Flow features in a hypersonic module with a compact cross-section

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Abstract. A model of a hypersonic air intake based on the principle of compression along the directions of the captured jet converging in space is studied. Such an air intake allows a high compression ratio and a compact section of the internal channel, which simplifies the heat protection of the air intake and the combustion chamber. Experimental studies were carried out in a pulsed wind tunnel IT-302M for Mach number $M = 6 - 8$ in the range of angles of attack from $0^\circ$ to $8^\circ$. Numerical simulation has been performed based on solving the full averaged Navier-Stokes equations, supplemented $k$-$\omega$ turbulence model. The pressure distributions on the compression surfaces and in the air intake channel are obtained, the coefficients of the total pressure recovery and flow rate, the Mach number in the throat of the air intake are determined. The features of the flow structure for three variants of the air intake in the area of external compression are established: with side walls, side walls with slots and without side walls. The influence of the boundary layer bleed and lateral spreading on the launch and integral characteristics of a hypersonic air intake with a compact cross-section of the inner channel is determined. Satisfactory agreement between the calculated and experimental data is shown.

1. Introduction

Recently, more attention has been paid to the development and the possibility of using three-dimensional air intakes, providing higher thrust and aerodynamic efficiency of the aircraft compared to traditional ones. In this regard, in the development of hypersonic jet engines, interest has arisen in using the configuration of air intakes in which the jet is compressed in directions converging to the center, which allows a compact cross-sectional shape of the entrance to the channel (combustion chamber). Reducing the surface area of the channel simplifies the heat protection of the air intake and combustion chamber [1]. Air intakes of this type (figure 1) were called convergent [2].

A well-known example of such air intakes is the convergent air intakes developed at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences [3] based on sector cutting from internal supersonic flows converging to the axis of symmetry, in particular, compression flows in conical funnels [4].

However, there are some difficulties arise associated with the launch of a convergent air intake due to the complex structure of the three-dimensional flow. The issues of ensuring the launch of such types of air intakes with a high degree of compression are not fully understood. The difficulty lies in the fact that with this configuration of the air intake, lateral spreading is difficult due to the flow draining to the center of symmetry and the associated thickening of the boundary layer at the entrance to the throat.
Therefore, it becomes extremely urgent to control the flow and bleed of the boundary layer to ensure the implementation of the inflowing and start the three-dimensional air intake. The boundary layer usually bleeds through slots or openings on the compression surfaces.

In the framework of this work, complex computational and experimental studies of a model of a hypersonic air intake with a compact cross section of the internal channel were carried out with the following objectives:

- obtaining flow parameters on the convergent surface of external compression of a given contour;
- determination of the integral characteristics of the air intake at Mach numbers \(M=6-8\) in the range of angles of attack from \(0^\circ\) to \(8^\circ\);
- determination of the influence of the effect of the boundary layer on the start-up and integral characteristics of the air intake by applying the bleed of the boundary layer through slots and lateral spreading on the external compression surface.

2. Models and experiment conditions

In [5], sector cuttings from the axisymmetric flow \(180^\circ, 90^\circ, \) and \(70^\circ\) were studied. It has been found that better supersonic spreading in front of the throat is achieved using a \(90^\circ\) sector cut. At initial external part, the external compression was formed on the basis of a cut of the internal conical section.

2.1. The experimental model of the air intake

For research, 3 variants of a convergent air intake were chosen, the schemes and main dimensions of which are shown in figure 1.

![Figure 1](image.png)

**Figure 1.** Convergent intake. 1-central body, 2-static pressure probes, 3-cowl, 4, 5-sidewall, 6-sting, 7-metal mesh, 8-nozzle, 9-total pressure rake. All dimensions in mm.

The design of the model allowed the installation on the body of the external compression section of the side walls of various shapes to study the influence of lateral spreading and the possibility of controlling the boundary layer. In the lateral walls there were slots of a rectangular shape with a height of 4 mm to drain the boundary layer. It is also possible to test the model without side walls in the area of external compression. The experimental model had an external contour surface 262.09 mm long, calculated on the Mach number 6.3. With this Mach number, the initial shock wave should come to the front edge of the cowl. The inner channel had a trapezoidal cross-sectional shape 100 mm long with 90° cut. The throat height of the model was 19.5 mm.

