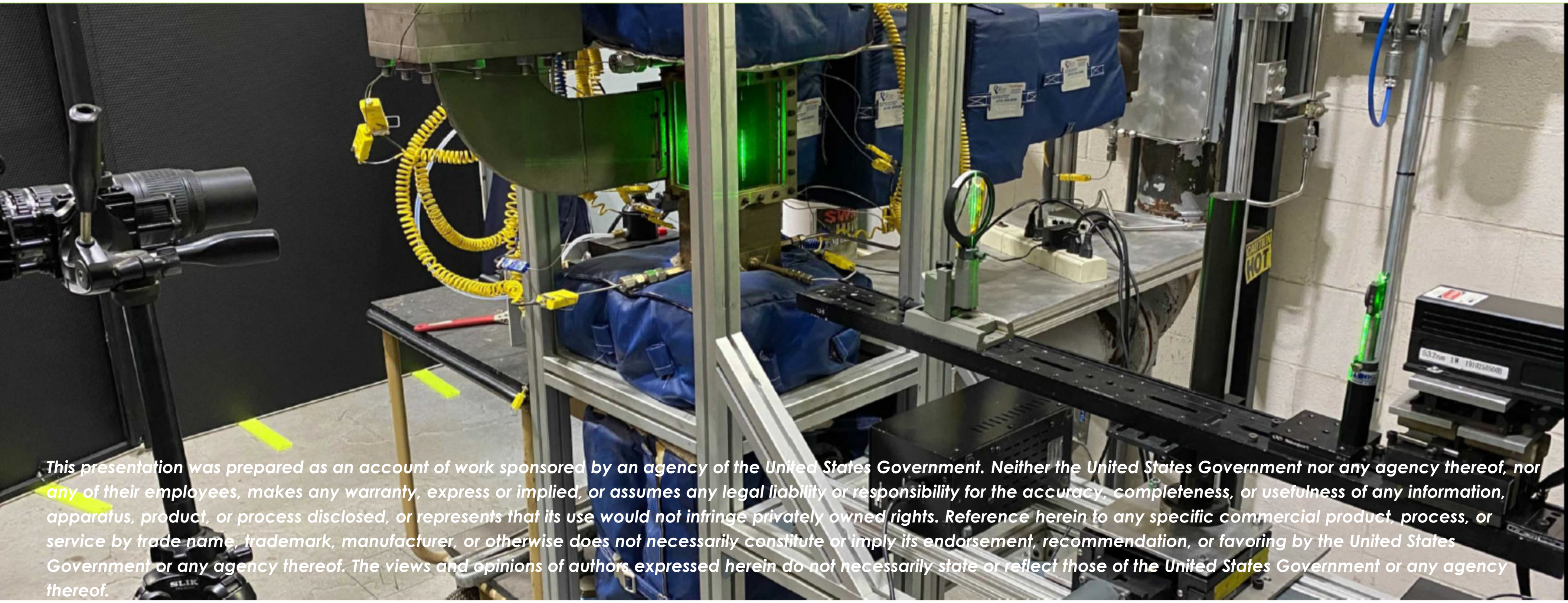
Internal and External Cooling Technologies for Brayton Cycles

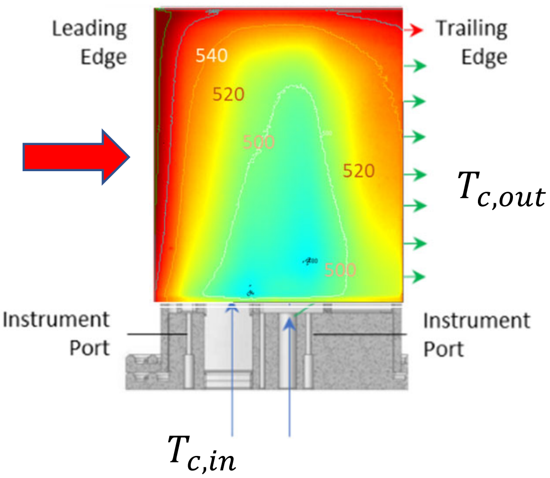
A Pathway To Higher Efficiency

Doug Straub, Justin Weber, and Matthew Searle



Gas Turbine Cooling Technologies Improve Performance Regardless of Fuel Used

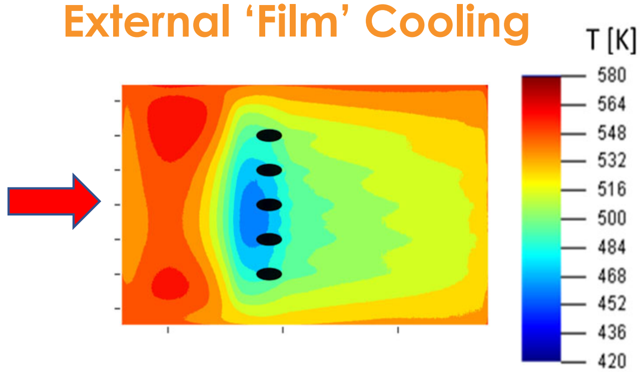
Internal Cooling



Internal Cooling Efficiency

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

External 'Film' Cooling

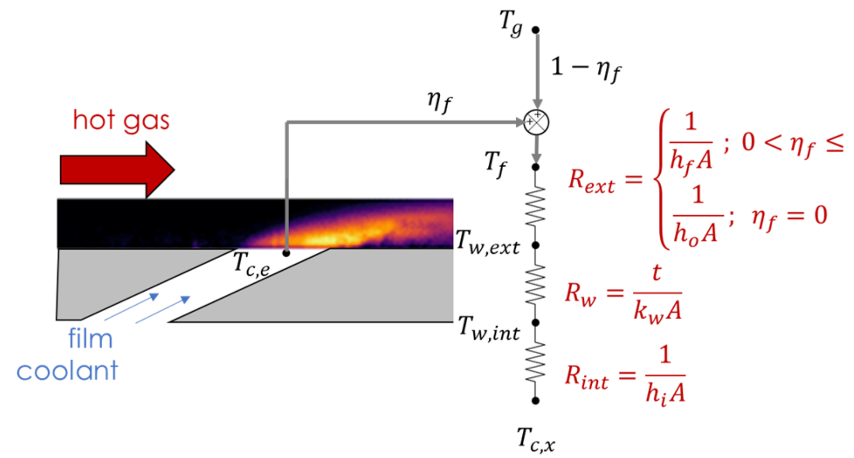


Film Cooling Effectiveness

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

Overall Cooling Effectiveness

$$\phi = \frac{\eta_f - \eta_f\eta_c + \eta_c HLP}{1 - \eta_f\eta_c + \eta_c HLP} = \frac{T_g - T_{m,ext}}{T_g - T_{c,in}}$$

