

AEROTHERMODYNAMIC CHARACTERISTICS OF A SPACE PROBE IN THE MARTIAN ATMOSPHERE

Egorov I. V.*, Palchekovskaya N. V.*, Pugach M. A.*
*Central Aerohydrodynamic Institute

Keywords: numerical simulation, nonequilibrium chemical reactions

Abstract

Aerodynamic characteristics and aerodynamic heating of a space probe during its motion in the Martian atmosphere are determined by the Navier-Stokes and Reynolds equations with nonequilibrium chemical reactions. Calculations are carried out for two possible descent trajectories in Martian atmosphere at zero angle of attack. Cases of absolutely noncatalytic and catalytic (with respect to atomic oxygen and nitrogen) surfaces of flight vehicle are considered.

1 Introduction

Currently theoretical and experimental studies, related to investigation and development of Mars, are carried out. One of the guidelines of this research is the development of space probes for various applications. Usually they represent strongly blunted axisymmetrical bodies, contour of which in meridional section is constructed from segments of elementary curves.

The best known among them are space probes Mars Pathfinder (American project) and Martian Sample Return Orbiter (MSRO) (European project). Both space probes are axisymmetrical blunted bodies, frontal surface of which has shape of a blunted circular cone with a wide half-angle, value of which close to the maximum one. They differ from each other by shape of the afterbody. In the first case it is constructed in the form of a blunted inverse cone, and in the second case – in the form of a circular cylinder of a finite length. Thus, it is convenient to divide space probes into two groups – a space probe type of Mars Pathfinder

and a space probe type of MSRO. Space probes of the first type provide greater volume for arrangement of bulky useful load, but they have difficulties with thermal protection. Space probes of the second type are characterized by developed global zone of the detached flow, where the container with useful load is fully located.

2 Numerical method

Navier-Stokes equations, describing axisymmetric flows of chemically non-equilibrium gas mixture, in a curvilinear coordinate system ξ, η , where $x = x(\xi, \eta)$, $y = y(\xi, \eta)$ – Cartesian coordinates, express laws of mass, momentum and energy conservation and are written in divergent form

$$\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{E}}{\partial \xi} + \frac{\partial \mathbf{G}}{\partial \eta} = \mathbf{S}$$

where \mathbf{Q} – vector conservative dependent variables, \mathbf{E} and \mathbf{G} – flux vectors in curvilinear coordinate system, \mathbf{B} – source vector. Vectors \mathbf{E} , \mathbf{G} and \mathbf{S} are related to corresponding vectors \mathbf{E}_c , \mathbf{G}_c and \mathbf{S}_c in Cartesian coordinate system by formulas

$$\mathbf{Q} = J\mathbf{Q}_c, \mathbf{S} = J\mathbf{S}_c,$$

$$\mathbf{E} = J \left(\mathbf{E}_c \frac{\partial \xi}{\partial x} + \mathbf{G}_c \frac{\partial \xi}{\partial y} \right), \mathbf{G} = J \left(\mathbf{E}_c \frac{\partial \eta}{\partial x} + \mathbf{G}_c \frac{\partial \eta}{\partial y} \right),$$

where $J = \partial(x, y) / \partial(\xi, \eta)$ – transformation Jacobian.

Coordinate system (ξ, η) is used for discretization on uniform grid: arbitrary computational grid in Cartesian coordinate

system is mapped on uniform grid in curvilinear coordinate system.

Cartesian components of flux vectors \mathbf{E}_c , \mathbf{G}_c and \mathbf{S}_c for axisymmetric Navier-Stokes equations are as follows:

$$\mathbf{Q}_c = \begin{pmatrix} \rho u \\ \rho v \\ \rho e \\ \rho_i \end{pmatrix}, \quad \mathbf{E}_c = \begin{pmatrix} \rho u^2 + p + \tau_{xx} \\ \rho uv + \tau_{xy} \\ \rho uH + q_x \\ \rho_i u + \mathbf{I}_x^i \end{pmatrix}, \quad \mathbf{G}_c = \begin{pmatrix} \rho uv + \tau_{xy} \\ \rho v^2 + p + \tau_{yy} \\ \rho vH + q_y \\ \rho_i v + \mathbf{I}_y^i \end{pmatrix},$$

