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Numerical analysis of air dissociation influence on spaceplane aerodynamic characteristics

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ABSTRACT

Hypersonic flow is a very complex regime due to high values of velocity that causes air dissociation and ionization. This paper explores the influence of air dissociation on aircraft aerodynamic properties. The approach is the creation of a block-structured mesh by means of ICEM CFD and further set-up of Fluent solver. Aircraft aerodynamics properties were calculated for cases of perfect gas and non-equilibrium flow. Based on the results of the calculation, a comparison was made between obtained drag pressure coefficients, skin friction coefficients, drag coefficients, lift coefficients, lift-to-drag ratios and pitching moment coefficients.

1. Introduction

As it is known flying at hypersonic velocity is a difficult task for any aircraft due to the high values of temperature on the surface. Such temperatures lead to the development of the complex thermal protection systems (TPS) which can consist of ablative armor, low thermal conductivity materials or passively-cooled TPS. Not less interesting are the processes occurring in the shock wave which is characterized by air dissociation and ionization. Air dissociation and ionization cause changes in chemical and physical properties of gas, e.g. viscosity [1], thermal conductivity [2–4], chemical composition, etc, which affects the spaceplane aerothermodynamic properties.

The increase in computing powers has made it possible to simulate such processes which allows to save money and time resources. Majority of CFD packages, for example ANSYS Fluent, are based on Reynolds-average Navier-Stokes equations (RANS equations) [5] which provide sufficient accuracy for the task of the aerodynamics and thermodynamics [6,7] and this has led to an increase in the popularity of these packages among engineers and researchers (e.g. works [8–10]).

As it is recalled in 2011 the program “Space Shuttle” was closed and this event made a break in the use of spaceplanes. Despite this, some countries continue to develop experimental spaceplanes, e.g. Boeing X-37 B [11] that landed in May 2017 after a two-year mission. Such interest in spaceplanes is caused by their possibility of further reuse as well as a more accurate landing in comparison with spacecraft like Soyuz due to the presence of aerodynamic surfaces.

It should be noted that many researchers while modeling air dissociation consider problems primarily related to heat exchange. Yang and Liu [12] proposed a new method of determining the first grid point off wall based on the molecular mean free path at the stagnation point for further analysis of heat exchange. Hao et al. [13] suggested an improved γ-Re_θ model for heat transfer prediction which showed a good accuracy. Wang et al. [14] conducted numerical analysis of aerodynamic heating using various chemical kinetic models for ELECTRE vehicle, Apollo command module and Space Shuttle and found that kinetic models show a significant difference in the heat flux with increasing complexity of geometry. Some researchers have investigated the influence of air dissociation on spacecraft aerodynamics. Liu et al. [15] investigated the effects of a thermochemical non-equilibrium flow on the aerodynamics of osculating-cone waverider for a range of small angles of attack. Massimi et al. [16,17] performed aerodynamics calculations for the EXPERT capsule and obtained dependence of drag pressure coefficients, skin friction coefficients and Stanton numbers along the lower centerline on Mach number for different altitudes. Jun et al. [18] explored the effect of high-temperature gas on aerodynamic characteristics of waverider and compared the obtained results for the pressure center and pitching moment coefficient depending on the Mach number. Tchuen and Zeitoun [19] modeled the air ionization flow over sphere-cones and compared skin friction coefficients for perfect gas, the paired vibration-dissociation model, and the electronic relaxation by the radius of the sphere. Li et al. [20] examined the dependence of lift-to-drag ratio and aerodynamic heating on the radius of blunting of the nose of the waverider and proposed the optimal blunting radius.

This paper raises the question of studying air dissociation influence on spaceplane aerodynamic properties. This work includes the creation

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of the mesh for a wide range of tasks, as for our case of aerodynamics with allowance of non-equilibrium chemical reactions (Section 3). The aerodynamic calculation will be performed for the cases with and without chemical reactions (Section 4) and further comparison of the obtained results for skin friction coefficients, drag pressure coefficients, drag coefficients, lift coefficients, lift-to-drag ratios and pitching moment coefficients (Section 5).

The hypersonic flow problem remains complex and interesting for many academics because it challenges in many fields of research such as aerodynamics, thermodynamics, design, etc.

2. Mathematics model

2.1. Flow equations

To model the flow it is necessary to write continuity and momentum equations. The generalized continuity equation in a differential form is as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0, \tag{1}$$

where ∇ – nabla operator, ρ – fluid density, t – time, $\vec{u}$ – flow velocity vector field.

