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Prediction of shock-layer ultraviolet radiation for hypersonic vehicles in near space

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Abstract A systemic and validated model was developed to predict ultraviolet spectra features from the shock layer of near-space hypersonic vehicles in the "solar blind" band region. Computational procedures were performed with 7-species thermal non-equilibrium fluid mechanics, finite rate chemistry, and radiation calculations. The thermal non-equilibrium flow field was calculated with a two-temperature model by the finite volume technique and verified against the bow-shock ultra-violet (BSUV) flight experiments. The absorption coefficient of the mixture gases was evaluated with a line-by-line method and validated through laboratory shock tube measurements. Using the line of sight (LOS) method, radiation was calculated from three BSUV flights at altitudes of 38, 53.5 and 71 km. The investigation focused on the level and structure of ultraviolet spectra radiated from a NO band system in wavelengths of 200–400 nm. Results predicted by the current model show qualitative spatial agreement with the measured data. At a velocity of 3.5 km/s (about Mach 11), the peak absolute intensity at an altitude of 38 km is two orders of magnitude higher than that at 53.5 km. Under the same flight conditions, the spectra structures have quite a similar distribution at different viewing angles. The present computational model performs well in the prediction of the ultraviolet spectra emitted from the shock layer and will contribute to the investigation and analysis of radiative features of hypersonic vehicles in near space.

1. Introduction

In recent years, near-space aircraft have aroused great interest because of their high success rates for penetration, hence the development of many hypersonic vehicle programs, such as United States' "HTV-2" and "X-37B", Russia's "Clipper", Japan's "Hope", and England's "HOTOL". When these aircraft glide through the Earth's atmosphere at incredibly fast speeds, the high-temperature shock layer around the vehicle surface will produce intense emissions accompanied with complex physical and chemical processes such as dissociation, ionization, recombination and chemiluminescence. It is understood that within the features of emission spectra from the shock layer, great attention should be paid to photo-electric offensive and defensive strategies. In practice, the detection of theater targets utilizes the mid-wave infrared (IR) spectral

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region (3–5 μm as a baseline and distinctive ultraviolet (UV) or visible spectral regions as a second detection band).[1] Note that, in the so-called "solar blind" band covering 200–300 nm, the dark sky background allows one to detect a vehicle as a signature source against a very low background with a striking contrast.[2] In this typical band region, ultraviolet emissions from the shock layer have great potential for the early warning systems (EWS), target intercept guidance techniques to monitor, identify and track unfriendly aircraft, and also for suppression of radiative noise through the optical window.[3,4] In support of these concepts, two bow-shock flight experiments were conducted at relatively low velocities (about 3.5 km/s)[5] and high velocities (about 5.1 km/s)[6] at different altitudes by the Innovative Science and Technology Office in 1990s, and a series of the spectra signal data were obtained. These are helpful to understand the mechanisms of the shock-layer ultraviolet emission and to calibrate computational models.[7–12] In a two-color detection strategy, the ultraviolet signature may offer many advantages over long wavelength systems in reducing false alarm rates, and as a supplementary technique for near-space hypersonic aircraft use in offensive and defensive confrontations; hence, it is of great significance to investigate the ultraviolet emission features in the shock layer by a high-fidelity numerical approach.

The purpose of this work is to develop an efficient model for prediction of shock-layer ultraviolet spectral radiation characteristics during hypersonic vehicle glide in the Earth's atmosphere. In fluid computations, a two-temperature model will be employed in the treatment of the non-equilibrium flow field of the shock layer, and a 7-species scheme is also considered, which consists of a mixture of ions, electrons, atoms and molecules at high temperature (O_2, N_2, O, N, NO, NO^+ and e^-). Navier-Stokes equations incorporating finite rate chemical kinetics are solved with the finite volume technique. For comparison with previous literature, cases at three altitudes will be investigated: 38, 53.5 and 71 km. In radiation models, in particular NO gamma and delta band systems, the radiative transition mechanisms of gas molecules are taken into account to predict spectra within wavelengths of 200–400 nm. In addition, the non-equilibrium population of the electronic state of species is characterized by a three-temperature model, and the absorption coefficient of mixture gases is evaluated with a line-by-line method. Considering the BSUV flights as the focus of this research, the radiative transfer equation (RTE) is integrated with the line of sight (LOS) method. We will compare the computational results of each module with a wide set of experimental data, and analyze the structure and level of the ultraviolet spectra emitted from the bow-shock layer in different flight cases.