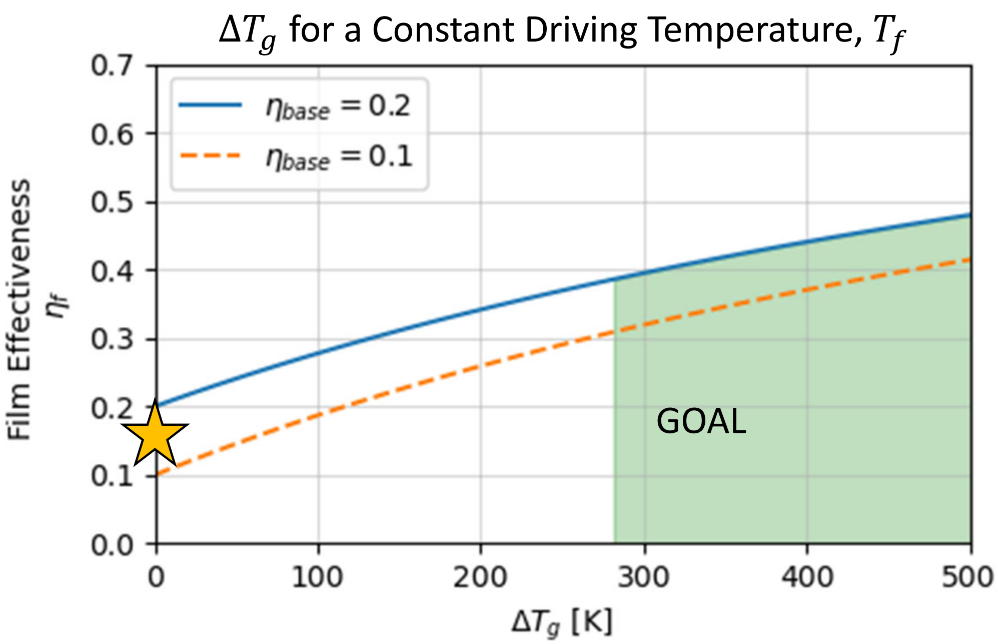


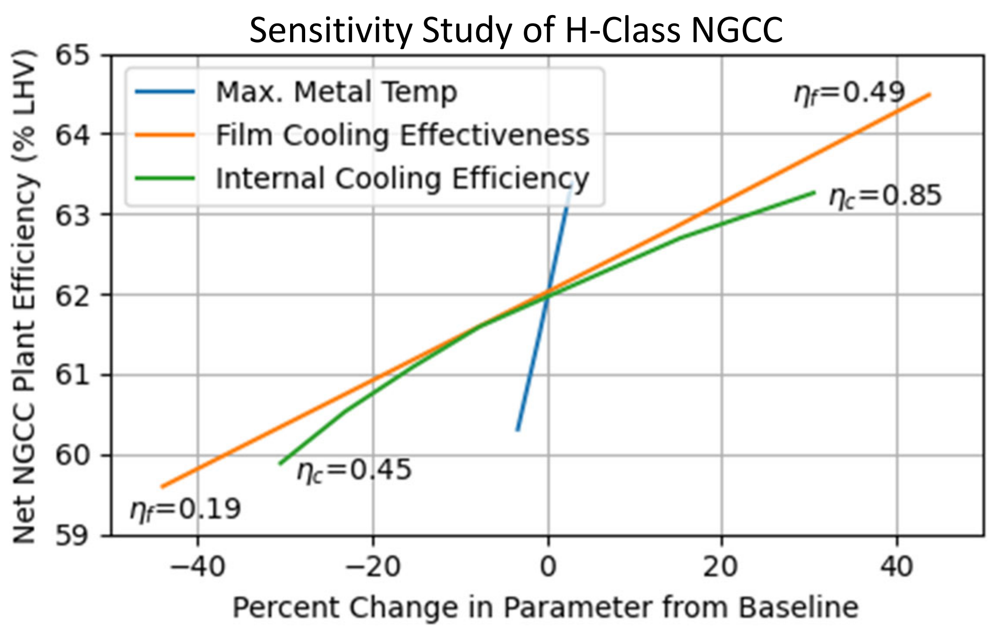
$$T_f = \eta_f T_{c,e} + (1 - \eta_f) T_g$$

By defining a SOTA reference → sensitivity between T_g and η_f for a constant T_f, and $T_{c,e}$

Cooling Benefits Are Significant

Cooling technologies are a viable pathway to more efficient H2 Turbines





SOTA:

- T_g = 1645K; $T_{c,e}$= 712K; 0.1< η_f<0.2

Adapted from: Uysal, S. C., 2020, "Analysis of Gas Turbine Cooling Technologies for Higher Natural Gas Combined Cycle Efficiency," *AIAA Propulsion and Energy 2020 Forum*

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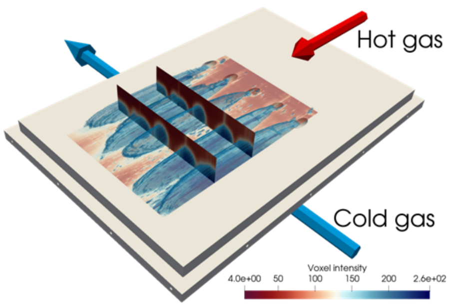
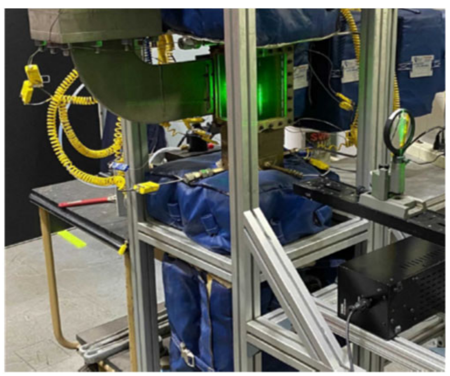
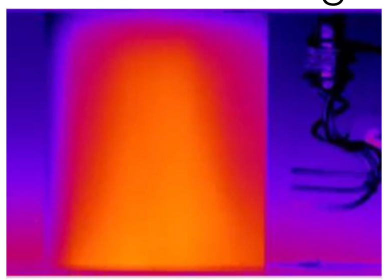
Brayton Cycles

Film Cooling

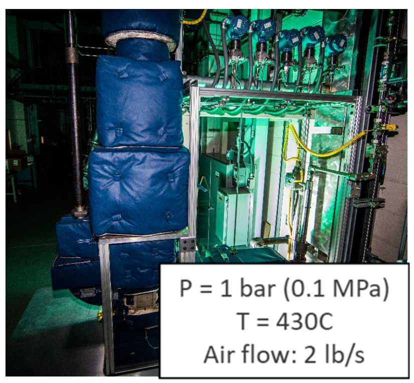




Internal Cooling

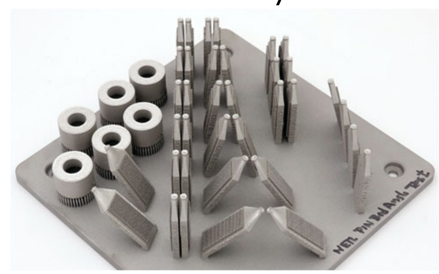


AM Airfoil Cooling – courtesy of ORNL & RCBI
(Increase TrIT by 100C for 5-10MW GT's)

