Development and Evaluation of a Novel Fuel Injector Design Method using Hybrid-Additive Manufacturing

Project DE-FE12806463, Oct. 2019 – Sept. 2022 (Sept. 2024 NCE)
Program Monitor: Mark Freeman

Project Review – October 30, 2023

PIs: Jacqueline O'Connor, Guha Manogharan, Yuan Xuan
Graduate students: Sagar Jalui, Pratikshya Mohanty

Mechanical Engineering
Pennsylvania State University

Industry Partner: Solar Turbines Incorporated
Engineers: Hanjie Lee, Michel Akiki, Dang Le

Overview of presentation

- Background and technical approach
- Highlights from this year
  - Geometry optimization for flashback
  - Understanding flow stability
- Next steps
- Publications and outreach

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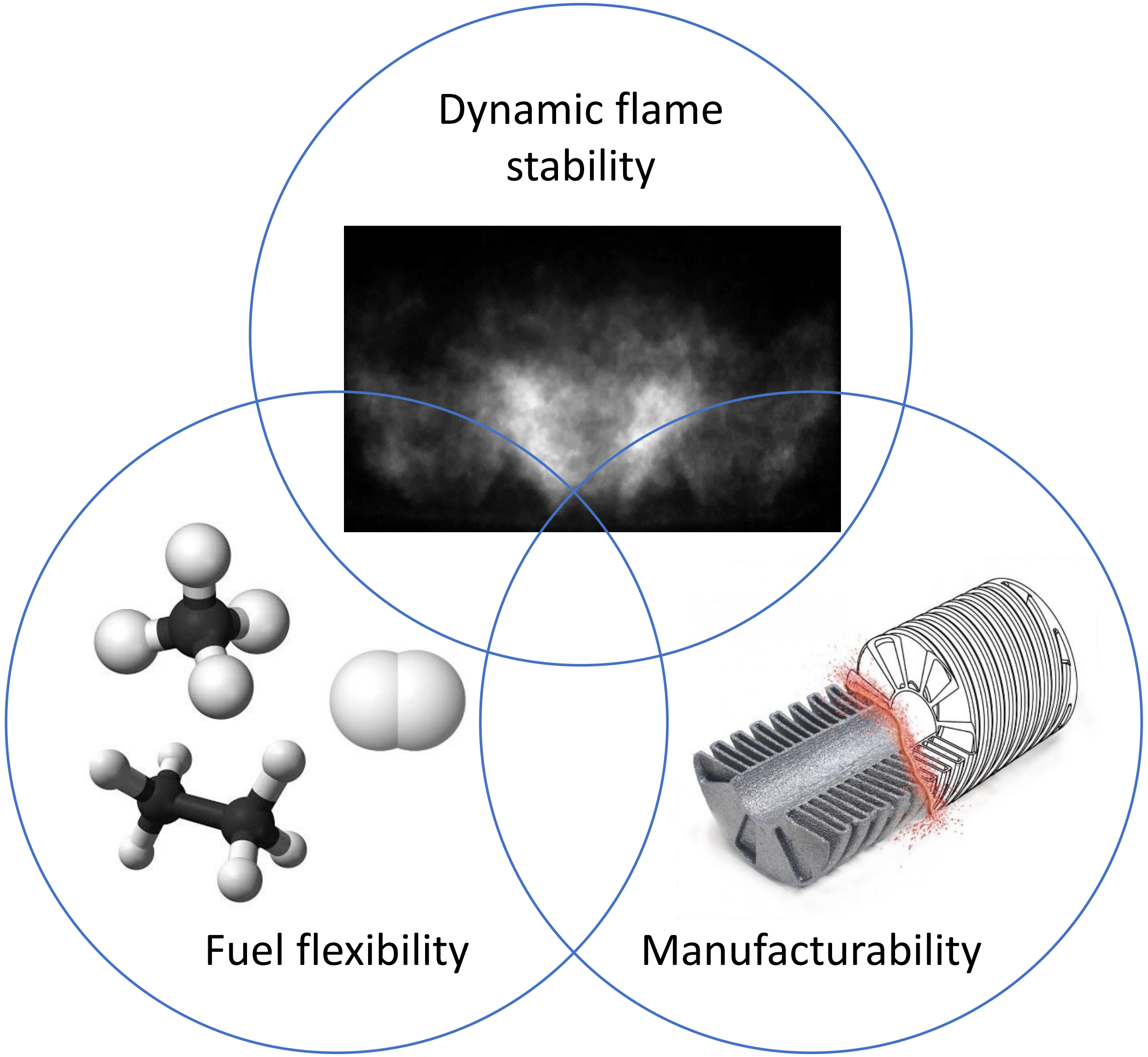
Project origin: Discussions with industry about issues related to combustion operability and fuel injector manufacturing

"Why do fuel injectors have to look like fuel injectors?"

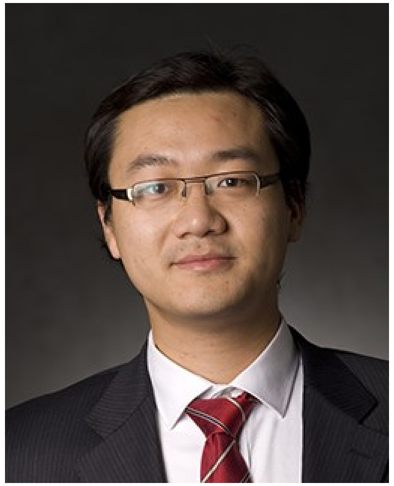
Goal of this project is to create a design optimization paradigm that marries combustion physics and manufacturing



The team is comprised of three PIs and two grad students from Penn State and industrial partners Solar Turbines

PI: Jacqueline O'Connor
Professor of ME
Combustion/Gas Turbines

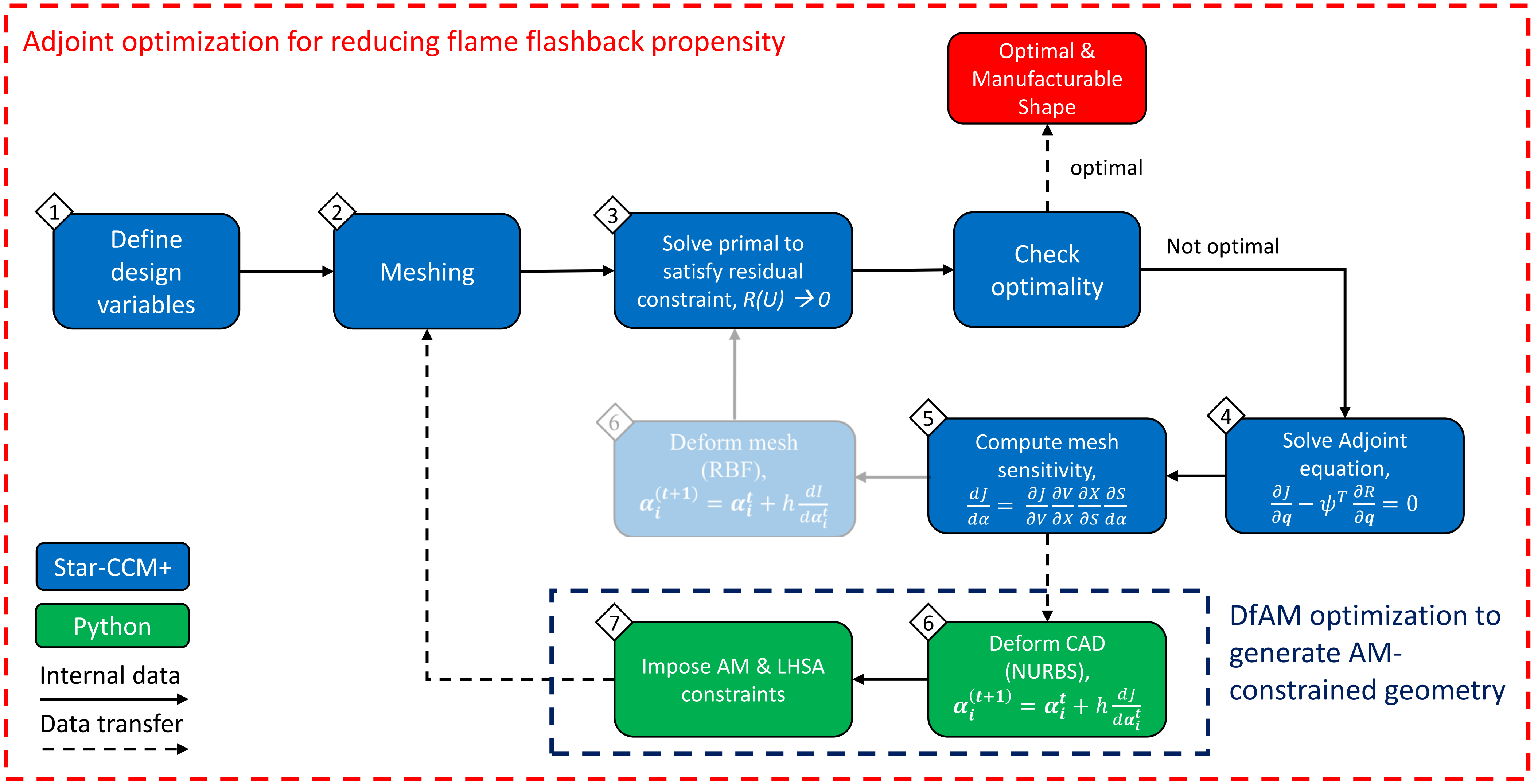
Co-PI: Guha Manogharan
Associate Professor of ME, IME
Hybrid-Additive Manufacturing



Co-PI: Yuan Xuan
Associate Professor of ME
Combustion simulation

Solar® Turbines
A Caterpillar Company

Technical approach uses an optimization framework for incorporating combustion and manufacturing constraints

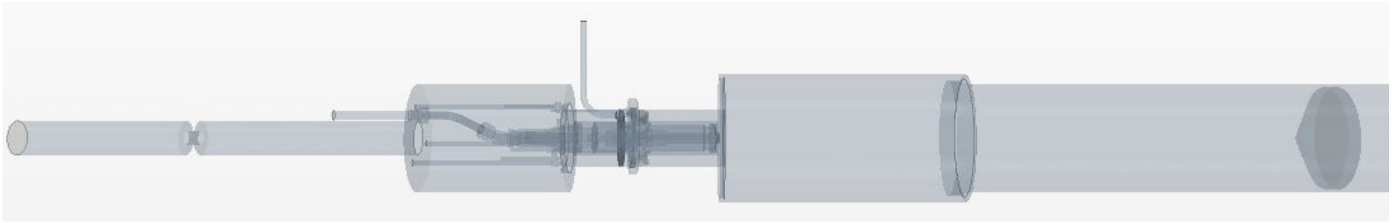


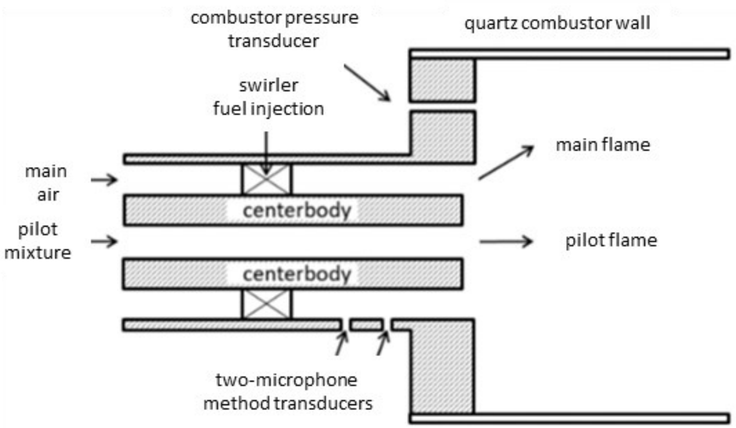
High-fidelity combustion simulation uses STAR-CCM+ to allow more rapid industry adoption

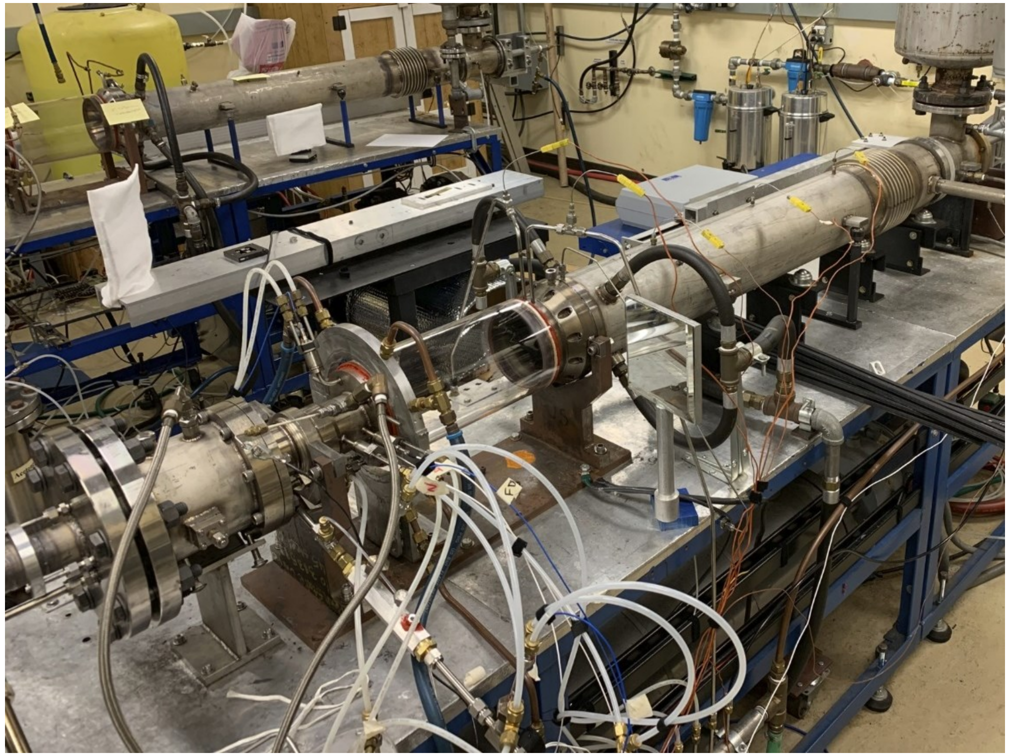
— Large eddy simulation (LES) using STAR-CCM+

