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Numerical study of infrared radiation characteristics of a boost-gliding aircraft with reaction control systems

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ABSTRACT

This work investigates the infrared radiation characteristics of high-temperature hypersonic flows with two reaction control system (RCS) plumes in the glide phase. Computational procedures are performed with thermal and chemical non-equilibrium fluid mechanics, gas-solid interaction, radiation physical parameter and transfer calculations. Hypersonic flows are simulated by solving two-temperature Navier-Stokes (N-S) equations with the finite volume technique. A 7-species, 6-reaction air-chemistry scheme and an 8-species, 10-reaction CO/H_2 plume reaction system are utilized. The line-by-line (LBL) method is used to evaluate radiative properties of high-temperature gases, and the radiation transfer equation (RTE) is integrated with the line of sight (LOS) method. Species formation, radiation properties of radiating species and radiation transfer calculations are verified against experimental and reference data. Three trajectory points of an HTV-2 type vehicle (at altitudes of 30, 50 and 70 km) are selected to analyze the radiation characteristics. Spectral intensities within the wavelengths of 2–12 µm at different observation angles are calculated. Computational results indicate that species NO mainly forms in the shock layer and its mole fraction reaches 10^{-2} order of magnitude. The high-temperature surfaces are near the head and leading edge of the vehicle, and surface emissions can be equivalent to a constant-temperature grey body. The spectral intensity of gases without RCS plumes is several orders of magnitude lower than surface emissions. Comparing the spectra with and without RCS plumes, it is shown that RCS plumes do change the spectral structure and increase the spectral intensity in the 2.7-µm and 4.3-µm bands. The integrated irradiances show that the instinct radiation intensity is closely related to the spectral band and the observation angle. In the 4.3-µm band, the presence RCS plumes has a significant contribution to the radiation.

1. Introduction

Boost-gliding aircraft is a good candidate of next generate hypersonic vehicles due to its lager supersonic lift-to-drag ratio than conventional vehicles. Hence, many agencies have started to develop these hypersonic vehicle programs, such as Unite state's Falcon HTV-2 [1], and Russia's Yu-71 [2] in recent years. Taking the example for HTV-2, it is a boost-glide vehicle with an arrow-head design and waverider configuration. Such an aircraft requires a series of operational phases to complete its mission: launch, pull-up, reentry, glide and terminal phases. In the reentry/glide phases, the HTV-2 can proceed to dive back to earth in the process reaching of up to Mach 20 [1]. When such an aircraft glide through the Earth's atmosphere, a strong shock layer will occur around the vehicle, and then surfaces will suffer from serious aero-heating, especially near the nose and leading edges. There exist complex physical and chemical processes such as dissociation, ionization, recombination, etc. in high-temperature flows so that part of the energy is emitted by radiations with specific spectra from hot gases [3,4]. On the other hand, these serious aero-heating can heat the aircraft's skin up to more than two thousand degrees Kelvin. The glowing surfaces also emit radiations with continuum spectra [5]. Naturally, the hot gases in the shock layer and glowing surfaces can be treated as radiation sources.

In practice, some stringent constraints, such as heat flux, structural load and guidance equipment, restrict the vehicle to fly within a narrow flight corridor within some feasible bounds of the angle of attack [6,7]. Therefore, gliding vehicles often equip an RCS to change its attitude and trajectory. Generally, the RCS consists of several thrusters with firing to produce rolling, pitching, and yawing moments. RCS jets can be characterized as pulsed unilateral control effectors with off/on states and acted as a non-uniform quantizer to apply a moment vector [8,9]. The RCS not only can provide various thrusts for attitude control but also be treated as an assistant of main engines with an appropriate mixture ratio (MR) [4]. Therefore, the exhaust plumes injected from

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pulse motors are a mass of high-temperature multi-species gases, meaning they may cause afterburning acting with ambient air if the plumes have some fuel-rich or unsteady products. Furthermore, the plumes of RCS can interact with the shock layer, which will form a complex wake flows in the downstream regions. Obviously, these flows can be analogous to booster exhaust plumes and can emit radiations.

