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 – September 24, 2024

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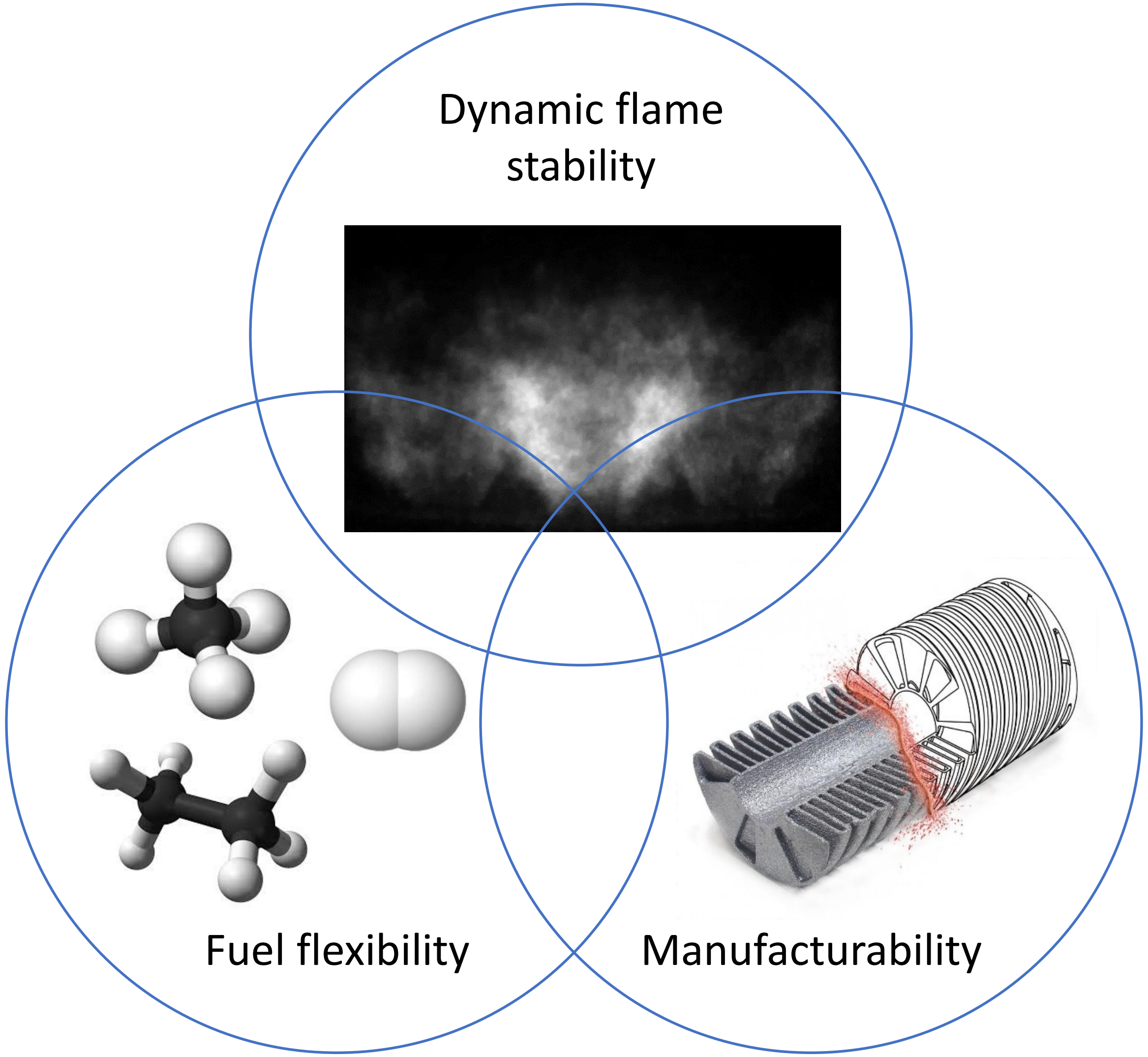
Goal of this project is to create a design optimization paradigm that marries combustion physics and manufacturing

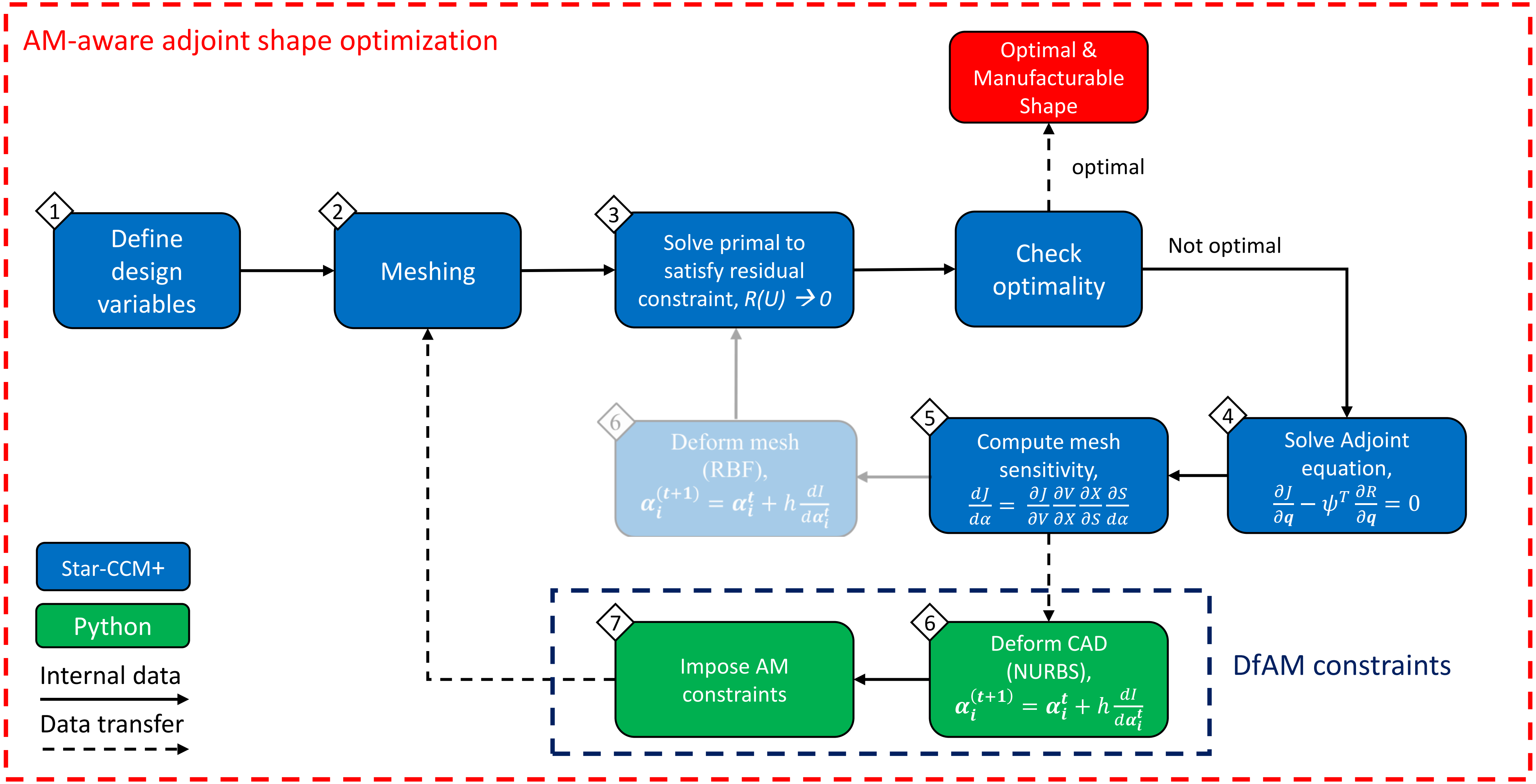


Dynamic flame stability

Fuel flexibility

Manufacturability

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



AM-aware adjoint shape optimization

1 Define design variables

2 Meshing

3 Solve primal to satisfy residual constraint, *R(U)* → *0*

Check optimality

optimal

Optimal & Manufacturable Shape

Not optimal

4 Solve Adjoint equation, $\frac{\partial J}{\partial q} - \psi^T \frac{\partial R}{\partial q} = 0$

5 Compute mesh sensitivity, $\frac{dJ}{d\alpha} = \frac{\partial J}{\partial V}\frac{\partial V}{\partial X}\frac{\partial X}{\partial S}\frac{\partial S}{d\alpha}$

6 Deform mesh (RBF), $\alpha_i^{(t+1)} = \alpha_i^t + h\frac{dI}{d\alpha_i^t}$

6 Deform CAD (NURBS), $\alpha_i^{(t+1)} = \alpha_i^t + h\frac{dI}{d\alpha_i^t}$

7 Impose AM constraints

DfAM constraints

Star-CCM+

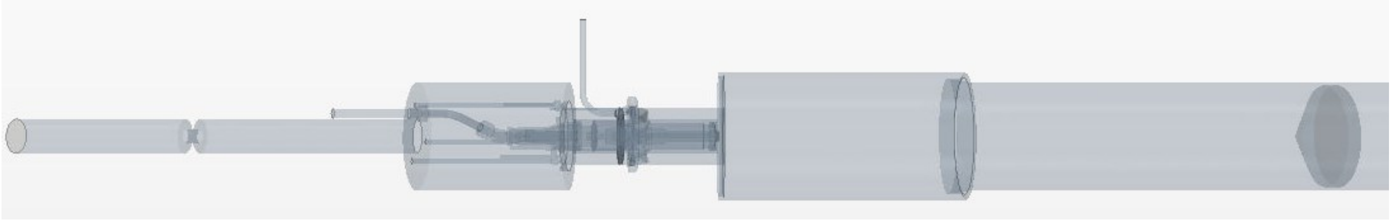
Python

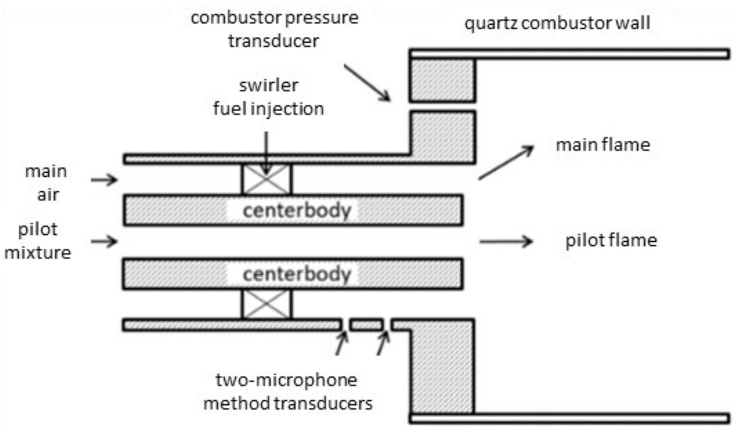
Internal data

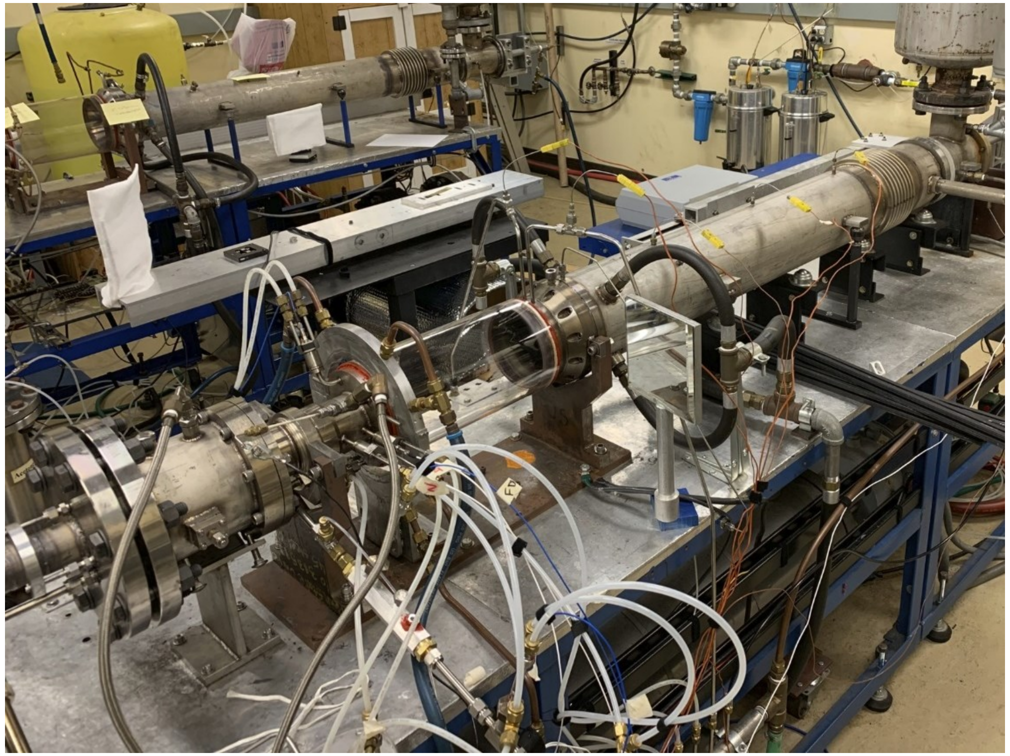
Data transfer

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)







Major accomplishments of this program

1. Integration of design for AM (DfAM) and combustion behaviors to optimize a design for fuel-flexible operation

2. Use of commercial tools and open-source resources (Python code, standard CAD definitions, etc.) to implement optimization for better translation

3. AM optimization based on mathematical formulation rather than grid-based, allowing better transference to other applications

4. Better understanding of the role of pilot jets in flow stability, flameholding

5. New understanding of the impact of AM surface roughness on flameholding

6. Design and testing of both optimized injector designs and clean-sheet design based on lessons learned from optimization process

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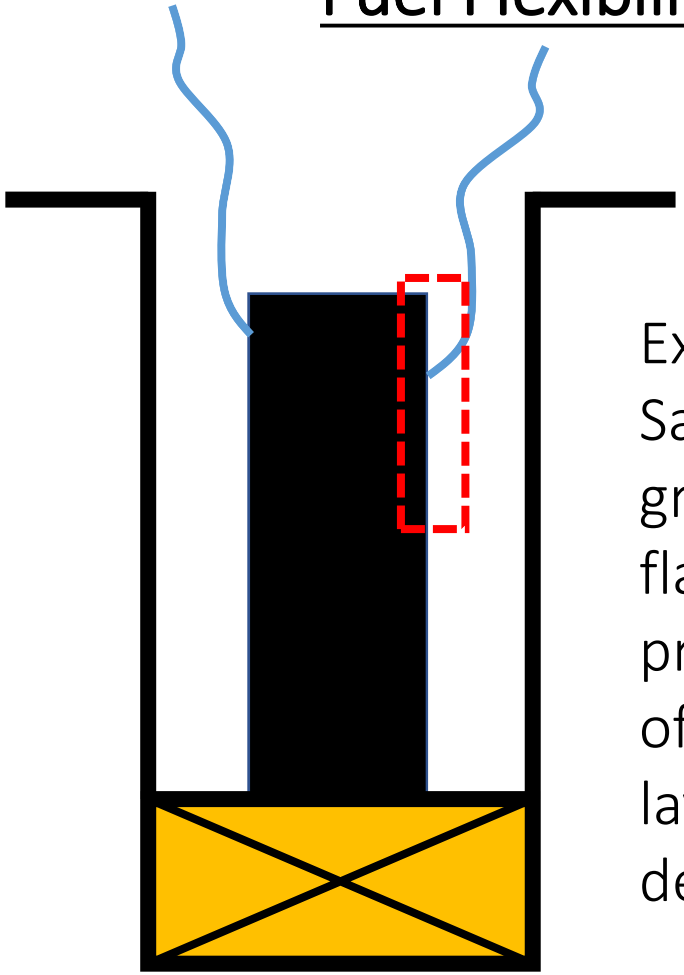
This framework integrates the optimization for fuel flexibility and the AM constraints into one workflow

