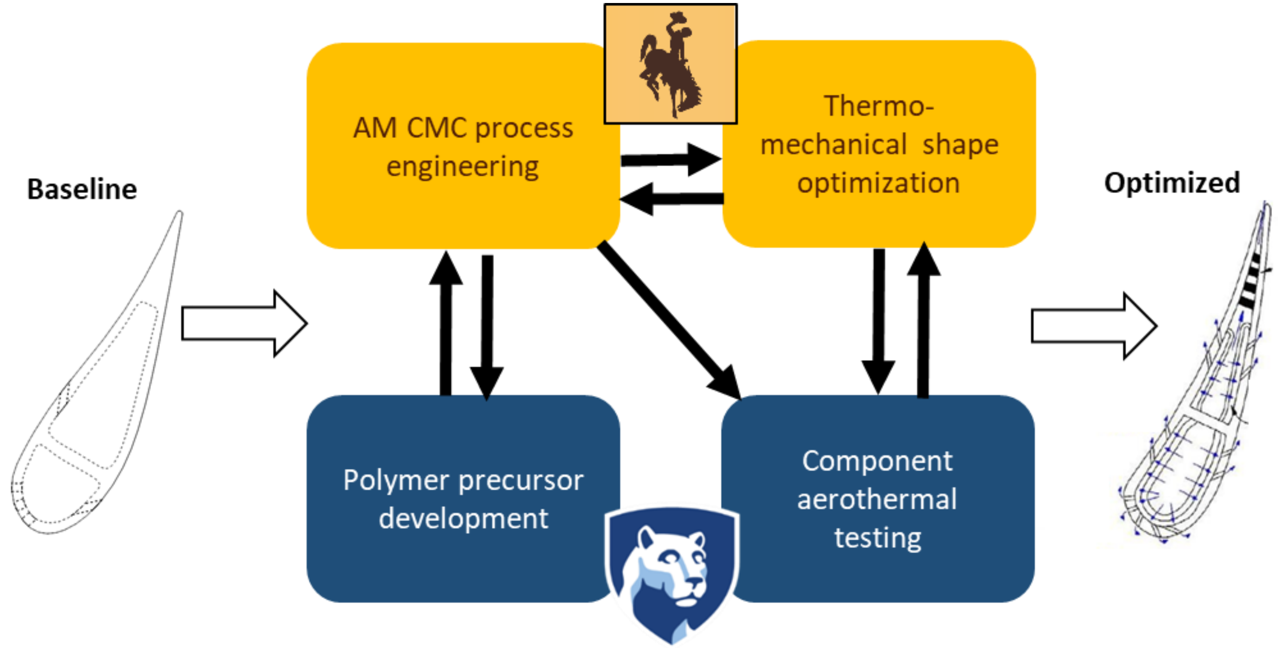
Development of Additive Manufacturing for Ceramic Matrix Composite Vanes



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Project: DE-FE0031758

This review covers the motivation, project plan, and Year 3 progress on our UTSR-supported project

Motivation: enable superalloy-like cooling features in CMC-like materials to enable higher temperature operation

Approach: push polymer-derived ceramics development through additive manufacturing engineering, polymer science, part design, and performance verification

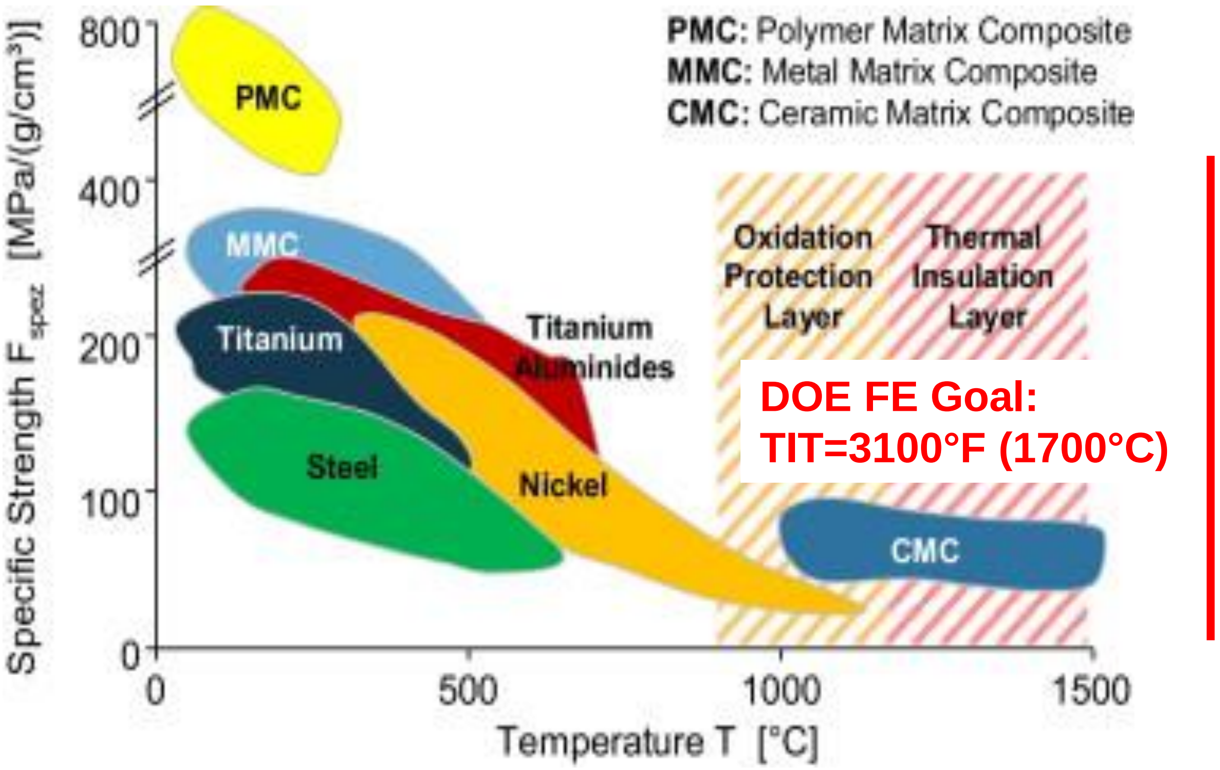
	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 1 - Project Management and Planning												
1.1 -- Update project management plan, assess risk, assess project resources	■											
1.2 -- Planning meetings/monthly teleconferences	■	■	■	■	■	■	■	■	■	■	■	■
Task 2 – Fabrication and Testing of SiOC/SiC Prototype Vane												
2.1 -- Design of a baseline vane geometry	■	■										
2.2 – Process characterization and fabrication of baseline vane geometry	■	■	■									
2.3 -- Aerothermal testing of baseline vane				■	■							
Task 3 – Modeling and Optimization of CMC Turbine Vane Designs												
3.1 -- Topology and morphology optimization for enhanced mechanical resilience	■	■	■	■								
3.2 -- Topology and morphology optimization for cooling design					■	■	■	■				
3.3 -- Coupled cooling and resilience optimization for vane design									■	■	■	■
Task 4 – Precursor Development and Optimization of New Resins for SiC Matrix												
4.1 – Develop new precursor resins for advanced matrices	■	■	■	■	■	■	■	■				
4.2 – Characterization of materials in composites and during pyrolysis					■	■	■	■	■	■	■	■

Project plan: execute simultaneous materials/design/process engineering to regularly produce vane test articles

Current progress

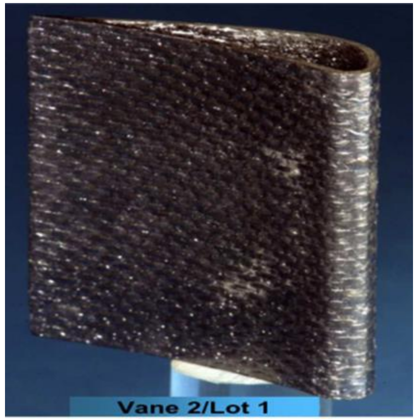
PENN STATE ExCEL

To achieve DOE firing temperature targets and push higher thermodynamic efficiency, even advanced CMC materials will require some cooling



Klocke, et al., CIRP Annals, 2014

Melt-infiltrated woven CMC



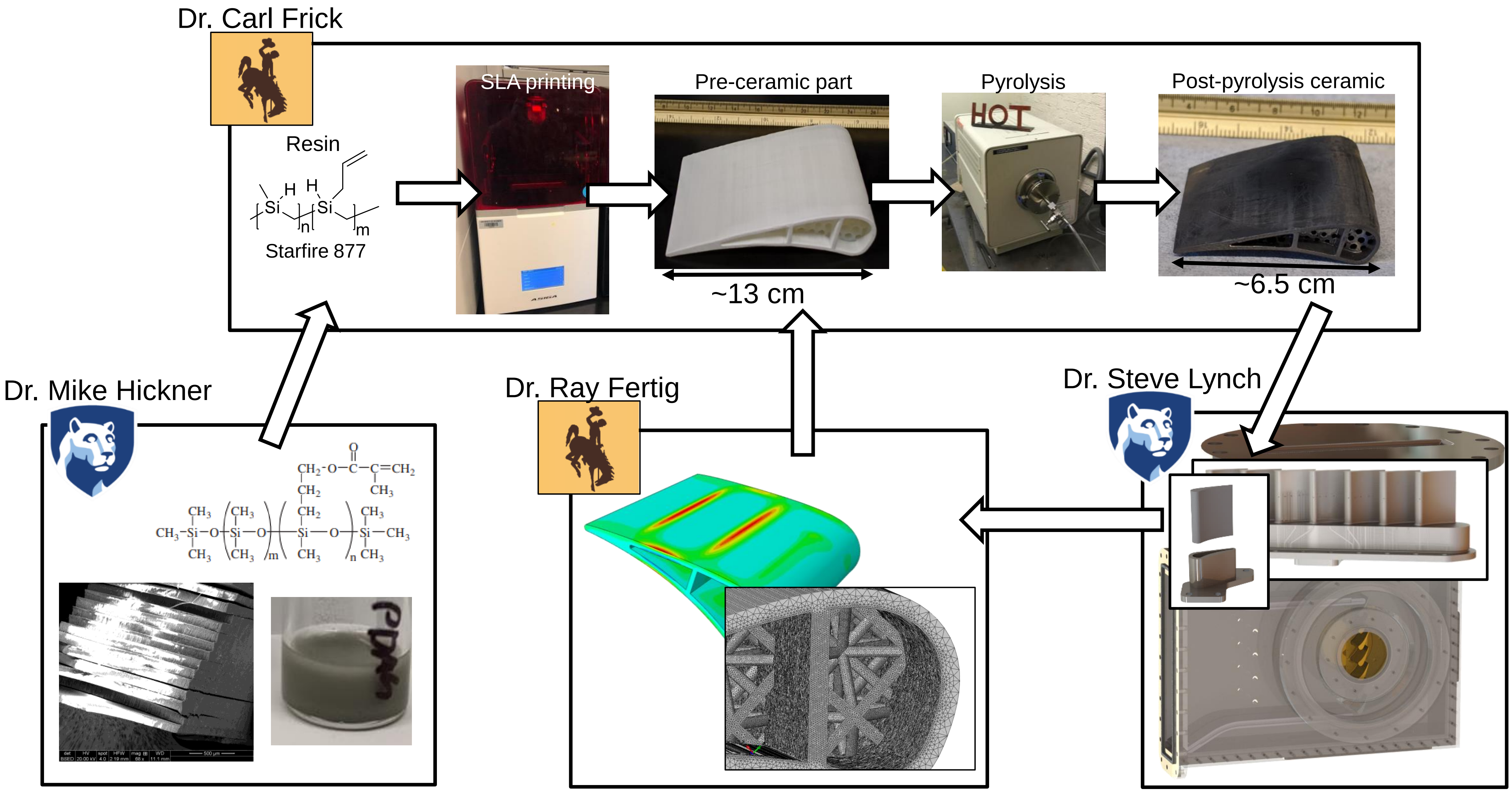
https://technology.nasa.gov/patent/LEW-TOPS-25

Binder-jet CMC with pass-through cooling

https://ntrs.nasa.gov/search.jsp?R=20160010285 2019-02-28T01:25:33+00:00Z

Project goal: enable complex cooling features in CMC-like materials for realistic shapes and confirm cooling benefit

Our approach is to develop novel chemistries and manufacturing processes, coupled with design optimization, to create internally cooled ceramic vanes that can be tested



The project has five technical tasks that address process engineering, material development, modeling, and validation of cooling technologies

Task 1: Project management

Success criteria: Project Coordinator delivers all required reports to NETL

Task 2: Design, fabrication, and testing of SiOC/SiC baseline vane

Success criteria: project team is able to obtain surface temperatures on baseline SiOC/SiC internally cooled vane test articles tested in the transonic cascade at Penn State

Task 3: Modeling and optimization of ceramic turbine vane designs

Success criteria: mechanical and thermal stresses reduced by 10% from baseline to optimized; increase overall cooling effectiveness by 0.05 relative to baseline

Task 4: Development of new precursor chemistries

Success criteria: demonstrate that new precursors have equivalent or better material properties than baseline formulation

Task 5: Integrate new precursor chemistries into AM process

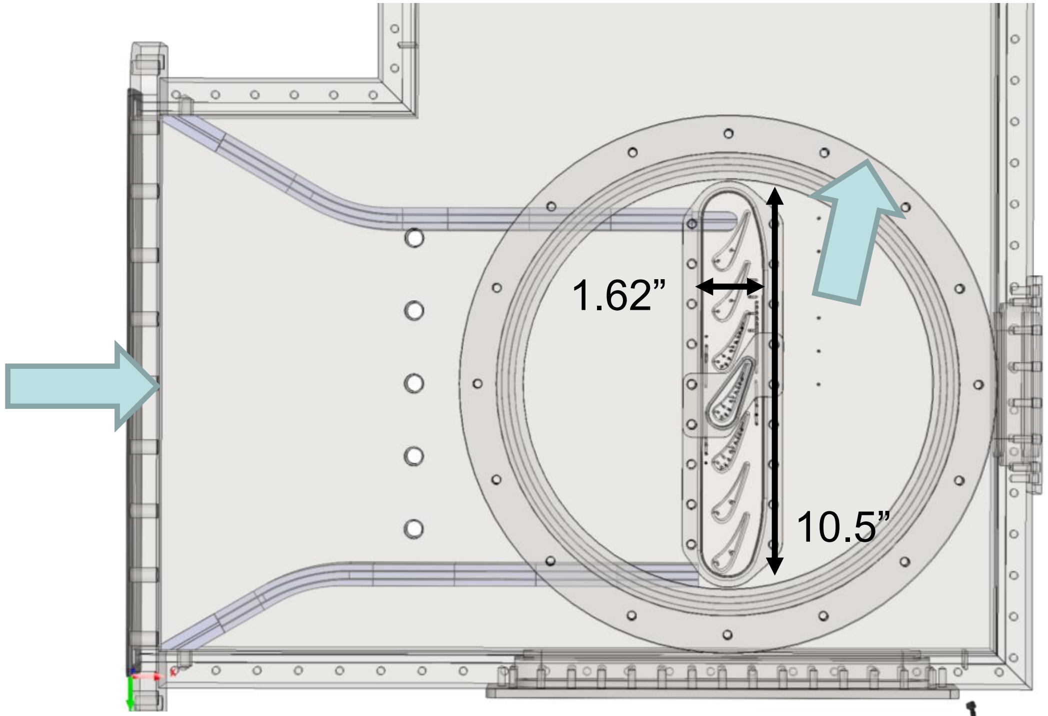
Success criteria: project team is able to deliver a baseline vane part for transonic cascade testing using new chemistry

Task 6: Fabricate and test optimized vanes with new chemistries

Success criteria: project team obtains surface temperatures on optimized AM vane and shows overall cooling effectiveness increase relative to baseline

Task 2.1: Fabrication, assembly, and testing procedures for AM fabricated ceramic vanes have been developed for Penn State's high speed linear cascade

Linear cascade and test hardware (1st stage vane, NASA C3X)

