Prediction of Emission Spectra Captured by an Embedded Miniature Spectrometer in a Hypersonic Re-entry CubeSat

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Abstract: The coupled gas-phase and surface non-equilibrium kinetics present significant challenges in predicting the flow behavior downstream of the shock during the hypersonic re-entry of a flight unit. To address this, we developed an approach to design in-flight experiments that aim to collect scarce aerothermodynamic data related to chemical species rotational and vibrational temperatures, as well as their number densities.

1. Introduction

During hypersonic re-entry flight experiments, the flow behind the shock wave exhibits phenomena such as vibrational and electronic excitations, ionization, dissociation, and recombination [1]. These chemical processes significantly impact energy distribution among the flow internal degrees of freedom, altering its properties. Furthermore, the high-speed conditions result in short gas residence times, causing these reactions to often occur under non-equilibrium conditions. Current state-of-the-art kinetic models typically use two-temperature approximations to calculate most chemical reaction rate coefficients [1].

Here, we design CubeSat-based flight experiments to gather critical aerothermodynamic data. These experiments target the continuum flow regime at altitudes of 50–80 km and speeds of 4–8 km/s.

2. Methods

The flight test article is compact, fitting within a 10 cm × 10 cm × 30 cm volume, equivalent to a 1U × 3U CubeSat footprint. With a low mass of just a few kilograms, it can be transported beyond the Kármán line during missions such as International Space Station resupply flights. It is then deorbited from Low Earth Orbit using a drag skirt attached to its body. A MgF_2 window and a miniature spectrometer in the nosecone allow the recording of emission spectra during the hypersonic descent. After the blackout phase, the collected data is transmitted to the ground via radiolink.

Our approach involves using US3D [2] to simulate the flow around the flight unit in the continuum regime, predicting steady-state 2D profiles of species number densities, as well as vibrational and rotational temperatures. From these simulations, line-of-sight (LOS) integrated data are extracted at various viewing angles relative to the vehicle centerline. This data is then input into the non-equilibrium air radiation program (NEQAIR), which generates absolute spectral radiance spectra for each viewing angle.

3. Results and Discussion

Figure 1 shows sample spectra predicted by NEQAIR [3] for a flight unit with a 40 cm radius of curvature, cruising at 7 km/s at an altitude of 61 km, observed from three different viewing angles. The spectra reveal emissions

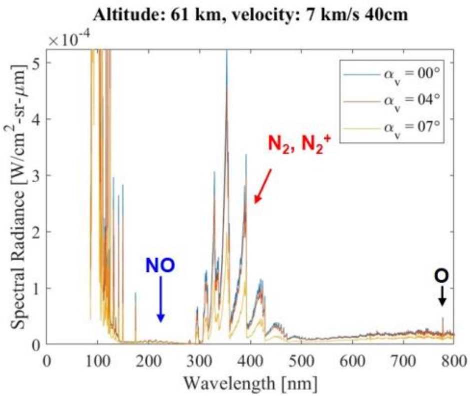

Fig. 1. Synthetic OES spectra predicted by NEQAIR and based on US3D simulations at different three viewing angles. Altitude = 61 km, speed = 7 km/s.

from NO, N_2, N_2^+, and O. These observations indicate that experimental measurements of such spectra could be used to determine the rotational and vibrational temperatures of these species, provided the predicted intensity matches the sensitivity of the detector and optical design. Notably, the emission intensity decreases with the viewing angle, suggesting that lower viewing angles are more suitable for maximizing the signal-to-noise ratio.

4. Conclusion

We have shown that our approach is suitable for designing hypersonic flight experiments. The full conference contribution will feature predicted spectra at various altitudes and speeds, along with an evaluation of optical designs for measuring the predicted absolute spectral radiances.

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