where u , v — Cartesian components of velocity vector \mathbf{V} , p pressure, ρ — total density of gas mixture, ρ_i — density of i -th gas mixture component ($i = 1, \dots, K$); K — the number of gas mixture species, $e = h - \frac{p}{\rho} + \frac{1}{2}(u^2 + v^2)$ — total energy per unit volume, $H = h + (u^2 + v^2)/2$ — total enthalpy, $h = \sum_{i=1}^K h_i C_i$ — static enthalpy of gas mixture, T — temperature, C_i , ω_i , h_i — mass concentrations, production rates, static enthalpies of gas mixture species correspondingly, $\boldsymbol{\tau}$ - symmetric viscous stress tensor, related to strain velocity tensor \mathbf{s} by linear dependence $\boldsymbol{\tau} = -\mu \mathbf{s}$.

Components of strain velocity tensor \mathbf{s} for compressible gas are as follows:

$$\mathbf{s}_{xx} = 2 \frac{\partial u}{\partial x} - \frac{2}{3} \operatorname{div} \mathbf{V}, \quad \mathbf{s}_{xy} = \mathbf{s}_{yx} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x},$$

$$\mathbf{s}_{yy} = 2 \frac{\partial v}{\partial y} - \frac{2}{3} \operatorname{div} \mathbf{V}$$

Heat flux vector \mathbf{q} is determined by following expression:

$$\mathbf{q} = -\lambda \operatorname{grad}(T) + \boldsymbol{\tau} \mathbf{V} + \sum_{i=1}^K h_i \mathbf{I}^i$$

Here \mathbf{I}^i — diffusive flux vector of i -th mixture species, which in this work is determined on basis of Fick law with approximation of binary diffusion model:

$$\mathbf{I}^i = -\rho D_i \operatorname{grad}(C_i)$$

where μ , λ and D_i — coefficients of molecular viscosity, thermal conductivity and diffusion.

For calculations of viscosity coefficient

dependency $\frac{\mu}{\mu_\infty} = \left(\frac{T}{T_\infty} \right)^\omega$ is used (in this work

$\omega = 0.731$), thermal conductivity coefficient is determined from expression for Prandtl number

$\operatorname{Pr} = \frac{\mu c_p}{\lambda} = 0.7$, and diffusion coefficients D_i —

from expression for Schmidt number

$\operatorname{Sc}_i = \frac{\mu}{\rho D_i} = 0.5$ for all species of gas mixture. Set

of equations is closed by algebraic equations: equation of state for gas mixture:

$$p = \frac{\rho R T}{M}, \quad M = \left(\sum_{i=1}^K \frac{C_i}{M_i} \right)^{-1}$$

where R — universal gas, M — molar weight of gas mixture; and also by relationships for sum of mass concentrations and diffusive fluxes of gas mixture components:

$$\sum_{i=1}^K C_i = 1, \quad \sum_{i=1}^K \mathbf{I}^i = 1$$

In software package there is an possibility of gas mixture simulation, which can be consisted of arbitrary number of species. In this work two variants of gas mixture is considered: 1) 8 - species gas model, representing Martian atmosphere ($K=8$: O, N, NO, O₂, N₂, CO₂, CO, C); 2) 5 - species gas model, representing air in wind tunnel ($K=5$: N₂, O₂, O, N, NO).

In calculation of thermodynamic characteristics of gas mixture it is assumed that for each chemical species there is a thermodynamic equilibrium of translational and rotational degrees of freedom of molecules, and vibrational degrees of freedom are in non-equilibrium state.

Static enthalpy of multicomponent gas mixture is calculated using formula:

$$h = \sum_{i=1}^K h_i C_i$$

where h_i , C_i — mass static enthalpy and mass fraction of i -th mixture species:

$$h_i = (c_{pi} T + E_v) \frac{R}{M_i} + h_{0i}$$

where c_{pi} , M_i , h_{0i} — specific heat at constant pressure (specified by translational and rotational degrees of freedom, molar mass and formation enthalpy of i -th species of gas mixture correspondingly; $E_v = T_v \exp(T_v / T - 1)$ — energy, specified by vibrational degrees of freedom of i -th species molecules, T_v — characteristic excitation temperature of vibrational degree of freedom.

