Numerical investigation of a single supersonic jet interaction with a wedge barrier

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Abstract. This article presents the results of mathematical modeling of the interaction of a single supersonic jet with a wedge barrier. The angles of the wedge were 0, 5, and 10 degrees. The distance from the nozzle to the barrier was 0.5 meters. The parameters of the gas of hydrazine combustion products at the nozzle inlet varied. Mach number at the nozzle exit was 4 and 5. It was found that the wedge angle of the barrier slightly affects the shape of the jet, the shape of the wall jets and the pressure along the barrier at an ambient pressure of 650 Pa and a temperature of 250 K. With an increase in the barrier angle, the pressure on the jet axis decreases and the first barrel of the wall jet is displaced.

1. Introduction
In the design and development of rocket and space technology, experimental and theoretical studies are conducted during the launch and landing of rockets and spacecraft. Attention is paid here to the interaction of supersonic jets with various obstacles for studying the occurrence of various negative effects. Lots of experimental and theoretical studies have been devoted to explore of jet flows and their interaction with barriers. Mathematical modelling using modern numerical methods and high-performance computing systems plays a significant role in theoretical studies. The results of an experimental investigation of the leakage of supersonic underexpanded jets onto a flat obstacle established perpendicular to the axis of the jet in the immediate vicinity of the nozzle exit (0.92d, 2.14d, 3.5d) are presented in [1]. In this paper, empirical formulas for the approximate construction of pressure diagrams on a barrier and indicate the applicability limits are given. The interaction of a supersonic axisymmetric single jet with obstacle perpendicular obstruction was given in an experimental study [2]. Theoretical and experimental studies was carried out at the Institute of Theoretical and Applied Mechanics of the SB RAS, Russia [3-6]. Experimental work on a specially created vertical jet facility was performed. The facility is equipped with recording sensors and modern instruments, they collect information in real time and allow monitoring the ongoing experiment. The structures of supersonic jets and the leakage of underexpanded and overexpanded supersonic jets into impermeable perpendicular and inclined obstacles and obstacles of various permeability was investigated. The tasks of landing the returned spacecraft with 16 nozzles are considered. Experimental studies of the distribution of the averaged pressure and pressure pulsations on the surface of the returned spacecraft and the landing surface was carried out. Mathematical modeling was performed using ANSYS Fluent. In the experiments, two nozzles with a Mach numbers 1 and 1.5 at nozzle exit are considered. The results was presented in the form of shadow images and processed by the PIV method. A series of works on the calculation and experimental study of the interaction of single and multi-block supersonic turbulent jets
with obstacle was carried out in [7-11]. These studies are devoted to the study of the processes occurring at the launch of rocket and space technology. Various particular qualities of physical processes accompanying the outflow of jets of combustion products of rocket fuels was shown. The mathematical model consists of the three-dimensional Reynolds averaged Navier-Stokes equations with the Menter’s SST turbulence model. Simulation was performed using LOGOS software. An analysis of the experimental and theoretical studies of the supersonic jets interaction with obstacles showed that despite the large volume of accumulated knowledge, the problem of supersonic turbulent jet interaction with obstacles at distances h/d=1.8-9.2 from the nozzle exit to obstacle and with Mach numbers on the nozzle exit M = 1.5÷3 was not considered in detail.

The aim of the work is a fundamental study of the interaction of a supersonic jet with wedge barrier in a wide range of applicability, namely with a rarefied atmosphere and Mach numbers at the nozzle exit 4-5.

2. Physical and mathematical model

In this study, the interaction of a single supersonic jet with a wedge barrier was considered. The supersonic jet expires from the nozzle with Mach numbers 5 and 6 at the nozzle exit. Hydrazine combustion products was used as a working fluid. Schematically, this interaction is shown in figure 1, where AA – nozzle exit; AB – jet boundary; AL – expansion fans; OT – barrel shock; TB – reflected shock; TD – contact discontinuity; TT – Mach disk (normal shock); T – triple point; C – critical point (braking point); 1 – continuation of the flow from the nozzle; 2 – expansion flow; 3 – near-axis region of free expansion flow; 4 – the annular area between the fronts of the branched shock waves; 5, 6 – flow in a stream behind a normal shock (impingement region); 7 – wall jet (peripheral flow) [10-12].