— Flamelet generated manifold (FGM) model

— Unstructured polyhedral mesh (~16.7 million cells)







Project objectives center around four gaps in the fuel injector design process to help industry

- Integrate issues related to flame static and dynamic stability more seamlessly into the design process

- Incorporate the use of hydrodynamic stability analysis for prediction of dynamic stability issues for efficient computational prediction

- Incorporate high-fidelity, multi-physics modeling into optimization processes

- Link post-processing steps of the AM component into the design optimization process

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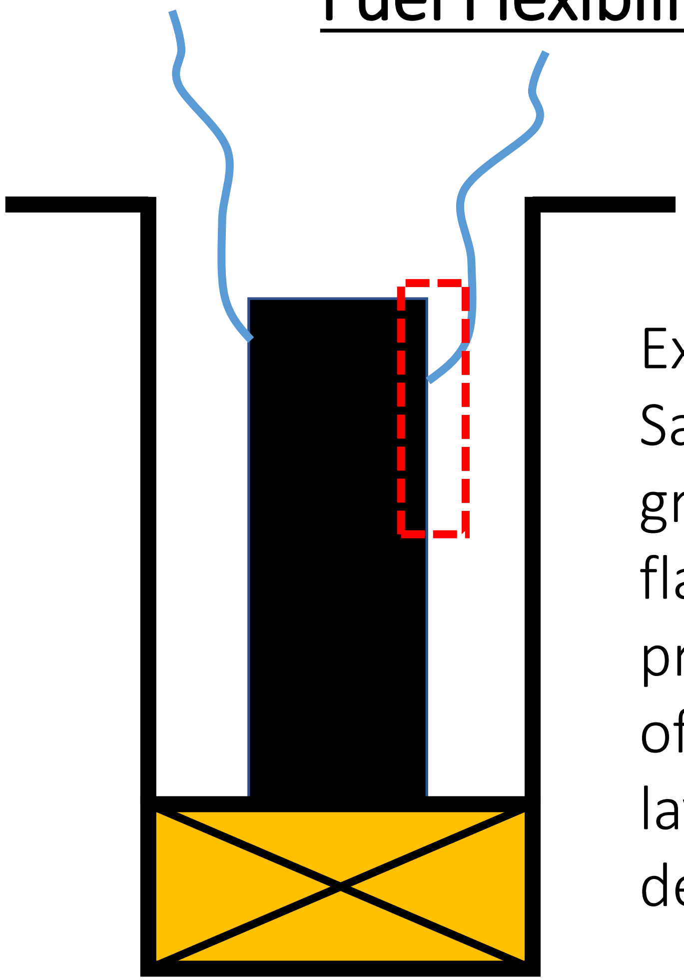
This year's work has focused on integrating the optimization for fuel flexibility and the AM constraints into one workflow

Fuel Flexibility



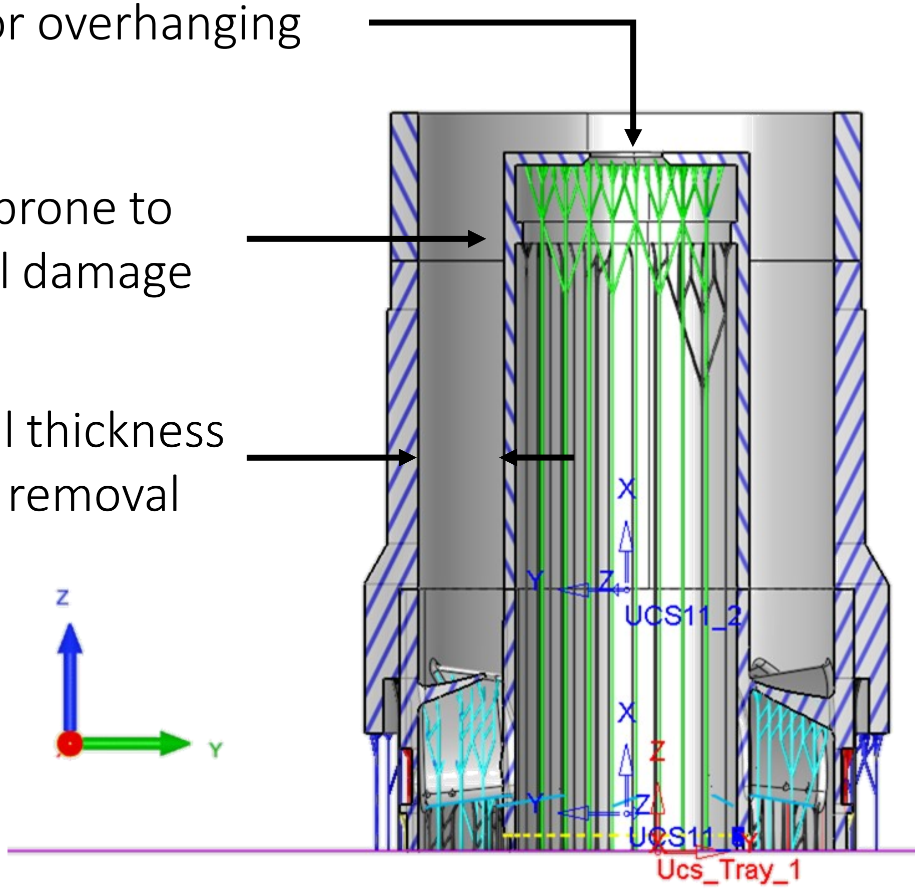
Extend theory by Sattelmayer’s group to predict flashback propensity based off boundary layer development

AM Constraints

Support structures required for overhanging areas

Thin walls prone to mechanical damage

Wall-to-wall thickness for powder removal

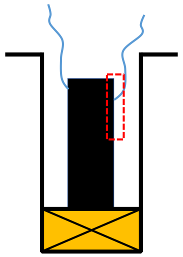


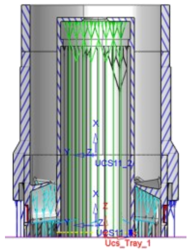
The dual objective function is enabled through a two-stage optimization that runs both within StarCCM+ and outside it

Optimization 1 (larger loop)