AEROTHERMODYNAMIC CHARACTERISTICS OF A SPACE PROBE IN THE MARTIAN ATMOSPHERE

To calculate external flow following boundary conditions are set. On the solid surface – no-slip boundary condition $u = 0$ and $v = 0$, heat balance condition and catalytic surface condition. On the inflow boundary – values of gas-dynamic variables and mass concentrations of gases in free stream (Dirichlet boundary condition). On the outflow boundary – extrapolation of dependent variables from inside of computational domain.

Uniform free stream condition can be used as an initial approximation, and flow field develops during solution of unsteady problem. As flow pattern is generated, time step is increased and then it is possible to solve steady problem. Initial-boundary problem, formulated above, is solved numerically on basis of finite-volume method. Quasi-monotone Godunov scheme and Roe technique for solution of Riemann problem are used.

For analysis of flow over descent vehicle numerical simulation on basis of Navier-Stokes equations for gas mixture in axisymmetric statement. Shape of descent vehicle in symmetry plane and computational domain are given in Fig. 1.

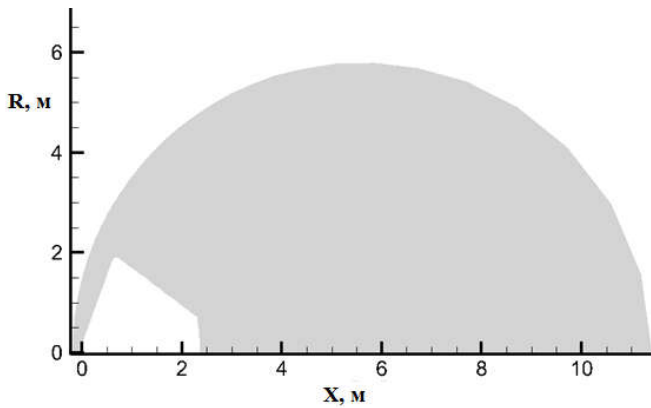


Fig. 1. Shape of the descent vehicle and computational domain

To simulate Martian atmosphere chemically non-equilibrium gas mixture of 8-th species is used: O, N, NO, O₂, N₂, CO₂, CO, C. Thermodynamic parameters of these gases are given in Table 1.

Chem. component	M _i , kg/mole	C _{pi}	Vibrational temperature T _v , K	Formation enthalpy h _{0i} , J × mole/kg
O	0,016	2,5	0,0	15,6×10 ⁶
N	0,014	2,5	0,0	33,9×10 ⁶
NO	0,03	3,5	2791,0	3,02×10 ⁶
O ₂	0,032	3,5	2256,0	0,0
N ₂	0,028	3,5	3354,0	0,0
CO ₂	0,044	3,5	960,0 1190,0 3380,0	-8,37×10 ⁶
CO	0,028	3,5	3122,0	-4,06×10 ⁶
C	0,012	2,5	0,0	59×10 ⁶

Table 1. Thermodynamic parameters of gases in Martian atmosphere model

The following dissociation and exchange reactions are taking into account in simulation of non-equilibrium physical-chemical processes:
 $N_2 + M \leftrightarrow N + N + M$, $O_2 + M \leftrightarrow O + O + M$
 $CO + M \leftrightarrow C + O + M$, $NO + M \leftrightarrow N + O + M$
 $CO_2 + M \leftrightarrow CO + O + M$, $NO + O \leftrightarrow N + O_2$
 $N_2 + O \leftrightarrow NO + N$, $CO + O \leftrightarrow O_2 + C$
 $CO_2 + O \leftrightarrow O_2 + CO$, $CO + N \leftrightarrow NO + C$
 $CO + CO \leftrightarrow CO_2 + C$, $NO + CO \leftrightarrow CO_2 + N$

Here M – catalytic particle, which can be any of species in the mixture. Generation of gas component is determined by Arrhenius law. In free stream gas mass concentrations are as for Martian atmosphere: $C_{CO_2} = 0.97$, $C_{N_2} = 0.03$ and $C_i = 10^{-10}$ for other gases. Effective value of adiabatic exponent for gas mixture is calculated in accordance with thermodynamic relationships. Prandtl number $Pr = 0.70$ and Schmidt number $Sc = 0.5$ are assumed to be constant; dependency of molecular viscosity coefficient on temperature — $\mu = T^{0.731}$.

