National Aeronautics and Space Administration

Analysis of Hybrid Rocket Combustion Efficiency based on Laser Spectroscopy

Principal Investigator: Ashley Karp (353); Co-Investigators: Elizabeth Jens (353), Isabelle Sanders (University of California, Los Angeles), Mitchell Spearrin (University of California, Los Angeles)

Program: FY21 SURP   Strategic Focus Area: Micro-propulsion

Objectives

Main Project Goals

- Develop a new in-situ sensing method using laser absorption tomography techniques for quantitative, spatially-resolved temperature and species measurements in a hybrid combustion reaction layer
- Use the thermochemical imaging technique to investigate hybrid rocket motor design elements and assess/improve combustion efficiency

Annual Objectives

2019 Develop in situ sensing method to visualize thermochemical structure (species, temperature) of a hybrid rocket reaction layer

2020 Investigate hybrid combustion under varying injector design / conditions via quantitative thermochemical imaging → improve c*

2021 Expand measurement capability to take in-chamber thermochemical measurements at elevated pressures

Background

Hybrid Rocket Combustion

- Hybrid rocket motor have potential performance, safety, and cost advantages over purely liquid- or solid-propellant rockets and are, thus, attractive for new space propulsion applications [1]–[3]
- Implementation of large-scale hybrid rocket systems has been hindered by sub-optimal combustion performance due to poor mixing [4]. These challenges have motivated research into varied hybrid rocket motor designs to improve the combustion performance

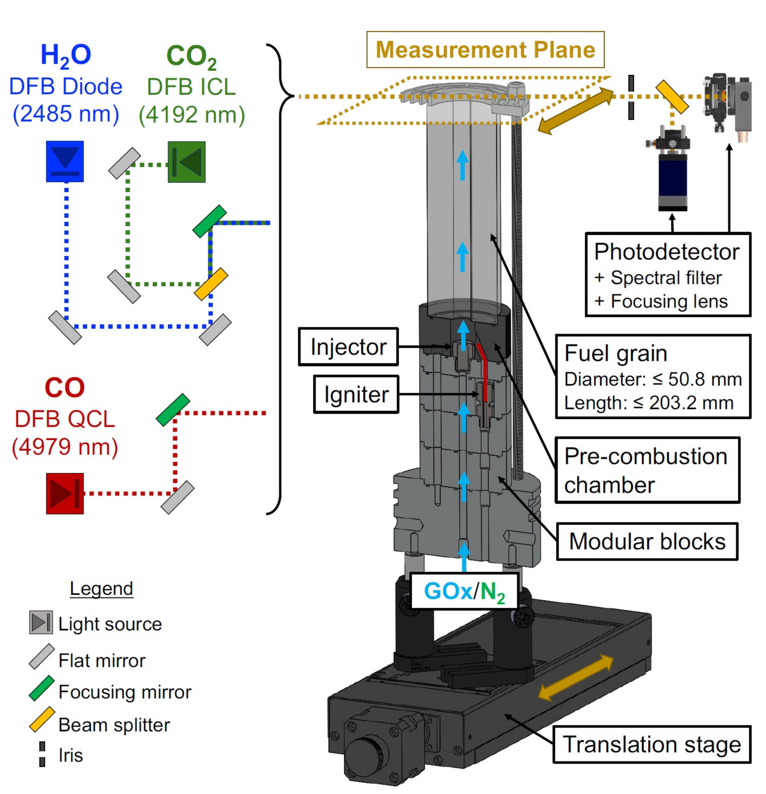

Figure 1: Vertical test stand utilized for exit-plane thermochemical measurements.

Combustion Performance/ c* Efficiency

- Combustion performance is typically quantified by the characteristic velocity (c*) efficiency. c* efficiency is typically determined via measurements of chamber pressure and mass flow rate; however, these global parameters do not capture more complex processes and they do little to inform the specific loss mechanisms that may lead to suboptimal performance
- A more detailed assessment of the thermochemical structure in the combustion zone is needed to better understand and improve upon current hybrid rocket performance

Project Background

- The test facility and imaging technique developed through this project have enabled spatially-resolved assessment of the combustion progress
- Employed developed method to examine comparative influence of geometric motor design variations. Application of the method has been particularly focused on the oxidizer injector design given its significant effects on the initial transport dynamics that govern turbulent mixing, viscous wall shear, and diffusion, and ultimately performance.

