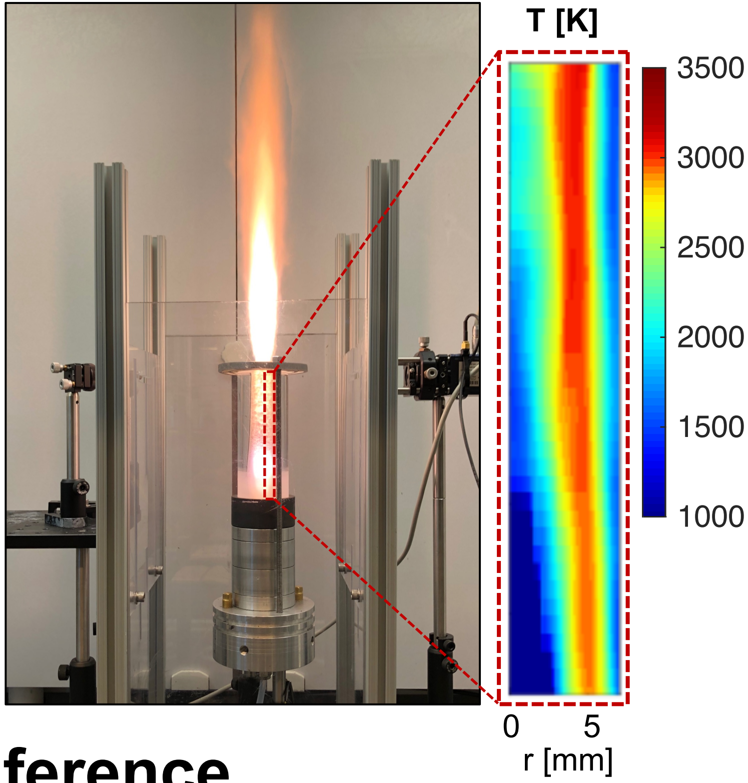
RPC 2020



Virtual Research Presentation Conference

Analysis of hybrid rocket combustion efficiency based on laser spectroscopy

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Students: Fabio Bendana (UCLA), Isabelle Sanders (UCLA), China Hagström (UCLA)
Program: SURP

Assigned Presentation #RPC-241

Jet Propulsion Laboratory
California Institute of Technology

Tutorial Introduction

Project Goals

A. Develop new in-situ sensing method to visualize the thermochemical structure (temperature, species) of a hybrid rocket combustor

B. Investigate hybrid combustion under varying design parameters / conditions through quantitative thermochemical imaging → improve performance

