SIMULATION OF HEAT TRANSFER TO SPACE VEHICLES DURING A GLIDING REENTRY INTO EARTH’S ATMOSPHERE

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Introduction

One of the basic problems arising under development of reentry vehicles entering Earth’s atmosphere with speed of an order of the circular orbital velocity is the accurate prediction of a level of intensive heat fluxes along vehicle surface during flight.

In dense layers of the atmosphere where the assumption about continuity of the medium is true, the detailed analysis of parameters of flow and heat transfer around a reentry vehicle can be made on the basis of numerical integration of the system of the Navier-Stokes equations accounting for the physical and chemical processes proceeding in a shock layer at hypersonic speeds of flight. For the solution of the problem significant computing resources are required, therefore serial calculations are usually carried out by simplified technique within the framework of which the inviscid flow field is specified by numerical integration of the Euler equations with account of physical and chemical processes, and parameters of heat transfer are estimated on the basis of integration of the boundary layer equations. Thus there is a task of verification of the employed techniques by comparison of the obtained numerical results with experimental data as well as estimation of adequacy of the simplified technique to the problem and reliability of a prediction of flow parameters and heat transfer.

Numerical method

An implicit iterative scheme [1] representing a variant of point Gauss-Seidel method was used at the solution of the Navier-Stokes equations cast in a conservative form for an arbitrary system of coordinates. Details of the method are described in [2]. The system of the Euler equations was solved by cell-centered finite volume method in the Cartesian system of coordinates. The whole flow region is subdivided onto two parts – section near nose bluntness with mainly subsonic flow behind a bow shock wave and a region about a side surface of the vehicle where flow is supersonic. In the first region the solution is searched by a steady-state approaching method, and in the second – by marching procedure downwind along a longitudinal axis of a body. At the solution of the Euler equations the shock wave is captured, and flow parameters on a surface are used as boundary conditions on the external border of a boundary layer. At integration of the Navier-Stokes equations the shock wave can be captured or fitted as a surface of discontinuity jump of flow parameters with the Rankine-Hugoniot conditions across it.

Parameters of heat transfer on a vehicle surface are defined on the base of the calculated inviscid flow using the approximate solution of the boundary layer equations by means of an integral method of local similarity [3] with use of axisymmetric analogy. The equations of the local similarity method were written on the same surface finite difference grid, as the equations of inviscid flow (except for a vicinity of a stagnation point where the local system of coordinates with a pole in this point is utilized), using the Cartesian components of a velocity vector. In more details this approach is described in [4].

Within the limits of a method of local similarity it is also possible to take approximately into account the effect of heterogeneous reactions on a surface of a reentry vehicle. For the considered flow conditions in the range of expected maximum levels of heat fluxes (at wall pressure \( P_w \leq 0.05 \) atm) gas phase reactions in a boundary layer can be supposed to be frozen. Thus chemical reactions proceed in the nonequilibrium regime in an inviscid flow and on a surface. The enthalpy of air at
wall is calculated accounting for diffusion across a boundary layer and heterogeneous recombination reactions on a surface.

**Thermo-chemical model of air**

The five-components model [5] was used in case of nonequilibrium air, and the following chemical components were taken into account – \( M = N_2, O_2, NO, N, O \) for which three reactions of dissociation and two exchange reactions take place:

\[
\begin{align*}
O_2 + M &= O + O + M, \\
N_2 + M &= N + N + M, \\
NO + M &= N + O + M, \\
O + N_2 &= N + NO, \\
O + NO &= N + O_2.
\end{align*}
\]

In the course of solution of Navier-Stokes equations diffusion fluxes of the \( i \)-th chemical component are defined according to Fick's law and look like (in a direction of \( X \) axis):

\[
d_{i,x} = -\rho D_i \frac{\partial c_i}{\partial x},
\]

