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

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

Project Review – November 18, 2020

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Graduate students: Sagar Jalui, Hyunguk Kwon, Drue Seksinsky
Undergraduate students: Nathan Love

Mechanical Engineering
Pennsylvania State University

Industry Partner: Solar Turbines Incorporated
Engineers: Hanjie Lee, Michel Akiki, Dave Voss

PennState

Overview of presentation

- Background and technical approach
- Highlights from Year 1
  - Defining geometry
  - Simulating combustion
  - Constraints from additive manufacturing
  - Experimental design
- Optimization process and next steps

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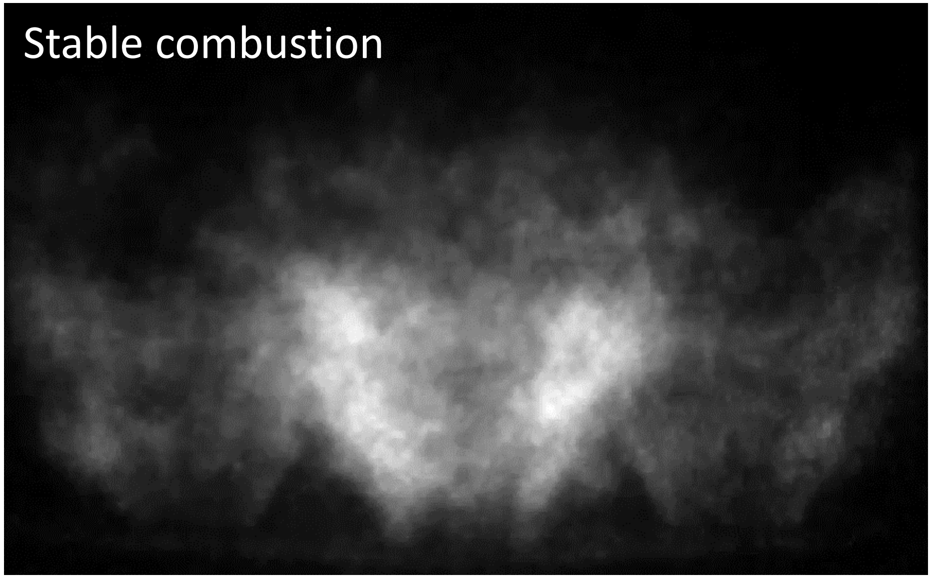
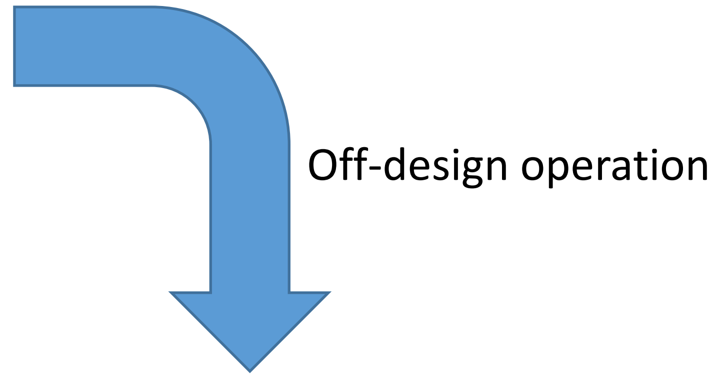
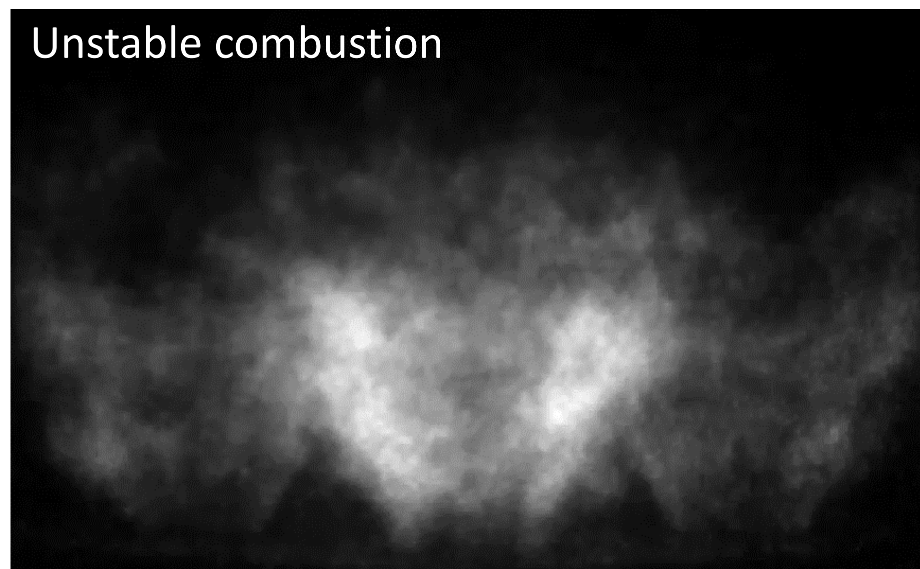
Project origin: Discussions with industry about issues related to combustion operability and fuel injector manufacturing

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

Current fuel injector designs do well at flame stabilization for a moderate range of fuel compositions, operating conditions



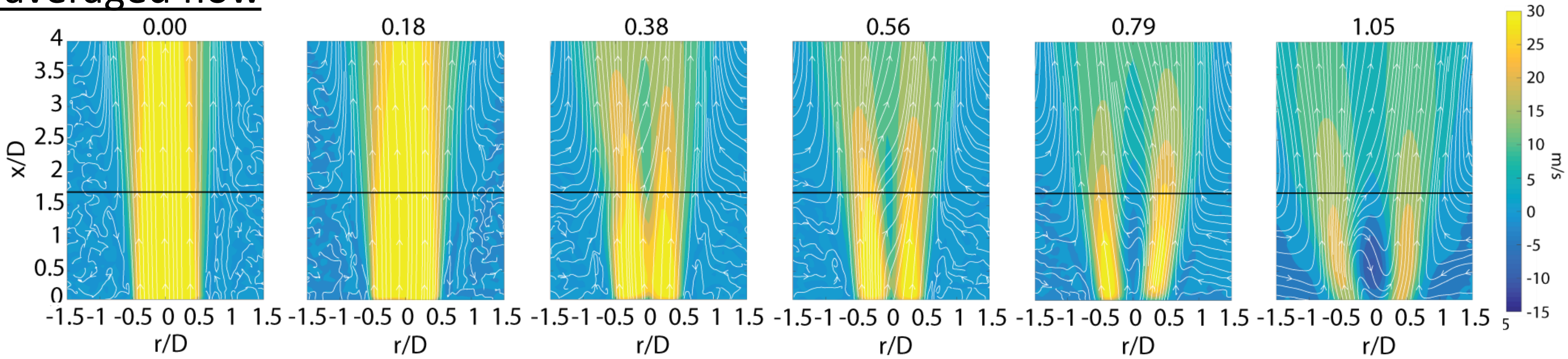




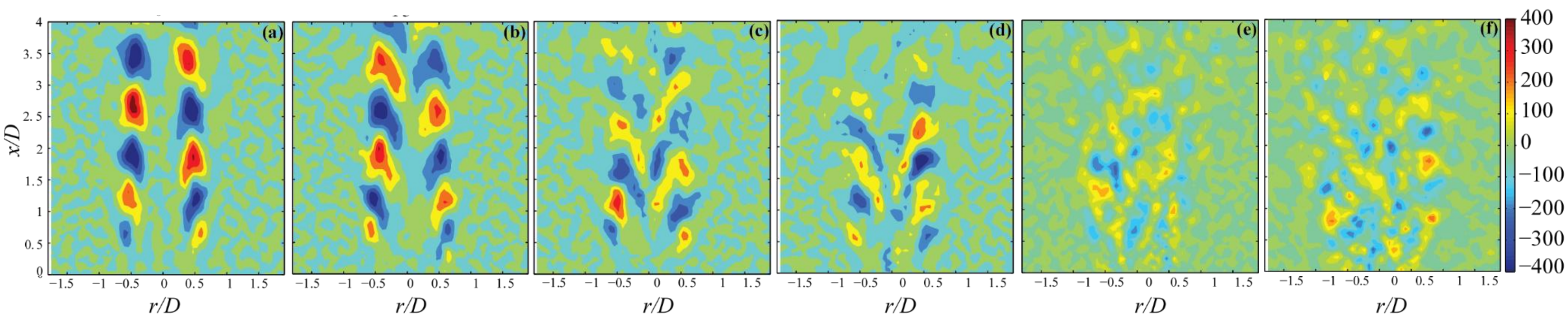
DOE University Turbine Systems Research Program, Mark Freeman (contract monitor), Grant DE-FE0025495

Recent work by PI and collaborators has showed that a stable flow can be “designed” using hydrodynamic stability analysis

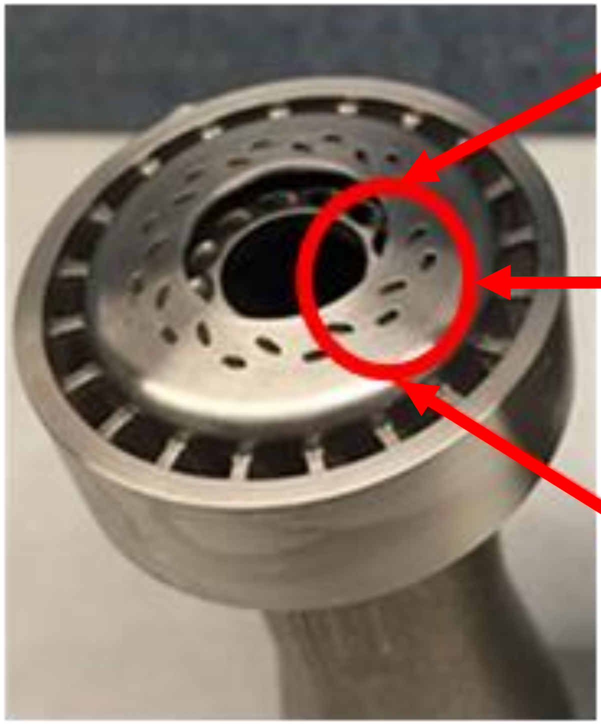
Time-averaged flow



Coherent response



Fuel injectors are notoriously difficult to manufacture and can be comprised of dozens of components, assembled by hand

