Recent Studies of Internal and External Cooling Technologies at NETL

A Pathway To Higher Efficiency
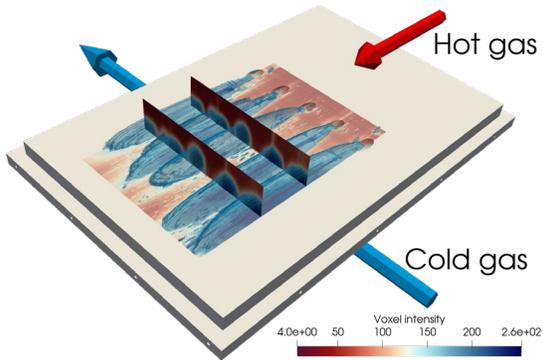
NETL — NATIONAL ENERGY TECHNOLOGY LABORATORY

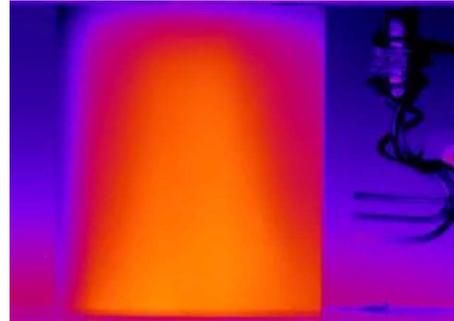*D. Straub, J. Weber, S. Ramesh, E. Robey, A. Roy, M. Searle, and J. Yip*
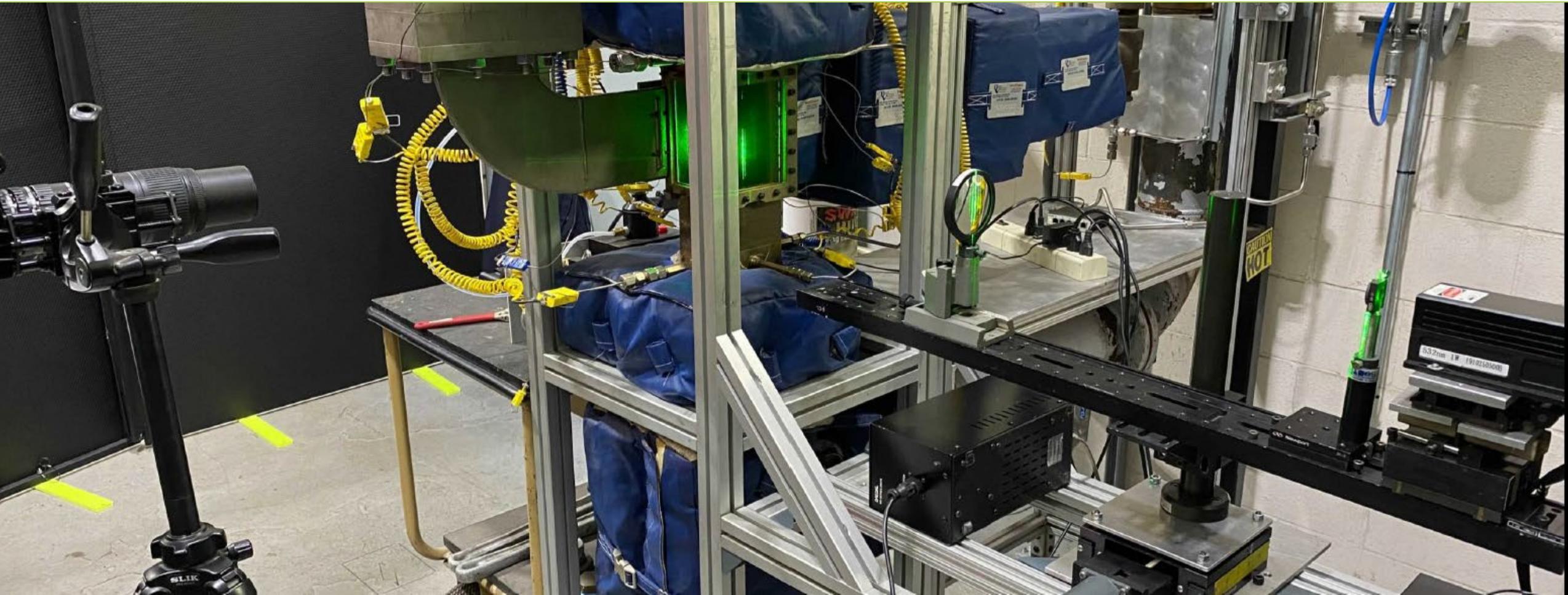
Experimental Heat Transfer and Thermal Science

Brayton Cycles

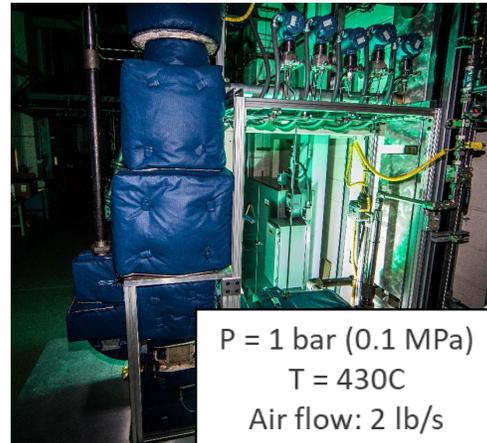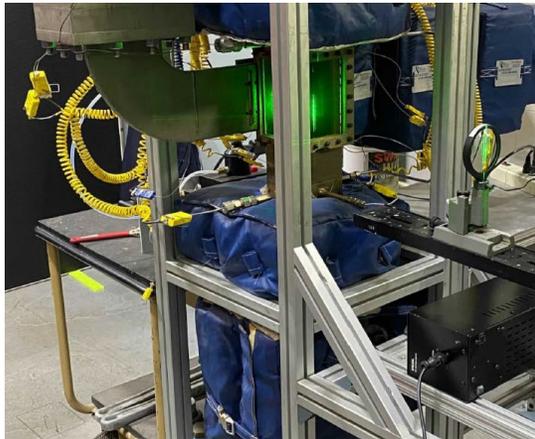### Film Cooling

Internal Cooling

AM Airfoil Cooling – courtesy of ORNL & RCBI
(Increase TrIT by 100C for 5-10MW GT's)

P = 1 bar (0.1 MPa)
T = 430C
Air flow: 2 lb/s

sCO2 Cycles

Indirect Cycles
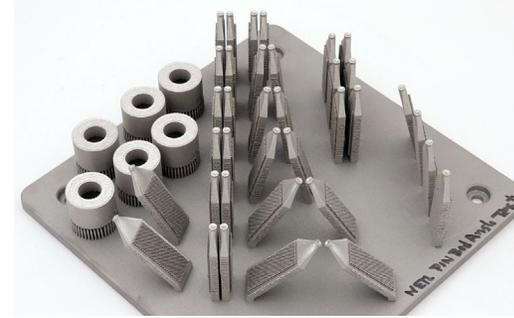
AM Plate Pin-Fin Prototypes – courtesy of ORNL
(recuperator 40% lighter than PCHE)