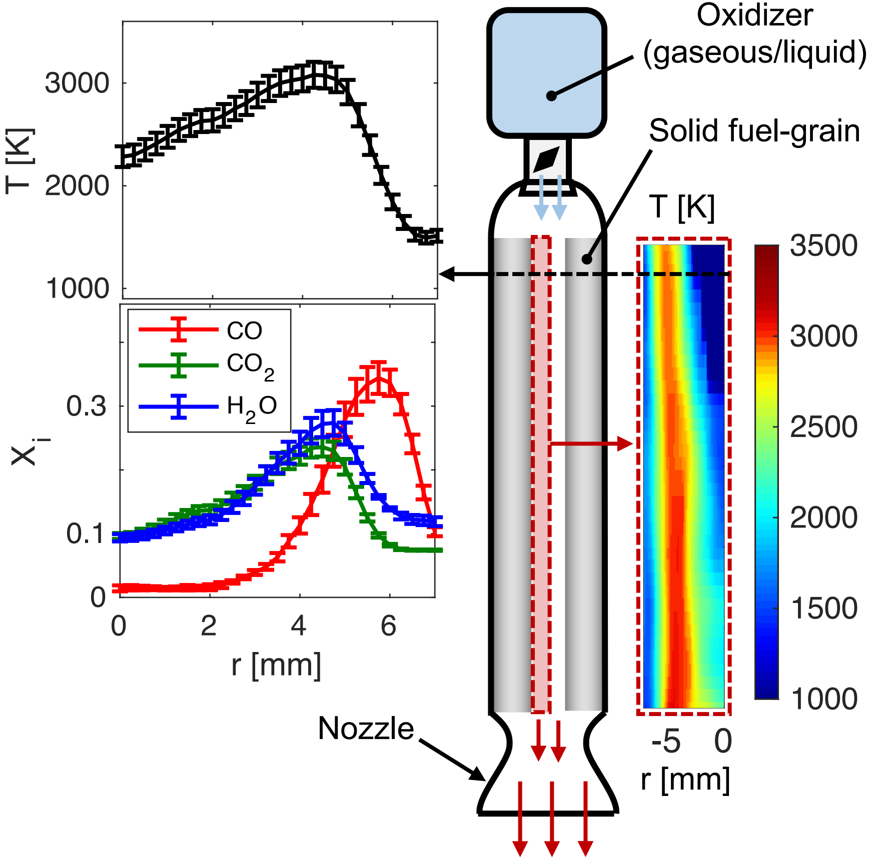
Achievements

- Developed/built modular hybrid rocket fuel combustion experiment at UCLA with optical access, remote operation
- Demonstrated novel laser absorption tomography (LAT) method for in-situ measurements of CO, CO_2, H_2O, and temperature
- Characterized the effects of oxidizer injector geometry on PMMA combustion using single-port and showerhead designs

Key Takeaways

1. **New technique provides a quantitative way of evaluating the performance impacts of different hybrid motor designs**
2. **Experimental results suggest injector design has a significant impact on hybrid combustion behavior**

Hybrid Rocket Combustion

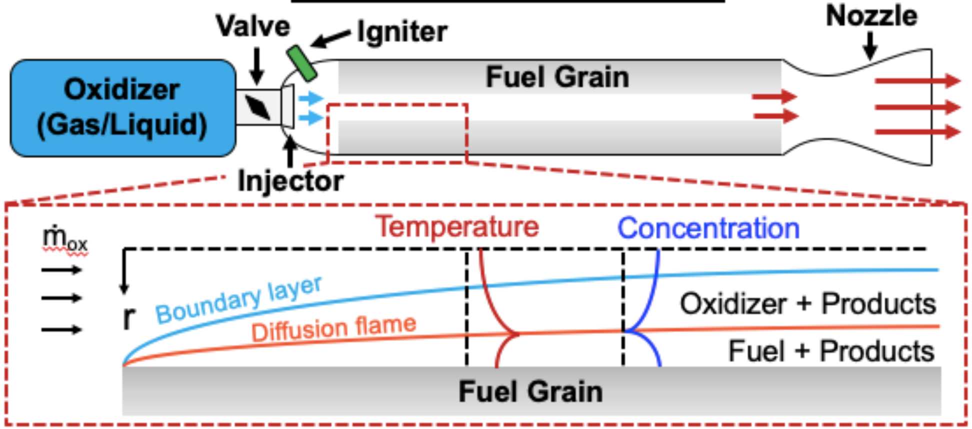


Problem Description

Motivation: Improve cost, safety, and performance of space propulsion systems for future interplanetary exploration missions, including SmallSats and a Mars Ascent Vehicle (MAV) → hybrid rockets

Challenges: Hybrid rocket technology currently exhibits sub-optimal combustion performance

Hybrid Rocket Combustion



Quantifying combustion performance

$$u_{eq} = gI_{sp} = \underset{\downarrow}{c^*} C_F$$

Chemical → Thermal

$$c^* = \frac{p_0 A^*}{\dot{m}} = \sqrt{\left[\frac{\gamma+1}{2}\right]^{\frac{\gamma+1}{\gamma-1}} \frac{\bar{R} T_{0c}}{\bar{M}\gamma}}$$

- Conventional method of assessing combustion performance is through chamber pressure (p_0) and mass flow rate ($\dot{m}$) measurements
  - p_0 and $\dot{m}$ are indirect aggregate metrics of complex combustion processes
- Combustion temperature (T_{0c}) and species ($\bar{M}$, γ) evolve spatially and directly reflect chemical-to-thermal energy conversion

