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Radiative heating of large meteoroids during atmospheric entry

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ABSTRACT

A high-fidelity approach for simulating the aerothermodynamic environments of meteor entries was developed, which allows the commonly assumed heat transfer coefficient of 0.1 to be assessed. This model uses chemically reacting computational fluid dynamics (CFD), coupled with radiation transport and surface ablation. Coupled radiation accounts for the impact of radiation on the flowfield energy equations, while coupled ablation explicitly models the injection of ablation products within the flowfield and radiation simulations. For a meteoroid with a velocity of 20 km/s, coupled radiation is shown to reduce the stagnation point radiative heating by over 60%. The impact of coupled ablation (with coupled radiation) is shown to provide at least a 70% reduction in the radiative heating relative to cases with only coupled radiation. This large reduction is partially the result of the low ionization energies of meteoric ablation products relative to air species. The low ionization energies of ablation products, such as Mg and Ca, provide strong photoionization and atomic line absorption in regions of the spectrum that air species do not. MgO and CaO are also shown to provide significant absorption. Turbulence is shown to impact the distribution of ablation products through the shock-layer, which results in up to a 100% increase in the radiative heating downstream of the stagnation point. To create a database of heat transfer coefficients, the developed model was applied to a range of cases. This database considered velocities ranging from 14 to 20 km/s, altitudes ranging from 20 to 50 km, and nose radii ranging from 1 to 100 m. The heat transfer coefficients from these simulations are below 0.045 for the range of cases, for both laminar and turbulent, which is significantly lower than the canonical value of 0.1. When the new heat transfer model is applied to a Tunguska-like 15 Mt entry, the effect of the new model is to lower the height of burst by up to 2 km, depending on assumed entry angle. This, in turn, results in a significantly larger ground damage footprint than when the canonical heating assumption is used.

1. Introduction

A meteor's mass loss rate is an important factor in determining the potential ground damage threat for a given size, entry velocity, entry angle, and composition (Aftosmis et al., 2016; Mathias et al., 2017; Revelle, 2004a; Hills and Goda, 1993; Wheeler et al., 2017). The mass loss rate is written as follows:

$$\frac{dM}{dt} = -C_H \frac{S\rho_\infty V_\infty^3}{2Q} \tag{1}$$

where M is the total mass of the meteoroid, C_H is the heat transfer coefficient, S is the cross-sectional area, V_∞ is the free-stream velocity, and Q is the heat of ablation. A significant uncertainty in applying this equation is C_H, which assuming a spherical geometry for the meteoroid, is written as Prabhu et al. (2016):

$$C_H = \frac{2\int_0^{\pi/2} q_{rad} \sin\theta d\theta}{\frac{1}{2}\rho_\infty V_\infty^3} \tag{2}$$

where θ is the angle from the stagnation point, q_{rad} is the radiative heating as a function of θ, and ρ_∞ is the free-stream density. This equation assumes convective heating is negligible relative to radiative heating, which is true for all cases considered in this work that include coupled ablation. A common assumption in asteroid threat assessment studies (Mathias et al., 2017; Wheeler et al., 2017) is to set C_H to 0.1. This constant value is based on the nonablating, inviscid, stagnation-line analysis by Page et al. (1968), Baldwin and Sheaffer (1971), which included coupled radiation (meaning the radiative energy source terms are coupled to the flowfield energy

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equations). It is also based on the best-fit to observational data, as discussed by Bronshten (1983). Since the simulations of Page et al. in 1968, significant advancements have been made in modeling the heating environment relevant to meteor entries (Park, 2016; Biberman et al., 1980; 1979; Nemtchinov et al., 1997; Golub et al., 1996). The most significant of these advancements is the treatment of coupled ablation, meaning the injection of ablation products into the flowfield is modeled. These coupled ablation simulations at meteor entry conditions were performed assuming an inviscid stagnation-line (Park, 2016; Biberman et al., 1980; 1979), inviscid full-body Shuvalov and Artemieva (2002), or ablating piston (Nemtchinov et al., 1997; Golub et al., 1996) model, which all predict C_H values significantly below 0.1 (e.g., C_H less than 0.05 at altitudes below 30 km). Svetsov et al. (1995) discusses how the observational data, interpreted previously by Bronshten (1983) with a C_H of 0.1, may be reinterpreted with C_H values below 0.1 by reducing the heat of ablation, which may be justified by assuming more melt than vaporization occurs. However, these lower values have not been adopted by many asteroid threat assessment studies, partly because higher-fidelity simulations that include, for example, viscous effects and turbulence are required to gain further confidence in the simulated C_H values Svetsov et al. (1995).