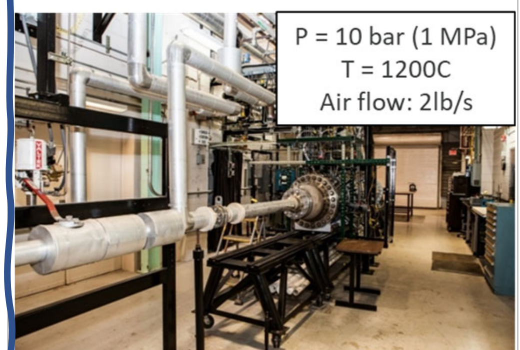


sCO2 Cycles

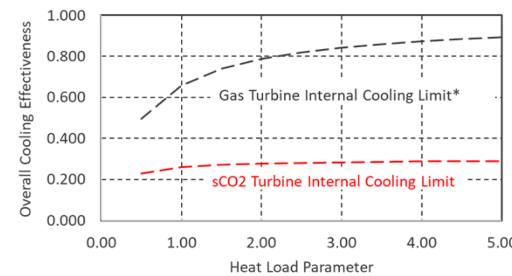
Indirect Cycles

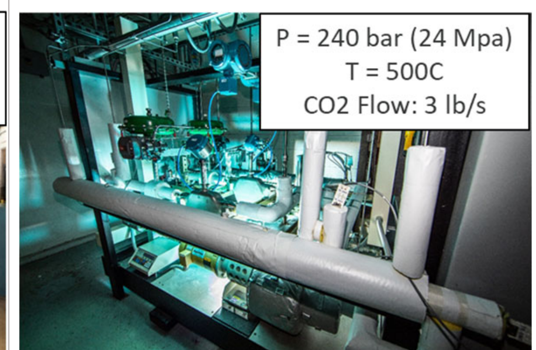


AM Plate Pin-Fin Prototypes – courtesy of ORNL
(recuperator 40% lighter than PCHE)



Direct Cycles





Presentation Scope

Internal Cooling

Phase 1: Increase turbine inlet temperature by 100 °C for small GT-CHP systems

- Advanced materials + Additive manufacturing + Advanced cooling designs

Phase 2: Demonstrate cooling technology at more realistic conditions utilizing a state-of-the-art blade design

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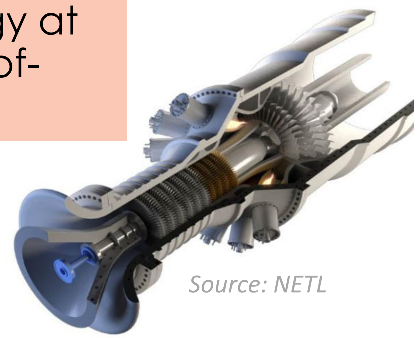
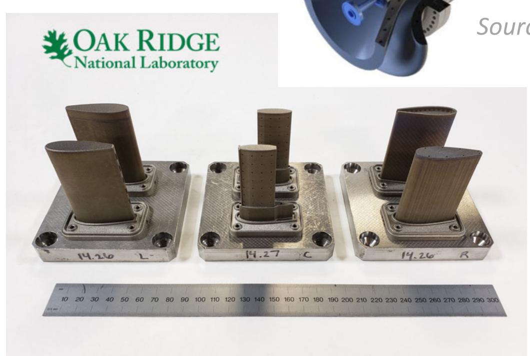
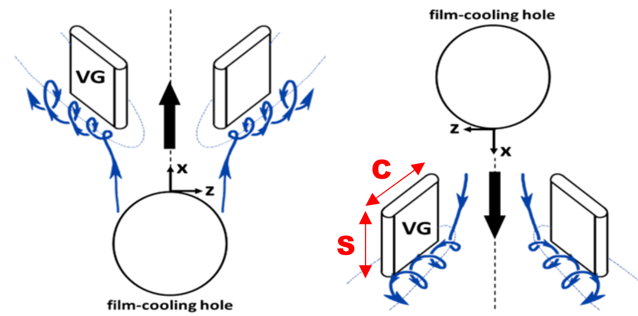
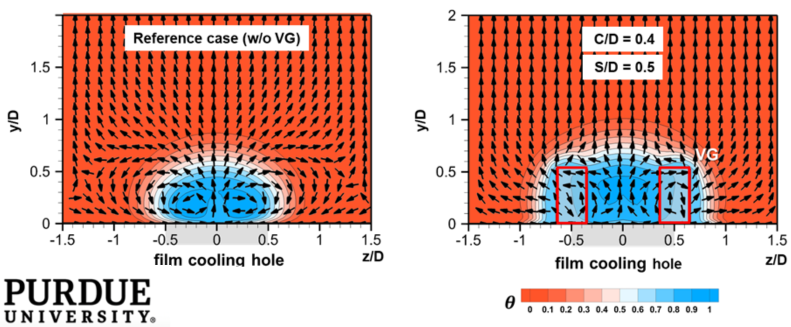




External Cooling

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





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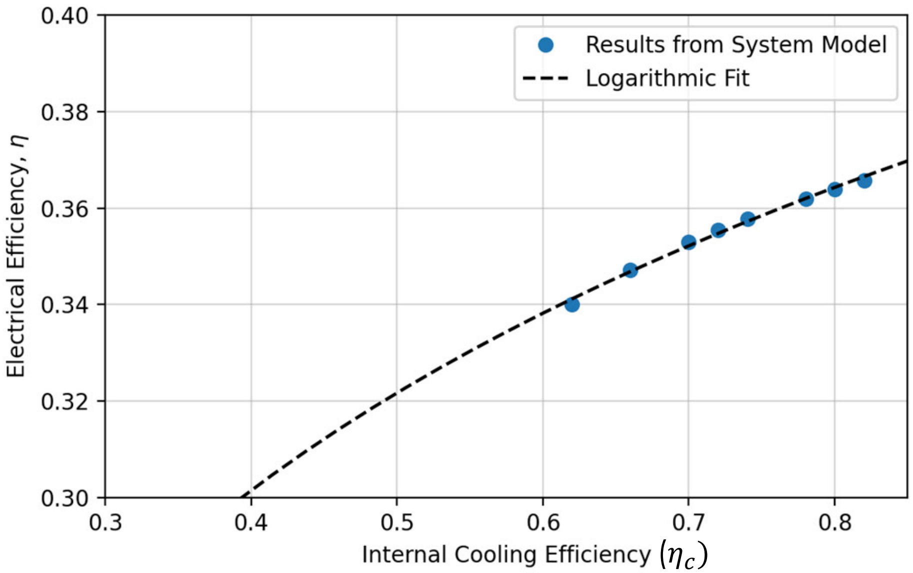
[2] Lee, Chien-Shing, Kenneth Bryden, and Tom I.P. Shih. 2020. "Downstream Vortex Generators To Enhance Film-Cooling Effectiveness." In *ASME GT2020-14317*

[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*.

