Validation of 3D model by the example of a supersonic inlet-isolator

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Abstract. In the paper three-dimensional model for hypersonic flow are described. Comparing the result of calculation with wall pressure data, obtained in the inlet-isolator model mounted to the floor of a Mach 2.75 wind tunnel at the Stanford University, presented in this article. The present results show that three-dimensional model is able to predict the shock wave structures in a scramjet inlet/isolator.

1. Introduction
The inlet is an essential element of the ramjet and scramjet, and their design greatly affects the overall performance of the engine. Therefore, at the initial stage of creating a gas-dynamic code for describing processes in ramjet and scramjet it is very important to correctly describe the inlet and the shock-wave structure in it. Inlets are with external compression, mixed compression and internal compression [1], but they have the same function in common. In the inlet, due to the appearance of the shock-wave structure, the incoming air is compressed and the Mach number decreases to the desired value at the entrance to the engine. The isolator is also an essential part of the ramjet and scramjet. The possibility of a correct description of the shock wave structure is very important for accurate calculations of the combustion chamber. In other words, by setting the parameters at the inlet to the air intake, it becomes possible to obtain the parameters at the inlet to the combustion chamber. The model described allows us to calculate the flow in the combustion chamber, which will be demonstrated in subsequent work. Recently, experiments have appeared with a complex shape of the air intake, so it is especially important to create three-dimensional codes. For example, Rectangular-to-Elliptical Shape Transition (REST) [2–4] scramjet become common in recent years.

There are many experiments with inlets [2–12]. In this paper we consider the model of inlet-isolator mounted to the floor of a Mach 2.75 wind tunnel at the Stanford University[9]. This type of experimental setup is called jet in supersonic cross-flow (JISCF). Absolutely similar experiments were conducted in China [5,6]. In this experiment, in addition to visual observations, pressure measurements were made on the upper and lower walls. In this paper, the validation is performed on the pressure distribution in this experiment on the top wall. Besides this verification case involves the computation of the supersonic flowfield past a wedge with a half-angle of 15 degrees.
2. Description of Stanford University inlet-isolator experimental setup
Stanford University conducted a series of experiments to study the injection of fuel into the supersonic flow, as well as to study shock-wave structure in the supersonic inlet-isolator mounted to the floor of a Mach 2.75 at the Expansion Tube Facility of the High Temperature Gasdynamics Laboratory at Stanford University. (figure 1). The experimental setup consists of an input ramp with an inclination angle of 10°, and a constant-section isolator. The height at the entrance to the air intake is 23 mm. The height of the constant part of the isolator is 15mm. The width of the chamber is constant and equal to 75 mm. From the bottom wall of the chamber perpendicular to the flow, fuel is injected through a nozzle 2 mm in diameter. The injection site is located in the center of the bottom wall of the chamber at a distance of 70 mm down from the leading edge of the inlet. In the experiment, in addition to visual observations, the pressure distribution on the lower and upper walls was investigated, as well as the interaction of the blown jet with the main air flow. In this paper, injection of fuel was not considered. The following incoming air flow parameters were used:
I. Incoming flow pressure: \( P = 0.40 \) atm;
II. Incoming flow temperature: \( T = 1250 \) K;
III. Incoming flow Much Number: \( M = 2.75 \);
IV. Incoming flow gas mixture: Air.

![Figure 1](image)

**Figure 1.** The side-view of inlet/isolator model [9].

3. Three-dimensional computational fluid dynamic model
For three-dimensional calculations we used the NERAT-3D computer code [13]. NERAT-3D realizes the time-relaxation method. At each time step the following groups of governing equations were integrated successively: the Navier–Stokes and continuity equations, the equations of mass conservation of chemical species, the equation of energy conservation. These equations are formulated in the following form:

\[
\frac{\partial \rho}{\partial t} + \text{div} (\rho \mathbf{V}) = 0, \quad (1)
\]

\[
\frac{\partial \rho \mathbf{V}}{\partial t} + \text{div} (\rho \mathbf{VV} + \mathbf{F}) = 0, \quad (2)
\]

\[
\rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{V} \text{grad} T = \text{div} (\lambda \text{grad} T) + \sum_{i=1}^{N_i} \rho c_p D_i (\text{grad} Y_i \cdot \text{grad} T) - \sum_{i=1}^{N_i} \hat{h}_i \hat{\omega}_i + \frac{\partial \rho}{\partial t} + \mathbf{V} \text{grad} p + \Phi,
\]

\[
\frac{\partial \rho_i}{\partial t} + \text{div} \rho_i \mathbf{V} = -\text{div} \mathbf{J}_i + \hat{\omega}_i, \quad i = 1, 2, \ldots, N_s, \quad (4)
\]
where: t – time; \( \mathbf{V} = iu + jv + kw \) – velocity vector with projections on the axis of the Cartesian coordinate system \( x, y, z \); \( p, \rho \) – pressure and density; \( T \) – temperature of translational movement of particles; \( \mu, \lambda \) – dynamic coefficient of viscosity and coefficient of thermal conductivity; \( c_p \) – specific heat of the mixture at constant pressure; \( c_p = \sum_{i}^{N} Y_i c_{p,i} \); \( N_s \) – number of gas mixture components; \( Y_i \) – mass fraction of the \( i \)-th component of the mixture; \( c_{p,i}, h_i \) – the specific heat at constant pressure associated with translational and rotational degrees of freedom, and the enthalpy of the \( i \)-th component of the mixture; \( \dot{w}_i \) – the mass velocity of chemical transformations for the \( i \)-th component of the mixture; \( D_i \) – the effective diffusion coefficient of the \( i \)-th component of the mixture; \( \mathbf{J}_i \) – the diffusion flux density of the \( i \)-th component of the mixture; \( sN \) – number of chemical components of the gas mixture. The components of the viscous stress tensor and the dissipative function were calculated by the formulas:

\[
\Pi_{i,j,k} = -p \delta_{i,j,k} + \mu \left[ \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \delta_{i,j} \left( \frac{\partial u_k}{\partial x_k} \right) \right], \quad i,j,k = 1,2,3
\]

\[
\Phi_\mu = \mu \left[ 2 \left( \frac{\partial u}{\partial x} \right)^2 + 2 \left( \frac{\partial v}{\partial y} \right)^2 + 2 \left( \frac{\partial w}{\partial z} \right)^2 \right]
\]

\[
+ \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right)^2 + \left( \frac{\partial w}{\partial z} + \frac{\partial u}{\partial x} \right)^2 - 2 \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right)^2 \right]
\]

The closing relations for the system of equations to be solved include the thermal equation of state of an ideal gas:

\[
\frac{p}{\rho} = \frac{R_0}{M_\gamma} T, \quad \frac{1}{M_\gamma} = \sum_{i}^{N} \frac{Y_i}{M_i}
\]  

(5)

The system of equations (1) – (5) was integrated numerically by the establishment method using computer code NERAT-3D. Equations (1) – (2) were integrated by an explicit finite-difference method according to the AUSM scheme [14]. The diffusion equations (4) and energy conservation were solved using an implicit finite-difference scheme of the second order of the Crank-Nicholson approximation. Numerical solution of finite-difference equations was carried out using multi-block technology. The number of blocks used in this technology is determined by the complexity of the geometry of the calculation area. In this case, 8 blocks of the grid were used. The calculations use a structured mesh of 60×50×14 dimensions in each block, if not stated other. Chemical reactions are neglected.

4. Results

The first verification case for 3D code involves the computation of the supersonic flowfield past a wedge with a half-angle of 15 degrees. Figures 2– 3 shows the main features of the flow field. The freestream consists of air. Mach number is of 2.5. The inlet temperature is equal to 280 K. The inlet pressure is equal to 1 atm. As the flow meets the leading edge of the wedge, an oblique shock is formed as the flow turns to become tangent with the wedge surface. The parameters of the flowfield (Mach number, pressure, temperature and angle of oblique shock) past the shock is uniform and presented in table 1. The calculations use a structured mesh of 40×40×30 dimensions in each of eight blocks. Table 1 presents a comparison of the calculation results behind the oblique shock for the
NERAT 3D and WIND 2D [15] with an analytical solution [16]. It can be seen that the relative error does not exceed 4 percent.

![Figure 2. Mach number distribution within the experimental setup.](image)

![Figure 3. Pressure distribution within the experimental setup.](image)

**Table 1.** Comparison of the results of calculating a flat wedge with an angle of 15° with analytical and calculated data.

|                     | Mach | Pres, atm | T, K  | angle |
|---------------------|------|-----------|-------|-------|
| NERAT 3D (this work)| 1.860| 2.560     | 373.0 | 37.14 |
| Analytical solution | 1.870| 2.467     | 370.1 | 36.95 |
| Relative error, %   | 0.540| 3.610     | 0.780 | 0.530 |
| WIND 2D [15]        | 1.868| 2.469     | 372.5 | -     |

The second validation case is Stanford University experimental setup. At the calculations the entrance to the inlet is set uniform flow. Figure 4 shows the results of calculated pressure distribution within the experimental setup. It should be noted the occurrence of a shock-wave structure in the
channel. However, the intensity of the shock waves attenuates. This is particularly noticeable on the results of calculated pressure distribution on the top wall. Comparison of calculated pressure distribution on the top wall obtained in this work (red line) and the experimental results (green squares) [9] presented in the figure 5. The position of first two the shock wave peaks is consistent, which allows us to conclude that the results are qualitatively identical.

![Figure 4. Pressure distribution within the experimental setup.](image)

![Figure 5. Comparison of calculated pressure distribution on the top wall obtained in this work (red line) and the experimental results (green squares) [9].](image)

5. Conclusion
Comparison of the calculation results behind the oblique shock for the NERAT 3D and WIND 2D and an analytical solution are presented. Comparison of the pressure distribution calculated by three-
dimensional model and pressure top wall distribution in the inlet-isolator model mounted to the floor of a Mach 2.75 wind tunnel at the Stanford University are presented. The present results show that our three-dimensional simulations are able to predict the shock wave structures in a scramjet inlet/isolator. This work presents a continuation of our efforts on the verification and validation of numerical methods and computational codes for calculation of various hypersonic vehicles and energetic devices [18–23].

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