Adjoint shape optimization

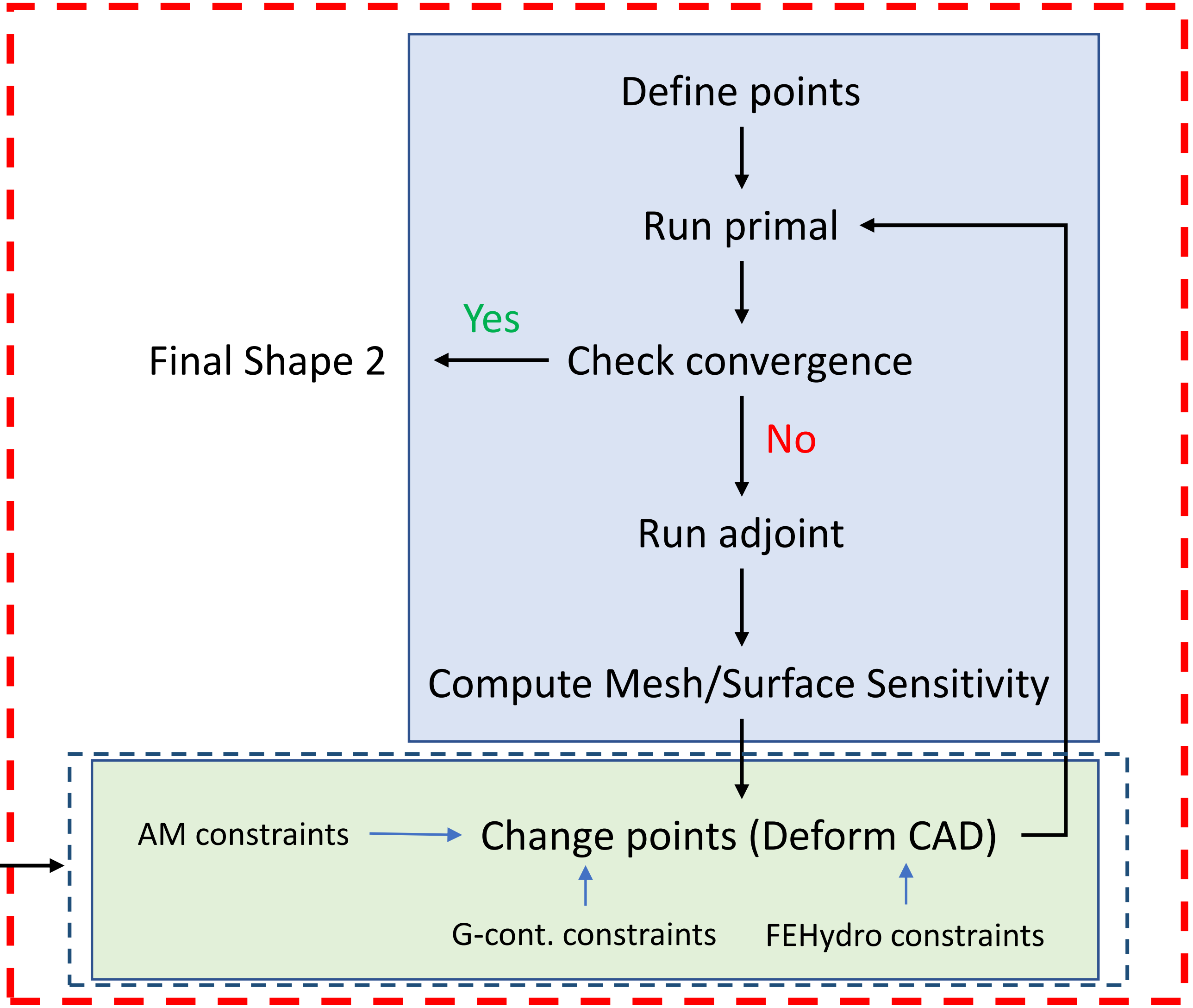
Fuel flexibility



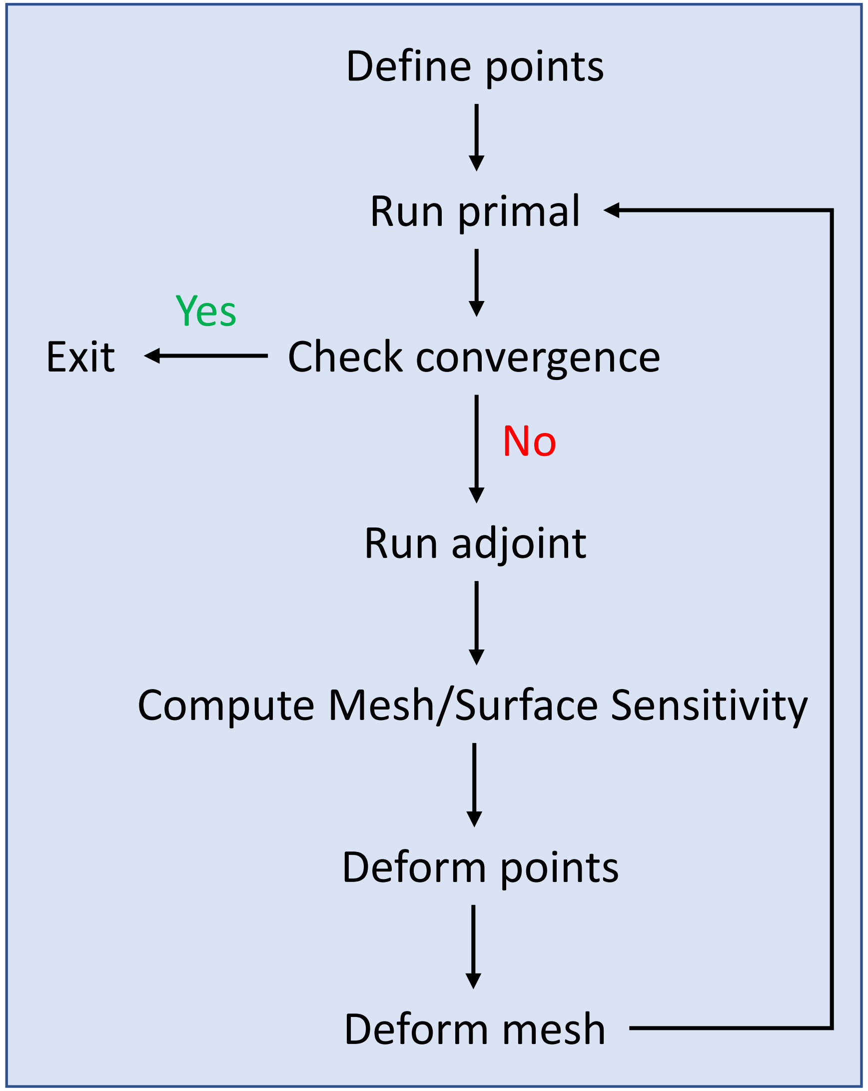


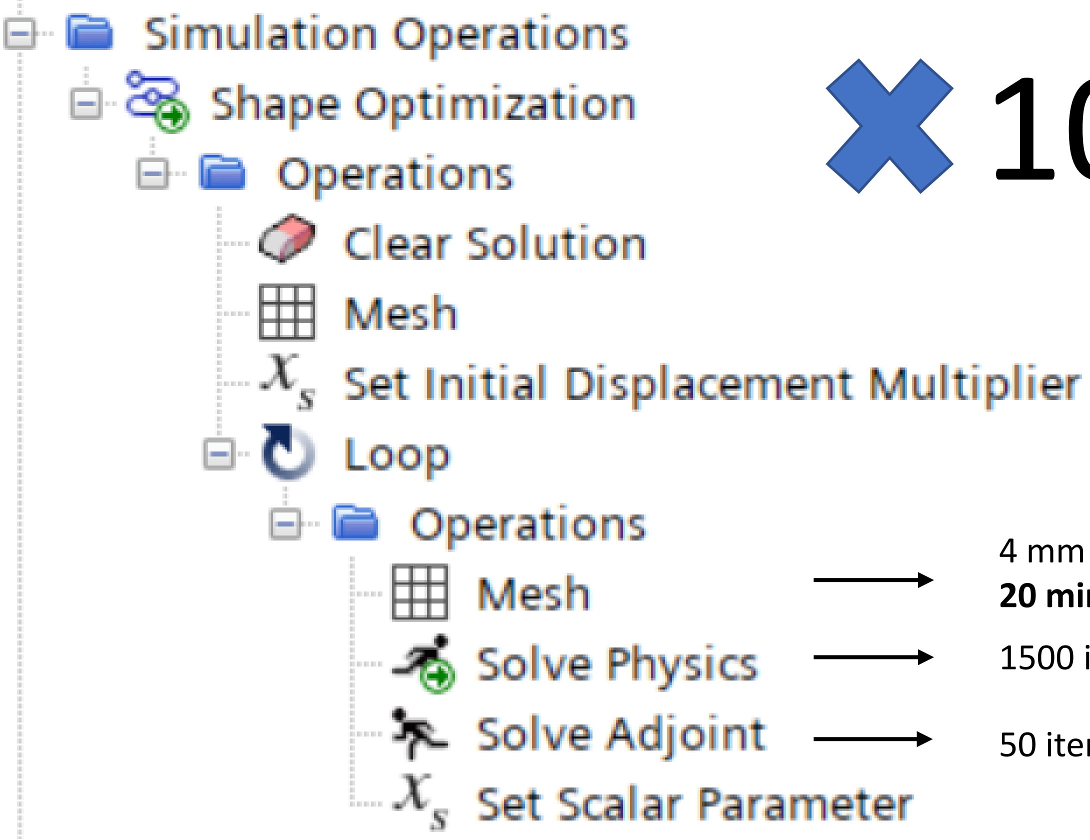
DfAM constraints

Optimization 2 (inner loop)



The adjoint shape optimization loop to minimize fuel flashback propensity was setup in Star-CCM+ using optimized mesh structure which allows for custom objective function definition





✖ 10 times

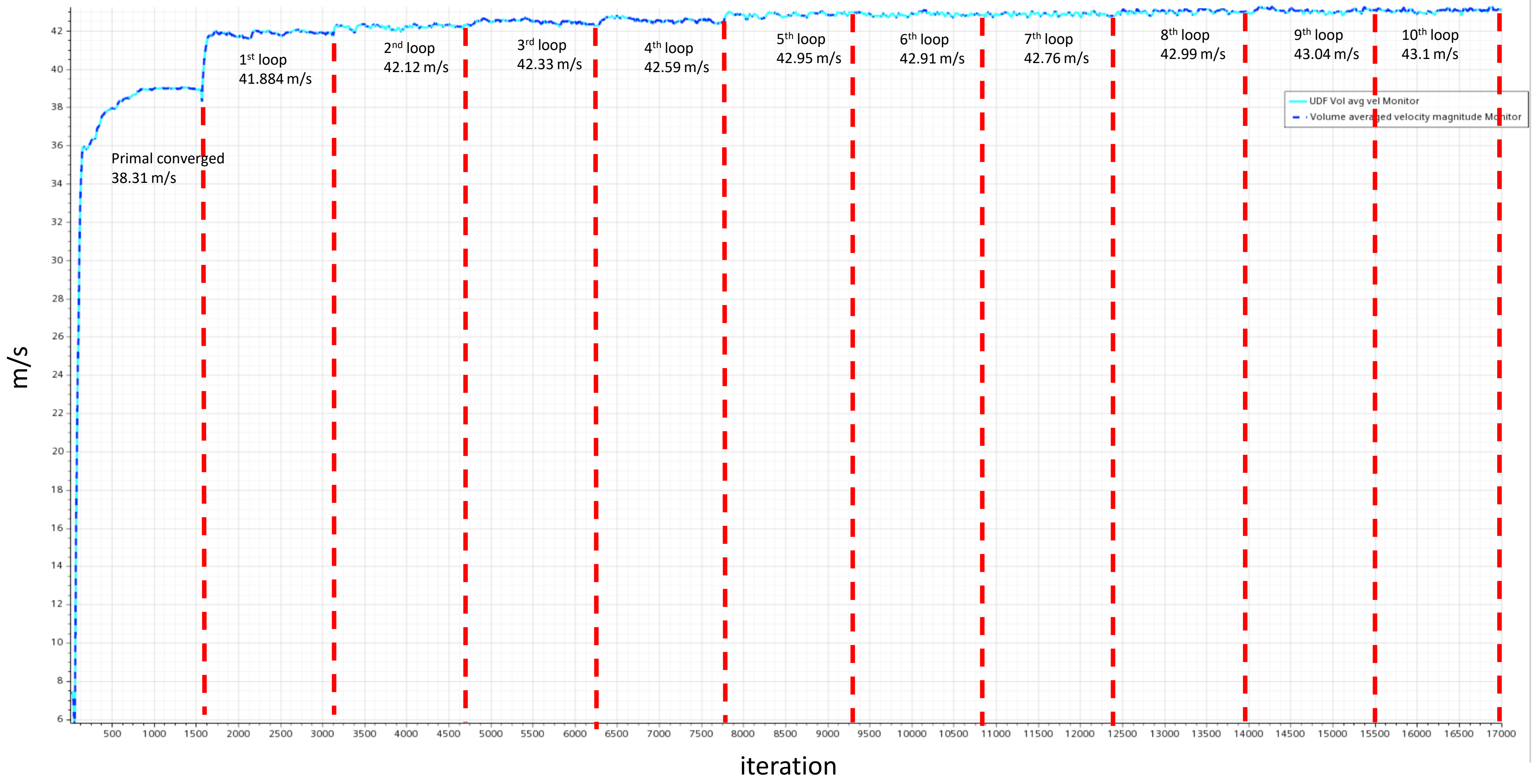
Mesh → 4 mm base size – ~4.5 million cells – **20 mins**

Solve Physics → 1500 iterations – **1h 26 mins**

Solve Adjoint → 50 iterations – **7 mins**

Maximizing the volume averaged velocity magnitude on the user defined annulus region to minimize flame flashback propensity

Volume Averaged Velocity Magnitude (m/s) plot



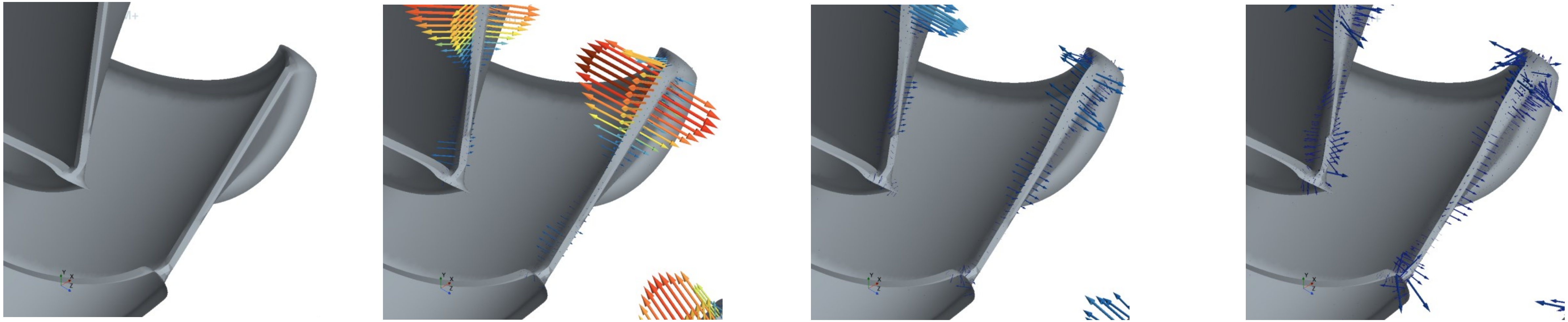
Key takeaways:

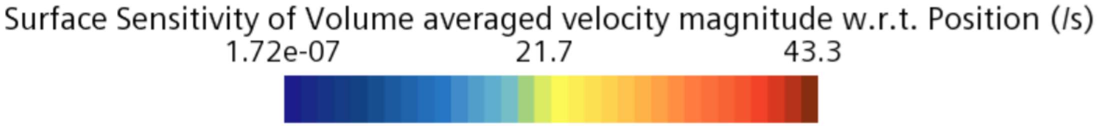
- Total change – 12.503% increase in vol avg vel mag
- 9.32% change after 1^{st} loop
- 2.9% change in next 9 loops

Trailing edge geometry is the most sensitive to increase flow speed downstream of the swirler vanes

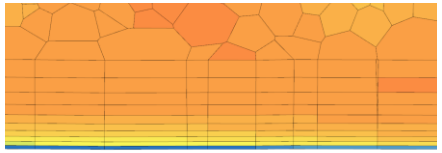
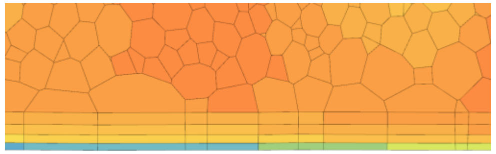
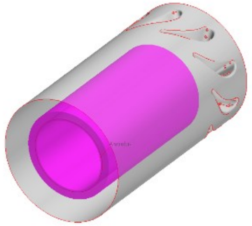
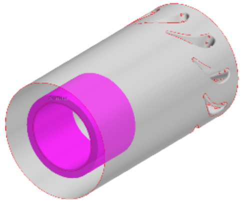
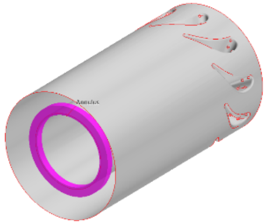
The magnitude of surface sensitivity stabilizes with more iterations (optimal solution convergence) most of the sensitivity is concentrated at the trailing edge

1500 | 3050 | 4600 | 17000





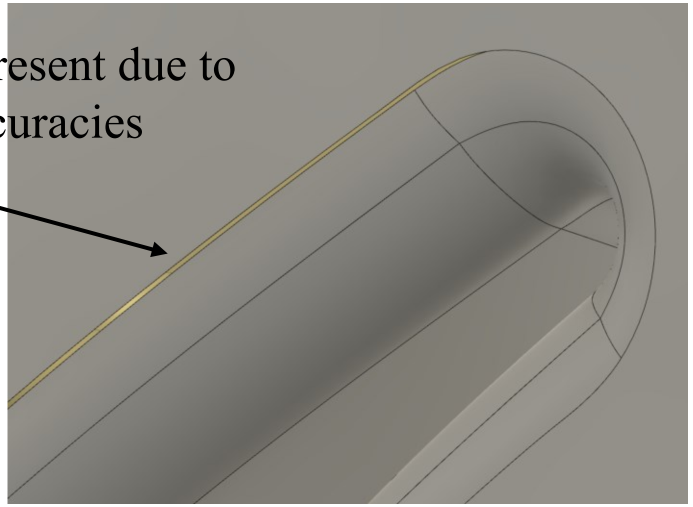
Through user defined region selection for the objective function with custom meshing controls we can obtain a well resolved boundary layer and investigate the effects of a variety of starting flow field on the resultant optimized shape

	 15 prism layers	 4 prism layers
	31.9 m/s	39.937 m/s
	26.1 m/s	32.89 m/s
	18.3 m/s	19.38 m/s

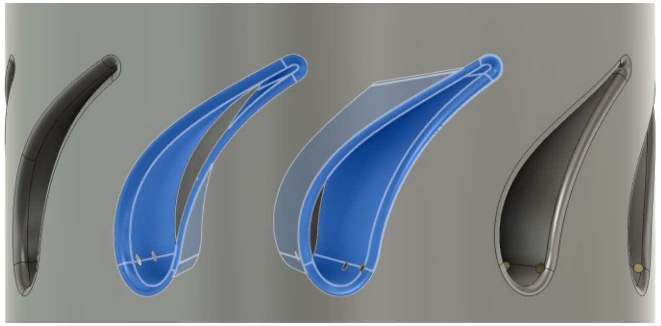
Introducing the reverse engineered NURBS swirler vanes into the adjoint optimization loop to exchange information between the 2-stage optimization routines

Original flow domain CAD

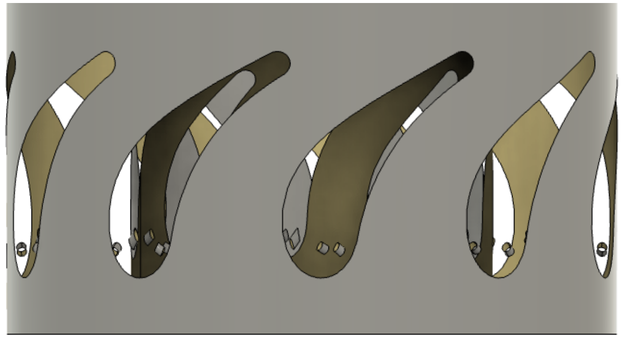
Surface discontinuities present due to reverse engineering inaccuracies