Internal Cooling Performance Benefits

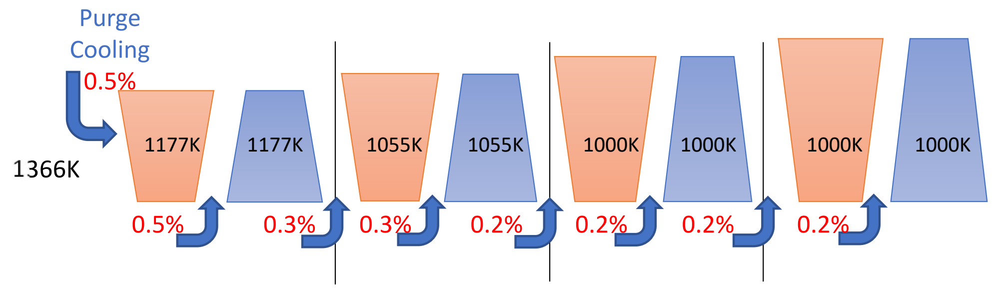
2-3% point improvement in cycle efficiency

Sensitivity Study of 5-10 MW Turbine
(no film cooling)



Adapted from: Uysal, et al., 2021

For η_c, What is the current state-of-the-art?



	Baseline Engine	ΔT_{T4}=100C Increase	Int. Cooling Eff. Increase (0.62 → 0.70)
Power (kW)	6100	7214	7592
Thermal Efficiency	33.1%	34.0%	35.3%
Exh. Temp. (K)	793	805	805
Coolant Fraction	9.6%	14.1%	12.9%

Using baseline engine model to define overall cooling effectiveness targets

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

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Ref: Uysal, S. C., Straub, D. L., and Black, J. B., 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," *ASME Paper GT2021-58718*.
Ref: Straub, D.; Searle, M.; Roy, A.; Ramesh, S.; Robey, E.; Floyd, T.; Ames, F. E. Advanced Airfoil Cooling Schemes to Increase Efficiency in Gas Turbines for Combined Heat and Power Applications; DOE.NETL-2023/3822, Energy-Analysis -- NETL

Design, 3D Printing, and Experimental Cooling Design Screening Tests

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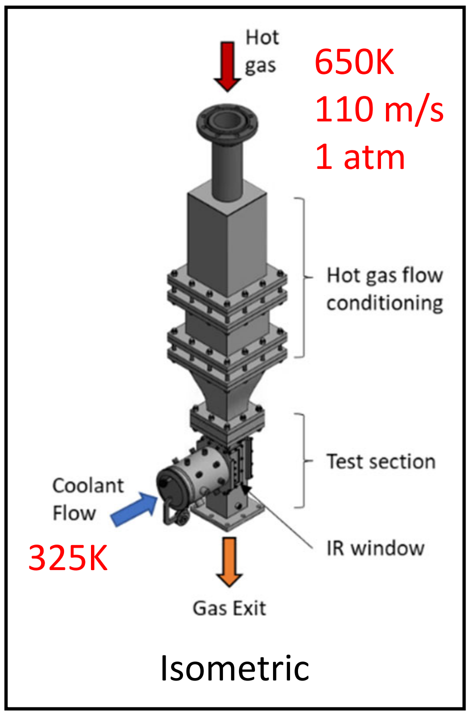
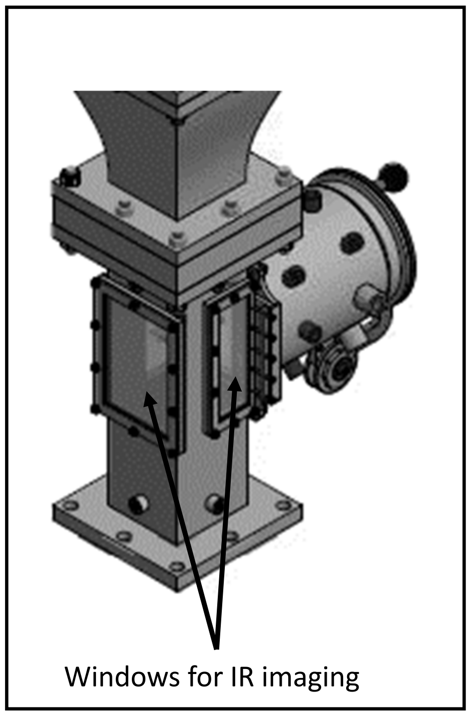
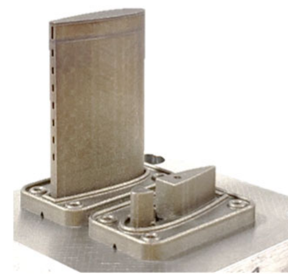
Symmetric (NACA-0024) metal airfoils/laser powder bed fusion/vertical build

Experimental Setup





1) Blade (baseline)



2) Vane (baseline)

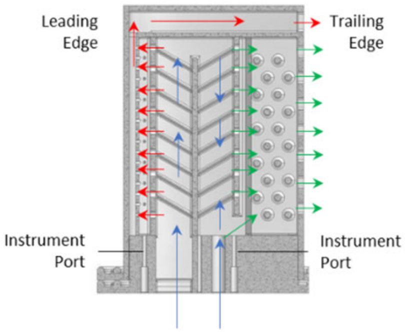
3) NETL Double Wall

4) Incremental Impingement

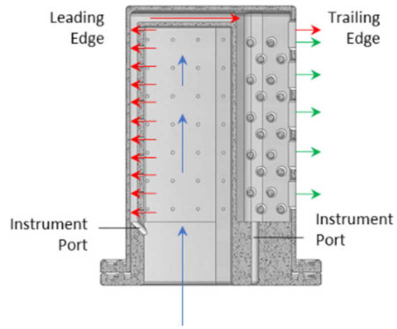
Ref: Straub, D., Ramesh, S., Searle, M., Robey, E. H., Roy, A., and Ames, F. E., 2022, "Performance of Additively Manufactured Internally Cooled Airfoils," *ASME Paper GT2022-83333*, [NETL.gov - Energy Analysis - GT2022-83333]

Ref: Searle, M., Roy, A., Ramesh, S., Floyd, T., Ames, F. E., and Straub, D., 2023, "Novel Additively-Manufactured and Internally-Cooled Airfoils for Increasing Small Industrial Gas Turbine Efficiency," *ASME GT2023-101006*

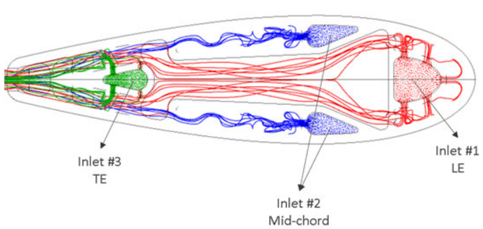
1) Blade (baseline)



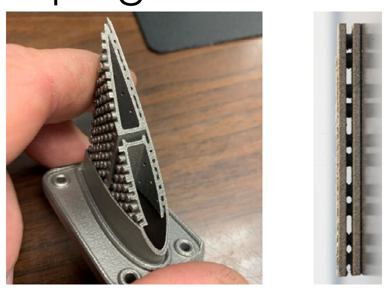
2) Vane (baseline)



