Radiation Heat Transfer Models for Re-Entry Aerothermodynamics

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Abstract. Computing models, intended for determination of integrated and averaged radiative characteristics are presented and analysed. These are: multi-group model of spectrum, the ray-tracing and Monte-Carlo methods for prediction radiation characteristics, half-moment method for calculation radiation heat transfer inside inhomogeneous shock layers in multi-group approximation and in view of random models of molecular lines. The numerical simulation models are realized together with computational fluid dynamic (CFD) codes intended for prediction of aerothermo-dynamics of entering space vehicles.

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I. INTRODUCTION

A problem of calculation of selective radiative heat transfer in shock layers and wakes of entering space vehicles, containing such optically active components as CO_2, H_2O, CH_4, N_2, O_2, NO, N_2^+, C_2, CO, etc., demands development of effective numerical simulation methods for prediction of spectral radiation fluxes both inside radiative volumes and on the space vehicle surfaces.

The following computing models of selective radiative heat transfer are in common use:

– Multigroup models of a spectrum, using averaged absorption coefficients in limits of each spectral group;
– Wide-band models of a spectrum;
– Narrow-band models of a spectrum;
– "Line by line" integration on a spectrum.

Detailed classification of different models, which are used in theory of radiation heat transfer, is presented in Ref.1. Each of these models uses actually similar computational algorithm, namely, an investigated spectral range is divided into finite spectral regions, in limits of which the equation of radiation heat transfer is solved at frequency-independed spectral coefficients of emission and absorption . Integrated absorptivity (emissivity) in a full spectral range is determined by summation of integrated absorptivity (emissivity) in separate ranges. The average characteristics are obtained by division of integral characteristics (integrated in spectral group) by value of the spectral group (spectral region) $\Delta\omega$. As expected, the computational economy of the models decrease with increase number of spectral region considered.

Radiation heat transfer in molecular gases has one very significant peculiarity: due to rotational line structure of diatomic and multi-atomic spectra an average transmission of any optically thick path is the non-linear function versus physical coordinate, therefore the averaging procedure described above valid only for optically thin emitting volumes. Unfortunately very often real conditions in shock layers and wakes can be characterised as the thick or the intermediate case between the optically thick and optically thin cases.

Some computing models, intended for determination of integrated (averaged) radiative characteristics are analysed in the study. The following methods are presented: multi-group model of spectrum, the ray-tracing and Monte-Carlo methods for prediction radiation characteristics, half-moment method for calculation radiation heat transfer inside inhomogeneous shock layers in multi-group approximation and in view of random models of molecular lines. The numerical simulation models are realized together with computational fluid dynamic (CFD) codes intended for prediction of aerothermodynamics of entering space vehicles. To create different multi-group spectral model a computing code ASTEROID[1] was used.

The opportunity of application of such models to calculation of averaged spectral characteristics is illustrated for entry conditions into Martian atmosphere[2,3] and for re-entry conditions in Earth atmosphere[4].

Computational fluid dynamic models, which were developed in the present study, are oriented to solve of radiation gasdynamic (RadGD) problems with weak radiative gasdynamic interactions. Numerical algorithms of radiation heat transfer enumerated above are included into the RadGD code. Several tests were performed for the CFD/RadGD models.

The first series of the test calculation was performed for conditions of experimental study.[5] Figures 1 show configuration of the test model studied in experiments,[5] temperature and field of velocity $V_x = u/V_\infty$ calculated for the experimental conditions. Distribution of convective heat fluxes along surface of the model predicted by the CFD/RadGD codes is shown also in Fig.1. In this case air was taken into account in accordance with Ref.5. Good agreement between experimental and calculated data is observed.

The second series of test calculations was performed for conditions of Martian entry for model space vehicle MSRO.[2,3,6] Analysis of these calculations has demonstrated acceptable accordance of presented predictions to numerical simulation data of other authors from European Space Agency.[3]

To solve radiation heat transfer problems jointly with gasdynamic and kinetic problems, which are typical for entry and re-entry space vehicles, the following classification is used:

1. Martian entry problems. These problems are characterized by the following: atmospheric gases are CO_2, N_2, and Ar; significant influence of catalytic properties of surface of thermo-protection system (TPS), because, as a role, the thermo-protection material is assumed as indestructible; significant role in heating of space vehicle surface of gasdynamic wake radiation emission; thin rotational line structure of atmospheric species has to be taken into account in the last case.
2. Earth re-entry problems. In this case, atmospheric gas is air; it is assumed that TPS can be destructible; significant role of radiation-gasdynamic interaction in shock layers; thin atomic line structure has to be taken into account at super-orbital entry velocities.