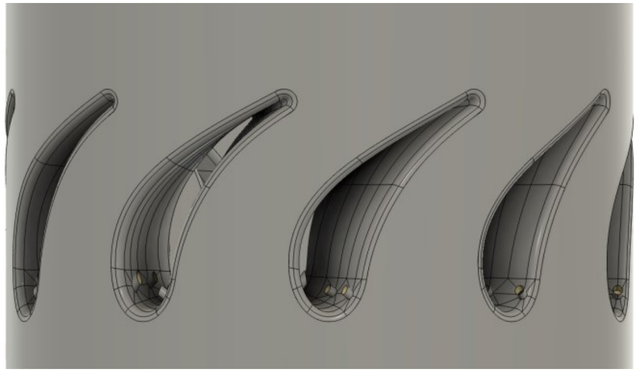


Swirler Vanes selected from baseline flow domain



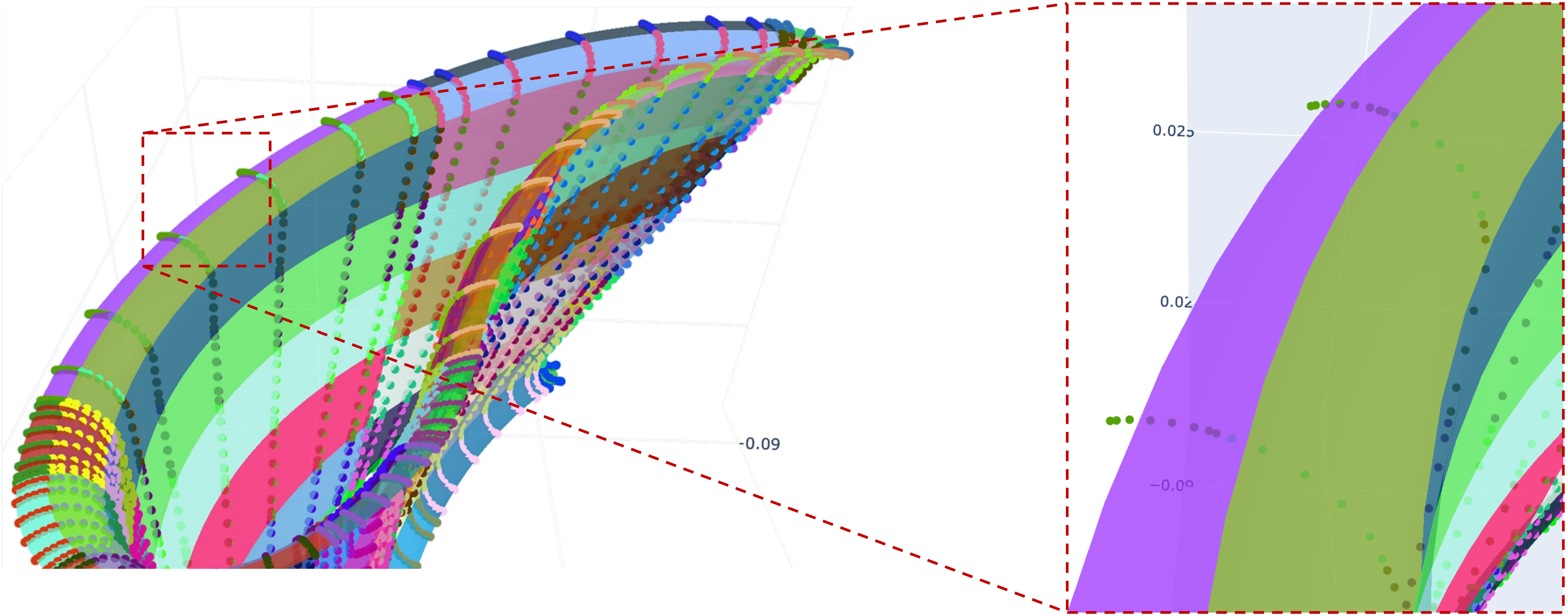
Swirler Vanes deleted from baseline flow domain





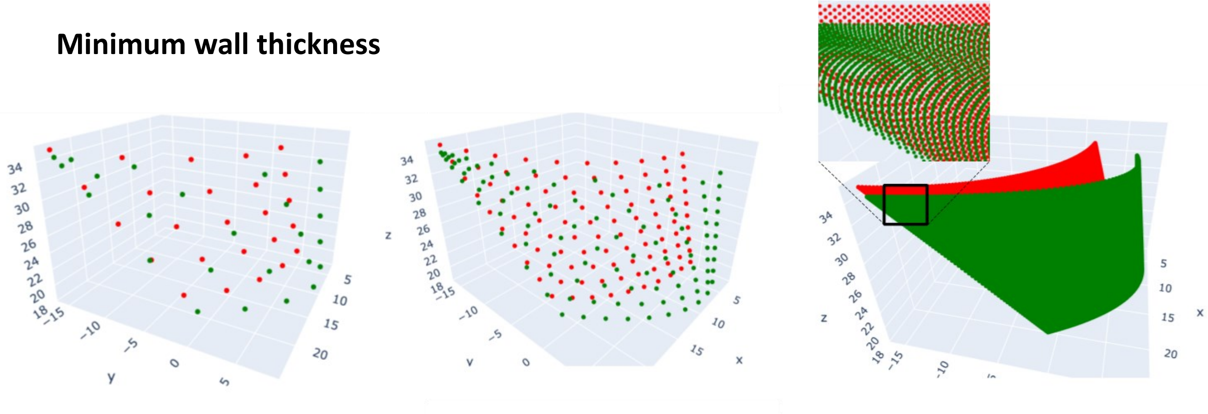
How can we ensure continuity of NURBS surfaces in an efficient manner while retaining a transferable CAD file format (IGES)?

Accessing Type 128 (NURBS Surface) & Type 126 (NURBS boundary curves) provides control over the shape



Metal AM constraints for the metal L-PBF process include thin walls, overhang angle, and feature reproducibility, and constraints can be adapted as the AM processing technology improves

Minimum wall thickness

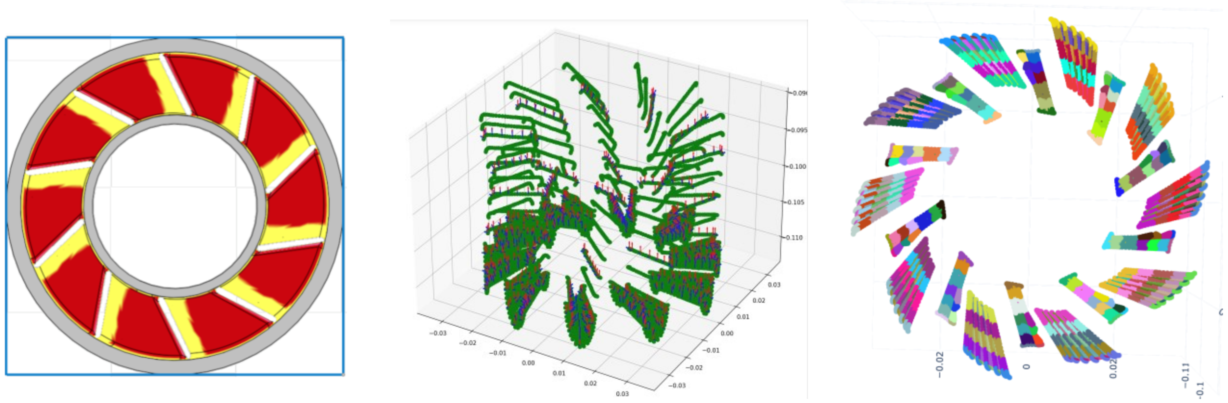


min. = 0.73 mm

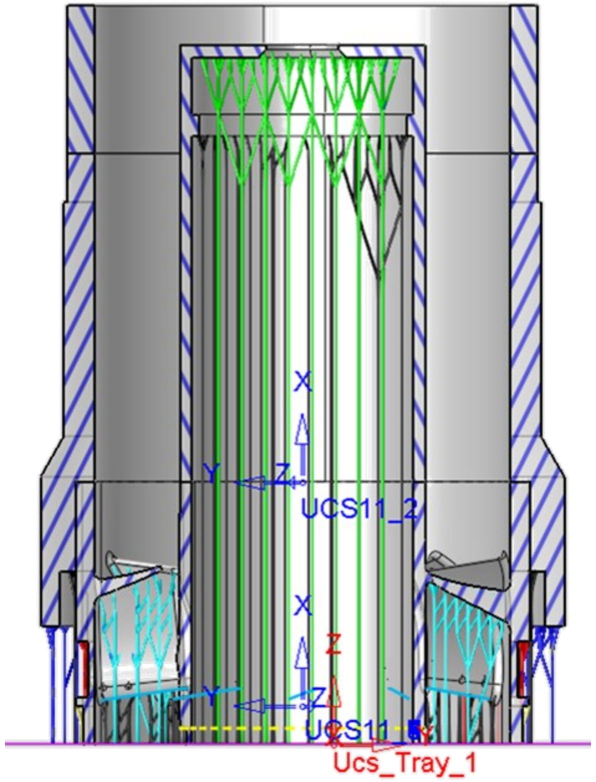
min. = 0.70 mm

min. = 0.68 mm

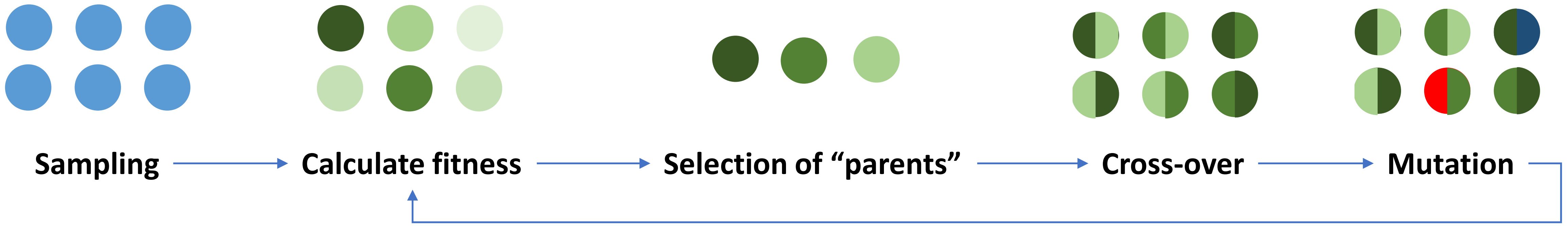
Overhang Angle - All surfaces that violate the 55° overhang angle limit were identified

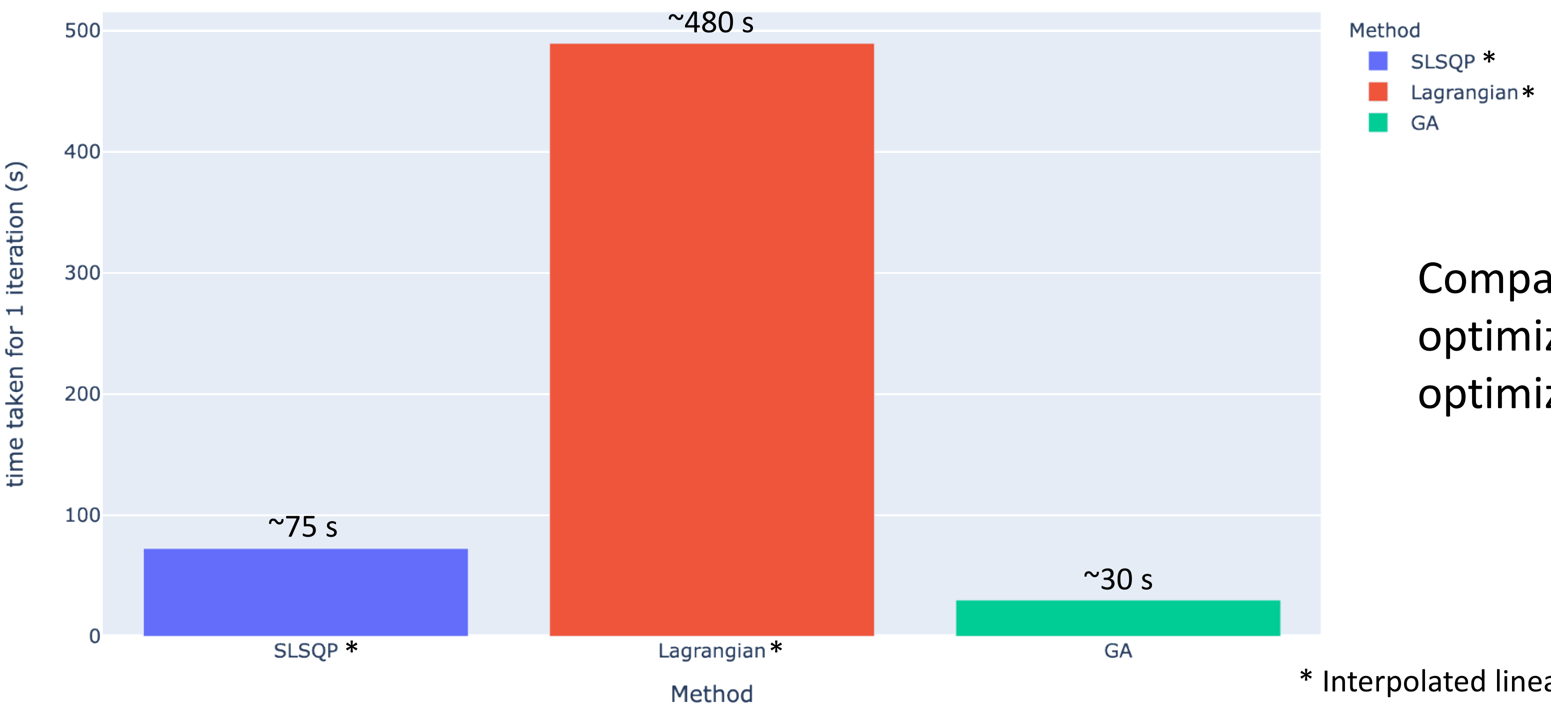


Impose constraints



Since we have many (54,400 x 3) design variables and a computationally efficient relationship (NURBS) between the design variables and the shape – we can use Genetic Algorithm optimization to solve surface continuity and shape fitting problems





Comparison between Numerical and GA-based optimization routines for 1 iteration of shape optimization demonstrates effectiveness of GA