3) NETL Double Wall



4) Incremental Impingement



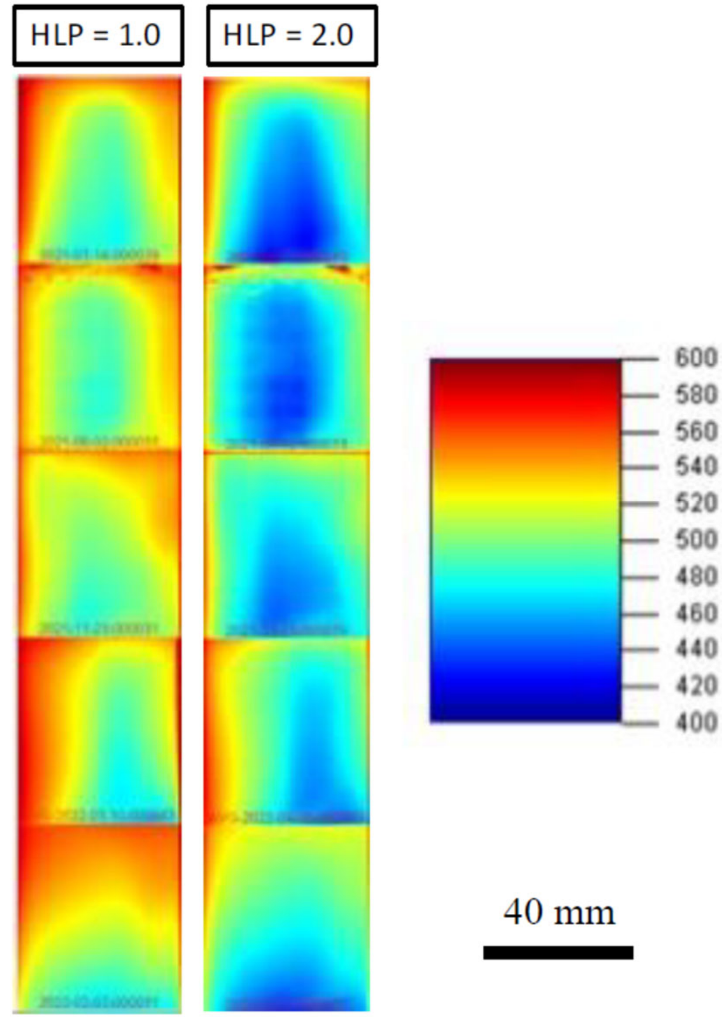
Baseline Blade

Baseline Vane

Double Wall

Incremental Imping.

Lattice



Ref: Searle, M., Roy, A., Ramesh, S., Floyd, T., Ames, F. E., and Straub, D., 2023, "Novel Additively-Manufactured and Internally-Cooled Airfoils for Increasing Small Industrial Gas Turbine Efficiency," *ASME GT2023-101006*

Experimental Approach

Independent Variable (non-dimensional cooling flow)

Heat Load Parameter

$$HLP = w^{+} = \frac{\dot{m}_c c_p}{h_{ext} A_{ext}}$$

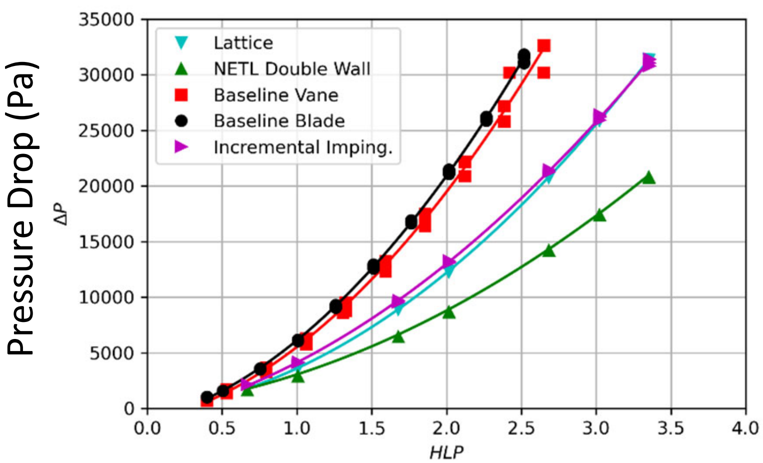
Dependent variables

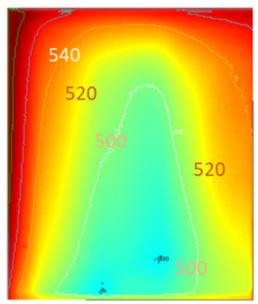
Overall cooling effectiveness

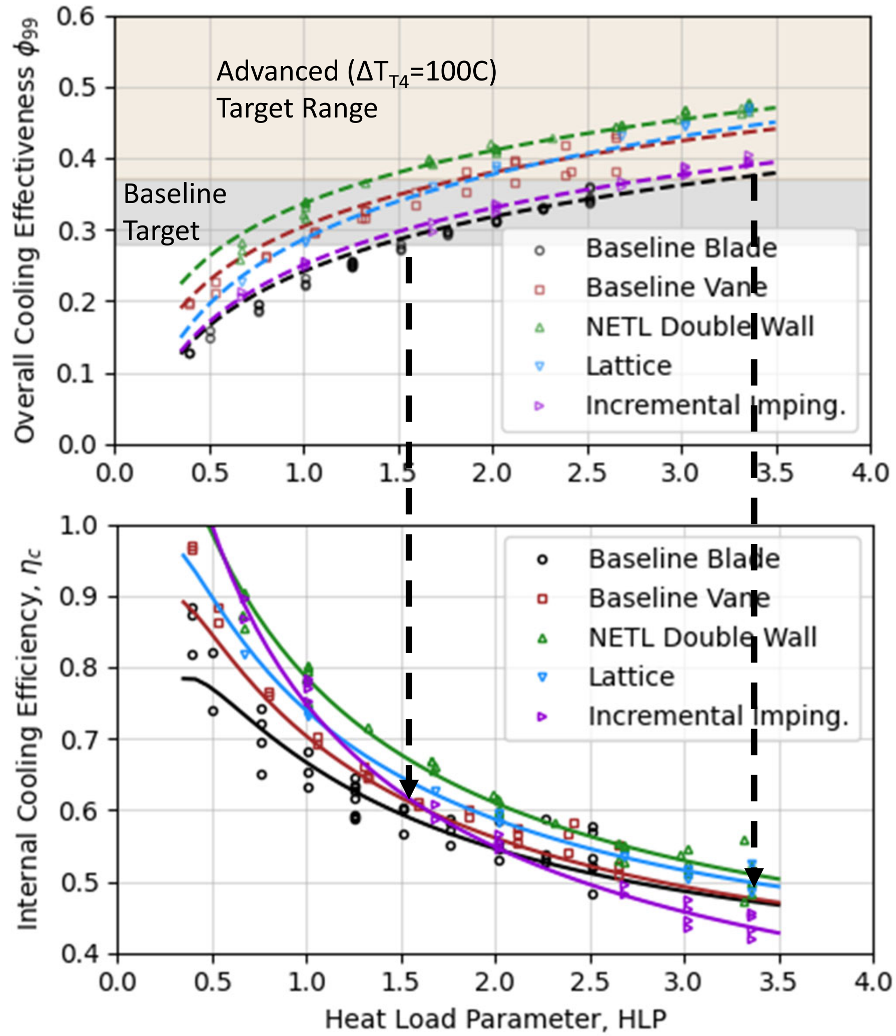
$$\phi = \frac{T_g - T_{w,ext}}{T_g - T_{c,in}}$$

