Modeling Heat Transfer and Scramjet Performance using Pareto-Efficient Combustion Modeling

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High-fidelity simulations of high-speed propulsion systems require accurate predictions of combustion physics and turbulence in the presence of compressible flow environments. However, the complexity of the chemical kinetics in conjunction with capturing flame-wall interaction pose significant challenges. Here, we present a Pareto-efficient combustion (PEC) framework to address these challenges. This framework dynamically partitions the computational domain into regions assigned to models of different fidelity subject to user-specified quantities of interest. With this, expensive finite-rate chemistry models are only employed in localized regions where it is necessary for accuracy, and low-order models are utilized in regions that comply with underlying model approximations. This partitioning technique is designed to minimize the predictive error in specific quantities of interest, which reflect the modeling goals of the simulation. This work extends the PEC framework to scramjet combustion, in which accurate prediction of heat release and wall heat flux are of interest. An error metric is presented which extends the classical PEC drift term to target the chemical energy and incorporates a measure of heat loss effects. This formulation is combined with domain decomposition algorithm which achieves optimal submodel assignment while maintaining low-cost parallelization. The framework is then applied to a scramjet simulation, in which the application of FRC modeling to only 10%-20% of the domain is sufficient to reduce modeling errors by more than 80% compared to a monolithic combustion simulation.