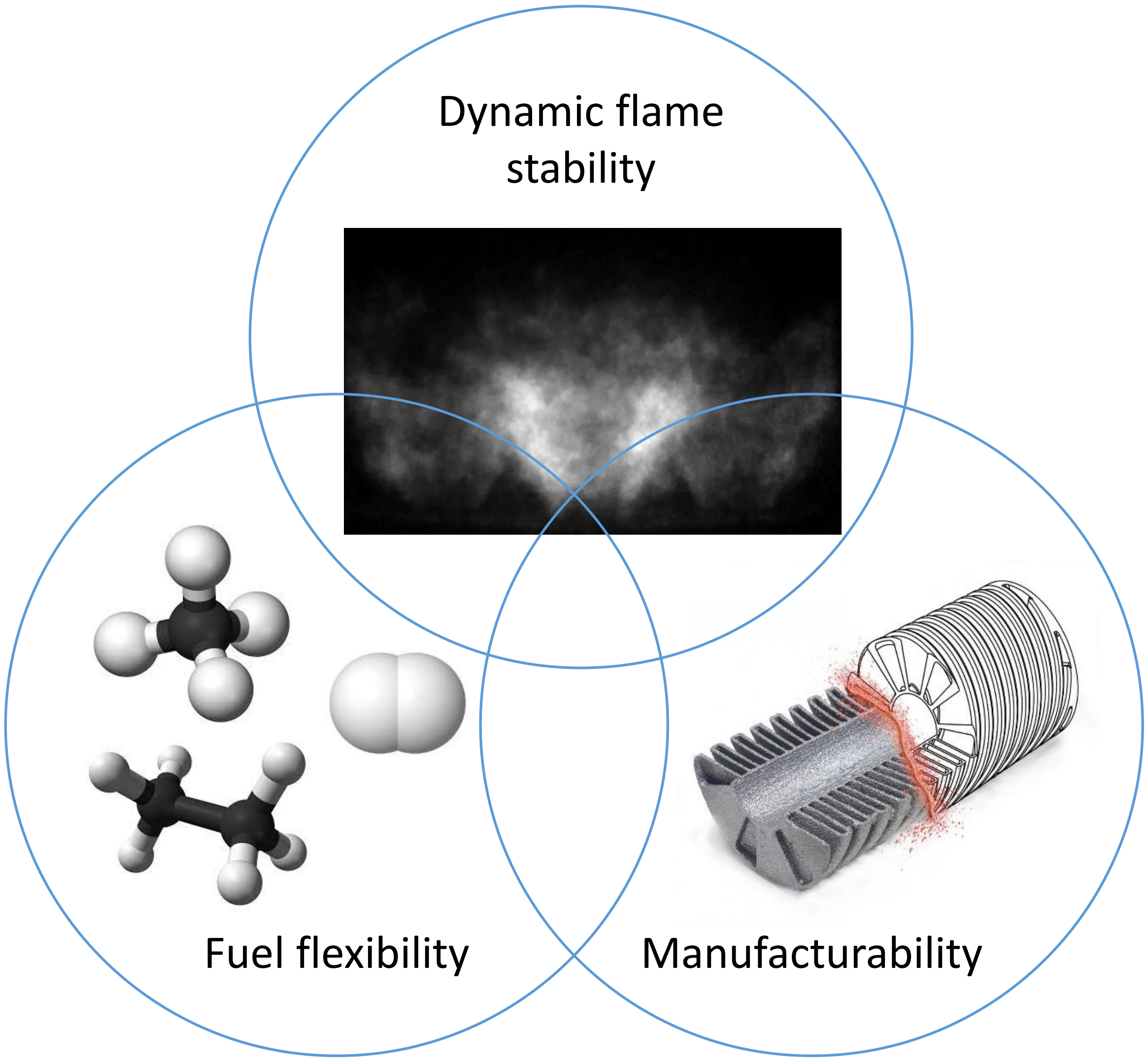


Complex aerodynamic surfaces

Small orifices with specified surface finish

Internal flow passages

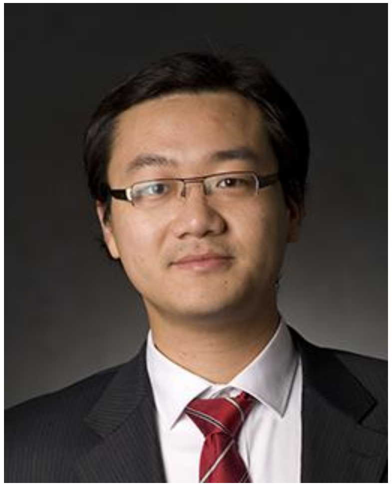
Goal of this project is to create a design optimization paradigm that marries combustion physics and manufacturing



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

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

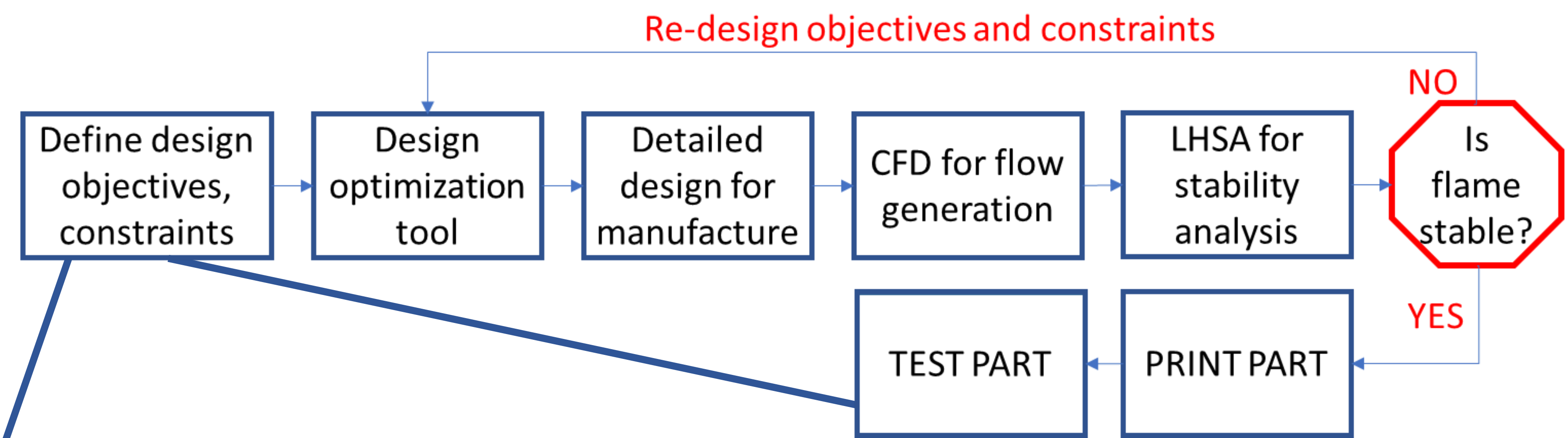
Co-PI: Guha Manogharan
Assistant Professor of ME
Hybrid-Additive Manufacturing



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

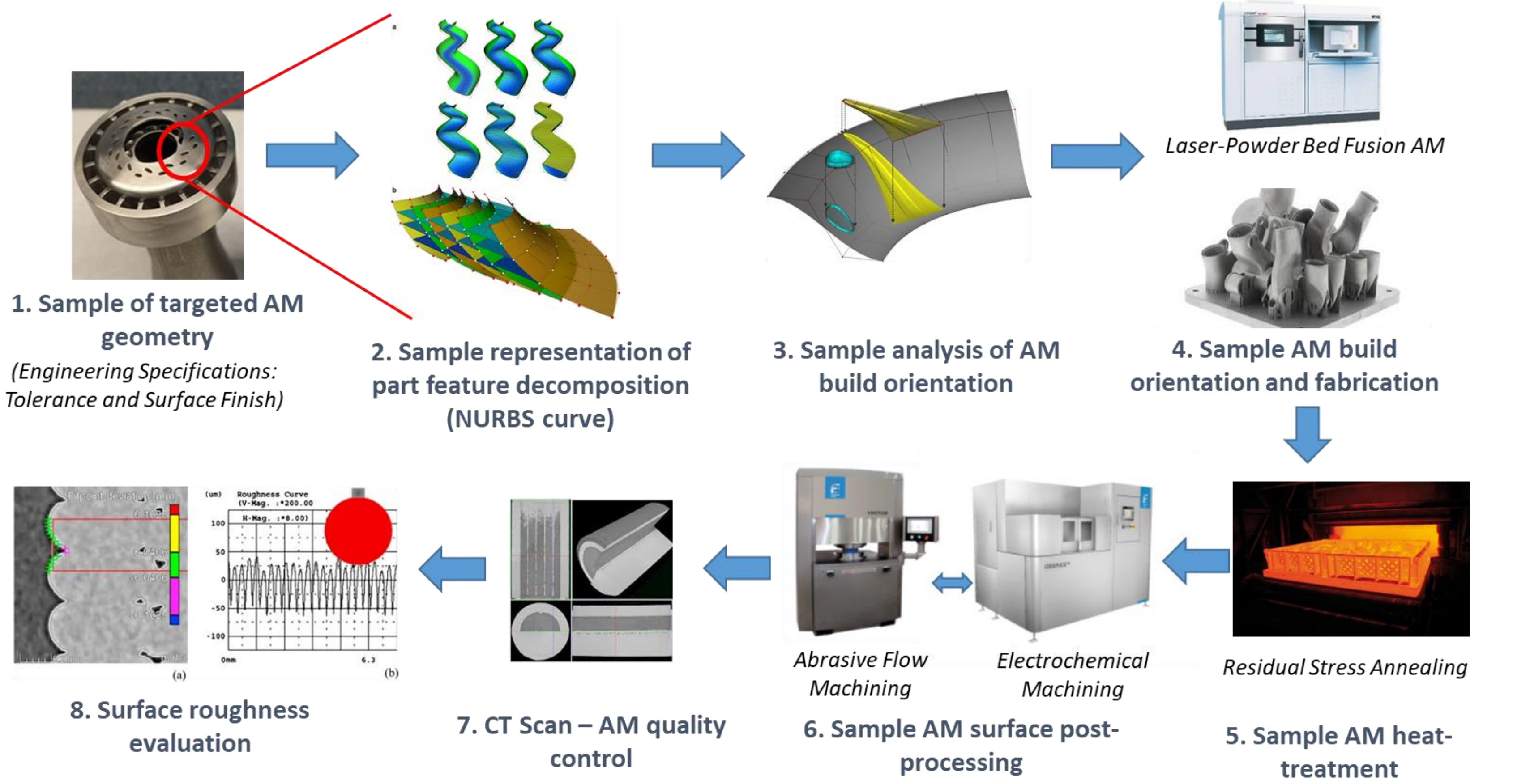
Solar® Turbines
A Caterpillar Company

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



1. Flame dynamic stability through flow response modeling
2. Flame static stability through computational fluid dynamics
3. Fuel flexibility through computational fluid dynamics
4. Additive manufacturing considerations for laser powder bed fusion
5. Surface finishing considerations for abrasive flow machining

Parametric design-process planning advanced manufacturing approach is proposed for fuel-injector applications



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

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

- Task 1: Project management and planning
- Task 2: Establish baseline
- Task 3: Develop design optimization tool
- Task 4: Implement optimization process on baseline configuration
- Task 5: Design process improvement
- Task 6: Integration of improved design process
- Task 7: Final process testing and technology transfer

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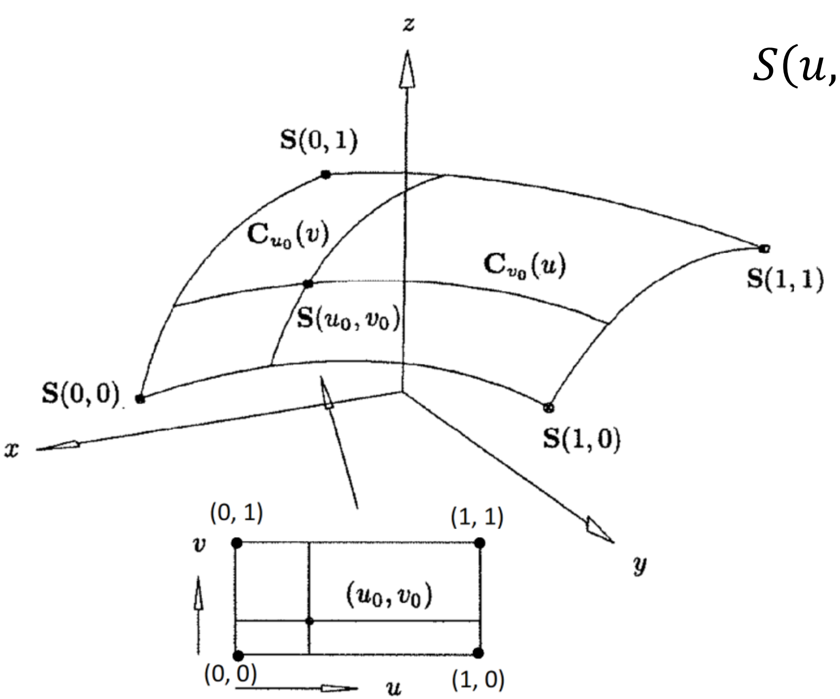
Injector surfaces are defined using NURBS to allow for precise shape quantification and flexibility in changing the shape