Internal cooling efficiency

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



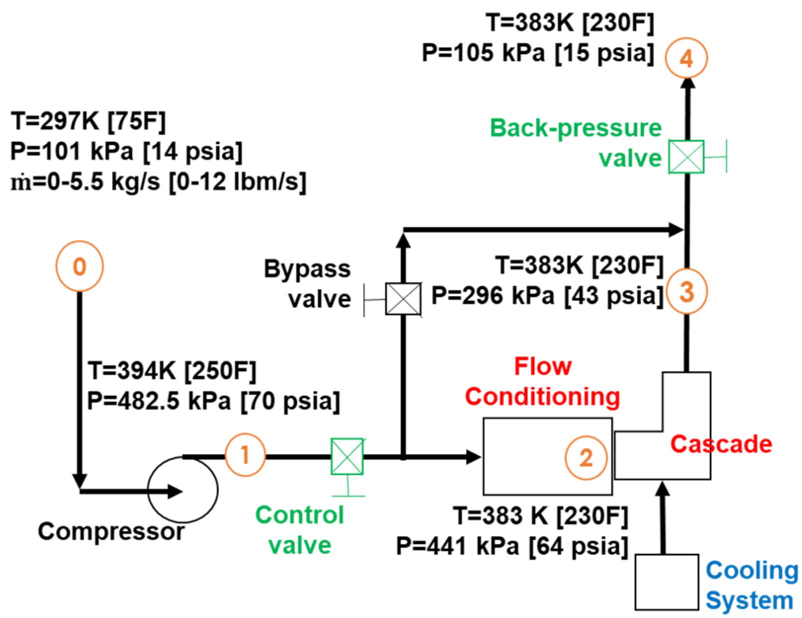


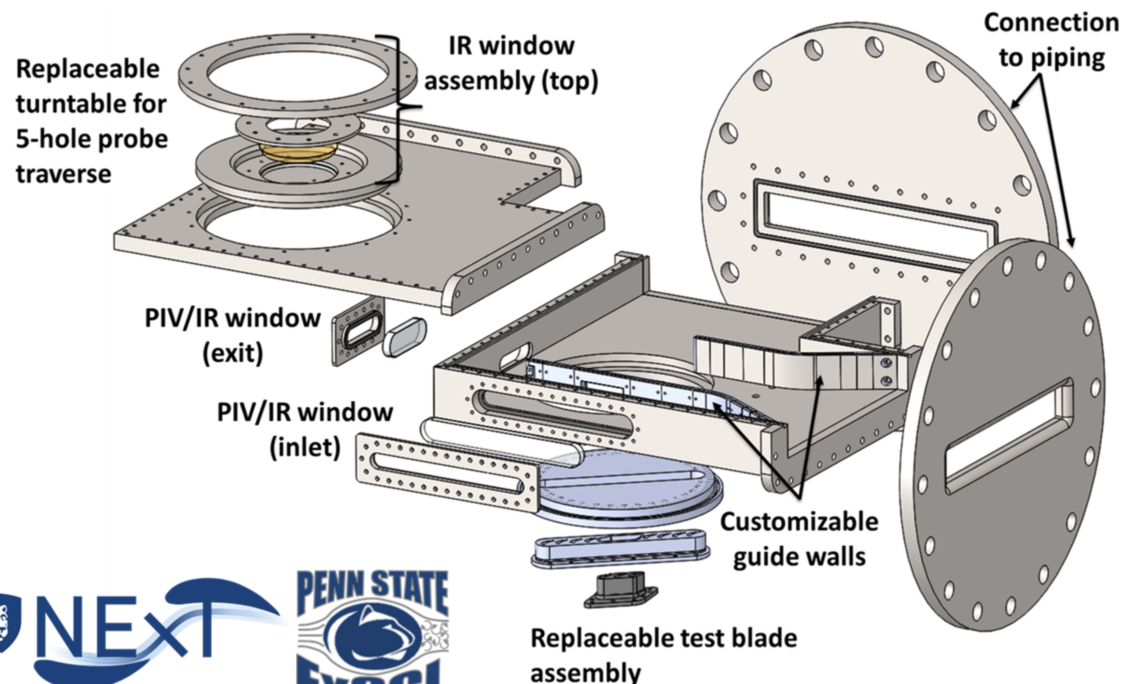


What’s Next?

Add value, increase TRL, and get industry “buy-in”?

- Evaluate ‘best’ advanced (and baseline) cooling designs in high-speed cascade test rig at Penn State University
  - Chord Reynold’s Number >1,000,000
  - Use NExT airfoil profile





How to measure adiabatic film effectiveness in a conjugate environment?

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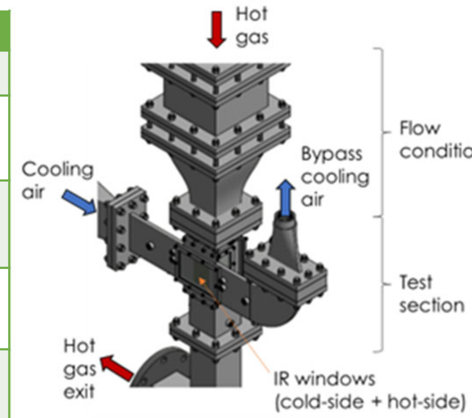
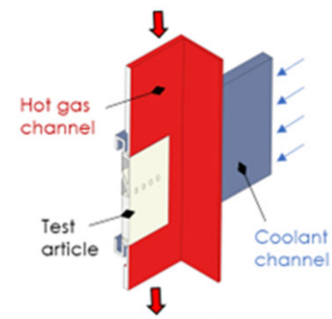
Experimental Constants

Parameter	Design Value
Cooling hole diameter, D	3.2 mm
Cooling hole pitch, (p/D)	3
Cooling hole length (L/D)	6
Number of cooling holes	5
Mainstream gas temperature	**650K**
Mainstream velocity, V_g	110 m/s
Mach Number – hot gas	0.22
Reynold's number, D, $(\rho_g V_g D/\mu_g)$	6,180
Mainstream Tu	<2%
Approach BL thickness, (δ/D)	1.1 (at LE of hole) 0.99 (x = -10D)
Temperature Ratio, (T_g/T_c)	**1.88**
Coolant channel hydraulic diameter, D_h	12.1 mm

Independent Variables

Parameter	Design Value
Blowing Ratio $(\rho_c V_j/\rho_g V_g)$	BR=0.75 & BR=1.00
Coolant channel velocity, $V_{ch,i}$	10 -- 40 m/s
Reynold's number, D_h, $(Re_{D_h} = \rho_c V_{ch,i} D_h/\mu)$	7,300 – 29,300
Mach Number – coolant channel	<0.12
VR at film hole Inlet $(\mathrm{VR_i} = V_{ch,i}/V_j)$	0.25–1.03 (BR=0.75) 0.19–0.77 (BR=1.0)
$\mathrm{VR_{ch}}$ $(V_{ch,i}/V_g)$	0.1 – 0.4
Film mass fraction $(\dot{m}_f/\dot{m}_{ch})$	19 – 4% (BR=0.75) 25 - 6% (BR=1.00)

