Aerothermodynamics calculation of the EXPERT reentry flight vehicle

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Abstract. This paper concerns the aerothermodynamics of high-speed gas flows around the EXPERT reentry flight vehicle moving at different angles of attack at an altitude of 50 km with the speed \( V_\infty = 5 \text{ km/s} \). Calculations were carried out using UST3D and UG3D computer codes developed at the Ishlinsky Institute for Problems in Mechanics RAS (IPMech RAS). The computer codes implement the numerical simulation of the flight vehicle aerothermodynamics by integrating the complete set of Navier–Stokes equations on unstructured mesh using the ideal gas model.

1. Introduction

The EXPERT reentry flight vehicle was developed by the European Space Agency (ESA) [1]. Flight tests of the vehicle were not conducted, but there is a sufficiently large amount of calculations and experimental data. Experimental data are presented this papers [2–5]. In papers [4–6] the numerical results are presented. At first glance, the geometry of this device may seem fairly simple, but the numerical simulation reveals the difficulties related to the design features of this type of vehicles.

2. Computational model

Flows around the EXPERT reentry flight vehicle were calculated using the UST3D and UG3D computational codes [7, 8]. These codes are designed to compute the aerothermodynamics of high-speed flight vehicles and can be used in a wide range of Mach numbers, altitudes and angles of attack [7–9]. The computer codes are based on the algorithms for solving the non–stationary three–dimensional set of Navier–Stokes equations (1) – (4) [10–12].

\[
\frac{\partial \mathbf{w}}{\partial t} + \frac{\partial F^x(w)}{\partial x} + \frac{\partial F^y(w)}{\partial y} + \frac{\partial F^z(w)}{\partial z} = \frac{\partial G^x(w)}{\partial x} + \frac{\partial G^y(w)}{\partial y} + \frac{\partial G^z(w)}{\partial z},
\]

\[
\mathbf{w} = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{pmatrix},
\]
The complete set of Navier–Stokes equations is used in conjunction with the equation of state for ideal gas (5).

\[ p = (\gamma - 1) \rho U = (\gamma - 1) \rho \left[ E - \frac{1}{2} (u^2 + v^2 + w^2) \right], \]  

The UST3D and UG3D computer codes execute numerical integration of the system using the splitting method with respect to physical processes and the Godunov–type method [13]. The methods are explicit and use the first–order and second–order approximation in time and second–order approximation in space. The problem is solved by obtaining the convergence [7–9].

During the verification of UST3D and UG3D computational codes, the results were compared with the ones obtained by the SolidWorks Flow Simulation module for gasdynamic computations. This module is based on the algorithms for solving the non–stationary three–dimensional set of Navier–Stokes equations using the ideal gas model, as well. Codes UST3D and UG3D were validated in [7, 8].

3. Problem statement for computing flows around the EXPERT reentry flight vehicle

In order to perform a numerical simulation of the flow process, a three–dimensional surface model of the EXPERT reentry vehicle was developed (figures 1, 2).

![Figure 1](image1.png)  
**Figure 1.** Three–dimensional surface of the EXPERT reentry vehicle.

![Figure 2](image2.png)  
**Figure 2.** Dimensions of the EXPERT reentry vehicle.
The model was created using the SolidWorks CAD environment. The model is a complete equivalent of the vehicle and considers all its design features.

4. Computational mesh
In this paper, a three-dimensional flow field near the flight vehicle was simulated using unstructured tetrahedral meshes (figures 3–6).

![Figure 3. Surface mesh of the EXPERT reentry vehicle.](image1)

![Figure 4. Volume mesh of the EXPERT reentry vehicle.](image2)

Several options of the computational mesh were generated: excluding and including the shock–wave feature of the flow structure (figures 4, 6). In the first case, the mesh was refined toward the vehicle head and toward the vehicle parts sensitive to the specific design features. The number of triangles on the surface was 98,454, and the total number of tetrahedrons in the volume was 1,024,290 cells (figures 3, 4). For an adaptive mesh, the refinement was carried out toward the head shock wave which position and structure depend on the incoming flow parameters [14]. The number of triangles on the surface was 65,210, and the total number of tetrahedrons in the volume was 5,383,515 cells (figures 5, 6).

