EPSC Abstracts
Vol. 12, EPSC2018-495, 2018
European Planetary Science Congress 2018

Shock layer radiation of an evaporating meteor

B. Dias(1), J.B. Scoggins (2) and T Magin (1)
(1)The von Karman Institute for Fluid Dynamics (VKI), Sint-Genesius-Rode, Belgium (barros@vki.ac.be)

Abstract

Meteor entry are characterized by complex shock layer physics such as radiation, evaporation of the meteoroid surface and the resulting chemistry process with the air constituents. In this work we present the analysis of a meteor entry using Computational Fluid Dynamic tools where a boundary condition for evaporation is implemented. Moreover the radiative source terms are derived by solving a 1D radiative transfer equations using a tangent slab method.

1. Introduction

The meteor phenomenon occurs daily around the planet Earth. Although a large number of the arriving particles are considered dust (micron-size grains) occasionally a large bolide burst into the atmosphere. The latter may represent a threat to the population as experienced during the Chelyabinsk event in 2013 [1]. At the range of velocities typical of meteor phenomena, radiation becomes highly significant, the intense light observed during a meteor entry is mainly due to the radiation of the air and metallic species, where the latter are coming from ablation products. The current models to study meteor entries are focus in the ablation of small particles in the upper atmosphere. They usually rely on a zero dimensional approach providing lack of an accurate treatment of the particle interaction with the atmosphere, from the fluid dynamic point of view. Therefore, for meteoroids big enough to survive this first phase of the atmospheric entry, a different approach has to be sought.

In this work we propose to study the meteor ablation with a numerical approach similar to those used in the aerospace community to model the gas-surface interaction over Thermal Protection System (TPS) materials. The flow governing equations are solved through a CFD code where a special boundary condition for evaporation is considered and a radiation solver is coupled. The flow properties are computed with the VKI physico-chemical library (Mutation^{++}).

2. Methodology

The 1D Stagnation-Line solver solves the Navier-Stokes equations along the stagnation line of spherical or cylindrical bodies. This model leads to an efficient way to calculate hypersonic flows with low computational costs.

The closure of the governing equations is done by the Mutation^{++} library built at the VKI [2] where thermodynamic properties are computed by the Rigid Rotor Harmonic Oscillator model while transport properties are derived by the Chapman-Enskog expansion from Kinetic Theory.

The evaporation of a molten layer can be modelled by limiting the control volume to a infinitesimal thin lamina where the surface is located. Typically mass conservation for the generic species i can be written in terms of a surface mass balance (SMB).

To solve this balance a suitable model to compute the surface reactions is needed, which in general can be solved by heterogeneous finite-rate chemistry. The evaporation/condensation of the material is estimated by the Knudsen-Langmuir law.

The surface temperature can also be estimated by computing an energy balance of the incoming and outgoing energy fluxes.

Energy and chemical (photoionization and photodissociation) source terms to account for radiation are included into the Navier-Stokes. These source terms are computed by solving the radiative transfer equations (RTE). Solving the RTE by conventional methods such as Line-by-Line (LBL) becomes computationally very expensive for complex molecular spectra. In this work we use a hybrid statistical narrow band model (HSNB) [3] which as the feature of presenting an accurate description of the radiative flux with low CPU by dividing the spectra into narrow bands and compute the intensity in terms of averages.

3. Results

As a preliminary study we considered a 1 dm radius ordinary chondrite at 60 km with a velocity of 15 km/s.

A two-temperature model was used for these simulations, i.e., T $=$ T$_{rot}$ and T$_{vib}$ $=$T$_{ele}$ and the wall temperature was imposed at 2600 K. The choice of this temperature was based on experimental and numerical observations of a melting ordinary chondrite [4].

A sensitivity analysis was initially made to the evaporation and condensation coefficients, in the Knudsen-Langmuir law, to evaluate the overall mass injection into the flow. The chosen coefficients are shown in Table 1.

Table 1: Coefficient parameters

Case #	coefficient
Case 1	α_{evap} = 0.1, α_{cond} = 0.1
Case 2	α_{evap} = 0.1, α_{cond} = 0.0
Case 3	α_{evap} = 1.0 , α_{cond} = 1.0

For all the cases the major vapour species is Na followed by NaO. For case 1 and 3 the evaporation rates are similar (around 10 $\%$ of Na at the surface) while for the case 2 the concentration of Na is represents almost 60 $\%$ of the total vapour since the choice of the condensation coefficient does not allow for this species to condensate. Since Na has a low ionization energy it quickly forms Na^+. Even though in the case 3 the evaporation coefficient is ten times higher than case 1 also the condensation coefficient follows the same trend. Meaning that the evaporation is higher but the condensation is also higher creating a balance between evaporation/condensation fluxes. The injection of mass shifts the shock position upstream due to the outgoing blowing velocity from the surface.

The final analysis was to include radiative source terms and to compare a 1 dm and 1 m radius OC at the same conditions as the one above for the case 1. For both radii it was observed a decrease of temperature in the shock layer due to the radiant emission increasing the heat flux at the surface. The radiative field becomes stronger for the 1 m case due to a larger shock layer. The ablation rate did not change significantly since the wall temperature as chosen to be the same as the first analysis. Interestingly, due to the strong shock emission the flow upstream of the shock undergoes photochemical processes. These processes leads to photoionization and photodissociation reactions increasing the electron density. In our case only photoionization mechanisms are considered. Moreover a departure from thermal equilibrium is also observed in the free-stream. For the 1 m radius body this departure is strong enough to have an exchange of energy between the internal and translation mode rising the translation temperature. This rise of the translation temperature leads to a strong dissociation of O_2 since the chemical rate is controlled by a geometrical temperature $T = \sqrt{TT_i}$.

4. Concluding Remarks

In this work a flow/radiation/ablation methodology was presented to study the meteor entry. It was observed that a stronger radiative field for bigger bodies which explains the stronger luminosity for bolides. In this case the surface energy balance was not considered. Further analyses will be made to compute the energy balance considering the incoming radiative flux to the surface.

Acknowledgments

This research is sponsored by the Belgian Research Action Through Interdisciplinary Networks “METRO: Meteor trajectories and origins”. Research of B. Dias is sponsored by fellowship from the “Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture.”.

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