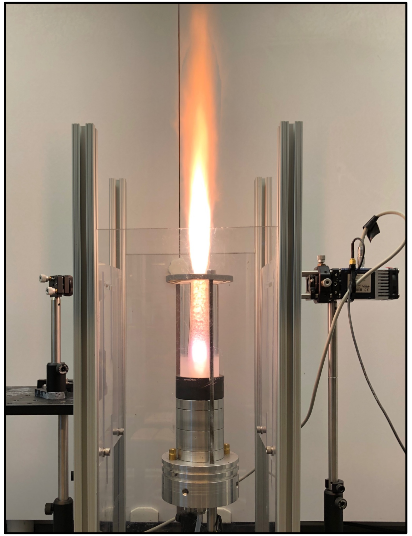
Objective: Provide insights into hybrid rocket combustion physics and reveal opportunities for improved performance / efficiency

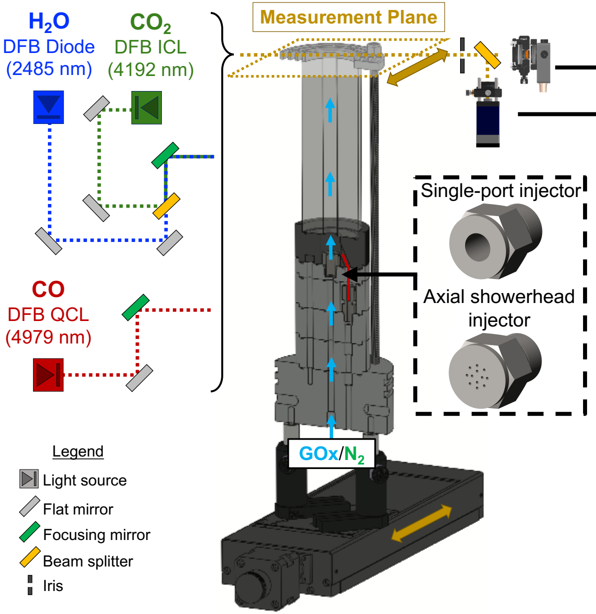
Methodology

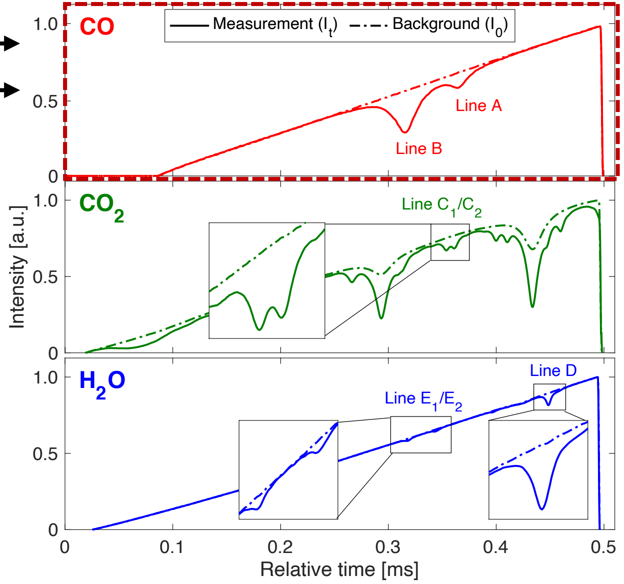
Approach: Use laser absorption spectroscopy to investigate hybrid rocket combustion → **improve c***

- In-situ sensing of temperatures and species (**CO**, **CO_2**, **H_2O**) measurements over varying fuel-grain lengths
- Investigate injector effects on hybrid rocket combustion behavior for PMMA/GOx

UCLA: Hybrid test rig
(atmospheric measurements)







Methodology

Approach: Use laser absorption spectroscopy to investigate hybrid rocket combustion