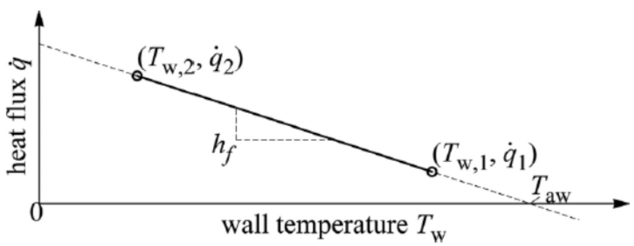




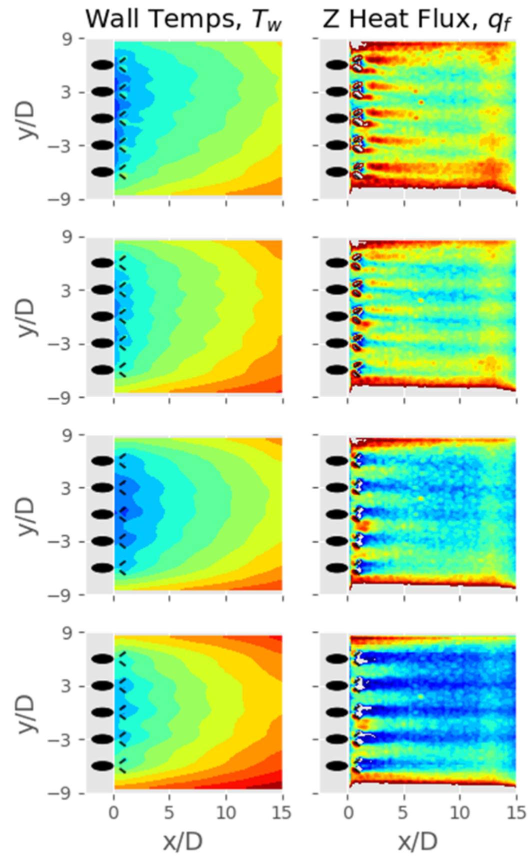
Experimental Approach – Perpendicular Crossflow

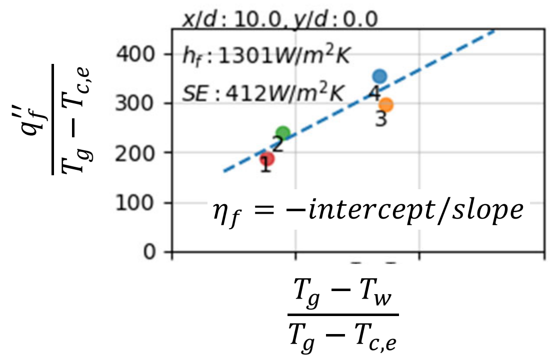
FEA BCs and Regression analysis → film effectiveness and HTC

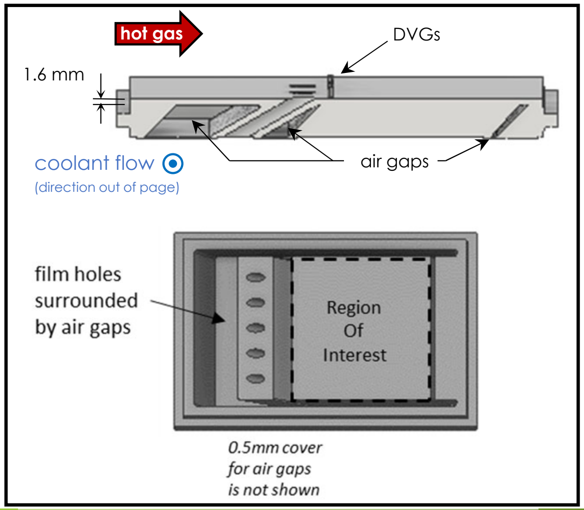
- Gritsch et al., ASME 98-GT-28
  - $q'' = -hT_w + hT_g$
- Kneer et al., 2016
  - $q''_f = -h_f T_w + h_f T_{f,aw}$



- Present work
  - $\frac{q''_f}{T_g - T_{c,e}} = h_f \frac{(T_g - T_w)}{T_g - T_{c,e}} - h_f \eta_f$







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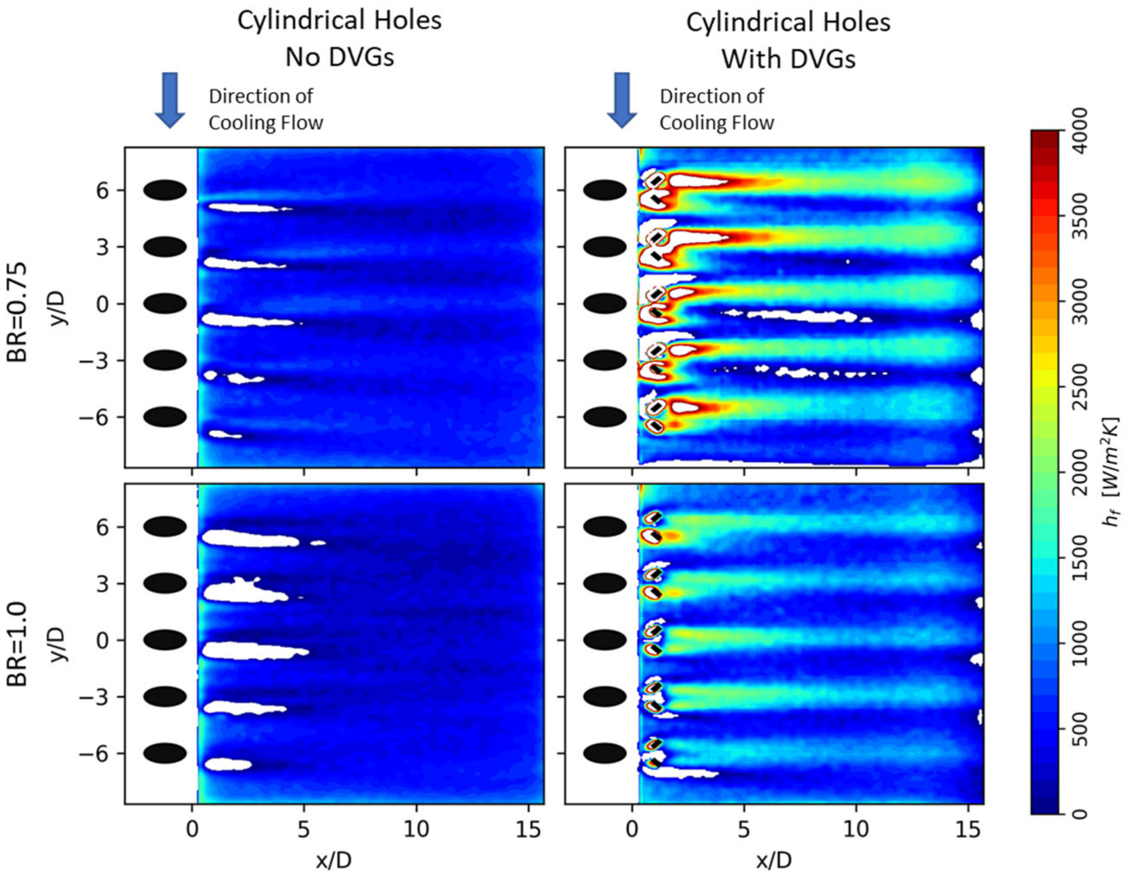
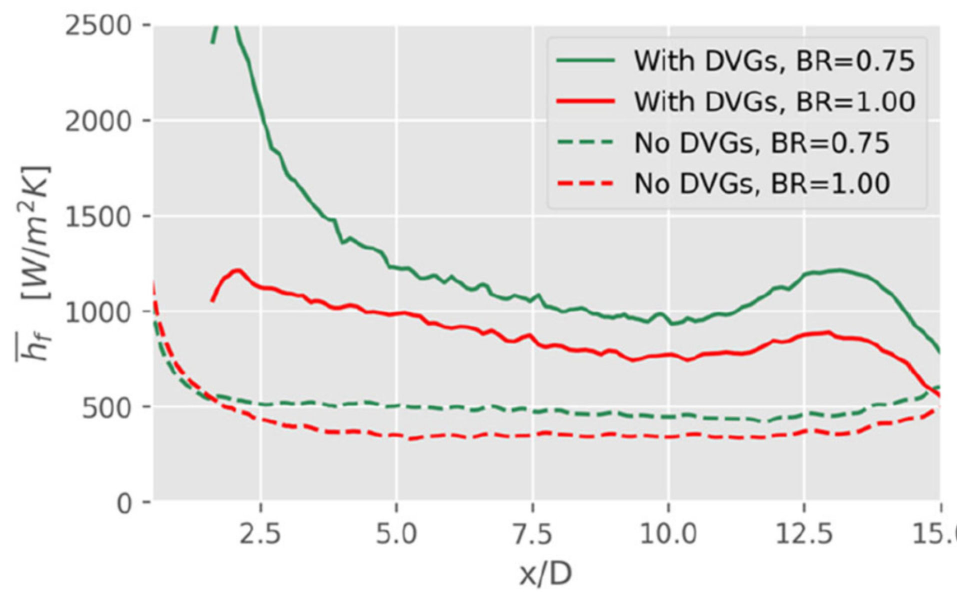
Heat Transfer Coefficients (with film cooling)