For the definition of diffusion coefficients \( D_i \) the approximation of constant Schmidt numbers \( Sc_i = \mu_i / \rho D_i \) is used which are accepted to be equal to 0.75 for neutral particles. The total heat flux \( q = (q_x, q_y, q_z) \) is the sum of heat fluxes due to the thermal conductivity and the diffusion of chemical components:

\[
q_x = -\kappa \frac{\partial T}{\partial x} + \sum_i h_i d_{i,x}
\]

where \( h_i \) – enthalpy of the \( i \)-th chemical component per unit mass. It was supposed in calculations that the temperature of electronic and vibrational degrees of freedom of atomic particles is equal to translational temperature. Viscosity \( \mu \) and heat conductivity \( \kappa \) of a gas mixture are determined according to the formulas of Wilke [6] and Mason and Saxena [7].

**Boundary conditions**

Flow slip condition is imposed on a vehicle surface for the Euler equations. For the Navier-Stokes equations and boundary layer equations the noslip and adiabatic conditions are used on a vehicle surface:

\[
q_w = \varepsilon_w \sigma T_w^4
\]

where \( q_w \) – total heat flux due to the heat conductivity and the diffusion of chemical components, \( \varepsilon_w = 0.8 \) – emissivity factor of a space vehicle surface, \( \sigma \) – the Stephan-Boltzmann constant. Concentrations of atomic species on a surface are determined from the equations of mass balance which are as follows:

\[
d_{i,n} + K_{i,w} \rho_i = 0; \quad K_{i,w} = \frac{2 \gamma_{i,w}}{2 - \gamma_{i,w}} \sqrt{\frac{1}{2\pi M_i}} \frac{RT}{M_i}
\]

here \( \gamma_{i,w} \) – a probability of heterogeneous recombination of the \( i \)-th chemical component. Concentrations of molecular species on a surface are calculated from conditions of conservation of chemical elements.
Flow over reentry vehicle with wings installed in the middle of fuselage

Atmospheric descent of a reentry space vehicle with wings in the middle part of a fuselage, which trajectory is shown in Fig.1, is considered. Numerical grids used in Euler and Navier-Stokes calculations were generated by Churakov D.A. [8].

Values of heat flux at the stagnation point of a reentry vehicle for four points of the trajectory, which parameters are given in table 1, are presented in Fig.2.

![Fig. 1. Flight trajectory of a reentry space vehicle with wings in the middle of fuselage](image1)

Table 1. Trajectory parameters

<table>
<thead>
<tr>
<th>H, km</th>
<th>( V_\infty ), m/sec</th>
<th>( M_\infty )</th>
<th>( \rho_\infty ), kg/m(^3)</th>
<th>( T_\infty ), K</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>4977</td>
<td>15</td>
<td>1.08 \times 10^{-3}</td>
<td>274.0</td>
</tr>
<tr>
<td>60</td>
<td>6382</td>
<td>20</td>
<td>3.32 \times 10^{-4}</td>
<td>253.4</td>
</tr>
<tr>
<td>70</td>
<td>7423</td>
<td>25</td>
<td>9.27 \times 10^{-5}</td>
<td>219.1</td>
</tr>
<tr>
<td>80</td>
<td>6818</td>
<td>25</td>
<td>2.09 \times 10^{-5}</td>
<td>184.9</td>
</tr>
</tbody>
</table>

Calculations were made by the two compared techniques (the Navier-Stokes equations as well as the Euler and boundary layer equations) for equilibrium and nonequilibrium air approximations at a probability of heterogeneous recombination of O and N atoms – \( \gamma_A = 0.01\). Under the given conditions the maximum levels of heat transfer in a vicinity of the stagnation point are reached at altitude about \( H = 60 \) km.

![Fig. 2. Heat flux in the stagnation point under flight conditions of a reentry vehicle](image2)
Section III

It can be seen that in a vicinity of the stagnation point the both techniques give the good agreement between each other. Equilibrium air approximation gives overestimation of heat flux magnitudes in all the considered range of altitudes in comparison with approximation of nonequilibrium air. The excess increases with growth of altitude and reaches at $H = 70$ km about two times.