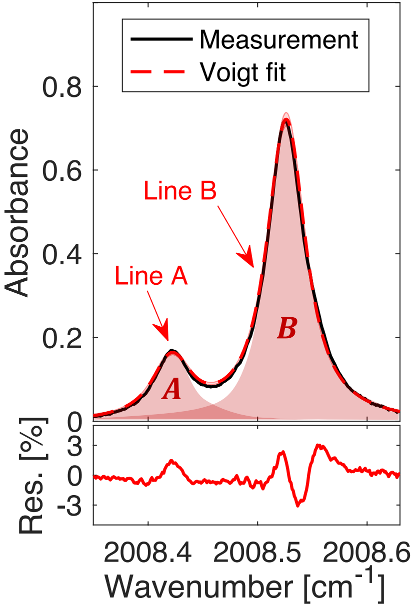
- Utilize absorption tomography for spatially-resolved thermochemistry

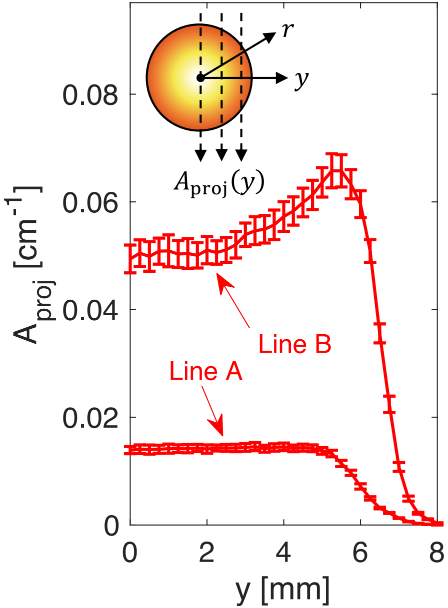
$$\alpha = -\ln\left(\frac{I_t}{I_0}\right) = \int_0^L S(T(l))X_i(l)P\phi_\nu \mathrm{d}l \rightarrow \int \alpha \mathrm{d}\nu = \boldsymbol{A_{proj}(y)} = \int_0^{L(y)} K(l)\mathrm{d}l = 2\int_y^R \frac{\boldsymbol{K(r)}r}{\sqrt{r^2-y^2}}\mathrm{d}r$$

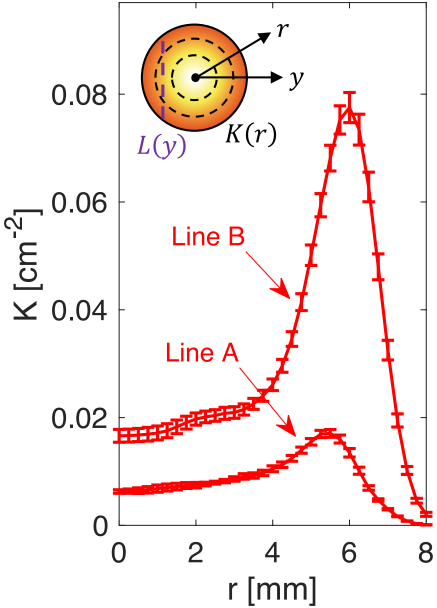
Two-line thermometry

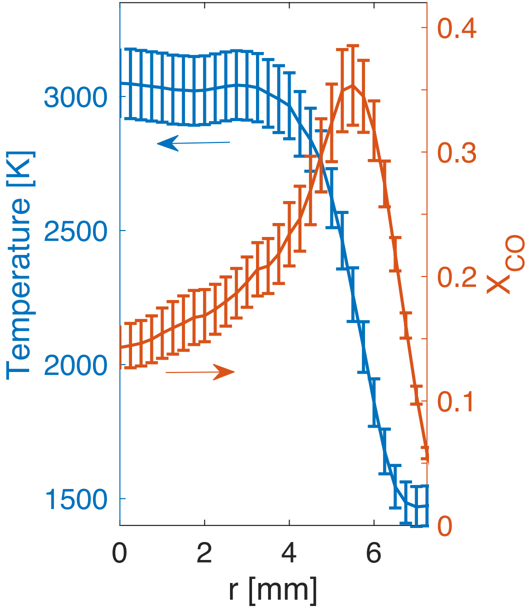
$$\frac{K_B(r)}{K_A(r)} = \frac{S_B(\boldsymbol{T(r)})\cancel{\boldsymbol{X_{CO}(r)}P}}{S_A(\boldsymbol{T(r)})\cancel{\boldsymbol{X_{CO}(r)}P}} = f(\boldsymbol{T(r)})$$