![Figure 5. Surface mesh of the EXPERT reentry vehicle.](image3)

![Figure 6. Volume mesh of the EXPERT reentry vehicle.](image4)
5. Results obtained

Figure 7 shows the density distribution on the surface and in the vicinity of the vehicle flying at zero angle of attack at an altitude of 50 km with the speed $V_\infty = 5$ km/s. Figure 8 illustrates pressure distribution on the vehicle surface. The calculation was carried out using the UST3D and UG3D computer codes and the SolidWorks Flow Simulation module. Index "a" denotes the results calculated using the adaptive mesh.

**Figure 7.** Density (in kg/m$^3$) distribution on the surface and in the vicinity of the EXPERT reentry vehicle. Angle of attack of 0°.

**Figure 8.** Pressure distribution on the surface of the EXPERT reentry vehicle. Angle of attack of 0°.

Figures 9 and 10 show density distribution on the surface and in the vicinity of the vehicle. The vehicle travels at an altitude of 50 km with the speed of $V_\infty = 5$ km/s at angles of attack of 10° and 15°.

**Figure 9.** Density (in kg/m$^3$) distribution on the surface and in the vicinity of the EXPERT reentry vehicle. Angle of attack of 10°.

**Figure 10.** Density (in kg/m$^3$) distribution on the surface and in the vicinity of the EXPERT reentry vehicle. Angle of attack of 15°.
Figures 11–16 show pressure distribution on the surface of the vehicle. Figures 11–14 show diagrams with the comparison of results for UST3D and UG3D computer codes. The calculations were carried out using the same mesh.

**Figure 11.** Pressure distribution on the surface of the EXPERT reentry vehicle. Angle of attack of $0^\circ$.

**Figure 12.** Pressure distribution on the surface of the EXPERT reentry vehicle. Angle of attack of $6^\circ$.

**Figure 13.** Pressure distribution on the surface of the EXPERT reentry vehicle. Angle of attack of $10^\circ$.

**Figure 14.** Pressure distribution on the surface of the EXPERT reentry vehicle. Angle of attack of $15^\circ$.

Figures 15 and 16 show the comparison of calculation results obtained with and without mesh adaptation using the UG3D computer code.

Strong fluctuations are observed on the head part of the vehicle surface when calculating without mesh adaptation.

The use of adaptive mesh increases the accuracy of the result obtained when calculating aerothermodynamics of flight vehicles (figure 17). But this leads to additional requirements for geometry construction and mesh generation [14].
Figure 15. Pressure distribution on the surface of the EXPERT reentry vehicle. Angle of attack of $10^\circ$.

Figure 16. Pressure distribution on the surface of the EXPERT reentry vehicle. Angle of attack of $15^\circ$.

Figure 17. Density (in kg/m$^3$) distribution on the surface of the EXPERT reentry vehicle.

Figures 18 and 19 show behavior diagrams of aerodynamic coefficients of lift and drag forces as a function of the angle of attack. The results are calculated using four computational codes: UST3D, UG3D, INTEG and SolidWorks Flow Simulation.
INTEG code was developed at the Institute of Theoretical and Applied Mechanics RAS. The computer code is based on the local bridge method and is designed to calculate aerodynamic characteristics.

**Figure 18.** Behavior of aerodynamic drag force coefficient as a function of the angle of attack of the EXPERT reentry flight vehicle. Angles of attack of $0^\circ, 6^\circ, 10^\circ, 15^\circ$.

**Figure 19.** Behavior of aerodynamic lift force coefficient as a function of the angle of attack of the EXPERT reentry flight vehicle. Angles of attack of $0^\circ, 6^\circ, 10^\circ, 15^\circ$.