Fuel Flexibility



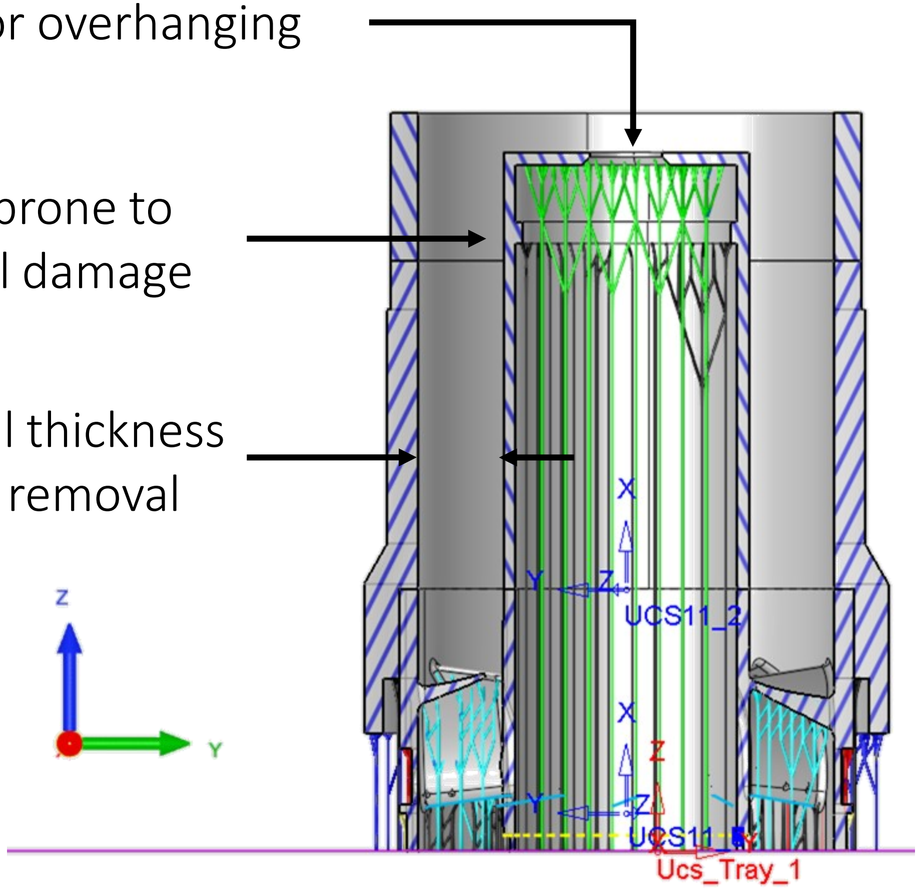
Extend theory by Sattelmayer’s group to predict flashback propensity based off boundary layer development

AM Constraints

Support structures required for overhanging areas

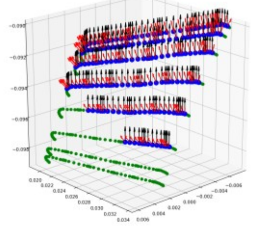
Thin walls prone to mechanical damage

Wall-to-wall thickness for powder removal

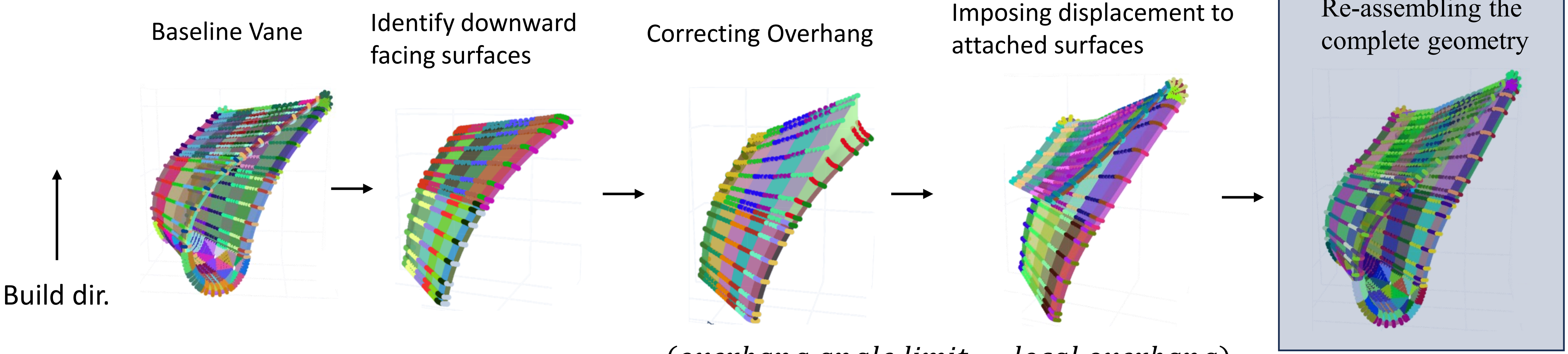


Integration of design for AM (DfAM) to optimize a design for self-supporting printing

Compute local overhangs



Design **f**or **A**dditive **M**anufacturing (DfAM) Vanes



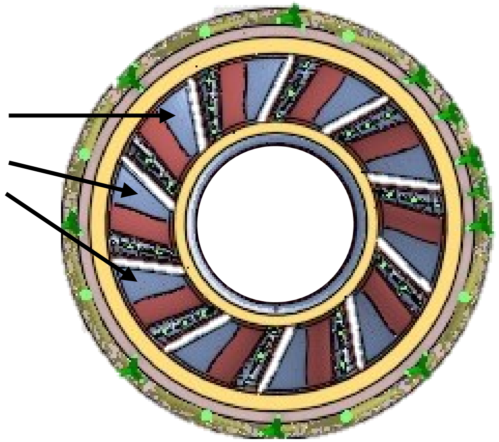
Baseline Vane → Identify downward facing surfaces → Correcting Overhang → Imposing displacement to attached surfaces → Re-assembling the complete geometry

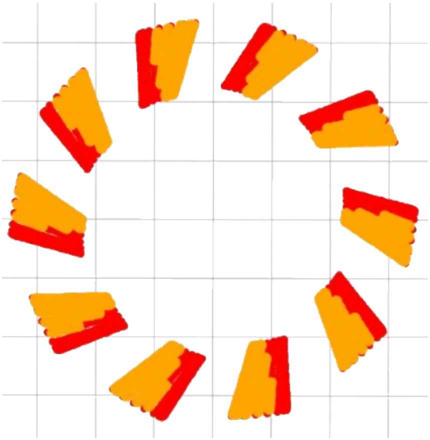
Build dir.

$$overhang\ correction\ displ. = \underbrace{max.displ}_{\text{Scale}} \times \underbrace{\frac{(overhang\ angle\ limit\ - local\ overhang)}{overhang\ angle\ limit}}_{\text{Materials/processes}} \times \underbrace{build\ direction}_{\text{Design}}$$

The overhangs identified using NURBS was in agreement with the 3DXpert setup for 55° self-supporting overhang angle limit on the ProX 320 machine

Critical overhangs identified in 3DXpert



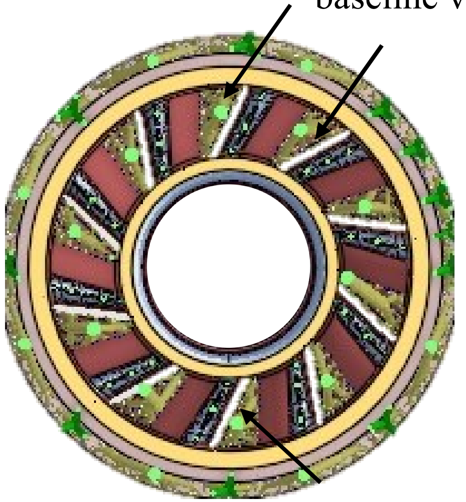


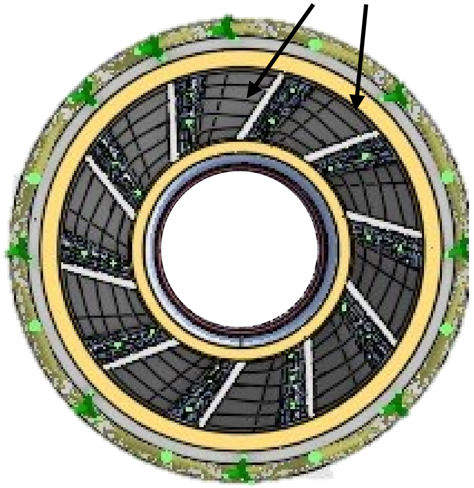
Critical overhangs identified in NURBS geometry

supports required for baseline vanes

No supports required for overhang corrected vanes

Support setup for Baseline Vanes

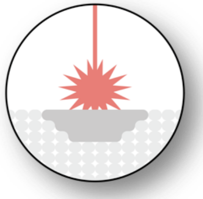




Support setup for DfAM vanes

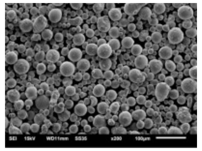
We printed the injector geometries using metal L-PBF on the 3DSystems ProX 320 in Inconel 718 for high temperature creep resistance

Method



Laser -
Powder Bed Fusion

Material

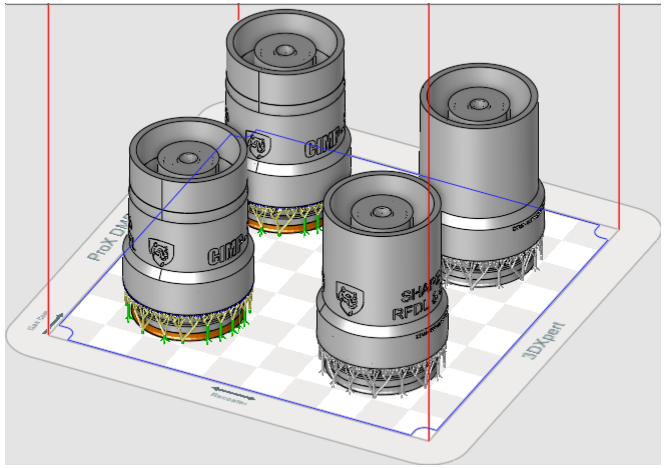


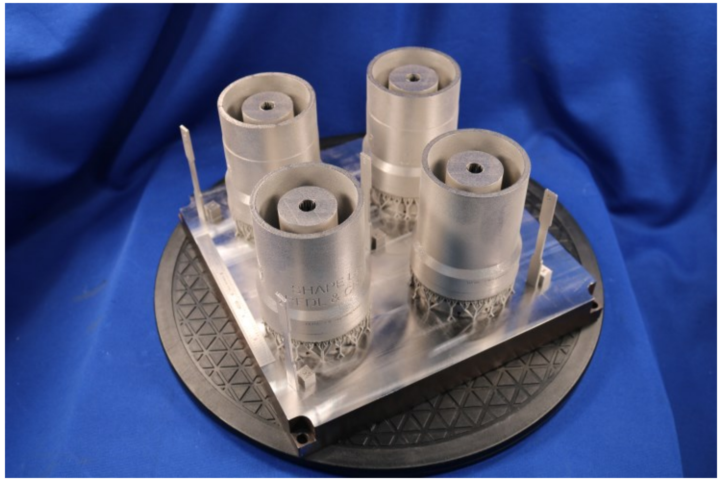
Inconel 718

Machine

3D Systems
Pro X 320

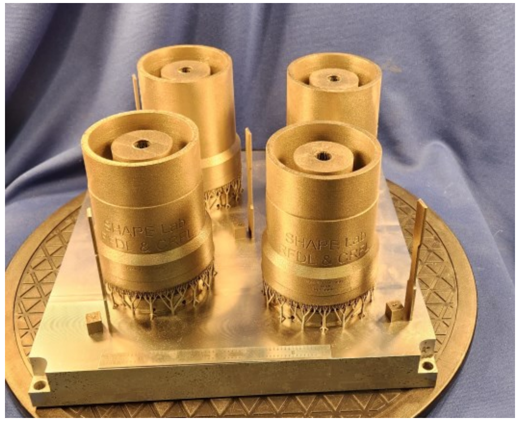
(Zhonggang et. al. (2020), 3D Systems, 3Dhubs)



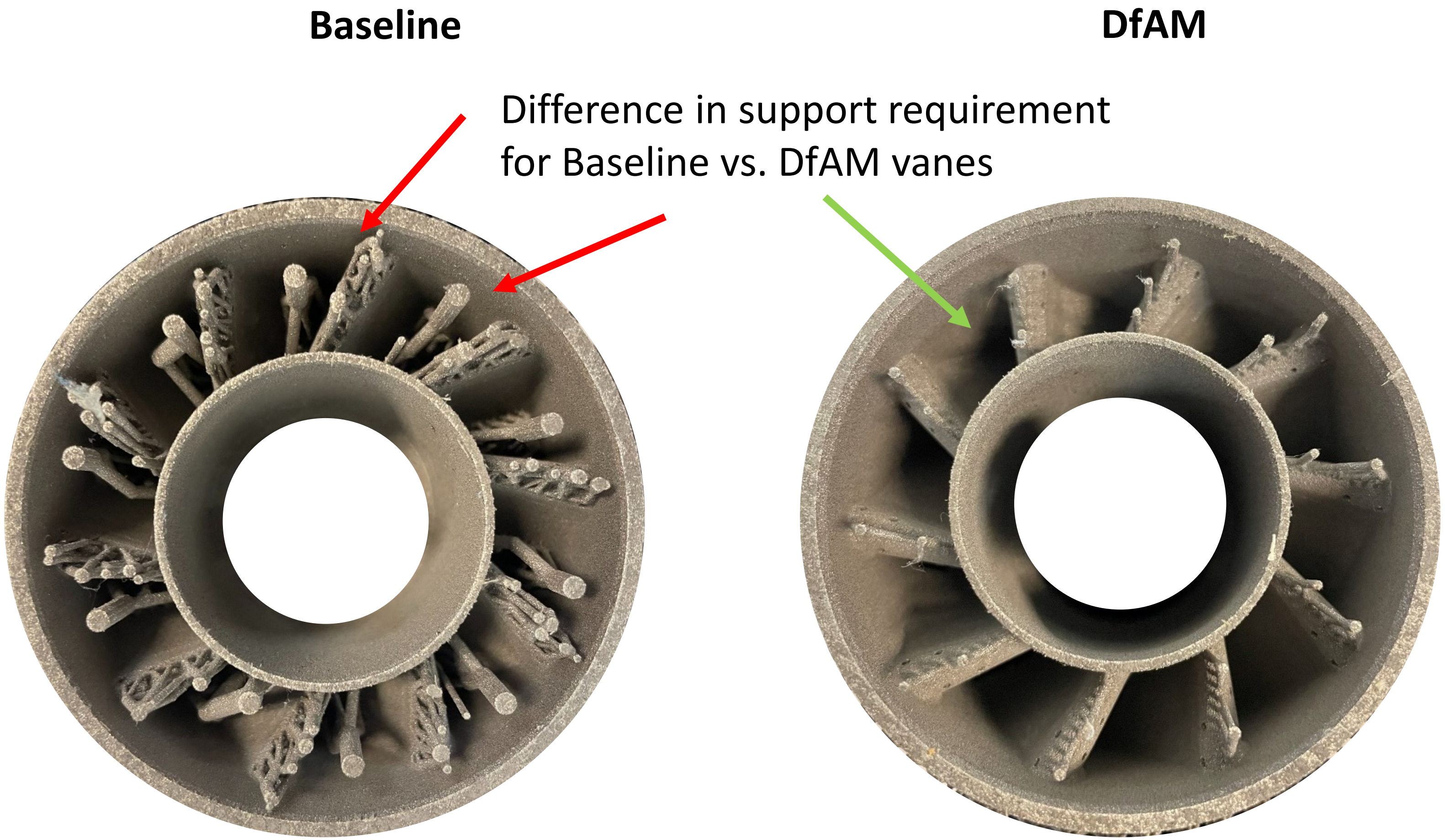


Baseline

DfAM



Having self-supporting structures is essential in AM L-PBF, especially for complex geometry and internal features that are challenging to machine