NURBS Surface:
Non-**U**niform **R**ational **B**asis **S**plines

- Super set of all surfaces:
  - Standard
  - Free-form

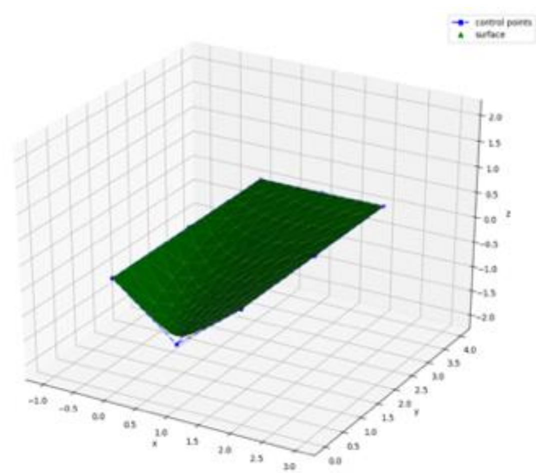
- Enable local control



Source: The NURBS Book (1997)

- Control points coordinates (in u & v)
- Number of control points (in u & v)
- Weights (for all control points)
- Degree (in u & v)
- Knot vectors (in u & v)

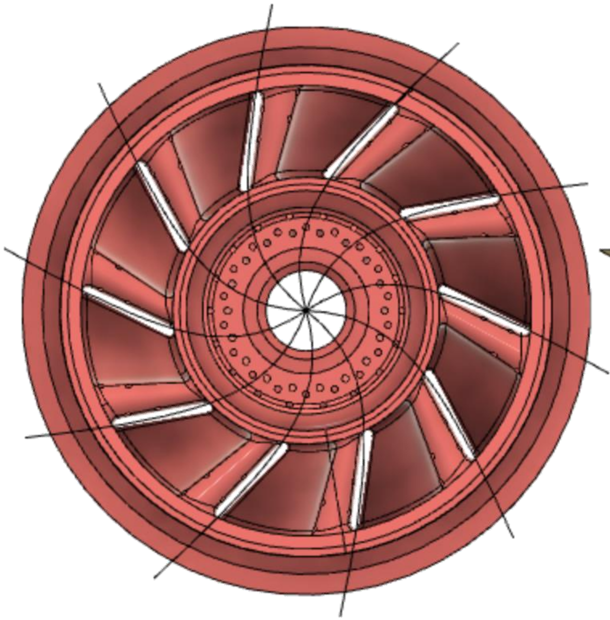
$$S(u,v) = \frac{\sum_{i=0}^{n}\sum_{j=0}^{m} N_{i,p}(u)N_{j,q}(v)w_{i,j}P_{i,j}}{\sum_{i=0}^{n}\sum_{j=0}^{m} N_{i,p}(u)N_{j,q}(v)w_{i,j}} \quad 0 \leq u,v \leq 1$$

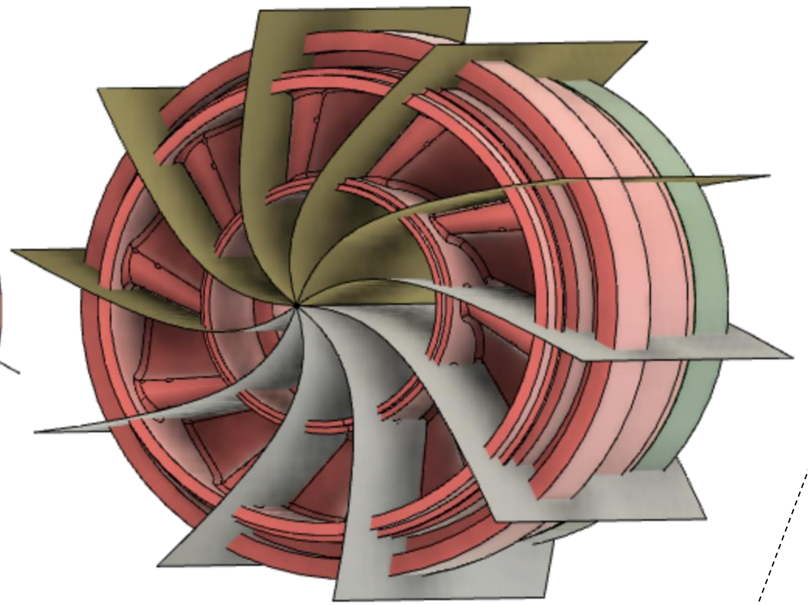


NURBS Python (geomdl)

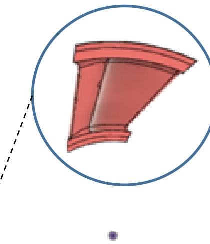
- Visualization
- Manipulation

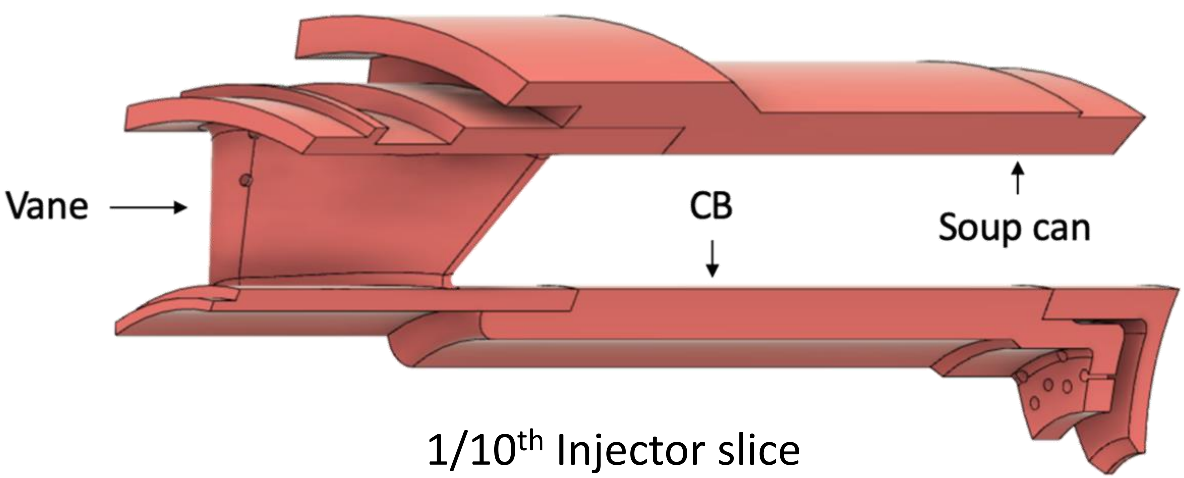
To understand the implementation of NURBS on an injector geometry, we looked at one section cut of a baseline injector



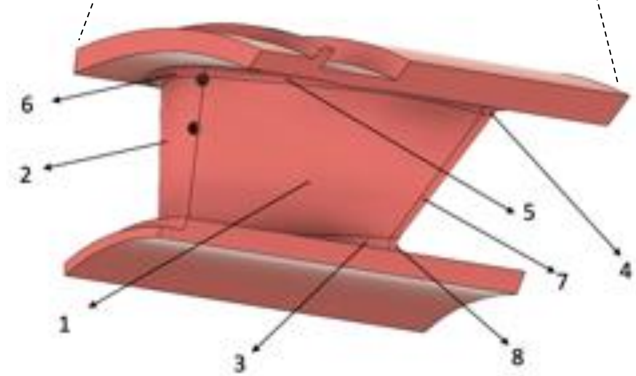


Vane Slice





1/10th Injector slice



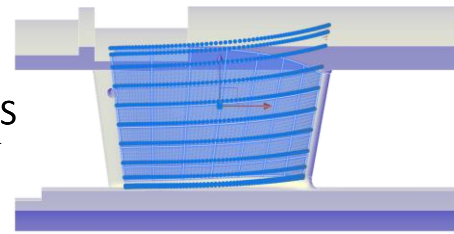
The CAD to NURBS conversion processes and the sensitivity of surface deformation to NURBS variation have been identified

Baseline - STEP

ConvtoNURBS → AutoCAD

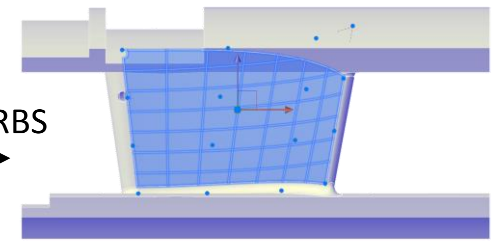
(Max deviation ~0.2 mm)

NURBS exact (IGES) – 78x11



Rebuild NURBS →

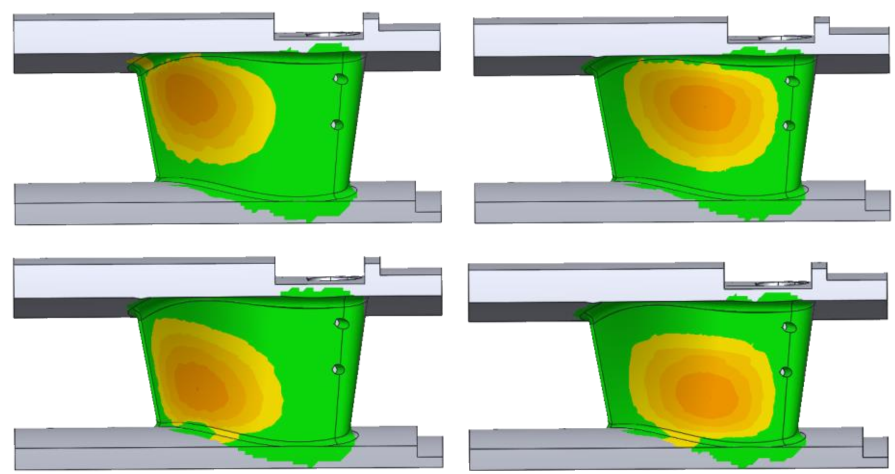
NURBS reduced (IGES) – 4x4

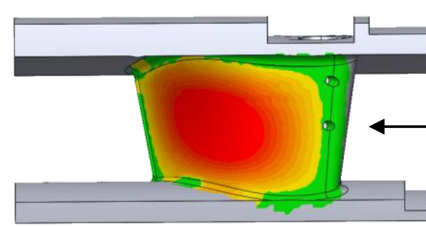


Choose the ***middle 4 control points*** of each surface as design variables to prevent discontinuity

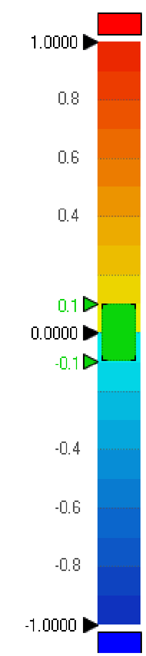
CAD File (IGES)
↓
Type 128
NURBS python
↓
Calculate
Surface normal
↓
Change control Point
↓
Export STL