* Interpolated linearly

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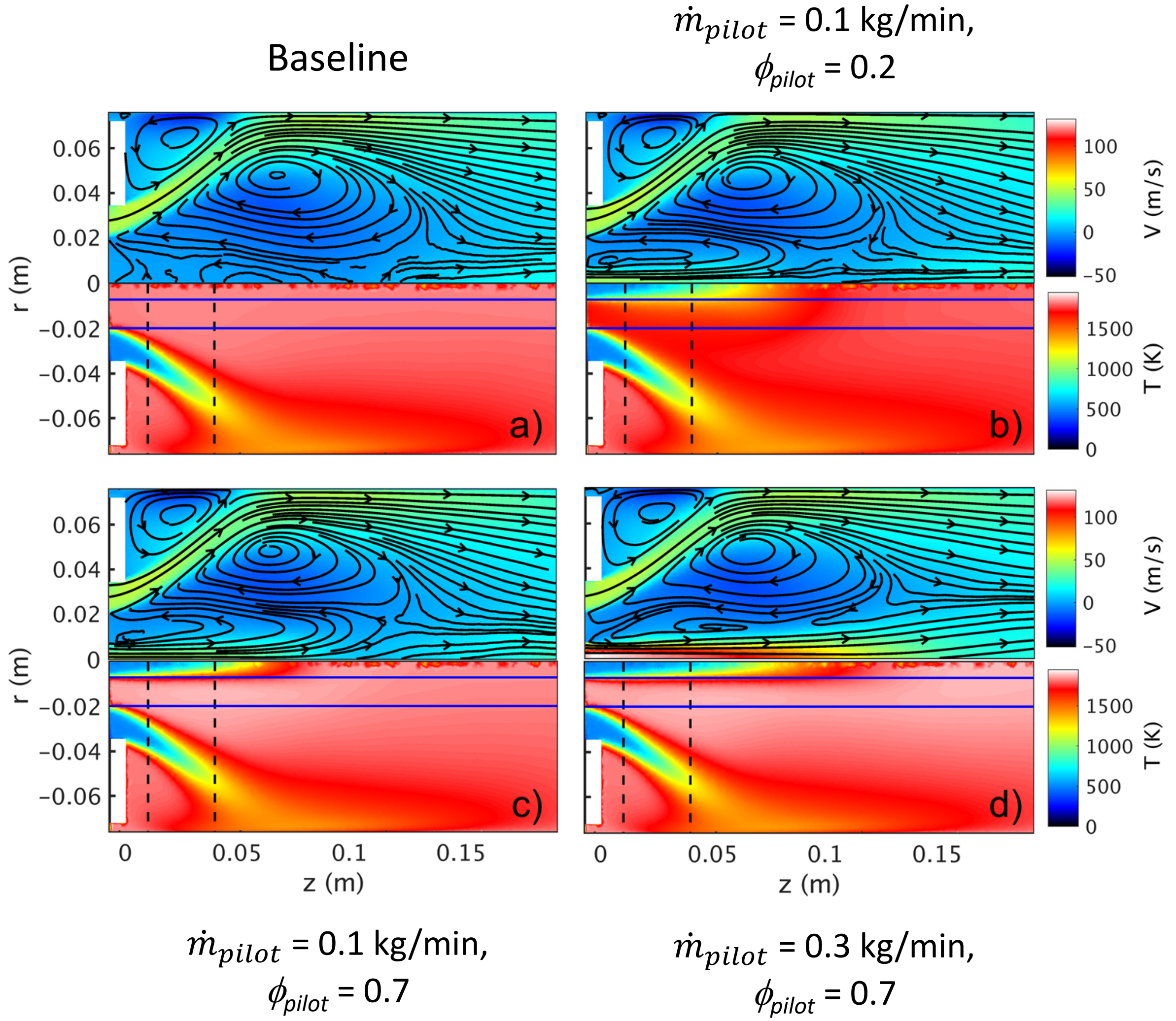
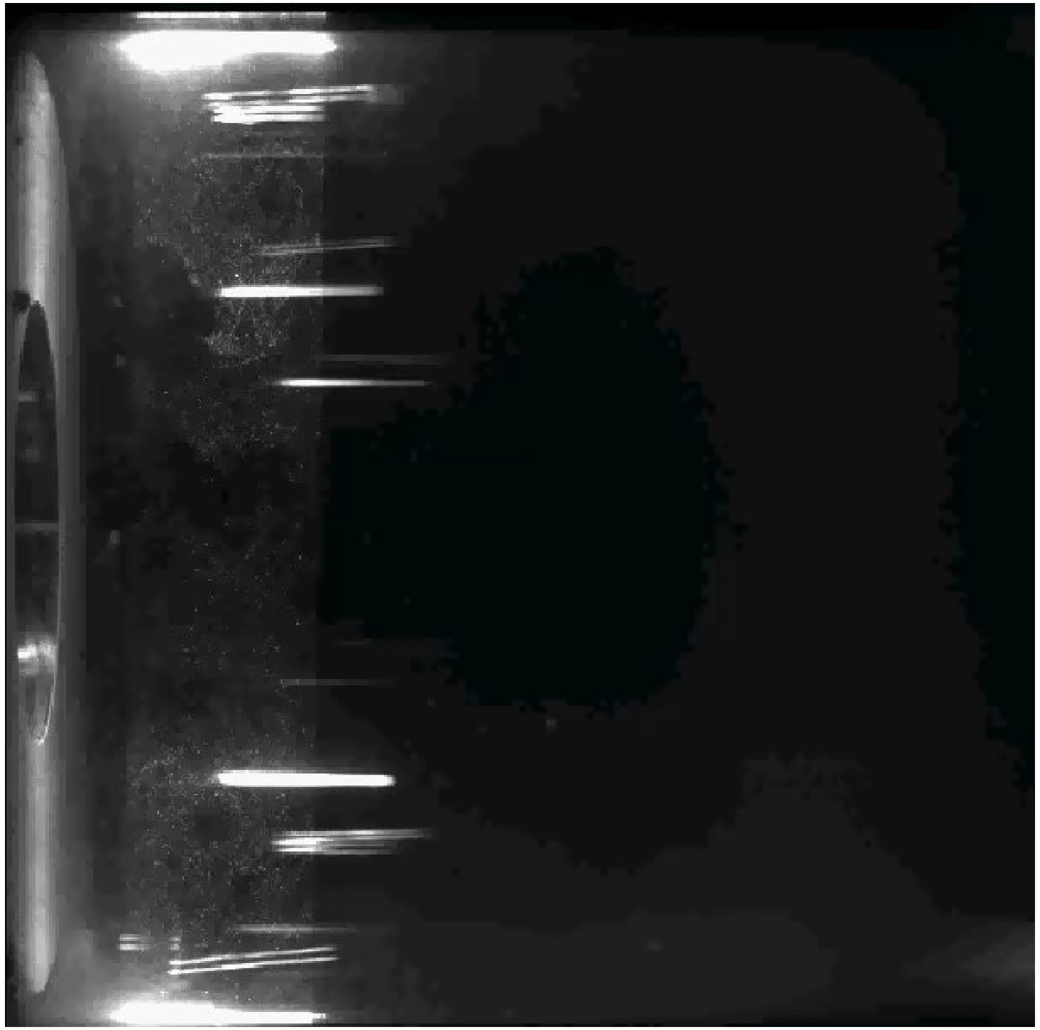
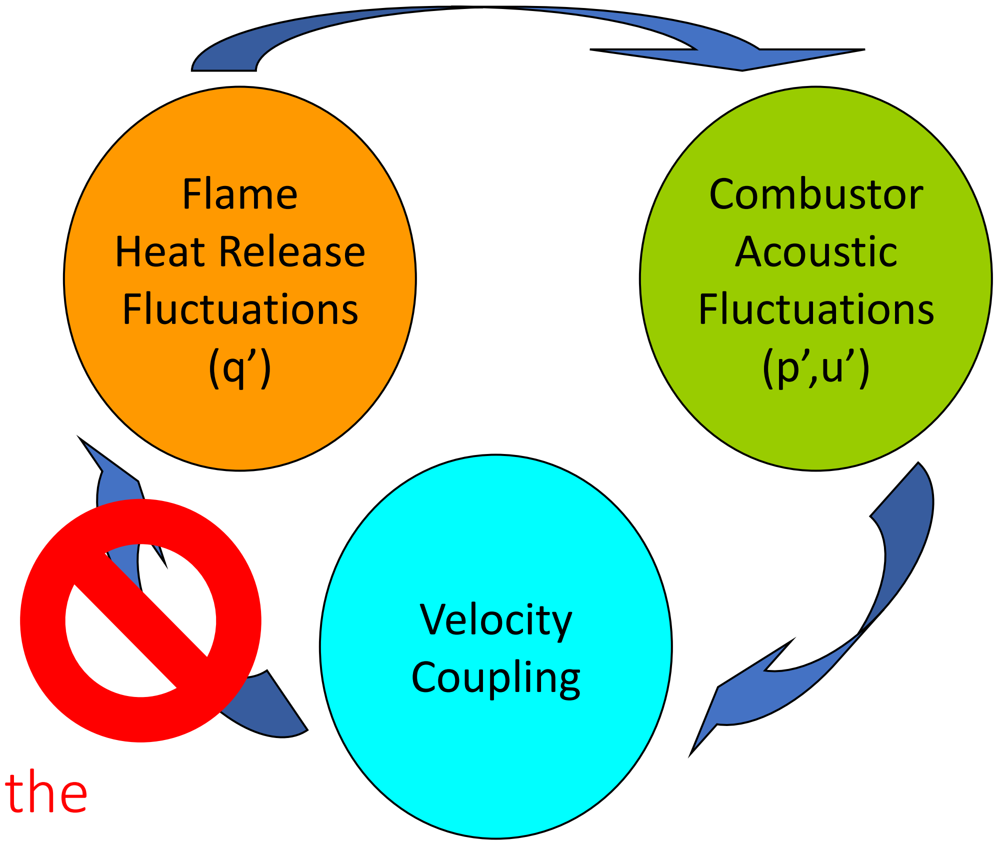
The goal of this work is the integration hydrodynamic instability constraints and understand more about the hydrodynamic instability of these complex flows





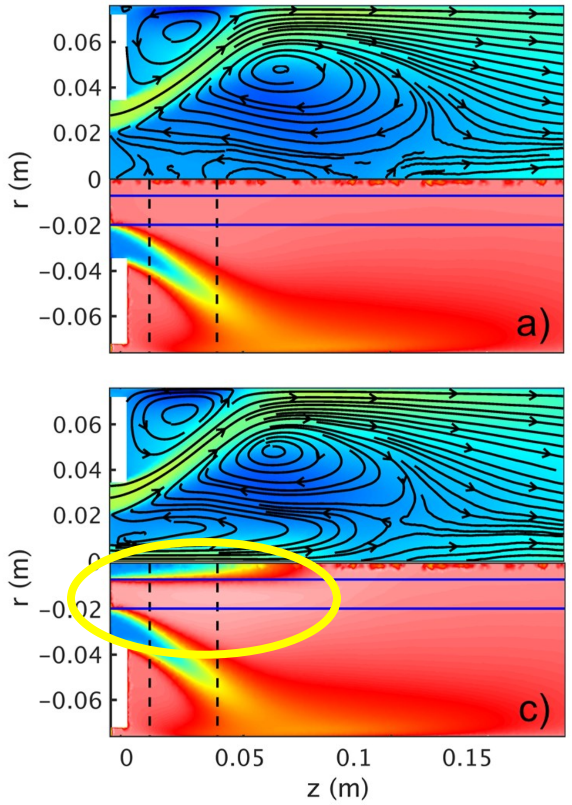
Li, J., Kwon, H., Seksinsky, D., Doleiden, D., Xuan, Y., O'Connor, J., Blust, J., Akiki, M., (2022) "Describing the Mechanism of Instability Suppression Using a Central Pilot Flame With Coupled Experiments and Simulations" in *Journal of Engineering for Gas Turbines and* Power, **144**(1), p. 011015.

While previous work suggested that pilot flames help suppress instability through a thermal mechanism, we know velocity-coupling processes are important



Suppression by making the *<u>flame</u>* less sensitive to input perturbations

Baseline



$\dot{m}_{pilot}$ = 0.1 kg/min,
ϕ_{pilot} = 0.7

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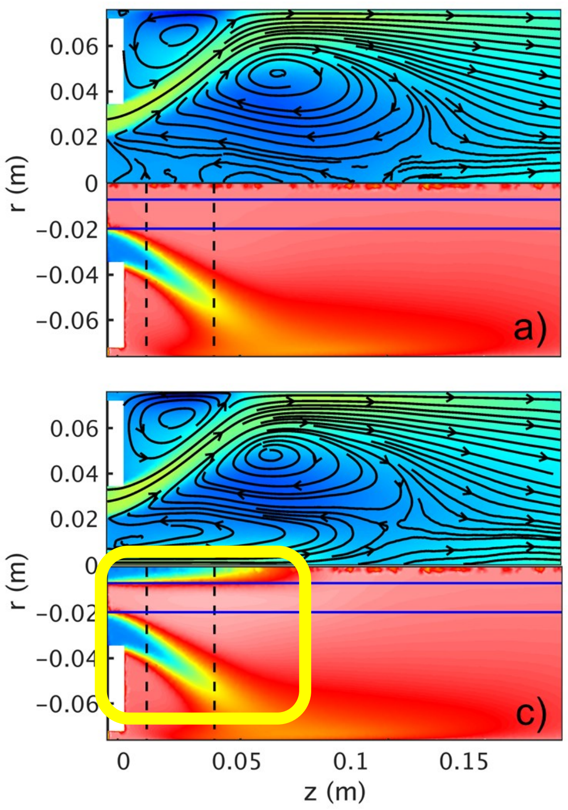