Eq. (1) can be averaged in time and completed by the Navier-Stokes momentum equation we obtain Reynolds-averaged Navier-Stokes equations [5]:

$$\frac{\partial}{\partial t}(\rho \overline{u_i}) + \frac{\partial}{\partial x_j}(\rho \overline{u_i}\overline{u_j}) = -\frac{\partial \overline{p}}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_j} - \frac{2}{3}\delta_{i,j}\frac{\partial \overline{u_i}}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}(-\overline{\rho u_i' u_j'}), \tag{2}$$

where $\overline{p}$ – average pressure flow, μ – dynamic viscosity, $\delta_{i,j}$ – Kronecker delta, $\overline{u_i}$ – average fluid velocity, u_i' – velocity fluctuation, $(-\overline{\rho u_i' u_j'})$ – Reynolds stress.

For a compressible flow it is also necessary to include the energy equation that has the following form (with the Reynolds stress model) [21]:

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}(\overline{u_i}(\rho E + \overline{p})) = \frac{\partial}{\partial x_j}\left(k_{eff}\frac{\partial T}{\partial x_i} + \overline{u_i}(\tau_{ij})_{eff}\right) + S_h, \tag{3}$$

where E – total energy, S_h – heat of chemical reaction, and any other volumetric heat sources, T – temperature, $(\tau_{ij})_{eff}$ – shear stresses, k_{eff} – effective thermal conductivity defined as:

$$k_{eff} = k + k_\tau, \tag{4}$$

here k – thermal conductivity, k_τ – turbulent thermal conductivity.

In Eq. (3) $(\tau_{ij})_{eff}$ has the following form:

$$(\tau_{ij})_{eff} = \mu_{eff}\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_j} - \frac{2}{3}\delta_{i,j}\frac{\partial \overline{u_i}}{\partial x_i}\right) \tag{5}$$

where μ_{eff} – effective viscosity defined as:

$$\mu_{eff} = \mu + \mu_\tau, \tag{7}$$

here μ_τ – eddy viscosity.

equations (1)–(3) must be closed by the one of the turbulence models. The following turbulence models are widely used: 2-equations models *k-ω* and *k-ε* due to their low requirement for RAM and rapid convergence [22,23] and 4-equation turbulence model *γ-Re$_\theta$ Shear Stress Transport* (*γ-Re$_\theta$ SST*) is also popular due to high accuracy of near-wall layer that is useful for hypersonic regimes and heat transfer [24]. But this accuracy leads to a decrease in convergence speed time and an increase in the cost of RAM. Also *γ-Re$_\theta$ SST* requires a good quality of mesh. To study the effect of air dissociation on spaceplane aerodynamics properties a turbulence model *γ-Re$_\theta$ SST* was chosen.

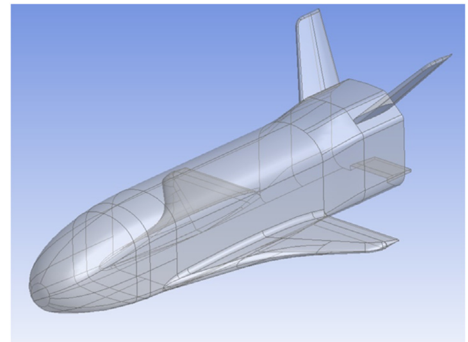

Fig. 1. Geometrics model.

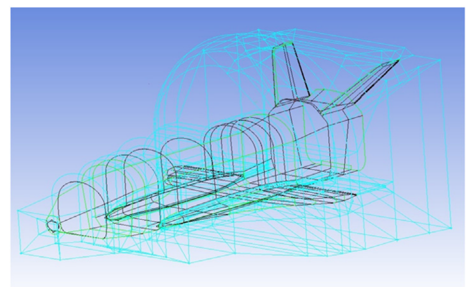

Fig. 2. Block structure.

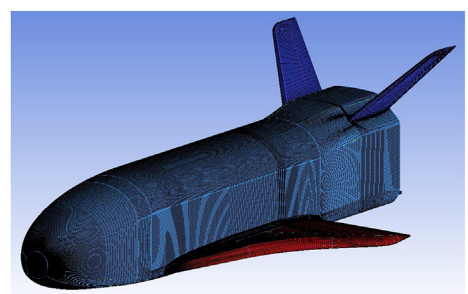

Fig. 3. Surface mesh.

Table 1
Flight parameters.

Altitude H, km	Mach number M_∞	Angles of attack α, degree	Upstream pressure p_∞, Pa	Upstream temperature T_∞, K
60	10	0.40	22	247

2.2. Chemical reaction equations

Usually the complete model of chemical reactions consists of 11 species (N_2, O_2, NO, N_2^+, O_2^+, NO^+, N, O, N^+, O^+, e^-). It is worth mentioning that the number of reactions differs depending on the kinetic model. The complete model can be simplified depending on the flow regime and the prevailing effects for reducing the calculation time. For the case of air dissociation the complete model decreases to 5 species (N_2, O_2, NO, N, O) and 17 reactions which can be grouped into 15 air dissociation reactions and 2 Zeldovich reactions. The list of reactions for air dissociation is as follows: