Journal of Applied Mathematics and Mechanics 80 (2016) 44–56

Contents lists available at ScienceDirect

Journal of Applied Mathematics and Mechanics

journal homepage: www.elsevier.com/locate/jappmathmech

Radiation aerothermodynamics of the Stardust space vehicle☆

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ARTICLE INFO

Article history:
Received 1 September 2015
Available online 16 June 2016

ABSTRACT

This paper presents a radiation-gasdynamic model and the results of calculating the radiative-convective heating of the Stardust space vehicle, obtained using the NERAT(2D)-ASTEROID computer code designed for solving the full system of equations of the radiation-gas dynamics of a viscous, conductive, physically and chemically non-equilibrium gas and radiation transfer in a two-dimensional geometry. The system of continuum mechanics equations is solved by the explicit method using a simplified procedure for solving the problem of the decomposition of an arbitrary discontinuity. The system of equations of energy conservation of translational degrees of freedom of gas particles and vibrational degrees of freedom of nitrogen, oxygen, and nitrogen oxide molecules is solved by the implicit finite difference method. A multiblock and multigrid procedure is used to obtain a numerical solution. Calculation of the transfer of selective thermal radiation is done using the line-by-line method on specially generated inhomogeneous calculation grids over the wavelength of radiation, making it possible to achieve an appreciable saving of computing resources. In a single cycle of the computing process, the spectral optical properties of high-temperature gases are calculated using *ab initio* quasi-classical and quantum mechanics methods.

The creation of a new generation of piloted and automatic space vehicles comes hand in hand with the development of novel approaches to designing and building new technologies for creating materials with the necessary properties, and also new computer information technologies to support all stages of design, production, and functioning of the products of space rocket technology. Traditionally, one of the most important problems is that of providing the space vehicle with thermal protection as it re-enters the Earth's atmosphere or enters the atmosphere of planets of the solar system. Among a number of current problems associated with improving the reliability of predictive aerophysical models, the following remain unresolved: the development of conjugated gas dynamics and kinetics models of non-equilibrium dissociation and ionization, models of relaxation and radiation processes, and the creation of effective computer codes for numerical integration of the Navier–Stokes equations on structured and non-structured grids in two-dimensional and three-dimensional formulations. In tackling questions of the thermal protection of superorbital space vehicles, to the given problems are added problems of radiative heating: integration of the equation of transfer of selective thermal radiation with respect to space, angular variables, and frequency of electromagnetic radiation; calculation of the spectral optical properties under conditions of a non-equilibrium population of excited states of atoms, molecules, and their ions; the creation of effective theoretical calculation models of radiation-gasdynamic interaction, etc.

Thus, the solution of problems of the radiative aerothermodynamics of superorbital space vehicles should be based on the construction and integration of a conjugated (interrelated) system of equations of continuum mechanics, physical and chemical kinetics, transfer of selective thermal radiation, and calculation of thermophysical, transport, and spectral optical properties. These problems form the basis of modern-day continuum mechanics. A practically important result of solving these problems is the determination of the convective and radiative heating of a surface along the trajectory of flight, which dictates the necessary thermal protection. The most important scientific result is the obtainment of the spatial fields of gas dynamics functions, which makes it possible to study in detail the laws governing the gas dynamics and physicochemical processes in the disturbed region of flow.

One of the models and the numerical results obtained with it for the Stardust automatic space vehicle[1,2] are given in the present work. This vehicle was launched to the comet Wild-2 on 7 February 1999, and its mission was completed on 15 January 2006. A principal feature

☆ *Prikl. Mat. Mekh.* Vol. 80, No. 1, pp. 60–79, 2016.
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http://dx.doi.org/10.1016/j.jappmathmech.2016.05.008
0021-8928/

of this space vehicle was that, on its return to Earth, it entered the atmosphere at a speed of 12.6 km/s. The surface of Stardust was not equipped with sensors, but several authoritative scientific groups had carried out preflight and post-flight[2–5] theoretical investigations of the radiation aerothermodyamic conditions of re-entry of the space vehicle into the Earth's atmosphere. A good correlation of the obtained data and their consistency with the state of the thermal protection of the returned space vehicle enable these data to be used for comparison with the results of newly developed models and for improving existing models.

Below we present the further development of a model[6,7] constructed using a multigroup model of transfer of selective thermal radiation, with the use of which data were obtained on the radiative-convective heating of the front surface of Stardust, in good agreement with available results.[2] However, the analysis of experimental flight data for the space vehicle Fire-II[8] with re-entry conditions similar to those of Stardust that has been carried out in recent years[9–11] has shown that the line structure of the spectrum of thermal radiation emission and variation of the kinetics models used may turn out to be fundamentally important.

The following problems are investigated in the present work: analysis of the effect of atomic lines on the radiative heating of the surface of Stardust, analysis of the effect of the choice of kinetics models on the calculated value of the thermal load on the space vehicle, and analysis of the role of radiation-gasdynamic interaction.

A computer model of the compressed layer at the surface of the re-entering space vehicle will be presented and investigated. The transfer of selective thermal radiation is calculated using the half-moment method and a line-by-line spectral model of transfer of selective radiation towards the surface of the space vehicle and towards the free stream of undisturbed air. The proposed approach to solving the problem of radiation transfer also includes an *ab initio* method for calculating the spectral optical properies (including the parameters of the atomic lines: the force of the line and its half-width).