P = 10 bar (1 MPa)
T = 1200C
Air flow: 2lb/s

Direct Cycles

Gas Turbine Internal Cooling Limit*

sCO2 Turbine Internal Cooling Limit

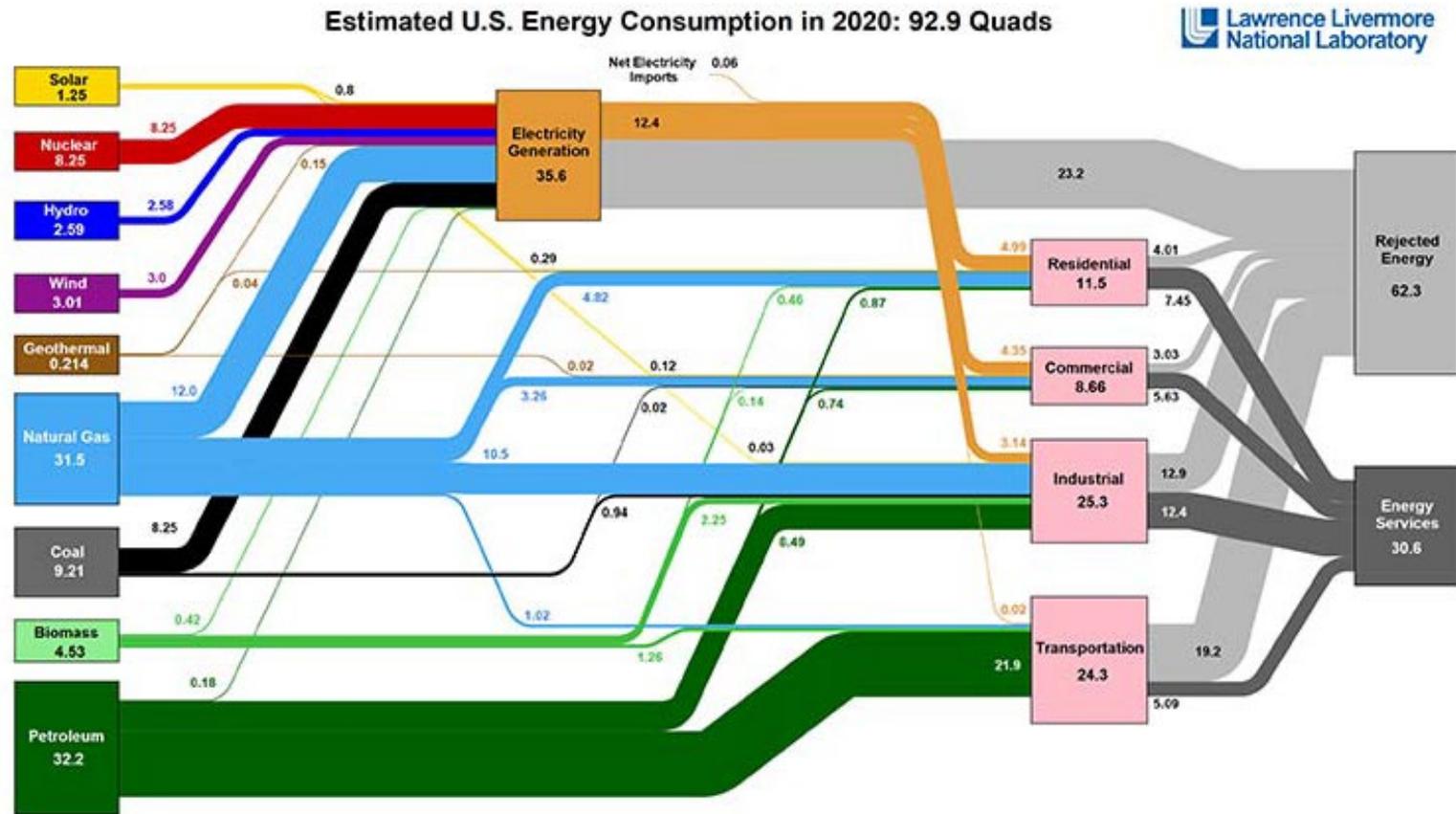P = 240 bar (24 Mpa)
T = 500C
CO2 Flow: 3 lb/s
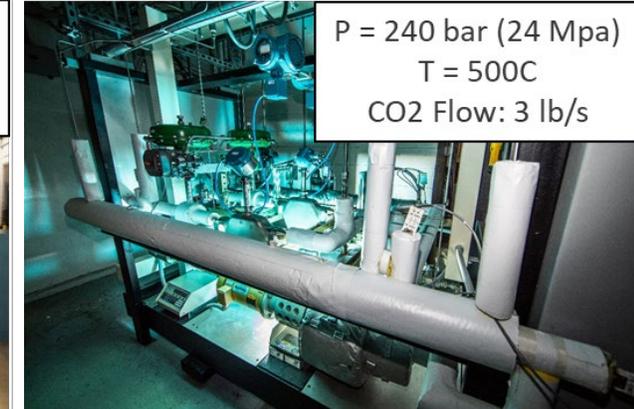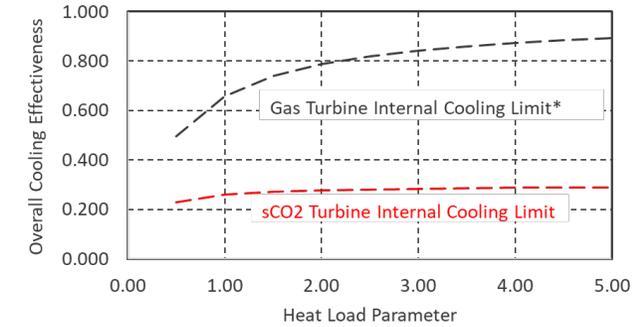
Higher Efficiency Reduces Waste Heat and <u>Avoids</u> CO$_2$ Emissions

Avoided CO2 emissions should have higher value than CCS

Estimated U.S. Energy Consumption in 2020: 92.9 Quads — Lawrence Livermore National Laboratory

67% of energy consumed is waste energy

Increased 5-10% pts relative to 2018
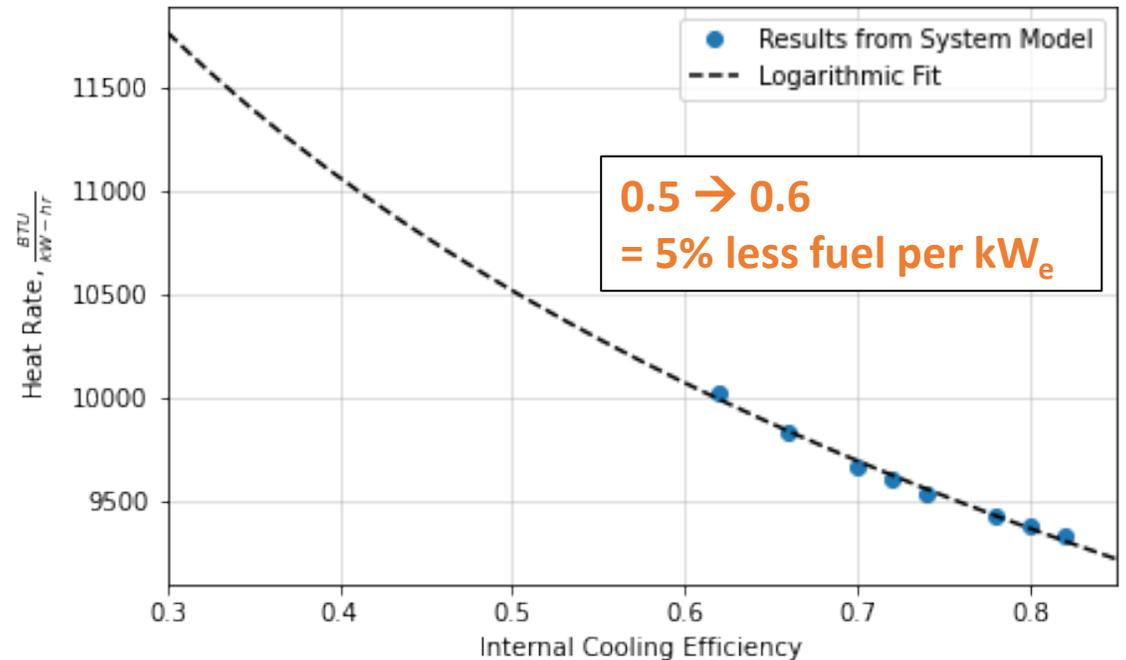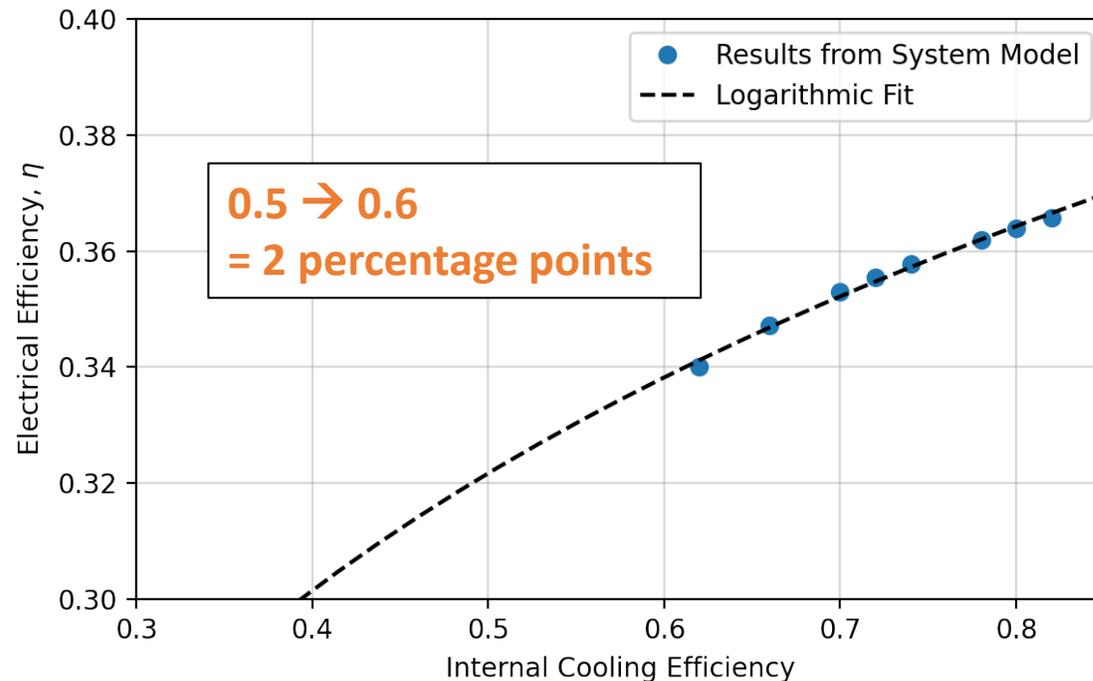
Combined Heat and Power systems can **avoid ~30%** of GHG emissions relative to non-integrated heat and power configurations

Why Is Internal Convective Cooling Efficiency Important?