Baseline

DfAM

Difference in support requirement for Baseline vs. DfAM vanes

Fewer supports

Reduced scan time

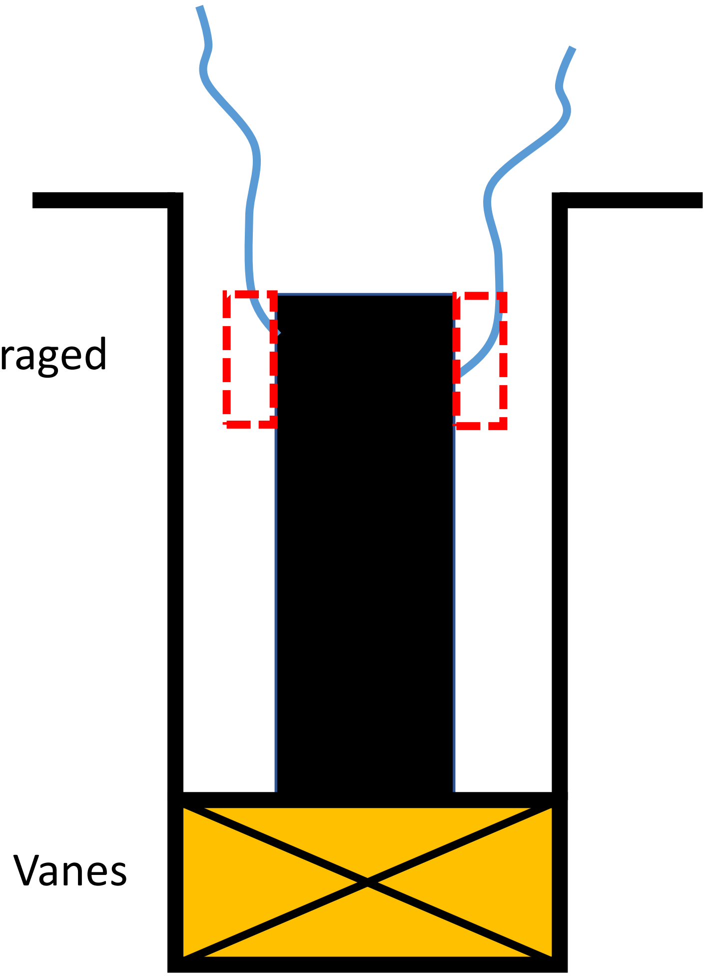
Lower machine time

Improved surface roughness

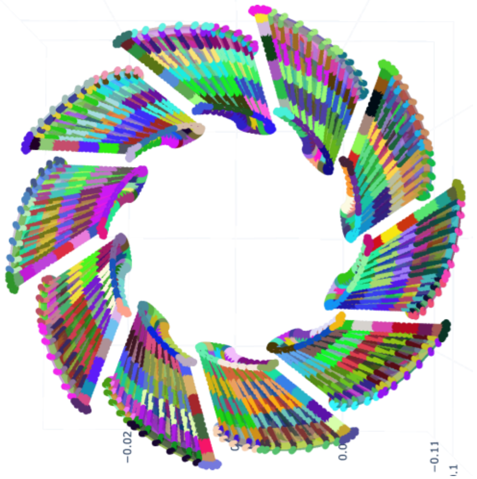
Lower post-processing costs

Incorporating combustion behaviors to optimize a design minimizing flame flashback propensity

Maximize
volume-averaged
velocity



By changing Vanes



Obtain NURBS

Baseline Design

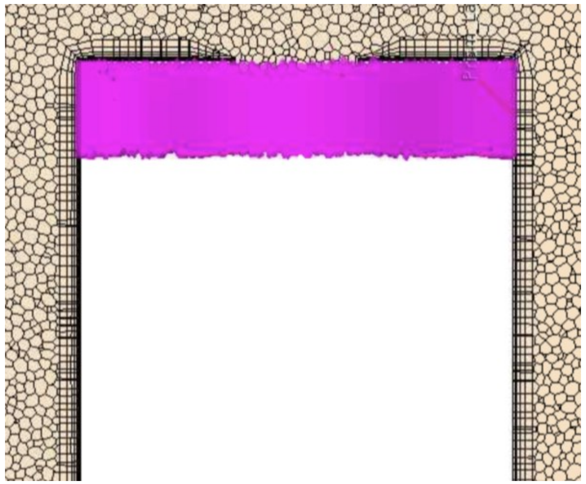
Maximize volume-averaged velocity

Turbulent boundary layer thickness

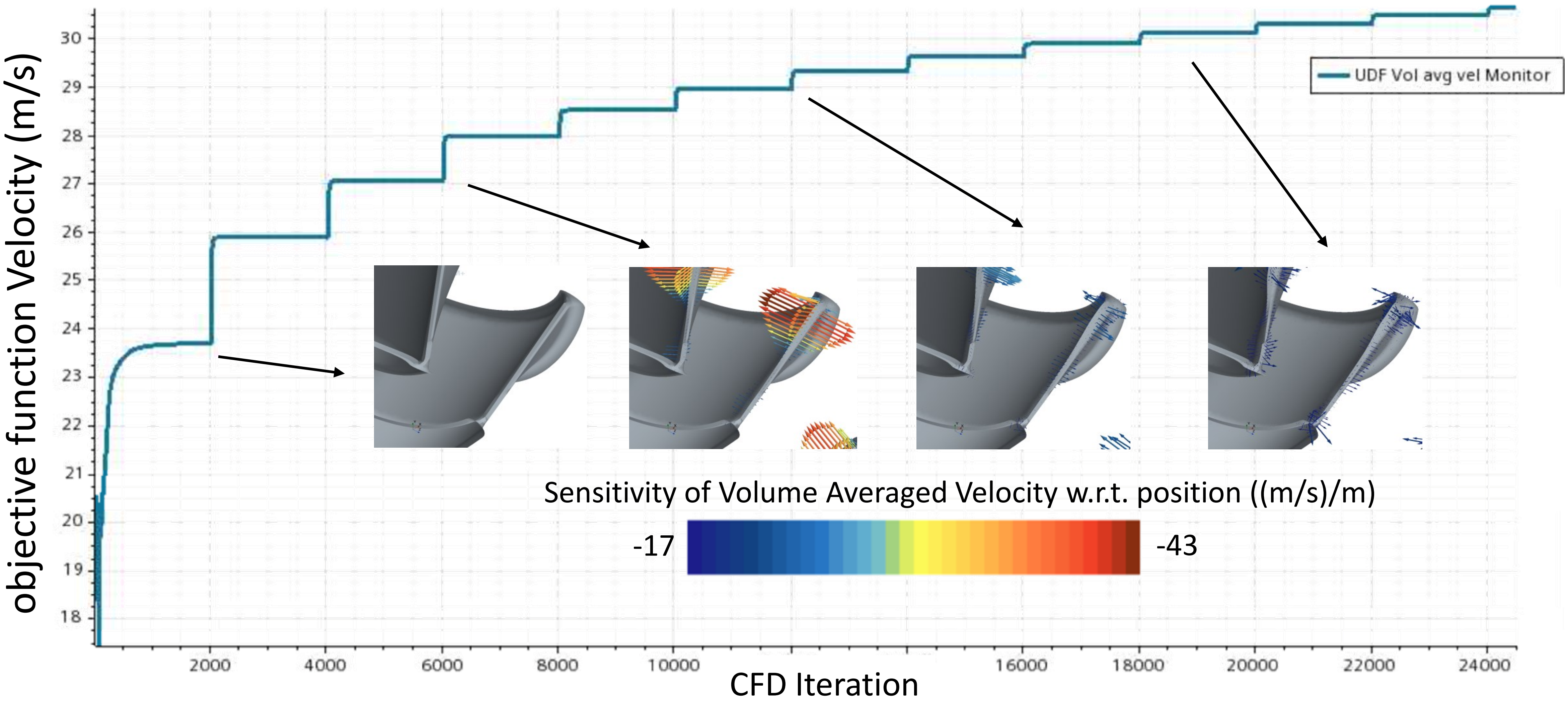
0.685 mm

6.85 mm

10:1



Integration of design for AM (DfAM) and combustion behaviors to optimize a design for fuel-flexible operation



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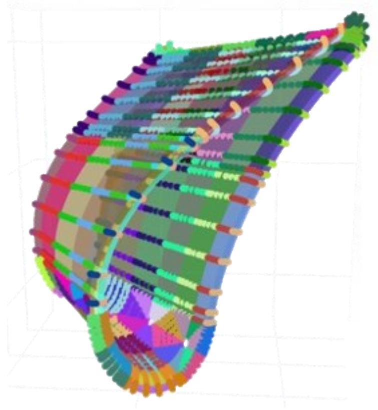
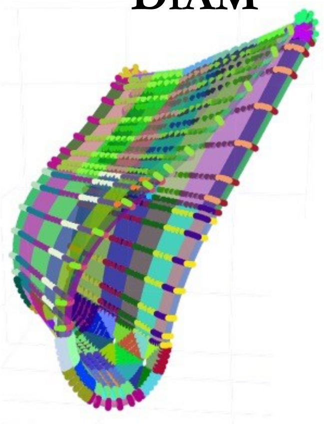
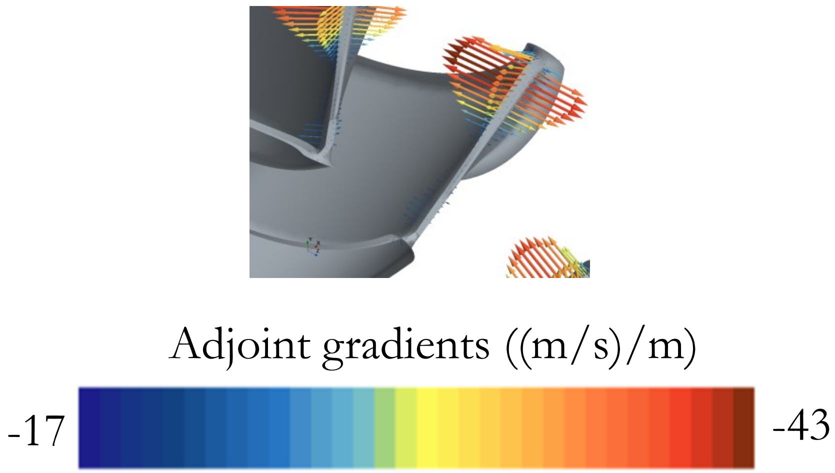
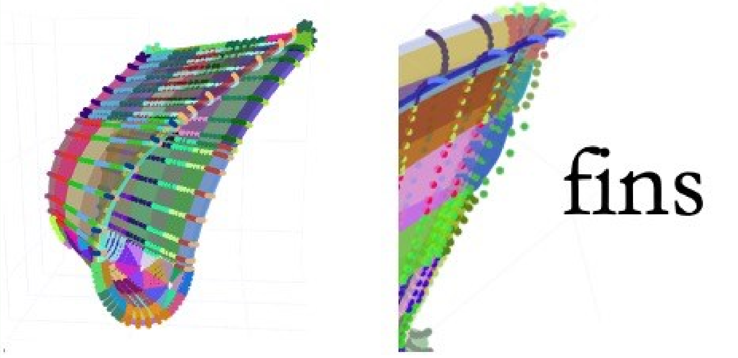


DfAM

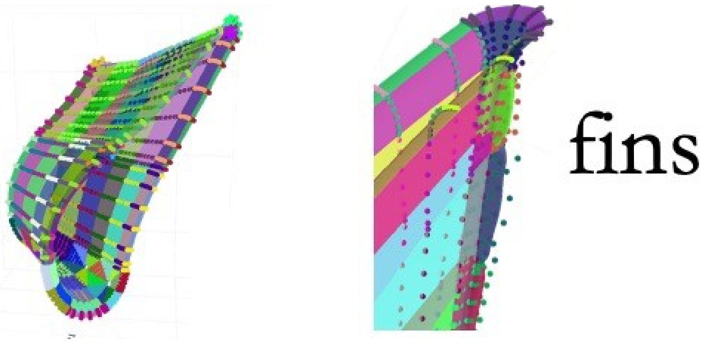




Flow Optimized

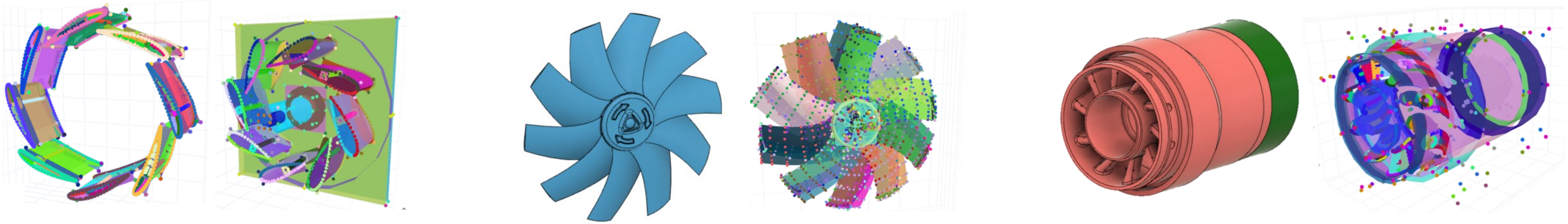


DfAM+flow optimized



Use of commercial tools and open-source resources (Python code, standard CAD definitions, etc.) to implement optimization for better translation

IGES file → Read NURBS → NURBS-Python (geomdl) → Modify & Replace NURBS → Modified IGES file



IGES file represents virtually any given CAD shape, free-form surfaces are stored as NURBS