Developed radiation heat transfer models were classified in accordance with these peculiarities:

1. One-dimensional radiation heat transfer models can be used for prediction of radiation heat transfer near to critical line of flowfield and in the vicinity of frontal thermo-protection sheath. Also, the one-dimensional models exceptionally useful for solving radiation heat transfer problems in cases of strong radiative-gasdynamic interaction. Analysis of different methods intended for solving radiation heat transfer equation in one-dimensional approximation shows that the half-moment method[6,7] is one of the best methods. It is shown in Ref.7 how the method can be used jointly with random model of atomic lines. In other words, it is actually shown that to predict radiation heat transfer subject to thin atomic line structure in shock layers at super-orbital velocities there is no necessity to use extremely time-expense line-by-line approach. It should be stressed that random models can not be used jointly with other methods, such as based on the integral-exponential functions and spherical harmonics approximation (diffusion approximation).
2. Two-dimensional radiation heat transfer models (the Spherical Harmonics method, diffusion approximation, the Discreet Ordinates method) can be used for prediction radiation heat transfer near to surface of space vehicle in the case when the one-dimensional approach is unacceptable (for example, due to complex geometry of TPS surface).

   Both mentioned groups of methods are very effective at fast calculations, but unfortunately, they can not predict radiation heat transfer for complex geometry of space vehicles at whole domain of flowfield (including wake region) and subject to thin atomic and molecular line structure. For these purposes should be used ray-tracing and Monte-Carlo methods:[2,6]
3. Ray-tracing method is recommended for prediction of radiative heating of spacecraft surface in the two- or three dimensional geometry.[6]
4. The Monte-Carlo method is recommended for prediction of radiative heating of spacecraft surface in the two- or three dimensional geometry,[2] especially in cases of light-scattering gases.[8]

General peculiarity of the last both models is possibility to calculate radiation heat transfer in domains of arbitrary geometry subject to fine molecular line structure (jointly with random models, or by using line-by-line approach). Such possibility was successfully demonstrated in Refs.2,3,9. Some numerical simulation results obtained by mentioned models are presented below.

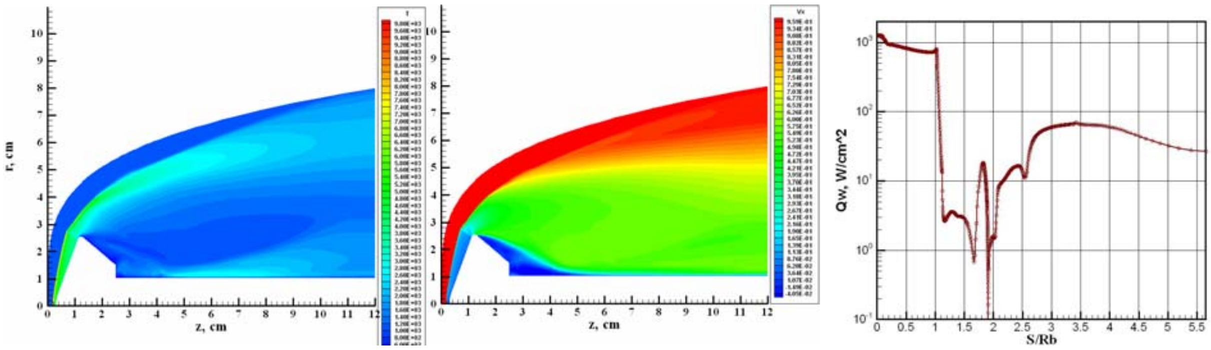

FIGURE 1. Reduced model of Pathfinder studied in experiments[5] and numerically predicted flowfield, and numerically predicted convective heat flux Q_w ; $R_b = 2.54$ cm, S is the coordinate along surface from the critical point