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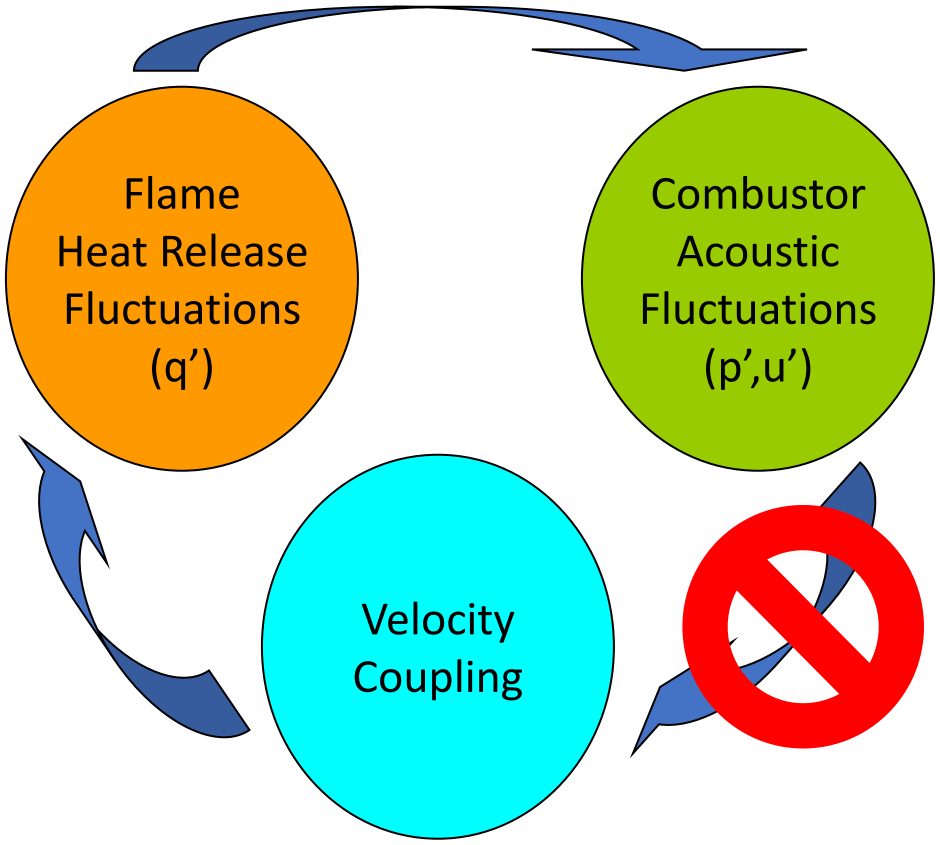
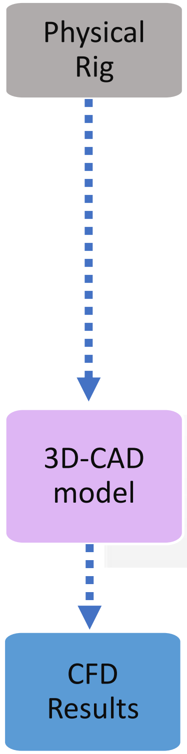


Suppression by making the *flow* less sensitive to input perturbations

The simulations are set up in StarCCM+ with four different pilot flow rates, matching the cases studied in previous thermal mechanism work

LES TOOL	Starccm+
Mesh specifications	Unstructured Polyhedral Mesh (~16.7 million cells)
Flame Chemistry	Flamelet Generated Manifold (FGM) model
Turbulence model	Dynamic Smagorinsky Model – Implicit unsteady
Solver	Implicit Unsteady 2^{nd} Order Time integration
Time step	5e-4 s | 10 inner iterations
Data Sampling time post steady state	At each timestep
Flow Temperature and Pressure	Atmospheric air heated to 250°C
Global Equivalence Ratio	Methane-air(21% O_2) → 0.6
Main Swirl flowrate	3.78 Kg/min



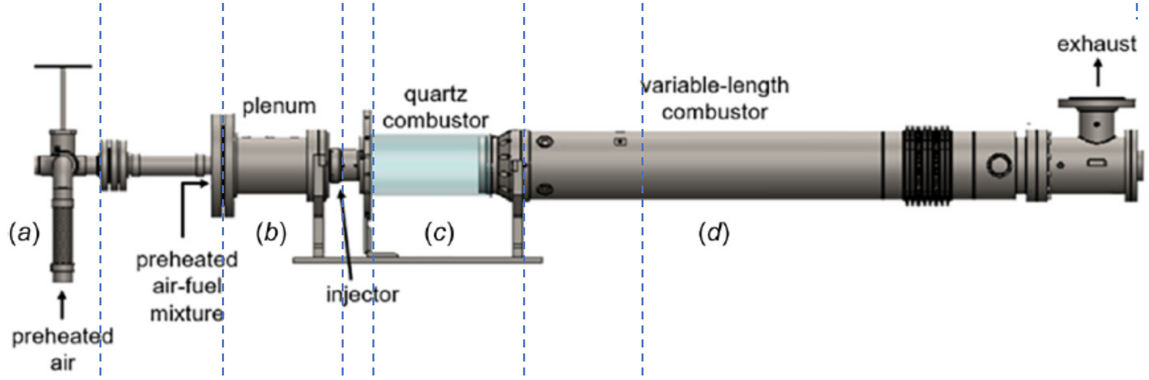
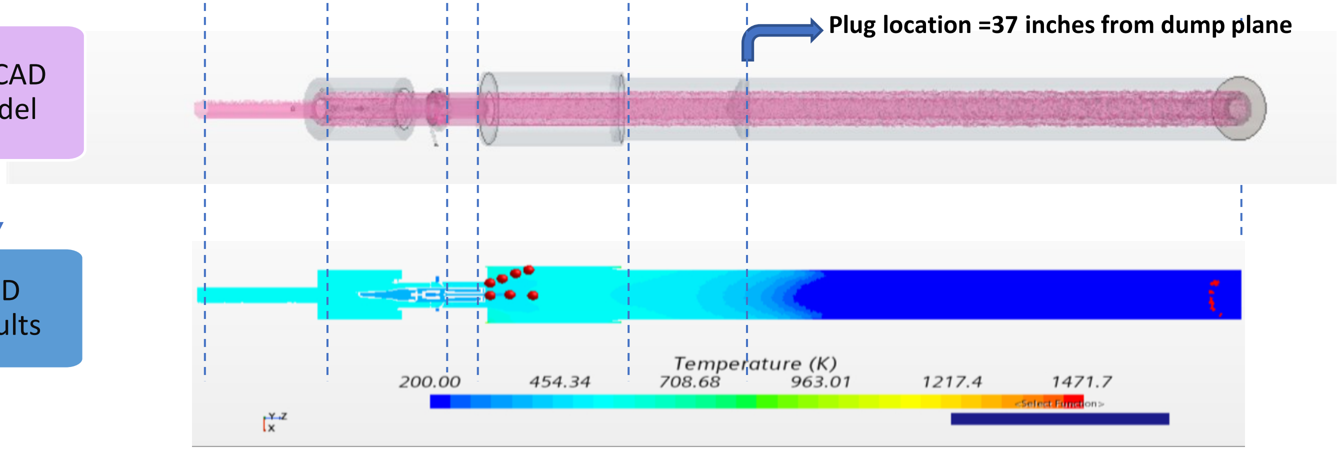
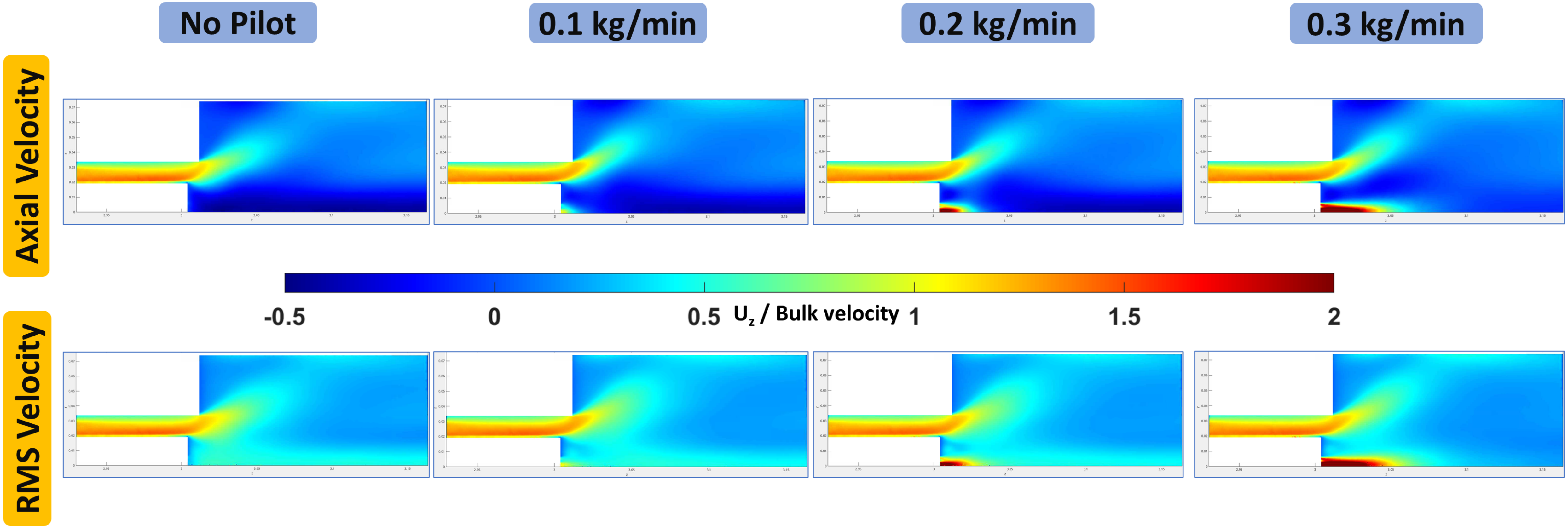


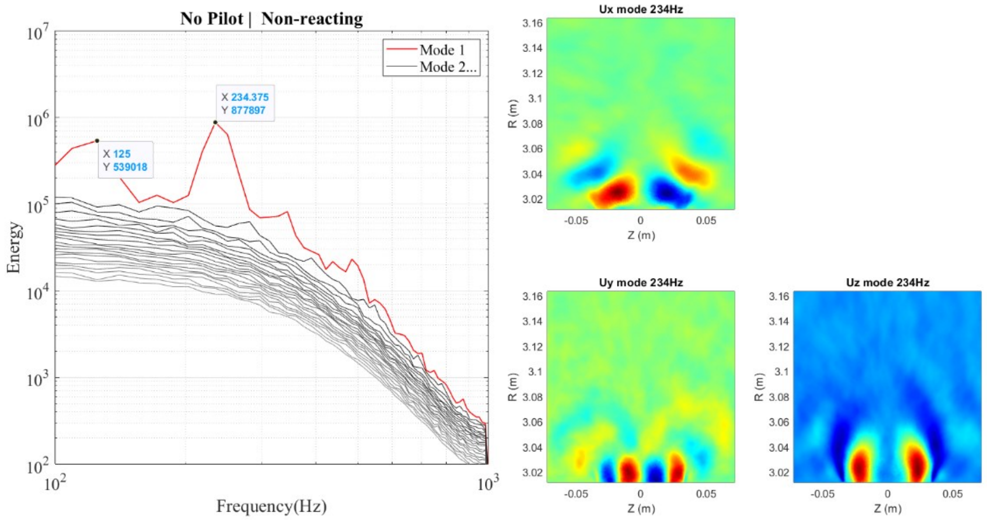
Fig. 1 The experimental apparatus showing: (*a*) the inlet section, (*b*) the plenum, (*c*) the quartz combustor, and (*d*) the metallic variable-length combustor

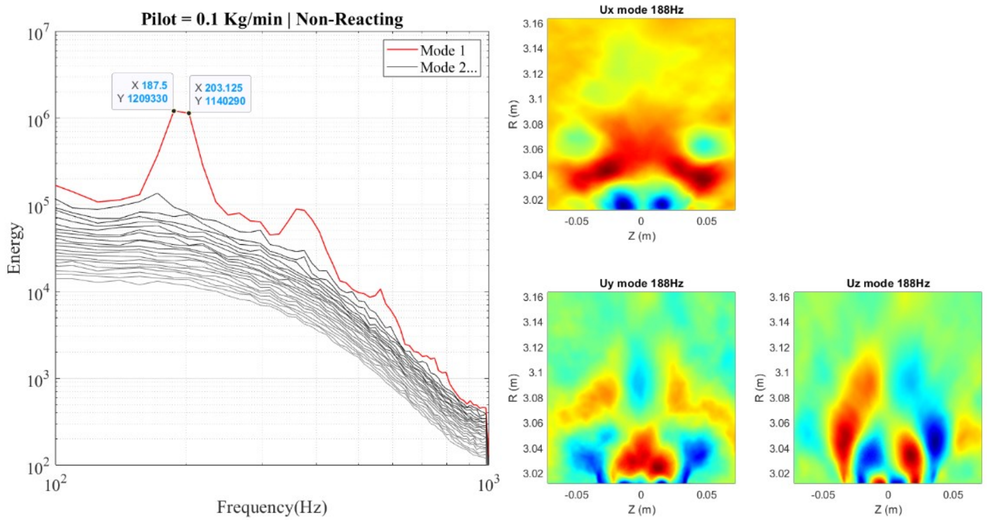


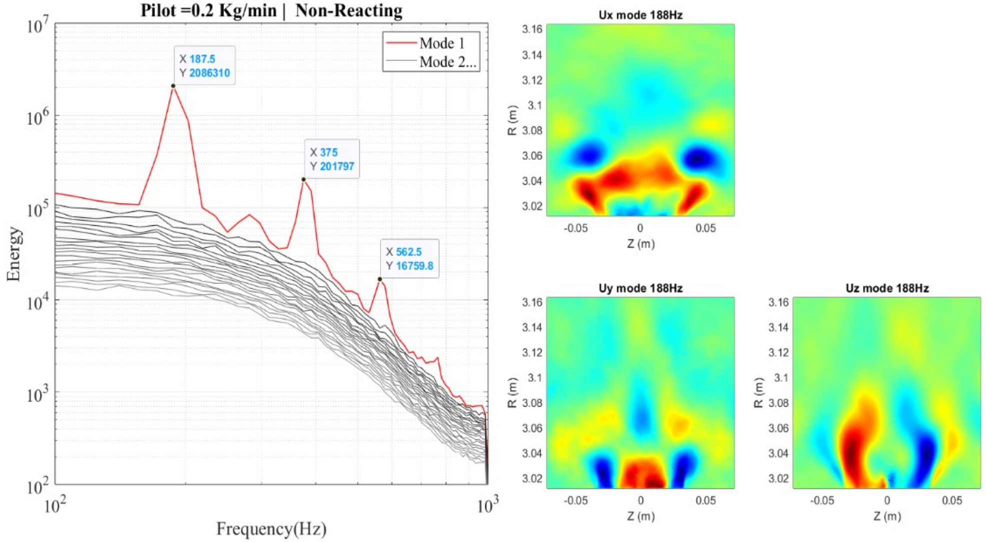
Changing the pilot flow rate does not dramatically change the structure of the main jet, but does change the centerline flow profile significantly