$$\boldsymbol{X_{CO}(r)} = \frac{K_A(r)}{S_A(\boldsymbol{T(r)})P} = \frac{K_B(r)}{S_B(\boldsymbol{T(r)})P}$$

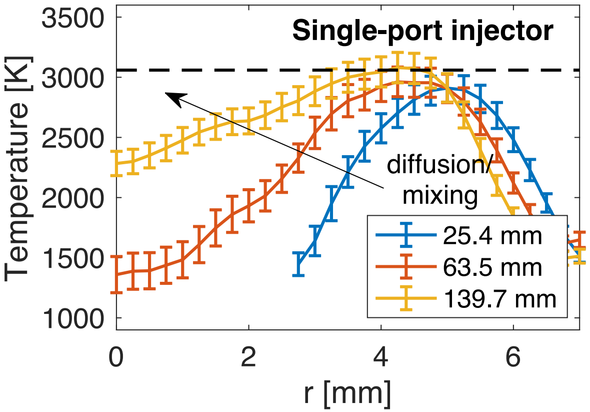


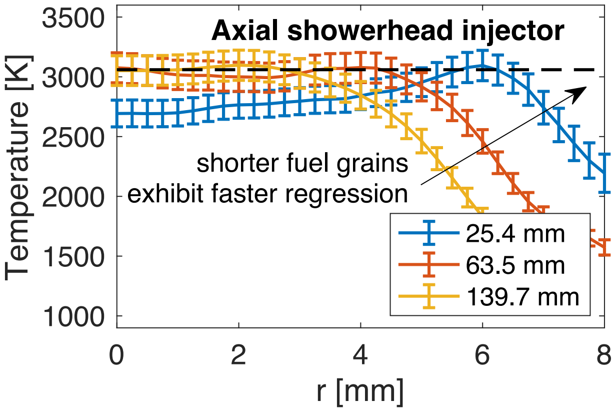


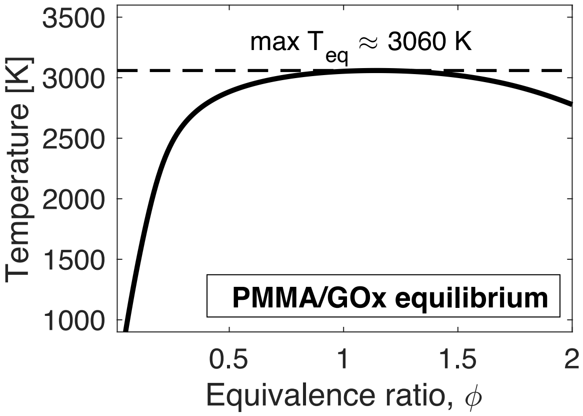


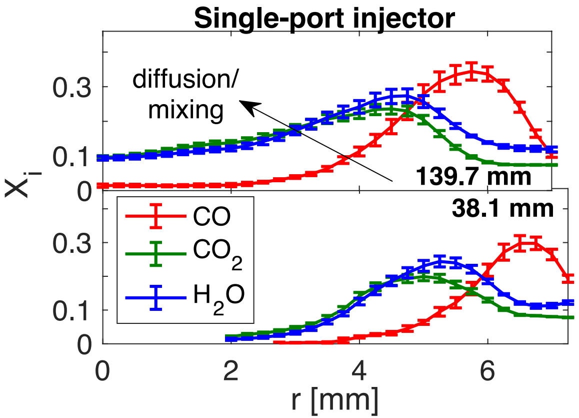


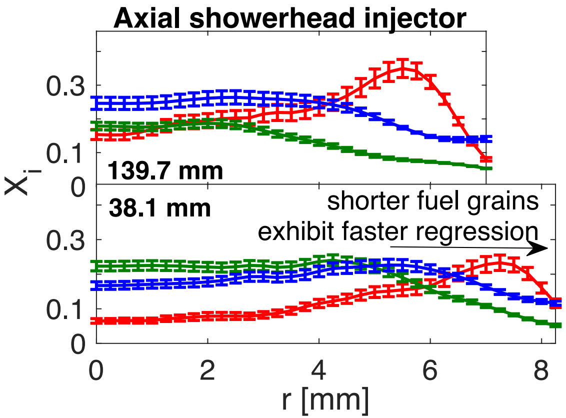
Results


Single-port injector
Temperature [K]
3500
3000
2500
2000
1500
1000
0
2
4
6
r [mm]
diffusion/
mixing
25.4 mm
63.5 mm
139.7 mm


Axial showerhead injector
Temperature [K]
3500
3000
2500
2000
1500
1000
0
2
4
6
8
r [mm]
shorter fuel grains