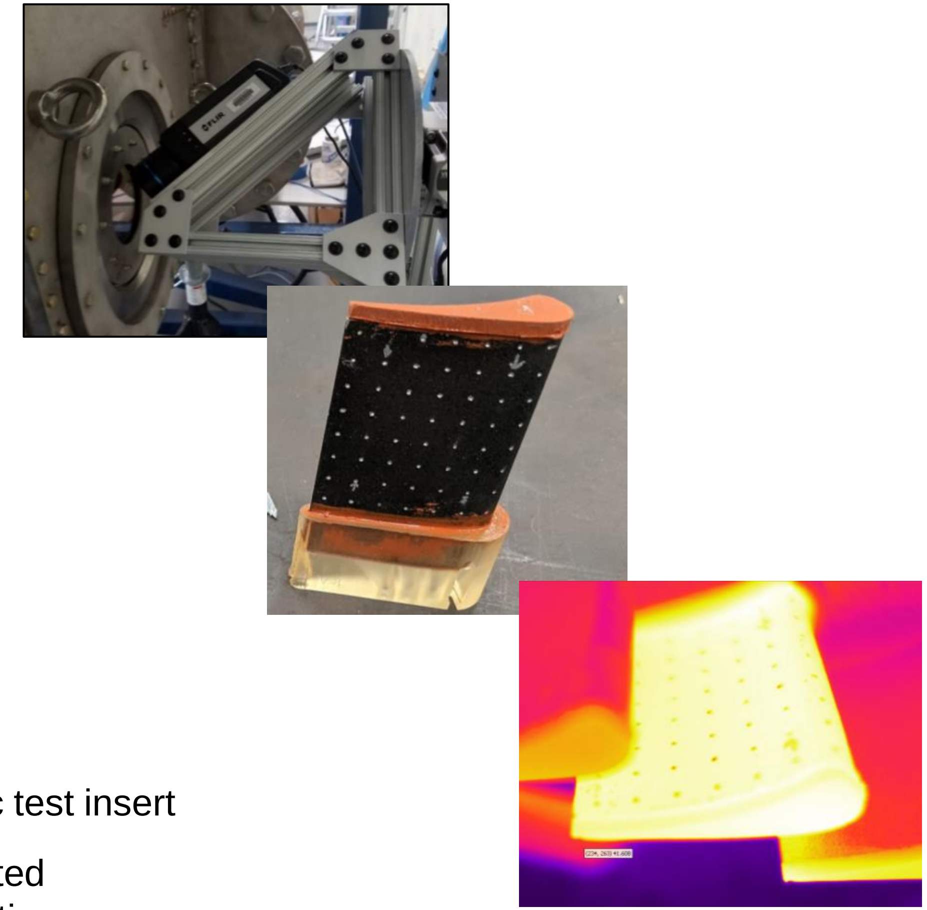


AM ceramic test insert

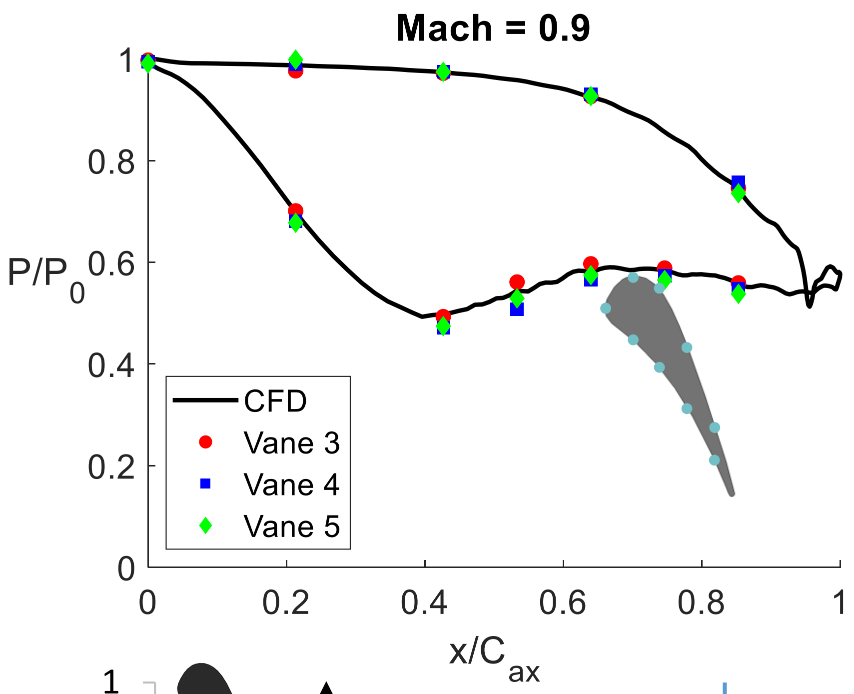
AM-fabricated coolant routing

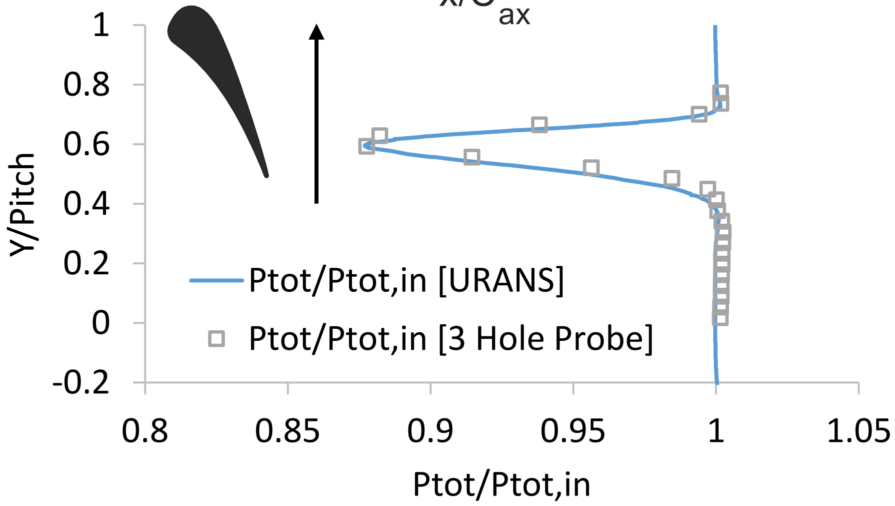
Coolant

Calibration vane with spatial markers visible in IR



Task 2.1: The aerodynamics of the high speed cascade were benchmarked, and a novel total pressure measurement technique using PIV was developed for aerodynamic characterization



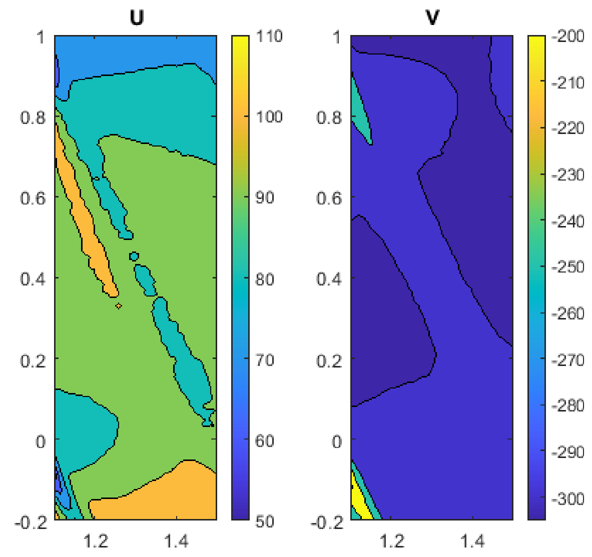


Momentum equation

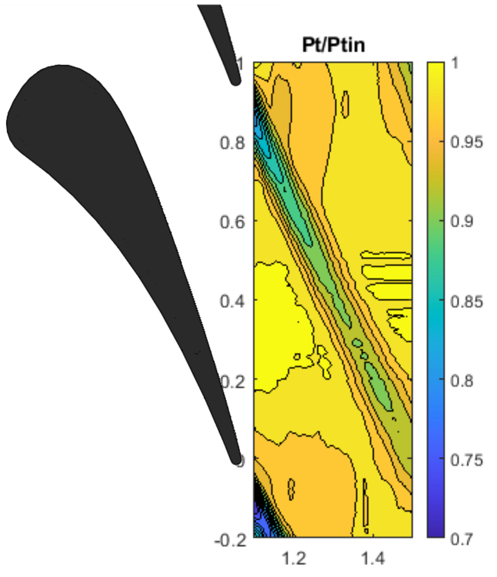
From measured velocity fields (PIV)

$$-\frac{\partial \bar{p}}{\partial x_i} = \rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} + \rho \frac{\partial \overline{u_i' u_j'}}{\partial x_j} - \mu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j}$$

Measured velocity fields



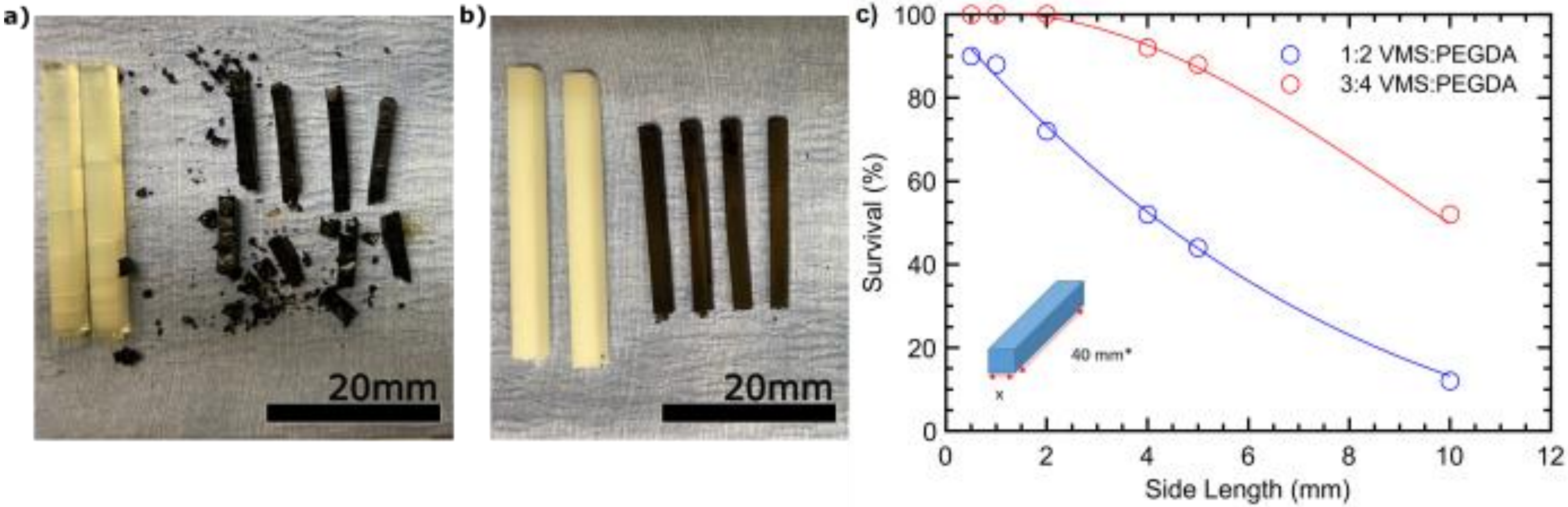
Total pressure field



Task 2.2: New baseline resin formulations were developed with more pyrolysis success in the feature size range of interest

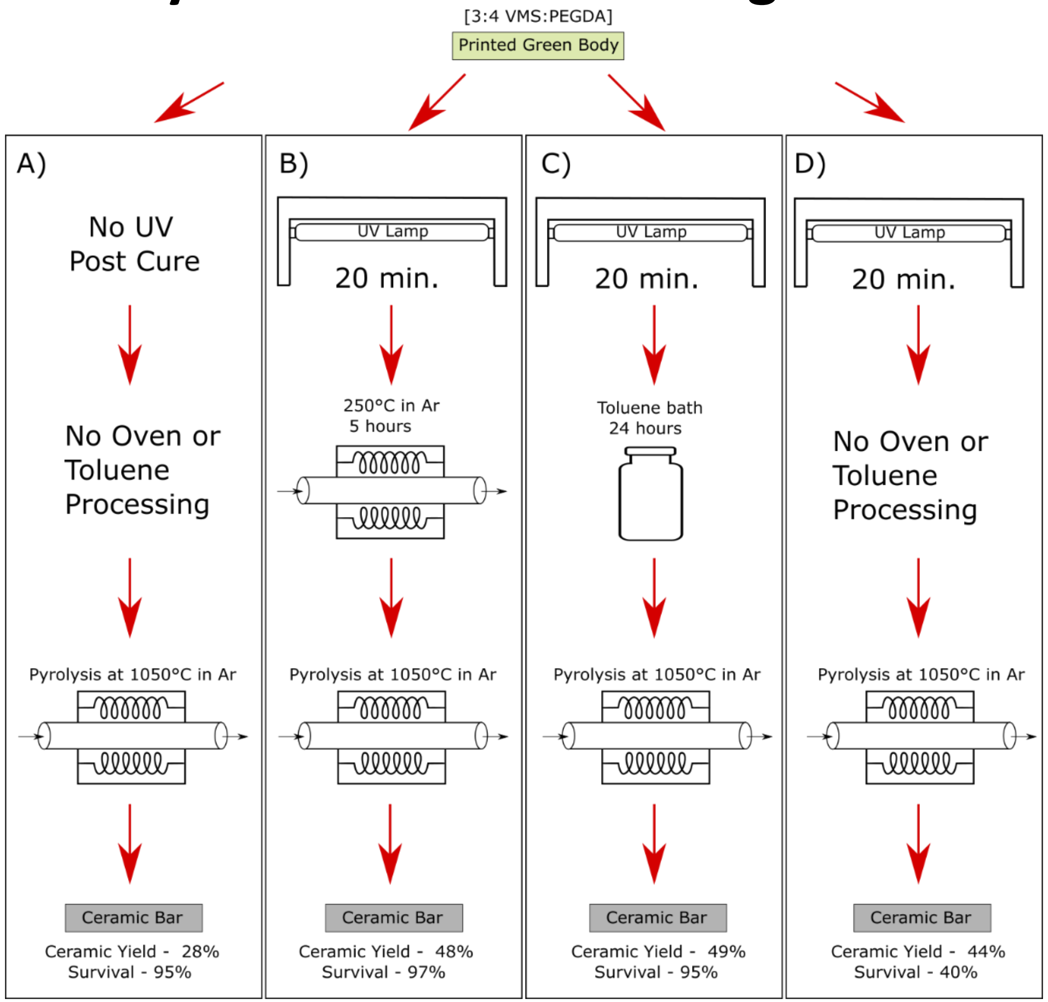
Prior formulation:
1:2 wt% VMS:PEGDA

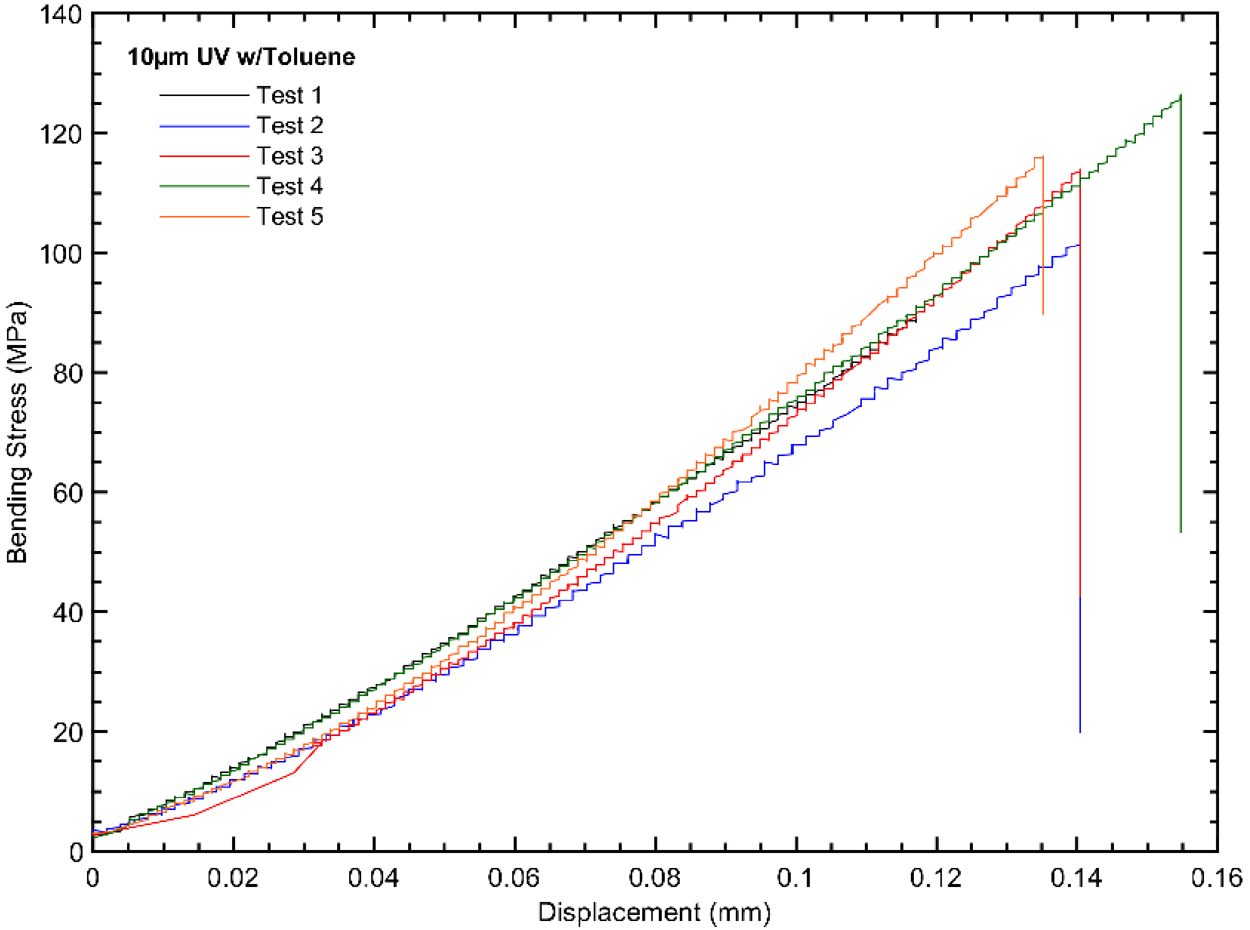
New formulation:
3:4 wt% VMS:PEGDA



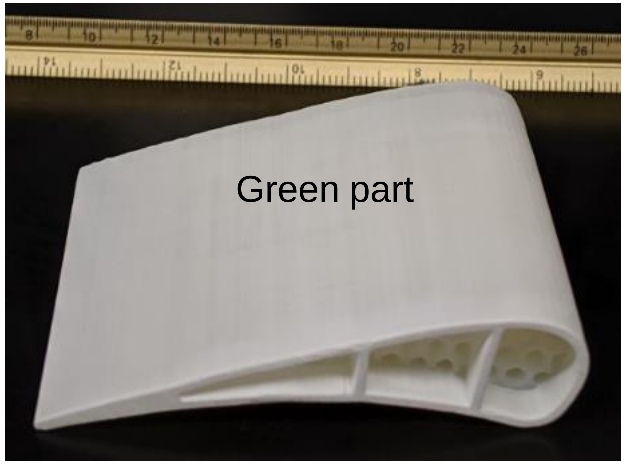
UNIVERSITY OF WYOMING

Task 2.2: Creation of a new post-processing procedure for green bodies resulted in even higher survivability and ultimate bending stress of over 100 MPa for test bars