In Fig.3 comparisons of heat fluxes and radiating equilibrium temperatures on surfaces of a re-entry vehicle, calculated by these two techniques, are presented. During the numerical analysis it is revealed, that the bottom surface of an edge or a "bump" in an initial part of a vehicle wing is a region with very high level of heat transfer in which the values of heat flux at different points of the trajectory can exceed by 10-20 % the value of heat flux at the stagnation point. It is caused by increase of pressure in this area with the subsequent large negative pressure gradients because of a turn of flow around the bump. The both effects lead to considerable enhancement of heat transfer.

![Fig. 3. Distribution of heat flux (kW/m²) and of constant temperature lines ($T$, °C) ($H = 80$ km, $\alpha = 30^\circ$, $M = 25$, $V = 6800$ m/s, nonequilibrium flow, $\gamma_A = 0.01$),
(a) Euler and boundary layer equations, (b) Navier-Stokes equations.](image)

In turn such a substantial increase of pressure is caused by as though "isolated" (from the flow on the windward side of the vehicle) gas stream over the bump in a shock layer with high density which takes place in hypersonic equilibrium flows. At the same time edges of the bump (as well as further downwind, edges of wings) are flowed round with turning stream of shock layer. And local increase of heat fluxes before the edges is caused by large negative gradients of pressure at its gen-
eral high level. This rather unfavorable effect of occurrence of the raised heating zones noticeably weakens with reduction of Mach number, and also with transition from equilibrium air to perfect gas approximation because in these cases there is decrease in levels of density and consequently also of pressure upon protruding elements.

Satisfactory conformity of the calculated parameters obtained with the two compared numerical techniques on the smooth part of windward side of the space vehicle is obtained. But appreciable difference in calculation results is observed in a vicinity of wing edges and, especially, in the region of the raised heat fluxes near the "bump" in an initial part of a wing. It is caused, first, by a strong deflection of streamlines in this area (by its deriving the integral method of local similarity is suitable only for slightly deflected streamlines with negligible secondary flows), and, secondly, by the presence of strong pressure gradients which are also not provided for by conditions of applicability of this integral method. Significant influence of secondary flows is also indicated by the presence of a local transverse flow separation, found out in Navier-Stokes solutions and not described within the framework of the Euler equations. In this connection the results obtained with employing of the Navier-Stokes equations are more reliable. The second method using the Euler and boundary layer equations as considerably less time consuming can be used to obtain evaluative data in a wide range of flow conditions, all the more so as both methods give quite similar results on the large part of the vehicle.

**Flow over reentry vehicle with wings at the bottom of fuselage**

Calculations of flow and heat transfer parameters have been made also for another configuration of a winged reentry vehicle [9] with wings installed in the bottom part of a fuselage. Only the Navier-Stokes solutions are presented for this case. The shock wave was captured, therefore free stream conditions were specified on the external entry boundary. In this section results are shown for the most heat-stressed point of a trajectory which parameters are given in Table 2. The angle of attack is equal to 35 degrees, flow regime is laminar. The finite difference grid is presented by Mikhailin V.A. [9] and is taken from inviscid flow calculation over the reentry vehicle for the case of the perfect gas at free stream Mach number $M_\infty = 16$. In calculation with use of thermo-chemical model of nonequilibrium air the vehicle surface was considered to be low catalytical with a probability of heterogeneous recombination of O and N atoms equal to $\gamma_A = 0.01$.

<table>
<thead>
<tr>
<th>H, km</th>
<th>$V_\infty$, m/sec</th>
<th>$Re_\infty$</th>
<th>$M_\infty$</th>
<th>$P_\infty$, atm</th>
<th>$T_\infty$, K</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>5150</td>
<td>$6.33 \cdot 10^5$</td>
<td>16.6</td>
<td>$1.59 \cdot 10^{-4}$</td>
<td>243</td>
</tr>
</tbody>
</table>

For cases of equilibrium dissociating and chemically nonequilibrium air isolines are presented in Fig.4 showing distributions of heat flux on windward and lateral surfaces of the winged reentry vehicle. Comparisons of distributions of pressure, heat flux and radiating equilibrium temperature along a surface in the symmetry plane ($z = 0$) of the vehicle for the models of equilibrium dissociating and chemically nonequilibrium air are shown in Fig.5.