exhibit faster regression
25.4 mm
63.5 mm
139.7 mm


max $T_{eq} \approx 3060$ K
Temperature [K]
3500
3000
2500
2000
1500
1000
0.5
1
1.5
2
Equivalence ratio, ϕ
PMMA/GOx equilibrium


Single-port injector
X_i
0.3
0.1
0
diffusion/
mixing
139.7 mm
38.1 mm
CO
CO_2
H_2O
0
2
4
6
r [mm]


Axial showerhead injector
X_i
0.3
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0
139.7 mm
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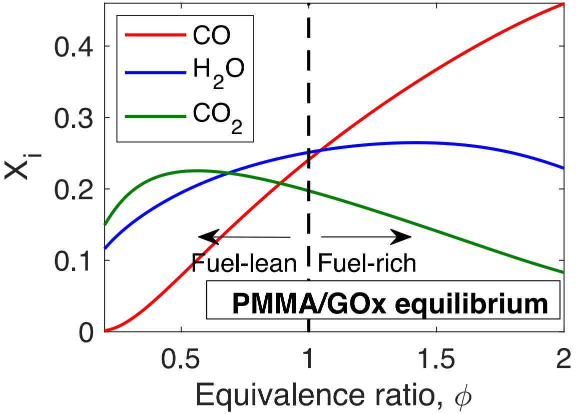
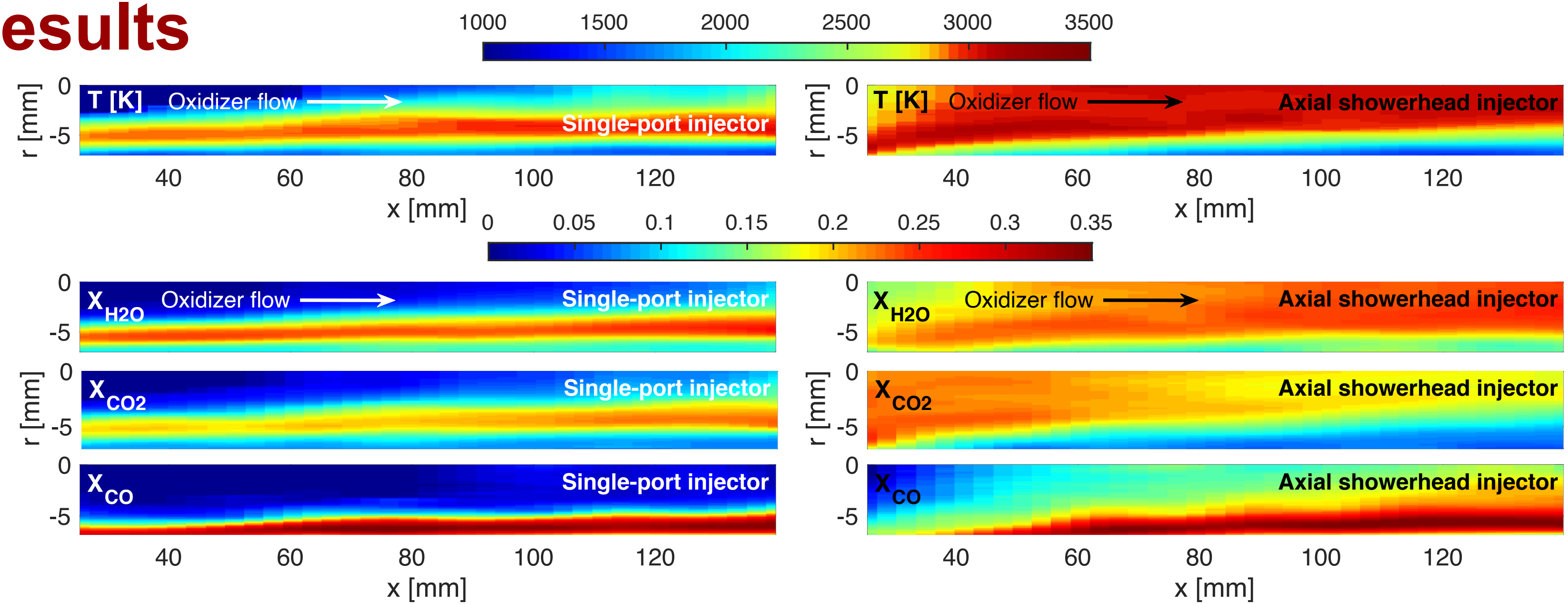
shorter fuel grains
exhibit faster regression
0
2
4
6
8
r [mm]


