Overview of NETL/RIC Heat Transfer Support for Brayton and sCO_2 Power Cycles

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NATIONAL ENERGY TECHNOLOGY LABORATORY

NETL/RIC – Heat Transfer Capabilities

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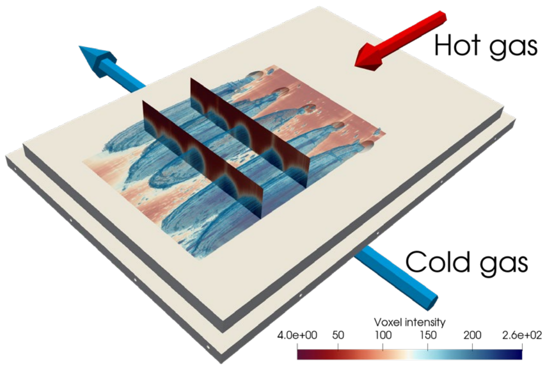
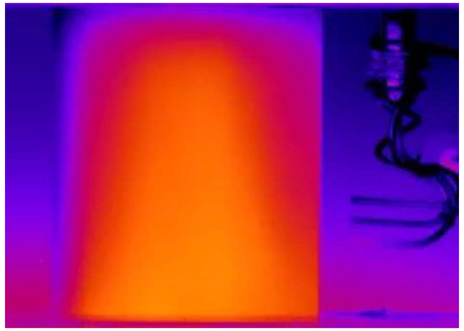
Brayton Cycles

sCO2 Cycles

Film Cooling

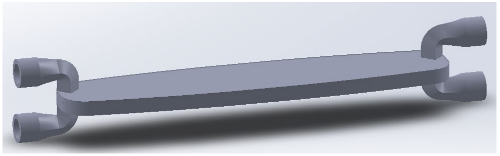


Internal Cooling



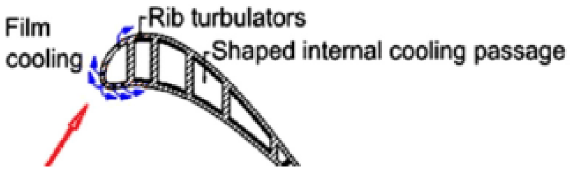
AM Airfoil Cooling
(Increase TrIT by 100C for 5-10MW GT's)

Indirect Cycles

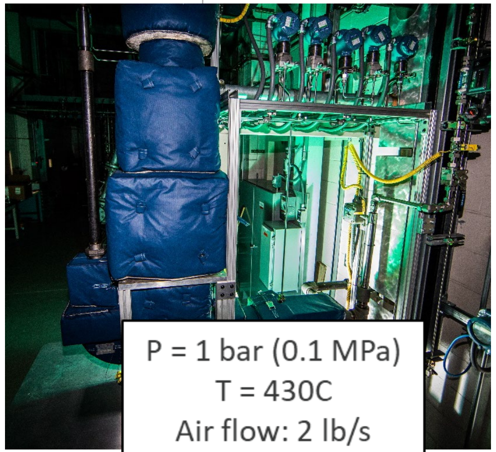


AM Plate Pin-Fin Prototypes – courtesy of ORNL
(recuperator 40% lighter than PCHE)

