3 shows that the decrease in the bleed coefficient at large Mach numbers slows down noticeably, but these curves qualitatively repeat those for small supersonic flow velocities. It can also be seen that the experimental data somewhat exceed systematically the calculated estimates. The influence of the slope angle of the bleed channel is remained over the entire range of Mach numbers considered.

Dependences of bleed coefficient on relative pressure, $C_d(P_{blch}/P_t)$ were obtained at throttling the exit nozzle of the bleed chamber. Figure 4 shows a comparison of data for the range of Mach numbers from 1.2 to 2.46 from [12] and the data of this work for the range of Mach numbers from 2.8 to 5.96.

![Figure 3. Bleed coefficient vs. Mach number.](image1)

![Figure 4. Bleed coefficient vs. relative pressure.](image2)

In all cases, the supercritical bleed mode was considered. These data indicate that the effect of relative pressure on the bleed coefficient with increasing Mach number leads to a decrease in $C_d$ value with increasing total pressure on the compression surface. The comparison shows that the range of variation of the bleed coefficient is very wide even if the entrance conditions are limited (Mach number, bleed inclination). Therefore, attempts are being made to generalize the known data to facilitate their practical application [15]. Using the proposed empirical relationships [12,15] to describe the dependence of the bleed coefficient on relative pressure shows that the experimental data are not always satisfactorily consistent with the calculation (figure 5) and, as a rule, the calculation gives an overestimated value of the bleed coefficient. This result is typical both for supersonic and hypersonic flow velocities. It should be emphasized that direct comparison of the properties of bleed systems is difficult, since the scale effects ($d, d/δ$) that affect the structure of the flow in the bleed channels not always coincide [7, 15].
Analysis of the known data showed that, despite the multi-parameter nature of the phenomenon, for the supercritical bleed mode, the dependence of the bleed coefficient on the Mach number can be ascertained. Comparison of the obtained experimental data with the calculation and the data of [5] (for M=2.46) shows their satisfactory agreement, despite the difference in the initial data for these two cases (figure 6). These data demonstrate a significant decrease in the bleed coefficient with an increase in the Mach number to 6. It can be seen that at M=2.5 and 3, the results of calculation and experiment agree satisfactorily, whereas at M=3, the calculation gives an overestimation. The reason for this difference may be an increase in the intensity of the "barrier" shock at an increase in the Mach number, growth of the fullness of boundary layer velocity profiles and discrepancy of the initial conditions. It should be noted that only the supercritical flow regime is considered here, but, at low supersonic speeds, all flow regimes can be realized simultaneously, especially with multi-row dense packing of holes.

Nevertheless, the calculations of the boundary layer bleed for hypersonic inlet in the range of Mach numbers from 3 to 7 indicate that the used bleed model provides realistic prediction of mass flow rate and its dependence on local conditions in front of the bleed area. The data in figure 7 confirm the satisfactory conformity between the calculation and the experiment for all Mach numbers. The data obtained show that in order to prevent boundary layer separation and to realize the inlet start it is sufficient to ensure the bleed mass flow rate not exceeding 5% of the total mass flow through the inlet.
This conclusion is confirmed by measuring the pressure distribution along the forebody length of the inlet. Figure 8 shows that the boundary layer bleed prevents an increase in local pressure in the inlet channel due to the boundary layer separation under the action of shock wave from the cowl. This leads to implementation of the design mode of the flow at the inlet and an increase in the air mass flow.

Summary
The paper presents data on the bleed flow coefficients at local Mach numbers from 2.5 to 6, which corresponds to flight Mach numbers from 3 to 7. These data were used to assess the applicability of the analytical models for determining the bleed flow coefficient at research of the hypersonic inlets.

These data indicate that the known analytical approaches of the calculation of the boundary layer bleed allow us to predict correctly the effect of relative pressure and the angle of inclination of the bleed holes on the flow rate coefficient at hypersonic flow speeds before the bleed region.

It is shown that at an increase in the local Mach number, there is a tendency for the bleed coefficient to decrease due to an increase in the intensity of the "barrier" shock on the rear wall of the bleed hole and the recirculation zone size in the channel.

It has been revealed that with an increase in the Mach number, a decrease in the angle of inclination of the bleed hole leads to a greater reduction in the bleed flow coefficient than at small supersonic flow velocities.

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