The difference between the results obtained and the data given in the paper is due to the fact that simulation of vehicle flights in dense atmosphere at high speeds requires the consideration of various physical and chemical processes in the air [6, 14, 15].

**Conclusion**

The paper demonstrates the necessity to refine the mesh on the head shock wave front and in the areas of high gradients. It leads to additional requirements for construction of geometry and computational mesh used in the calculation of aerothermodynamics of flight vehicles.

In the future, it is planned to develop an automated mesh adaptation.

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**References**

[1] [http://www.esa.int/ESA](http://www.esa.int/ESA)

[2] Adamov N P, Kharitonov A M, Mazhul I I, Vasenyov L G, Zapryagaev V I, Zvegintsev V I and Muylaert J M 2008 Investigations of Aerogasdynamics of Re-Entry Ballistic Vehicle Expert International conference on Methods of Aerophysical Research

[3] Kharitonov A M, Adamov N P, Chirkashenko V F, Mazhul I I, Shpak S I, Shplyuk A N, Vasenyov L G, Zvegintsev V I and Muylaert J M 2012 Aerothermodynamics of Expert Ballistic Vehicle at Hypersonic Speeds Progress in Flight Physics 3 pp 277–294

[4] Brazier J P, Schramm J M, Paris S and Gawehn T 2015 An overview of HyFIE Technical Research Project: cross testing in main European hypersonic wind tunnels on EXPERT body 50th 3AF International Conference on Applied Aerodynamics

[5] Muylaert J, Cipollini F, Walpot L, Ottens H 2005 Flight Experiments for Hypersonic Vehicle Development Expert RTO AIV RTO–EN–AVT–116

[6] Martinez Barrio A, Sudars M, Gavira J, Aulisio R, Ratti F, Massobrio F, Walpot L, Passarelli G, Thoemel J, and Thirkettle A 2011 EXPERT – The ESA EXPERIMENTAL Re–Entry Test–Bed Trajectory and mission design AIAA Guidance Navigation and Control Conference
AIAA 2011–6342

[7] Surzhikov S T 2017 Validation of computational code UST3D by the example of experimental aerodynamic data J. of Physics: Conference Series 815 012023

[8] Kotov M A, Kryukov I A, Ruleva L B, Solodovnikov S I, and Surzhikov S T 2015 Supersonic Air Flows Around Some Geometrical Primitives 33rd AIAA Applied Aerodynamics Conference AIAA 2015–3012

[9] Zheleznyakova A L and Surzhikov S T 2013 Application of the method of splitting by physical processes for the computation of a hypersonic flow over an aircraft model of complex configuration High Temperature 51 pp 816–829

[10] Surzhikov S T 2011 Radiative–Convective Heat Transfer of a Spherically Shaped Space Vehicle in Carbon Dioxide High Temperature 49 pp 92–107

[11] Shang J S and Surzhikov S T 2010 Simulating Nonequilibrium Flow for Ablative Earth Reentry J. of Spacecraft and Rockets 47 pp 806–815

[12] Surzhikov S T, Seleznev R K, Tretyakov P K and Zabaykin V A 2014 Unsteady Thermo-Gasdynamic Processes in Scramjet Combustion Chamber with Periodical Input of Cold Air 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference AIAA 2014–3917 p 25

[13] Godunov S K 1959 A finite-difference method for the numerical computation and discontinuous solutions of the equations of fluid dynamics Mat. Sb. 47 pp 271–306

[14] Surzhikov S T 2013 Convective heating of small-radius spherical blunting for relatively low hypersonic velocities High Temperature 51 pp 231–245

[15] Surzhikov S T 2017 Spatial Multiphysics Models of the Radiation Gas Dynamics of Super Orbital Re–Entry Space Vehicles. J. of Physics: Conference Series 837 012021