COMPUTATIONAL PROBLEMS OF THERMAL RADIATION IN AEROSPACE ENGINEERING

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This article reports on the three computational studies presented at the Radiation Panel of the 7th International Symposium on Advances in Computational Heat Transfer (CHT-17), which focus on aerospace applications.

KEY WORDS: heat transfer, thermal radiation, space vehicles, atmospheric re-entry, thermal protection, solar probe

1. INTRODUCTION

Thermal radiation is an important mode of heat transfer in many problems of aerospace engineering. The present paper is an extended summary of three studies presented at the Radiation Panel of the 7th International Symposium on Advanced Computational Heat Transfer (CHT-17). The order of three sections of the paper corresponds to the order of the names of the authors.
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2. RADIATIVE TRANSFER IN THE MARS ATMOSPHERIC ENTRY FLOWS

Several space missions to the planet Mars have successfully (e.g., Viking 1976; MSL 2012) or unsuccessfully (e.g., Exomars-2016) landed a space module on the surface of the planet. Some other missions are planned in the near future (InSight 2018; Exomars-2020) with the challenging objective to prepare manned space missions. One of the most dangerous phases in these missions is the atmospheric entry of the capsule where part of the atmospheric gas kinetic energy is converted into heat and sustains dissociation of molecular species. At high velocities, i.e., high altitudes, radiative transfer from the heated shock layer in front of the capsule to its surface becomes significant, and its accurate prediction is required for the design of thermal heat shields. The rear surface of the capsule is also exposed to significant radiation from the wake flow, and its thermal protection is sometimes required.

The Martian atmosphere is mainly composed of CO$_2$ (96% molar fraction) and N$_2$ (3%). The main radiating species are the molecular and atomic species CO$_2$, CO, N$_2$, NO, N, and O, that are not necessarily at local thermodynamic equilibrium. The incident radiative flux at the surface of the vehicle, $q_R = \int_0^\infty d\nu \int_0^{4\pi} I_{\nu}(u) u d\nu du$, requires the integration of the spectral intensity $I_{\nu}(u)$ over the wave number $\nu$ and propagation direction $u$. The quantity $I_{\nu}(u)$ obeys the radiative transfer equation (neglecting scattering):

$$\frac{dl_{\nu}(u)}{ds} = \eta_{\nu} - \kappa_{\nu} I_{\nu}(u),$$

where $\eta_{\nu}$ and $\kappa_{\nu}$ are the medium intrinsic emission and absorption coefficients, respectively. They are given for bound-bound transitions between upper and lower levels $u$ and $l$ by

$$\eta_{\nu} = \sum_{ul} \frac{A_{ul}}{4\pi} h\nu_{ul} n_u f_{ul}(\nu - \nu_{ul}),$$

$$\kappa_{\nu} = \sum_{ul} (n_l B_{lu} - n_u B_{ul}) h\nu_{ul} f_{ul}(\nu - \nu_{ul}).$$

These expressions show that the computation of radiative properties requires the knowledge of:

- fundamental spectroscopic data: one of the three Einstein coefficients $A_{ul}$, $B_{ul}$ or $B_{lu}$, line center position $\nu_{ul}$, and line broadening parameters determining the line shape $f_{ul}$;
- the upper and lower level populations, $n_u$ and $n_l$.

2.1 Spectroscopic Data

For atomic and diatomic molecular species, exhaustive and accurate line lists and continuum process cross sections have been built and gathered in the High Temperature Gas Radiation (HTGR) database (Chauveau et al., 2002, 2003; Babou et al., 2009; Soufiani et al., 2013). However, for Martian entries, several studies have shown that the infrared CO$_2$ radiation may be dominant compared to other mechanisms both for the front shield [see, e.g., (Babou et al., 2006)] and rear shield (Rouzaud et al., 2008). Several theoretical spectroscopic databases
have been developed for CO$_2$. An experimental study of Depraz et al. (2012a,b), combining a microwave plasma torch with high resolution Fourier transform emission spectroscopy, has shown that the spectroscopic database CDSD400 (Tashkun and Perevalov, 2011) yields good accuracy at medium spectral resolution for temperatures of up to 4000 K. Figure 1 shows an

![Graph](image)

**FIG. 1:** Comparison between measured line-of-sight integrated radiative intensities and calculated intensities using the spectroscopic databases developed by Scutaru et al. (1994) and CDSD400 (Tashkun and Perevalov, 2011). For legibility, the high-resolution spectra are convolved with a rectangular function of width 10 cm$^{-1}$. Adapted from Depraz et al., (2012b).
example of comparison between experimental and predicted results in the two important spectral regions near 2.7 and 4.3 μm. CDSD4000 is therefore recommended for CO₂ radiation in Martian atmospheric entries.