2.2. The experimental setup and measurement system

Tests of the convergent air intake model were carried out in a pulsed wind tunnel IT-302M for Mach number \(M = 6-8\) in the range of angles of attack from \(0^\circ\) to \(8^\circ\). The flow parameters during the tests varied in the range of total pressures \(P_0 = 42-294\) kg/sm² and total temperature \(T_0 = 1600-1900K\).

During the tests, measurements were made: the distribution of static pressure on the compression surfaces, the total and static pressure in the throat, the total and static pressure at the output of the sonic...
flowmeter nozzle. Based on the results of these measurements, the flow rate and the total pressure recovery coefficients and the Mach number in the throat were determined. The Schlieren visualization of the flow around the model entrance was carried out in all experiments. Visualization of the flow and measurement made it possible to determine the conditions for starting the air intake and the implementation of the calculated flow in the throat and channel of the model.

Due to the short start-up time (~100ms) in pulsed wind tunnel IT-302M, changing the angle of attack of the model during the experiment is impossible. Therefore, the experimental technique consisted of a discrete change in the angle of attack of the model before each experiment.

3. Numerical model, boundary conditions, calculation method and grid

Numerical calculations were performed using the commercial software product ANSYS Fluent based on the complete Reynolds averaged Navier-Stokes equations supplemented by the k-ω/SST turbulence model. A finite-volume difference scheme based on the solution of equations for density (Density-Based) was used. The numerical calculations were considered in a stationary setting.

Given the symmetry of the model, the computational domain included only half of the model, which was limited only by the area of external compression and the internal channel (throat) in order to optimize and reduce the calculation time (figure 2).

![Figure 2](image1.png)

**Figure 2.** Computational domain.

In the computational domain, a regular rectangular grid was constructed with thickening of nodes towards solid surfaces and to areas with an increased pressure gradient. Due to the complex three-dimensional curved surfaces, the computational grid for each configuration contained a different number of nodes in three directions. In most calculations, the grid contained 170–250 nodes in the x-direction, 150–220 in the y-direction, and 50–100 in the z-direction. As an example in figure 3 show computational grid in the plane of symmetry for the configuration of the model without side walls.

![Figure 3](image2.png)

**Figure 3.** Computational grid.

In the computational domain, a regular rectangular grid was constructed with thickening of nodes towards solid surfaces and to areas with an increased pressure gradient. Due to the complex three-dimensional curved surfaces, the computational grid for each configuration contained a different number of nodes in three directions. In most calculations, the grid contained 170–250 nodes in the x-direction, 150–220 in the y-direction, and 50–100 in the z-direction. As an example in figure 3 show computational grid in the plane of symmetry for the configuration of the model without side walls. On the surface of the model, the slip condition for the velocity and the conditions for the constancy of the wall temperature $T_w = 300K$ were used.

4. Results and discussion

The pressure distribution along the model for various variants is shown in figure 4 (a), which shows data for models without side walls and with side walls in which there were slots for the boundary layer bleed. The pressure is significantly greater increase at utilization of variant with side walls than without their installation. This effect is weakened as the Mach number decreases. The experimental data are consistent with the calculation before entering the channel, especially for $X \leq 225$ mm. In the cross section of the entrance to the model channel with the walls, the calculated pressure is much higher than the experimental values. Slots in the side wall for drainage of the boundary layer do not lead to a noticeable decrease in pressure, which is a confirmation of the tendency for a decrease in the effect of the boundary layer on pressure increase with increasing Mach number. This conclusion is also confirmed by Schlieren visualization of the flow (figure 5).