Calculations are carried out with assumption of laminar axisymmetric flow without turbulence.

In assumption that almost full convective heat flux dissipates because of radiation, the following equation is valid

$$\left[\lambda^* \frac{\partial T^*}{\partial n^*} \right]_w = k \sigma^* (T_w^{*4} - T_\infty^{*4})$$

where k – body emissivity, in this work $k = 0.9$, $\sigma^* = 5.67040 \times 10^{-8} J \cdot s^{-1} \cdot m^{-2} \cdot K^{-4}$ – Stefan–Boltzmann constant. Dimension variables are

designated by superscript «*». In dimensionless form this condition of heat flux balance is written as:

$$\frac{\mu}{\text{Re}_\infty \text{Pr}(\gamma-1)M_\infty^2} \frac{\partial T}{\partial n} \Big|_w = k \frac{\sigma^*}{\rho_\infty^* V_\infty^{*3}} T_\infty^{*4} (T_w^4 - 1)$$

For mass concentrations of gas species on the surface following conditions are set:

- a) Quasi-catalytic surface (absolutely catalytic surface with respect to atomic oxygen and nitrogen):

$$\frac{\partial C_{\text{NO}}}{\partial n} \Big|_w = \frac{\partial C_{\text{CO}_2}}{\partial n} \Big|_w = \frac{\partial C_{\text{CO}}}{\partial n} \Big|_w = 0, \quad C_{\text{O}} \Big|_w = C_{\text{N}} \Big|_w = 0$$

- b) Non-catalytic surface:

$$\frac{\partial C_{\text{O}}}{\partial n} \Big|_w = \frac{\partial C_{\text{N}}}{\partial n} \Big|_w = \frac{\partial C_{\text{NO}}}{\partial n} \Big|_w = \frac{\partial C_{\text{CO}_2}}{\partial n} \Big|_w = \frac{\partial C_{\text{CO}}}{\partial n} \Big|_w = 0$$

On the outer boundary of computational domain either free stream boundary conditions (in the left), or extrapolation of dependent variables from inside of the domain are set. It is possible, since supersonic flow is considered and disturbances don't propagate upstream.

Preliminary calculations are made using coarse structured orthogonal grid, consisting of 201×201 nodes. Grid is clustered near the surface in order to resolve boundary layer. Grid topology is monoblock, but for parallel calculations the grid is splitted on block in longitudinal direction. Grid fragment is shown in Fig. 2.

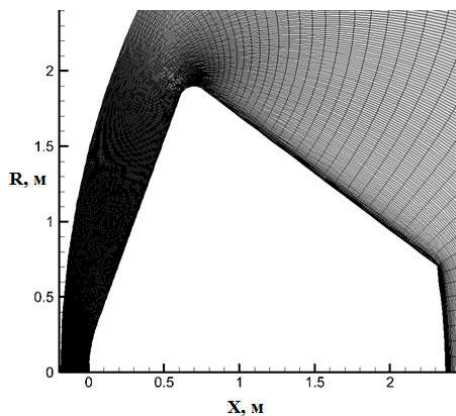


Fig. 2. Fragment of the computational grid

3 Results and discussions

Numerical simulation is fulfilled using in-house software package HSFlow on multi-processor supercomputer of MIPT. Cluster consists of 46 servers, each of them incorporates 2 Intel Xeon processors with 12 cores. For parametric calculations up to 480 cores are used simultaneously. For one flow regime 24 cores are used.

Aerodynamic characteristics and aerodynamic heating of a space probe during it motion in the Martian atmosphere are determined by the Navier-Stokes equations [1, 2] equations with nonequilibrium chemical reaction. It is assumed that the surface is absolutely thermally non-conductive, and equation of the local thermal balance is used as boundary condition on this surface.