Nonetheless, it should be mentioned that CDSD4000 gathers 573,881,316 transitions. Using this spectroscopic database, line-by-line (LBL) direct predictions of radiative transfer in entry applications require a huge amount of computer CPU time, especially if the radiation computations are to be coupled with flow field calculations. Two ways have been explored to handle the spectral complexity in atmospheric entry flows. Global models have been developed by Bansal and Modest (2013) for carbonaceous atmospheres with three nonoverlapping diatomic electronic band systems. However, if a large number of overlapping systems must be considered, the implementation of global models becomes quite tedious. Instead, statistical narrow-band (SNB) models have been developed by Lamet et al. (2010) for Earth re-entries with account for thermodynamic nonequilibrium. Similar models have been successfully developed and used for simulating various atmospheric entries (Rouzaud et al., 2008; Babou et al., 2006; Rivière and Soufiani, 2012; Soucasse et al., 2016). The SNB models provide up to three orders of magnitude in CPU time reduction with an accuracy of a few percent on radiative fluxes and volumetric powers. In addition, they keep the spectral information that is required for comparison of calculations with in-flight measurements.

2.2 Level Populations

Prior to the determination of level populations required in Eqs. (2)–(3), macroscopic equations of mass, momentum, and total energy balance in the flow field must be solved in association with a dedicated chemical kinetic model [see, e.g., (Park et al., 1994) for Mars entries]. Then, level populations can be calculated depending on the thermodynamic description of the medium. The vibrationally specific multitemperature model is the most practicable model to be coupled in nonequilibrium flow calculations. In this model, each vibrational mode of each molecule is assumed to be in internal equilibrium with specific vibrational temperature, and translation and rotation are assumed to equilibrate at a single temperature $T_{tr}$. However, for the CO₂ molecule, the symmetric stretching vibrational mode ($v_1 = 1388$ cm$^{-1}$) and the bending mode ($v_2 = 667$ cm$^{-1}$) are strongly coupled by Fermi resonance and must be described by the same temperature $T_{12}$, the asymmetric stretching mode ($v_3 = 2349$ cm$^{-1}$) being described by another temperature $T_3$. The governing equations for $T_{12}$ and $T_3$ are given in this model by

$$\rho C_v C_{v,12} \frac{dT_{12}}{dt} + \nabla \cdot \mathbf{q}_{12} + \nabla \cdot \mathbf{q}^R_{12} = R_{12};$$

$$\rho C_v C_{v,3} \frac{dT_3}{dt} + \nabla \cdot \mathbf{q}_3 + \nabla \cdot \mathbf{q}^R_3 = R_3,$$

where $C_{v,12}$ and $C_{v,3}$ are the vibrational specific heats, $\mathbf{q}_{12}$ and $\mathbf{q}_3$ are the diffusive heat fluxes, and $\mathbf{q}^R_{12}$ and $\mathbf{q}^R_3$ are the partial radiative fluxes. The collisional exchange terms $R_{12}$ and $R_3$ can be determined from a dedicated vibrational kinetic model [see, e.g., (Nagnibeda and Kustova, 2009)]. Once the vibrational temperatures are known, the population of a vibrational CO₂ level $l$ can be calculated from
where \( Q \) is the three-temperature internal partition function of CO\(_2\), \( g_j \) is the level degeneracy,
and \( E_{12}, E_3, \) and \( E_{rot} \) are the level energies in the vibrational modes (1, 2) and (3),
and in the rotational internal mode, respectively. These energies are assumed uncoupled in such
multi-temperature model.

### 2.3 Radiation Transfer Solver

Depending on the required degree of coupling with the flow field, different solvers of the
radiative transfer equation can be employed. When only wall fluxes are required (no cou-
pling with the flow field), a direct ray tracing method can be used as in Rivière and Soufiani
(2012) for the simulation of the afterbody region of the Viking capsule. The most common and
simple model for radiation computation in the forebody region is the tangent slab approxima-
tion where the temperature and composition fields are assumed to be locally one-dimensional
fields, determined according to the line normal to the wall [see, e.g., (Babou et al., 2006;
Soucasse et al., 2016)]. This approximation yields an accuracy of the order of 10 to 20%. The
Monte Carlo ray tracing method (MC) is more and more used with different strategies for the
treatment of spectral complexity (Rouzaud et al., 2008; Lamet et al., 2009; Feldick and Mod-
est, 2011; Soucasse et al., 2016).