The indicated line-by-line method for calculating the transfer of selective thermal radiation is based on a specially developed numerical procedure for constructing a non-uniform calculation grid along the wavelength of thermal radiation. This computing procedure ensures a marked reduction in the number of grid nodes, which in turn makes it possible to carry out high-accuracy calculations on grids containing no more than 80 thousand nodes. Note, for comparison, that typical line-by-line calculations are carried out on grids with about two million nodes.

All elements of the presented model for calculating the radiation-gasdynamic and the radiantion transfer of energy are realized in the computer code NERAT(2D)-ASTEROID, which is used to predict the convective and radiative thermal heating of the surface of the space vehicle in a two-dimensional geometry.[12] Results of extending the given model to the three-dimensional case have been given elsewhere.[13]

1. System of integrable equations

The computer model of the radiation aerothermodynamics of hypersonic gas flow around a segmental conical space vehicle includes equations of discontinuity, Navier–Stokes equations, equations of the conservation of energy of translational motion of particles in the form of the Fourier–Kirchhoff heat condition equation, equations of the conservation of mass of the chemical components, and equations of conservation of vibrational energy in individual modes:

$$\frac{\partial\rho}{\partial t}+\operatorname{div}(\rho\mathbf{V})=0 \tag{1.1}$$

$$\frac{\partial\rho u}{\partial t}+\operatorname{div}(\rho u\mathbf{V})=-\frac{\partial p}{\partial x}-\frac{2}{3}\frac{\partial}{\partial x}(\mu\operatorname{div}\mathbf{V})+\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(\frac{\partial \upsilon}{\partial x}+\frac{\partial u}{\partial r}\right)\right]+2\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right) \tag{1.2}$$

$$\frac{\partial\rho \upsilon}{\partial t}+\operatorname{div}(\rho \upsilon\mathbf{V})=-\frac{\partial p}{\partial r}-\frac{2}{3}\frac{\partial}{\partial r}(\mu\operatorname{div}\mathbf{V})+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial \upsilon}{\partial x}+\frac{\partial u}{\partial r}\right)\right]+2\frac{\partial}{\partial r}\left(\mu\frac{\partial \upsilon}{\partial r}\right)+2\mu\frac{\partial}{\partial r}\left(\frac{\upsilon}{r}\right) \tag{1.3}$$

$$\begin{aligned}\rho c_p\frac{\partial T}{\partial t}+\rho c_p\mathbf{V}\operatorname{grad}T&=\operatorname{div}(\lambda\operatorname{grad}T)+\frac{\partial p}{\partial t}+\mathbf{V}\operatorname{grad}p+\Phi_\mu-Q_{\mathrm{VT}}-\\&-\sum_{i=1}^{N_s}h_i\dot{w}_i+\sum_{i=1}^{N_s}\rho c_{p,i}D_i(\operatorname{grad}Y_i\cdot\operatorname{grad}T)+\operatorname{div}\mathbf{W}_r\end{aligned} \tag{1.4}$$

$$\frac{\partial\rho_i}{\partial t}+\operatorname{div}\rho_i\mathbf{V}=-\operatorname{div}\mathbf{J}_i+\dot{w}_i,\quad i=1,2,\ldots,N_s \tag{1.5}$$

$$\frac{\partial\rho_{i(m)}e_{V,m}}{\partial t}+\operatorname{div}(\rho_{i(m)}e_{V,m}\mathbf{V})+\operatorname{div}(e_{V,m}\mathbf{J}_{i(m)})=\dot{e}_{V,m},\quad m=1,2,\ldots,N_V \tag{1.6}$$

where x, r are the orthogonal cylindrical coordinates, u and υ are projections of the velocity vector $\mathbf{V}$ onto the coordinate axes x and r, p is pressure, ρ is density, T is the temperature of translational motion of the particles, μ is the dynamic viscosity coefficient, λ is the thermal conductivity, Φ_μ is a dissipative function, c_p is the specific heat of the mixture at constant pressure, $c_p=\sum_i^{N_S}Y_ic_{p,i}$, N_s is the number of chemical components of the gas mixture (in the case examined, 11 components of high-temperature air are taken into account: N, O, e^-, N_2, O_2, NO, N_2^+, O_2^+, NO^+, N^+, O^+), $c_{p,i}$ is the specific heat at constant pressure that is related to translational and rotational degrees of freedom, h_i and Y_i are the enthalpy and mass fraction of the ith component of the mixture, $\dot{w}_i$ is the mass rate of chemical transformations, $\mathbf{J}_i=-\rho D_i\operatorname{grad}Y_i$ is the vector of the diffusion flux density, D_i is the effective diffusion coefficient of the ith component of the mixture, $e_{V,m}$ is the rate of change in energy in the mth vibrational mode, which here is defined by two processes: exchange of energy between the translational degrees of freedom of motion of particles and the vibrational degrees of freedom of diatomic molecules $\dot{e}_{\mathrm{VT},m}$ (so-called VT