II. MULTI-GROUP MODELS

2.1. Prediction Of One-Side Radiation Heat Transfer Fluxes Along The Stagnation Line For Testcase TC3 Of The European Working Group

Initial conditions for these calculations are shown in Figs.2. Calculations were performed by codes ASTEROID+RAD_PLANE. Code RAD_PLANE realises half-moment method for prediction radiation heat transfer in one-dimensional approximation. Numerical simulation results for four series of the calculations are presented in Figs.3,4. Figures 3 show distributions of the incident spectral radiation heat fluxes at the stagnation point on the surface of space vehicle. In the first case (Fig.3, left), spectral region $\Delta\omega = 1000 \div 4000\,\text{cm}^{-1}$ was divided by 10 spectral groups. In the second, the third, and the fourth cases, the same spectral region was divided by Ngroup = 37, Ngroup = 100 and Ngroup = 500 correspondingly.

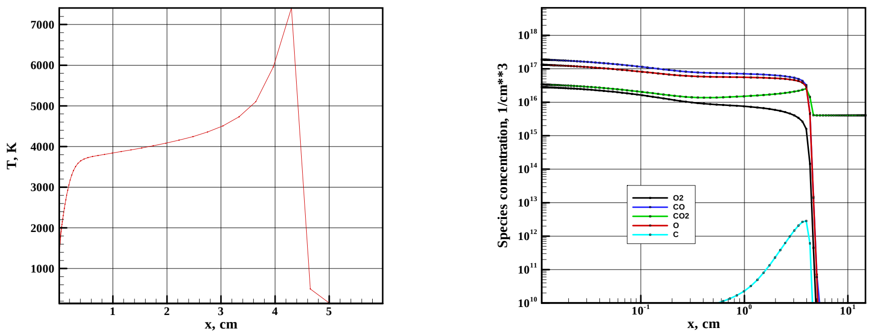

FIGURE 2. Temperature, K, and species volume concentrations along stagnation line, 1/cm^3

Figures 5 show distributions of integral radiation heat fluxes along stagnation line for the same calculation cases (self-emissivity of surface was omitted here and further). It is visible that, in this given case, the chosen group model plays more significant role in formation of distributions of integral fluxes.

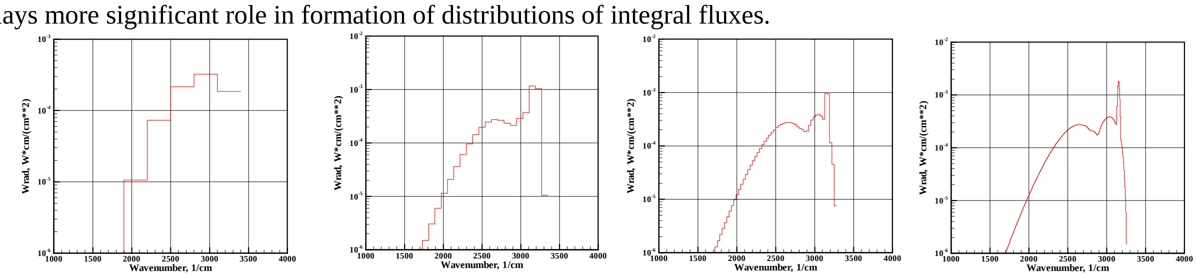

FIGURE 3. Spectral radiation heat fluxes in stagnation point, W*cm/(cm^2); N_{group} = 10, 37, 100, 500

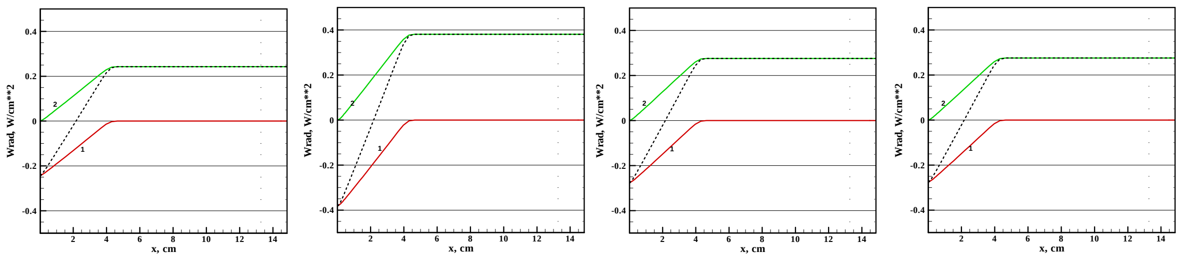

FIGURE 4. Integral one-side radiation heat fluxes distribution along stagnation line, W/cm^2; N_{group} = 10, 37, 100, 500; 1 − M_1^-, 2 − M_1^+; dashed line – is the total integral radiation heat flux

