Validation of two-dimensional model by the example of a supersonic inlet-isolator

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Abstract. In the paper two-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 5 wind tunnel at the University of Texas, presented in this article. The present results show that two-dimensional simulations are 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 isolator is a constant cross-section passage in order to prevent choking. There are many experiments with inlets [2][3][4–6]. In this paper we consider the model of inlet-isolator mounted to the floor of a Mach 5 wind tunnel at the University of Texas [4,6,7]. In this experiment, it is important to consider the thickness of the boundary layer at the inlet. In this paper, numerical experiments are carried out that take into account the thickness of the boundary layer, as well as experiments with a uniform flow at the inlet. The results of the calculation are compared with the results obtained by other authors [8–10], as well as with the results of the experiment.

2. Description of University of Texas inlet-isolator experimental setup

Wagner [4,6–8] conducted a series of experiments on the study of shock-wave structure in the supersonic inlet-isolator mounted to the floor of a Mach 5 wind tunnel (figure 1). The experimental setup consists of an input ramp with an inclination angle of 6°, and a constant-section isolator (figure 2). At the end of the isolator a special flap is installed, raising it can lead to nonstationary formation with subsequent choking of the flow. With the flap is completely lowered, a small part of it protrudes from the bottom wall of the chamber, as shown in figure 2. However, in this paper, as in the
works of other authors[9−13], it is considered that the floor is completely smooth. The following incoming air flow parameters were used:

- Incoming flow pressure: $P = 0.0538$ atm;
- Incoming flow temperature: $T = 57.4$ K;
- Incoming flow Much Number: $M = 4.9$;
- Incoming flow gas mixture: Air.

3. Two-dimensional computational fluid dynamic model
For two-dimensional calculations we used the NERAT-2D computer code [13]. NERAT-2D 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:

$$\begin{align*}
\frac{\partial \rho}{\partial t} + \text{div} (\rho \mathbf{V}) &= 0, \\
\frac{\partial \rho \mathbf{u}}{\partial t} + \text{div} (\rho \mathbf{u} \mathbf{V}) &= -\frac{\partial \rho}{\partial x} - \frac{2}{3} \frac{\partial}{\partial x} (\mu \text{div} \mathbf{V}) + \frac{1}{r} \frac{\partial}{\partial r} \left[ r \mu \left( \frac{\partial \mathbf{V}}{\partial x} + \frac{\partial \mathbf{u}}{\partial r} \right) \right] + 2 \frac{\partial}{\partial x} \left( \mu \frac{\partial \mathbf{u}}{\partial x} \right), \\
\frac{\partial \rho \mathbf{V}}{\partial t} + \text{div} (\rho \mathbf{V} \mathbf{V}) &= -\frac{\partial \rho}{\partial x} - \frac{2}{3} \frac{\partial}{\partial r} (\mu \text{div} \mathbf{V}) + \frac{\partial}{\partial x} \left[ \mu \left( \frac{\partial \mathbf{V}}{\partial x} + \frac{\partial \mathbf{u}}{\partial r} \right) \right] + 2 \frac{\partial}{\partial x} \left( \mu \frac{\partial \mathbf{u}}{\partial x} \right) + 2 \frac{\partial}{\partial r} \left( \mu \frac{\partial \mathbf{u}}{\partial r} \right) + 2 \mu \frac{\partial}{\partial r} \left( \frac{\mathbf{V}}{r} \right), \\
\frac{\partial \rho_{i}}{\partial t} + \text{div} \rho_{i} \mathbf{V} &= -\text{div} \mathbf{J}_{i} + \dot{w}_{i}, \quad i = 1, 2, \ldots, N_{s},
\end{align*}$$

Figure 1. Schematic of the model of the inlet/isolator model mounted on the wind tunnel floor [4].