Control X





Combined movement of all 4 control points changes almost entire surface



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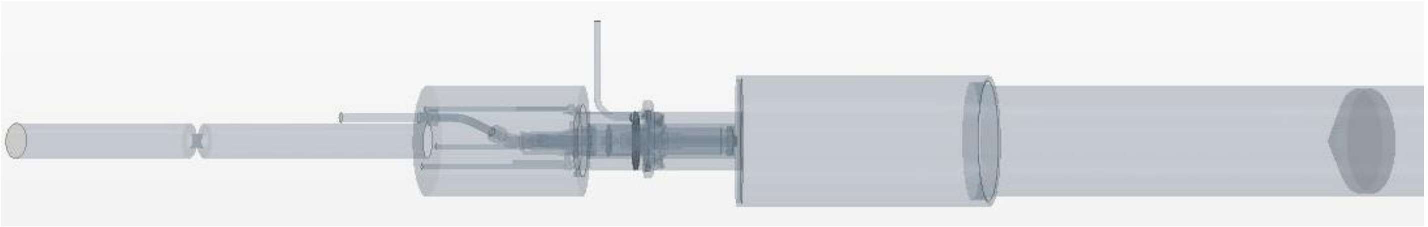
High-fidelity combustion simulation uses STAR-CCM+ to allow more rapid industry adoption

- Large eddy simulation (LES) using STAR-CCM+
- Flamelet generated manifold (FGM) model
- Unstructured polyhedral mesh (~16.7 million cells)

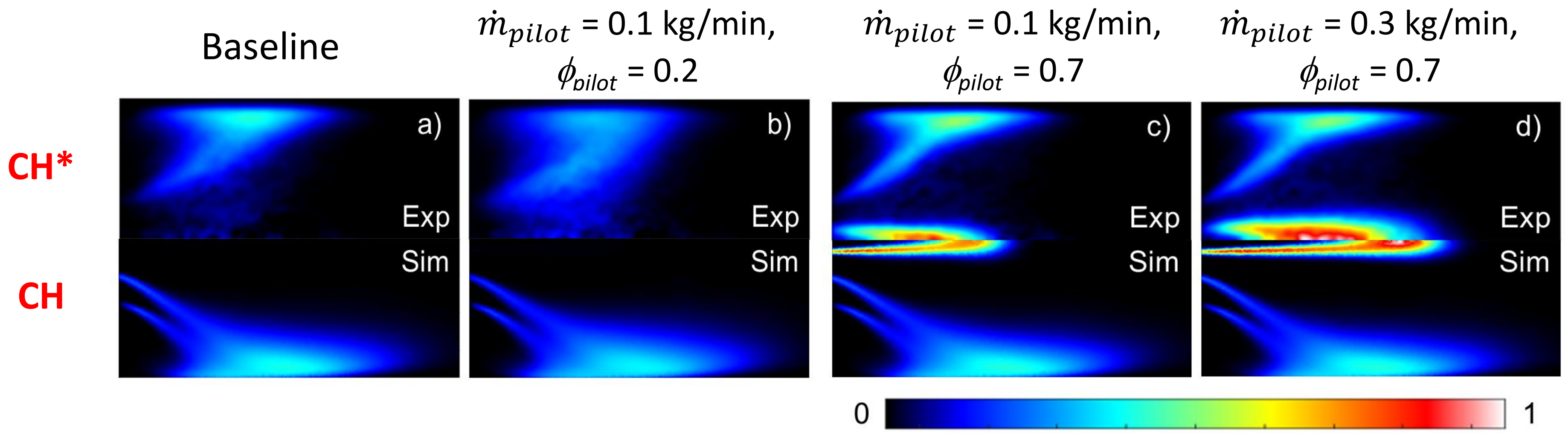


Main-flame equivalence ratio (φ_{main})	0.6
Combustor length (L_{comb})	711.2 mm
Air inlet temperature (T_{in})	250° C
Pilot flame equivalence ratio (φ_{pilot}) and Pilot mixture flow rate ($\dot{m}_{pilot}$)	case a) $\dot{m}_{pilot}$ = 0 kg/min case b) $\dot{m}_{pilot}$ = 0.1 kg/min, φ_{pilot} = 0.2 case c) $\dot{m}_{pilot}$ = 0.1 kg/min, φ_{pilot} = 0.7 case d) $\dot{m}_{pilot}$ = 0.3 kg/min, φ_{pilot} = 0.7

Flame shape has been compared against experimental measurements, trends captured

- The simulations qualitatively capture the impact of equivalence ratio and pilot flow rate on flame shape.

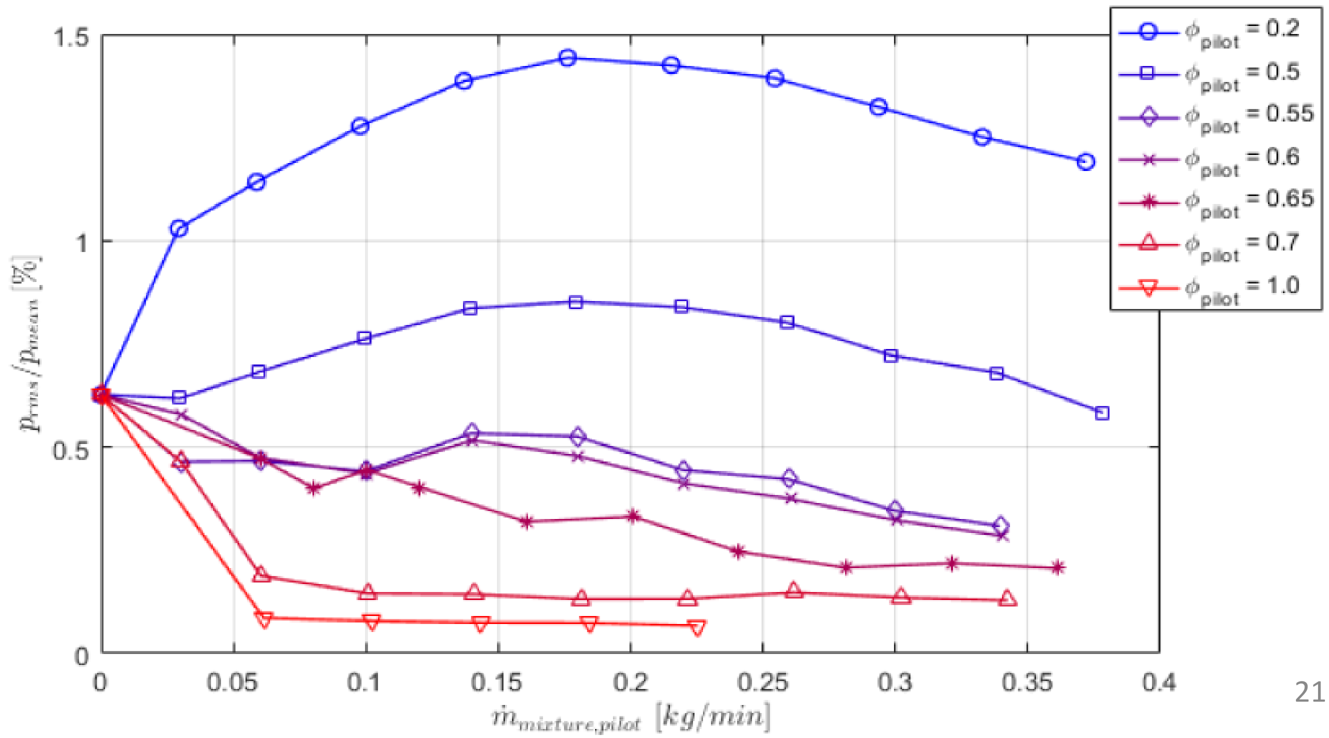
- The main flame is more spread out and the pilot flame is longer compared to the experimental images.



Effects of pilot flame equivalence ratio and mass flow rate on combustion instability suppression

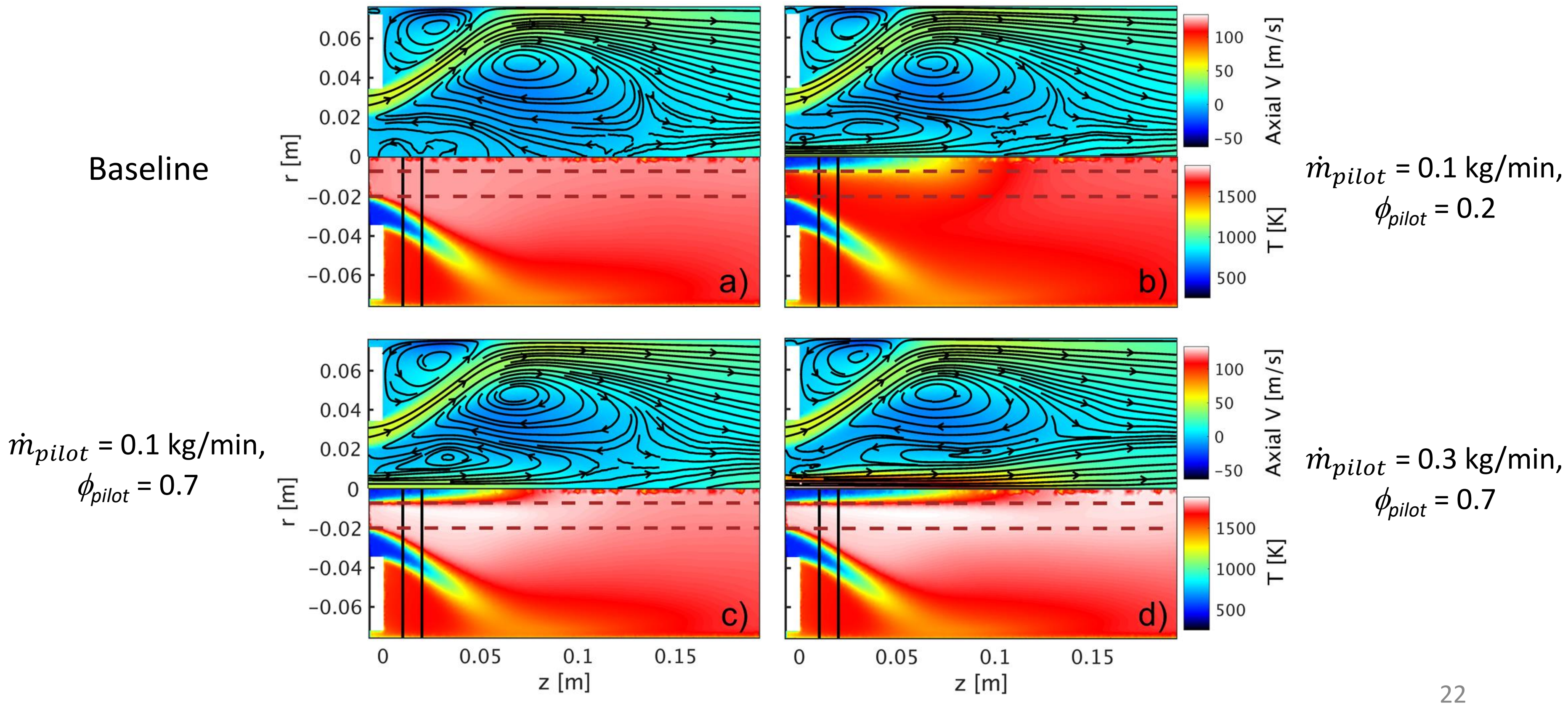
— Instability suppression is more sensitive to equivalence ratio

— Hypothesis: Combustion oscillation suppression occurs as the pilot provides hot gases to the vortex breakdown region of the flow.



