Designing Liquid Rocket Engine Injectors for Performance, Stability, and Cost

Overview

NASA is developing the Space Launch System (SLS) for crewed exploration missions beyond low Earth orbit. Marshall Space Flight Center (MSFC) is designing rocket engines for the SLS Advanced Booster (AB) concepts being developed to replace the Shuttle-derived solid rocket boosters. One AB concept uses large, Rocket-Propellant (RP)-fueled engines that pose significant design challenges. The injectors for these engines require high performance and stable operation while still meeting aggressive cost reduction goals for access to space. Historically, combustion stability problems have been a critical issue for such injector designs. Traditional, empirical injector design tools and methodologies, however, lack the ability to reliably predict complex injector dynamics that often lead to combustion stability. Reliance on these tools alone would likely result in an unaffordable test-fail-fix cycle for injector development.

Recently at MSFC, a massively parallel computational fluid dynamics (CFD) program was successfully applied in the SLS AB injector design process. High-fidelity reacting flow simulations were conducted for both single-element and seven-element representations of the full-scale injector. Data from the CFD simulations was then used to significantly augment and improve the empirical design tools, resulting in a high-performance, stable injector design.

Project Details

One SLS AB concept is a liquid rocket engine designed to run on O_2/RP propellants. An injector with elements designed to enable robust propellant mixing and combustion was simulated using the Loci-STREAM CFD program. This program features an extremely efficient parameterization of the hundreds of reactions that occur during the O_2/RP combustion. Multiple large, 3D, time-varying simulations of a single-element injector configuration were run to iteratively fine-tune the performance of the initial design. Then, a seven-element configuration was simulated to quantify the effects of enhanced intra-element mixing. Time-averaged data for heat release, pressure drops, and fluid properties were extracted from the CFD simulations and provided enhanced as inputs for the empirical tools used to assess combustion stability.

Results and Impact

The primary result of this effort is an injector design that meets packaging requirements, pressure budget, and performance requirements. The design, as modeled, also performs in a stable manner. The CFD simulations supplied critical data to the design and stability assessment process. Moreover, the CFD simulations provided greater amounts of, higher-fidelity data than would have been possible using traditional sub-scale hot fire testing. These types of detailed CFD simulations have the potential to help NASA reduce the cost of access to space by reducing reliance on costly full-scale hot fire testing. This effort represents MSFC's most extensive use to-date of high-fidelity CFD simulations to augment and improve the injector design process.

Role of High-End Computing (Why HPC Matters)

Access to thousands of processors on NASA's Pleiades supercomputer was a game changer for this project. These CFD simulations required large computational meshes on the order of 100 –350 million cells, and long run times at time steps of one microsecond or less. Despite their large size, these runs were routinely executed in less than two weeks on Pleiades using 2,000 – 4,000 processors. This remarkably quick turn-around time enabled the results to be used in a design cycle where multiple iterations must be accomplished in a relatively short time.

What's Next (optional)

The CFD simulation capability used for this project is relatively new and requires further validation. That validation data is currently being generated at the Air Force Research Laboratory and Purdue University. All of the validation simulations will be run on Pleiades to facilitate timely turn around. These data and CFD simulations will also be used to develop a process for quantitatively evaluating the CFD-generated improvements in the current design tools. This will shed light on the next steps to continue to improve the injector design process for propulsion systems for NASA's launch vehicles.

Douglas G. Westra, Jeffrey S. West, NASA Marshall Space Flight Center
douglas.g.westra@nasa.gov, jeffrey.s.west@nasa.gov
Space Exploration