Figure 2. Inlet/isolator model mounted on the wind tunnel floor [4].
\[ \rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{V} \text{grad}T = \text{div} \left( \lambda \text{grad}T \right) + \frac{\partial p}{\partial t} + \mathbf{V} \text{grad} p + \]
\[ + \Phi_\mu \left[ 2 \left( \frac{\partial \mathbf{V}}{\partial r} \right)^2 + 2 \left( \frac{\partial \mathbf{V}}{\partial x} \right)^2 + \left( \frac{\partial \mathbf{V}}{\partial x} + \frac{\partial \mathbf{V}}{\partial r} \right)^2 - \frac{2}{3} \left( \frac{\partial \mathbf{V}}{\partial x} + \frac{\partial \mathbf{V}}{\partial r} + \frac{\mathbf{V}}{r} \right)^2 \right] \]
\[ \text{is the dissipative function; } \mu, \lambda \text{ are the viscosity and heat conductivity coefficients, } c_p \text{ is the specific heat capacity of gas mixture; } c_p = \sum_i Y_i c_{p,i}; \ Y_i \text{ is the mass fraction of species } i; \ h_i \text{ are the specific heat capacity at constant pressure and specific enthalpy of species } i; \ \dot{w}_i \text{ is the reaction rate for species } i; \ D_i \text{ is the effective diffusion coefficient of species } i; \ \rho_i, \mathbf{J}_i \text{ are the density and mass diffusion flux for species } i; \ \mathbf{J}_i = -\rho D_i \text{grad} Y_i; \ N_i \text{ is the number of species. The calculations use a structured mesh of 500x100 dimensions, if not stated other. Chemical reactions are neglected.} \]

4. Results

At the initial stage of calculations, at the entrance to the inlet a uniform flow is set. Figure 3 shows the results of calculated pressure distribution within the experimental setup on structured mesh of 1000 x1000.

Figure 4 shows the results of calculated pressure distribution on the bottom wall obtained in this work with the results by Lutsky [9] and Zhukov [8].

Figure 4. Comparison of calculated pressure distribution on the bottom wall obtained in this work (black line) and the results obtained by Lutsky [9] (red tangles) and Zhukov [8] (green squares).
It can be seen that the flow pattern is described qualitatively. However, in the experiment, the input flow was uneven with a thick boundary layer. The incoming boundary layer profiles were extracted from a method, based on well-known formulas for the boundary layer on a thick plate together with a modification from the work [9,14]. However, it should be noted that in the case of using this model without using the turbulence model, a vortex zone appears before the first shock wave, which changes the flow in the channel. As the results show [10–13,15], the use of the turbulence model avoids the appearance of a vortex. In this work, it was decided to artificially increase the viscosity of a factor of 1000 in the region ahead of the shock wave, as shown in figure 5. This led to the fact that the vortex disappeared. Figure 6 shows a comparison of the pressure distribution on the lower chamber wall obtained in this work (black line) with the experimental results [4,6] (green squares), and the results obtained by Lutsky [9] (red squares)and Koo[10,15] (blue delta). The pressure amplitude obtained in my calculations is just below the amplitude obtained by other authors. However, it should be noted that the position of the shock wave peaks is consistent, which allows us to conclude that the results are qualitatively identical.

![Viscosity distribution](image)

**Figure 5.** Viscosity distribution within the experimental setup.

5. Conclusion
Comparison of the pressure distribution calculated by two-dimensional model, the results obtained by other authors and pressure distribution in the inlet-isolator model mounted to the floor of a Mach 5 wind tunnel at the University of Texas is presented. The present results show that two-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 [16–23]. The results obtained in this study in the study of the shock wave structure in a supersonic air inlet can be used later to study the effect of a surface discharge on a hypersonic flow as it was numerically studied in [24,25].
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Pressure, erg/cm³

![Graph image]

**Figure 6.** Comparison of calculated pressure distribution on the bottom wall obtained in this work (black line) with the experimental results [4,6] (green squares), and the results obtained by Lutsky [9] (red squares) and Koo[10,15] (blue delta).

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