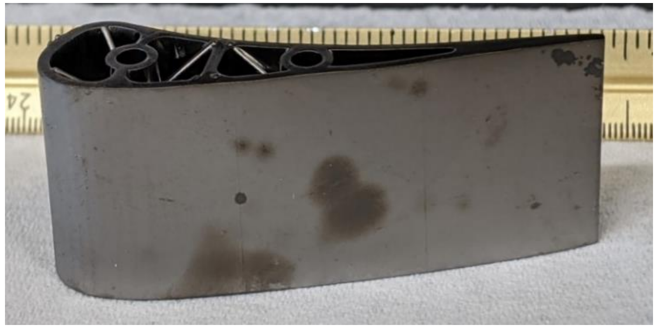


Task 2.2: The resulting process improvements were able to generate airfoils with good dimensional tolerance and high survivability in pyrolysis

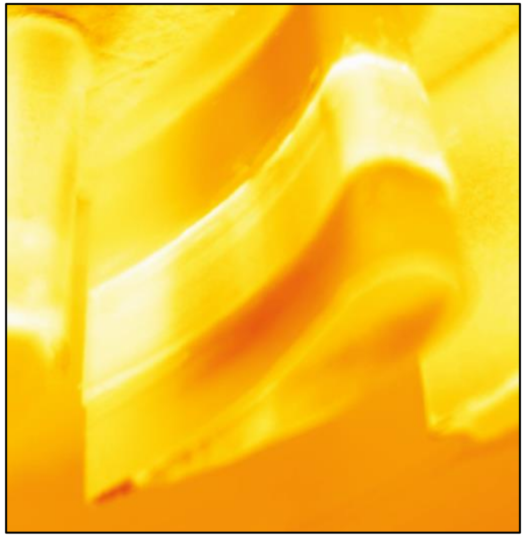


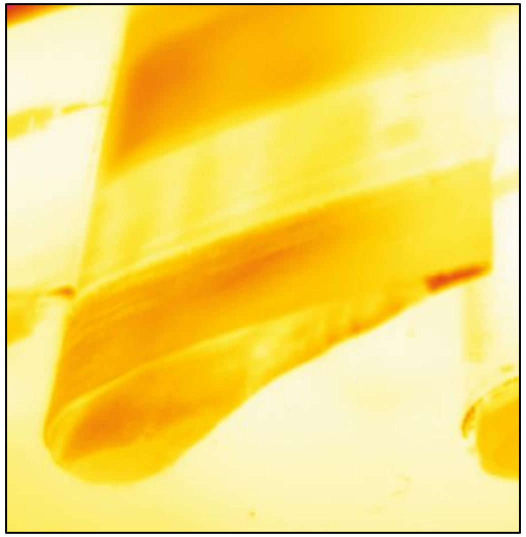
~13 cm

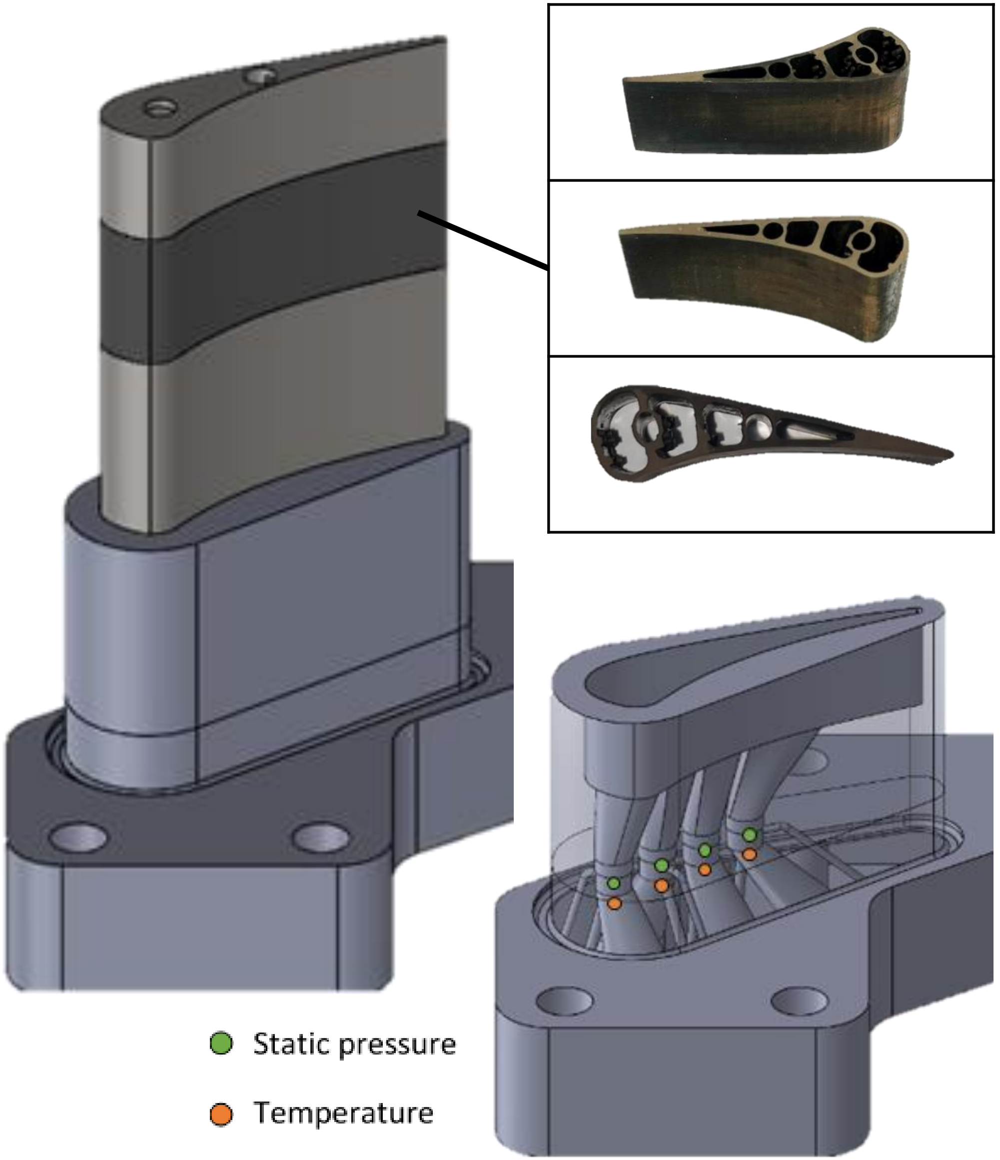
~6.5 cm



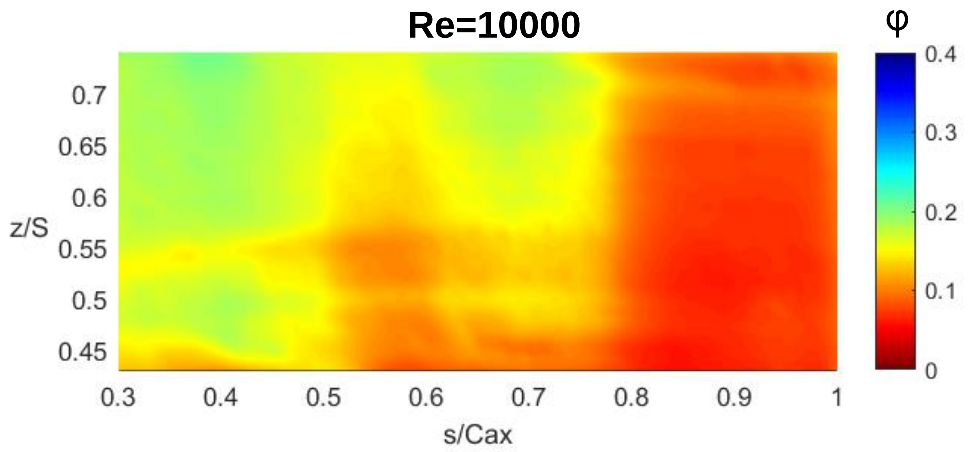
Task 2.3: IR measurements coupled with embedded temperature & pressure instrumentation in the blade’s coolant channels allow for cooling performance evaluation of the ceramic

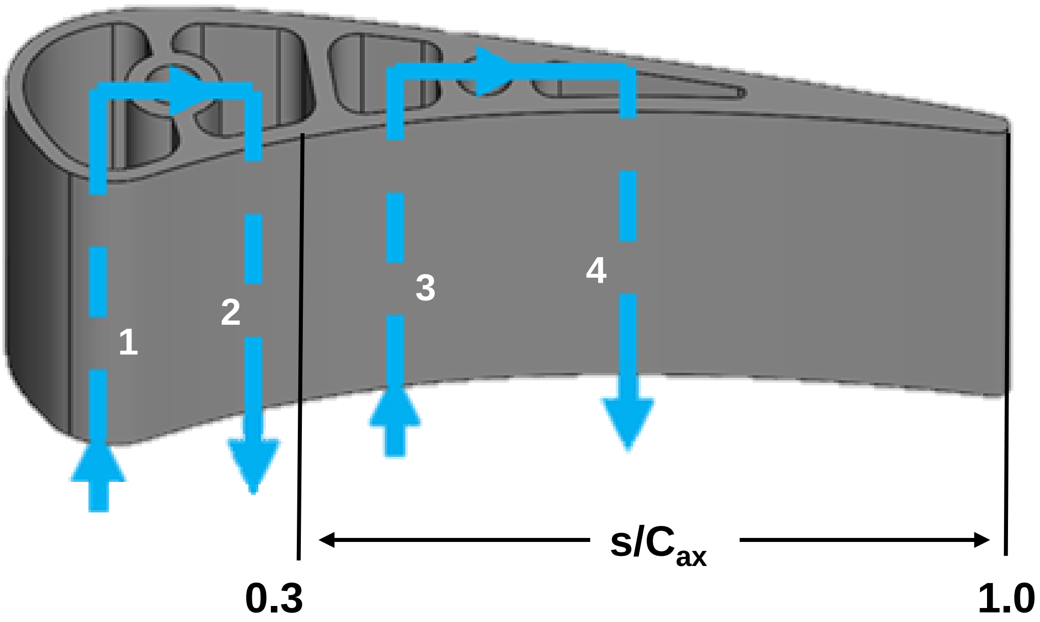


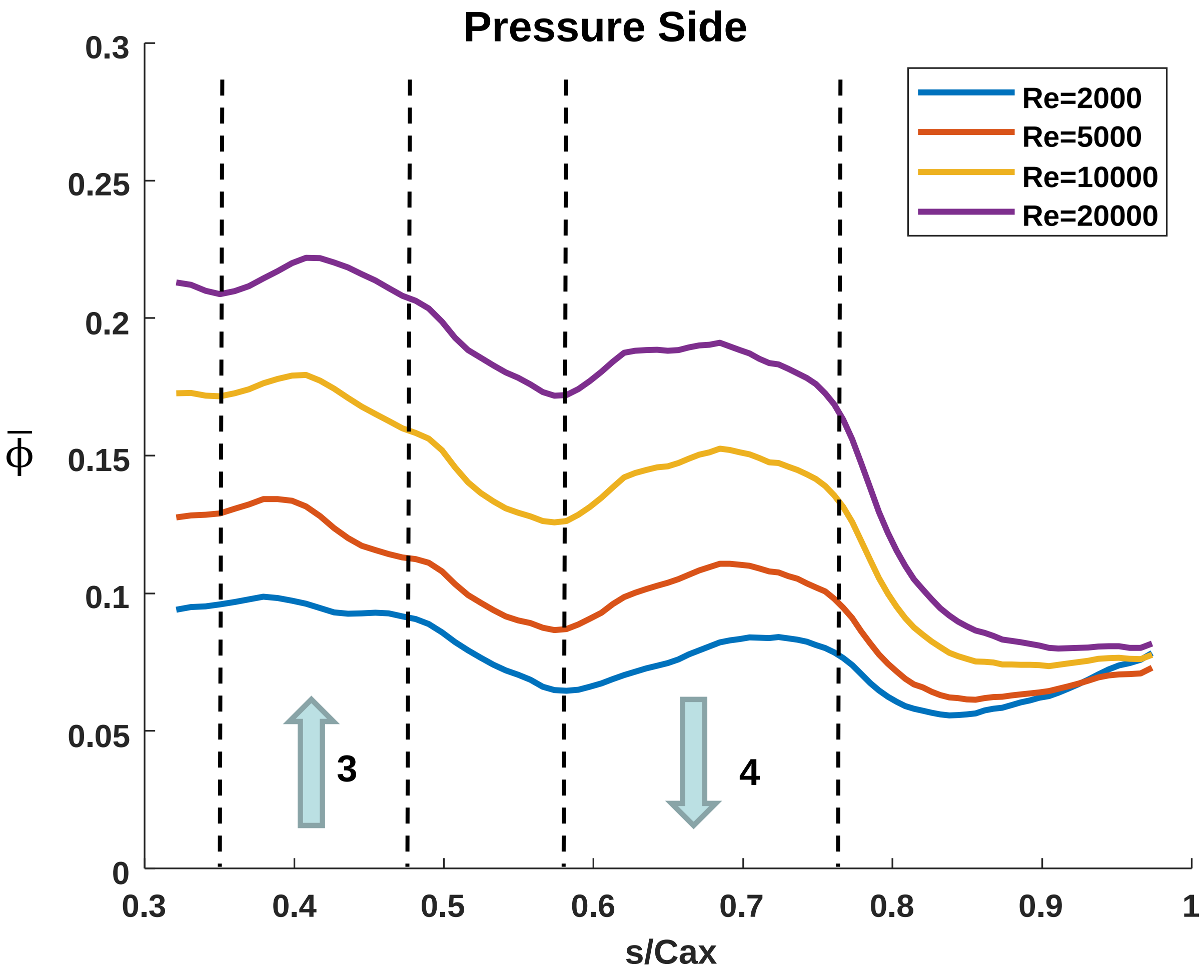




Task 2.3: Laterally averaged cooling effectiveness of the baseline geometry increases with coolant flow rate & decreases across the coolant bypass loop as seen from the pressure side

