Gas dynamics of the body flight in the channel

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Abstract. The gas dynamics of the body high-speed flight in a channel is studied by the numerical simulation method. It is shown that in the considered formulation of the problem, it is possible to implement one of the two versions of the gas-dynamic flow pattern: the body movement with a forward straight shock wave ("unstart") and the supersonic current near the body ("start"). The behaviour of aerodynamic and thermodynamic loads on the body as it accelerates to high speeds is studied.

1. Introduction
Interest in the problem of high-speed motion of a body in a long channel arose against the background of public attention to the idea of a promising vacuum-levitation transport system [1]. It is believed that the vehicle of such a transport system relying on the magnetic levitation cushion flies at a high speed in a sealed pipeline. The pressure in the pipeline is significantly below the atmospheric one. There is a significant gap for air flow between the vehicle walls and the pipeline.

The literature review revealed a significant gap in knowledge about the gas dynamics of the high-speed flight in the channel. The exception is the problem of the piston (projectile) in the pipe, analytical solutions and numerous numerical studies which result from the development of a variety of throwing systems for military, industrial and scientific purposes.

Comparison with the work of air intake devices of power plants of high-speed aircraft gives the good results for the analysis of the problem stated. The geometric similarity of axisymmetric air intake devices with the body flying in the channel is evident (figure 1). The channel walls play the role of an infinite feedwell.

![Figure 1. a) Air intake device of the high-speed aircraft, b) The body in the channel.](image)

The air intake of an air-jet engine is designed to take a portion of air from the incoming flow, brake this portion with minimal losses of total pressure and supply air to the combustion chamber. The most
important characteristics of the air intake are the air flow coefficient ($\phi$) and the compression ratio ($F_{\text{neck}}/F_{\text{overpass}}$) of the captured flow. The flow coefficient characterizes the ratio of the actual air flow passing through the engine to the maximum possible at a given flight speed and the air intake size. The high flow compression ratio ensures the efficiency of the fuel combustion process in the engine combustion chamber.

Often, in a real flight, not the air entering the air intake can be accepted ($\phi \leq 1$), herewith at the entrance before the feedwell, a direct shock wave forms, and part of the air is forced out into the atmosphere. This mode is characterized as an air intake “unstart” (see figure 2 [2]). Generally, the fixed geometry air intake operates only in a narrow range of design flight parameters.

![Figure 2. Start-no-start diagram of flow compression limits within the channel.](image)

Figure 2 shows the “start-no-start” diagram widely used by developers of air intake devices for the high-speed aircraft. Here, the areas of all possible air intake operation modes are delineated by the known limits – the isentropic compression limit and the Kantrowitz limit (with the forming direct shock wave). For the fixed geometry, the region “1” defines the conditions under which the gas-dynamic “start” of the channel (air intake) never realizes. Area “2” defines the conditions when the channel “start” occurs spontaneously. Area “3” defines the conditions under which the channel can be “started”, but this requires certain additional activities. Area “3” is for developers of high-speed aircraft the field of implementation of their scientific and technical ideas to create effective air intake devices.

The diagram (figure 2) is useful for analyzing the problem of uniformly accelerated motion of the body in the channel and comparing it with the work of the air intake. The horizontal line drawn at the level of the selected geometric compression ratio (figure 3) permits tracing every gas-dynamic regime in the path of the body as it accelerates.

Similarly, in the case of a body flying through the channel, all the air on its way must pass from the bow to the stern as efficiently as possible, with minimal losses of the total pressure. However the significant difference is evident. For the problem of body flight in the channel, as the “body + channel” system is unable to swallow completely all the incoming air, it obviously leads to the appearance of a leading shock wave in front of the body. This is a consequence of the “feedwell” infinity and the inability to discharge the excess air into the surrounding space. Numerical modeling helps to trace how the leading shock wave forms, as well as the gas-dynamic flow pattern develops during the body acceleration.
2. Numerical simulation of the body acceleration in the channel

This paper presents a series of numerical simulations of acceleration of axisymmetric simple geometry bodies (figure 1) from rest to high supersonic speeds. At a constant diameter of the channel \( D=100 \) mm, acceleration of bodies of different sizes (\( d=20 \) mm (4% blocking channel), \( d=30 \) mm (9%), \( d=40 \) mm (16%), \( d=50 \) mm (25%), \( d=60 \) mm (36%) and \( d=70 \) mm (49%), see figure 3) was calculated.