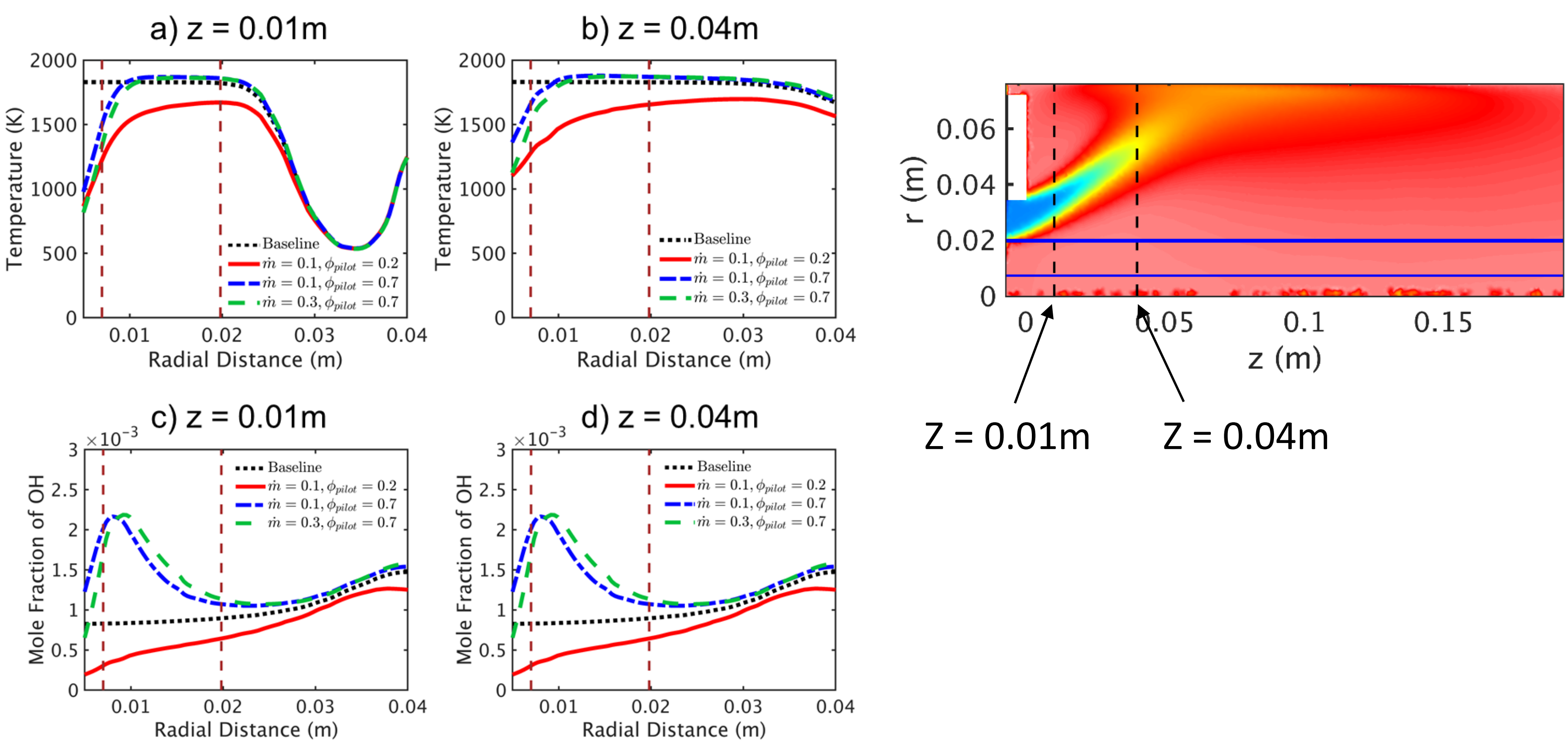
Effects of pilot flame equivalence ratio and mass flow rate on combustion instability suppression

— Higher pilot equivalence ratio leads to a stronger inner recirculation zone.



Effects of pilot flame equivalence ratio and mass flow rate on combustion instability suppression

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



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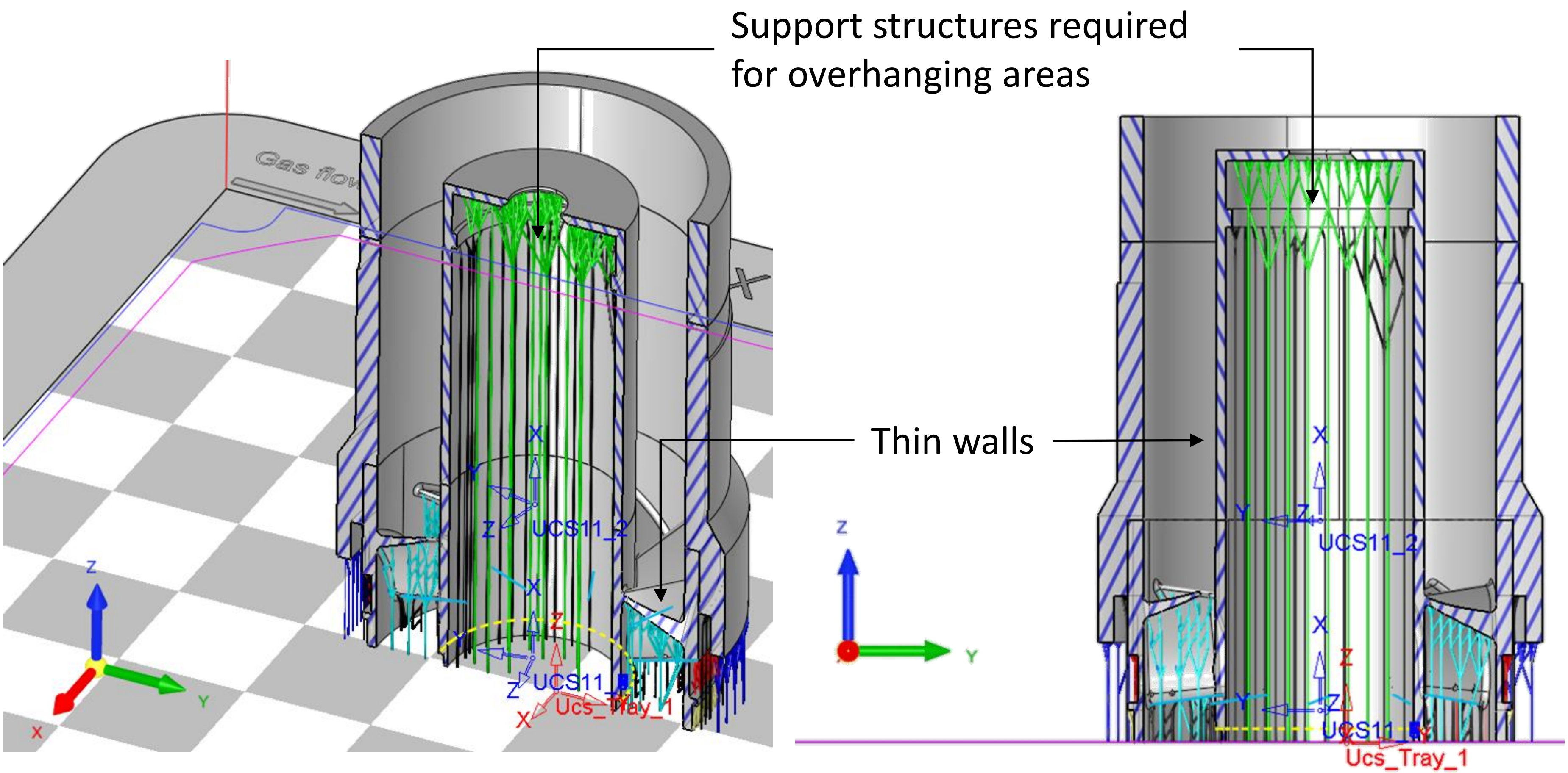
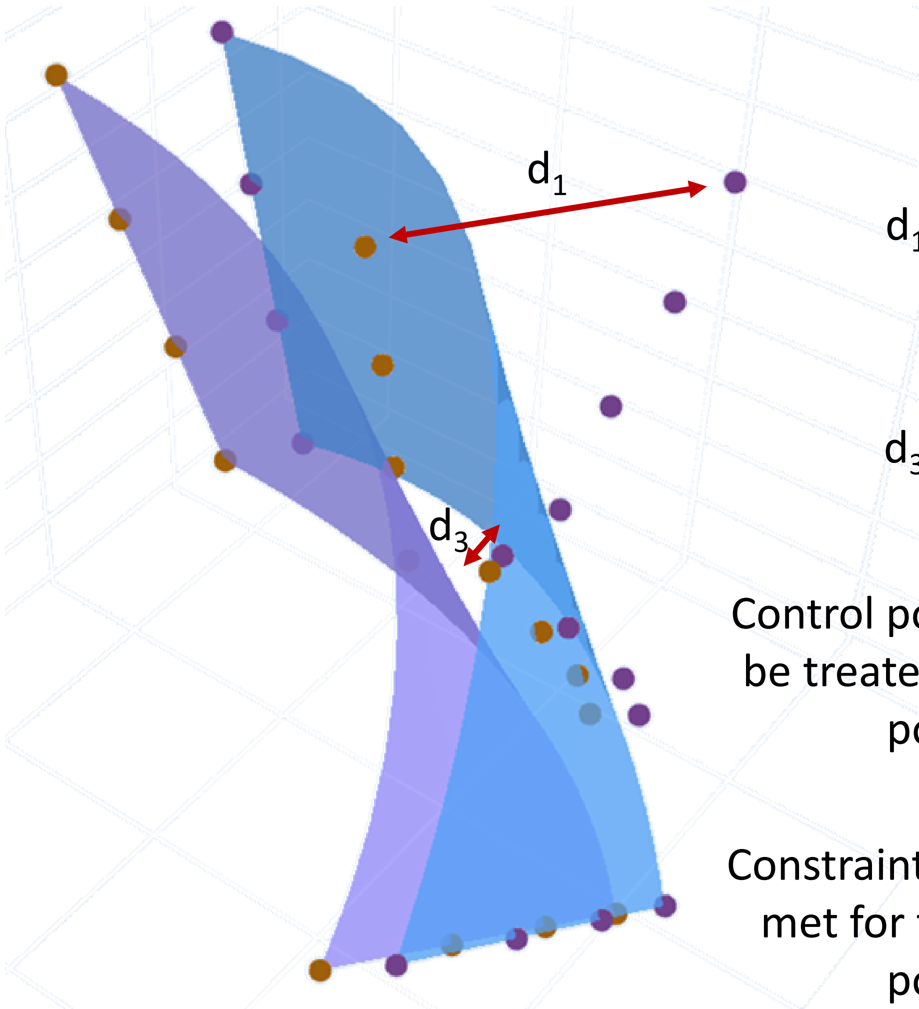
Additive manufacturing printability analysis and constraints have been explored using 3DXpert analysis



Critical AM constraints identified using 3DXpert analysis:

1) **Overhang constraints**: Lower bound on overhang angle (make components self-supporting)
2) **Thin wall constraints**: Lower bound on min. dist. between 2 surfaces (sustain fabrication + post-processing)

Imposing geometric manufacturing constraints like wall thickness to NURBS definition of baseline design