The analysis of these figures shows that distribution of pressure on the windward surface of the vehicle practically does not depend on the thermo-chemical model of gas – difference is about 1 - 2 %. On the leeside the level of pressure on the vehicle surface for nonequilibrium air flow can be almost twice below, than for equilibrium air (for example, in a vicinity of tail-plane). Possibly, it is caused by the fact that the effective ratio of specific heats for nonequilibrium air is greater than for equilibrium air because with the account of final rate of chemical reactions the gas flow on the leeside is frozen and high enough concentration of atoms is observed there.
Fig. 4. Heat flux distribution (kW/m²). Navier-Stokes equations, 
(a) equilibrium dissociating air, (b) nonequilibrium air, $\gamma_A = 0.01$.

The account of nonequilibrium chemical processes and a finite value of catalytical activity of a surface ($\gamma_A = 0.01$) noticeably reduces calculated levels of heat transfer in comparison with the case of the model of equilibrium dissociating air. The most significant decrease in heat fluxes is observed in a vicinity of the nose part of the vehicle (at $x \leq 1m$) and in a vicinity of the tail fin. For example at the stagnation point the heat flux decreases approximately for 40% - from 640 to 385 kW/m², thus the surface radiating equilibrium temperature decreases almost for 15% - from 1670 to 1430 °C. It is necessary to note a high level of surface heating on thin edges of wings comparable with a heat flux value at the stagnation point.

Especially strong heating is observed in a place of a wing deflection where values of heat flux and surface temperature even exceed a little their values at the forward stagnation point. In case of equilibrium air the excess for heat flux is about 10% (710 and 640 kW/m²), for temperature – 3% (1720 and 1670 °C). In case of nonequilibrium air this exceeding is more considerable, for a heat flux – 30% (540 and 385 kW/m²), for temperature – 10% (1570 against 1430 °C).

On the rest surface of the vehicle the difference in heat transfer values for two models of air is not so considerable and it decreases downstream that is caused, apparently, by gradual recombination of atoms in a boundary layer in case of nonequilibrium air during flow along a surface.
Fig. 5. Distributions along the surface of the reentry vehicle in symmetry axis: (а) pressure \( p_w/\rho_\infty \bar{V}_\infty^2 \), (б) heat flux (kW/m²), (в) temperature (°C).

Navier-Stokes equations, equilibrium dissociating and nonequilibrium air, \( \gamma_A = 0.01 \).

**Conclusions**

Heat transfer parameters of a winged reentry vehicle of two geometric configurations moving in Earth’s atmosphere are obtained for various points of a trajectory of descent on the basis of computer simulation of hypersonic flow. Areas of the maximal thermal loadings to a vehicle surface and their dependence on governing flow parameters are investigated.
Satisfactory conformity is observed of the calculated parameters obtained with use of the Euler and boundary layer equations and the Navier-Stokes equations on windward side of a space vehicle. At the same time there is an appreciable difference in results of calculations in a vicinity of wing edges and, especially, in the region of the raised heat fluxes near the "bump" in an initial part of a wing. Therefore, use of the Euler and boundary layer equations in areas where viscous-inviscid interaction is strong, and also on a leeside of a vehicle, can lead to appreciable errors and for correct determination of surface heat fluxes it is necessary to use the Navier-Stokes equations.

It is shown that depending on a configuration of a space vehicle use of equilibrium dissociating air approximation overestimates heat flux values from 40 % up to two times for high-altitude flight conditions in comparison with the model of nonequilibrium air for a value of probability constant of heterogeneous recombination typical for modern low catalytical heat-shielding coverings.

REFERENCES