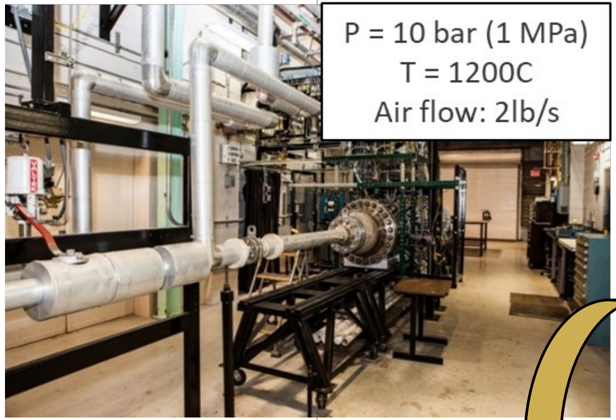
Direct Cycles



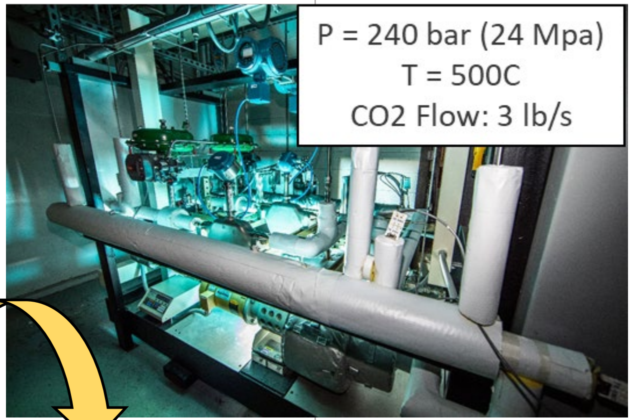
Conventional Cooling Technologies at sCO2 Conditions



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



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

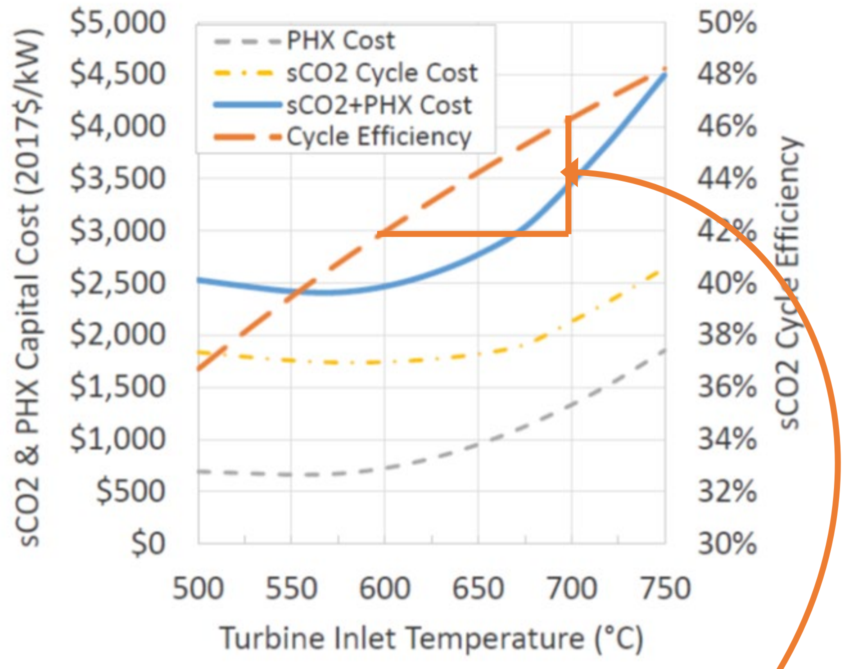


P = 240 bar (24 Mpa)
T = 500C
CO2 Flow: 3 lb/s

Link two existing capabilities together
"SCORPION" –
SCO_2 @ Realistic Pressure, Intensity, and OperatiNg conditions

Motivation for sCO2 Heat Transfer Research

- Higher efficiencies than steam cycle
- Heat exchangers are critical system cost components
  - Primary heaters, recuperators, and coolers
- Validated heat transfer correlations → smaller (less expensive) heat exchangers
- Large range of flow regimes encountered in sCO2 cycles
  - Buoyancy, flow acceleration, and property variation



ΔT=100C → Δη=4 % points[2]

How much is 1 percentage point worth in US electricity market[1]?