Based on NETL study on small (5-10 MW$_e$) GT-Combined Heat & Power[1]

$$\eta_c = \frac{T_{c,out} - T_{c,in}}{T_{w,ext} - T_{c,in}}$$

0.5 → 0.6
= 2 percentage points

0.5 → 0.6
= 5% less fuel per kW$_e$

GAP: For η_c, where is the current state-of-the-art?

[1] Uysal, Selcuk Can, Douglas L. Straub, and James B. Black. 2021. "Impact on Cycle Efficiency of Small Combined Heat and Power Plants From Increasing Firing Temperature Enabled by Additive Manufacturing of Turbine Blades and Vanes." In *ASME Paper GT2021-58718*.

Why is External Film Effectiveness (adiabatic film effectiveness) Important?

$$\eta_f = \frac{T_g - T_f}{T_g - T_{c,out}}$$

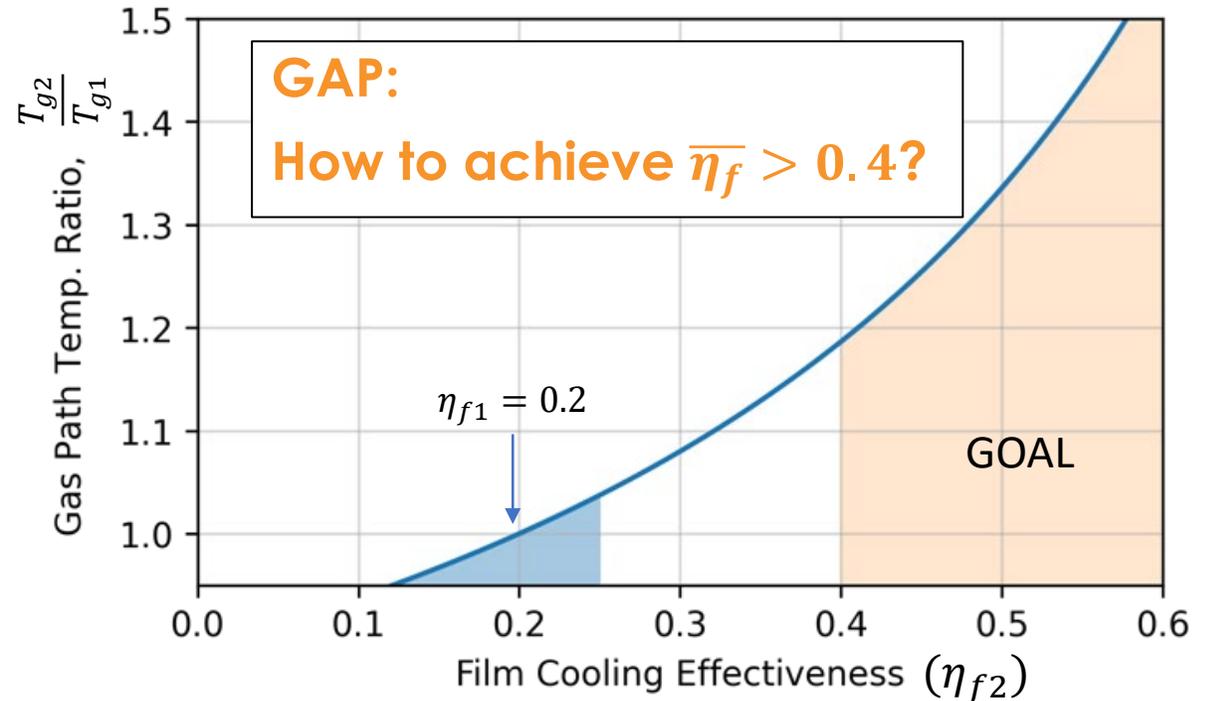$T_{f1} = \eta_{f1}T_c + (1 - \eta_{f1})T_{g1}$ ⟵ Current SOTA

$T_{f2} = \eta_{f2}T_c + (1 - \eta_{f2})T_{g2}$ ⟵ Future Goal

Assume
1) $T_c = T_{c,out}$ is constant
2) $T_{f1} = T_{f2}$

$$\frac{T_{g2}}{T_{g1}} = \frac{\eta_{f1} - \eta_{f2}}{1 - \eta_{f2}}\frac{T_c}{T_{g1}} + \frac{1 - \eta_{f1}}{1 - \eta_{f2}}$$

GAP:

How to achieve $\overline{\eta_f} > 0.4$?

$\eta_{f1} = 0.2$

GOAL

Gas Path Temp. Ratio, $\frac{T_{g2}}{T_{g1}}$

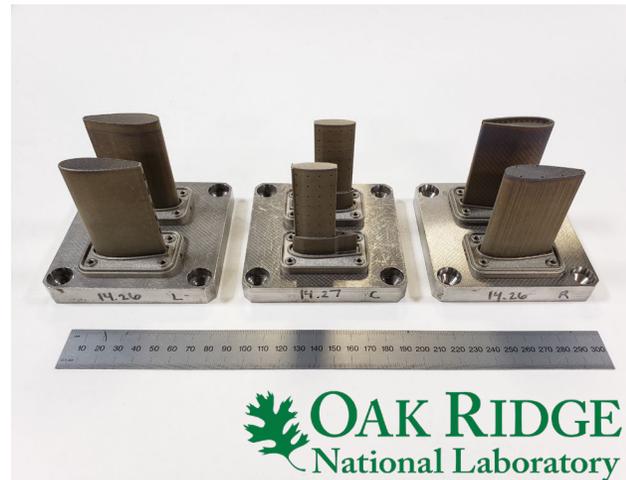Film Cooling Effectiveness (η_{f2})

Film cooling is a technology pathway to reach higher temperature goals for DOE Turbines Program
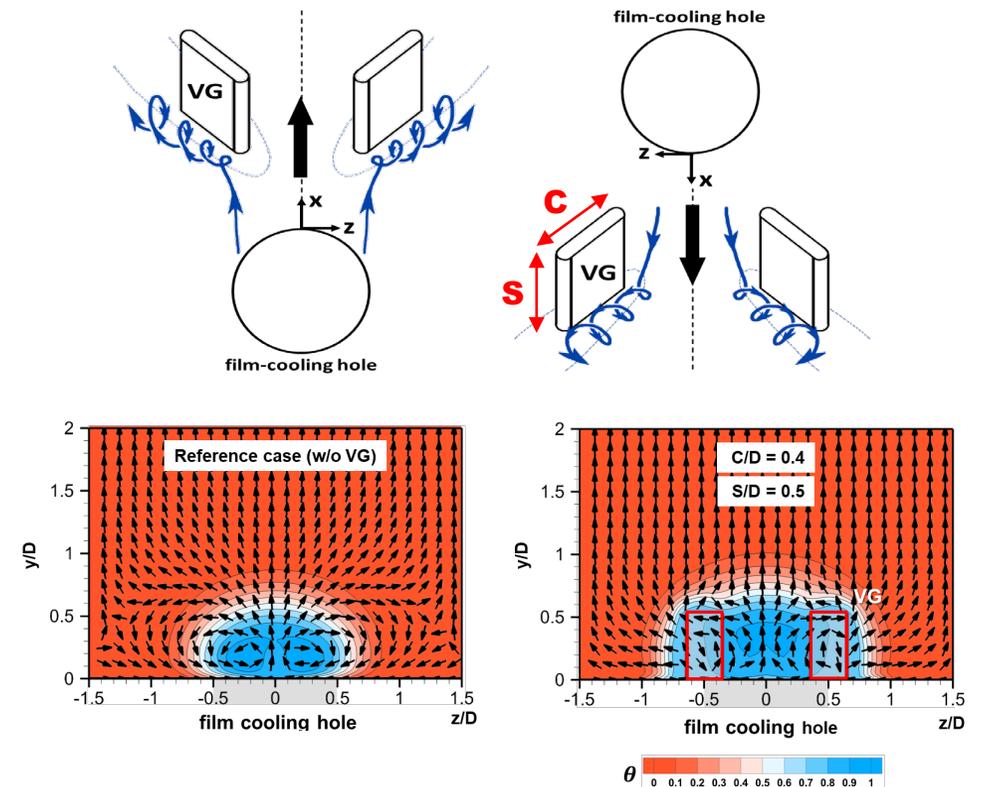
Presentation Outline

Internal Cooling

- ## Internally Cooled AM Airfoils
  - Small GT engine model
  - Baseline cooling designs
  - Advanced designs
  - Results

Source: NETL

🌳 OAK RIDGE National Laboratory

External Cooling

- ## New Film Cooling Concepts
  - Downstream vortex generators[2,3]
    - Controls counter-rotating vortices

[2] Lee, Chien-Shing, Kenneth Bryden, and Tom I.P. Shih. 2020. "Downstream Vortex Generators To Enhance Film-Cooling Effectiveness." In *ASME GT2020-14317*
[3] Lee, Chien-Shing, Tom I-P. Shih, Douglas Straub, and Justin Weber. 2022. "Computational And Experimental Study Of Film-Cooling Effectiveness With And Without Downstream Vortex Generators." In *ASME GT2022-82675*.