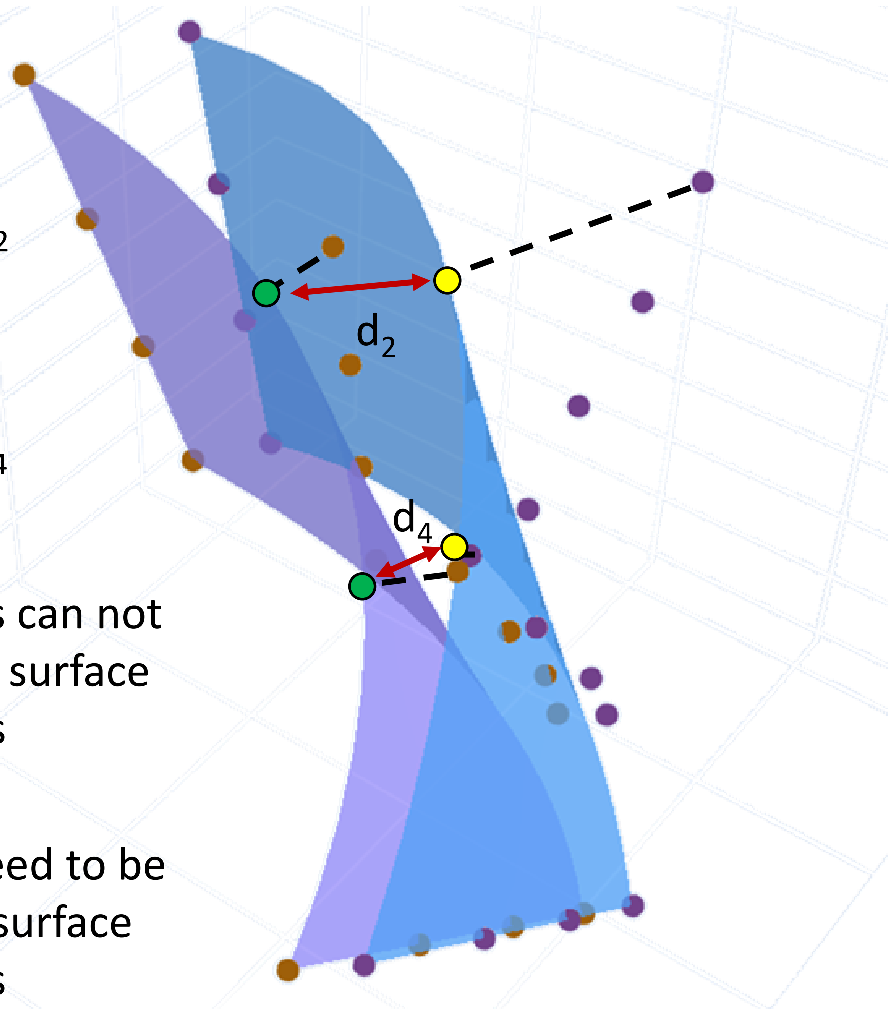


$d_1 > d_2$

$d_3 < d_4$

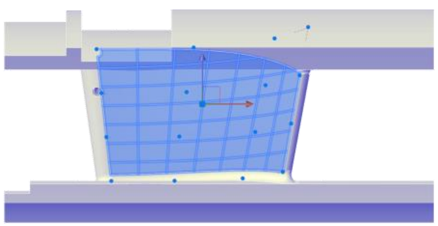
Control points can not be treated as surface points

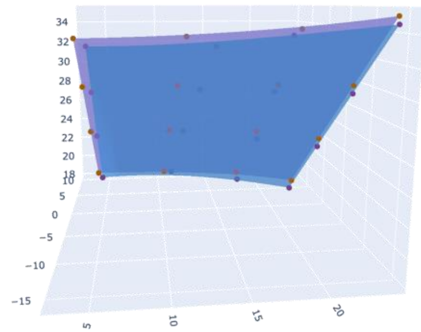
Constraints need to be met for the surface points

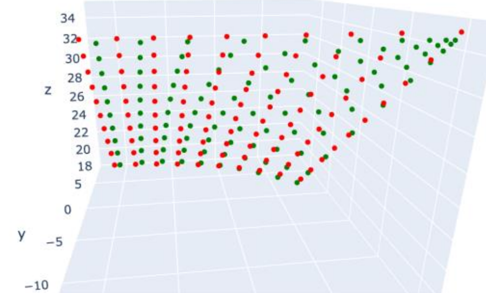


Imposing thin wall constraints to NURBS definition of baseline design is a multi-step process, integrated with optimization

IGES → Extract Type 128 using regex → Extract parameters using indices → Create NURBS surfaces using parameters → Set sample size → Get surface points using Surf.evalpts







Constraint on min. dist. between point on one surface to all points on other surface

$S(u_1, v_1)$

[[x0, y0, z0],
[x1, y1, z1],
.
.
.
.
.
[xn, yn, zn]]

$S(u_2, v_2)$

[[x0, y0, z0],
[x1, y1, z1],
.
.
.
.
.
[xn, yn, zn]]

$S(u_1, v_1)$

[[x0, y0, z0],
[x1, y1, z1],
.
.
.
.
.
[xn, yn, zn]]

$S(u_2, v_2)$

[[x0, y0, z0],
[x1, y1, z1],
.
.
.
.
.
[xn, yn, zn]]

....

$S(u_1, v_1)$

[[x0, y0, z0],
[x1, y1, z1],
.
.
.
.
.
[xn, yn, zn]]

$S(u_2, v_2)$

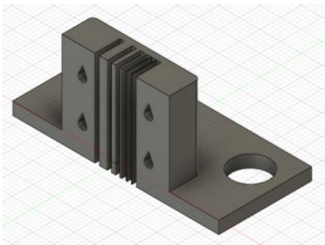
[[x0, y0, z0],
[x1, y1, z1],
.
.
.
.
.
[xn, yn, zn]]

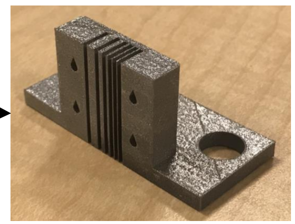
Output: list of lists

Effects of Abrasive Flow Machining on additively manufactured thin walls & internal channels informs wall thickness limits

Software
- SolidWorks
- Fusion 360
- 3DXpert

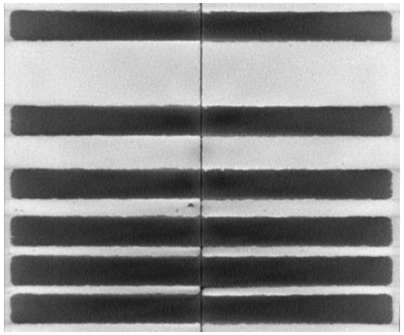
Hardware
- 3D Systems ProX 320
- Ti6Al4V
- Wire EDM



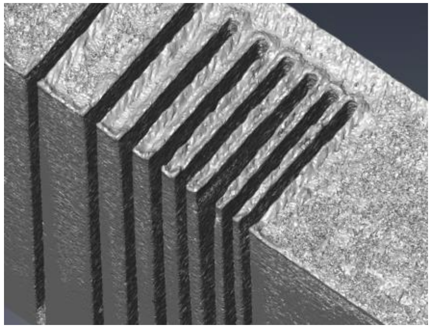


AM Fabrication – Design for AM to CAD to Part

2D micro-X-ray CT image

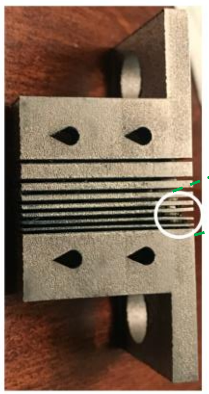


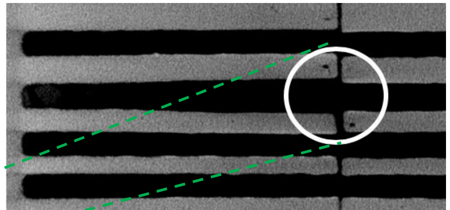
3D reconstructed image

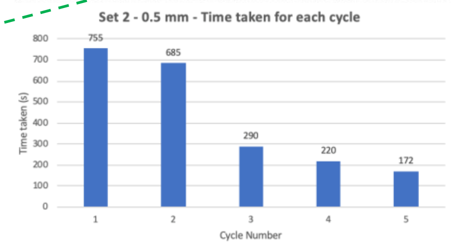


Advanced Inspection Techniques – Micro-X-ray CT

Advanced post-processing techniques – AFM



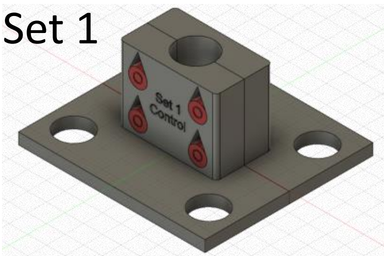


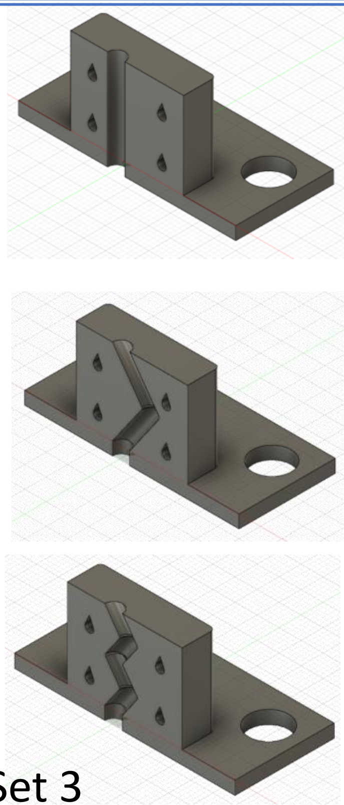


Analysis & documentation– of results post-AFM

Tests on wall thickness as well as channel bends have been tested with abrasive flow machining

Set 1

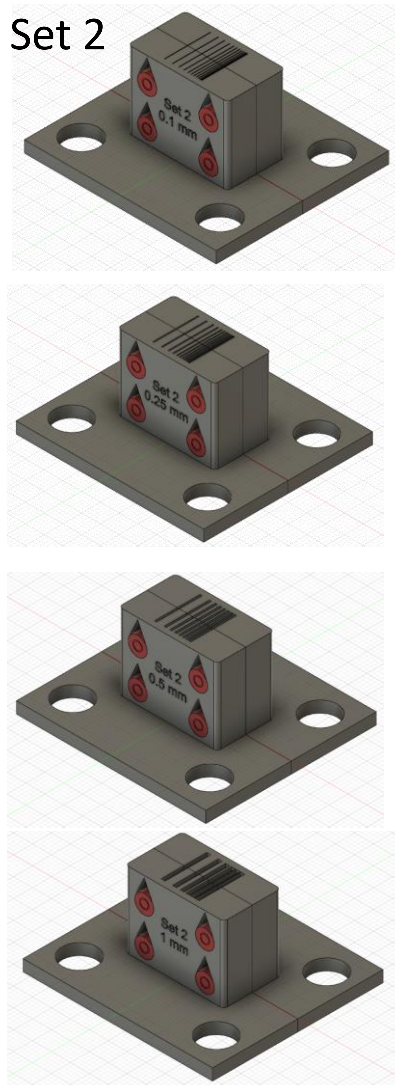




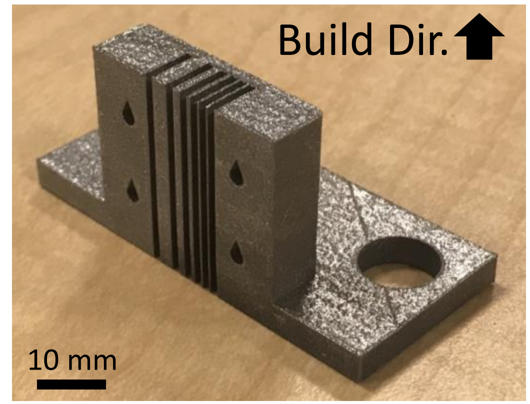
Set 3

Increasing no. of bends

Set 2



Increasing slot width



- ✓ Low Print Time
- ✓ Detail
- ✓ 100% Dense parts
- ✓ Surface roughness

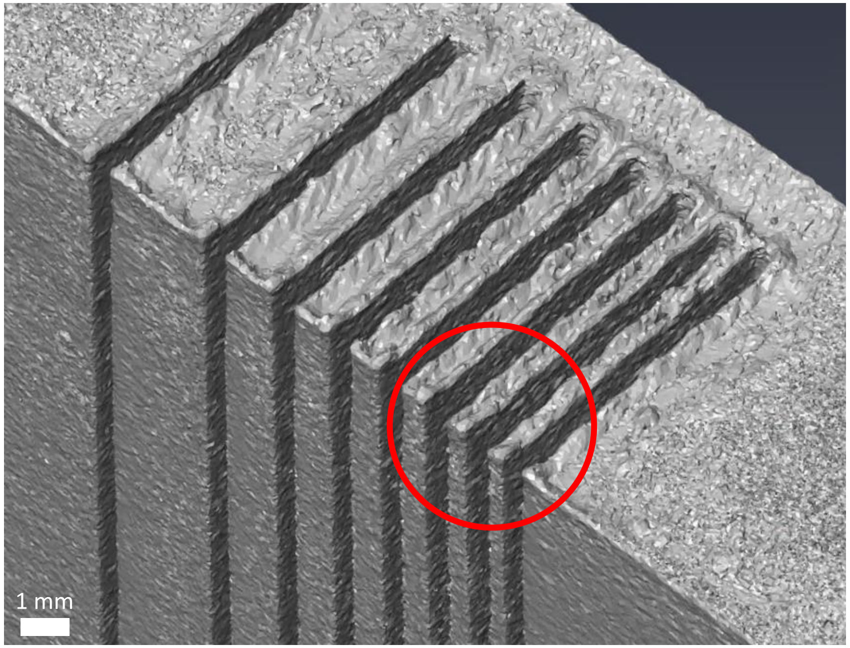
Process: **Laser based Powder Bed Fusion**
Machine: **3D Systems ProX 320**
Parameters:

Layer Thickness = 60 µm
Laser Power = 245 W
Hatch Spacing = 82 µm
Material = Ti-64

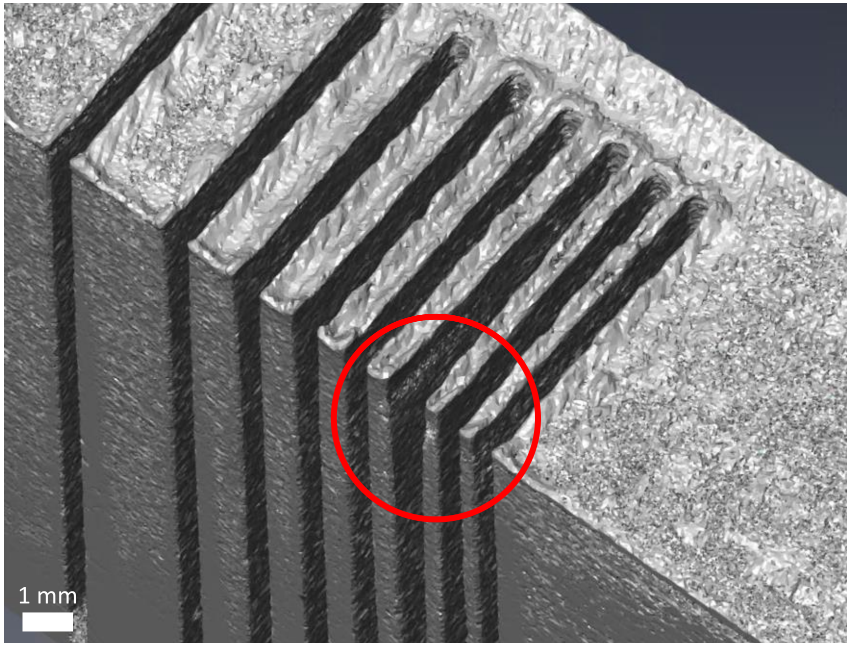
2-way AFM Experiment
Set 1, Set 3 – 15 cycles
Set 2 – 5 cycles

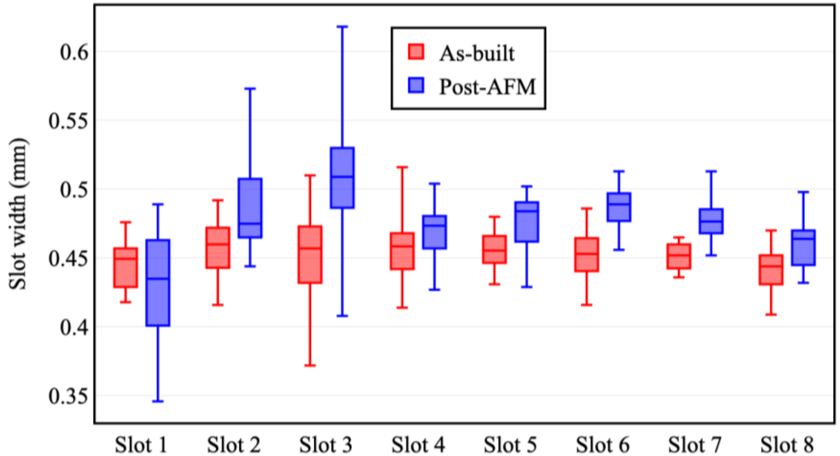
Initial testing has provided guidance as to the thin wall limit for aerodynamic parts in the injector

As-built



Post-AFM





- Thin walls < 0.5 mm bent after AFM
- Max. deviation ~43% (0.216 mm)
- Slots < 0.1 mm were not fabricated
- Slots < 0.25 mm were not feasible to AFM

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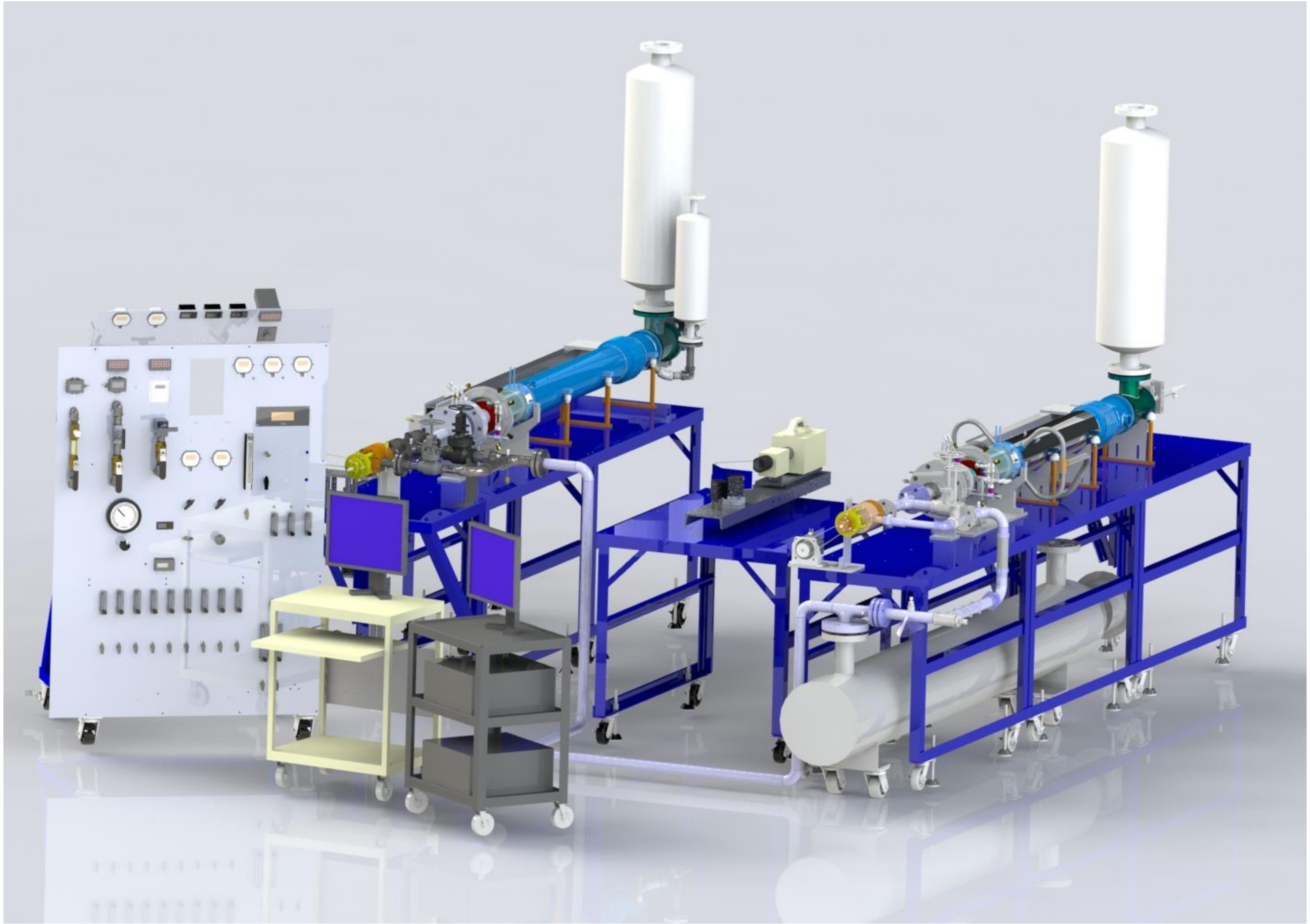
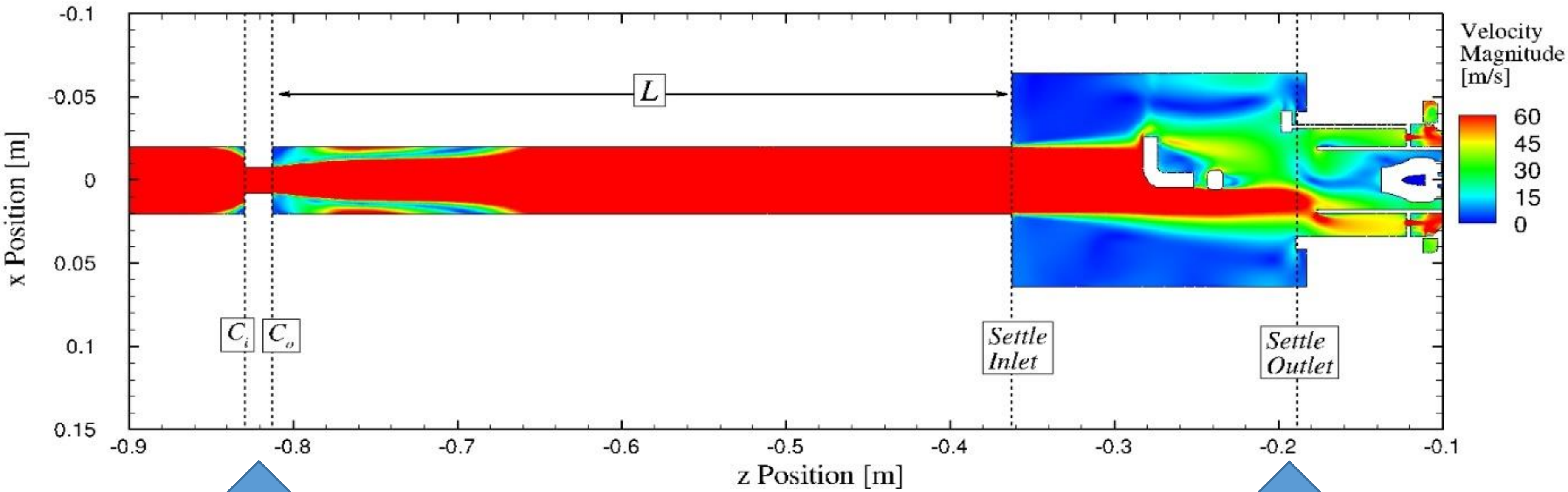
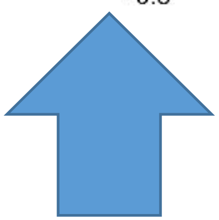
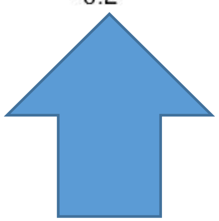
New experimental facility is a renovation of a current rig – will share flow system with current Solar rig



Simulations indicate that current rig sizing will work and still allow us to reduce the computational domain