- $250M per year in fuel savings
- 3M tonnes per year in avoided CO_2 emissions
- 7B gallons of water saved per year
- $7B in economic benefit (according to keynote presentation*)

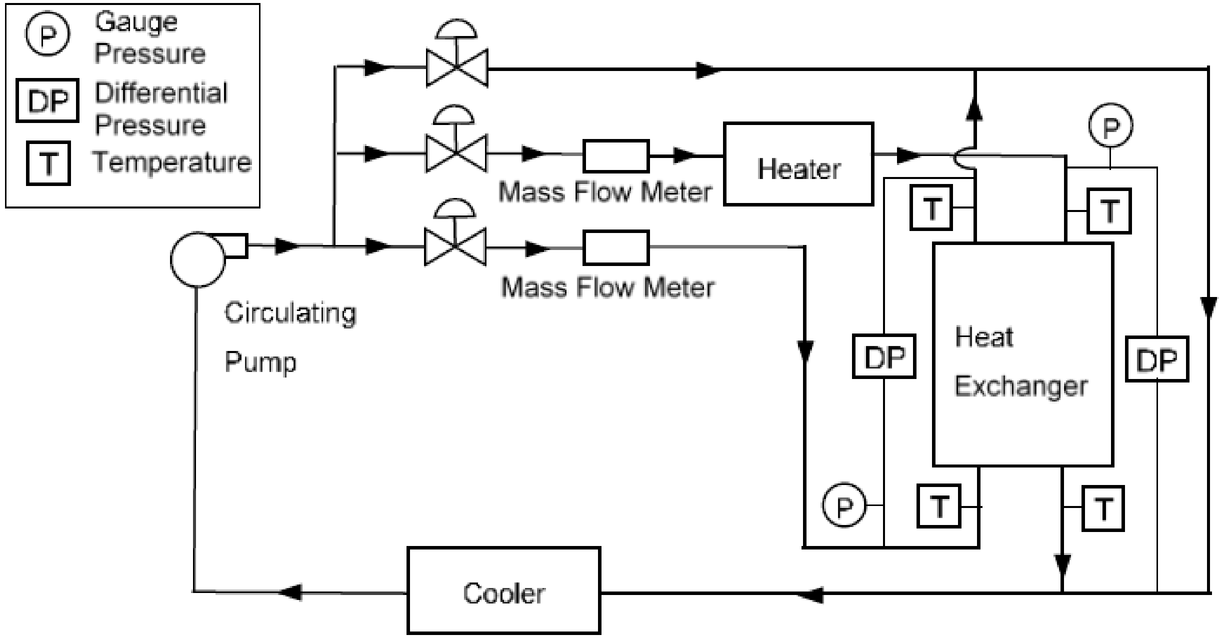
[1]Keynote at 2019 UTSR Meeting, Orlando, FL

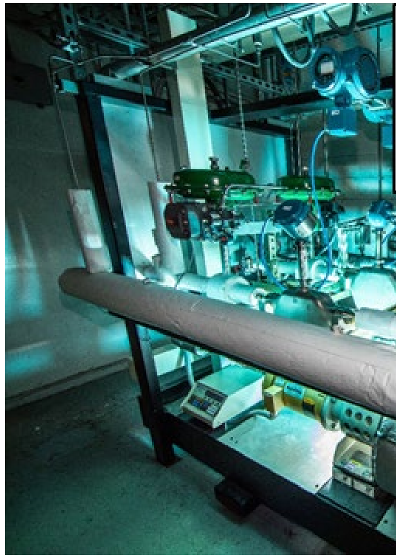
[2]Weiland, Lance, and Pidaparti (2019), Presentation at ASME GT2019-90493

HEET (Heat Exchange and Experimental Test) Facility

sCO2 Cycles

- Measure average HTCs using Wilson Plot method
- Test additively manufactured (AM) concepts
  - Internal heat transfer enhancements
  - Compact heat exchanger designs





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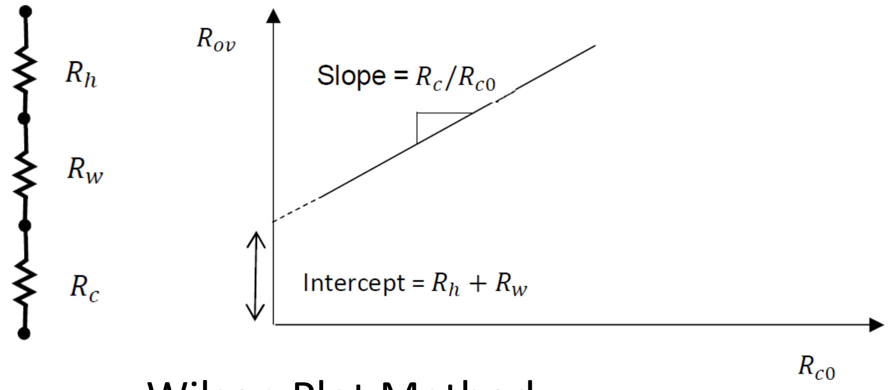