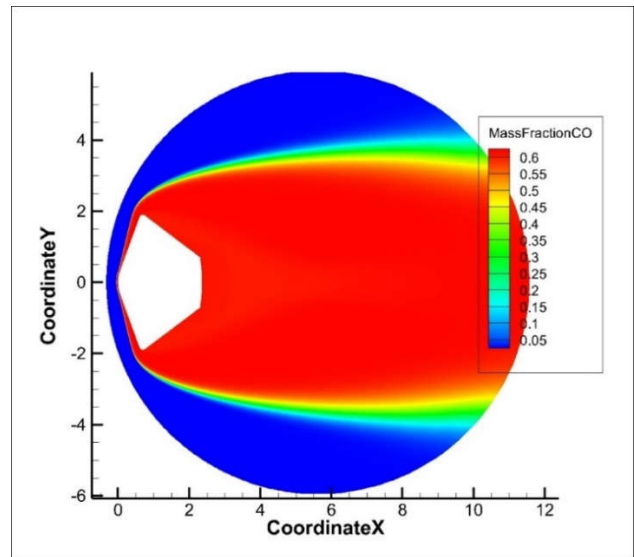


Fig. 3. Distribution of CO species. Re = 60556, M = 31, V=6000 m/s

For example in Fig. 3 carbon monoxide concentration near the space vehicle at the point of a trajectory, corresponding to the part of descent in Martian atmosphere with high level of heat flux, are shown. The results are obtained on basis of numerical solution of Navier-Stokes equations for zero angle of attack. Analysis of numerical data indicates rather complicated structure of separated high-temperature gas flow in the back surface. Here normal shock, resulting from deceleration of reversed streamlines in reversed (separated) flow,

AEROTHERMODYNAMIC CHARACTERISTICS OF A SPACE PROBE IN THE MARTIAN ATMOSPHERE

secondary separations, tail shock and other flow features can be seen. Uniform distribution of carbon monoxide concentration (Fig. 3) in flow field after bow shock indicates that carbon dioxide, which is a base of Martian atmosphere, is practically dissociated. As a result, there is a substantial influence of catalytic properties of heat-shielding coating (heterogeneous chemical reactions) on aerodynamic heating of front surface of space vehicle. Curves correspond to extreme values of catalytic activity for body surface with respect to atomic oxygen. Difference in heating is about 400°K . In Fig. 4 distribution of drag coefficient for space probe on a hypersonic part of trajectory, calculated on basis of modified Newton formula and solution of Navier-Stokes equations, is shown. It should be noted that these approaches are in good agreement.

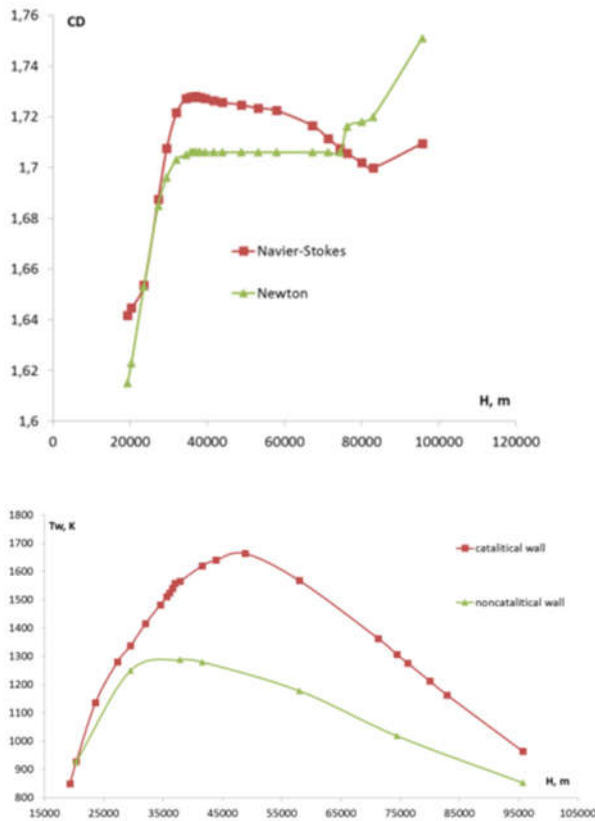


Fig. 4. Distributions of drag coefficient and wall temperature at stagnation point along descent trajectory

For more detailed analysis of flow field near the vehicle three characteristic points of the second trajectory are chosen: the first one – in upper Martian atmosphere, the second one

corresponds to the maximum heat flux at stagnation point, the third one – in lower atmosphere. Trajectory parameters and free stream conditions for these points are given in Table 2.