Test Approach For Internally Cooled Airfoil Testing

Measure ϕ and η_c curves for each internal cooling design

Data from Public Engine Model (Uysal et al., 2021)

	Hot Gas Path T_g	Coolant $T_{c,in}$	Max. Metal Temp, $T_{w,ext}$	Overall Cooling Effectiveness
Baseline	1366K	685K	1178K	$\phi > 0.28$
Advanced Target	1466K	685K	1178K	$\phi > 0.37$

Test Conditions

	Hot Gas Path T_g	Coolant $T_{c,in}$	Overall Cooling Effectiveness	Max. Metal Temp, $T_{w,ext}$
Baseline	650	325K	$\phi > 0.28$	560K
Advanced Target	650	325K	$\phi > 0.37$	530K

Overall Cooling Effectiveness

$$\phi = \frac{T_g - T_{w,ext}}{T_g - T_{c,in}}$$

Heat Load Parameter (non-dimensional cooling flow)

$$HLP = \frac{\dot{m}_c c_p}{h_{ext} A_{ext}} = \dot{m}_c c_p R_{ext}$$

Internal Convective Cooling Efficiency

$$\eta_c = \frac{T_{c,out} - T_{c,in}}{T_{w,ext} - T_{c,in}} = \frac{\phi}{HLP(1 - \phi)}$$
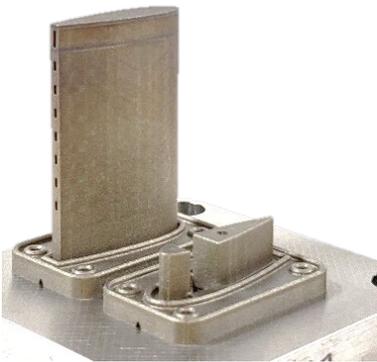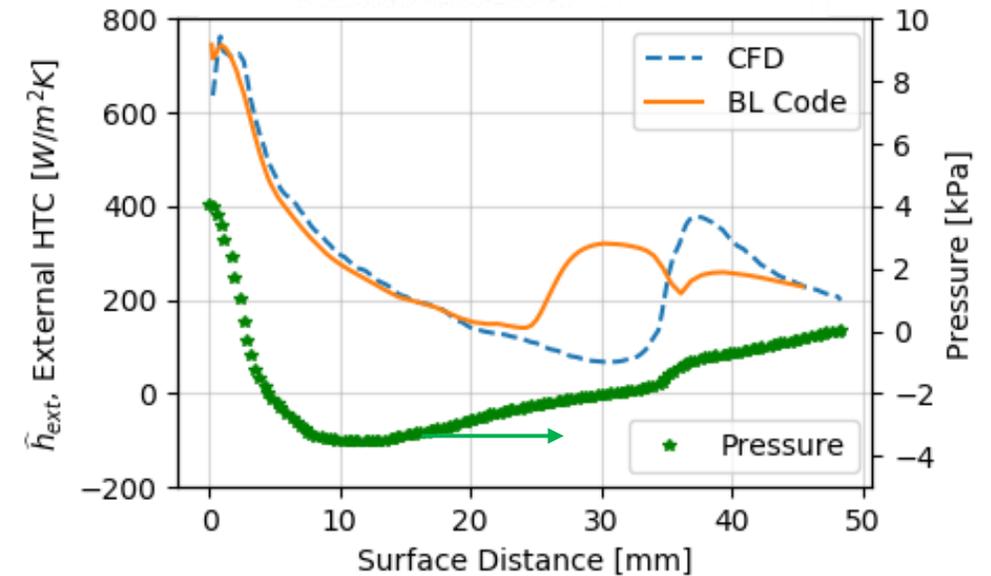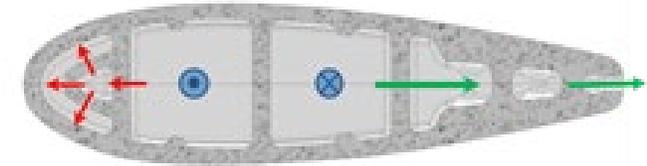
Independent variables
- $\dot{m}_c$
- Cooling designs

Dependent variables
- $T_{w,ext}; \phi$
- $T_{c,out}; \eta_c$

Keep External Thermal Resistance Constant

External geometry and conditions

- NACA-0024 external profile
  - Symmetric design for screening different cooling designs

- External test conditions = constant
  - $T_g = 650 K; P_g = 0.11\ MPa$
  - $\dot{m}_g = 0.64\ kg/s \rightarrow V_g \cong 120\ m/s$
 - $Ma_g = 0.2$

- Surface roughness

| Airfoil Internal Cooling Design	Ra As Received (microns)	Ra After Painting (microns)
Baseline Vane		
Span-wise	5.0 ± 0.6	1.4 ± 0.3
Chord-wise	5.7 ± 1.7	1.5 ± 0.4
Baseline Blade		
Span-wise	3.6 ± 0.8	0.8 ± 0.15
Chord-wise	3.8 ± 0.6	1.0 ± 0.2
NETL Double wall		
Span-wise	1.1 ± 0.2	1.0 ± 0.3
Chord-wise	1.1 ± 0.15	0.7 ± 0.3

mean $\pm$ 2 standard deviations

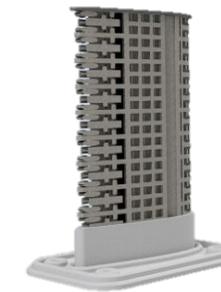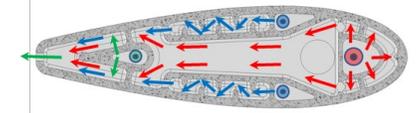# Internal Resistance Varies with Design and Flow

Some of the internal cooling designs tested

- Baseline Vane
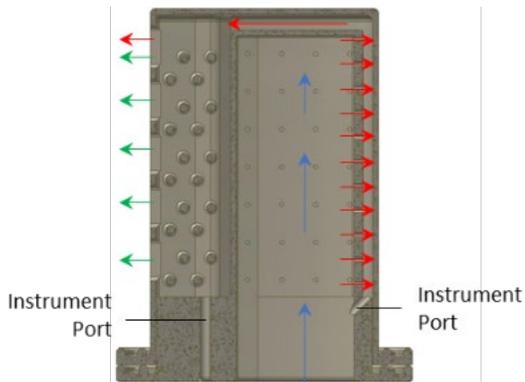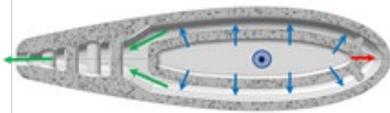
- Baseline Blade

- NETL Double Wall

Instrument Port   Instrument Port

Instrument Port   Instrument Port
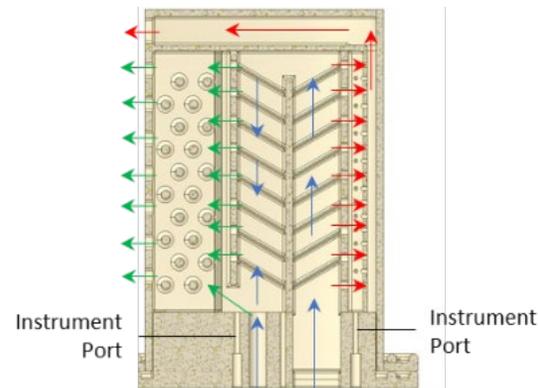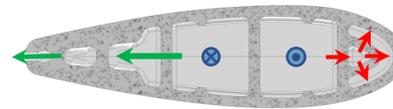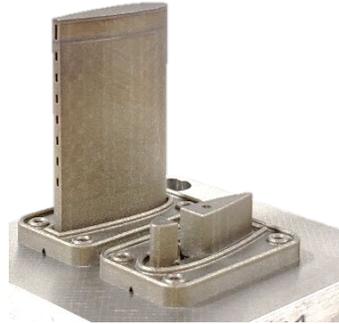
External Surface Removed in CAD
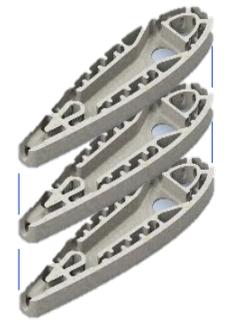
Infrared Surface Temperature Measurements