Wilson Plot Method

Searle, M., Black, J., Straub, D., Robey, E., Yip, J., Ramesh, S., Roy, A., Sabau, A. S., and Mollot, D., 2020, "Heat Transfer Coefficients of Additively Manufactured Tubes with Internal Pin Fins for Supercritical Carbon Dioxide Cycle Recuperators," Appl. Therm. Eng., **181**, p. 116030.

Test Setup Validated at sCO2 Pressures and Temperatures

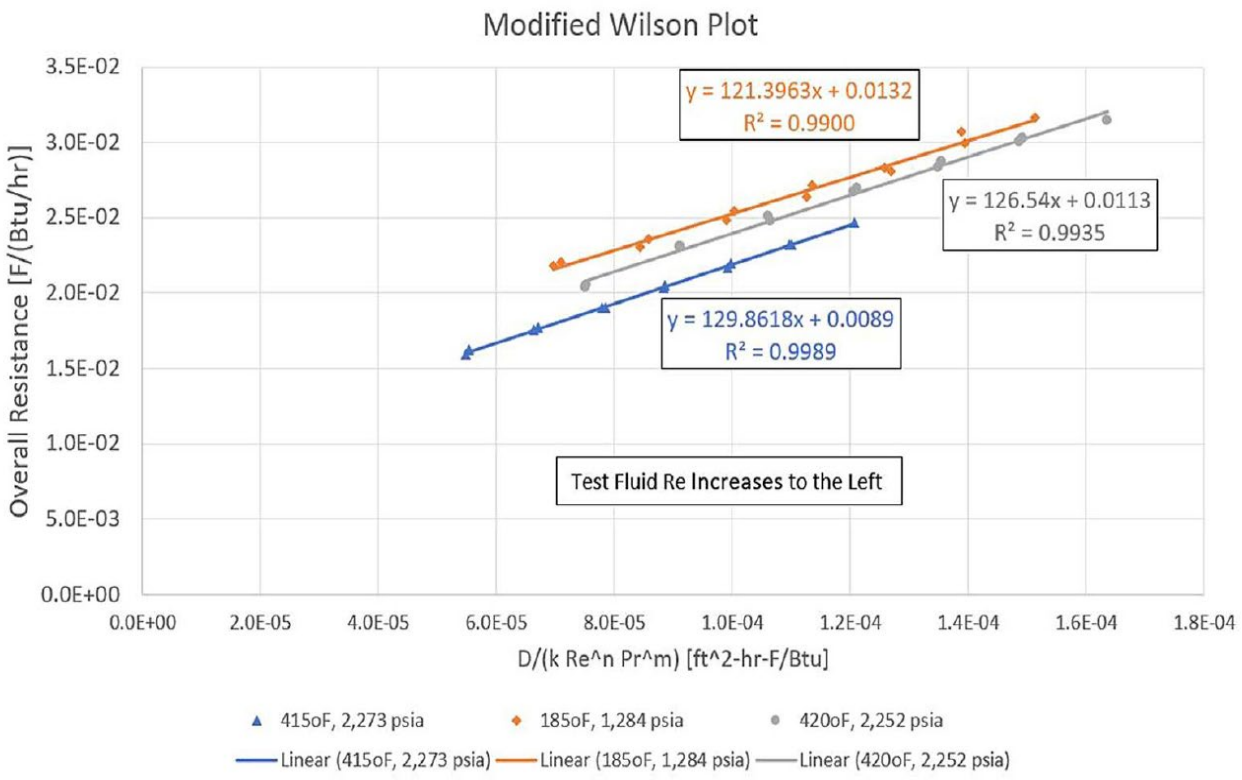
Shakedown Test Results – Smooth Tubes

- Friction factors within 5% of McAdams correlation (smooth)
- Nu numbers match Dittus-Boelter correlation within 5%

$$Nu = 0.023\, Re^{0.8} Pr^{\frac{1}{3}}$$

Table 1 Nu correlation coefficient

Process conditions	Slope	C_o
415 °F, 2273 psia	129.9	0.0212
185 °F, 1284 psia	119.7	0.0230
420 °F, 2252 psia	126.6	0.0218
	Average	0.0220