![Figure 3. Stages of body acceleration in the channel. Pressure fields.](image)

The numerical simulation is performed with the aid of the software product Fluent. The unsteady Navier-Stokes equations for the laminar flow were solved in the axisymmetric statement. Air was used as the working gas. The pressure in the channel was assumed to be \( P_{\infty}=1000 \) Pa. Adhesion conditions and adiabatic temperature conditions were set on the model and channel surface. Free borders (pressure outlet) were set on the left and on the right of the calculated area. In the computational domain, a structured grid is constructed, with decreasing cell size of near the channel and model walls. The
minimum cell size is 0.2 x 0.2 mm. To set the motion of the model, we used a software module (User defined function) which defines the dependence of the speed on time. The model movement was given by a rectilinear uniformly accelerated along the axis from right to left, with an acceleration of \( a = 20500 \text{ m/s}^2 \). The time step was \( \Delta t = 10^{-6} \text{ s} \). The computational grid was rebuilt at each time step - the entire grid moved with the model, the cells disappeared on the left border and were added on the right. The solution at every time instant was accepted as agreed if discrepancies were below \( 10^{-7} \).

In the diagram of the isentropic compression limit and the Kantrowitz limit (figure 4), dotted lines indicate the geometric characteristics of the models for which the calculations were performed.

Figure 3 presents the characteristic pressure fields near the body (\( r=20\text{mm} \)) at different times as it accelerates, for one of the calculation options. The diagrams show the stages of the shock wave formation in front of the body, catching up of the wave front to the body and the shock wave swallowing with in the supersonic flow regime.

For every case, the body acceleration begins in the favorable, from the gas-dynamic point of view, “start” area of the channel (area “2”, see figure 2). Despite this, the calculation results show that not all the air encountered in the body path is swallowed by it. A bit of air is pushed forward by the body (see figure 4), creating a zone of high pressure which later develops into a shock wave (figure 5). This is probably due to the imperfection of the aerodynamic body shape which does not provide its smooth and continuous flow.

Figure 4. Proportion of air ingested.

Figure 5 shows how the pressure profile changes and the shock wave front forms in front of the body (\( r = 35 \text{ mm} \)) as it accelerates in the channel.

Figure 4, for different cases of calculation, shows the relationship which in percentage terms demonstrates what part of the “incoming” air (\( G^+ \)) flows from the bow to the stern of the body (\( G^- \)) as it accelerates. It is clearly seen on these graphs due to what and how the zone of high pressure forms in front of the body.

The lowest air flow through the duct between the body and the channel, for all calculated cases, coincides with the Mach number close to \( M=1 \), which is in good agreement with the theory of the isentropic compression limit. In the supersonic region of flight, the difference in flow \( \Delta G = (G^+)-(G^-) \): incoming (\( G^+ \)) and ingested (\( G^- \)) decreases.

At some point, the mass of the incoming gas becomes less than the mass of the “ingested” \( \Delta G<0 \). It results in the gradual disappearance congestion of the air in front of the body, leading shock wave weakening and reaching its “ingestion” moment. A favorable regime of supersonic flow is formed (see figure 4, the moment of the curve falling to the mark of 100%).
Figure 5. Pressure profile in front of the body (Ød=70 mm) as it accelerates.

Figure 6. Temperature distribution (in Kelvins) around the body that flies at the speed of U = 820 m/s.

Figure 7. Dependences of aerodynamic drag coefficients of different size bodies as they accelerate in the channel.

Comparing the moments of the channel “launch” and the supersonic flow onset around the body (see figure 4) on the diagram of the isentropic compression and Kantrowitz limits (figure 2), one sees that the body moving to the favorable supersonic region “2” continues to move in the high pressure zone, behind the shock wave for quite a long time. This is due to the presence of an air plug in front of the body and the time to absorb it, according to figure 4. In this case, the body experiences high aerodynamic (figure 7) and thermal loads (figure 6).

The greater the transverse size of the body, the greater the exit section length to the supersonic flow regime. Obviously, the reduction of this segment promises significant energy benefits for the
implementation of the acceleration process. The solution of the problem of Kantrowitz limit overcoming, in this formulation, is the task of further research for the authors.

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