FLIR A8300sc Camera
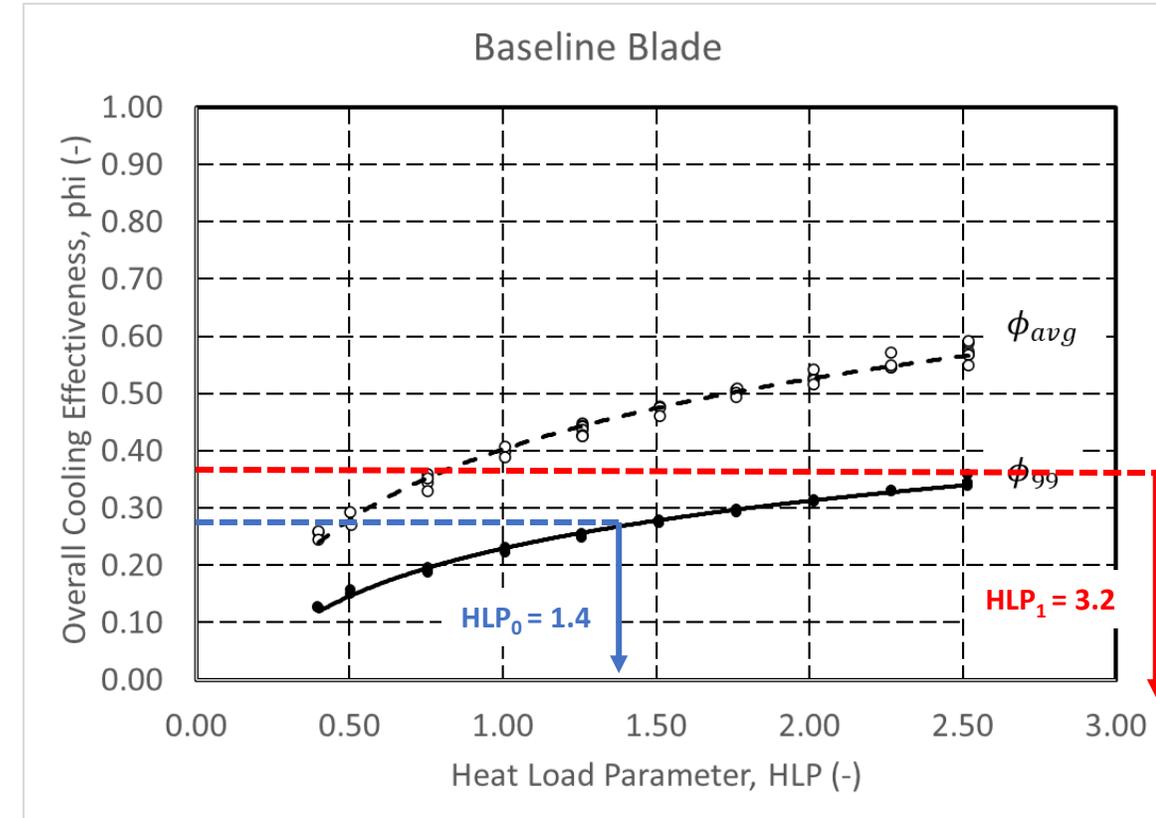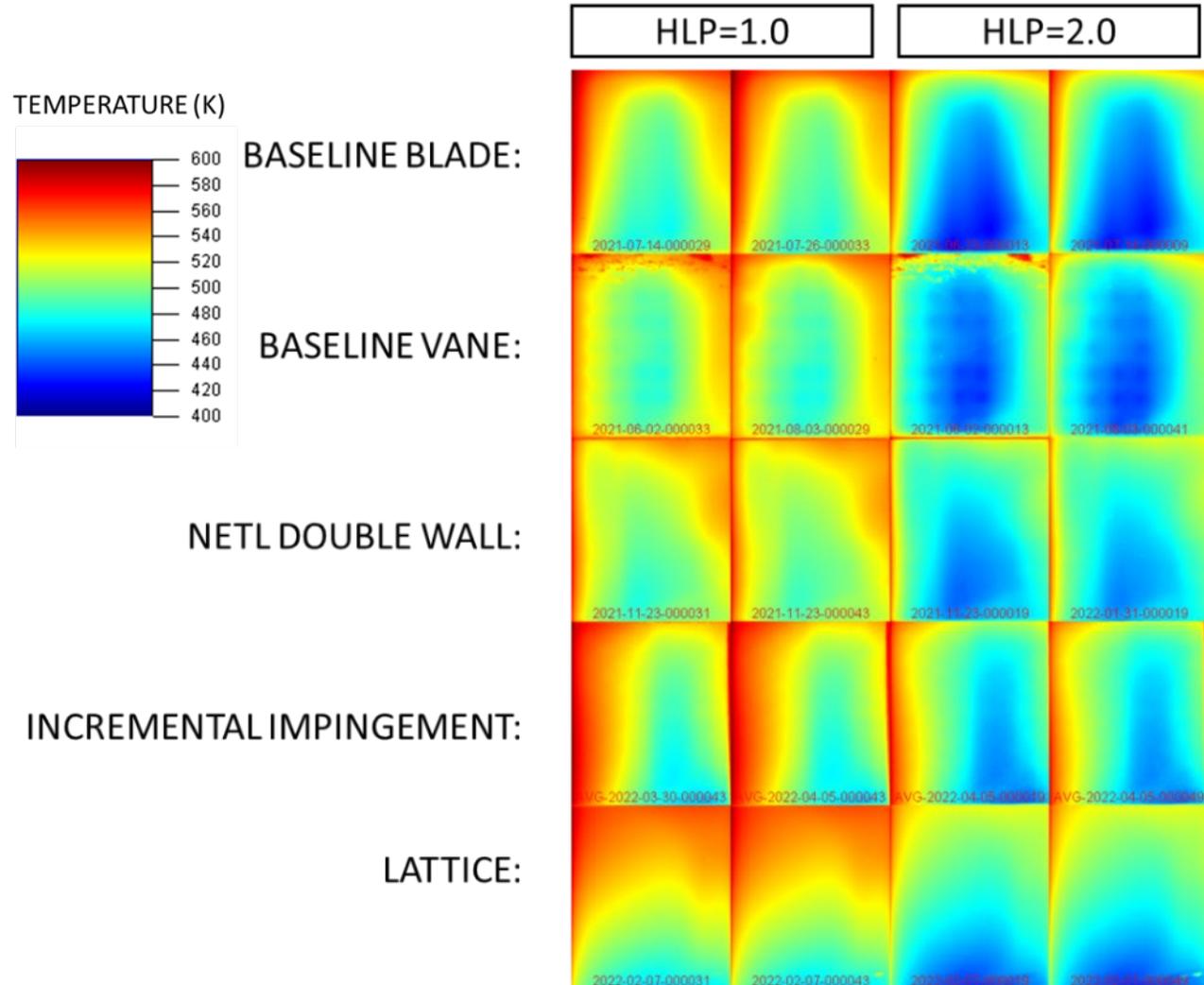
Cooling Technology Curves