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

Approach and FY2021 Results

Thermochemical imaging to investigate swirl injectors to assess relative performance and swirling flow effects

- Hybrid rocket oxidizer injectors with variable initial swirl to axial velocity ratios were designed and manufactured to evaluate their influence on combustion zone development with PMMA
- Spatially-resolved thermochemical results indicate that improved performance from swirling inlet flow is largely contained to a region immediately downstream of injection with low L/D ratios

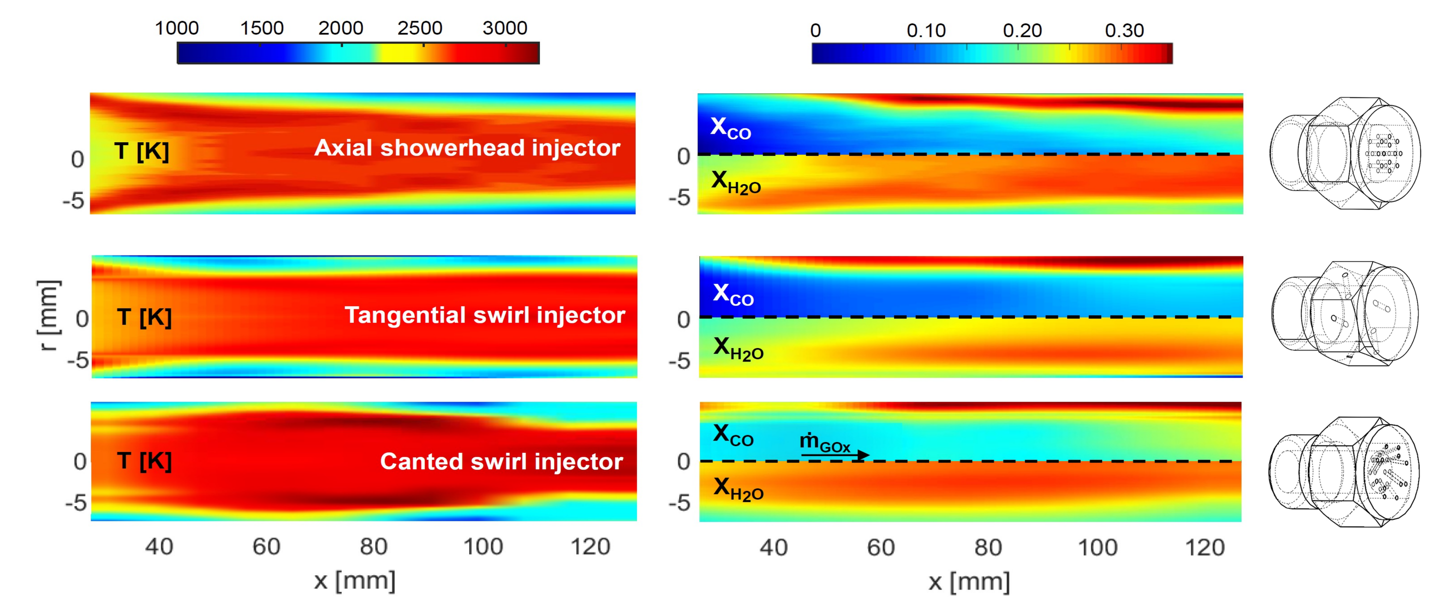

Figure 2: Two-dimensional thermochemistry measurements demonstrating combustion progress in the axial showerhead, tangential swirl, and canted swirl injectors

Obtain localized characteristic velocity (c*) based on gas temperature and composition measurements to assess hybrid combustion

- A method for experimentally determining a local c* was developed to analyze rocket combustion progress based on spectroscopic measurements of temperature and gas composition.
- Measuring c* from spatially-varying thermochemical provides insight into the underlying mechanisms governing combustion performance.

$$c^* = \sqrt{\left[\frac{\gamma+1}{2}\right]^{\frac{\gamma+1}{\gamma-1}} \frac{\bar{R}T_{0c}}{\bar{M}\gamma}}$$