N	Height, m	Density $\times 10^4$ kg/m ³	T_{∞} , K	Velocity, m/s
1	75008,4	0,1233	147	5964
2	41141,7	3,429	208	5192
3	25226,3	13,85	218	3288

Table 2. Characteristic points of descent trajectory

At these points profiles of O, CO concentrations and temperature on the symmetry axis are plotted (Fig. 5 to Fig. 7). On all pictures blue, red, green lines correspond to points 1, 2 and 3 from Table 2.

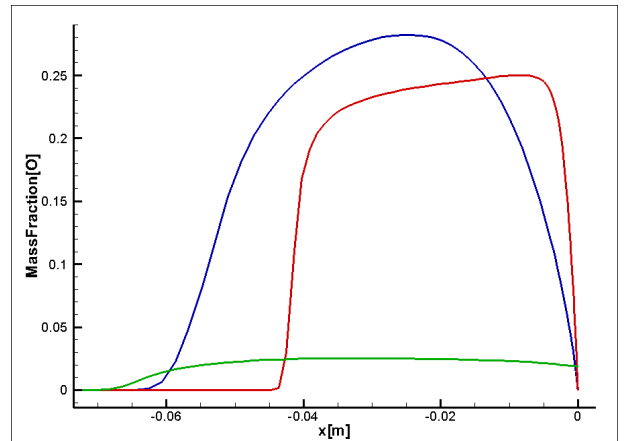


Fig. 5. Profile of oxygen mass concentrations

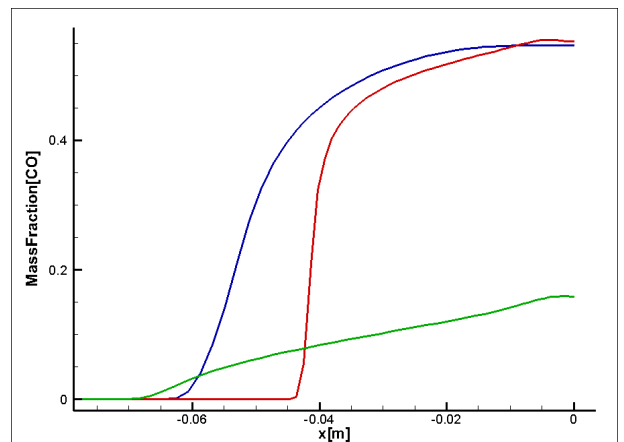


Fig. 6. Profile of CO mass concentrations

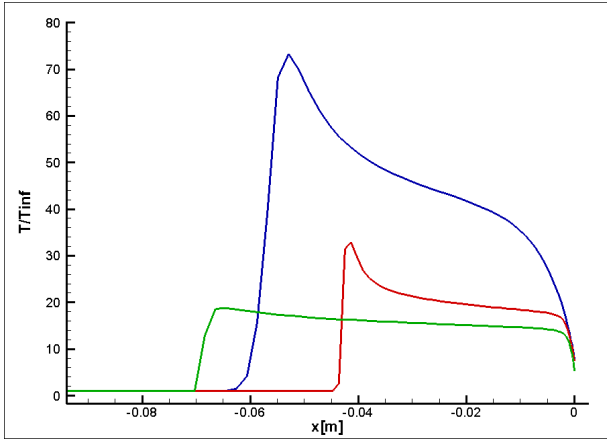


Fig. 7. Profile of temperature

Mass concentrations and temperature field for the second trajectory point are presented in Fig. 8 to Fig. 10.