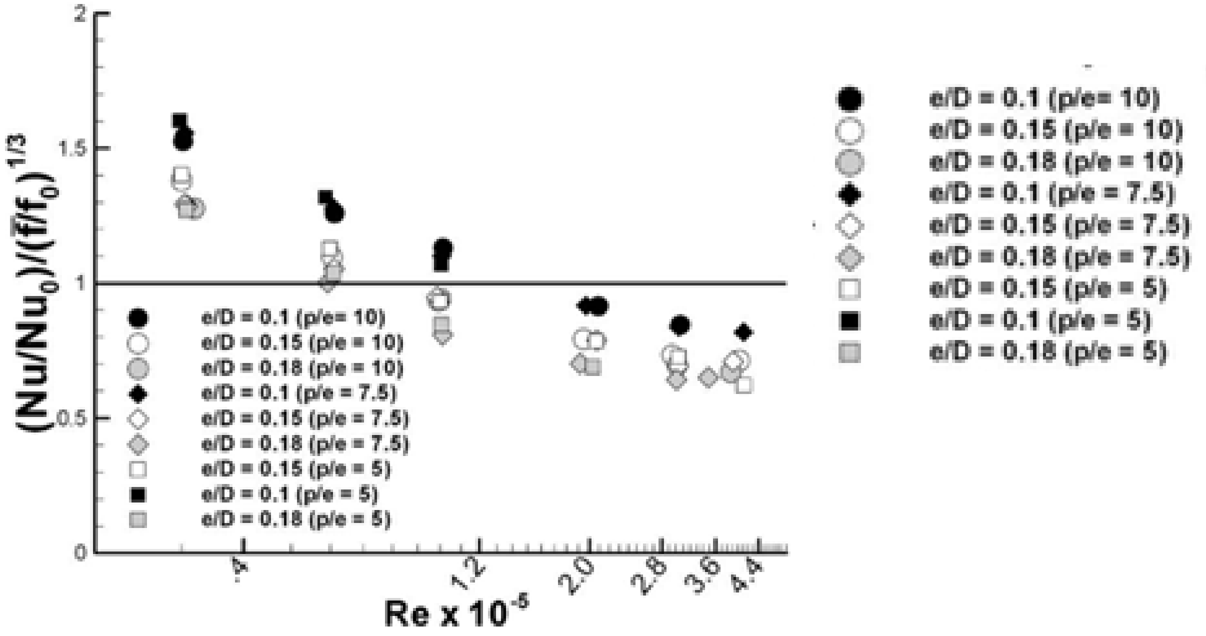


Black, J., Straub, D., Robey, E. H., Yip, M. J., Ramesh, S., Roy, A., and Searle, M., 2020, "Measurement of Convective Heat Transfer Coefficients With Supercritical Co2 Using the Wilson-Plot Technique," J. Energy Resour. Technol., **142**(July), pp. 1–10.