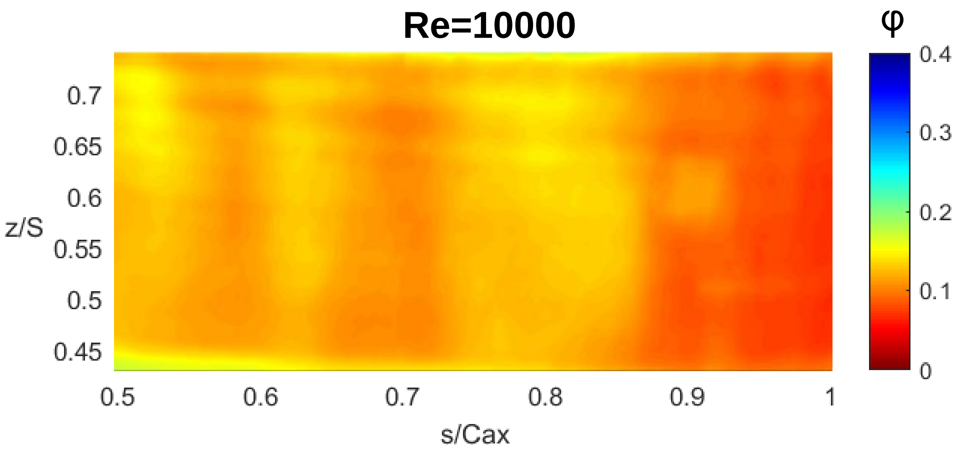


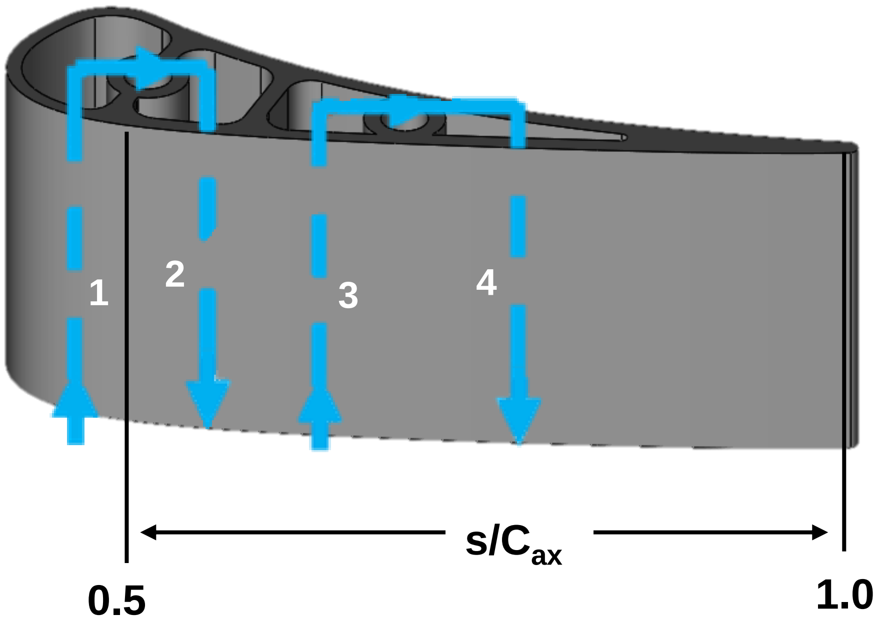


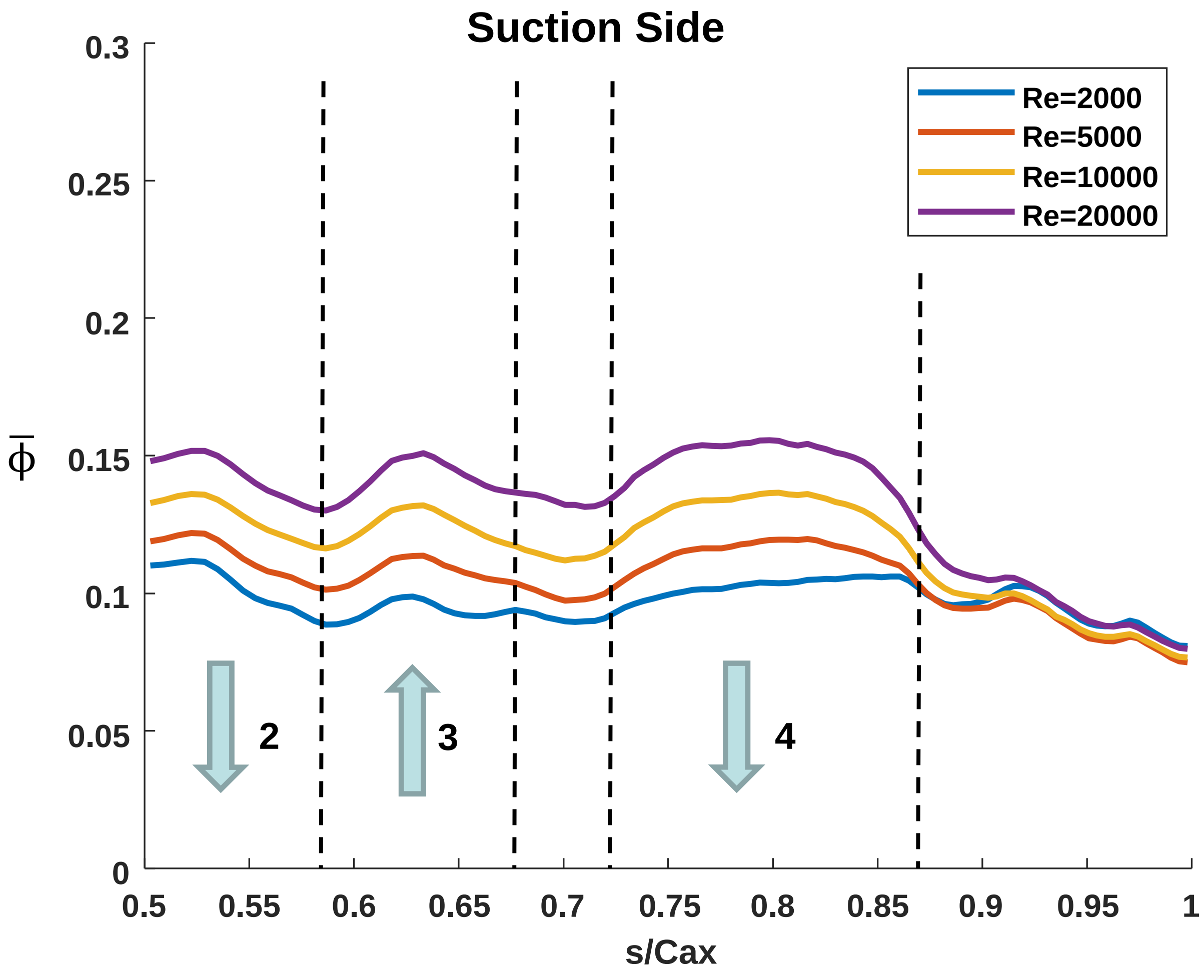


$$\phi = \frac{T_\infty - T_w}{T_\infty - T_{c,avg\ 1,3}}$$

Task 2.3: The cooling effectiveness is lower on the suction side and does not change as much with internal cooling flow rate due to higher external convection coefficients

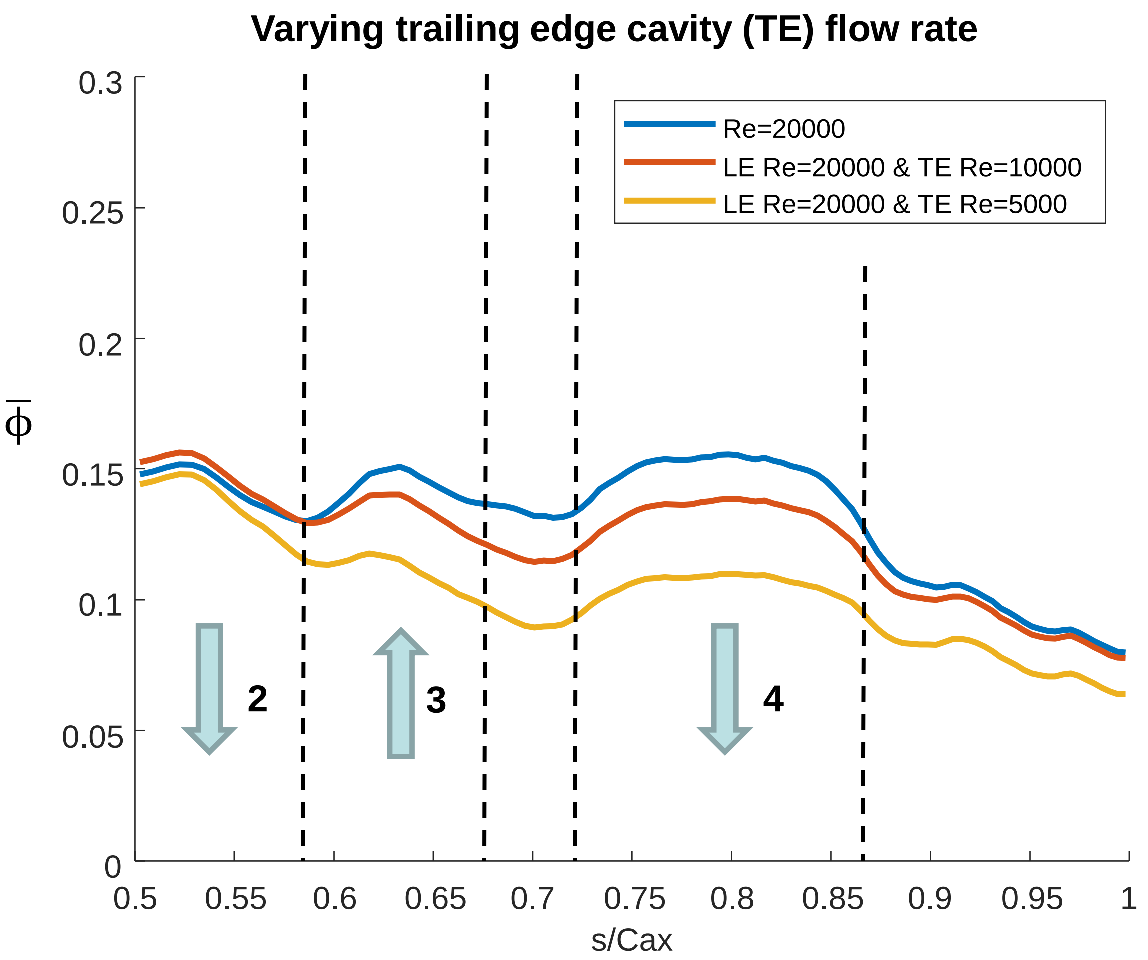


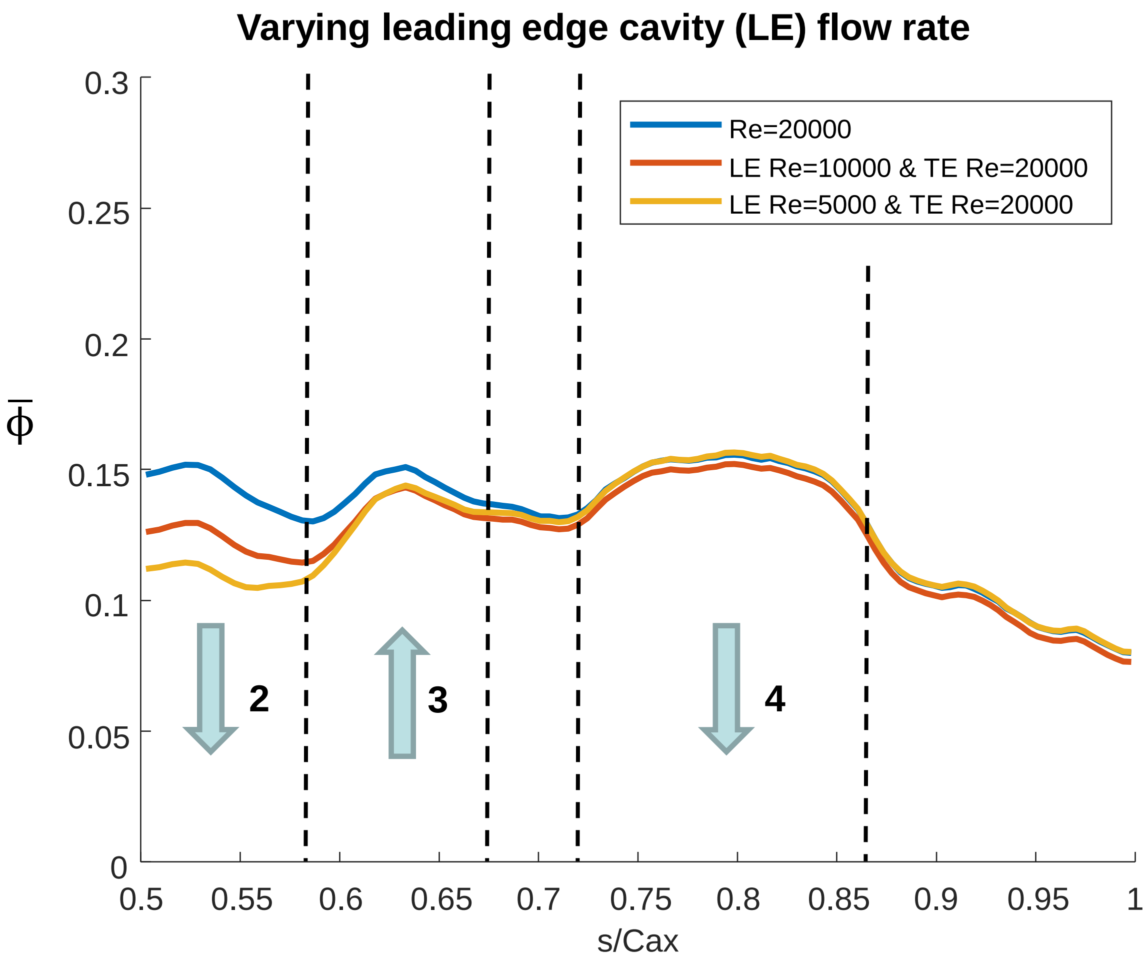




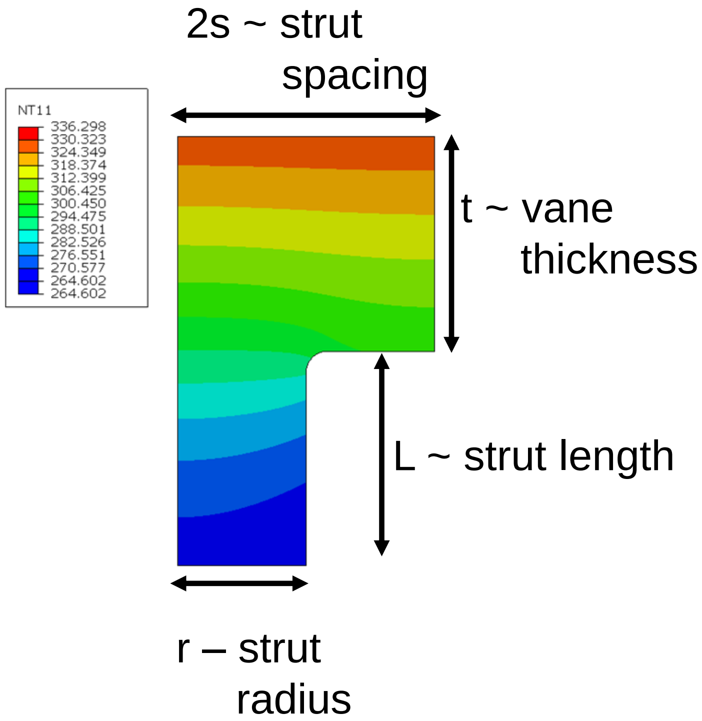
$$\phi = \frac{T_\infty - T_w}{T_\infty - T_{c,avg\ 1,3}}$$

Task 2.3: Independently varying each coolant channel's Reynolds number shows the localized effect of internal cooling on the vane suction side temperatures

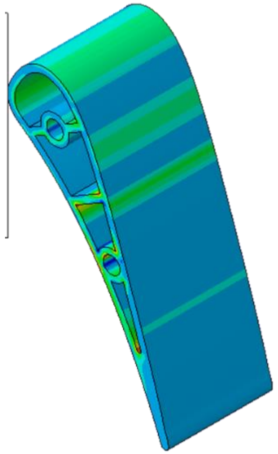


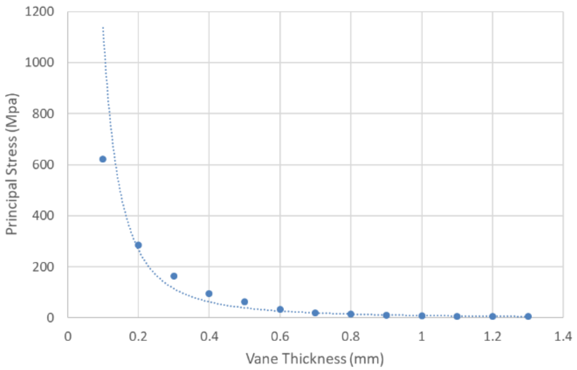


Task 3.1-3.2: We have developed a multi-fidelity process for thermo-mechanical design of optimal vane internal cooling architecture to maximize cooling efficiency



Critical thickness





Baseline Mechanical Model

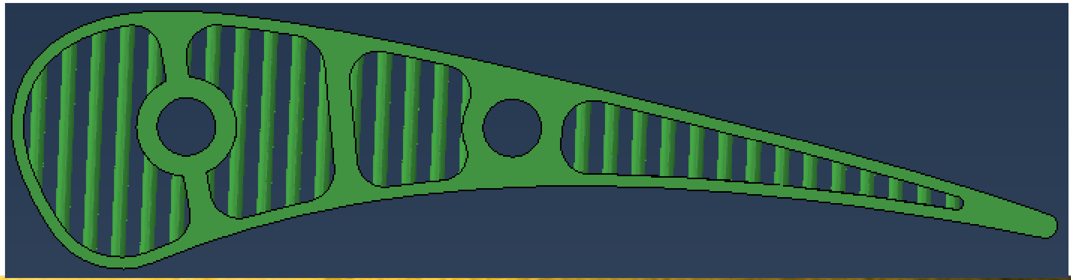
- Used to predict wall thickness to peak stress relationship for limiting thickness in axisymmetric model
- Demonstrated that thermal stresses were negligible compared with mechanical stresses → optimize mechanical and thermal sequentially

Axisymmetric Thermal Model

- Wall thickness limited by mechanical stress
- Optimized pin fin parameters (spacing, radius, length) using convex methods
- Utilized correlations for convection coefficients for pin arrays