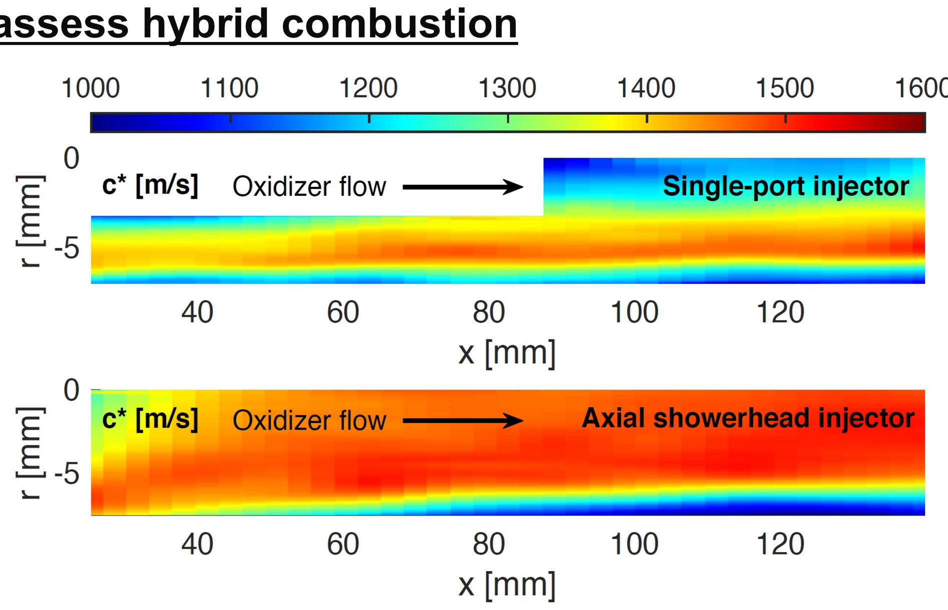

Figure 3: Spatially-resolved c* measurements for two injector geometries (single-port, axial showerhead) in a PMMA/O_2(g) hybrid rocket combustion experiment.

Extend the thermochemical imaging technique to higher pressures

- A post-combustion chamber with optical access was designed to extend the pressure capability of the developed method for spatially-resolving the thermochemical structure of hybrid PMMA combustion
- In-chamber measurements at elevated pressures of (2-10 bar) will result in a novel data-set at conditions relevant to hybrid rockets that can demonstrate the pressure-dependance of the flow field

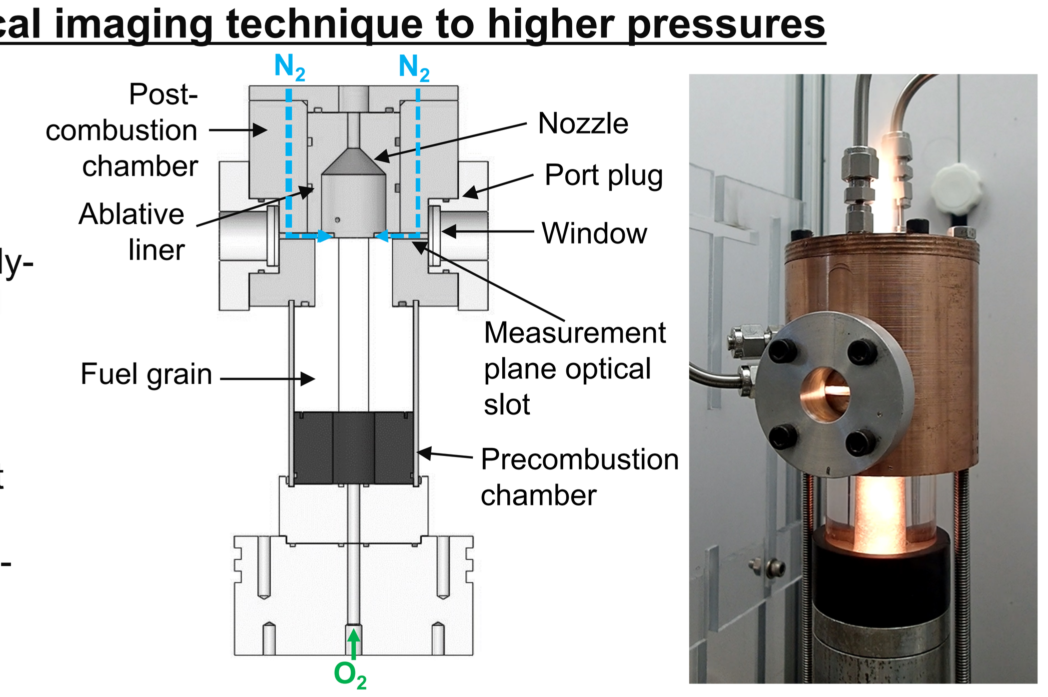

Figure 4: Diagram and hot fire image of test facility for high pressure hybrid combustion measurements with optical access.