### 2.4 Example of Computations

It is insightful to use the available in-flight experiments in order to validate simulation models
and numerical tools. In fact, there are very few missions to Mars with experimentally equipped
capsules: Viking capsule (1976) was equipped with two thermocouples on the back shield;
MSL (2012) had seven in-depth thermocouples mounted in the front shield; and the Schiapare-
relli lander of Exomars-2016 mission was equipped with a wide-band radiometer and three
narrow-band radiometers (ICOTOM) on the back shield. The simulation of the radiative flux
on the back shield of the Viking capsule is presented below and compared with experimental
data. The temperature histories at two points (M\(_1\) in aluminum wall and M\(_2\) in fiberglass) were
analyzed in terms of total incident fluxes by Edquist et al. (2006). We have simulated the in-
cident radiative fluxes at these two points based on the flow field calculations carried out by
Beck and Merrifield (2012). A two-temperature model (\( T_T \) for translation–rotation, and \( T_{ve} \) for
all vibrational modes of all molecules and for electronic excitation) was used in these calcula-
tions, and no coupling with radiation was considered.

Figure 2 shows the predicted incident radiative flux on point M\(_1\) at three trajectory times
(11,700.5 s, 11,710.5 s, and 11,716.5 s) and in the two important CO\(_2\) infrared spectral re-
regions. The results from statistical narrow-band models, with either the Curtis–Godson or the
Lindquist–Simmons approximations, are in good agreement with the line-by-line calculations.
The Lindquist–Simmons approximation yields slightly more accurate results in the 4.3-μm
region.

The cumulated incident radiative fluxes at the points M\(_1\) and M\(_2\), for the three trajec-
tory times are shown in Fig. 3 where the predominance of the 4.3-μm CO\(_2\) bands is clearly
FIG. 2: Low spectral resolution incident flux on wall point M₁ of Viking capsule calculated using LBL and SNB model with the CG or LS approximations. Trajectory times 1, 2, and 3 refer to times 11,700.5, 11,710.5, and 11,716.5 s, respectively. The calculations are based on the translation–rotation temperature field \( T_{tr} \).

FIG. 3.
highlighted. Results assuming local thermodynamic equilibrium at the translation–rotation temperature field $T_{tr}$, or at the vibration-electronic temperature field $T_{ve}$ are very close. This shows that vibrational disequilibrium does not play a significant role in this Martian entry at a moderate velocity (around 6 km/s). However, this result should be considered with caution owing to the simple two-temperature model used for aerothermal predictions. The predicted radiative fluxes are also compared in Fig. 3 with the estimated total fluxes (radiative and convective) inferred from thermocouple measurements by Edquist et al. (2006). The range of total fluxes shown in the figure takes into account uncertainties in material properties, wall emissivity, and conduction effects. The calculated incident radiative fluxes are clearly higher than the total fluxes inferred from the experiments. Several reasons may explain this result. First, the incident fluxes should be multiplied by wall emissivities to obtain the absorbed fluxes, but the exact values of the radiative properties of the employed aluminum and fiberglass materials were not known. Another explanation could be the cooling of the wake flow by radiation losses, which is not taken into account in the present simulations, and that certainly would lead to lower values of wall radiative fluxes, as was predicted in coupled simulations of the Mars Sample Return Orbiter in Rouzaud et al. (2008). This comparison highlights the need of two-way coupling between aerothermal fields and radiative transfer in Martian atmospheric entries.

FIG. 3: Comparisons between cumulated incident radiative fluxes on wall point M$_1$ (a) and M$_2$ (b) using translation–rotation and vibration temperature fields for the three trajectory times. The numbers in parentheses indicate the estimated ranges of total fluxes inferred from thermocouple measurements in Edquist et al. (2006).
3. COMPUTATIONAL HEAT TRANSFER FOR THERMAL PROTECTION SYSTEMS IN ATMOSPHERIC RE-ENTRY

Thermal protection systems (TPS) are employed for spacecraft to survive high temperature conditions during atmospheric re-entry. For space shuttle type entries, ceramic tiles traditionally shield the payload from exposure to high heat fluxes due to their near-zero conductivity. Recent research has focused on the use of medium to low density TPS materials. Such novel ablative composite materials acting as TPSs with a smaller weight or lower density require a better understanding of the volumetric ablation and multimode heat transfer phenomena in order for the TPSs to be properly designed. This understanding can help to reduce TPSs’ weight and the weight of supporting structures at the benefit of an increase in the payload carrying capacity.

Radiation plays a particularly important role for these less dense and less optically thick composite materials which are exposed to the high convective and radiative heat fluxes of the shock layer. Furthermore, TPSs’ thermal behavior is strongly dependent on the morphology of the composite material as well as the reaction extent, i.e., the extent of ablation and the corresponding exposure time to the shock layer. Analysis of the radiative heat transfer in these materials often requires the use of numerical models based on volume averaging methods to satisfactorily account for the multiple scales involved, i.e., the pore scale and the macroscale. The accuracy of these methods relies on the determination of effective radiative properties, which depend on bulk properties, discrete-scale interface boundary conditions, and on the morphology of the porous media. Advanced tomography-based direct pore-level simulations can be used for an accurate determination of these effective properties (Haussener et al., 2009; Banerji et al., 2017).