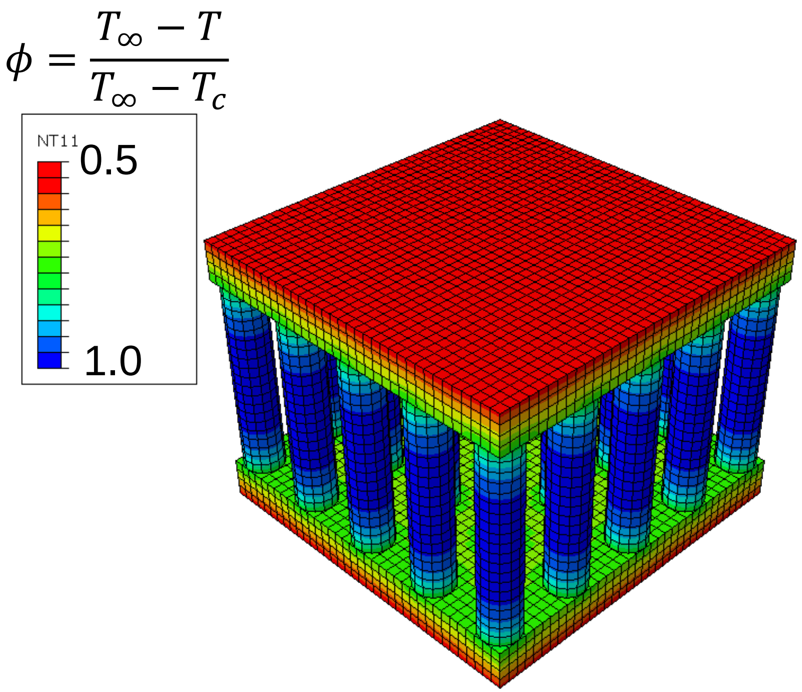
Convection coefficient + spacing/radius + limitations on printing

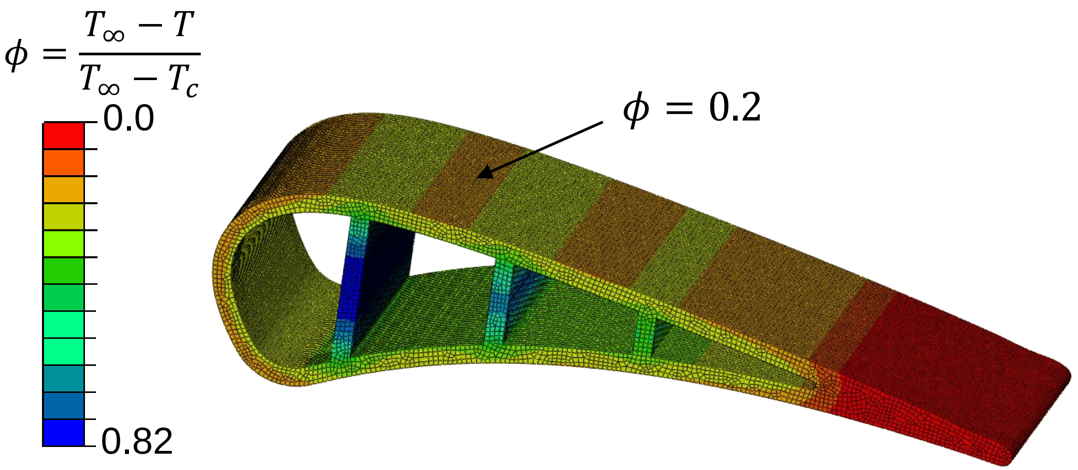
Optimized Vane Model

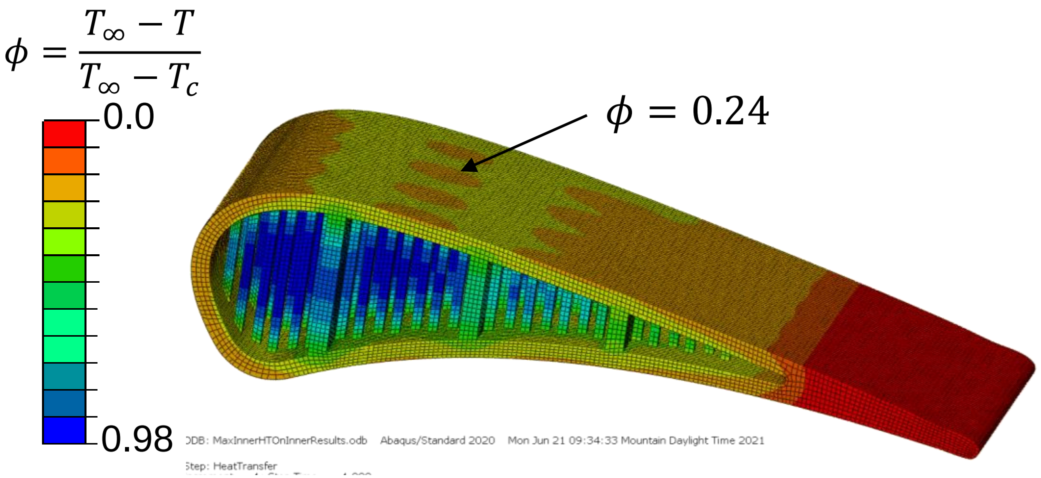


Task 3.2: A design with multiple internal struts increases the vane outer surface overall cooling effectiveness nearly to the success criteria target of Δφ=+0.05

Temperature distribution in notional struts

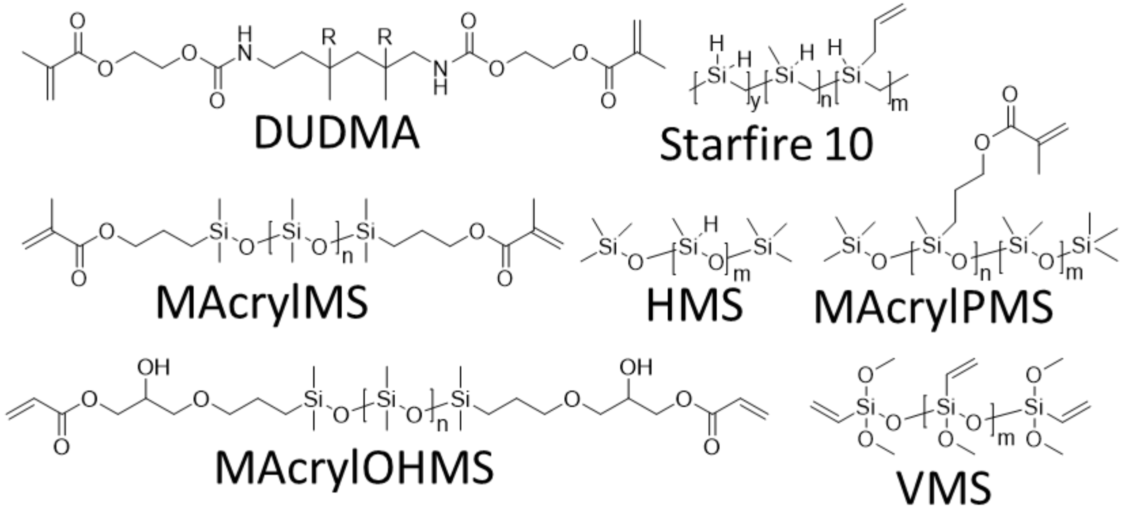


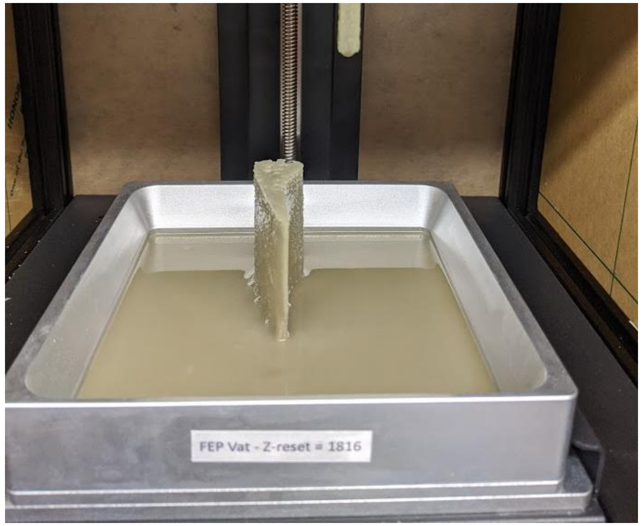




Task 4.1: Several new resin formulations were developed using acrylate siloxanes (SiOC precursor) to attempt to increase ceramic yield and decrease shrinkage

Resin 10	wt%	**Resin 16**	wt%	**Resin 28**	wt%
VMS	38.6	VMS	35.71	Starfire 10	50
MAcrylPMS	40	HMS	35.71	DUDMA	25
AcrylOHMS	20	AcrylOHMS	27.45	PPGGDMA	25
PhTrimPO	1	PhTrimPO	0.26	PhTrimPO	0.3
TMTBOHB	0.3	TiCp2Cl2	0.04	TMTBOHB	0.7
Sic whiskers	0.1	SiC Whisker	0.82	TiCp2Cl2	0.195
Average shrinkage	***26.1***	***Average shrinkage***	**25.2**	***Average shrinkage***	***23.2***
Ceramic yield	***39.7***	***Ceramic yield***	**48.4**	***Ceramic yield***	***48.3***

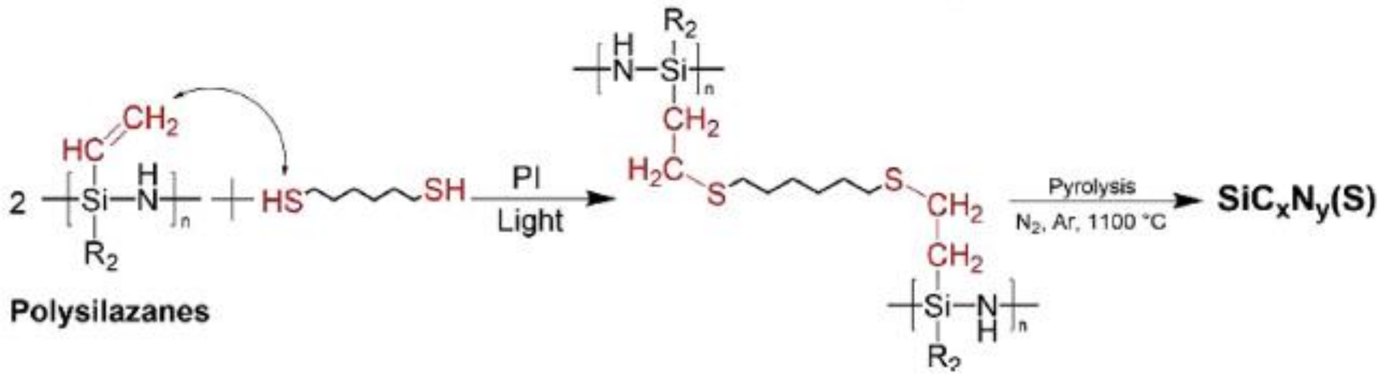


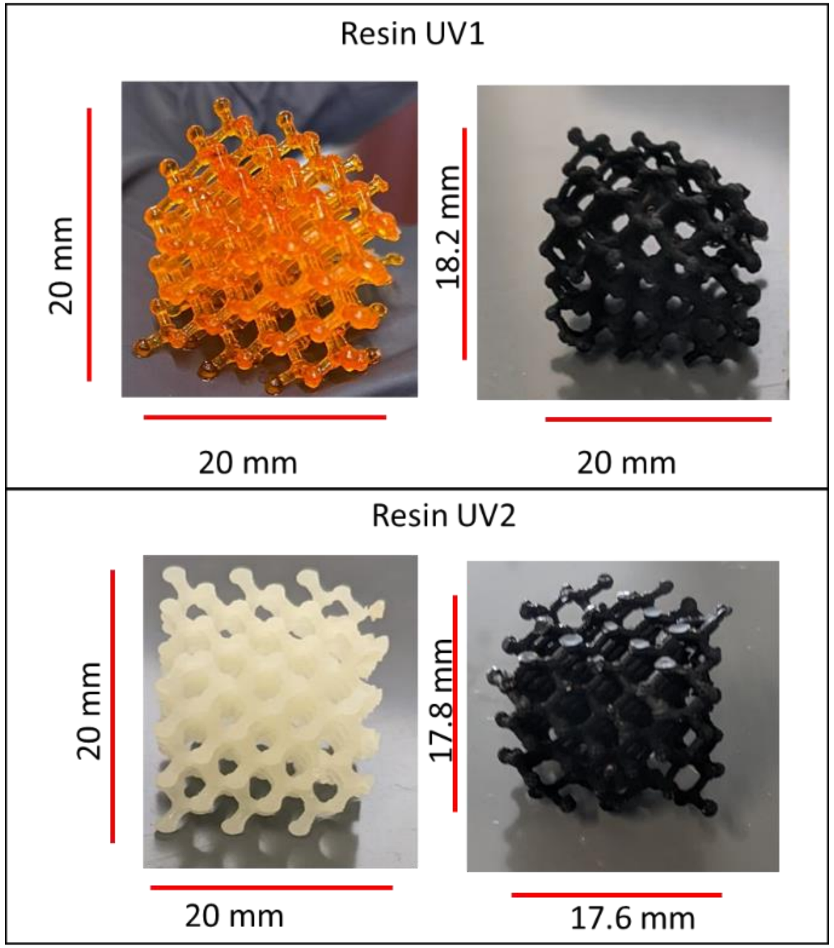


Task 4.1: We also investigated Durazane (polysilazane, SiN precursor) with potential for higher ceramic yield and reduced shrinkage

Base resin	Crosslinkers	Amount of crosslinker	Expected composition	Shrinkage % (volumetric)	Ceramic yield %
Durazane	Hexandithiol	10%	SiCN	15-17	~ 50-55
	Tri thiol	12%	SiCN	22-24	~ 60
	Tetrathiol	10%	SiCN	20-25	~ 60
	DUDMA	20%	SiOC	30-35	~ 32-35

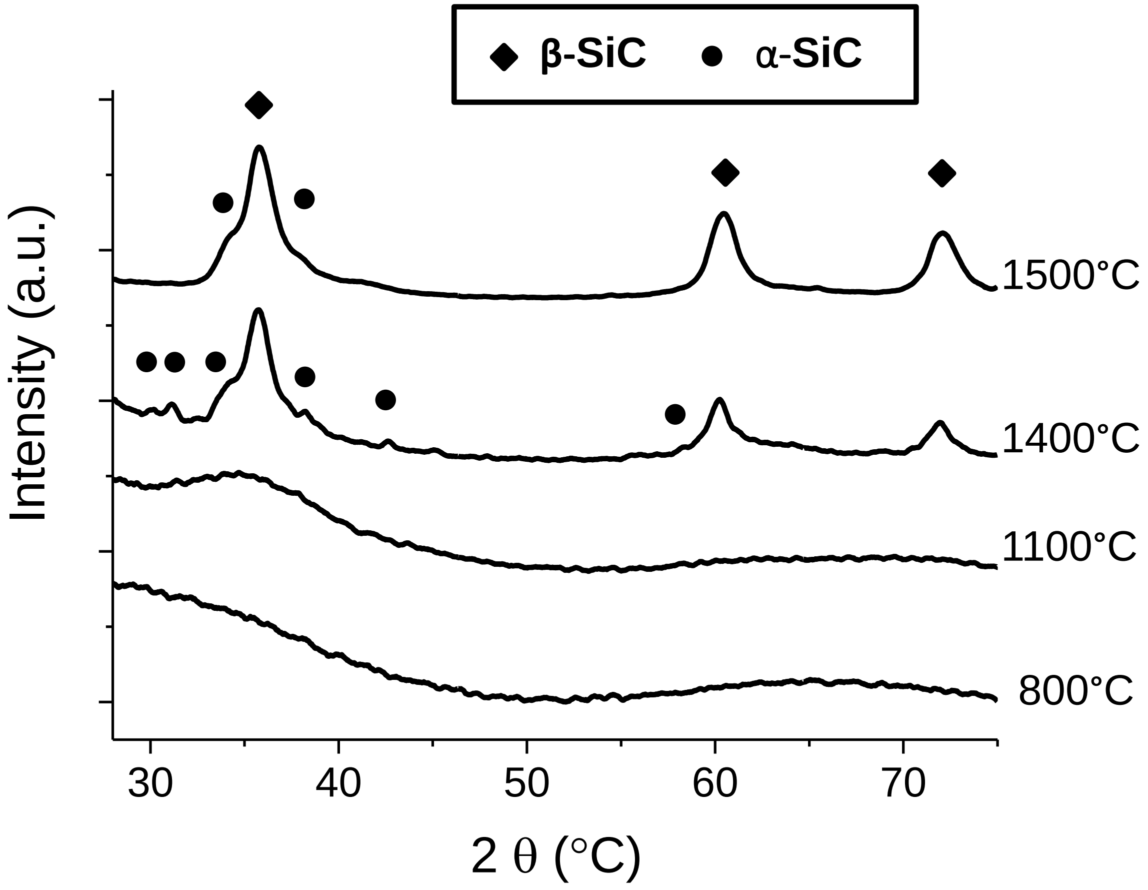
Click reaction for crosslinking Durazane with hexandithiol provides best materials to date (**~15% shrinkage, vs >35%**)