Using ϕ_{99} to Define Critical Heat Load Parameters

Cooling Technology Curves (ϕ_{99})
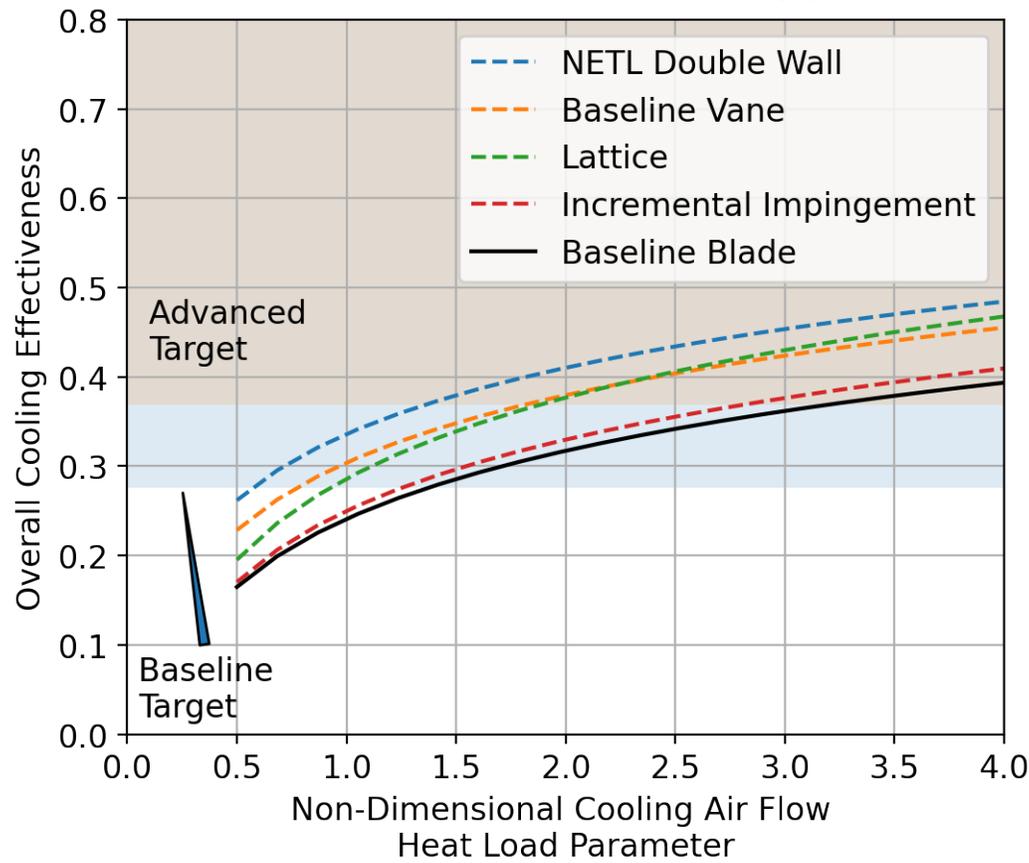
Cooling Design	Minimum HLP	
	Base HLP_{base}	Advanced HLP_{adv}
Baseline Blade	1.38	3.22
Baseline Vane	0.77	1.81
NETL Double Wall	0.57	1.36
Lattice	0.93	1.89
Incremental Impingement	1.26	2.83

Lessons Learned From Coolant Outlet Temperature Measurements

Average Coolant Outlet Temperature Can Be Higher Than Average T_{wall}
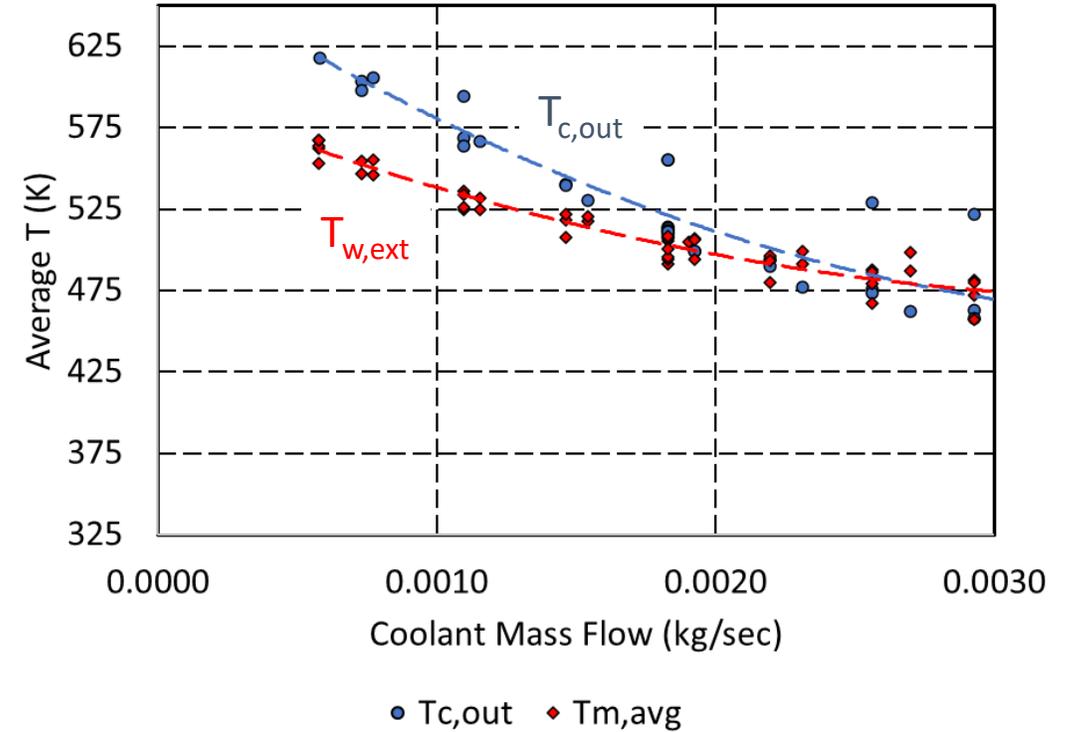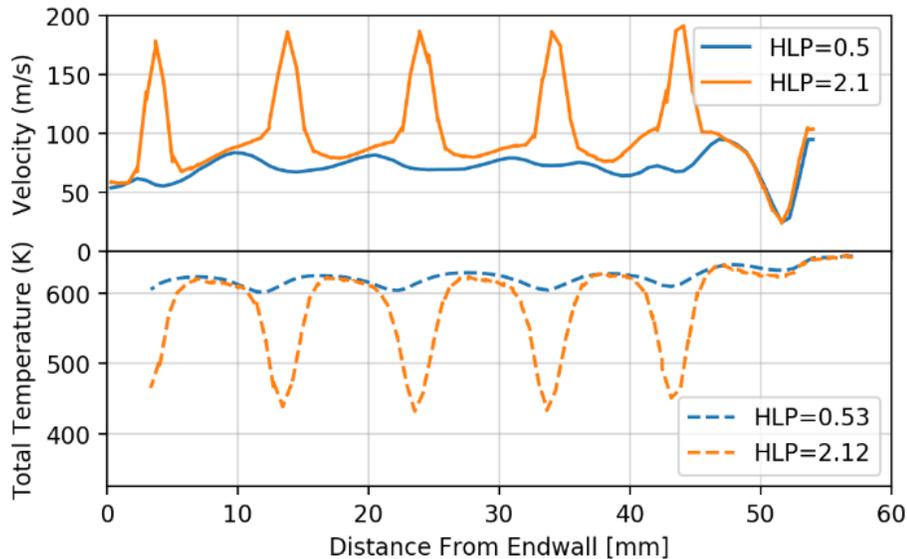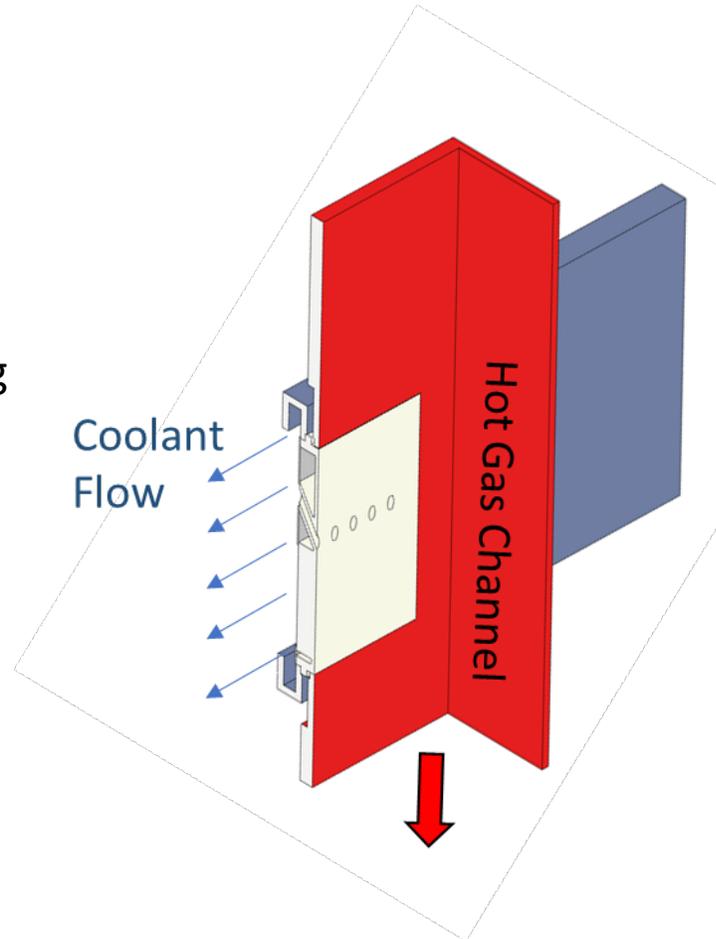

$$\eta_c = \frac{T_{c,out} - T_{c,in}}{T_{w,ext} - T_{c,in}} = \frac{\phi_{avg}}{HLP(1 - \phi_{avg})}$$

