SEMINAR

Department of
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Kinetic Treatment of High-Speed Flows: Non-equilibrium, Thermochemistry and Stability Considerations

SPEAKER

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ABSTRACT

This talk presents a comprehensive kinetic treatment analysis of high-speed flows at high altitudes, emphasizing the critical role of high-fidelity numerical methods in capturing non-equilibrium phenomena and flow instabilities. The presentation is divided into two main parts: non-equilibrium thermochemistry and instability considerations to demonstrate the range of which the kinetic methods can be effective tools. The first part focuses on the modeling of hypersonic flows to study nitric oxide (NO) ultraviolet (UV) emissions, which serve as a rigorous test for high-fidelity thermochemical models for both laser measurements in ground test facilities and flight tests of hypersonic aircraft. Collisional radiative models are constructed to predict electronic quantum state populations which are crucial in determining the UV radiation characteristics of N2 and NO using quasi-steady-state (QSS) and overlay mass transport (MassTR) approaches applied to Direct Simulation Monte Carlo (DSMC) flowfields. The results demonstrate that coupling flow transport with the formation of electronic quantum states, a feature often simplified in lower-fidelity models, leads to significantly higher populations in expansion and wake regions and thus much higher radiation strength. Furthermore, the study highlights the sensitivity of NO emission profiles to oxygen dissociation models and vibrational favoring, underscoring the need for accurate kinetic descriptions in predicting radiation signatures. Accurately predicting these radiation signatures is essential for the design of thermal protection systems and communication blackout mitigation in spacecraft re-entering the atmosphere. The second part investigates flow unsteadiness and stability in high-speed compression ramp flows, a common geometry in supersonic and hypersonic vehicles. These flows feature complex interactions involving shocks, shear layers, and large separation bubbles that can trigger transition to turbulence, affecting heat transfer and structural integrity. Particle-kinetic DSMC is employed alongside data-driven methods, such as Spectral Proper Orthogonal Decomposition (SPOD), and continuum-based BiGlobal linear stability analysis. DSMC is particularly effective for its ability to resolve the detailed inner structure of shock layers and capture non-equilibrium effects that continuum methods may miss. This approach reveals key mechanisms of unsteadiness, such as reattachment shock oscillations and Kelvin-Helmholtz instabilities. Notably, a previously unknown traveling global mode is discovered at the leading edge, resolved only by kinetic simulations that capture internal shock structures. The talk will also cover the nonlinear evolution of these instabilities, documenting the formation of lambda vortices, hallmarks of the transitional process, seen for the first time in a kinetic simulation. Understanding these instability mechanisms is vital for predicting when airflow becomes turbulent, which can drastically increase surface heating and aerodynamic drag on hypersonic vehicles.

ABOUT THE SPEAKER

Irmak Taylan Karpuzcu is a PhD candidate in the Department of Aerospace Engineering at the University of Illinois at Urbana-Champaign, working under the supervision of Prof. Deborah Levin. He earned his Master of Science degree in Mechanical Engineering (2019) and his Bachelor of Science degree (2015) from Middle East Technical University, where he conducted his graduate research under the supervision of Prof. Cüneyt Sert. He is a certified graduate teacher and a MAVIS future faculty fellow. His research focuses on the numerical simulation of high-speed fluid flows, leveraging high-performance computing techniques. His master's work centered on modeling turbulence in supersonic flows using large eddy simulation. His initial PhD research focused on the non-equilibrium thermochemistry of hypersonic flows. Currently, his research involves investigating the stability of high-speed laminar flows at high altitudes using kinetic theory, linear stability analysis, and data-driven approaches.

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