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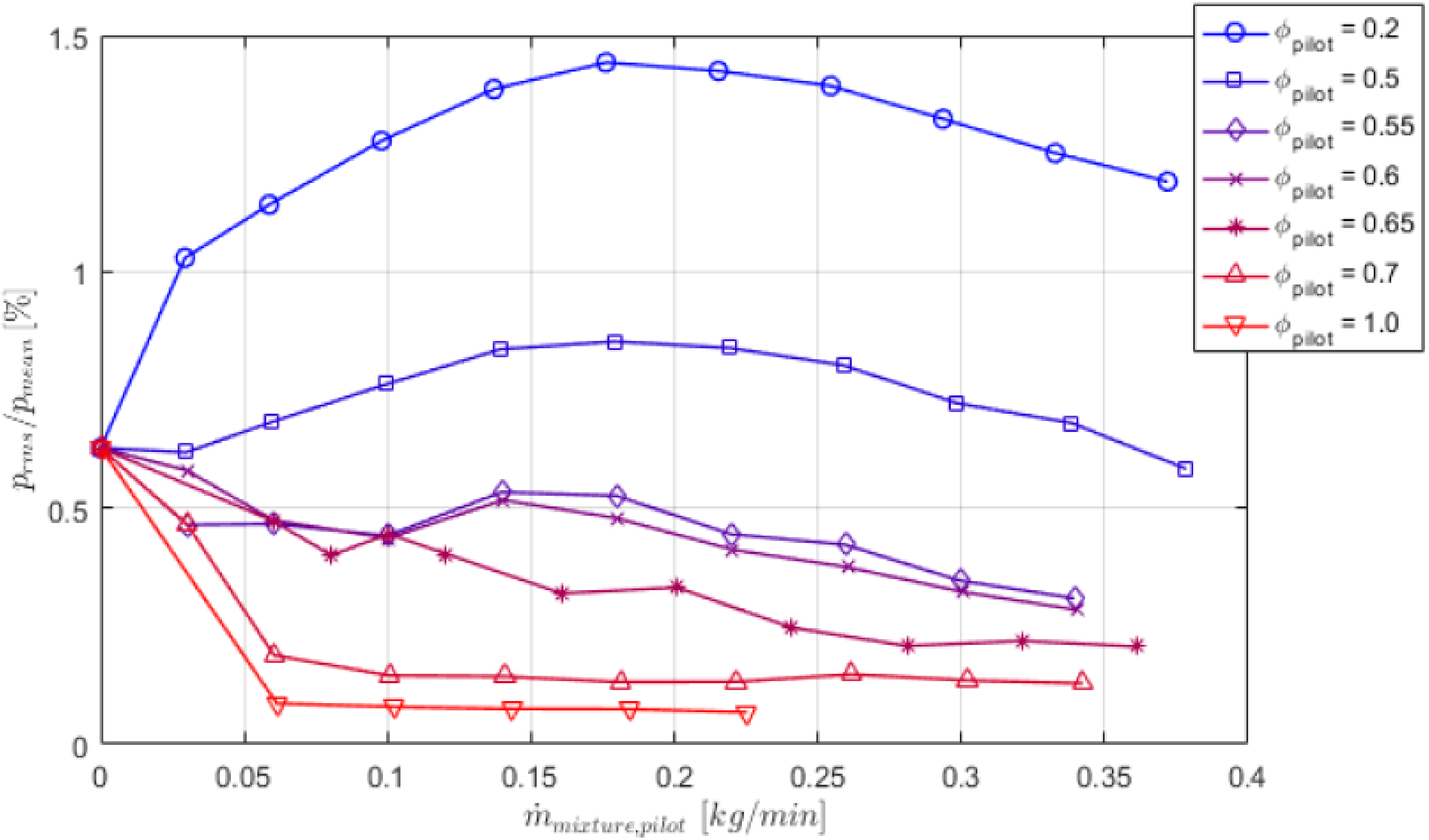
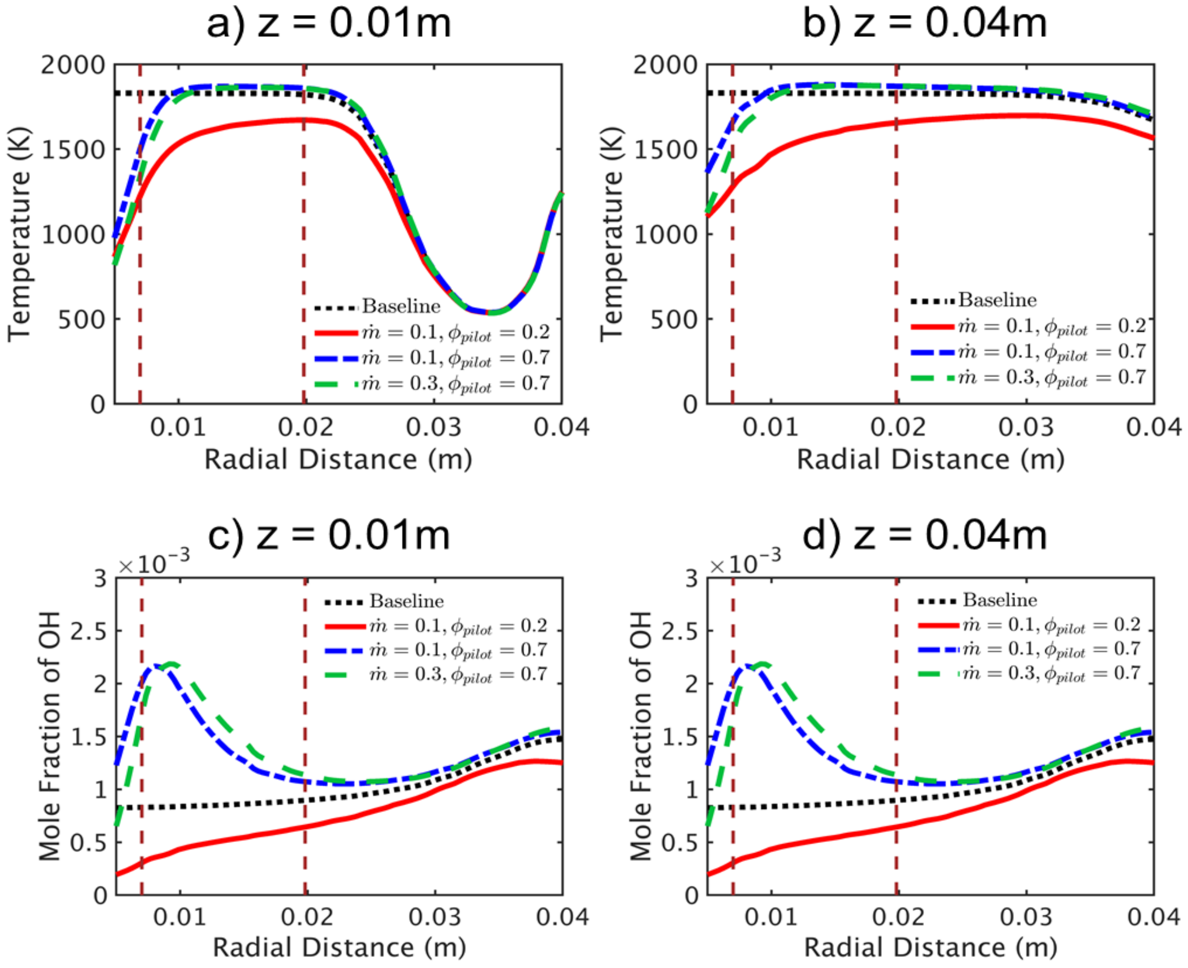
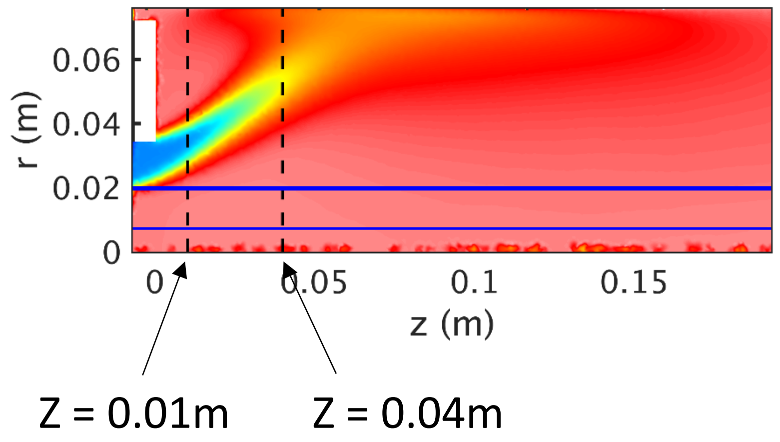
Effects of pilot flame equivalence ratio and mass flow rate on combustion instability suppression explored in combined experimental + computational study



Li, J., Kwon, H., Seksinsky, D., Doleiden, D., Xuan, Y., O'Connor, J., Blust, J., Akiki, M., (2021) "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

Higher pilot equivalence ratio leads to higher temperatures and higher radical concentrations in the recirculation region





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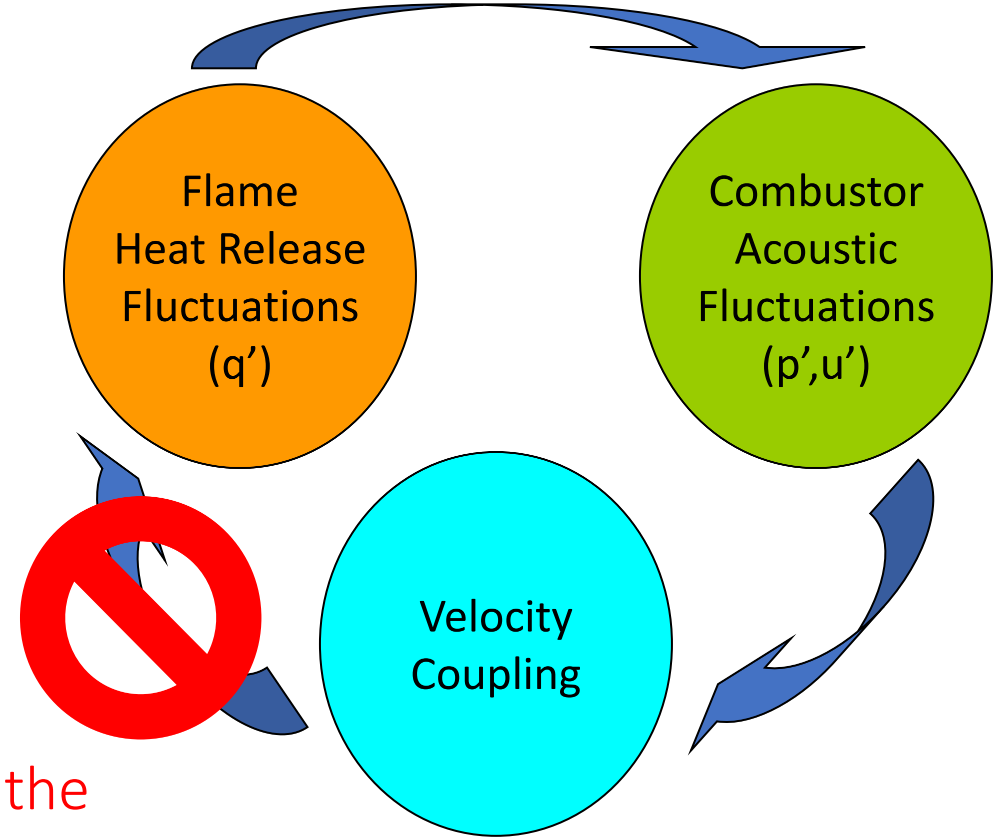
While previous work suggested that pilot flames help suppress instability through a thermal mechanism, we know velocity-coupling processes are important



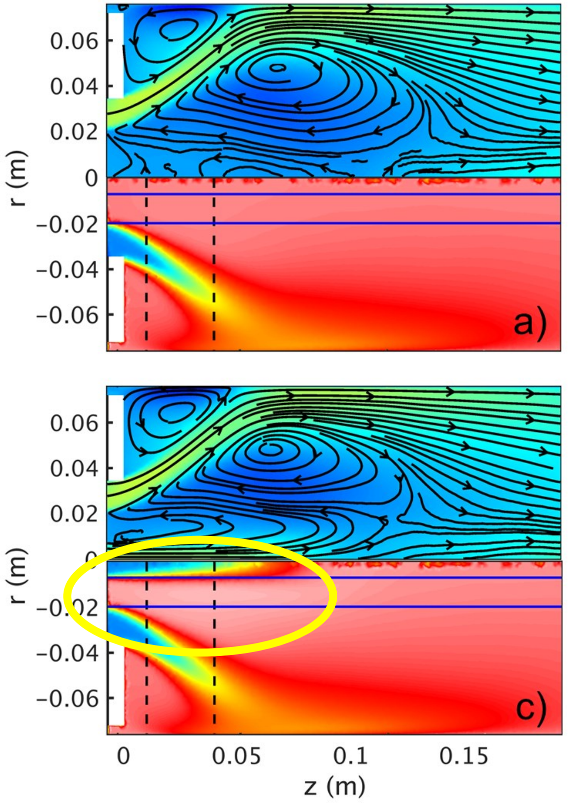
Flame Heat Release Fluctuations (q’)

Combustor Acoustic Fluctuations (p’,u’)

Velocity Coupling

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

Baseline



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

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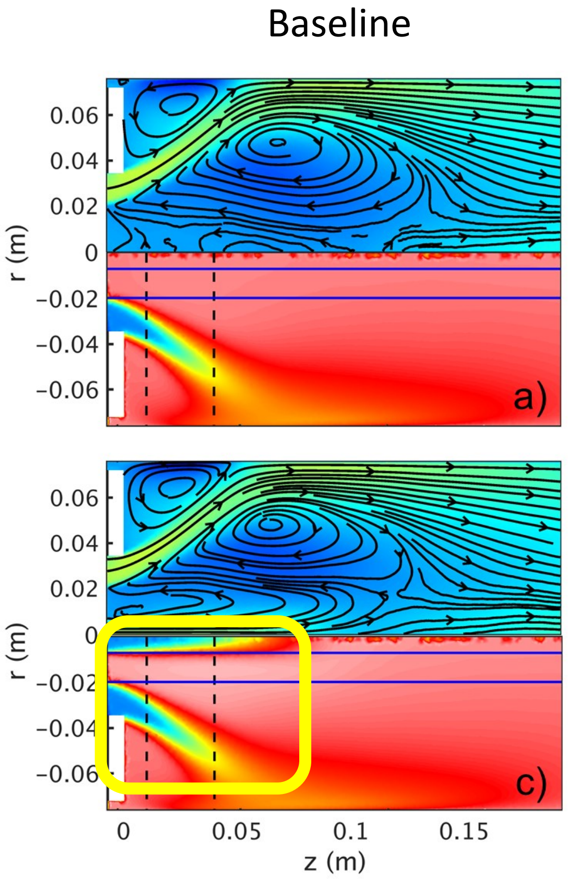