Internal Nu-Enhancements – Air Brayton Cycles vs sCO2 Direct Cycle Applications

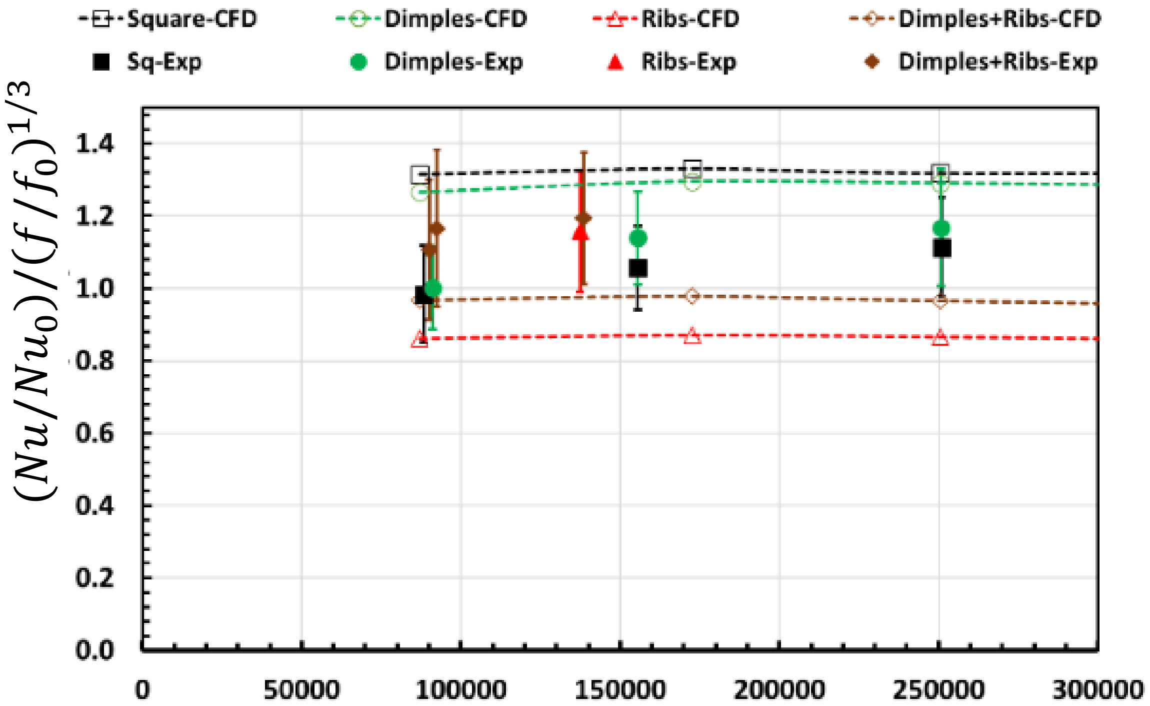
NETL Experiments with AM Rectangular Cross-Sections at sCO2 Conditions

Air



(Rallabandi et al, 2009)

sCO2



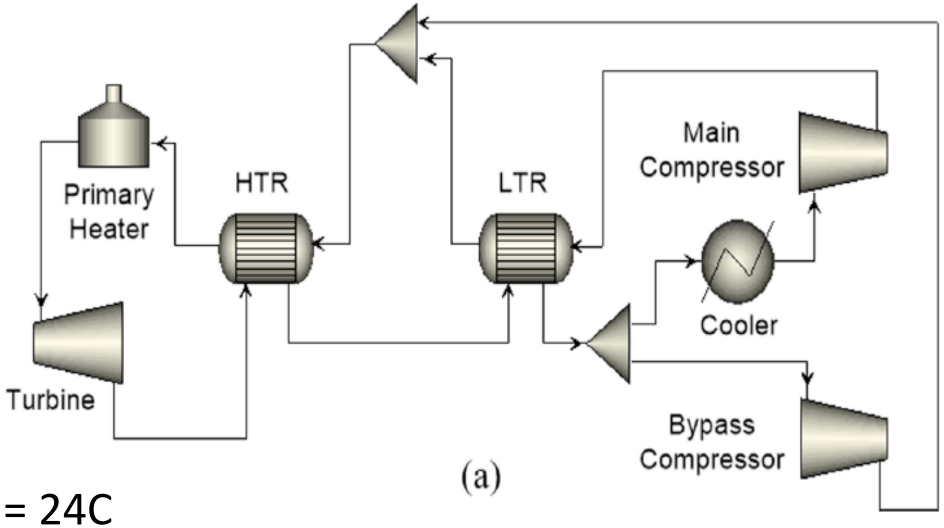
(Searle, Roy et al, 2021)

For CO2, thermal performance factor does not decay with increasing Re as expected for air in conventional Brayton Cycles

Searle, M., Roy, A., Black, J., Straub, D., and Ramesh, S., 2021, "Investigating Gas Turbine Internal Cooling Using Supercritical CO2 at High Reynolds Numbers for Direct Fired Cycle Applications," J. Turbomach., pp. 1–15.