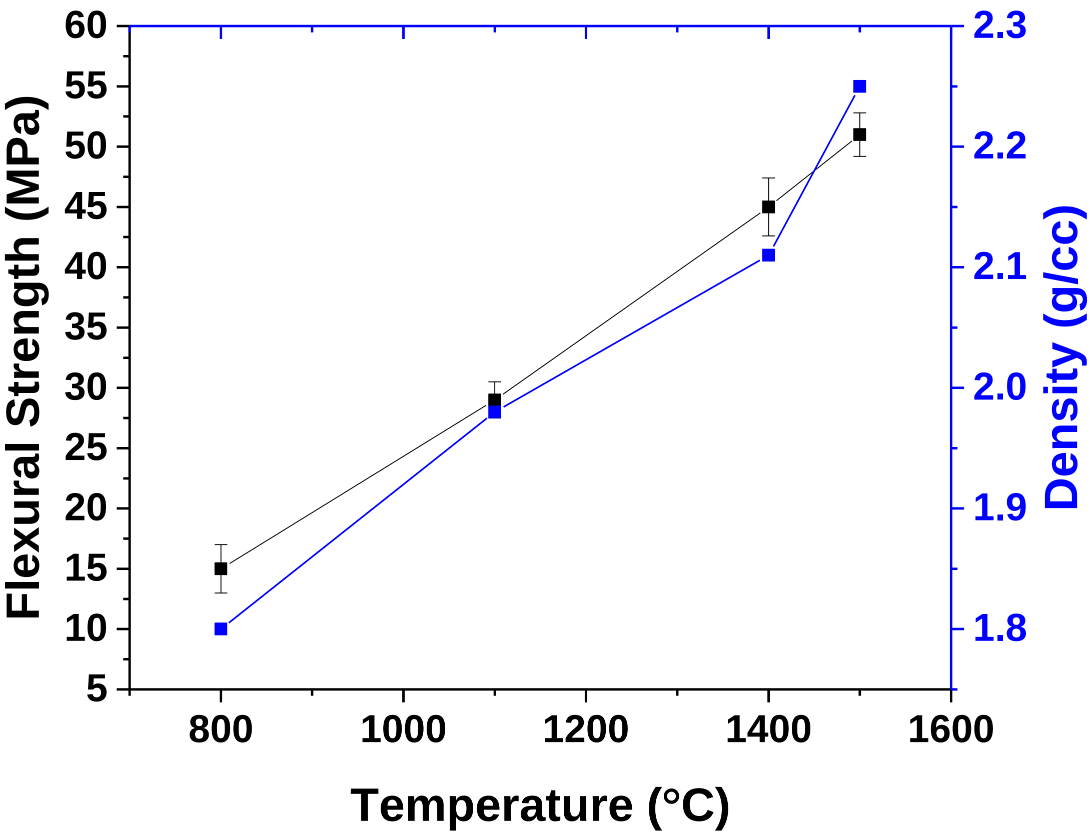


Task 4.2: We have started to investigate the effects of higher temperature pyrolysis on chemistry and mechanical strength

X-Ray Diffraction (peaks indicate crystalline phases of SiC)

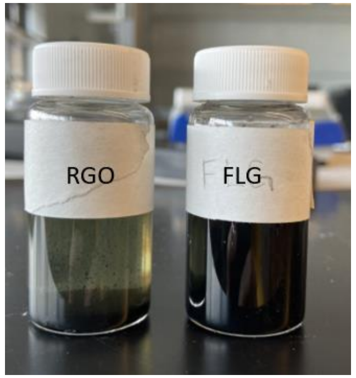


Flexural strength of bars under 3 point bend

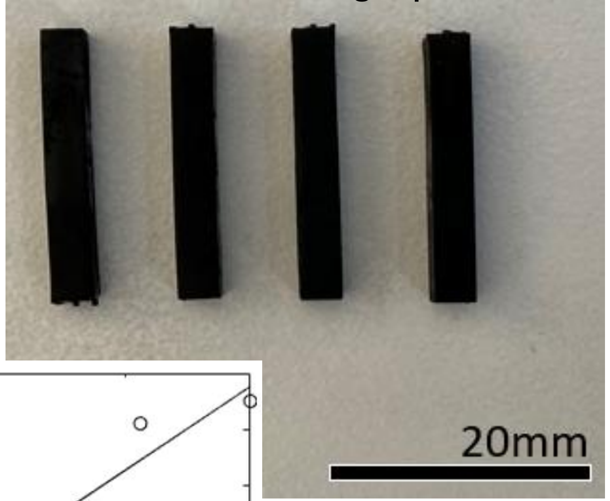


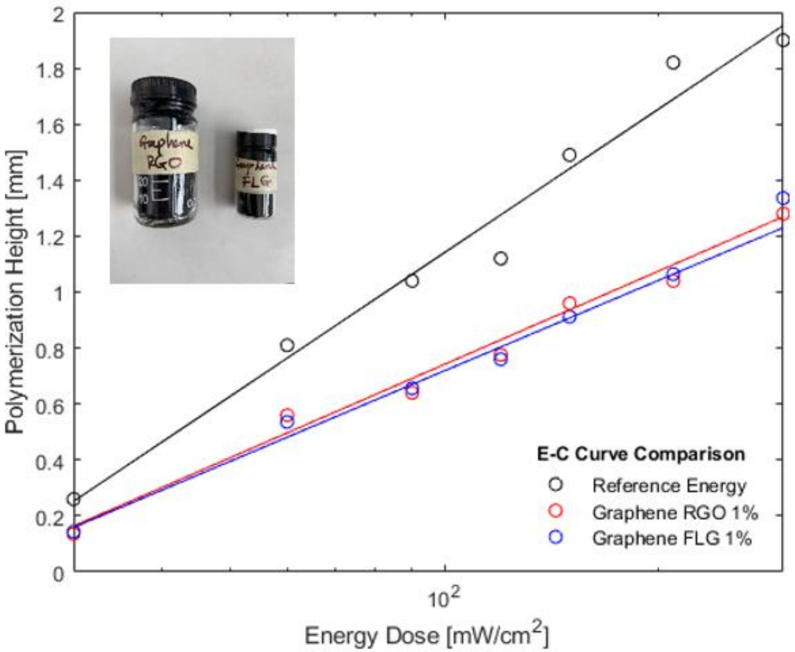
Task 4.2: High weight percent of additives have been investigated for PDC formulations but they do decrease feature resolution and influence the UV curing process

Polysiloxane formulation (SiOC precursor)



1% functionalized graphene oxide

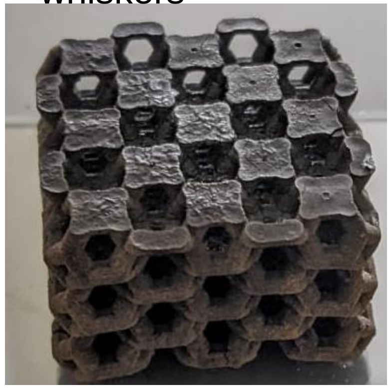




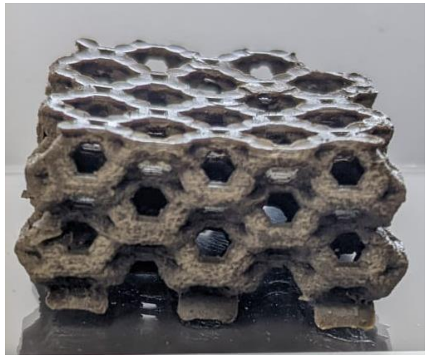
Durazane formulation (SiN precursor)

0% silicon nitride whiskers

5% silicon nitride whiskers



10% silicon nitride whiskers



Task 5: We have fabricated vanes using new PDC chemistries but have some limitations on printer/furnace size available, preventing us from making full size parts in all formulations

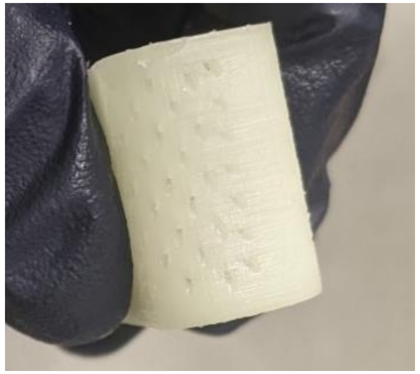
Durazane (SiN precursor)

Green body

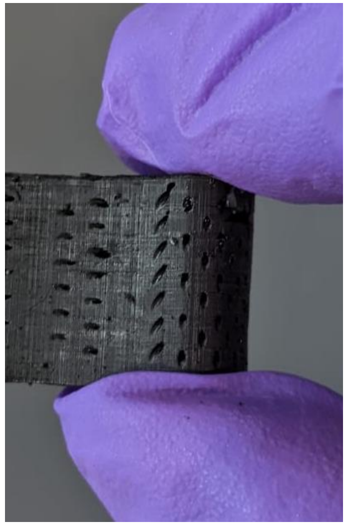
After pyrolysis

Starfire (SiC precursor)

Green body

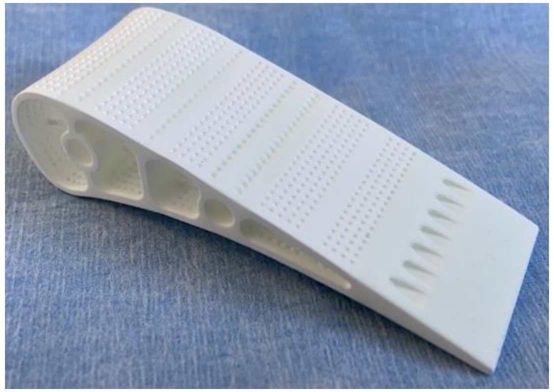


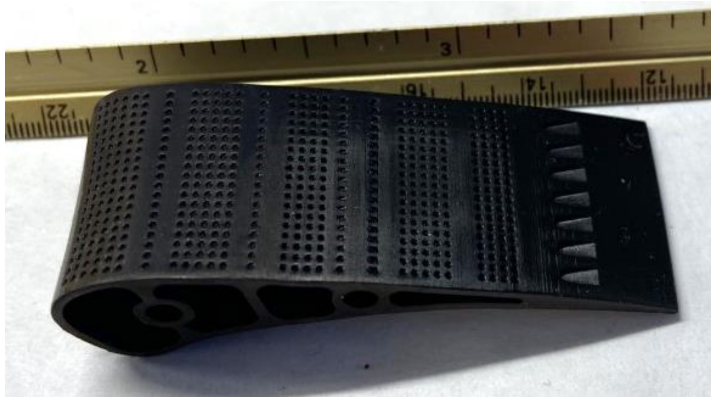
After pyrolysis



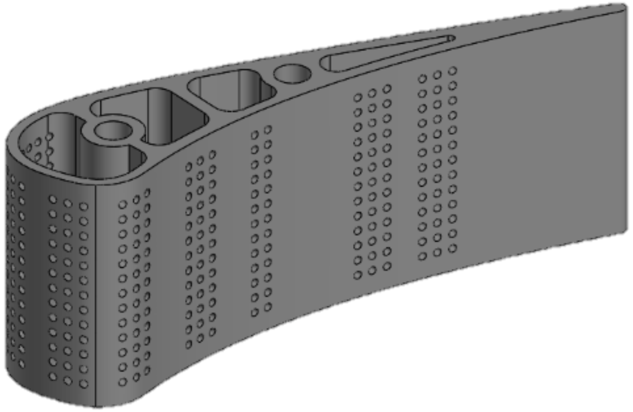
Task 6.1: Advanced cooling designs (full coverage film cooling, transpiration cooling) have been printed and have survived pyrolysis; are being tested now in the high speed cascade

Advanced transpiration cooling design

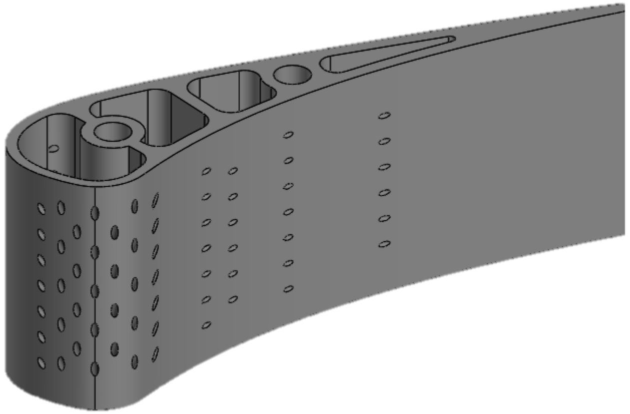




Transpiration and film cooled designs

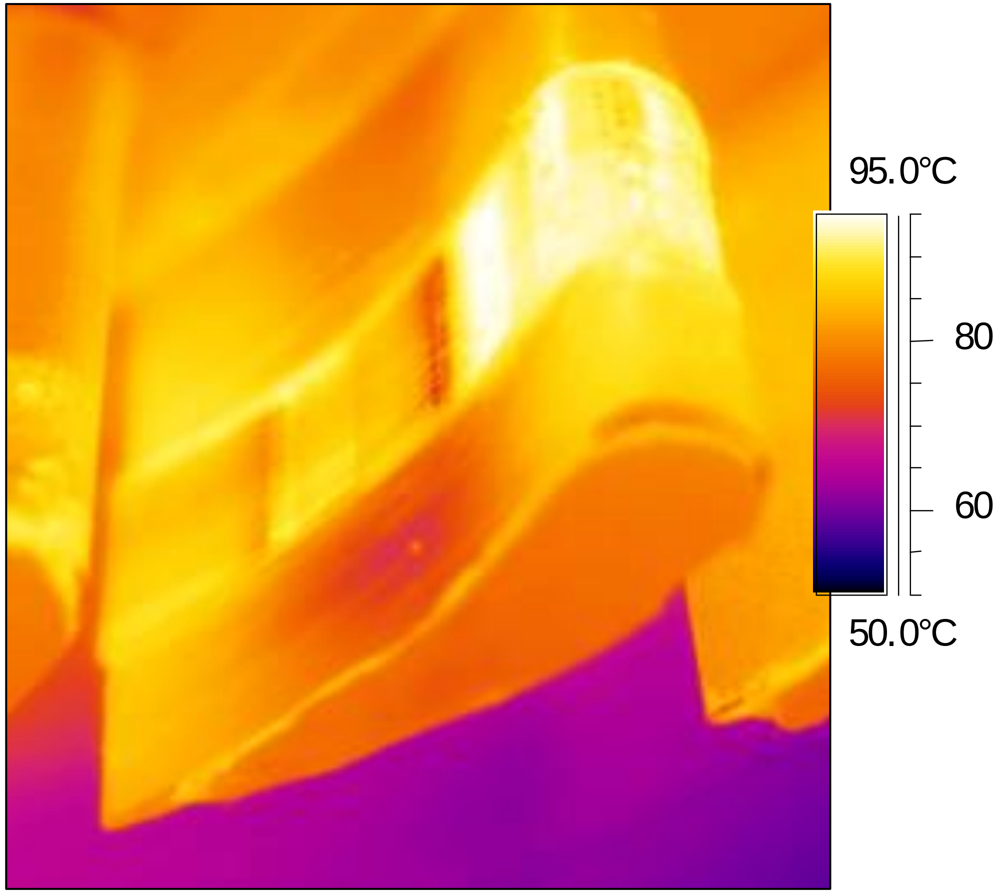


Based on design presented by Min, Huang, Parbat, Yang, & Chyu, J. Turbomach. 2019



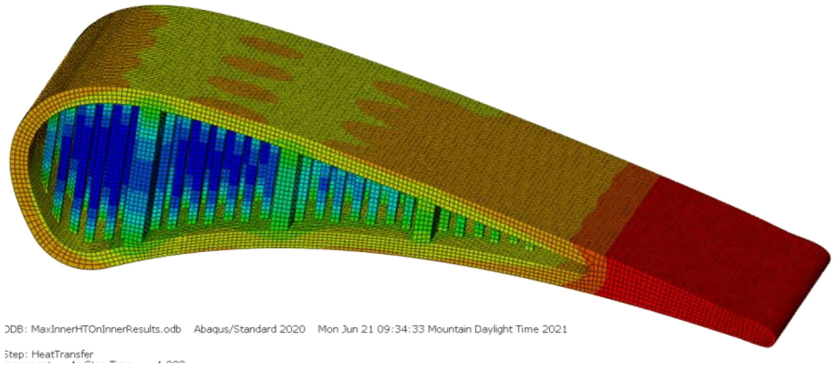
Adapted from design presented by Dyson McClintic, Bogard, & Bradshaw, ASME Paper GT2013-94928

Advanced transpiration cooling design in high speed cascade

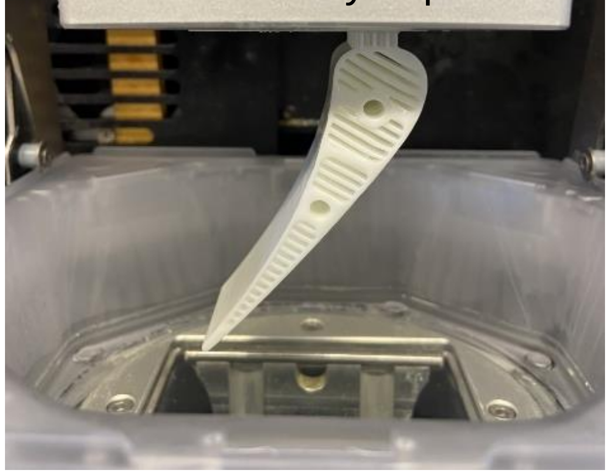


Task 6.1: We have started to fabricate the first thermo-mechanically optimized geometry but want to try more designs