Here, we discuss the accurate radiative characterization of ablative materials in their generalized, nondimensional form, and the subsequent preliminary use of such properties in advanced material response codes which separate conduction and radiation heat transfer modes. The latter separation is recommended to better decouple radiation and conduction phenomena and to better understand which heat transfer mode is responsible for the observed behavior and, in turn, allow for an optimization of the TPSs’ morphology for an optimized thermal response. These macroscale models of the TPS can be dynamically coupled to the external flow and radiation fields. Plasma torch and high-flux solar simulator experimentation — operating at similar convective and radiative fluxes as in the real (re-)entry situation — can be used to test the accuracy of the modeling assumptions and the modeling results, in addition to the few datasets from actual space expeditions.

3.1 Radiative Characterization of TPS Materials

The material from this section has meanwhile been published in Banerji et al. (2017), and a short summary of the theory, methodology, and results is given here. TPSs’ materials are typically heterogeneous media composed of carbon or glass fiber matrices impregnated with an organic resin. Generally, small fractions of enclosed bubbles/gas phase pockets in the resin phase are also present, even though they are usually unwanted by-products of the manufacturing process. Once the composite is exposed to the intense heat fluxes of the shock layer, the material absorbs the heat and uses it to increase the sensible energy (i.e., the temperature of the material) and as an input to drive the endothermic surface and volumetric
thermochemical reactions, and phase change reactions. The latter two will ensure the dissipation of the energy and make sure that the material and payload are cooled. During the pyrolysis process, the resin phase is sublimated and pyrolyzed. The resulting absorbing gas products are released and eventually leave the medium through the exposed surface. Effectively, the medium is composed of the carbon or glass fiber matrix surrounded by pyrolyzing gas phase. Once all the resin is used in the chemical and phase change reactions, the carbon or glass fiber matrix is directly exposed to the high flux conditions. All pyrolysis products have been removed from the system, and the solid matrix was surrounded by a transparent gas phase.

We applied a combined experimental-numerical approach for the quantification of the effective radiative properties of TPSs materials. The approach consists of the use of the exact morphological information of the media obtained by noninterfering and nondestructive microscopic techniques, specifically here by computed X-ray tomography. We used absorption mode providing us with a matrix of three-dimensionally resolved absorption values, with a spatial resolution of 0.33 μm. The data was segmented using a histogram-based segmentation approach, basically assigning a range of absorption values to each individual phase. Specifically, we separated solid carbon or glass fiber matrix, organic resin phase, and gas phase inclusions. The digitalized structural information was used for a detailed and quantitative assessment of the various materials’ morphological characteristics, namely their phase volume fractions, their phase size distributions, and interface areas. Two different types of TPSs’ materials were investigated: a medium density carbon phenolic sample and a high-density graphite reinforced polymer composite (Fig. 4). The phenolic sample had a porosity of 57% (43% was the fiber matrix and resin) before pyrolysis and of 81% after pyrolysis (19% was the remaining fiber matrix). The graphite reinforced composite had a porosity of 8% (92% was the fiber matrix and resin) before pyrolysis and of 28% after pyrolysis (72% was the remaining fiber matrix). These values were calculated based on ex situ samples. This was mostly done due to the fact that in-situ tomography was not easy to implement and the temporal resolution was not sufficiently small to reach high-quality tomographic images. However, in situ imaging of few samples and conditions was successfully achieved and confirmed that the solid matrix was relatively unaffected by the pyrolysis process. The digitalized structure was then used in Monte Carlo simulations for the radiative characterization of the TPSs’ materials (Tancrez and Taine, 2004; Haussener et al., 2009). Effective properties for two phases were considered: a fluid phase with subscript 1 (virgin state: gas enclosures, pyrolyzed state: gas enclosures and pyrolyzed resin phase), and a solid phase with subscript 2 (virgin state: mixture of resin and solid matrix, pyrolyzed state: solid matrix only). These effective properties are essential for the solution of the volume-averaged radiative transfer equations (RTEs) for a two-phase medium given by