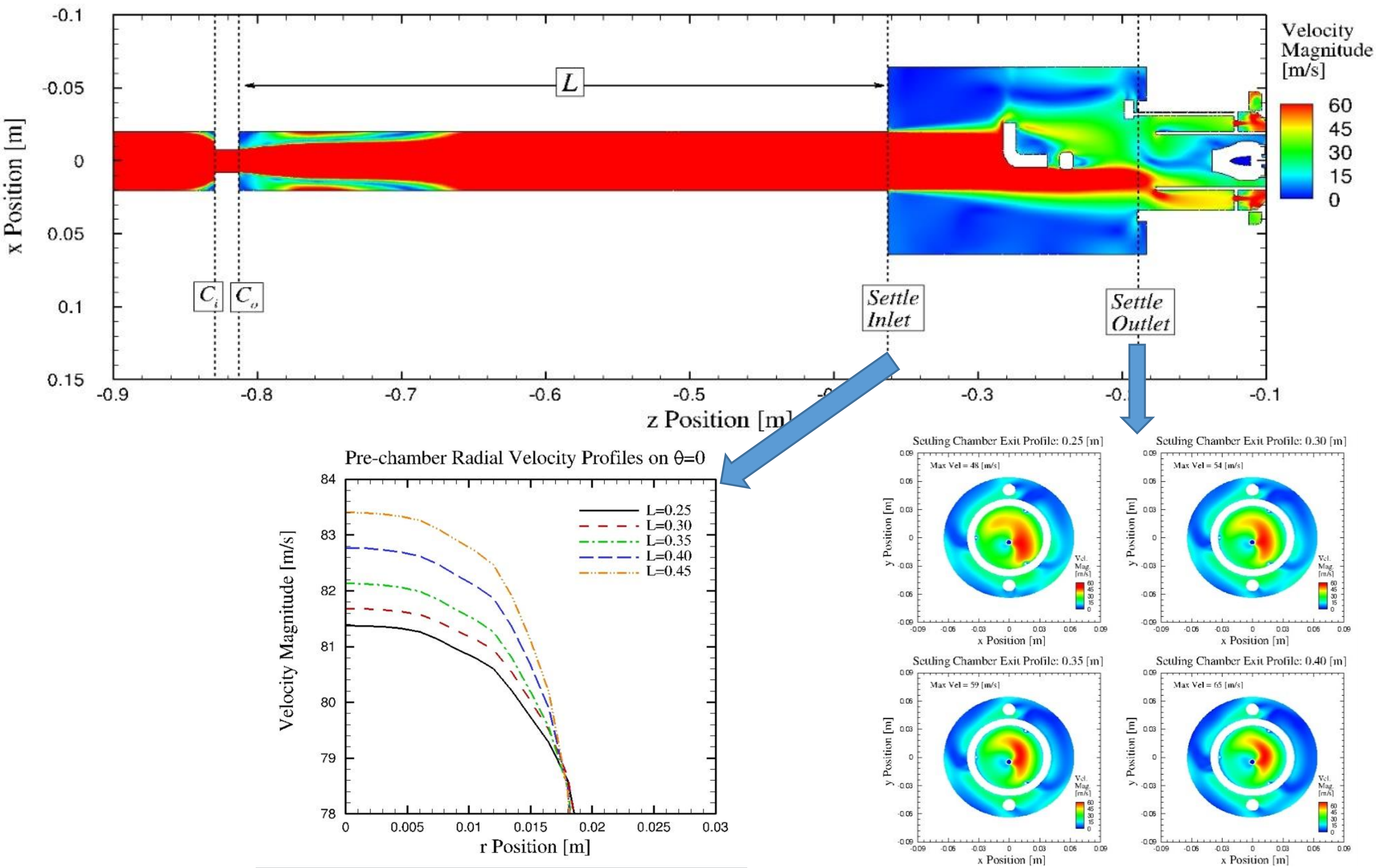




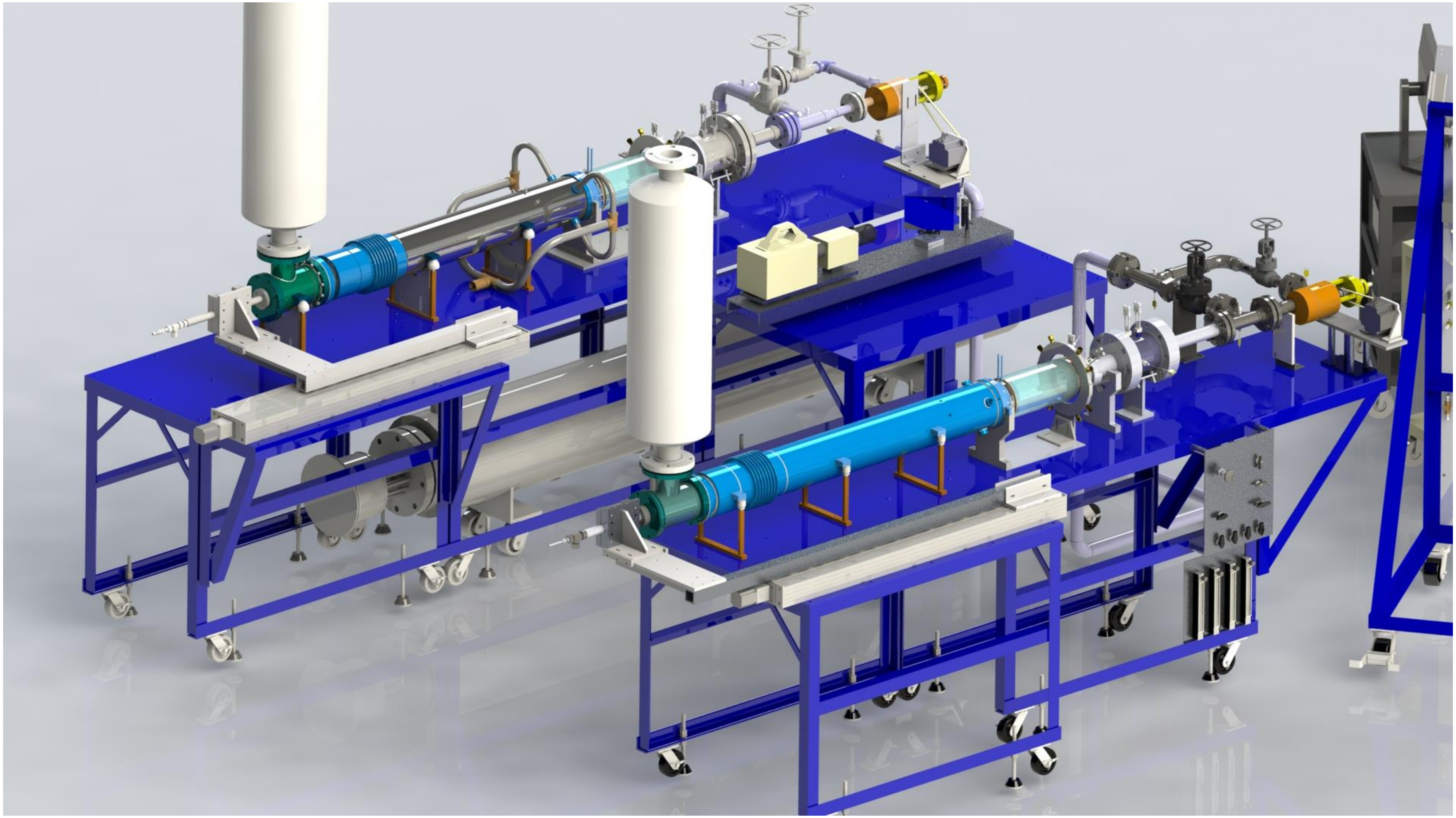
Need a choke point

Want to start simulation here

Simulations indicate that current rig sizing will work and still allow us to reduce the computational domain



Test section has been designed and awaiting build in the Penn State College of Engineering machine shop



Overview of presentation

- Background and technical approach
- Highlights from Year 1
  - Defining geometry
  - Simulating combustion
  - Constraints from additive manufacturing
  - Experimental design
- Optimization process and next steps

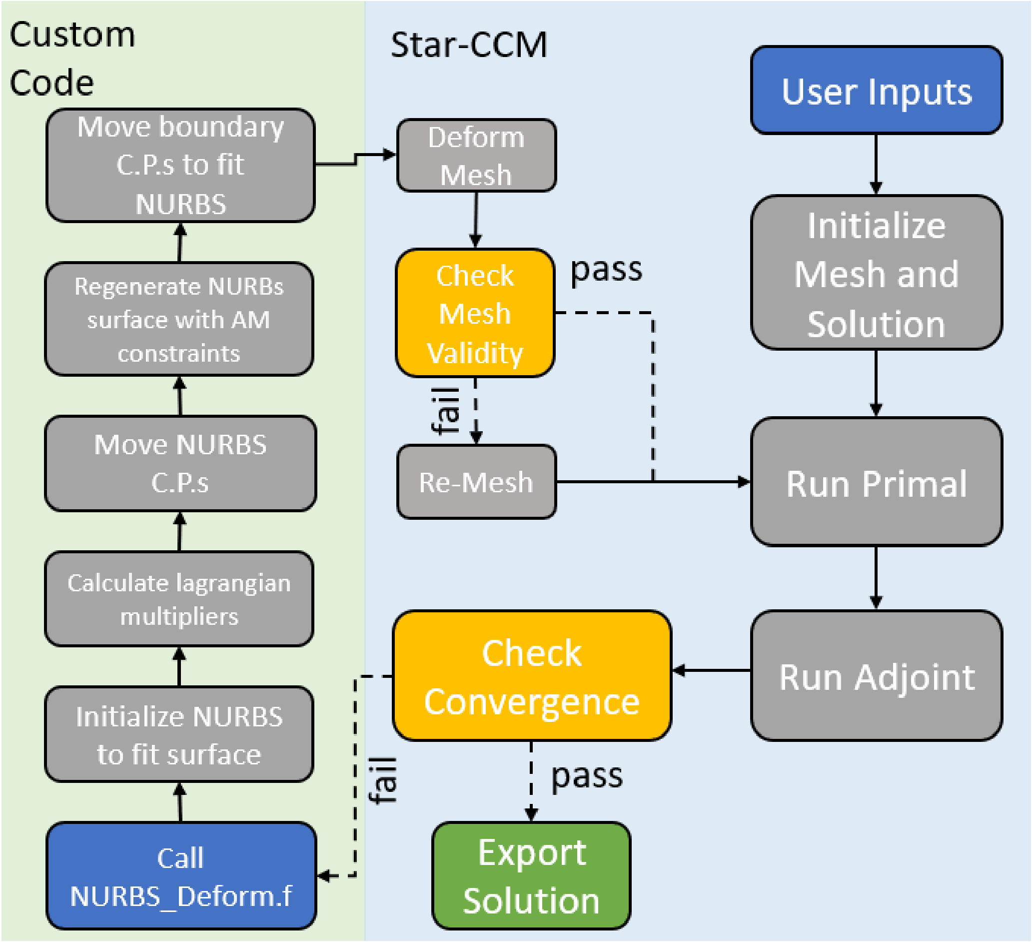
Optimization Process and Next Steps

— Optimization loop using an in-house FORTRAN code

— Code forces Star-CCM into recognizing NURBs for the mesh deformation

— NURBs allow us to include AM constraints

— Langrangian multipliers allow us to weigh the cost functions against each other



Questions?

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

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

PIs: Jacqueline O'Connor, Guha Manogharan, Yuan Xuan
Graduate students: Sagar Jalui, Hyunguk Kwon, Drue Seksinsky
Undergraduate students: Nathan Love

Mechanical Engineering
Pennsylvania State University

Industry Partner: Solar Turbines Incorporated
Engineers: Hanjie Lee, Michel Akiki, Dave Voss

PennState