These radiation sources can be used for aerodynamic heat-resist diagnosis and trajectory synthesized optimization by observing and tracking upon ground-based or space-based stations. To understand the radiation characteristics of boost-glide vehicles, it is necessary to investigate the contribution of each radiation source to the total radiance and its level. Generally, the radiation predictions of hypersonic vehicles with complex structures adopt the decoupling treatment between flow field and radiative transfer calculations [10]. In recent years, most investigations of radiation characteristics of hypersonic vehicles focus on ultraviolet, visible and near-infrared spectral bands during space capsule reentry [4,10,11]. Most of these investigations analyzed the radiative heating and spectral structures in the shock layer. The studies of infrared spectra and radiation characteristics of the hypersonic flows are mainly on radiation noise acting on the optical windows [12–14]. A series of remote infrared observations of the space shuttle Orbiter was carried out by NASA [15–17]. It is indicated that the optical properties of the vehicles need to account for spectral and angular variation as well as the sensor spectral response behavior of the vehicle surface. Up to now, it is not deeply investigated for the radiation characteristics of the hypersonic aircraft as mentioned above. However, to the best of the author's knowledge, there are few reports on the infrared radiation characteristics of a boost-glide aircraft with an RCS. In fact, what the researchers are most interested in: (1) how much contribution each radiating source, including surfaces, shock layer flows and wake flow makes to the total source, and (2) whether RCS plumes can change the spectral structure and irradiance intensity.

The purpose of the present work is to examine the radiation characteristics of a hypersonic boost-glide vehicle with/without RCS motors during the glide phase. This paper is organized as follows: Section 2 describes the numerical models, which consist of the computational fluid dynamics (CFD) solver, spectral parameter calculations and radiative transfer mechanisms. Section 3 shows validity studies of separate modules. Section 4 gives computational conditions in terms of geometry size, trajectory points, RCS type, grids and boundaries. Section 5 discusses IR irradiance sources, spectra, and integrated intensities at different observation angles with/without RCS plumes. Section 6 provides conclusions from this discussion, followed by the reference list and acknowledgments.

2. Numerical models

2.1. Governing equations of flow field

The flow is modeled on the assumption that the continuum approximation is still valid below altitudes of 70 km. To take account of thermal nonequilibrium effects, the conservation of internal energy should be added in the basic compressible Navier–Stokes (N-S) equations. Thus, four groups of conservation equations can be written as follows [18,19]:

$$\begin{gathered}\frac{\partial\rho_s}{\partial t}+\frac{\partial\rho_s u_j}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\rho D_s\frac{\partial Y_s}{\partial x_j}\right)+\dot{\omega}_s\\ \frac{\partial\rho u_i}{\partial t}+\frac{\partial\rho u_i u_j}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial\tau_{ij}}{\partial x_j}\\ \frac{\partial\rho E}{\partial t}+\frac{\partial\rho H u_j}{\partial x_j}=-\frac{\partial}{\partial x_j}\left(\eta\frac{\partial T}{\partial x_j}\right)+\eta_{ve}\frac{\partial T_{ve}}{\partial x_j}+\frac{\partial}{\partial x_j}\left(\rho\sum_{s=1}^{N_s}h_s D_s\frac{\partial Y_s}{\partial x_j}\right)+\frac{\partial\tau_{ij}u_i}{\partial x_j}\\ \frac{\partial\rho E_{ve}}{\partial t}+\frac{\partial\rho E_{ve}u_j}{\partial x_j}=-\frac{\partial}{\partial x_j}\left(\eta_{ve}\frac{\partial T_{ve}}{\partial x_j}\right)+\frac{\partial}{\partial x_j}\left(\rho\sum_{s=1}^{N_s}h_{ve,s}D_s\frac{\partial Y_s}{\partial x_j}\right)+\dot{\omega}_{ve}\end{gathered}\tag{1}$$