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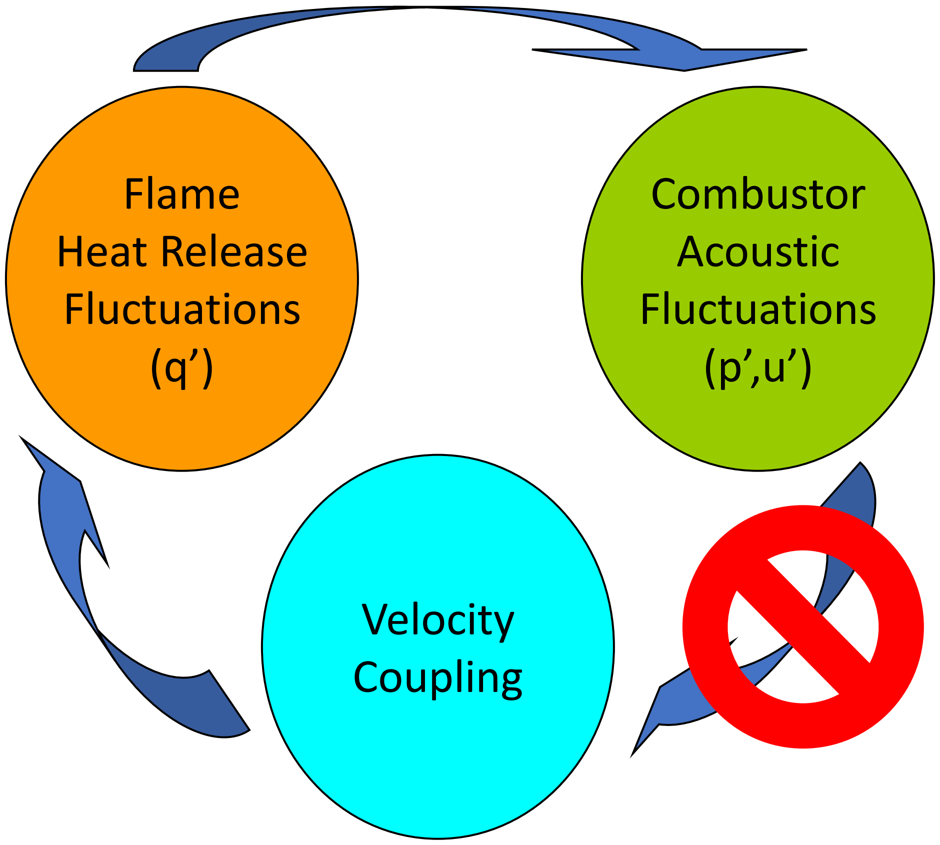


Flame
Heat Release
Fluctuations
(q’)

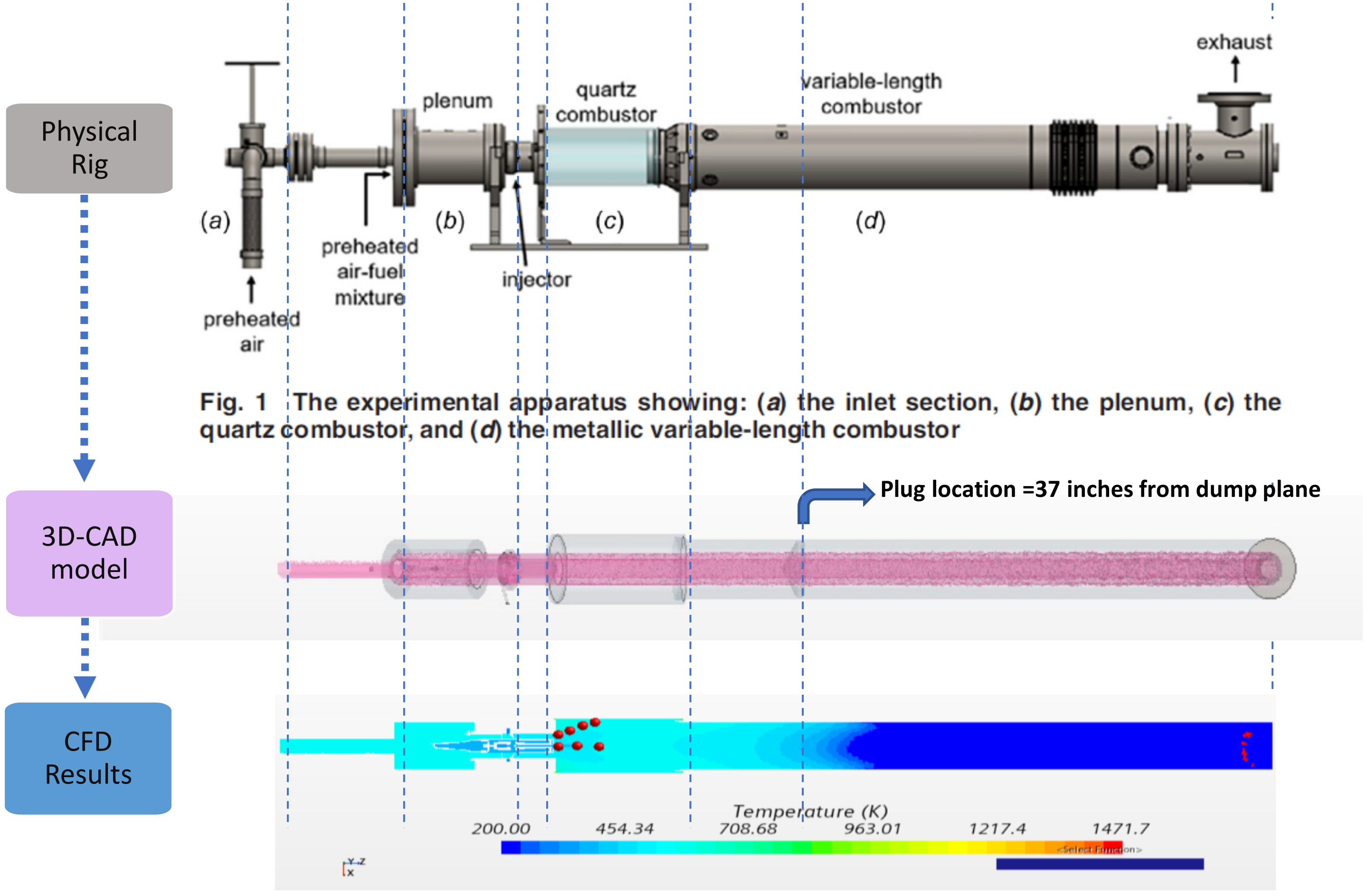
Combustor
Acoustic
Fluctuations
(p’,u’)

Velocity
Coupling

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

The experiment is modeled and simulated using LES in STARCCM+ for a range of pilot flow rates that mimic the experiments

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 2nd 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


Physical Rig

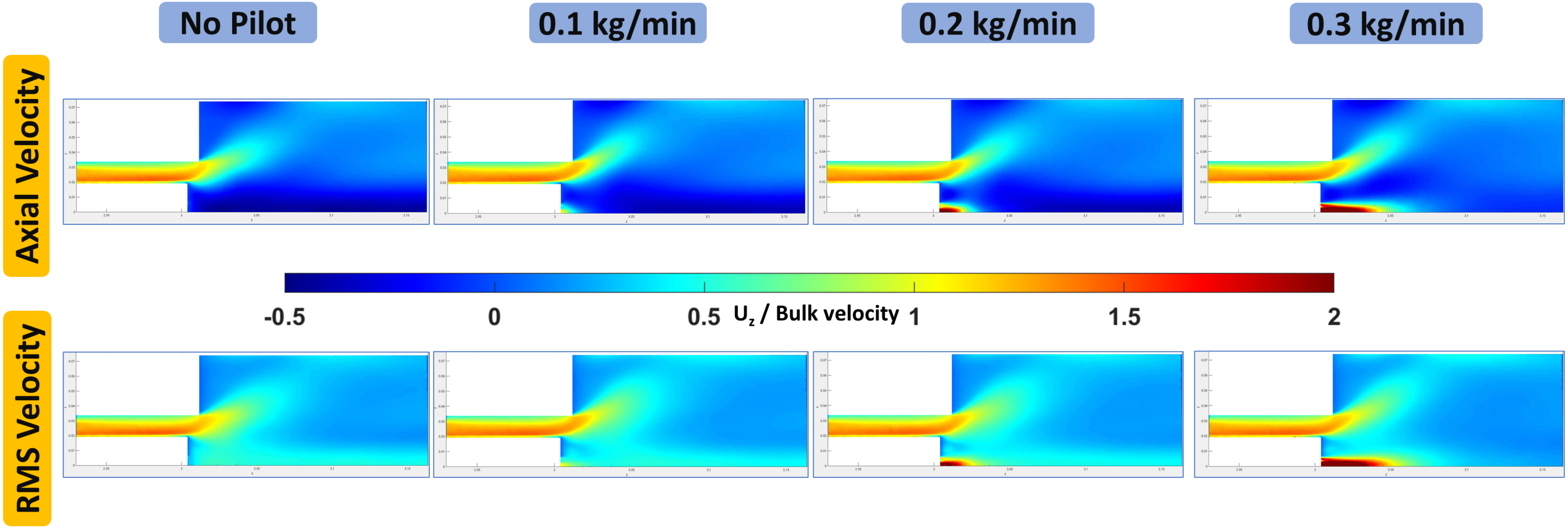
3D-CAD model

CFD Results

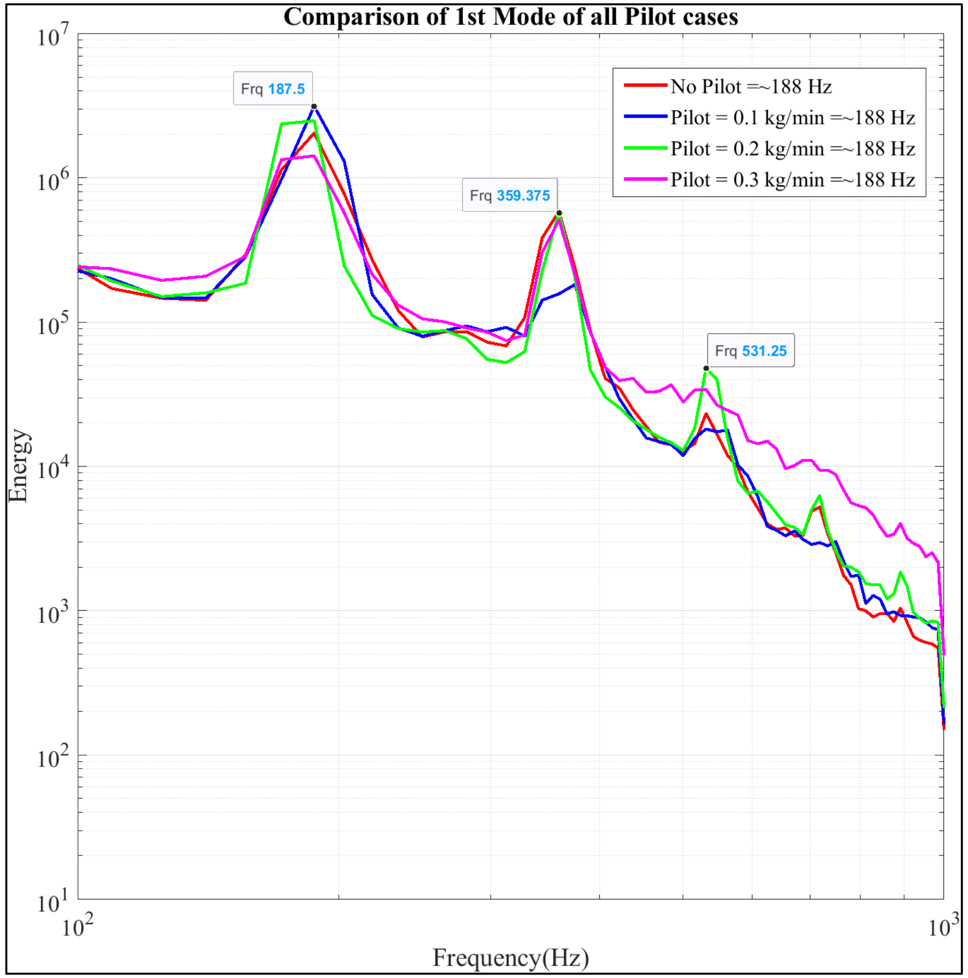
Fig. 1 The experimental apparatus showing: (*a*) the inlet section, (*b*) the plenum, (*c*) the quartz combustor, and (*d*) the metallic variable-length combustor

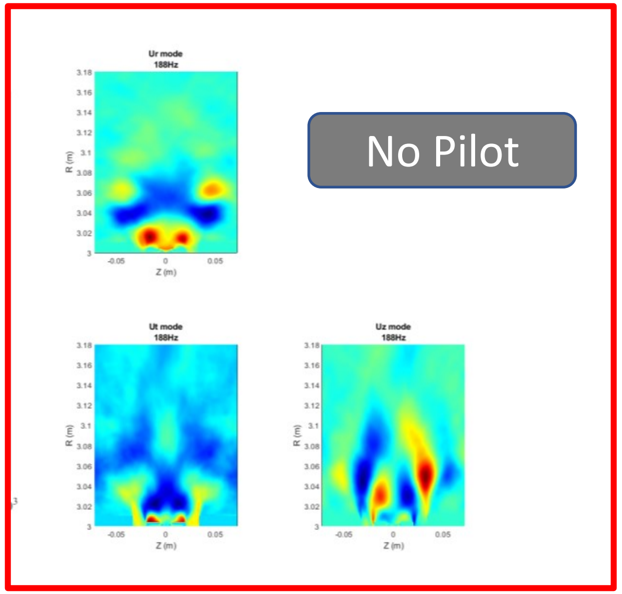
Plug location =37 inches from dump plane

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

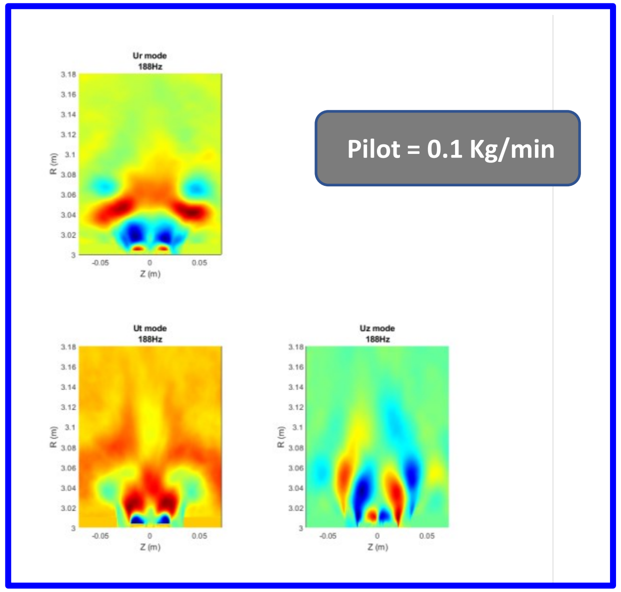


Spectral proper orthogonal decomposition is used to understand the dynamics of the system, where all cases show significant oscillations in the shear layer

