Abstract #XXX *(to be filled by the organizers)*
Preferred Topics: **AEROFLIPHY**, **CFDMPS** *(3 maximum from the list of topics)*
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From First-Principles Physics to Massively Parallel Simulations: A High-Fidelity Plasma Tunnel Model for Hypersonic Flight Conditions

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Abstract

Advanced thermal protection systems are essential to ensure the safe re-entry of spacecraft, and their design and testing often require extensive campaigns in high-enthalpy wind tunnels that reproduce the extreme aerothermal environment encountered during hypersonic flight. However, the harsh conditions in these wind tunnels make it difficult to directly measure the thermophysical properties of the flow, and therefore, accurate characterization relies heavily on modeling anchored on limited experimental data. To address this challenge, high-fidelity models for plasma tunnels are essential.

This study presents a high-fidelity simulation of the plasma flow inside the Plasmatron X facility, a recent addition to the CHESS testing infrastructure at the University of Illinois. Our model incorporates the latest advances in non-equilibrium flow chemistry and thermophysical property modeling based on first-principles physics and uses state-of-the-art computational infrastructure to create a predictive model capable of massively parallel simulations with unprecedented physical fidelity. We have based our physical model on the Multi-group Maximum Entropy Method (MGME) developed at CHESS, and the CHESS kinetic database derived using electronic structure calculations, which has been validated against available experimental data. In addition, we use advanced algorithms to efficiently evaluate the rigorous Chapman-Enskog transport systems for modeling transport properties.

Our numerical simulation includes modeling the electromagnetic discharge, the flow physics in the torch and test section, radiation transport, and the interaction of the plasma with the ablative material sample. Each physics is described by a separate solver, with the plasma physics modeled using the HEGEL code, a three-dimensional finite volume solver for non-equilibrium plasmas, and the PLATO library, which provides thermodynamics, transport, and chemical properties. The electromagnetic field, radiation transfer, and thermal protection system (TPS) material samples are modeled using FLUX, MURP, and CHYPs, respectively. We use the preCICE library to couple these tools.

The predictions of the computational framework are compared against experimental results collected on the Plasmatron X facility and provide crucial insights into the behavior of thermal protection systems under extreme hypersonic flight conditions and can inform the design and testing of advanced thermal protection materials for spacecraft re-entry.

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