The distribution of the static pressure $P_z$ across the model was calculated. The calculations showed (figure 4 (b)) that, in the configuration without side walls, the decrease of pressure to the side edges reaches 70% in the initial ($X = 165$ mm) section of external compression from the maximum pressure
in the plane of symmetry. This value varies depending on the Mach number and decreases downstream to 30% at the channel inlet (X = 258 mm).

Figure 4. Static pressure distribution on the convergent inlet surface (a) in the symmetry plane, (b) in Z planes for Mach number M=7 and angle attack $\alpha=4^\circ$.

Figure 5. Started air intake for the configuration of models (a) with side walls and slots and (b) without side wall for Mach number $M = 7, \alpha = 4^\circ$.

Figure 6. Static pressure fields in Z planes for the configuration of models (a) with side walls and slots and (b) without side wall for Mach number $M = 7, \alpha = 4^\circ$. 
The installation of the side walls leads to a decrease in spreading, as follows from the same figure. The absence of drainage of the boundary layer even leads to some increase in pressure near the lateral side walls due to the complex interaction in the angular configuration. The data obtained suggest the non-uniformity of the pressure field across the channel width at the inlet of the engine can be ensured at an acceptable level by selecting the appropriate slots for the boundary layer bleed. The structure of the three-dimensional flow around the external compression surface is shown in figure 6. Downstream of the leading edge, the shock wave changes shape from concave in the initial section to convex in the final section. This form of the shock wave near the leading edge remains concave over the entire range of Mach numbers.

![Figure 7](image1.png)

**Figure 7.** Mass flow rate coefficient.

![Figure 8](image2.png)

**Figure 8.** Total pressure recovery coefficient.

![Figure 9](image3.png)

**Figure 9.** Mach number at the combustor entrance.

The flow rate $f$ and total pressure recovery $v$ coefficients are determined by measuring total and static pressure at the outlet of air intake. The use of a large number of pressure receivers makes it possible to obtain an accuracy of measuring air flow not worse than 3% under conditions of uneven supersonic flow.

With the Mach number $M = 8$, the flow rate coefficients with the installed side walls are almost equal to each other (figure 7). The flow rate coefficients for the convergent air intake without side walls were less due to intensive lateral spreading. An increase of attack angle leads to a proportional increase of flow rate coefficient and ensures a supersonic flow in the throat even without regulation and control of the boundary layer over the entire range of Mach numbers.

The total pressure recovery coefficients and Mach numbers in throat ($M_{th}$) based on the measured total and static pressures in the throat of the model, were determined (figure 8 and 9). It can be seen that over the entire range of Mach numbers of the oncoming flow, the velocity in the throat of the model
remains supersonic, even when a thick boundary layer arrives at the model input. It can be seen that the total pressure recovery coefficient with slots was lower at \( M = 6 \) than in the configuration without slots, but at high Mach numbers \( M = 8 \), the pressure recovery coefficient for all three variants becomes the same.

Comparative calculation and experimental studies of convergent air intakes of various variants should allow a more correct comparison of the characteristics of such air intakes. Calculation and experimental studies of a hypersonic air intake with a compact section of the internal channel allowed:

- To obtain flow parameters and characteristics of the boundary layer on the compression surface and in the channel of the convergent air intake.
- Determine the integral characteristics of the air intake for Mach numbers \( M = 6, 7 \) and \( 8 \) and attack angles \( \alpha = 0^\circ, 4^\circ \) and \( 8^\circ \).
- Determine the influence of the boundary layer bleed and lateral spreading.
- To establish that the maximum flow coefficient is achieved in the variant of the model with side walls without slots \((f = 1.17 \text{ at } M = 8)\) with the maximum total pressure recovery coefficient \((\nu = 0.22 \text{ at } M = 6)\). The average Mach number in the throat \( M_t \) for all variants of the model was supersonic and ranged from \( M_t = 1.58 \) (side walls without slots) to \( M_t = 2.4 \) (without side walls).
- To establish that the shock start in the impulse wind tunnel made it possible to obtain the air intake starting in the entire range of Mach numbers and angles of attack under study, including the version of the model with side walls without slots.

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