DVGs increase the laterally averaged HTC's by roughly 2X





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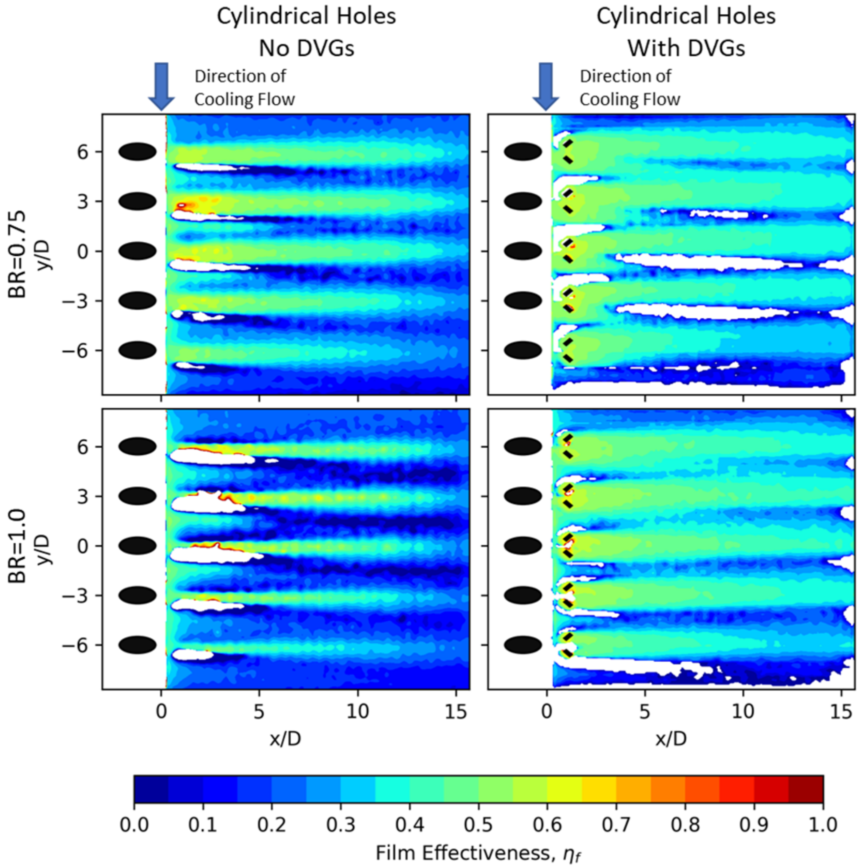
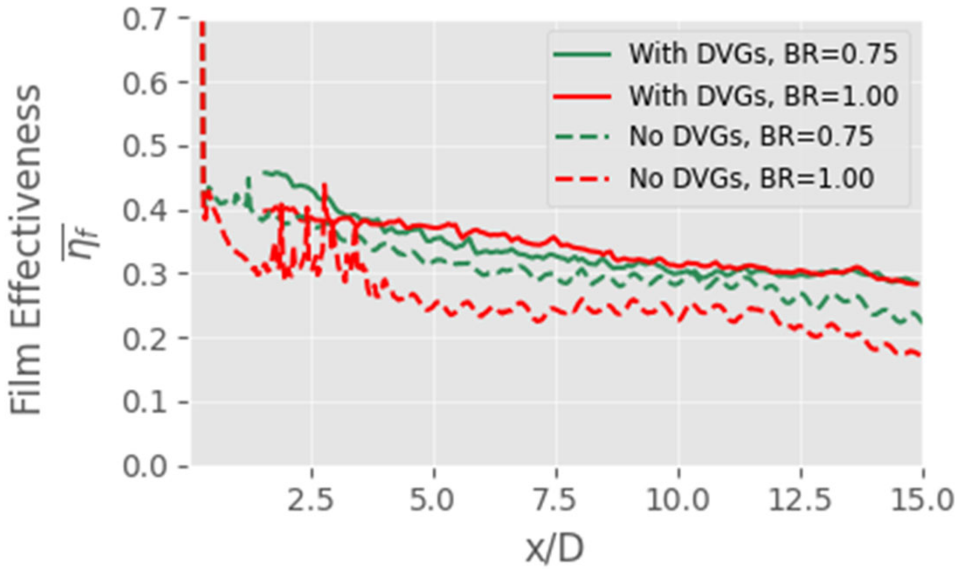
Film Effectiveness In a Conjugate Flat Plate

BR=0.75 → similar film effectiveness; BR=1.0 → DVGs slight improvement





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Internal and external cooling technologies are pathway to higher efficiency!

Summary

- Better cooling → percentage pt improvements in efficiency
- Internal cooling
  - Important for small (and large) GT turbine applications
  - Based on preliminary testing, NETL double-wall design looks promising
  - Plan to scale design to more realistic airfoil and more realistic Re and Ma
- External 'film' cooling
  - Goal: $\bar{\eta}_f > 0.4$ for x/d > 10
  - New method for measuring local HTC's and adiabatic film effectiveness in a conjugate test rig
  - At some conditions, downstream VG film cooling concept looks promising
  - Coolant in crossflow configuration is important effect
    - Cylindrical holes perform better;
    - Other hole designs experience performance degradation

Questions, Comments

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