CO
H_2O
CO_2
X_i
0.4
0.3
0.2
0.1
0
Fuel-lean
Fuel-rich
PMMA/GOx equilibrium
0.5
1
1.5
2
Equivalence ratio, ϕ

Results



Accomplishments: **(1) Spatially-quantified combustion progress and (2) demonstrated the sensitivity of oxidizer injector geometry on PMMA combustion**

- Efforts aim to increase hybrid rocket TRL by identifying mechanisms that may lead to suboptimal performance
- Thermochemistry provides a basis for characterizing performance impacts of different motor designs under consideration for interplanetary SmallSats and a Mars Ascent Vehicle (MAV)
- Next steps: Investigate new injector/fuel-grain geometries that promote mixing and extend imaging technique to higher pressures (20 bar)

Publications

1. 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
2. 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, CO_2, and H_2O. Experiments in Fluids, 61(9), 190. https://doi.org/10.1007/s00348-020-03004-7
3. 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
4. Sanders, I. C., Bendana, F. A., Hagström, C. G., & Spearrin, R. M. (2020) Injector effects on hybrid polymethylmethacrylate combustion assessed by thermochemical imaging. Journal of Propulsion and Power. (Under review).

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1. Karp, A. C., Nakazono, B., Story, G., Chaffin, J., & Zilliac, G. (2019). Hybrid Propulsion Technology Development for a Potential Near- Term Mars Ascent Vehicle. In 2019 IEEE Aerospace Conference. https://doi.org/10.1109/AERO.2019.8741854
2. Jens, E. T., Cantwell, B. J., & Hubbard, G. S. (2016). Hybrid rocket Propulsion Systems for Outer Planet Exploration Missions. *Acta Astronautica*, *128*, 119–130. https://doi.org/10.1016/j.actaastro.2016.06.036
3. Conversano, R. W., Rabinovitch, J., Strange, N. J., Arora, N., Jens, E., & Karp, A. C. (2019). SmallSat Missions Enabled by Paired Low- Thrust Hybrid Rocket and Low-Power Long-Life Hall Thruster. In 2019 IEEE Aerospace Conference. https://doi.org/10.1109/AERO.2019.8741678