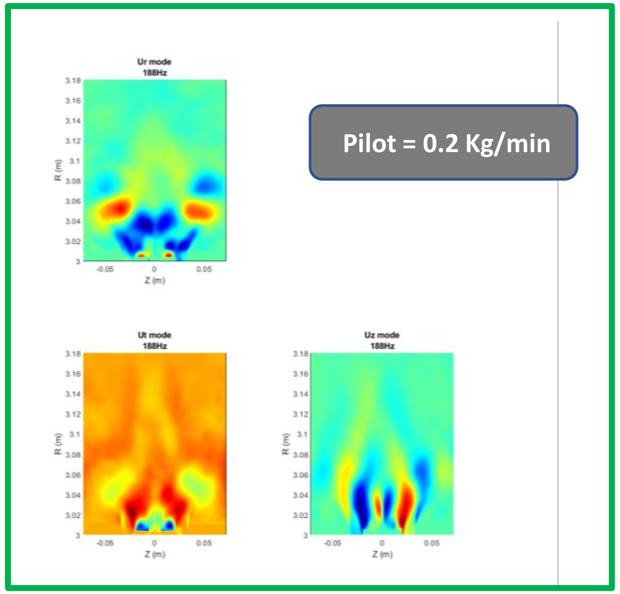




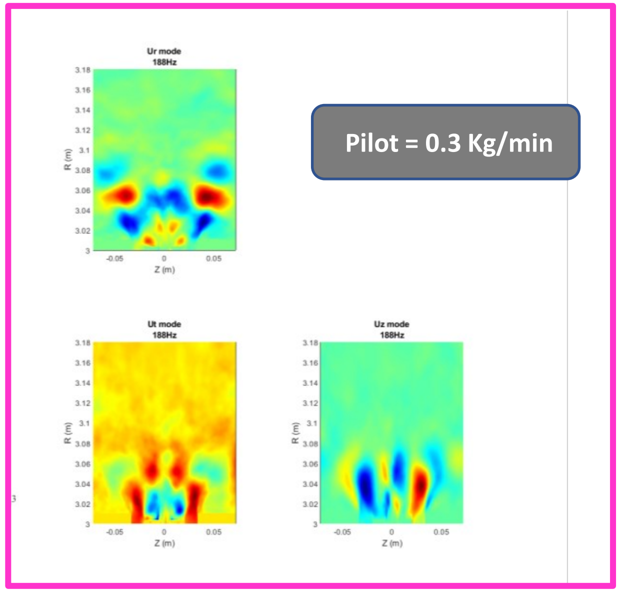
No Pilot



Pilot = 0.1 Kg/min



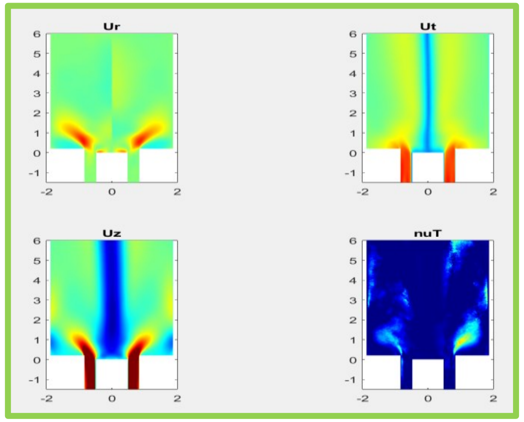
Pilot = 0.2 Kg/min



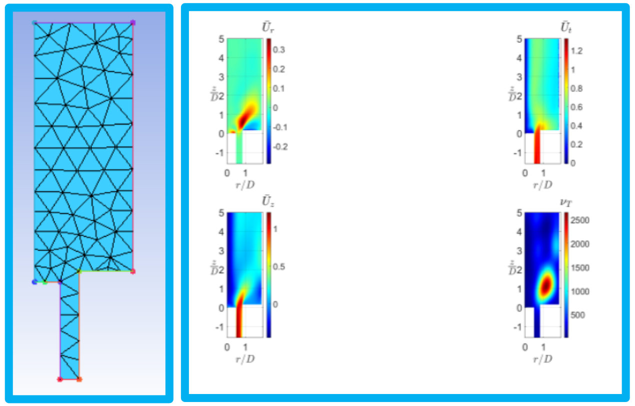
Pilot = 0.3 Kg/min

The stability of the system is analyzed using a linear hydrodynamic stability tool – FEHydro – to determine

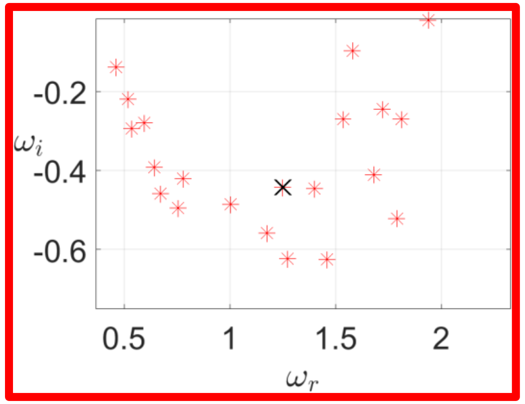
1. Obtain Time Averaged fields of velocities and eddy-viscosity



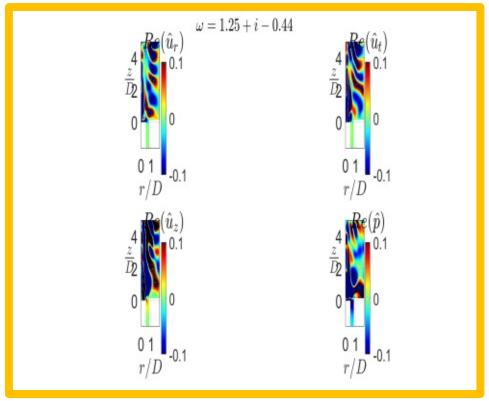
2. Interpolate normalized Data onto Triangular adequately refined Mesh



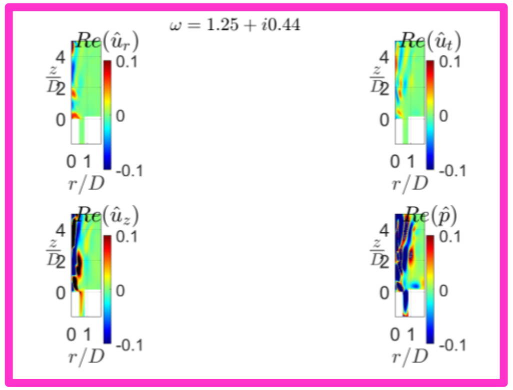
3. Global Eigenvalue Spectrum



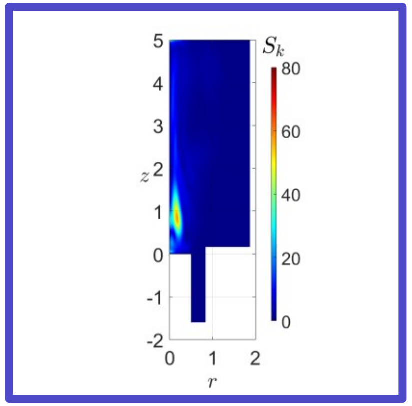
4. Spatial Variation of the Eigen Components



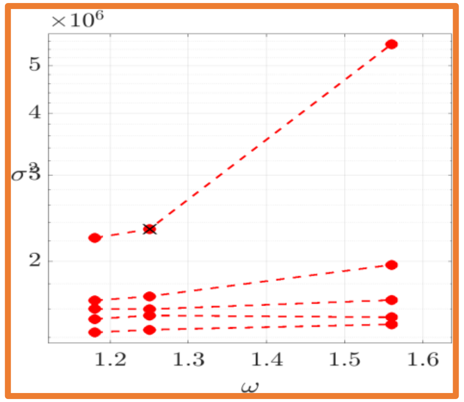
5. Generate the Adjoint of the dominant mode



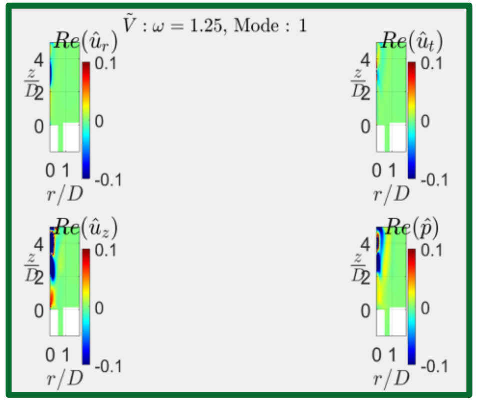
6. Structural Sensitivity analysis provide to regions of the flow most sensitive to disturbances



7. Resolvent Analysis: Modes respond strongly to external forcing



8. Corresponding mode-shapes from resolvent analysis



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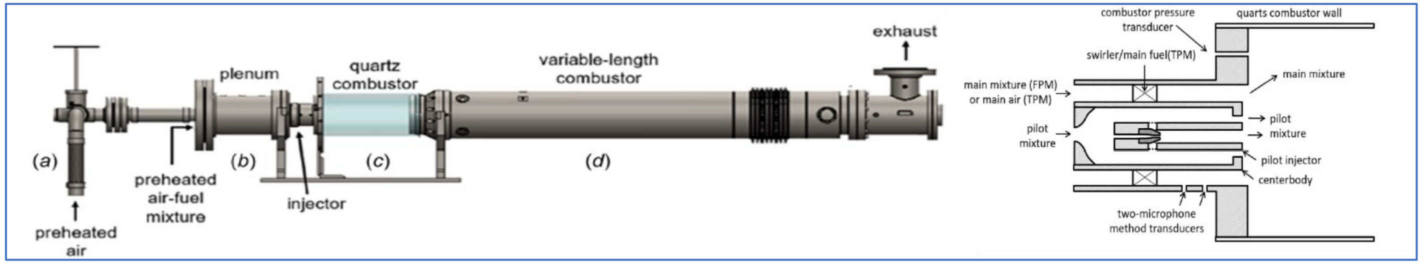
4. Better understanding of the role of pilot jets in flow stability, flameholding

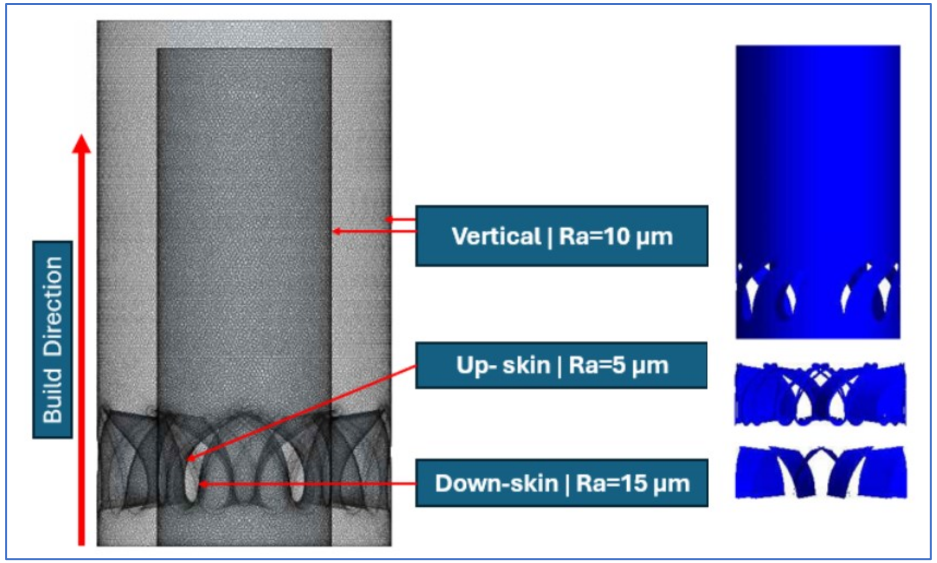
5. New understanding of the impact of AM surface roughness on flameholding

6. Design and testing of both optimized injector designs and clean-sheet design based on lessons learned from optimization process

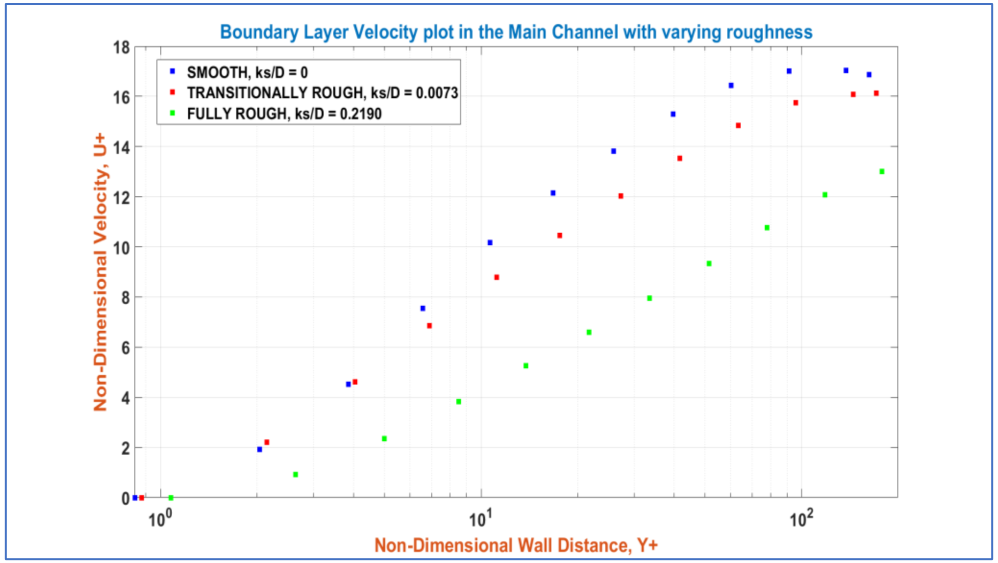
Realistic equivalent sand-grain roughness were defined in the RANS simulation performed to study roughness effects on flame stability