where ρ_s is the individual density of species s, ρ is the total density of mixture, D_s is the diffusion confident of species s, u_j is the component velocity in the jth direction, p represents the pressure, Y_s is the mass fraction of species s. h_i is the sensible enthalpy per unit of mass of species s. E denotes the total energy and E_{ve} is the vibrational-electronic energy per unit mass of mixture. η and η_{ve} are the thermal conductivities in translational-rotational and vibrational-electronic states, respectively. N_s is the number of species. $\tau_{ij}$is the shear stress tensor. $\dot{\omega}_{ve}$is the internal energy source term and defined as [18]:

$$\dot{\omega}_{ve}=\sum_{s=mol}\rho_s\frac{(e^*_{ve,s}-e_{ve,s})}{\langle\tau_s\rangle}+\sum_{s=mol}\dot{\omega}_s E_{ve,s}\tag{2}$$

where $\langle\tau_s\rangle$is the average relaxation time. It can be calculated by introducing Milikan-White's semi-empirical formula [20] within the range of 300–8000 K and the Park's collision limited correction [21] for temperatures higher than 8000 K. As a matter of fact, the radiation heat transfer contributes a substantial amount of energy transfer in addition to the conductive and convective processes [22]. The treatment of coupling the radiation into flow field simulations has been reported in many literatures [10,23]. It is noted that most of those computing models are the Sample Return Capsule (SRC). However, the current geometry model is different from the SRC. The aircraft structure is assumed to be made of a no-ablation heat-resistance material. For such an HTV-2 like vehicle, the high-temperature region is mainly concentrated around the head of the vehicle. In addition, the radiating trace species in air, such as CO_2, CO, H_2O, CH_4, etc., are not considered due to a small number of their concentrations. The RCS plumes are analogous to the rocket motor exhaust plumes. Saladino and Farmer [24] stated that the radiation source within gaseous radiation is negligible compared to other source terms for the high-temperature exhaust plume simulation. Furthermore, the computational time, as well known, will be greatly increased if the coupling effect of the radiation on the flow is introduced. Thus, the numerical model of flow field does not consider the radiative heat transfer contribution of gas.

Dalton's law is utilized to determine the mixture pressure of gases, which is given as:

$$p=\sum_{i=1}^{N_s}\rho_i\frac{R}{M_i}T\tag{3}$$

where R is the universal gas constant and M_s is the molar weight of species s. As the form of pressure, the connections of variables between mixture and individual species are given as:

$$\rho=\sum_{i=1}^{N_s}\rho_i;\quad\sum_{i=1}^{N_s}Y_i=1;\quad\sum_{i=1}^{N_s}\dot{\omega}_i=0\tag{4}$$

In the structure, the heat transfer can be described by the following form:

$$\frac{\partial T_s}{\partial t}=\frac{\kappa_s}{\rho_s c_s}\left(\frac{\partial^2 T_s}{\partial x^2}+\frac{\partial^2 T_s}{\partial y^2}+\frac{\partial^2 T_s}{\partial z^2}\right)\tag{5}$$

where T_s is the temperature of the structure, κ_s is the structural thermal conductivity, ρ_s and c_s are the structural density and specific heat, respectively.

There is an interface between the fluid (in Eq. (1)) and solid (in Eq. (5)) domains, via which the two different regions can be achieved the conjunction heat transfer. The coupling relationship at the interface on the basis of heat flux balance can be established and given in Eq. (6):

$$-\kappa\frac{\partial T}{\partial n}\bigg|_w-\kappa_{ve}\frac{\partial T_{ve}}{\partial n}\bigg|_w-\rho\sum_{s=1}^{N_s}h_s D_s\frac{\partial Y_s}{\partial x_j}\bigg|_w=-\kappa_s\frac{\partial T_s}{\partial n}\bigg|_w+\sigma\varepsilon(T_\infty^4-T_w^4)\tag{6}$$

where ε is the emissivity of the surface, $\sigma$is the Stefan-Boltzmann constant. T_∞ denotes the temperature at infinity, and T_w is the surface temperature.