Spectral Model Reduction for Overlapping Radiative Systems during Hypersonic Entry

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The radiation field arising from photophysical and photochemical processes can significantly influence energy transfer and thermochemical composition in a range of scientific and engineering applications. The primary challenge while determining radiative transfer stems from the rapid fluctuations in emission/absorption properties with respect to frequency. Fundamental radiative transitions, namely bound-bound, bound-free, and free-free, in atomic and molecular species involve photons with specific energies. The resultant spectral dependence of spontaneous/stimulated emission and absorption coefficients is resolved by a hierarchy of models that typically offer a trade-off between fidelity and concomitant costs. The line-by-line (LBL) approach [1] provides an exact representation of radiative properties by employing a finely discretized spectral grid comprising of potentially millions of frequency points. Since computational costs scale with the number of individual frequencies, an LBL spectral description combined with the necessary spatial-angular discretization often renders complex three-dimensional (3D) simulations practically unfeasible. Narrow-band models [2] represent a step towards improving efficiency by appropriately averaging radiative properties across a narrow spectral range. However, the degree of coarsening performed on the spectral grid is still inadequate for enabling cost-effective analysis, especially with flow-radiation coupling, for large-scale problems.

The critical need to mitigate computational overheads has motivated the development of wide-band methods [2] that aggregate individual frequency points into fewer reduced-order groups. The transport equations governing group-wise radiative intensities are derived by integrating the monochromatic radiative transfer equations (RTE) over the frequency intervals contained within the group. While group-wise emission is simply a summation of frequency-wise contributions, formulating a closure for the group-averaged absorption coefficient necessitates knowledge of the unknown spectral intensity distribution. Previous work [3] by the author demonstrated that utilizing a simple Planck distribution for reconstructing the spectral intensity, often referred to as Planck-averaging, yields accurate results even for complex radiative problems owing to constrained entropy maximization. Furthermore, a newly proposed non-equilibrium grouping strategy, i.e., the rationale for dividing discrete frequency points into reduced-order groups, allowed both total quantities of interest as well as detailed spectral features to be predicted for different entry scenarios with up to two orders-of-magnitude speed-ups. Recent advances [4] have focused on evolving the requisite numerical framework for constructing independent reduced-order spectral databases. These databases inherently capture the physical dynamics of radiative transitions rather than relying on calibration against a constrained set of flow simulations. Consequently, such reduced-order models (ROMs) can be readily applied to a wide gamut of entry scenarios while maintain high levels of physical realism and computational efficiency. Another key challenge addressed in subsequent developments has been ensuring that ROMs can retain sufficient accuracy while tackling multiple radiative systems that overlap in the frequency domain. Modifications to the grouping methodology allows the interaction between disparate species to inform the model reduction while operating within the same numerical architecture designed for single-species ROMs.

The current work provides a detailed overview of the new non-equilibrium model reduction paradigm that is aimed at being gas flow-agnostic, allows non-Boltzmann internal state populations, and effectively processes spectral interplay between disparate species. The efficacy of these ROMs has been evaluated using both 1D lines-of-sight calculations and predictions of 3D radiative heat flux to entry vehicles. The investigation initially considers non-interacting radiative systems (N, CN-C_2, CO_2-CO) before advancing to a comprehensive treatment of Earth entry radiation (involving spectral overlap between N, O, and N_2). The ROM methodology consistently accelerates simulations by two to three orders-of-magnitude compared to full set predictions while reproducing both detailed frequency features and spectrally integrated total intensity/heat flux.

Bibliography

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