First optimized design: thin outer wall, high pin density

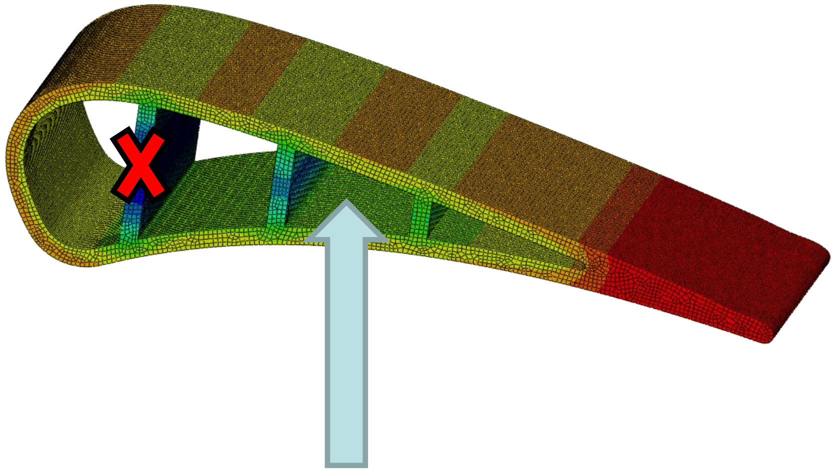


Green body in printer

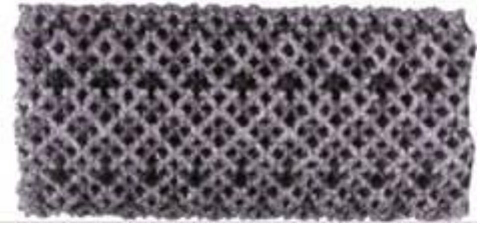


Pyrolyzed part

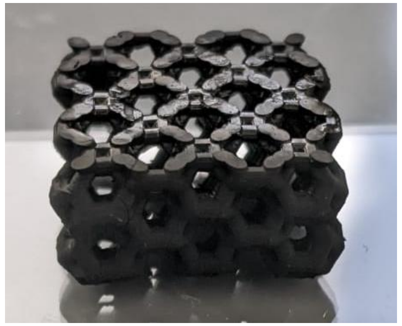
Future design: add internal lattice, remove or simplify internal struts



Lattice in SiOC



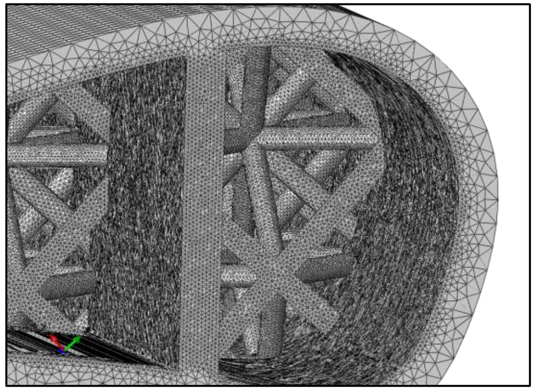
Lattice in SiN

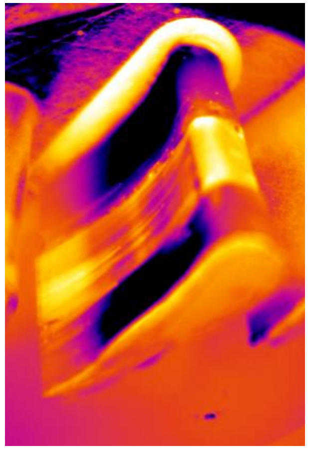


We have a one-year extension with two tasks to incorporate more advanced designs in the processes developed here

Task 7 (UWYO):

- Design lattice-based internal cooling scheme that further improves cooling effectiveness and structural rigidity
- Evaluate using FEA code at PSU test conditions AND at representative gas turbine conditions





Task 8 (UWYO/PSU):

- Fabricate and test lattice based design, compare to prior designs

Color key: process engineering, material development, modeling, validation of cooling technologies

To date, several students on the project have received graduate degrees and we have disseminated work through conferences, company reviews, and invited seminars

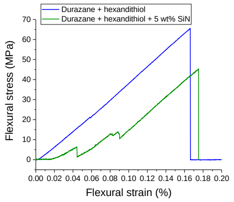
- Publications to date:
  - Rusted & Lynch, “Determining Total Pressure Fields from Velocimetry Measurements in a Transonic Turbine Flowfield”, ASME Paper GT2021-59388
- Publications under review:
  - Brinckmann, Young, Fertig, Frick, “Effect of Print Direction on Mechanical Properties of 3D Printed Polymer-Derived Ceramics and their Precursors”, Additive Manufacturing Letters
- Students graduated to date:
  - PSU: Yifan Deng (PhD), Alex Rusted (MS)
  - UWYO: Jackson Rambough (MS), Stefan Brinckmann (PhD), Jennifer Hankins (MS)
- Other outreach:
  - PSU
    - Invited presentation (virtual) for New Mexico State University Graduate Seminar
    - American Institute for Aeronautics & Astronautics: “Frontiers in Gas Turbine Technology” seminar
  - UWYO
    - Interaction with NETL (Dr. Christopher Matranga) on Graphene oxide additives for PDCs

The project has several milestones that are being tracked for progress

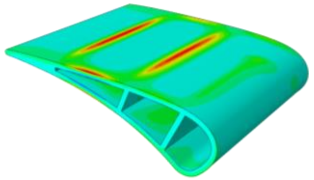
Task/ Subtask	Milestone Title & Description	Planned Completion	Actual Completion
2.1	M1: Baseline cooled vane design complete	Feb 2020	Feb 2020
2.2	M2: Fabrication of baseline cooled SiOC/SiC vane complete	Dec 2020	Dec 2020
3.1	M3: Topology optimization code for mechanical loading complete	Dec 2020	Dec 2020
4.1	M4: First generation SiC precursor chemistry delivered from PSU to UWYO	Dec 2020	Dec 2020
3.2	M5: Topology optimization code for thermal stress/cooling complete	Aug 2021	Oct 2021
4.2	M6: Detailed property characterization for SiC precursor complete	Aug 2021	Oct 2021
5.2	M7: Fabrication of baseline cooled vane with new chemistry complete	Aug 2021	Oct 2021
5.3	M8: Comparison of SiOC/SiC to SiC/SiC vane temperatures	Nov 2021	
6.2	M9: Comparison of baseline SiC/SiC vane temperature to optimized design	Aug 2022	

Color key: process engineering, material development, modeling, validation of cooling technologies

In conclusion, we have demonstrated resin and manufacturing procedures to fabricate ceramic airfoils with complex internal cooling features

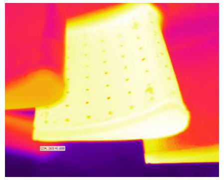


Development of resin improvements and post-processing steps has improved mechanical properties, ceramic yield, and pyrolysis survivability



Thermomechanical optimization has indicated we can achieve target improvements in cooling over baseline levels

Complex geometries including transpiration and film cooled configurations are possible with the AM PDC processes developed



Evaluation of ceramic airfoils in a high speed environment will help understand the cooling potential of novel AM ceramic designs

Questions?

PENN STATE ExCCL

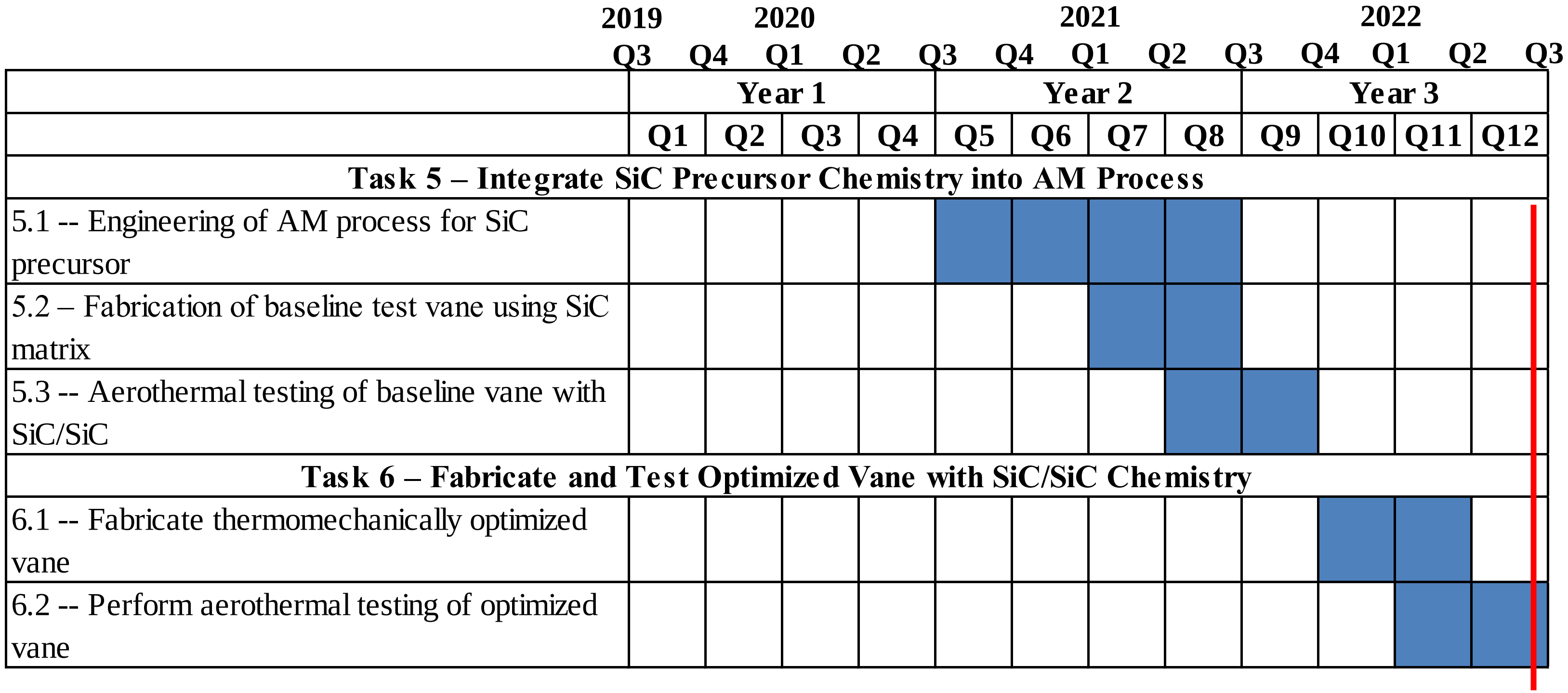
Appendix

The project schedule is designed to produce improved airfoil cooling geometries and chemistries at regular intervals throughout

2019 Q3 | Q4 | 2020 Q1 | Q2 | Q3 | Q4 | 2021 Q1 | Q2 | Q3 | Q4 | 2022 Q1 | Q2 | Q3

	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 1 - Project Management and Planning												
1.1 -- Update project management plan, assess risk, assess project resources	■											
1.2 -- Planning meetings/monthly teleconferences	■	■	■	■	■	■	■	■	■	■	■	■
Task 2 – Fabrication and Testing of SiOC/SiC Prototype Vane												
2.1 -- Design of a baseline vane geometry	■	■										
2.2 – Process characterization and fabrication of baseline vane geometry	■	■	■									
2.3 -- Aerothermal testing of baseline vane				■	■							
Task 3 – Modeling and Optimization of CMC Turbine Vane Designs												
3.1 -- Topology and morphology optimization for enhanced mechanical resilience	■	■	■	■								
3.2 -- Topology and morphology optimization for cooling design					■	■	■	■				
3.3 -- Coupled cooling and resilience optimization for vane design									■	■	■	■
Task 4 – Precursor Development and Optimization of New Resins for SiC Matrix												
4.1 – Develop new precursor resins for advanced matrices	■	■	■	■	■	■	■	■				
4.2 – Characterization of materials in composites and during pyrolysis					■	■	■	■	■	■	■	■

The project schedule is designed to produce improved airfoil cooling geometries and chemistries at regular intervals throughout



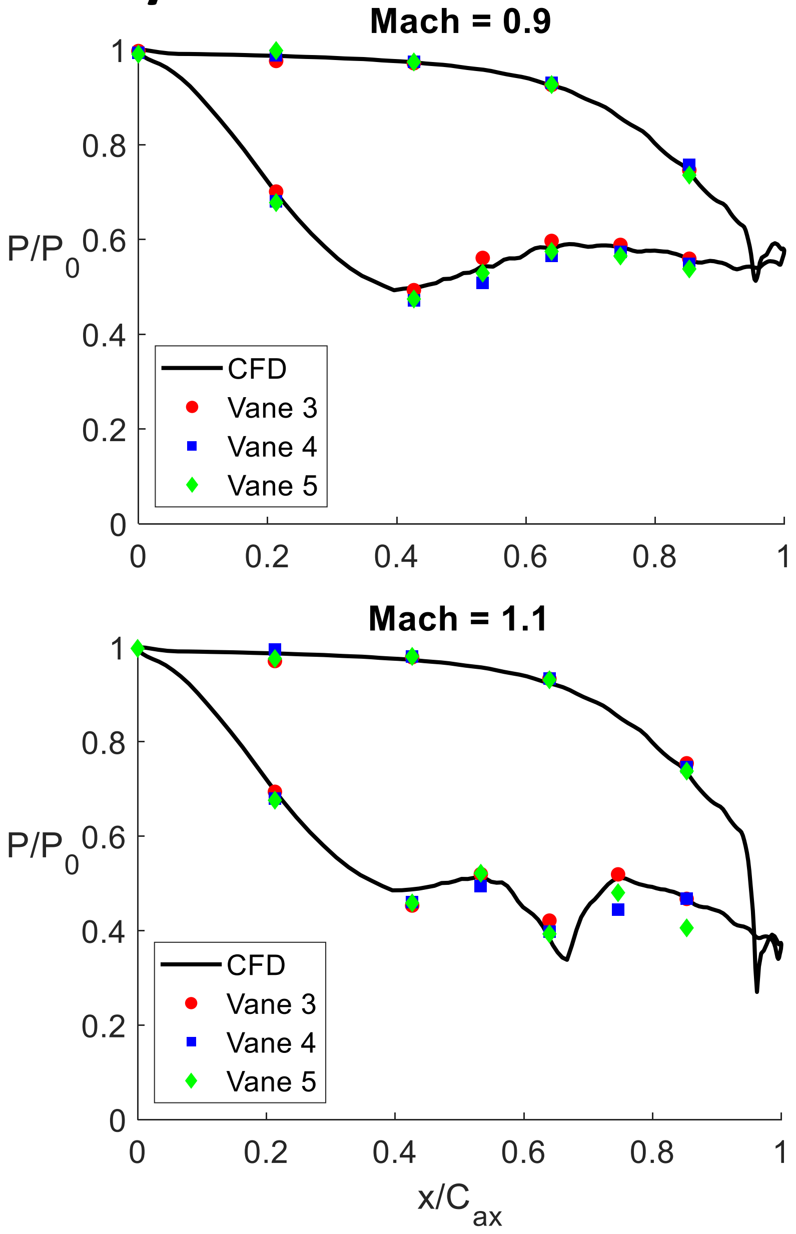
We expect financial and schedule risks will be easily manageable with outlined research plan

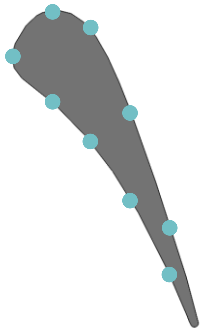
Perceived Risk	Risk Rating (Low, Med, High)			Mitigation/Response Strategy
	Probability	Impact	Overall	
Financial Risks:				
High cost for polymer precursor materials (Task 2, 4, 5, 6)	Low	Med	Low	Fewer extra test parts will be produced and materials will be conserved.
Cost of vane test hardware is high (Tasks 2.3, 5.3, 6.2)	Low	Low	Low	Fewer extra test parts will be produced, or will be sourced through lower-cost vendors.
Schedule Risks:				
Unable to schedule time in transonic testing facility (Tasks 2.3, 5.3, 6.2)	Low	Low	Low	There is plenty of buffer in schedule to account for conflicts with other facility users
Shape optimization tool development takes longer than planned (Task 3.1-3.3)	Low	Low	Low	Existing structural optimizers can be used as a backup, or a design can be developed manually and model can be validated with that design.
Novel SiC precursor material development takes longer than planned (Task 4.1)	Med	Low	Low	Intermediate precursor recipes can be provided early to build expertise.