To provide these higher-fidelity simulations (which will be shown to provide further motivation for the use of C_H values significantly below 0.1), the present work develops chemically reacting Navier-Stokes (i.e., viscous) flowfield simulations that include coupled ablation (Johnston et al., 2016; 2009; Park, 2016; Dias et al., 2015), in addition to coupled radiation. This work represents the first coupled radiation and ablation meteor simulations performed with Navier-Stokes flowfield solvers at altitudes below 50 km, which is the important range for potentially hazardous impacts. In addition to treating viscous effects, the present Navier-Stokes flowfield solver also allows surface regions downstream of the stagnation point to be simulated (as well as turbulence), which is required to accurately compute an effective C_H for the body. The goals of this work are therefore to assess the impact of coupled radiation and ablation on q_{rad} at meteor entry conditions, to compare the resulting C_H values with the constant 0.1 value, to develop a C_H correlation based on these detailed solutions, and finally to demonstrate the impact of this new model (relative to the constant 0.1 model) for a sample asteroid threat analysis.

This paper is separated into four primary sections: the first considers coupled radiation, the second considers coupled ablation, the third compiles the C_H database, and the fourth applies the developed C_H model to a Tunguska-like entry scenario. The first of these sections, Section 2, begins by presenting details of the coupled radiation flowfield simulation. It then examines the impact of nose radii and altitude on the coupled radiation influence, as well as the impact of the radiative precursor. Similarly, Section 3 begins by presenting details of the coupled ablation flowfield and radiation models. It then examines the impact of coupled ablation on q_{rad} and shows the influence of modeling boundary layer turbulence. Section 4 applies the full coupled radiation and ablation model developed in the previous two sections to create a database of C_H values, which may be used for meteoroid entry simulations. Finally, Section 5 applies the new C_H model to a Tunguska-like (15 Mt) entry scenario to illustrate its effect on predicted airburst properties.

2. Impact of coupled radiation

The potential of meteoroids to reach altitudes below 50 km, while maintaining velocities above 14 km/s, makes the treatment of coupled radiation essential for simulating accurate radiative heating values. Details of the coupled radiation model developed for this analysis are presented in Section 2.1. Section 2.2 then examines the impact of coupled radiation on a meteor flowfield, and identifies unique features that are not seen for more commonly studied reentry vehicles. Finally, Section 2.3 examines the impact of the free-stream gas, ahead of the meteoroid, absorbing shock layer radiation, also referred to as precursor absorption.

2.1. Flowfield and radiation modeling for coupled radiation

This work applies NASA's Laura v5 Navier-Stokes solver Mazaheri et al. (2010). Because altitudes below 50 km are considered here, along with nose radii of 1 m or greater, the impact of thermal nonequilibrium is expected to be small, at least in the forebody region, which is exclusively considered in the current work. Therefore, a single temperature model is used (except for the study of precursor absorption, which required a two-temperature model). Chemical nonequilibrium is treated to allow the present models to be applied in the future to wake simulations, where chemical nonequilibrium effects are significant. For the present cases without ablation, the following 13 species are treated in the flowfield: N, N^+, N^{++}, O, O^+, O^{++}, N_2, N_2^+ O_2, O_2^+, NO, NO^+ and e^-. Thermodynamic properties for N, N^+, N^{++}, O, O^+, and O^{++} are obtained from the high-temperature curve fits developed by Johnston et al. (2016). For the remaining species, the thermodynamic properties are obtained from Mcbride et al. (2002). The transport properties are obtained from Wright et al. Wright et al. (2005, 2007) where available. The remaining species are treated using the approximate approach of Svehla (1962) modified as suggested by Park et al. (2001). Laminar flow is assumed for all simulations in this section. An axisymmetric hemisphere grid with 128 points in the body-normal direction and 32 points along the surface was applied for all cases.

All radiation computations are made using the HARA radiation code Johnston et al. (2013b). For air species, HARA applies a comprehensive set of radiation properties, including spectral data and non-Boltzmann models for diatomic molecules and atomic species, which were critically assessed and chosen in studies by Johnston et al. (2008b,a). The accuracy of HARA's predictions for high-temperature air, at conditions relevant to meteor shock layers, has been assessed through comparisons with shock tube measurements (Johnston et al., 2013a; 2013d; Brandis et al., 2012). These studies show that measurements and HARA simulations agree within 30% at equilibrium conditions.

Coupled radiation refers to a flowfield computed with the divergence of the radiative flux (S_{rad}) included in the flowfield energy equations (Gnoffo et al., 2010). This is in contrast to the uncoupled radiation approach, where the flowfield is computed with S_{rad} set to zero, followed by the radiative heating being computed from this flowfield as a post-processing step. Therefore, in the uncoupled approach the flowfield computation is completely uncoupled from the radiation computation, and fails to account for important phenomena such as radiation absorption in the flowfield, or nonadiabatic cooling of the shock layer. Because of the significant impact of S_{rad} on the flowfield, this uncoupled approach will be shown to be unacceptable for meteor entry conditions.

For coupled radiation, the divergence of the radiative flux is written for a point z in the flowfield as

$$S_{rad,\nu}(z) = 4\pi j_\nu(z) - \kappa_\nu(z) \int_{4\pi} I_\nu d\Psi \tag{3}$$

where the first term represents the emitted energy and the second term represents the energy absorbed from the incoming radiation from the surrounding flowfield. A recent study by Johnston and Mazaheri (2017) showed that the second term in this equation may be accurately approximated by the tangent-slab approximation, which reduces the computational cost of evaluating this term by two orders of magnitude. The tangent-slab approximation, which