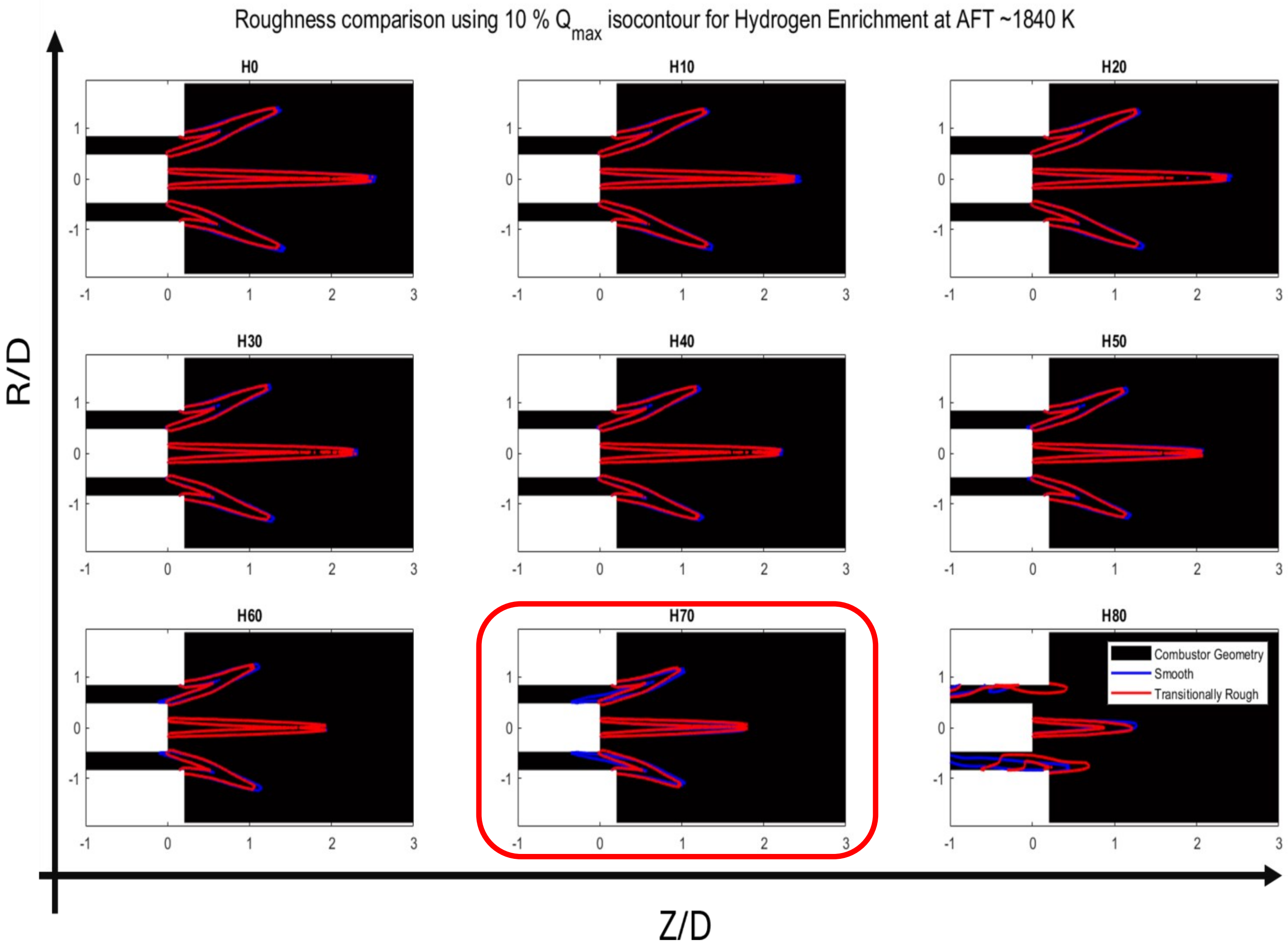
As-built roughness for the printed injector selectively and realistically simulated

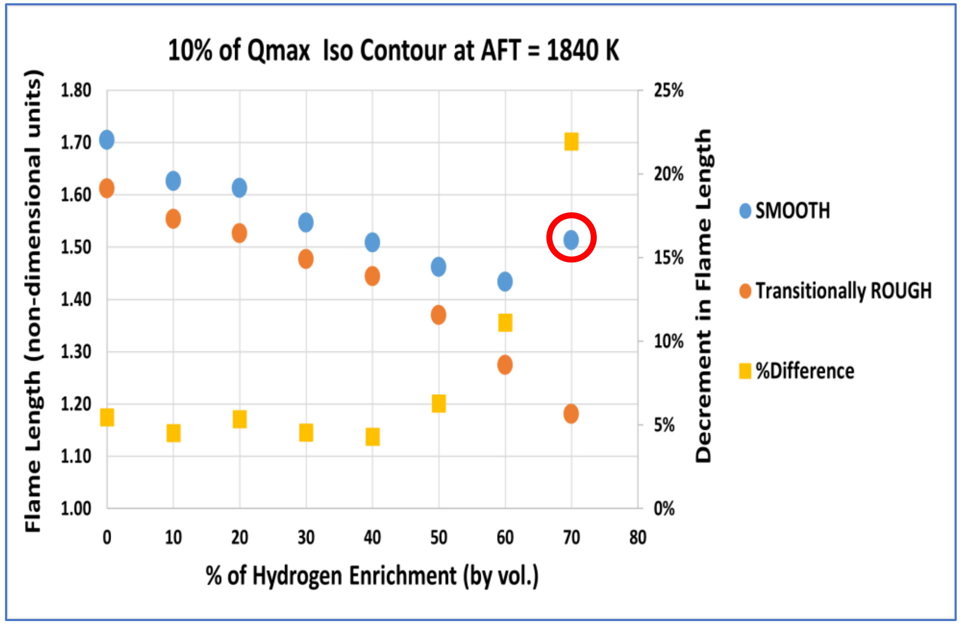


Change in Boundary layer profile for different roughness regimes in the Vertical section of injector



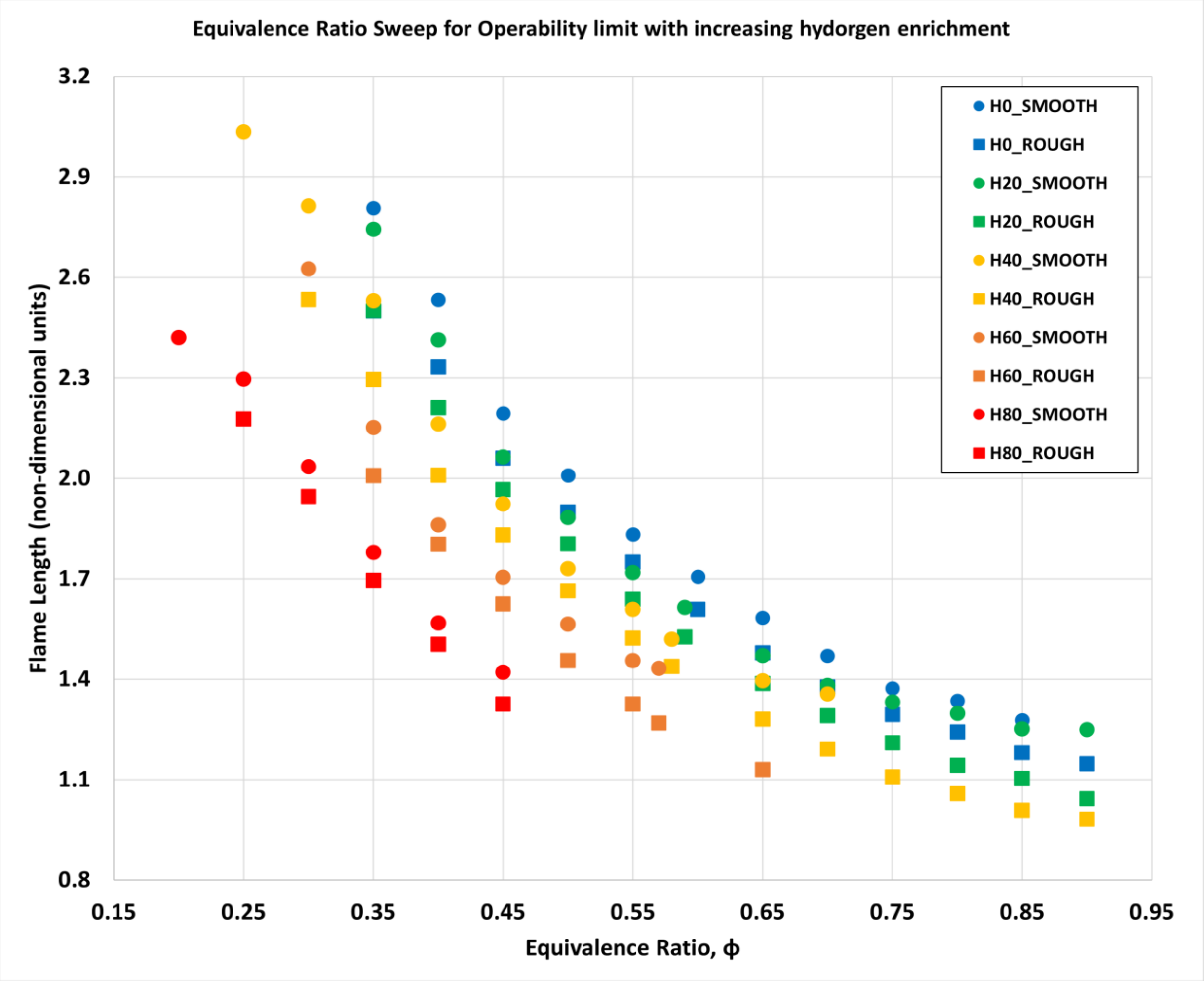
The heat release distributions show decrease in flame-length between rough and smooth injector



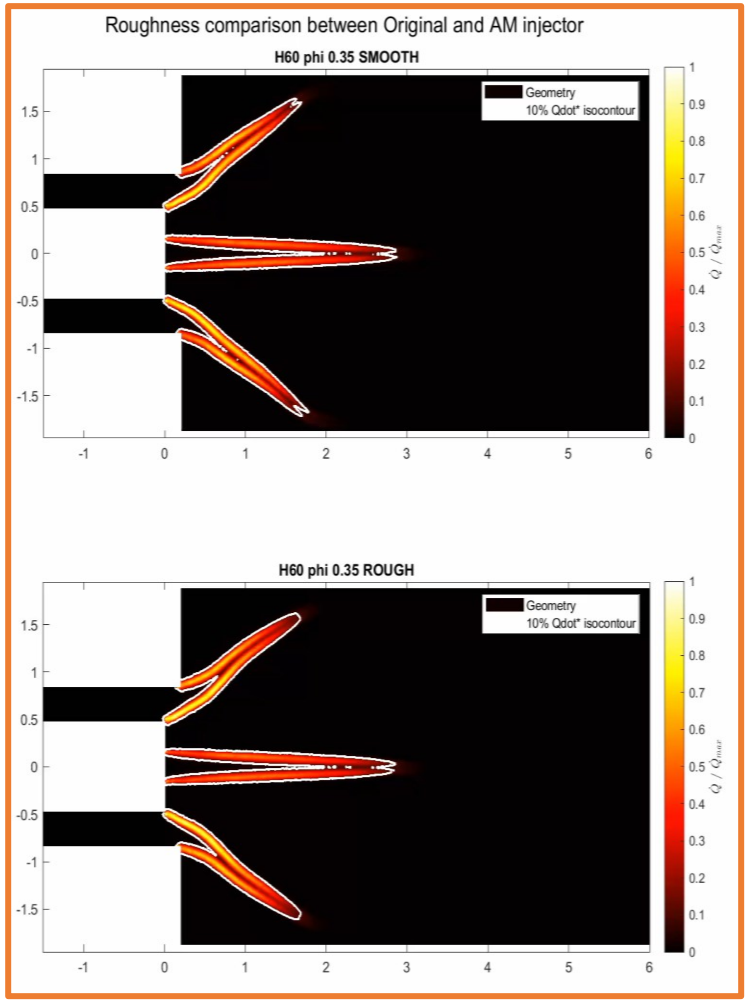


At H70 case, the flame-length is both the actual flame-length as well as the flashback length, hence the overall flame-length increases in the smooth Injector.

With increasing hydrogen enrichment, smooth injector becomes blow-off resistant, whereas rough injector is resistant to flashback.



60% H2
(phi-0.35-0.75)

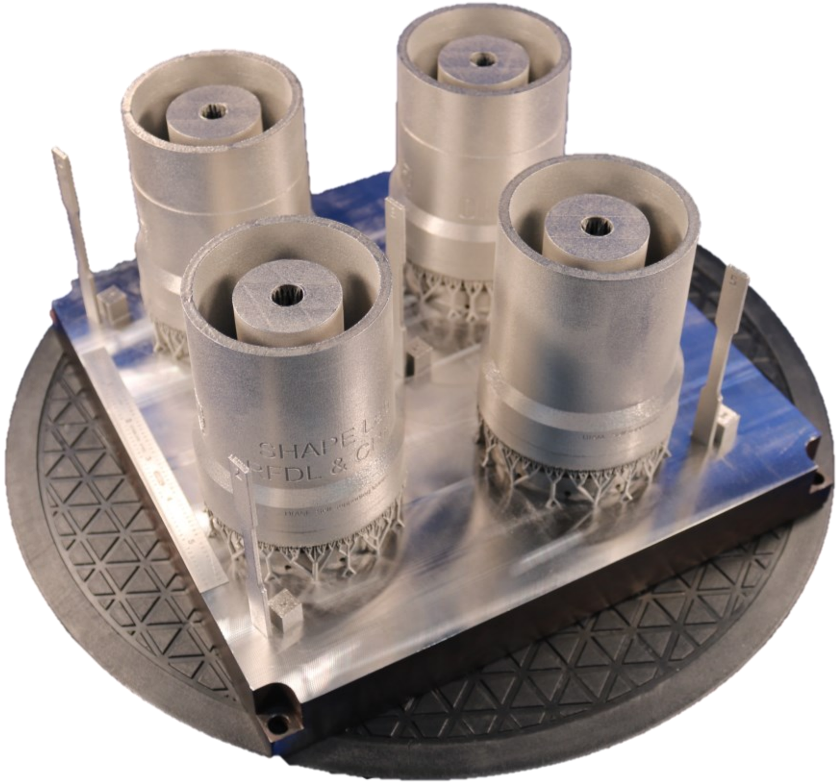


Major accomplishments of this program

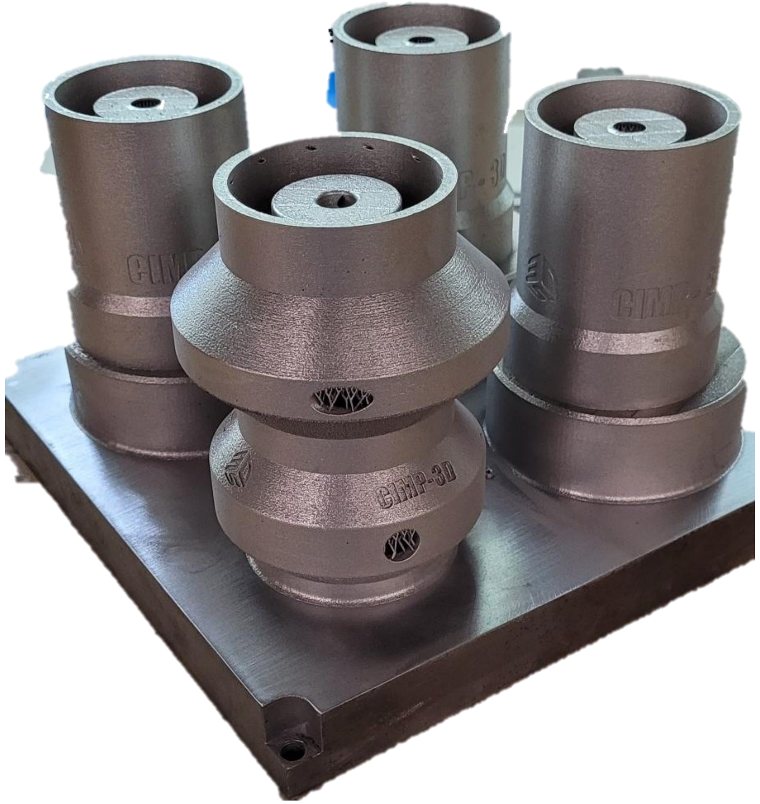
1. Integration of design for AM (DfAM) and combustion behaviors to optimize a design for fuel-flexible operation
2. Use of commercial tools and open-source resources (Python code, standard CAD definitions, etc.) to implement optimization for better translation
3. AM optimization based on mathematical formulation rather than grid-based, allowing better transference to other applications
4. Better understanding of the role of pilot jets in flow stability, flameholding
5. New understanding of the impact of AM surface roughness on flameholding
6. Design and testing of both optimized injector designs and clean-sheet design based on lessons learned from optimization process