PI/Task Mgr Contact
Email: Ashley.C.Karp@jpl.nasa.gov

Significance

- The results from this partnership are the first in-situ quantitative 2D measurements of temperature and species (CO, CO_2, H_2O) in the oxidation layer of a hybrid rocket fuel
- Spatially-resolved thermochemical measurement studies of both axial and swirl injection effects illustrated the importance of the oxidizer injector in hybrid rocket combustion performance particularly in the region immediately downstream of the injection point
- Extended capability to obtain measurements at elevated pressures provides additional insight into the pressure dependence of the flow field

Benefits to JPL and NASA

- The technique developed in this study can be implemented to better understand hybrid rocket performance as it relates to SmallSats being developed at JPL
- It is envisioned that results from this method could be used to constrain complex multi-physics models of solid-fuel oxidation and inform design considerations for hybrid rocket motors and extended to other propulsion systems under development
- Results from this work have also been used to anchor computational results from a PDRDF modeling PMMA combustion.

Publications

A. Bendana, F. A., Castillo, J. J., Hagström, C. G., & Spearrin, R. M. (2019). Thermochemical structure of a hybrid rocket reaction layer based on laser absorption tomography. In AIAA Propulsion and Energy 2019 Forum. https://doi.org/10.2514/6.2019-4337

B. Bendana, F. A., Sanders, I. C., Castillo, J. J., Hagström, C. G., Pineda, D. I., & Spearrin, R. M. (2020). In-situ Thermochemical Analysis of Hybrid Rocket Fuel Oxidation via Laser Absorption Tomography of CO, CO2, and H2O. Experiments in Fluids, 61(9), 190. https://doi.org/10.1007/s00348-020-03004-7

C. Sanders, I. C., Bendana, F. A., Hagstrom, C., & Spearrin, R. M. (2020). Assessing oxidizer injector design via thermochemical imaging of PMMA combustion in a hybrid rocket motor geometry. In AIAA Propulsion and Energy 2020 Forum. https://doi.org/10.2514/6.2020-3747

D. Sanders, I. C., Bendana, F. A., Hagström, C. G., & Spearrin, R. M. (2021). Injector effects on hybrid polymethylmethacrylate combustion assessed by thermochemical imaging. Journal of Propulsion and Power (Article in Advance). https://doi.org/10.2514/1.B38316

E. Bendana, F. A., Sanders, I. C., Stacy, N. G., & Spearrin, R. M. (2021). Localized characteristic velocity (c*) for rocket combustion analysis based on gas temperature and composition via laser absorption spectroscopy. Measurement Science and Technology, 32(12). https://doi.org/10.1088/1361-6501/ac18d3

F. Sanders, I. C., Bendana, F. A., Stacy, N. G., Schwarm, K. K., & Spearrin, R. M. (2021). Swirl Injection in Hybrid Polymethylmethacrylate Combustion Assessed by Thermochemical Imaging. In AIAA Propulsion and Energy 2021 Forum. https://doi.org/10.2514/6.2021-3513

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[2] E. T. Jens, B. J. Cantwell, and G. S. Hubbard, "Hybrid rocket propulsion systems for outer planet exploration missions," *Acta Astronaut.*, vol. 128, pp. 119–130, Nov. 2016.

[3] R. W. Conversano, J. Rabinovitch, N. J. Strange, N. Arora, E. Jens, and A. C. Karp, "SmallSat Missions Enabled by Paired Low- Thrust Hybrid Rocket and Low-Power Long-Life Hall Thruster," in *2019 IEEE Aerospace Conference*, 2019, vol. 2019-March, pp. 1–8.

[4] A. Karabeyoglu, "Challenges in the Development of Large-Scale Hybrid Rockets," *Int. J. Energ. Mater. Chem. Propuls.*, vol. 16, no. 3, pp. 243–261, 2017.

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