$$\hat{s}_i \lambda \mathbf{I}_{i,\lambda} (\mathbf{x}, \hat{s}) = - \left[ \kappa_{d,\lambda} + \sigma_{d,\lambda} + \sigma_{i,\lambda} + \sigma_{i,\lambda} \right] I_{i,\lambda} (\mathbf{x}, \hat{s}) + n_i^2 \kappa_{b,\lambda} I_{b,\lambda} (\mathbf{x}) + \frac{1}{4\pi} \int \Omega_{in} \mathbf{I}_{i,\lambda} (\mathbf{x}, \hat{s}_{in}) \left[ \sigma_{d,\lambda} \Phi_{d,\lambda} (\hat{s}_{in}, \hat{s}) + \sigma_{i,\lambda} \Phi_{i,\lambda} (\hat{s}_{in}, \hat{s}) \right] d\Omega_{in} + \frac{\sigma_{i,\lambda}}{4\pi} \int \Omega_{in} \mathbf{I}_{j,\lambda} (\mathbf{x}, \hat{s}_{in}) \Phi_{i,\lambda} (\hat{s}_{in}, \hat{s}) d\Omega_{in}, \quad i, j = 1, 2 \text{ and } i \neq j.$$  

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FIG. 4: The normalized effective extinction coefficient as a function of the normalized bulk extinction coefficient of the gas phase [••• virgin carbon phenolic, ××× decomposed carbon phenolic] (a), and the solid phase [+++ virgin graphite, ••• decomposed graphite] (b), for the virgin and pyrolyzed state of a medium porosity carbon phenolic composite sample and a high-density graphite reinforced polymer composite sample. Reprinted from Banerji et al. (2017) with permission from Elsevier.
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Their derivation of the volume-averaged RTEs has been detailed in Lipiński et al. (2010a,b) and Petrasch et al. (2011) and the corresponding definition of the effective properties \((\sigma_{\text{int},ii}, \sigma_{\text{int},ij}, \Phi_{\text{int},ii}, \text{ and } \Phi_{\text{int},ij})\) have been given. The latter four scattering phase functions and scattering coefficients are dependent on the exact morphology of the sample only while the bulk material properties \((\kappa_{d,i}, \sigma_{d,i}, \text{ and } \Phi_{d,i})\) are independent of the morphology. The effective extinction coefficients for the two phases (subscript 1: fluid, subscript 2: solid) are the sum of the bulk absorption and extinction coefficient and the effective scattering coefficients. Figure 4 shows the normalized extinction coefficients for the fluid and solid phase for the two samples (carbon phenolic, graphite reinforced composite) in the two states (virgin and pyrolyzing). The order of the curve follows the volume fraction of the fluid phase (extinction coefficient of phase 1) and the volume fraction of the solid phase (extinction coefficient of phase 2), respectively, namely the increasing volume fraction leads to a smaller normalized effective extinction coefficient. The curves generally show two separate regions: i) a region for large bulk optical thicknesses which is dominated by the interface extinction, and ii) a region for small bulk optical thickness which is dominated by the bulk extinction. Similar calculations can be done for the effective scattering coefficients, which largely depend on the interface properties, namely, the refractive indexes and the applicability of the generalized Snell’s law and Fresnel’s correlations. The scattering phase function turns out to be relatively insensitive to the morphology, consistent with previous observations (Haussener et al., 2009). The detailed effective properties are then used in Eq. (6) to assess the absorption in a layer of TPS materials. This was done to assess the changes in absorption behavior of a TPS layer undergoing the complete pyrolysis reaction. It became apparent (Fig. 5) — especially for the medium density carbon phenolic — that a significant change in the optical properties was experienced during the pyrolysis. For example, for the carbon phenolic at a wavelength of 1 μm, the absorption changed from 76% to 94%. It becomes apparent that this change will have a significant effect on the transient material response. Uncertainty in the knowledge of the bulk material properties can easily been quantified from Figs. 4 and 5 by simply moving horizontally along the curves. It becomes apparent that small variation in material properties can have a significant effect on the absorption behavior, especially of the virgin samples, given by the large gradient of the curves (Fig. 5).

3.2 TPS Material Response

The detailed radiative properties can then be incorporated in a continuum thermal response model. The normalized form is especially useful in this case, as these functions can be provided to the code and solved for the particular situation in terms of bulk properties and, consequently, the extent of reaction/ablation. However, many of these codes use the Rosseland approximation to describe and account for the radiative behavior. The assumptions for the applicability of this approach are less and less given for less dense composite TPS materials. Consequently, the governing energy equations have to be updated and specifically the radiation term has to be separately solved for in the energy equation:

\[
\begin{align*}
\partial_t (\rho e_t) + \partial_x (f_v \rho g h_g v_g) + \partial_x \left( \sum_{k=1}^{N_g} Q_k \right) &= \partial_x (k \partial_x T) + \\
&= \rho c_p \partial_t T + \rho \partial_x (f_v \rho g h_g v_g) + \sum_{k=1}^{N_g} Q_k
\end{align*}
\]