2. Available experimental data

Two BSUV flight experiments[5,6] were developed by the Innovative Science and Technology Office of the Strategic Initiative Organization in the 1990s in order to validate certain issues with hypersonic vehicles at low and high altitudes. These included the spectral distribution and intensity of ultraviolet radiation emitted from the bow-shock layer around the nose cone, the plume exhausted from rocket motors, vehicle aerodynamics, and gas radiative noise in the optics window. In the BSUV experiments, instruments in the payload, with a half cone angle of 15° and a 0.1016 m-radius dome, consisted of a scan spectrometer, eight optic photometers, an electro density microprobe, and two vacuum ultraviolet (VUV) photometers. The forward structure of the vehicle can be seen in Fig. 1, and the arrangement of detectors in the payload shown in Fig. 2. The spectrometer is used to measure the emission intensity as a function of the wavelengths within 200–400 nm. Photometers, as a redundancy and supplement to the spectrometer, are arranged with viewing angles of 0°, 30° and 50° from the vehicle centerline and used to individually detect spectra variations with the precession during flights. Each photometer is employed to identify spectral features of one particular molecule near the center wavelength λ_0, such as NO ($\lambda_0 = 215$ nm and 230 nm), OH radical ($\lambda_0 = 310$ nm) and N_2^+ ($\lambda_0 = 391$ nm). A series of spectral profiles of ultraviolet emissions created in the bow-shock layer, covering 38–70 km at 3.5 km/s and 100–65 km at 5.1 km/s, are available to validate computational models of radiation.

3. Numerical models

Broadly speaking, there are four parts to predicting the ultraviolet radiation emitted from high-temperature shock layers around a vehicle[13]: (1) flow field; (2) population of the exited electronic states; (3) spectra parameters; and (4) radiative transfer calculation. These can be obtained through three methods: multi-species thermo-chemical non-equilibrium fluid mechanics, multi-temperature non-equilibrium radiation modules, and radiative transfer calculation procedures.

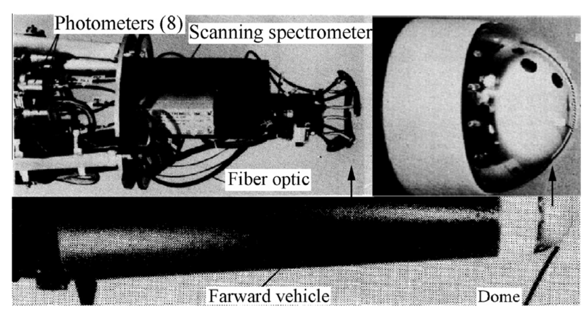

Fig. 1 Forward structure of missile and instruments for measuring the intensity of selected spectral features.

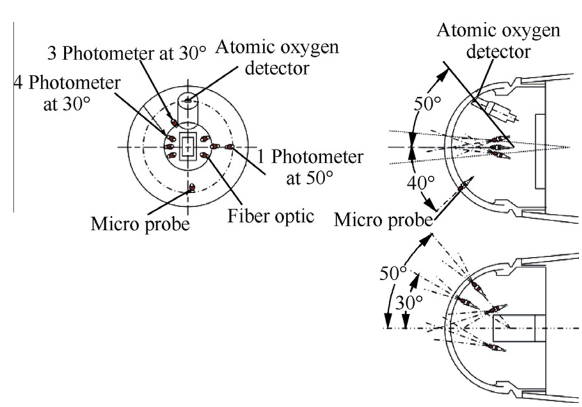

Fig. 2 The layout of BSUV's detectors from Ref.[5].