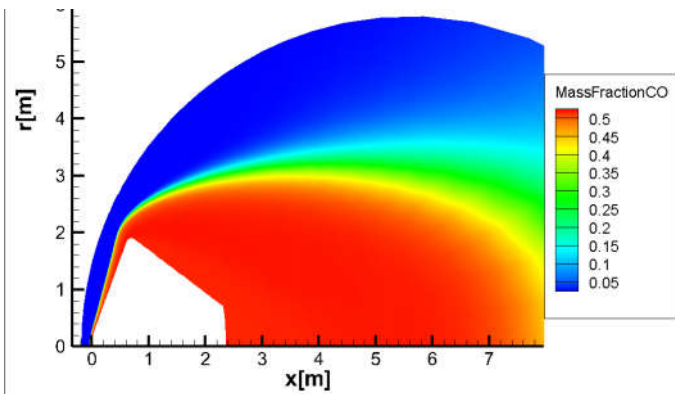


Fig. 8. Field of CO mass concentrations (Trajectory point 2: H = 41 km, M = 22,55)

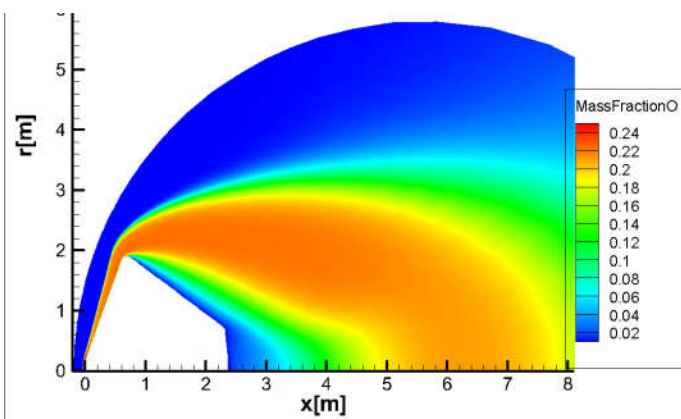


Fig. 9. Field of O mass concentrations (Trajectory point 2: H = 41 km, M = 22,55)

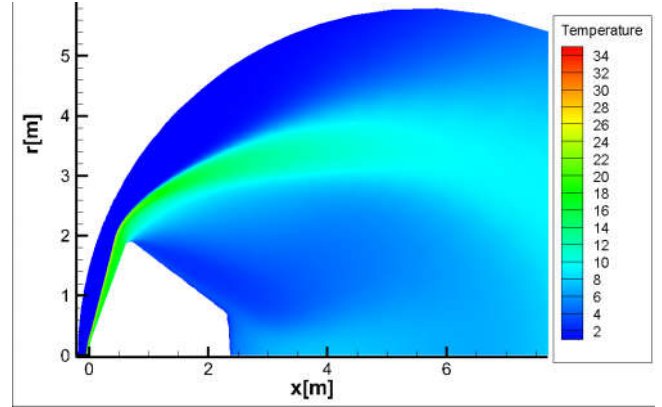


Fig. 10. Temperature field (Trajectory point 2: H = 41 km, M = 22,55)

It can be seen that chemical reactions are more intensive in upper atmosphere (point 1, H = 75 km), where vehicle has higher velocity. Here there is a large separation zone behind the vehicle, where flow is circulating. Then, as vehicle descending along trajectory its velocity decreases, and chemical reactions here are not so intensive. At point of maximum heat flux on the symmetry axis (point 2, H = 41 km) shock layer thinner and separation zone behind the vehicle is smaller, than at point 1. Temperature field here is more smeared, and wake behind the vehicle is more heated, than in upper atmosphere. Continuing descent, the vehicle intensively decelerates, and at height 25 km (point 3), Mach number in free stream is close to 14, chemical reactions here are not so intensive, and CO and O concentrations, both in shock layer, and in wake are rather small. As atmosphere becomes more dense, shock layer becomes thicker, and shock wave detachment from the body is higher, than at height of 41 km. It should be noted that wake behind the vehicle here is heated well, and in lower atmosphere heating of rear part of vehicle is also significant. Heating of rear part of the vehicle during the descent can be estimated using dependency of vehicle rear point temperature on the symmetry axis on trajectory height (Fig. 11). Vehicle surface is assumed to be absolutely catalytic.