(7)
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where the divergence of the radiative flux accounts for the properties calculated in the direct numerical simulations. Without going into the details (Banerji, 2017), utilizing the PATO material response model, and the open TACOT material property database, the temperature in the heat shield of the MSL (2012) mission has been used for the validation of our calculations and to get an insight on the effect of separated treatment of the internal radiation and its effect on the thermal response of the composite TPS materials (Fig. 6). The baseline modeling (with nonseparated radiation–conduction effects) and the updated separated radiation and conduction approach provide accurate predictions of the recorded data. Relatively little difference between the two approaches is observed, which we hypothesized to be a result of the fact that the heat flux boundary from the shock layer for this particular case was dominated by convective flux.

This first reporting of a coupling between the macroscale heat shield and material response model (and its adaptation to separate the radiation and conduction terms) and its coupling to the microscale heat transfer characteristics can be continued and more detailed investigations can be conducted providing a better understanding of the material response of low density composite materials to be considered for TPSs.

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The complex physical effects in the solar photosphere and also in the vicinity of the Sun have attracted the interests of researchers during many years. A series of space missions are planning including the NASA project "Solar Probe Plus" with the launch in 2018 (Congdon et al., 2010; Reynolds et al., 2013). One of the main technical problems to be solved for the success of such a mission is an acceptable thermal regime of the probe equipment at very high radiative heat flux from the Sun. The ordinary ablating thermal protection may be insufficient to reach a desirable duration of the mission, and it is important to find a novel method to protect the space vehicle.

One of the possible ways of attenuation of the solar radiation can be based on the use of micron-sized particles generated by an advanced thermal protection material during the matrix ablation. It has been recently shown by Dombrovsky et al. (2017) that this solution to the thermal protection problem is more promising than the use of special reflecting coatings. The main computational results for the case problem with SiC particles are presented below. Silicon carbide was chosen because it is characterized by a very weak absorption in the main part of the solar spectrum and also by a relatively low sublimation rate. The data for optical and
thermal properties of SiC are discussed in Dombrovsky et al. (2017). One can find also more details in Choyke and Palik (1985), Rousseau et al. (2016), Lilov (1993), Ma et al. (2003), and L’vov (2007).

The central problem of this analysis is a spectral radiative transfer through a cloud of absorbing and scattering particles. It was shown in monograph by Dombrovsky and Baillis (2010) that the details of scattering phase function of single particles can be neglected in many radiative heat transfer problems. Without doubt, this approach is correct in the case of multiple scattering (Dombrovsky et al., 2013, 2015, 2016c, 2017). Moreover, even in the case of an optically thin layer of a scattering medium, one can employ the transport approximation (Dombrovsky, 2012). A good accuracy of this approach in solving combined heat transfer problems is explained by the integral character of the main radiation field parameters such as the radiative flux and its divergence.

It is convenient to introduce the normalized values (per unit volume fraction of particles) of both the absorption and transport scattering coefficients (the subscript \( \lambda \) is hereafter omitted for brevity):

\[
E_a = \alpha / f_v, \quad E^v_s = \sigma / f_v.
\]

These normalized coefficients calculated using the Mie theory (Van de Hulst, 1957; Bohren and Huffman, 1983) are plotted in Fig. 7. One can see that scattering of solar radiation by

![FIG. 7: Normalized coefficients of (a) absorption and (b) transport scattering for SiC particles of different radii: solid curves — \( a = 2 \) \( \mu \)m, dotted curves — \( a = 10 \) \( \mu \)m; 1) \( T = 2000 \) K, 2) 3100 K. Adapted from Dombrovsky et al. (2017).]
SiC particles is weakly sensitive to the particle temperature, whereas the absorption increases significantly with temperature at $\lambda > 0.5$ $\mu$m. This increase in absorption takes place for both small and large particles, but the scattering is predominant in all cases. It is clear that small particles would be better at relatively large distances from the Sun, whereas large particles are preferable for the radiation shielding at the final stage of the mission because of not so fast heating and sublimation.

The radiative transfer problem is simplified as much as possible to obtain physical estimates only, but the following special features of the real problem are still taken into account: the spectrum of solar radiation and the spectral properties of particles. The main simplifications are as follows:

- The plane-parallel cloud of particles is positioned just above the protected surface facing the Sun, and the cloud has the same profiles of all parameters in every cross section.
- It is assumed that the incident solar radiation is diffuse at the final stage of the mission.
- The temperature difference in the particle and effects of nonuniform absorption and emission of radiation in semi-transparent particles are neglected (Dombrovsky, 2000, 2004).
- The composite material generating SiC particles is opaque, nonreflective, and heat losses to the internal region of the material layer are neglected. The wall is assumed to be absolutely black.