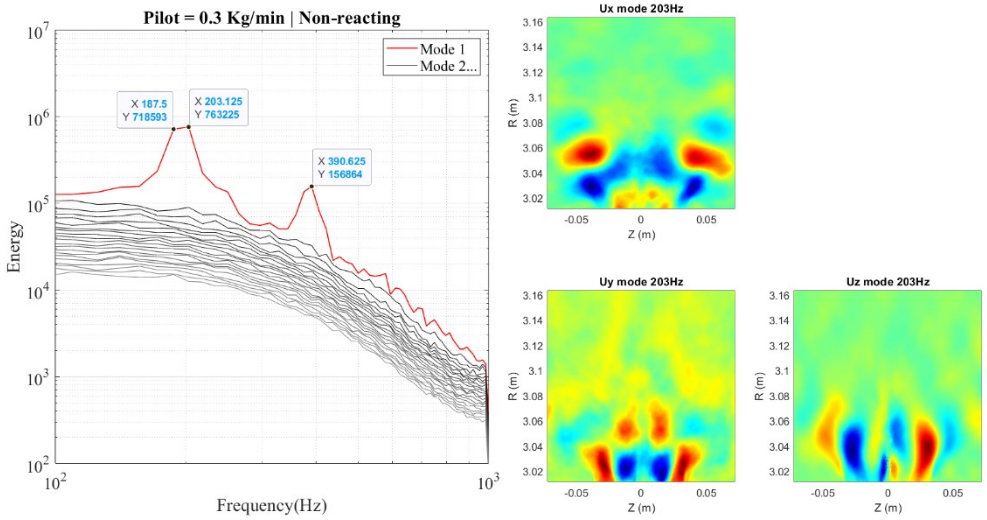


Spectral proper orthogonal decomposition is used to understand the dynamics of the system, where all cases show significant oscillations in the shear layer









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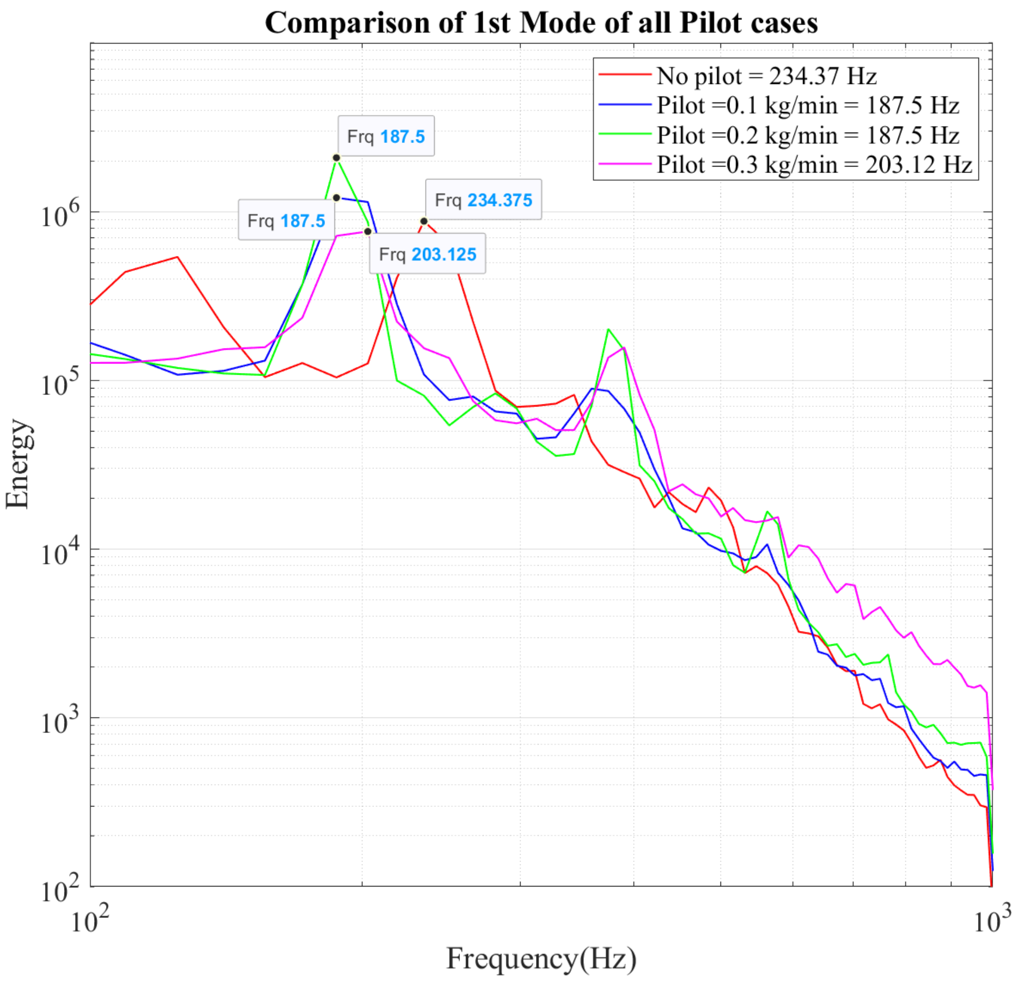
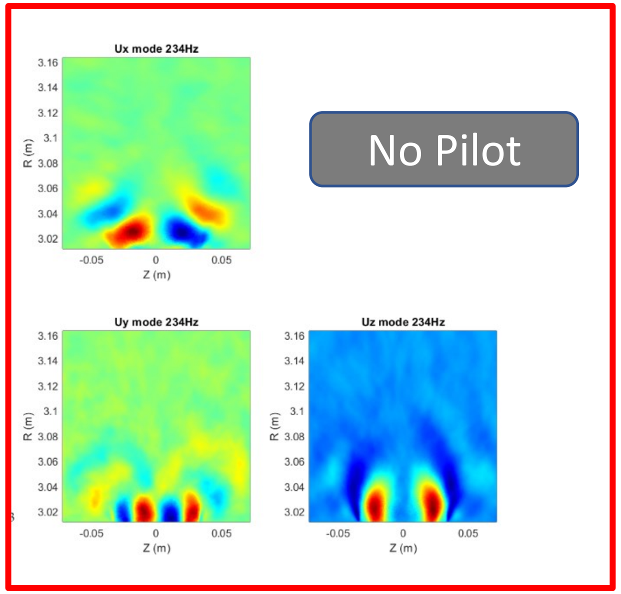
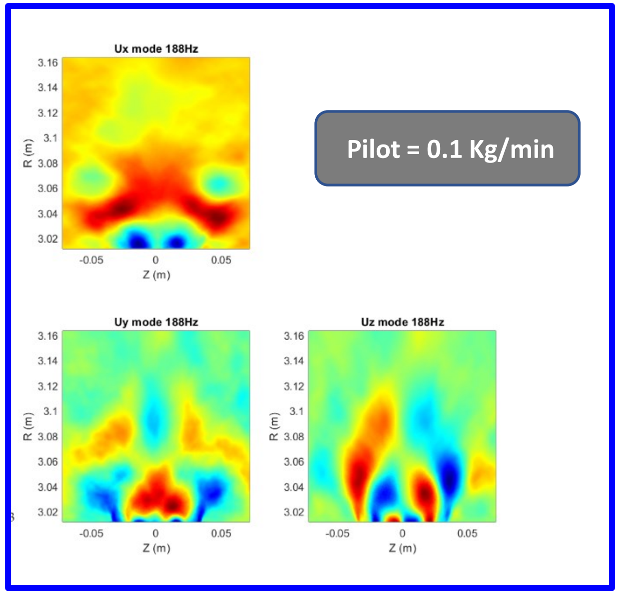
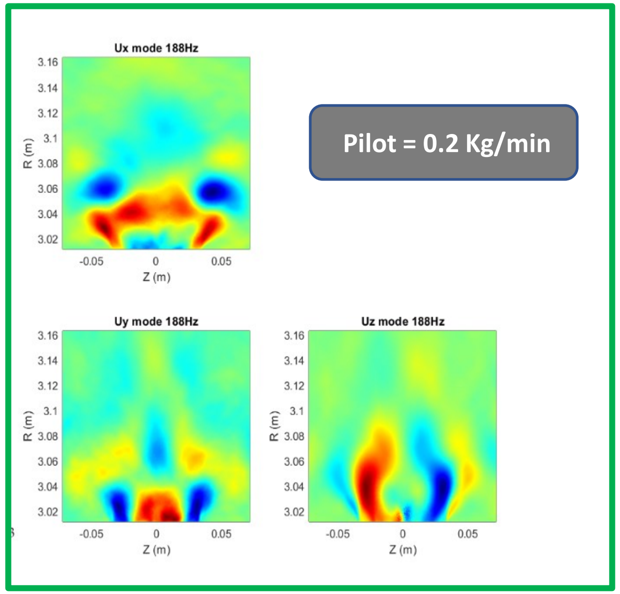
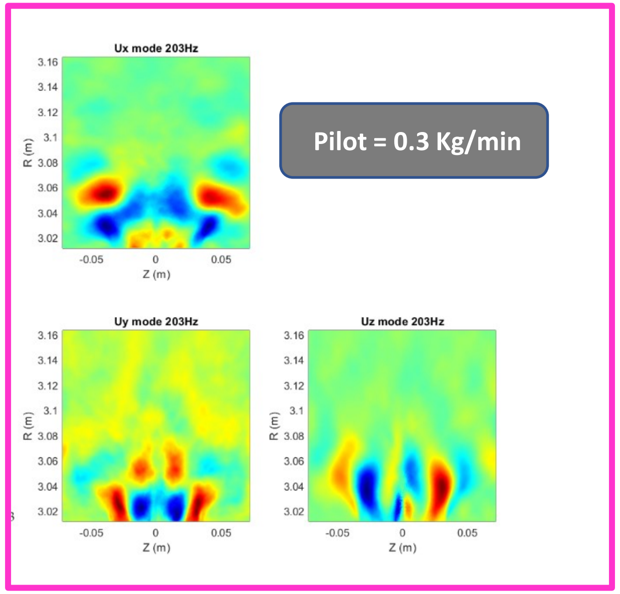




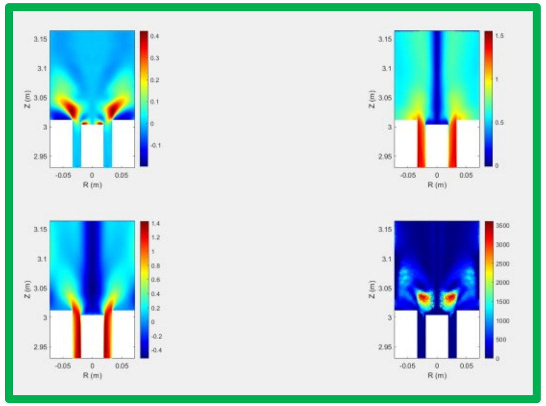




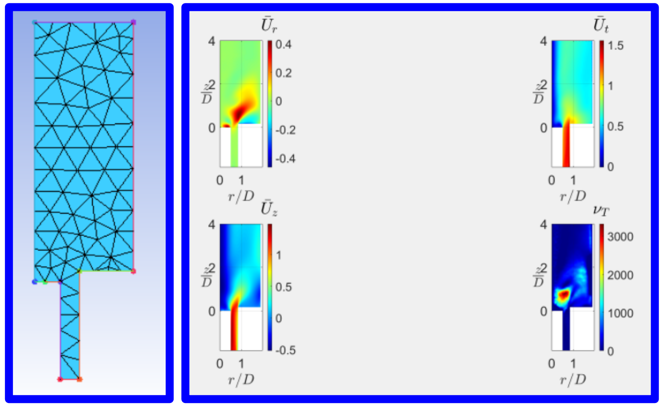


The stability of the system is analyzed using a linear hydrodynamic stability tool – FEHydro – to determine the modes, their shapes, and their adjoints

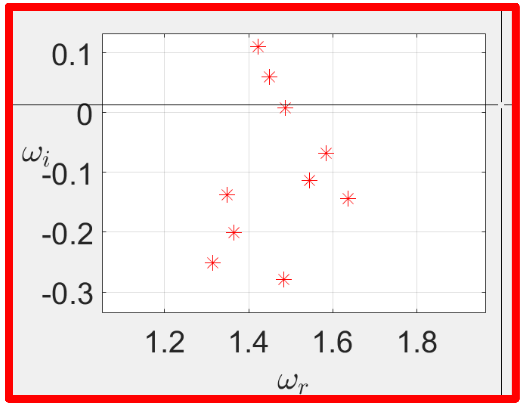
1. Obtain Time Averaged fields of velocities and eddy-viscosity



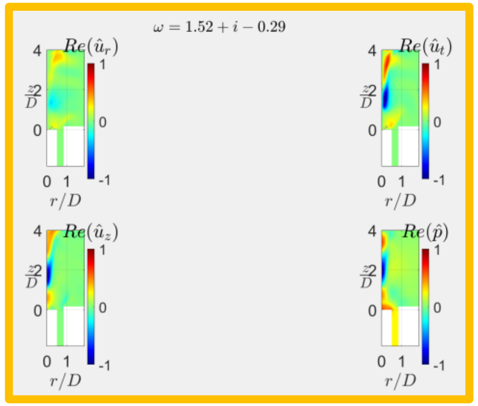
2. Interpolate normalized Data onto Triangular Mesh