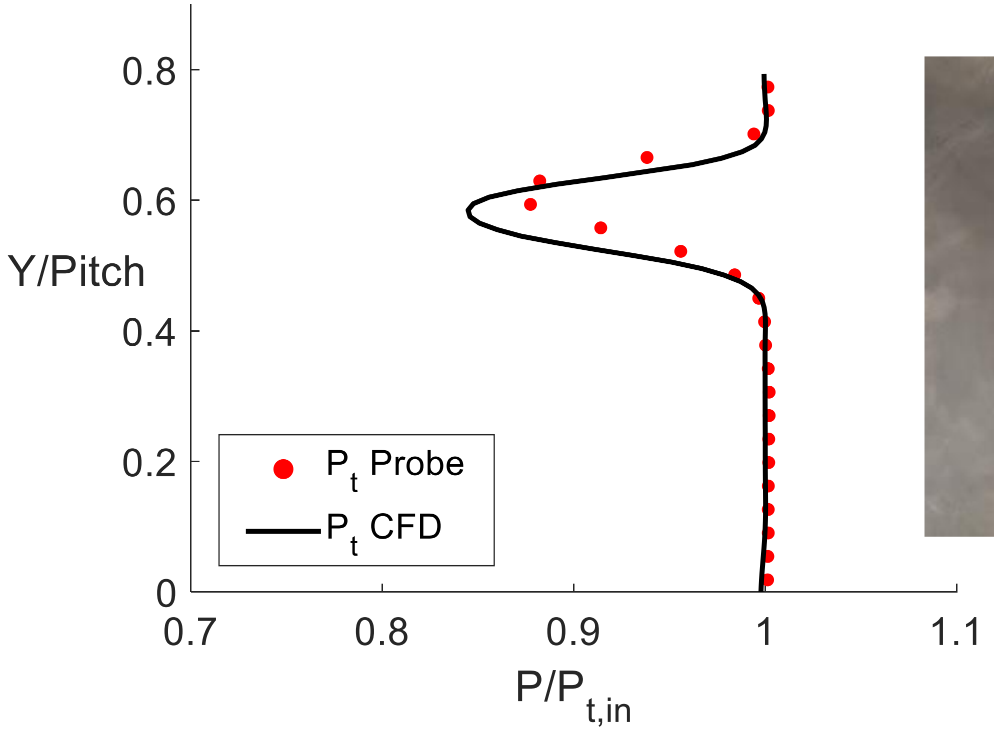
There are some technical risks for this low-TRL project but high payoff if the technology is successful

Perceived Risk	Risk Rating			Mitigation/Response Strategy
	Probability	Impact	Overall	
	(Low, Med, High)			
Technical Risks:				
Unable to fabricate cooled SiOC CMC vane with large internal cavity (Task 2.2)	Low	Med	Med	UWYO has fabricated turbine-like test parts previously, but if thin walls are an issue, can resort to thicker walls. If film cooling is a problem, can be removed from design without impact to technical goals.
Unable to integrate new SiC material into SLA process (Task 5.1)	Low	Med	Med	3D printable variants of the SiC precursor formula would be investigated although may not have the same desired material capabilities of SiC.
Unable to fabricate optimized vane shape using SiC/SiC (Task 6.1)	Med	Low	Low	This risk is avoided early by creating intermediate test prints as novel designs are developed, so that final design fits within manufacturing constraints.
Management, Planning, and Oversight Risks:				
None				Organizational team is collaborative and all PI's have management experience.
ES&H Risks:				
None				Co-PI's have expertise and facilities to handle volatile chemicals and hot furnace objects.
External Factor Risks:				
None identified				

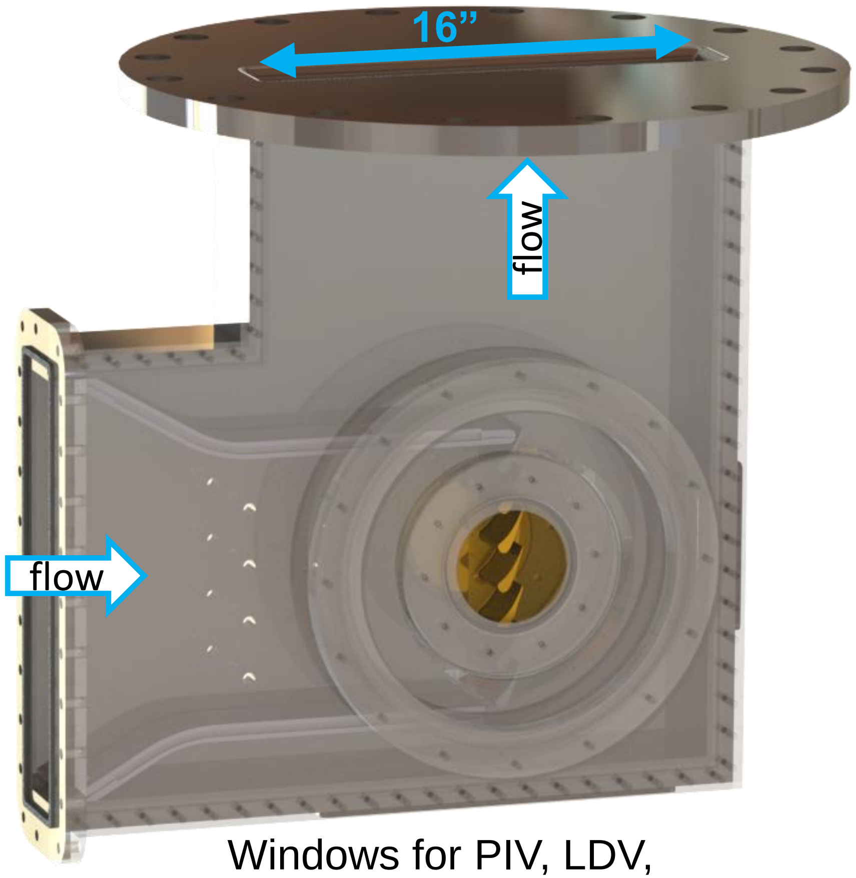
Task 2.1: Aerodynamic measurements have been taken to benchmark the cascade and vane assembly without CMCs



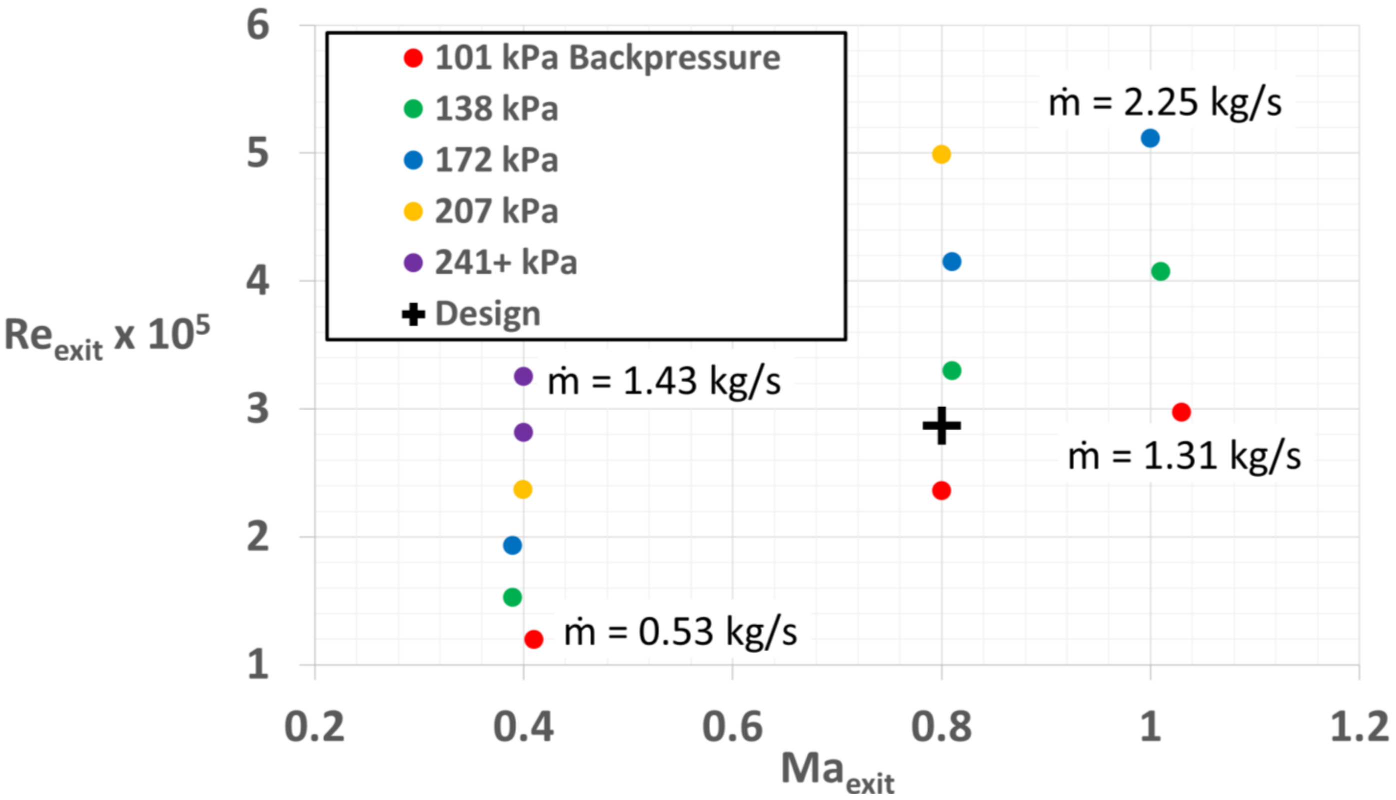




Task 2.1: The vane assembly will be tested in a new high speed cascade facility at Penn State capable of relevant Mach and Reynolds numbers, as well as cooled air capability

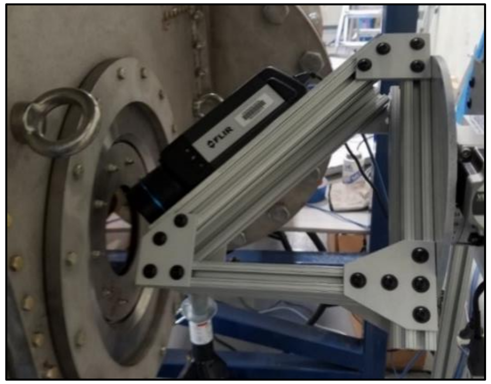


Windows for PIV, LDV, and IR measurements

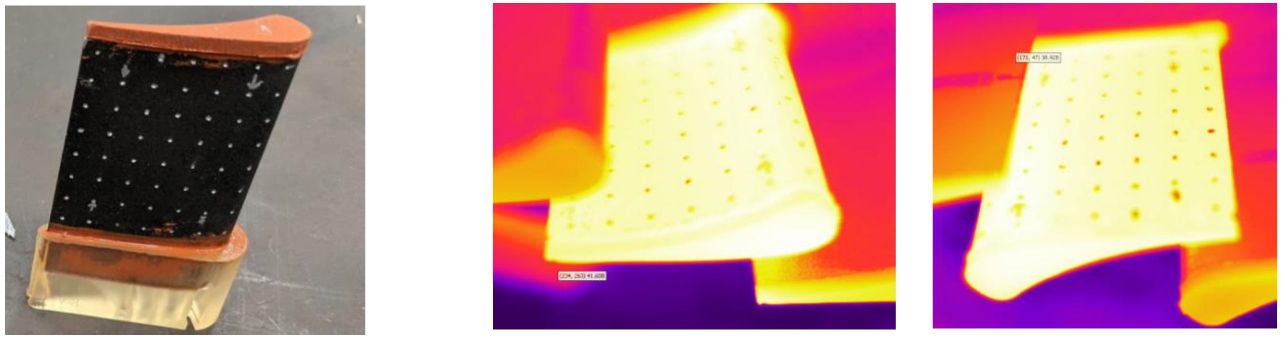


Task 2.1: We have developed in-situ infrared image spatial/temperature calibration for cooling performance, as well as novel total pressure measurement for aerodynamic performance

Infrared camera in facility



Calibration vane with spatial markers visible in IR

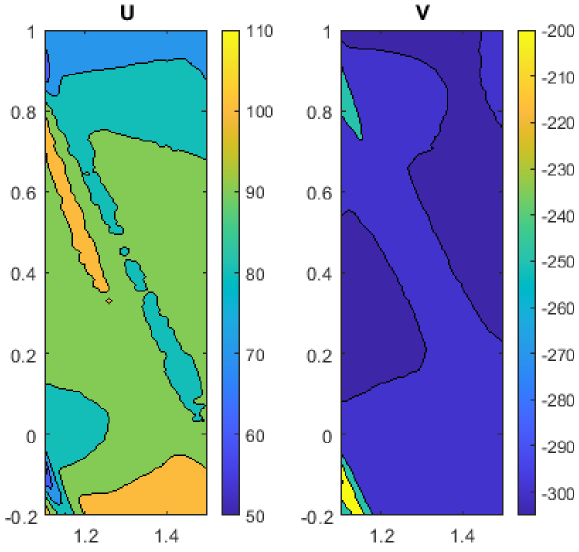


Momentum Equation

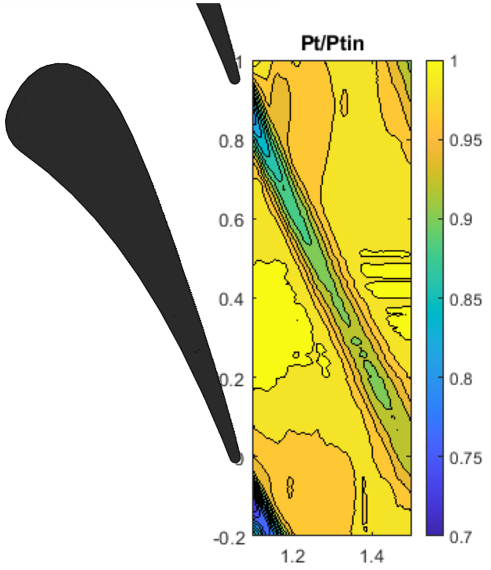
From measured velocity fields (PIV)

$$-\frac{\partial \bar{p}}{\partial x_i} = \rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} + \rho \frac{\partial \overline{u_i' u_j'}}{\partial x_j} - \mu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j}$$

Measured velocity fields

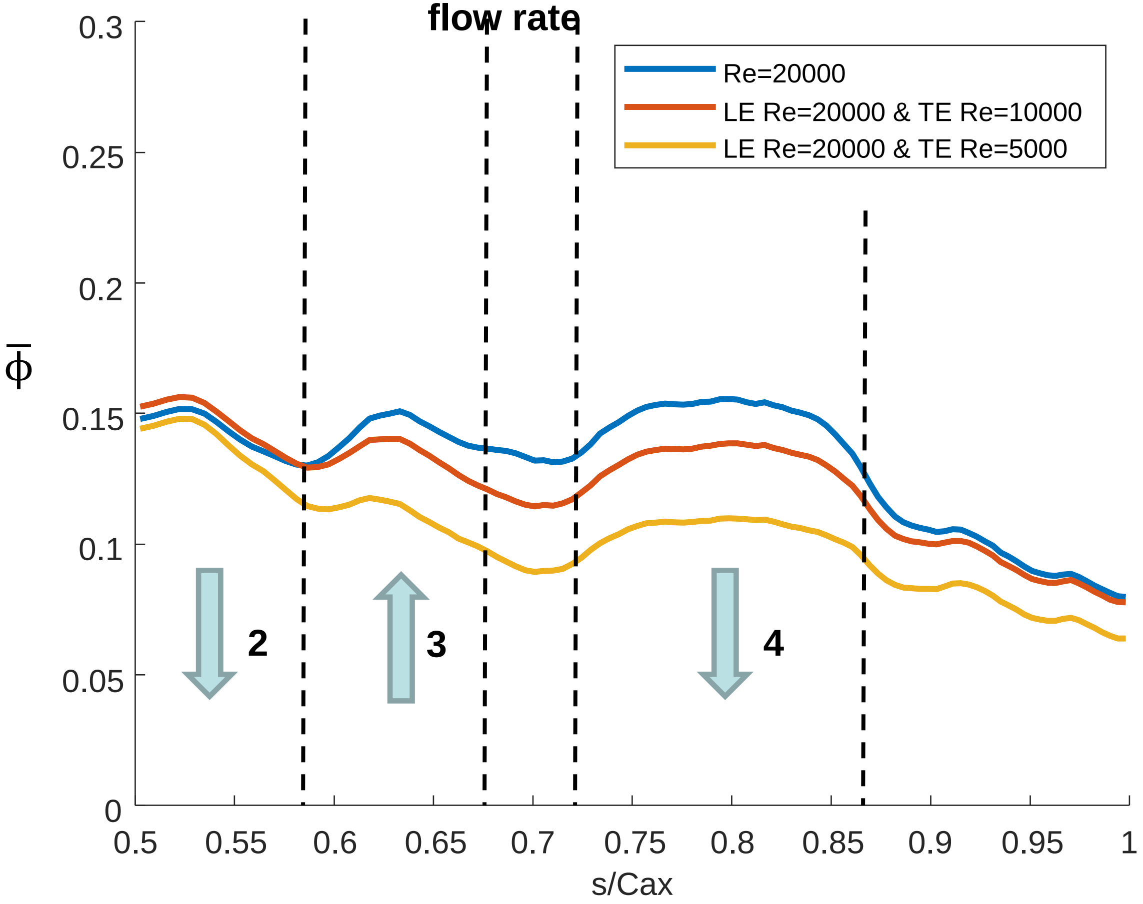


Total pressure field



Independently varying each coolant channel's Reynold's number shows a divergence in cooling effectiveness values as the difference between them increases.

Varying trailing edge (TE) flow rate



Varying leading edge (LE) flow rate