The 1D radiative transfer equation is still complex even with the use of transport approximation. Therefore, the two-flux method, which is also known as the Schuster–Schwarzschild approximation (Modest, 2013), is employed. The error of this method in both the radiative flux and its divergence is small in the case of smooth profiles of temperature and medium properties. The boundary-value problem for the spectral irradiance $G(z)$ is as follows (Dombrovsky and Baillis, 2010):

\[
- \left( DG'(z) + \alpha G = \alpha F_p(z) \right) \quad 0 < z < d, \tag{9a}
\]

\[
DG'(0) = (G(0) - F_w)/2 \quad DG'(d) = (F_{sol} - G(d))/2, \tag{9b}
\]

\[
D = 1/(4\beta_{tr}) \quad \beta_{tr} = \alpha + \sigma_{tr} \quad F_{sol} = 4\pi J_b(T_{sol})/R^2 \quad F_w = 4\pi J_b(T_w). \tag{9c}
\]

The relative distance from the solarphotosphere is defined as $R = R/R_{sol}$, and $J_b(T)$ is the Planck function. The spectral and integral radiative fluxes to the protected surface are

\[
q_w = (G(0) - F_w)/2 \quad q_w^{\text{int}} = \int q_w d\lambda. \tag{10}
\]

The radiation power absorbed in the cloud is calculated as follows:

\[
W(z) = \int_0^\infty w(z)d\lambda. \quad w(z) = \alpha \left( G(z) - F_p(z) \right). \tag{11}
\]

Strictly speaking, a complex motion of particles may lead to the presence of particles of different size and temperature in every elementary volume of the cloud. Note that neglecting of particle motion leads to the simple relations.
\{\alpha, \sigma_{tr}\} = f_v \left\{E_u, E_{s\sigma}\right\}
F_p = 4\pi I_b \left(T_p\right). \tag{12}

In this case, the mathematical problem statement can be completed with the following energy equation and kinetic equation for the sublimating particles:

\[ T_p(0, z) = T_w, \tag{13} \]

\[ \frac{\partial a}{\partial t} = -\dot{m}(t, z)/\rho \quad T_p(0, z) = T_w. \tag{14} \]

It was shown by Dombrovsky et al. (2017) that the Arrhenius law can be used to calculate a sublimation rate of silicon carbide in vacuum. Obviously, the volume fraction of particles decreases because of their sublimation:

\[ f_v(t, z) = f_{\nu 0} \left(a(t, z)/a_0\right)^3. \tag{15} \]

Some numerical results are presented in Fig. 8. The main input parameters are: \( R = 5 \), \( T_w = 2000 \) K, and \( f_{\nu 0} = 2 \times 10^5 \). One can see in Fig. 8a that it takes a little bit greater than 20 s for almost total sublimation of SiC particles with initial radius of \( a_0 = 10 \) \( \mu \)m which are

\[ \text{FIG. 8.} \]
positioned at the irradiated surface of the particle cloud, but there is a smooth variation of particle radius from the initial value at the shadow surface of the cloud to the approximately three times smaller value at the cloud surface oriented to the Sun. The partial sublimation of particles makes the shielding effect considerably less than that in the process beginning, but Fig. 8b indicates that the shielding efficiency of the particle cloud remains rather high (the radiative flux without the cloud is equal to 2940 kW·m⁻²). The rate of mass losses due to sublimation is almost constant (Fig. 8c), and an upper estimate for the case problem gives very low rates of mass loss at the level of 1.5 kg·m⁻²·h⁻¹. It should be noted that there is an effect which works to decrease additionally this value. It is the light pressure which increases strongly with the decrease in size of sublimating particles (Burns et al., 1979). For single particles, the light pressure force is expressed as follows (Van de Hulst, 1957):

\[ F_{\text{rad}}(t, z) = \frac{\pi a^2(t, z)}{c_0} \int_0^\infty q(t, z)Q_{tr}(t, z) d\lambda, \]  

(16)

where \( c_0 \) is the speed of light and \( Q_{tr} \) is the transport efficiency factor of extinction. The light pressure leads to propagation of small particles inside the cloud, where they are protected from too fast sublimation. As a result, the large particles appear at the front of the cloud and con-
continue to fight against the heating of protected surface. Note that the resulting pattern is similar to that recommended for water spray curtains used in fire radiation shielding (Dombrovsky et al., 2016 a,b).

Various engineering solutions for the composite material of thermal protection containing SiC particles can be considered to generate a cloud of particles to shield the Space Probe from thermal radiation of the Sun at the last stage of the space mission. One of the promising variants is a carbon foam matrix. The high porosity of carbon foam will increase the linear sublimation rate and make possible to produce a desirable amount of SiC particles, which can be randomly embedded in the material.