![Figure 1. The structure of a single supersonic jet interaction with wedge barrier](image)

The system of shock waves in front of the surface coincides with the flow in a free jet with the same parameters in the outlet section of the nozzle. If the obstacle is located in the sections between the central shock of the seal and the end of the first "cell" of the free jet, a large vacuum may form. Therefore, a relatively small part of the total gas flow will pass through the normal shock of the jet cross section. This part of the gas flow, spreading over the surface of the obstacle, forms a thin layer between the surface of the obstacle and the contact discontinuity coming off the contour of the normal shock (region 6). The bulk of the gas in the jet moves near the wall obstacle, passing through a system of shock waves. After the last shock wave, this mass of gas enters the area called the main peripheral flow or wall jet region (region 7). The nature of gas motion in region 7 has a significant effect on the distribution of pressure along the obstacle surface.
For the mathematical description of the interaction of supersonic jet with a flat obstacle the compressible Euler equations are used as a governing equations for ideal gas [12-15]. The system equations include continuity, momentum, and energy equations. In the integral conservative form given as:

\[
\frac{\partial}{\partial t} \iiint_V \rho \, dV + \iiint_{\partial S} \mathbf{F}(\mathbf{U}) \cdot \mathbf{n} \, d\mathbf{S} = 0
\]  

Where:

\[
\mathbf{U} = [\rho, \rho u, \rho v, \rho w, \rho E]^T
\]  

\[
\mathbf{F}(\mathbf{U}) \cdot \mathbf{n} = \begin{bmatrix}
\rho \hat{u} \\
\rho \hat{u} u + p_n \\
\rho \hat{u} v + p_n \\
\rho \hat{u} w + p_n \\
\rho \hat{u} (E + RT)
\end{bmatrix}
\]  

Where \( \hat{u} \) is velocity component normal to the surface \( \partial S \), \( \hat{u} \cdot \mathbf{n} = un_x + vn_y + wn_z \).

To implement the physical and mathematical model (1)-(5) and conduct numerical research free software OpenFOAM-Extended was used [16-18]. Numerical method on finite volume method is based. Hexahedral numerical mesh was make using Salome Platform software. From the approximate solution of the Riemann problem according to the Rusanov scheme in dbnsFoam solver of OpenFOAM-Extended, there was fluxes through the faces of the computational grid cells. System of linear of algebraic equations using the Gauss-Seidel method was solved. The time sampling by a four-step Runge-Kutta method was carried out. Numerical investigation using SKIF Cyberia supercomputer of Tomsk State University was done.

3. Numerical results

The geometric characteristics of the nozzle were as follows: nozzle throat diameter 0.03613 m, nozzle diameter 0.19395 m, and the angle of the semi-solution of the nozzle is 10 degrees. The angle of wedge barrier was 0, 5, and 10 degrees. For numerical calculations at the initial time unmoved environment was assumed. The ambient pressure was 650 Pa, and temperature was 250 K. Two variants was considered for parameters at the nozzle inlet. The first variant: pressure – 0.28 MPa, temperature – 1180 K, adiabatic index – 1.33719, the second variant: pressure – 1.962 MPa, temperature – 1336 K, adiabatic index – 1.29222. The distance from nozzle exit to flat obstacle was 0.5 meter.

The results of Mach number in figure 2 (first variant) and 3 (second variant) are shown. According to results from the figures the wedge angle of 5 and 10 degrees practically does not affect the shape of the main jet and the wall jets for the first and second variants. For the second variant, a change in the shape of the Mach disk in front of the barrier with increasing wedge angle is noticeable. The near-wall jet also hardly changes. In figure 4 and 5 distribution of pressure on wedge barrier for two variants with wedge angle 0, 5, and 10 degree are shown.

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Figure 2. Mach number for the first variant

Figure 3. Mach number for the second variant
In Figure 4, the wedge angle has almost no effect on the pressure distribution along the barrier. For the first variant, there is a slight decrease in pressure on the jet axis of a relatively flat barrier, and the near-wall jet almost coincides. For the second option, also on the jet axis, there is a slight decrease in pressure with increasing wedge angle. For a wedge with 5 and 10 degrees, the near-wall jet coincides. There is a slight displacement of the wall jet for the wedge 5 and 10 degrees by 3 cm relative to the flat barrier.

4. Conclusion
Mathematical modeling of the interaction of a single supersonic jet with wedge barrier are done. Calculations using OpenFOAM-Extended dbnsFoam solver are done. Two variants with different parameters at the inlet nozzle with wedge angle 0, 5, and 10 degree are considered. Results of the calculations showed a weak influence of the wedge angle on the jet shape and pressure distribution along the barrier for two variants. A 3 cm deflection of the wall jet is noted for a flat barrier as opposed to wedge with 5 and 10 degree.
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