3. Global Eigenvalue Spectrum



4. Spatial Variation of the Eigen Components



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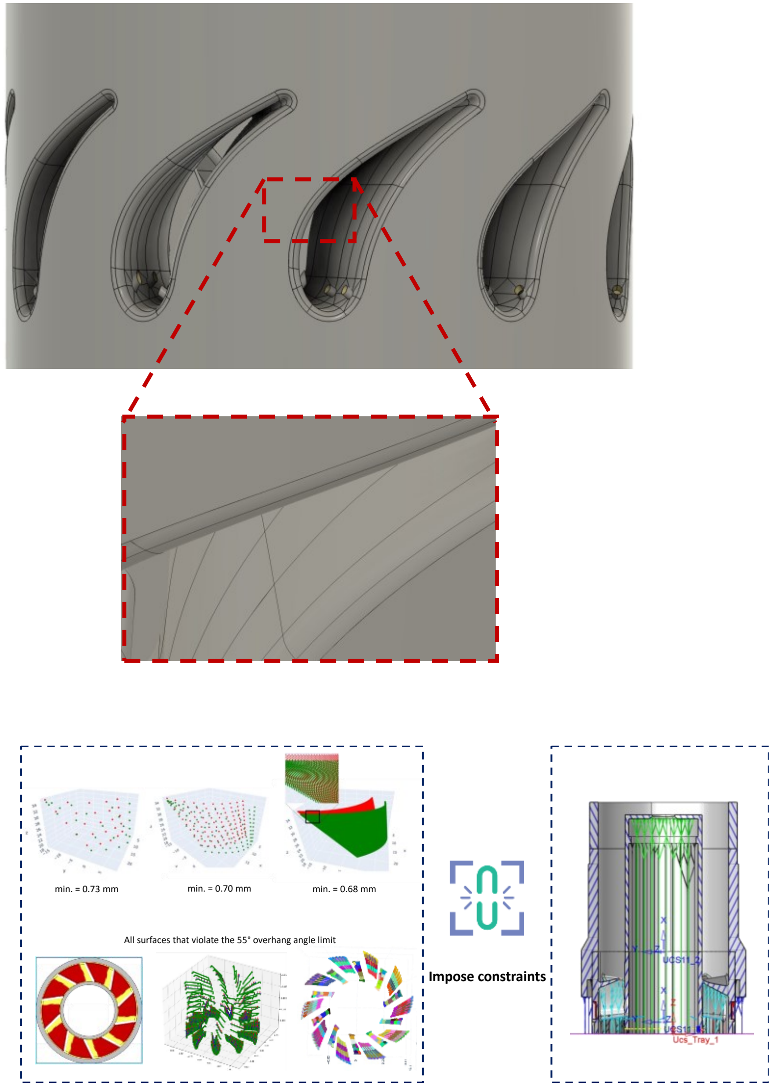
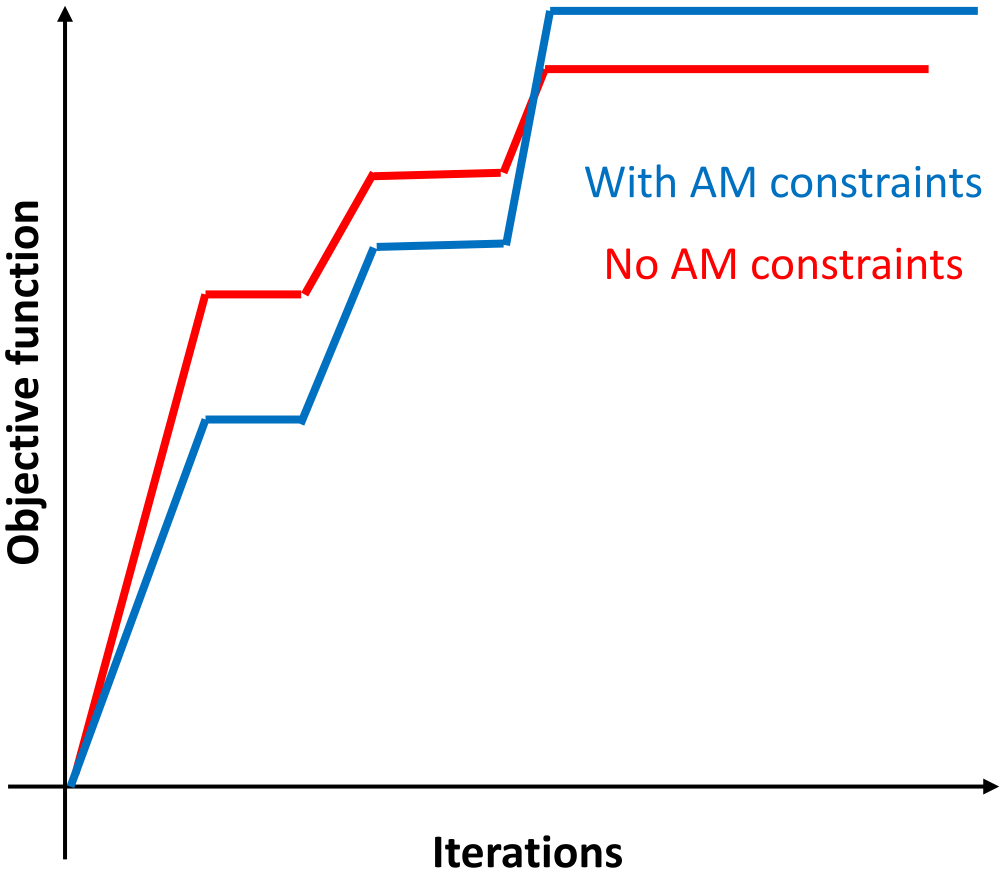
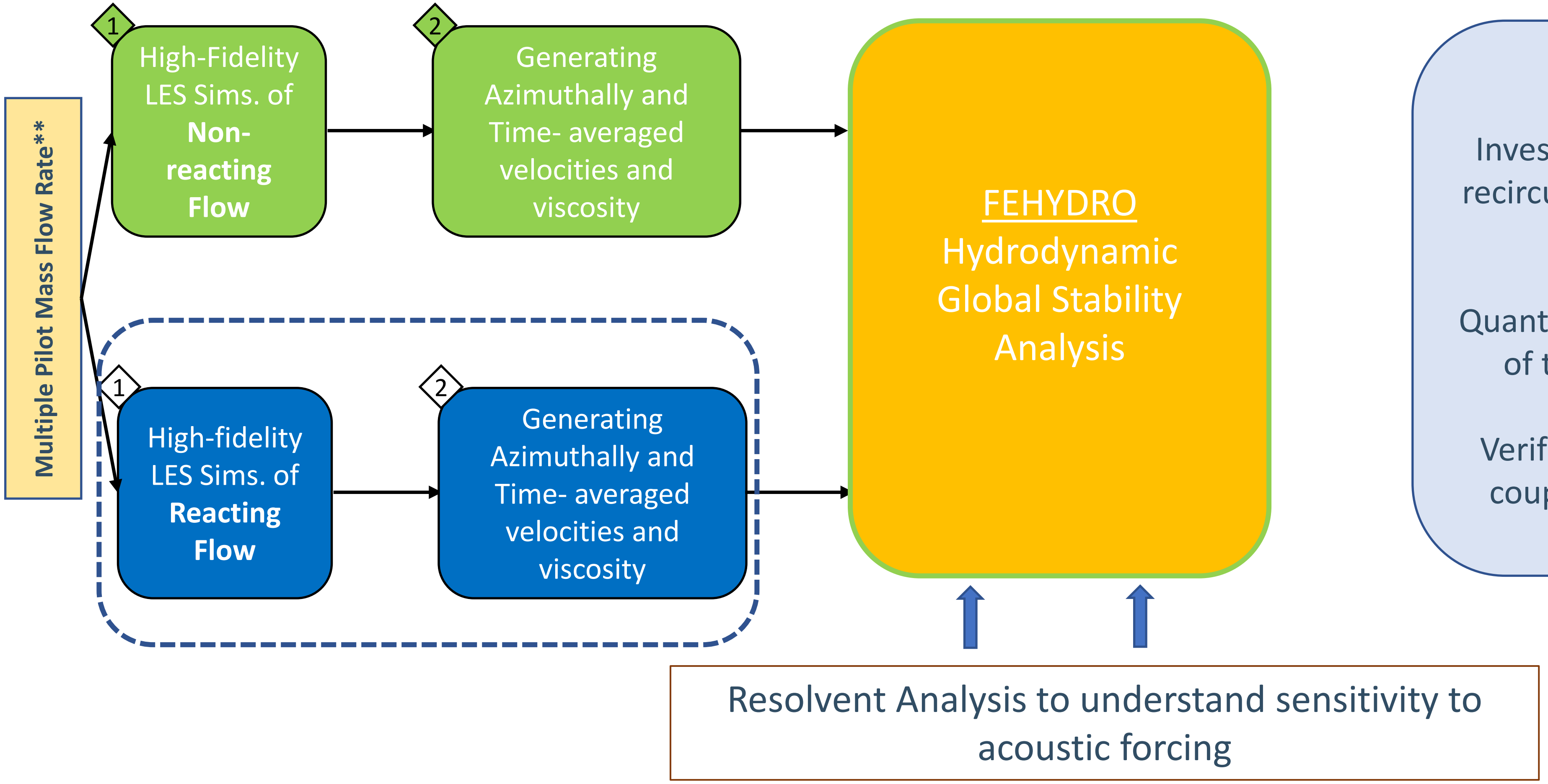
Having set up the adjoint optimization loop and identified the AM constraints, the next step is to compare AM vs non-AM fuel injector designs using print preparation software, simulation and flame tests



Star-CCM+
+
NURBS



The simulations will be extended to reacting flow to better understand velocity oscillations and the variations in behavior with different fuel blends



Premise

Investigating changes in the central recirculation zone due to central pilot jet.

Quantifying the stability and structure of the global modes of the flow.

Verifying the hypothesis of velocity coupling of combustion instability behavior.

Overview of presentation

- Background and technical approach
- Highlights from this year
  - Geometry optimization for flashback
  - Understanding flow stability
- Next steps
- Publications and outreach

Publications

Published

- Li, J., Kwon, H., Seksinsky, D., Doleiden, D., O'Connor, J., Xuan, Y., Akiki, M. and Blust, J., (2022) “Describing the Mechanism of Instability Suppression Using a Central Pilot Flame With Coupled Experiments and Simulations,” *Journal of Engineering for Gas Turbines and Power*, 144(1), p. 011015.
- O’Connor, (2022) “Understanding the Role of Flow Dynamics in Thermoacoustic Combustion Instability,” *Proceedings of the Combustion Institute*
- Jalui, S. S., Spurgeon, T. J., Jacobs, E. R., Chatterjee, A., Stecko, T., and Manogharan, G. P., (2021) “Abrasive Flow Machining of Additively Manufactured Titanium: Thin Walls and Internal Channels,” Proceedings of Solid Freeform Fabrication Symposium 2021.

In progress

- Jalui, S., O’Connor, J., Xuan, Y., Manogharan, G. (2023) “A novel framework for NURBS-based adjoint shape optimization for metal AM.” *Computer Aided Design Journal*
- Jalui, S., Xuan, Y., Manogharan, G., O’Connor, J., (2023) “Understanding adjoint shape sensitivity for a gas turbine fuel injector design using metal-AM.” *ASME Journal of Engineering for Gas Turbines and Power*
- Mohanty, P., Gupta, S., Hemachandra, S., Xuan, Y. ,O’Connor, J., (2023) “Investigation of the effects of central pilot jet on non-reacting swirling flow.” *Physical Review Fluids*
- Mohanty, P., Gupta, S., Hemachandra, S., Xuan, Y. ,O’Connor, J., (2024) “Impact of central pilot jet on the stability of reacting swirling flow.” *ASME IGTI Turbo Expo 2024, London, UK*

Outreach

Trade Publications

— Feature in *Additive Manufacturing Magazine* and *The Cool Parts Show*
  — https://www.youtube.com/watch?v=no_7eZe-Muo
  — https://www.youtube.com/watch?v=B9ScUHspMQs

Conferences

— Manogharan, G. (2021) "A Design for Additive Manufacturing Challenge for Gas Turbine Industry," *Additive Manufacturing 2021 Conference*, Cincinnati, OH

— Mohanty, P., Gupta, S., Hemachandra, S., Xuan, Y. ,O'Connor, J.(2023) "Impact of a Central Pilot Jet on the Stability of a Swirling Flow," *ASME IGTI Turbo Expo 2023 Conference,* Boston, MA

Curriculum

— ME 556: Design for Additive Manufacturing – two teams design challenge for gas turbine swirler design to enhance lean blow-off limits

— ME 404: Gas Turbines – case study on additive manufacturing in gas turbine engines

Undergraduate Research

— Summer Research Experience for Undergrads hosted by Penn State Center for Gas Turbine Research, Education, and Outreach (GTREO) and Center For Innovative Materials Processing Through Direct Digital Deposition (CIMP-3D) on additive manufacturing for fuel injectors

— NSF REU (PIs: J. O'Connor and K. Thole) with projects focused on thermoacoustics, design optimization, and additive manufacturing

Questions?

Development and Evaluation of a Novel Fuel Injector Design Method using Hybrid-Additive Manufacturing

Project DE-FE12806463, Oct. 2019 – Sept. 2022 (Sept. 2024 NCE)
Program Monitor: Mark Freeman

PIs: Jacqueline O'Connor, Guha Manogharan, Yuan Xuan
Graduate students: Sagar Jalui, Pratikshya Mohanty

Mechanical Engineering
Pennsylvania State University

Industry Partner: Solar Turbines Incorporated
Engineers: Hanjie Lee, Michel Akiki, Dang Le

PennState