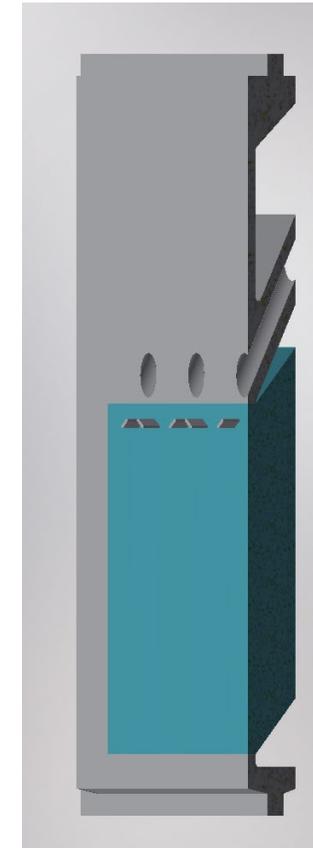# How to measure adiabatic film effectiveness in a conjugate environment?
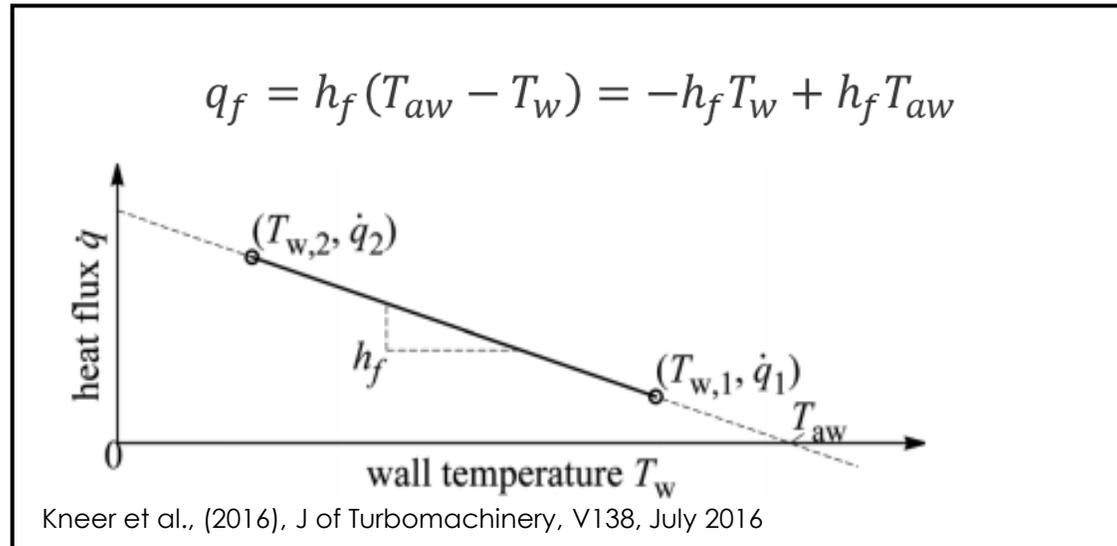

Flow Conditioning

Test Section

Approx. CAD model
(Shown without 0.5mm shim stock welded to cold side)

Coolant Flow

Hot Gas Channel
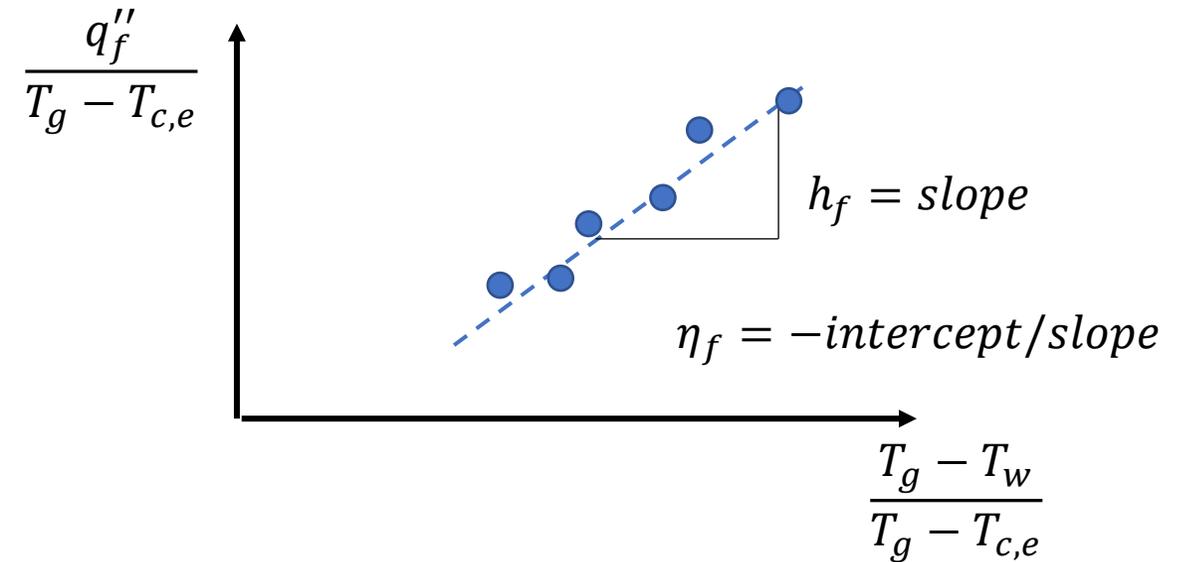
Revised Experimental Approach

Vary Cold-Side Resistance Only

$$q_f = h_f(T_{aw} - T_w) = -h_f T_w + h_f T_{aw}$$

Kneer et al., (2016), J of Turbomachinery, V138, July 2016

Modified Approach

$$T_{aw} = \eta T_{c_{ex}} + (1 - \eta)T_g$$

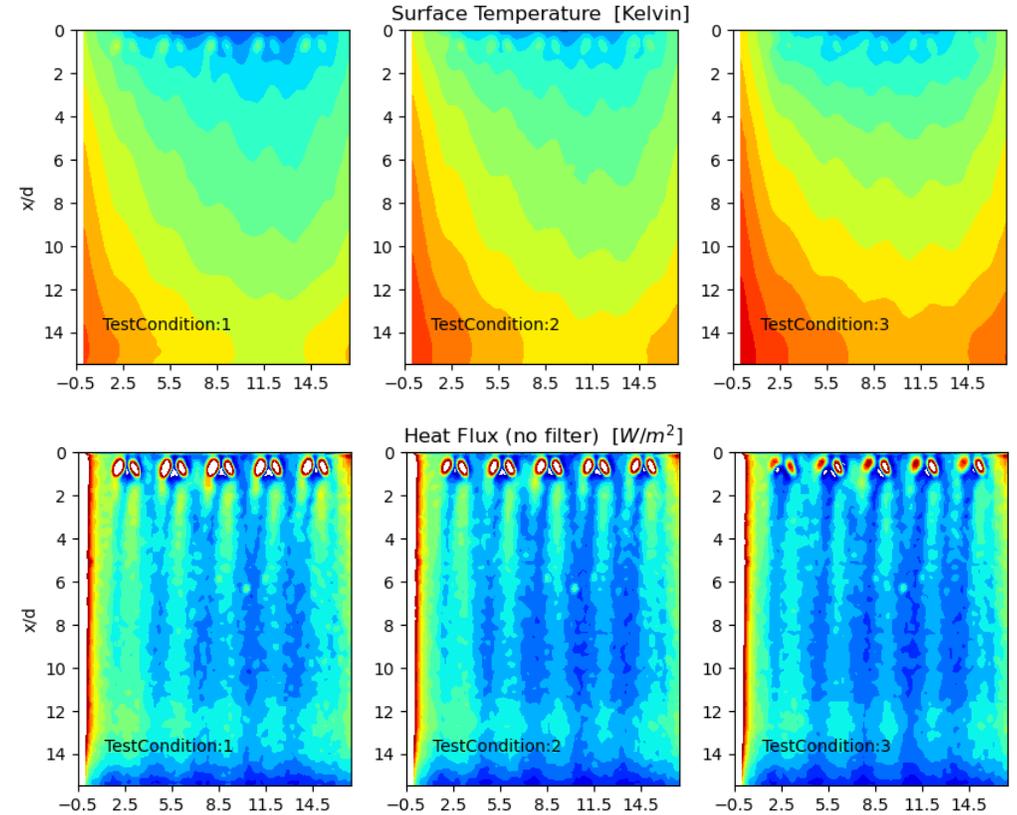$$\frac{q_f''}{(T_g - T_{c,e})} = h_f \frac{(T_g - T_w)}{(T_g - T_{c,e})} - h_f \cdot \eta$$