Design and testing of both optimized injector designs and clean-sheet design based on lessons learned from optimization process

Build #1 :
Baseline & DfAM designs with different surface roughness (processing)



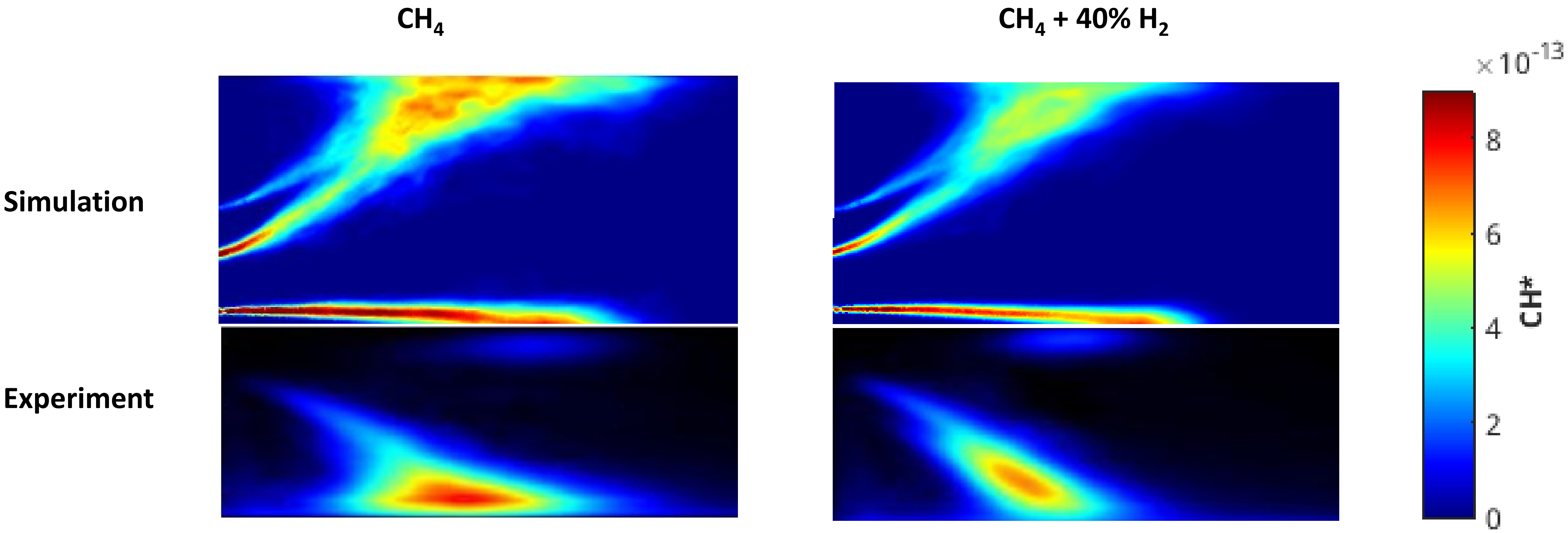
Build #2 :
DfAM + Flow optimized designs with fuel delivery; Clean-sheet design



Part consolidation using AM:
10 parts → 1 part

Fuel Injector

The CH* chemiluminescence images collected experimentally matched up the trends with the CH* distribution obtained from the simulations of the baseline

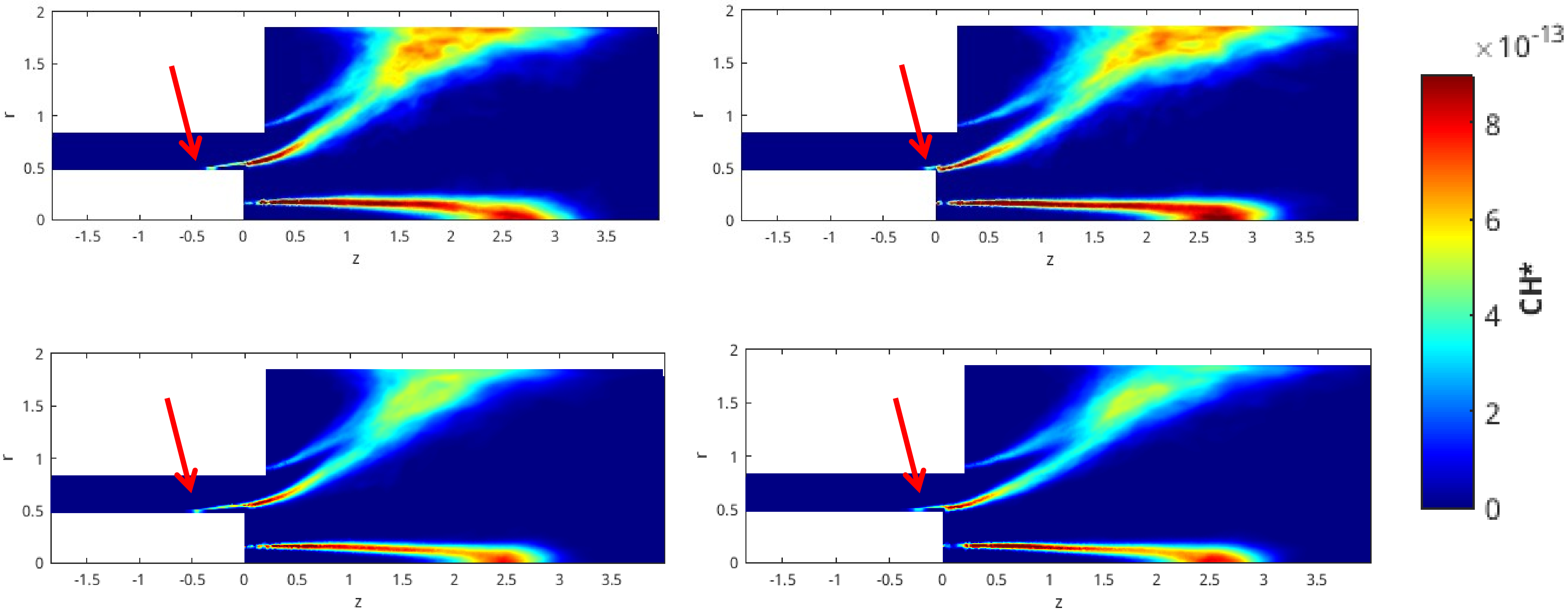


We also ran the same simulation settings on the DfAM geometry, and we did see that the flame anchored upstream

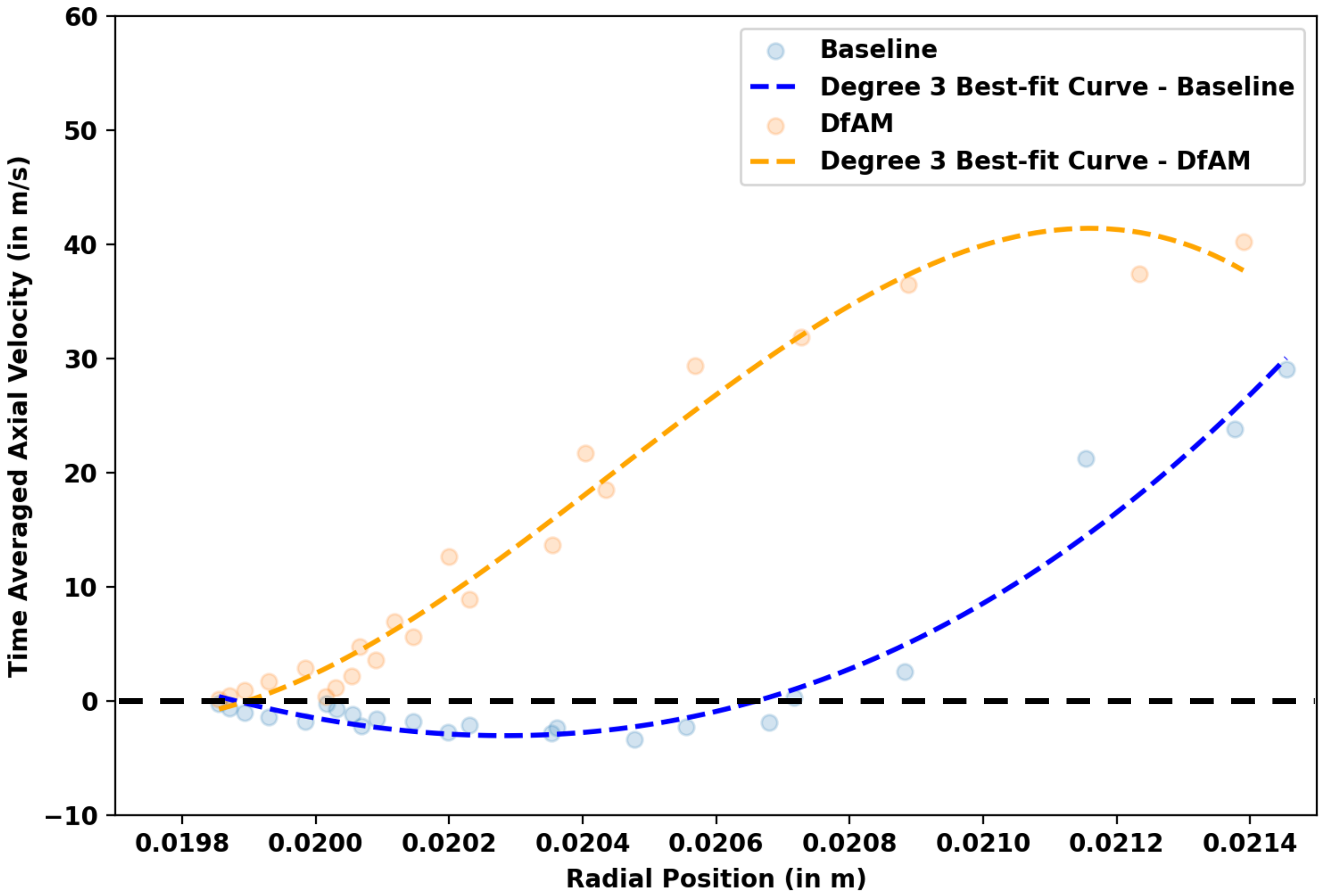
Baseline **DfAM**

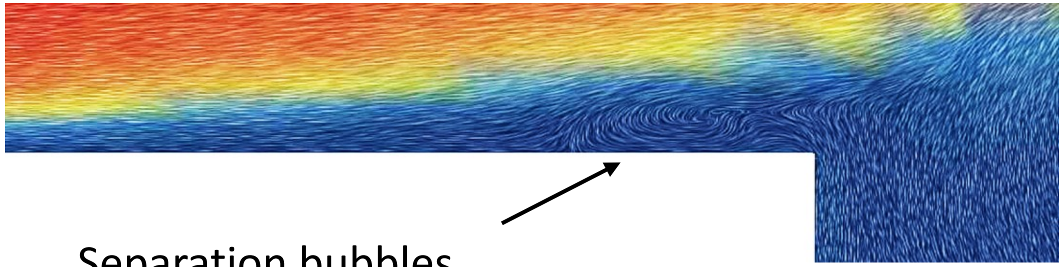
CH_4

CH_4 + 40% H_2



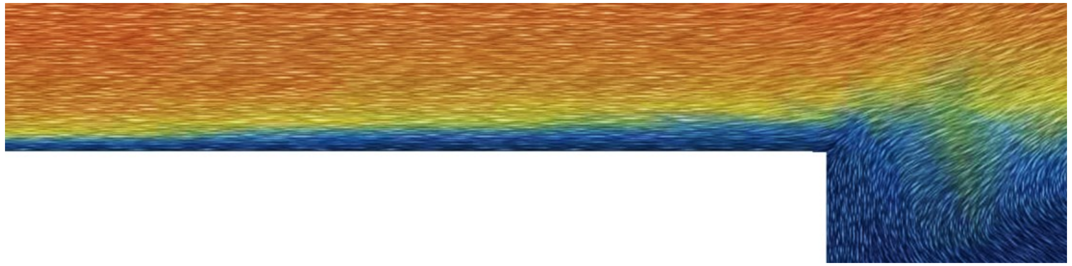
We found near wall negative velocities (flow separation) in LES for the baseline design which represents complex flow features not captured by RANS



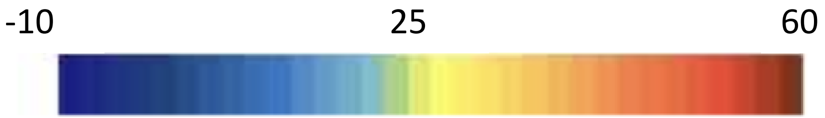


Separation bubbles

DfAM



Time-averaged axial velocity (m/s)



DfAM design changes the swirl number such that boundary layer separation does not occur

Design and testing of both optimized injector designs and clean-sheet design based on lessons learned from optimization process

Discrete adjoint method - CFD

- Checks primal convergence
- Performs adjoint calculations
- Provides gradients for large no. of design variables
- StarCCM+

Additive Manufacturing constraints

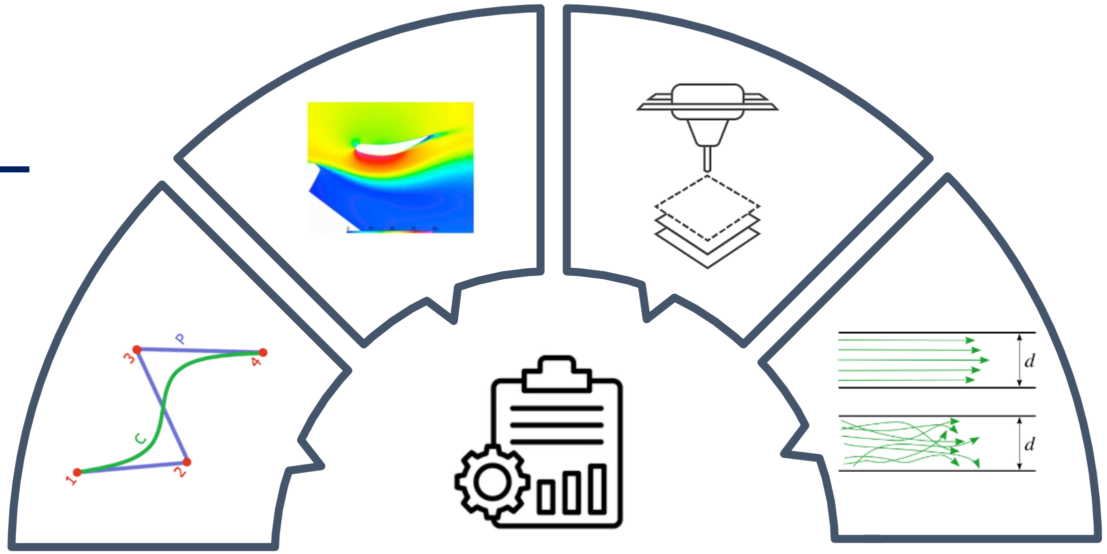
- Ensures fabrication of complex structures
- Enables generation of self-supporting structures
- 3DXpert, Control X, Pro X 320, IN718

NURBS-based design

- Represents complex, organic shapes
- Provides control points
- Info exchange stored in standard CAD formats – IGES
- DesignX, Python 3.9 – geomdl

Physics Considerations

- Ensures flame stability
- Prevents flashback
- Accounts for fuel flexibility



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)
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