2.2 Prediction Of One-Side Radiation Heat Transfer Fluxes Along The Stagnation Line For Flight Data FIRE-II ($t = 1648.5$ s)

Initial conditions for these calculations are presented in Figs. 5. Calculations were performed by codes ASTEROID+RAD_PLANE. Numerical simulation results for four series of calculations are presented in Figs.6, 7. Figures 6 show distributions of the incident spectral radiation heat flux at the stagnation point on the surface of space vehicle. In the first case (Fig.6, left), the spectral region $\Delta\omega = 1613 \div 50015$ cm^{-1} was divided by 10 spectral groups. In the second, the third, and the fourth cases the same spectral region was divided by N_{group}= 37, N_{group}= 100 and N_{group}= 500 correspondingly.

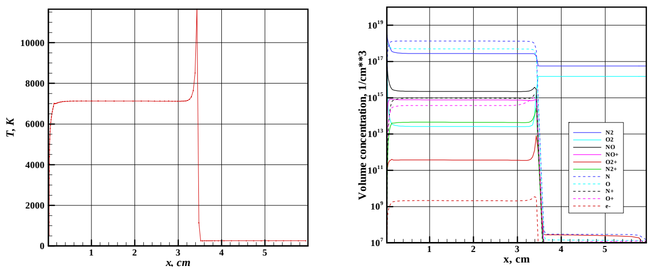

FIGURE 5. Temperature, K, and species volume concentrations along stagnation line, 1/cm^3

Figures 7 show distributions of integral radiation heat fluxes along stagnation line for the same calculation cases. It is clearly visible that these distributions depend weakly on the spectral group number. In other words, to predict radiation heat flux at the stagnation point, it is enough to use 37 spectral groups. Nevertheless, it should be stressed that the influence of spectral group number on integral radiation fluxes can be significant in other calculation cases.

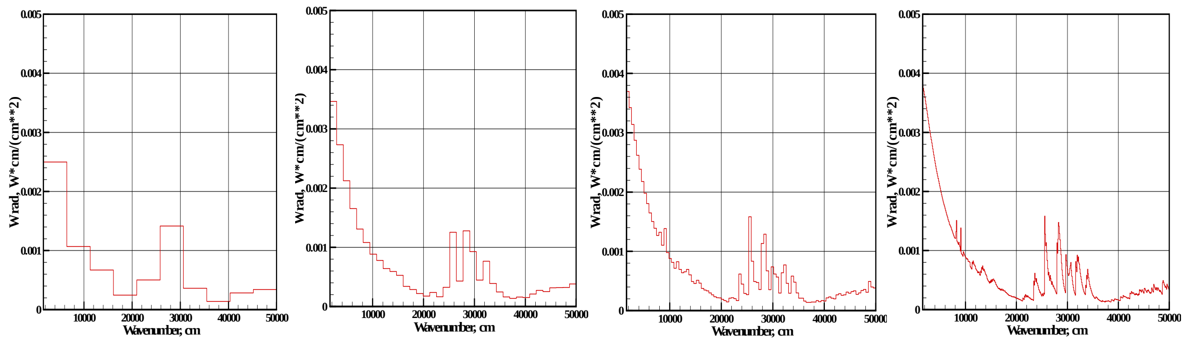

FIGURE 6. Spectral radiation heat fluxes in stagnation point, W*cm/(cm^2); N_{group}= 10, 37, 100, 500