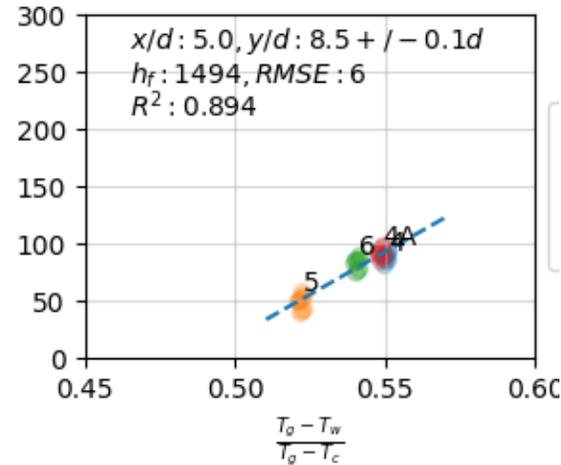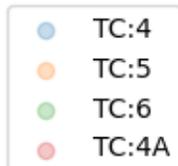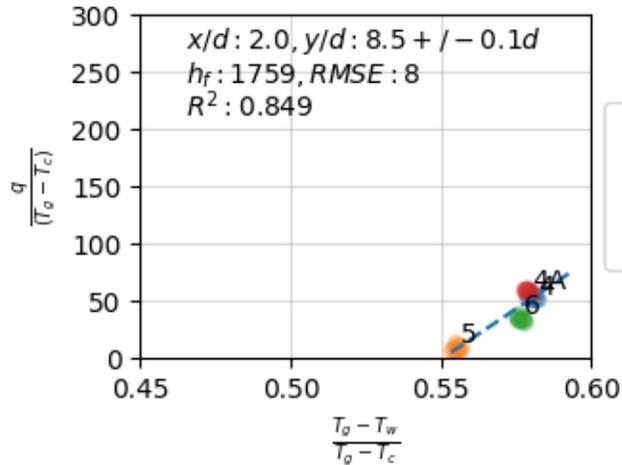$h_f = slope$

$\eta_f = -intercept/slope$

Experimental Results (1 of 3)

Experimental Method
1. Measure hot and cold side temperature fields
2. Measure/define boundary conditions on ROI volume
3. Calculate heat flux distribution using FEM
4. Perform regression analysis

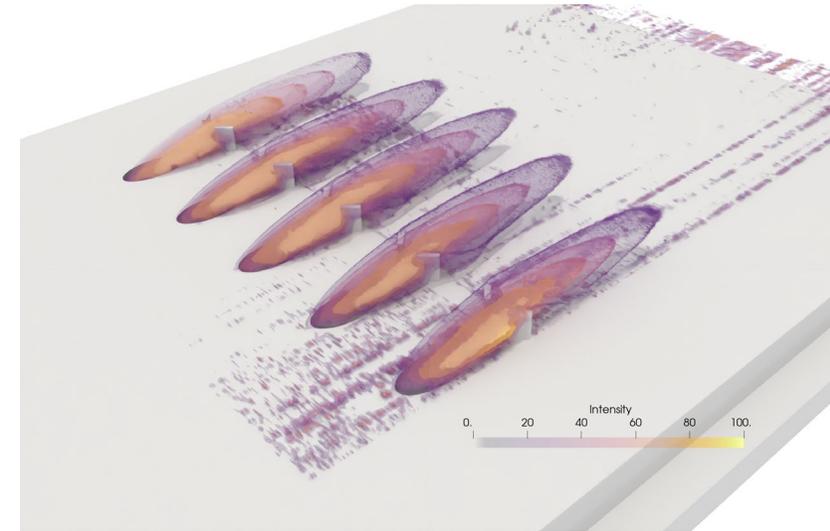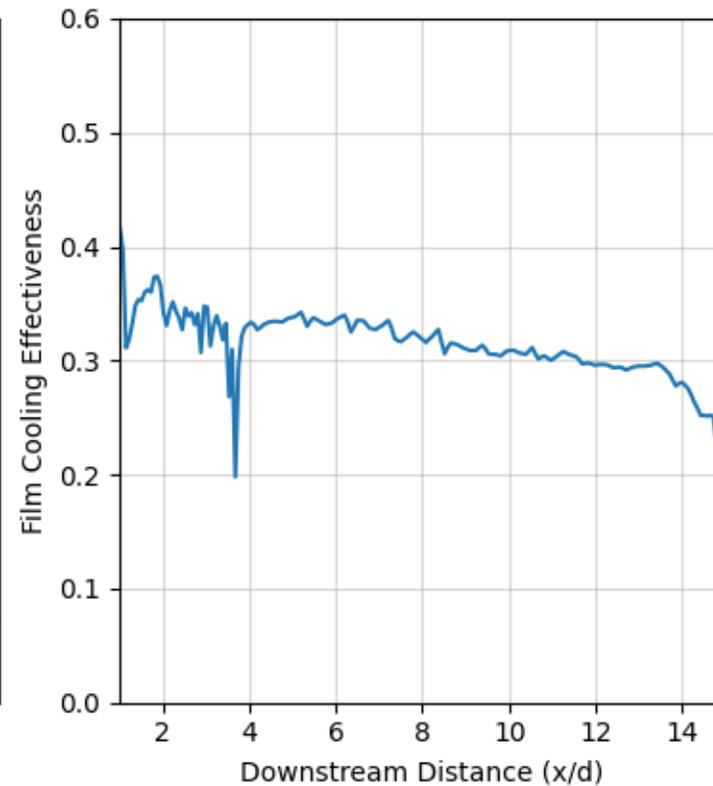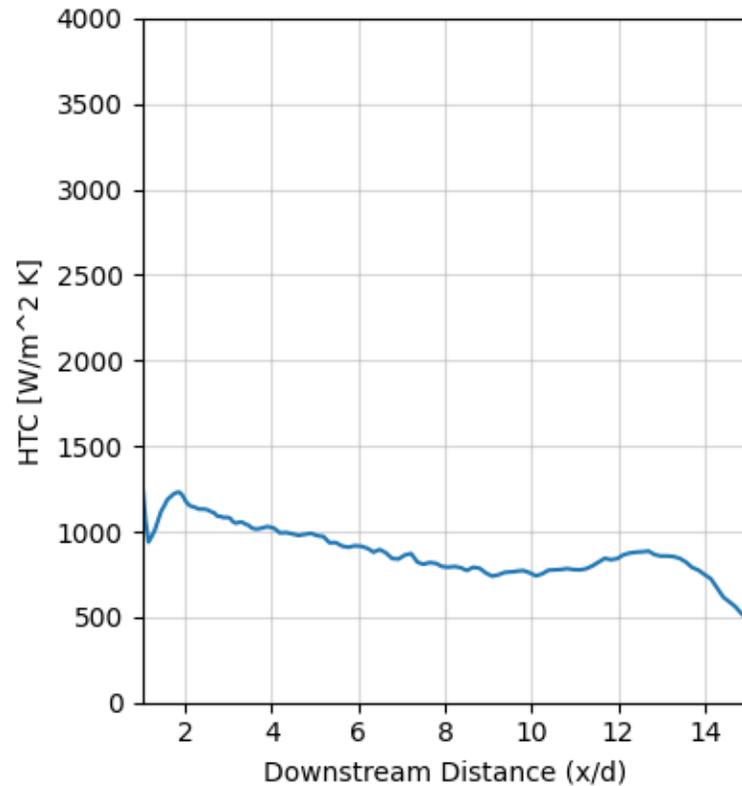$$\frac{q_f''}{(T_g - T_{c,e})} = h_f \frac{(T_g - T_w)}{(T_g - T_{c,e})} \; - \; h_f . \eta$$

← Increasing bypass coolant flow
BR=constant for all cases shown

Laterally Averaged Parameters (BR=1)

[4, 5, 6, 7]

Flow Visualization

Internal and external cooling technologies are pathway to higher efficiency!

Summary and conclusions

- Need more work to understand and predict internal cooling efficiency, η_c

- Laterally averaged film effectiveness, $\overline{\eta_f} > 0.4$, could significantly impact current SOTA temperature constraints

- Based on preliminary testing, NETL double wall AM airfoil cooling design looks promising

- New method for measuring local HTC's and adiabatic film effectiveness in a conjugate test rig has been described.

- Downstream VG film cooling concept looks promising
  - $\overline{\eta_f}$ is 2X better than cylindrical holes without VG's
  - $\overline{\eta_f} > 0.3$ for x/d >10 at blowing ratio of 1

Questions, Comments

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f **@NationalEnergyTechnologyLaboratory**

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