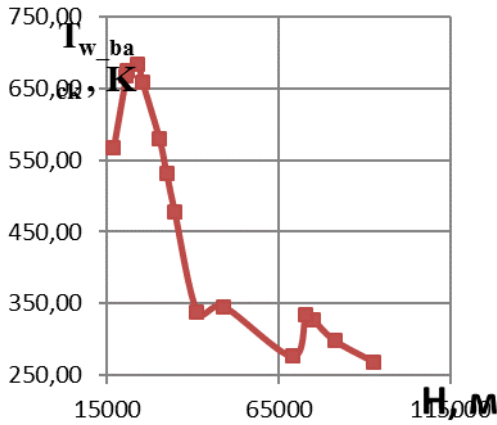


Fig. 11. Temperature at rear point on the symmetry axis during vehicle descent for trajectory 2

For grid verification of the results regime, corresponding to trajectory point at height 41 km (point 2 in Table 2), where the maximum heat flux at stagnation point is observed. For these free stream parameters calculations are carried out using grids, consisting of 401x401, 601x601, 801x801 and 1001x1001 nodes. In Fig. 12 dependency of calculated temperature on the vehicle surface at forward stagnation point on the grid dimension.

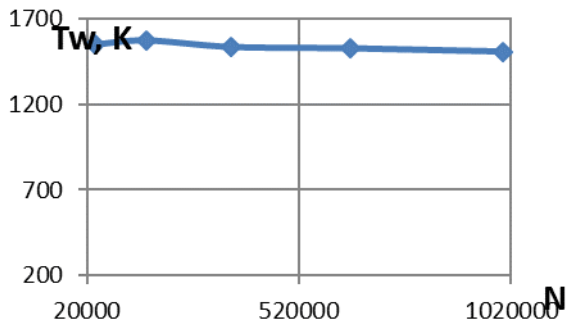


Fig. 12. Dependency of temperature at the stagnation point on nodes number in computational grid

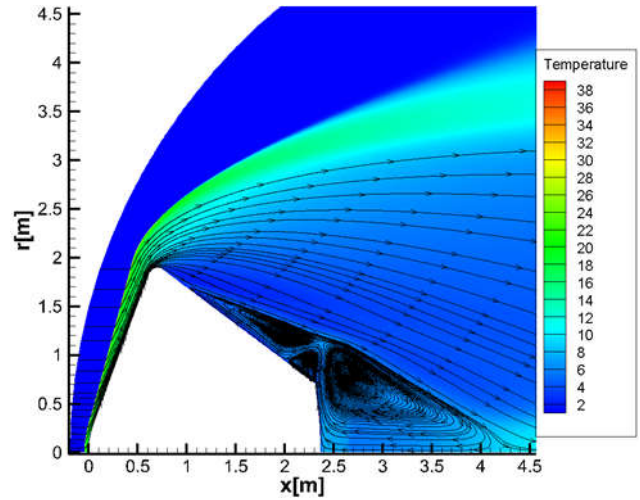


Fig. 13. Temperature field and streamlines. Grid 1001x1001

Streamlines in Fig. 13 show that flow pattern becomes more precise as the number of nodes increases, and complex system of vortex circulation flows reveals. For 201x201 grid separation zone with one vortex is observed behind the body, and for 1001x1001 grid separation zone is larger – it begins on lateral surface of the vehicle and there are three vortices are observed.

4 Conclusions

There is a substantial influence of catalytic properties of heat-shielding coating (heterogeneous chemical reactions) on aerodynamic heating of front surface of space vehicle. Difference in heating is about 400° K. Along given trajectories values of equilibrium surface temperature and heat flux in assumption of its balance with equilibrium radiation on the model surface are obtained.

This work was supported by Russian Scientific Foundation (Project No.14-19-00821).

References

[1] Egorov I.V., Ivanov D.V., Novikov A.V. CFD studies of supersonic aerodynamics of the Earth descent module for Phobos-grunt interplanetary mission. *7 European Symposium on Aerothermodynamics for Space Vehicles*, Brugge, Belgium. 2011.

- [2] Bashkin V.A., Egorov I.V. *Numerical simulation of perfect viscous gas flow*. Fizmatlit, Moscow, 2012 (in Russian).

Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.