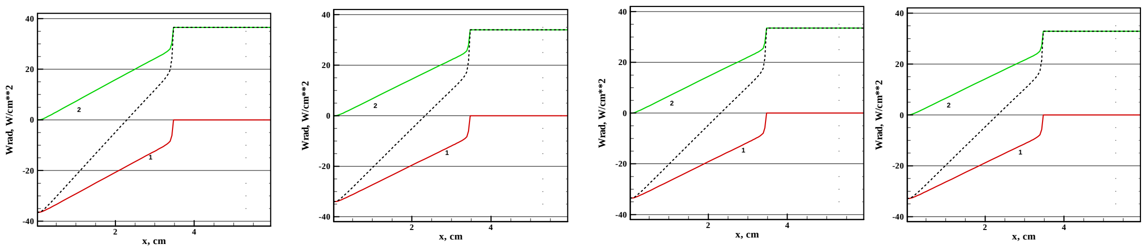

FIGURE 7. Integral one-side radiation heat fluxes distribution along stagnation line, W/cm^2; N_{group}= 10, 37, 100, 500;
$1 - M_1^-$, $2 - M_1^+$; dashed line – is the total integral radiation heat flux

III. RAY-TRACING AND MONTE-CARLO MODELS

The ONERA radiative model stands on a Statistical Narrow-Band (SNB) model for the optical part and a Monte-Carlo approach to solve the Radiative Transfer equation. The optical model[10] is based on the Local Thermodynamic Equilibrium condition and accounts for the radiation of CO and CO_2 molecules in the infrared part of the spectra. The band width is equal to 25 cm^{-1} and the specific contributions of each species are:

- CO molecule: 67 bands inside 2 spectral groups $\Delta\omega = 1650 \div 2325\,\text{cm}^{-1}$ and $\Delta\omega = 3400 \div 4350\,\text{cm}^{-1}$;
- CO_2 molecule: 84 bands inside 4 spectral groups $\Delta\omega = 525 \div 1100, 1925 \div 2425, 3250 \div 3775$, and 4750, 5150 cm^{-1}.

The SNB model has been assessed by comparison with line-by-line spectra for a pressure varying between 1 Pa and 500 Pa and a temperature varying between 1000 K and 4000 K. Its use is still possible out of these ranges but its accuracy becomes limited. Some numerical simulation results obtained by line-by-line approach are also presented in Ref.10.

Concerning the Monte-Carlo approach,[11] the ASTRE code is a parallel solver dealing with 3D multi-block unstructured grids. After having estimated the emitted power of each computational cell, the total number of optical paths is “reparti” over all cells “selon” an uniform distribution or a non-uniform one. In the latter case, the number of optical path associated to each cell is directly proportional to the emitted power of the cell. Afterwards, one determines stochastically the source point, the direction and the associated wavenumber of each optical path. Absorption is treated in a deterministic way, considering a cut-off value. Once energy of the bundle is lower than the threshold value, the path is stopped in the next cell which absorbs the left energy. Current results provide the radiative heat flux along the boundaries, the radiative power in the flow and the standard deviation associated to these values.

Similar numerical simulation approach, which is based on the ray-tracing numerical algorithms, was realized in Refs.6,12. Averaged on rotational line structure spectral model[13] was used there. Distributions of total radiation heat fluxes along surface MSRO were predicted by this method (see Fig.8). In this case the ray-tracing method was used both for frontal and back-side of the space vehicle.

Comparison of numerical simulation results for back-side surface obtained with use of different optical models and radiation heat transfer methods showed acceptable agreement between these predictions.

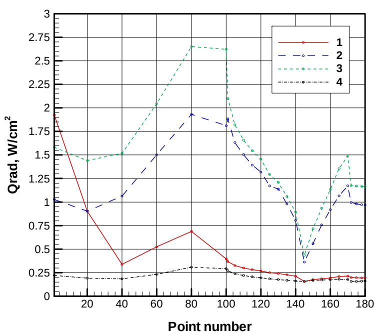

FIGURE 8. Total radiation heat flux on the MSRO surface with non-catalytic properties. Four lines correspond to four trajectory points (the trajectory parameters are presented in Refs.2, 6).
Points are distributed uniformly along surface profile elements (front surface, back surface) of the space vehicle

CONCLUSION

Results of performed analysis of spectral optical models and radiation heat transfer models can be used for prediction of radiative heating of projectible descent space vehicles and for creation of aerothermodynamic computational fluid dynamic codes.

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