Let us consider the conjugated heat transfer problem to describe approximately the formation of a quasi-steady cloud of SiC particles and to estimate the duration of this process. This can be done with the use of a simple approach of effective enthalpy for thermal destruction of carbon at fixed surface temperature (Dombrovsky et al., 2017). Similar calculations can be reproduced at different conditions typical for quite different host/matrix material of a composite thermal protection layer.

An analysis of particle motion should take into account two opposite forces: the drag force of a gas flow from the destructed thermal protection layer and the variable light/radiation pressure in the particle cloud. Strictly speaking, variable values of both forces should be considered to calculate the motion of particles and obtain transient profiles of all the parameters in the cloud cross section. After that, the radiative transfer problem for a multi-temperature medium could be solved. At the same time, the accuracy of the complete procedure is expected to be not high because of a great uncertainty in drag force and other data. Therefore, the lower and upper estimates are considered. In the first variant, the motion of particles is ignored and it is assumed that a quasi-steady particle cloud is formed due to the balance between the cloud mass losses and the mass flow rate of particles supplied by a destructed material. In the second variant, the ideal mixing of particles in the cloud is assumed. It means that all particles have the same size and temperature. The lower and upper estimates are physically sound and can be considered at the first step of the problem solution.

The results of calculations for the lower and upper estimates (variants 1 and 2, respectively) are presented in Fig. 9. The relative distance from the Sun center was taken equal to $R = 5$. The volume fraction of silicon carbide particles in a composite material is assumed to be equal to 1% and the initial radius of particles is equal to $a_0 = 10 \mu$m. The monotonic curves in Fig. 9 indicate an increase in optical thickness of the particle cloud with time. In the first variant, it takes approximately 2 min to generate a quasi-steady cloud with a transmitted radiative flux about 58% of the initial value obtained without any attenuation of solar radiation by a cloud. The quasi-steady rate of mass loss of the cloud is very small even in the first variant, and the resulting value of $\dot{M} \approx 1.4 \text{ kg/m}^2 \cdot \text{h}^{-1}$ is practically the same as that obtained above. The upper estimate of a cloud mixing due to the complex particle motion (variant 2) is characterized by a relatively slow transfer to the quasi-steady regime and much lower values of both the transmitted radiative flux and the rate of mass losses. Most likely, one can use the following estimate for the quasi-steady rate of mass loss from the sublimating particle cloud: $\dot{M} \approx 1 \text{ kg/m}^2 \cdot \text{h}^{-1}$. The low value of $\dot{M}$ can be treated as the main advantage of the suggested concept of the solar radiation shielding at small distances from the Sun. Note that this estimate is independent of thermal properties of the matrix of a composite material containing SiC particles.
5. CONCLUSIONS

1. The computation of radiative transfer in Martian atmospheric entries is a complex task due to the coupling with the aerothermal fields, possible vibrational and electronic disequilibrium effects, and the nature of spectral radiative properties of the involved gas mixtures. Work under progress includes the full coupling of vibrational CO₂ disequilibrium with radiation, which is not practicable using the line-by-line approach. The development of vibrationally specific statistical narrow-band models will make this type of simulation tractable. It is planned to apply the developed tools to the simulation of Schiaparelli entry (part of the Exomars-2016 mission) and compare prediction results with measurements by the ICOTOM narrow-band radiometers mounted on this capsule.

2. A first, conceptual coupling between the detailed pore-level simulations — specifically applied to the radiative characterization — and the macroscopic material response of composite TPSs has been conducted, providing evidence the such a coupling is possible, meaningful, has the potential to increase the accuracy of the modeling predictions, and provides in-depth insight into the volumetric multi-mode heat transfer characteristics (specifically separated between radiation and conduction) and the chemical and phase change reactions.
3. A new concept of Solar Probe protection from solar radiation at the final stage of the space mission is suggested. It is suggested to use micron-sized particles of silicon carbide generated during ablation of a composite thermal protection material. A computational model for generation and evolution of the particle cloud takes into account both thermal destruction of the matrix of thermal protection layer and sublimation of particles. An upper estimate of the light pressure effect on small partially sublimated particles is included in the computational model. The computational data showed a significant attenuation of solar radiation and very small mass loss of a particle cloud due to sublimation of particles even at small distances from the Sun. This indicates that embedding of silicon carbide or other particles into a layer of composite thermal protection and the resulting generation of a particle cloud can be considered as a promising way to decrease considerably the minimum working distance of a space vehicle from the solar photosphere.

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REFERENCES