Novel Heat Exchanger Design Using Additive Manufacturing

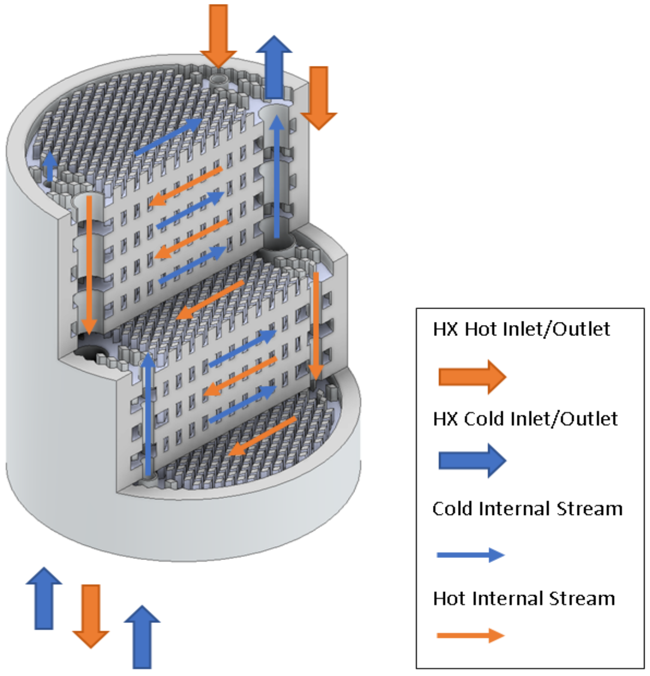
High-Temperature Recuperator (HTR) Designs (Jiang et al. - 2018)



Heat Duty: 45.15 MW, LMTD = 24C

	Conventional Shell & Tube (d = 6.4 mm)	Printed Circuit Heat Exchanger
Pressure drop (bar)	2.39	2.48 (cold side: 1.4 bar)
Mass/Heat Duty (kg/kW)	**0.532**	**0.246**

ORNL Baseline Concept For AM Plate Pin-Fin Heat Exchanger

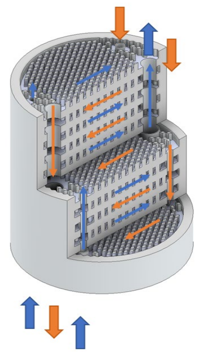


Jiang, Y., Liese, E., Zitney, S. E., and Bhattacharyya, D., 2018, "Design and Dynamic Modeling of Printed Circuit Heat Exchangers for Supercritical Carbon Dioxide Brayton Power Cycles," Appl. Energy, **231**, pp. 1019–1032..

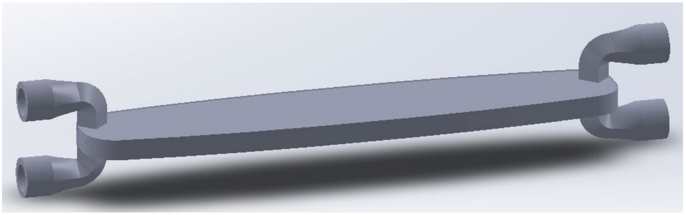
Design Optimization For AM Plate Pin Fin Design

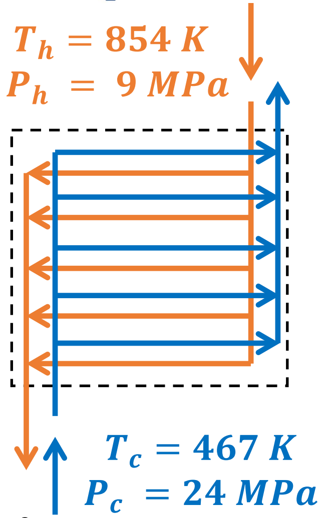
Can AM be leveraged → lower cost sCO2 Recuperators

ORNL Baseline



5kW Prototype for Future Test

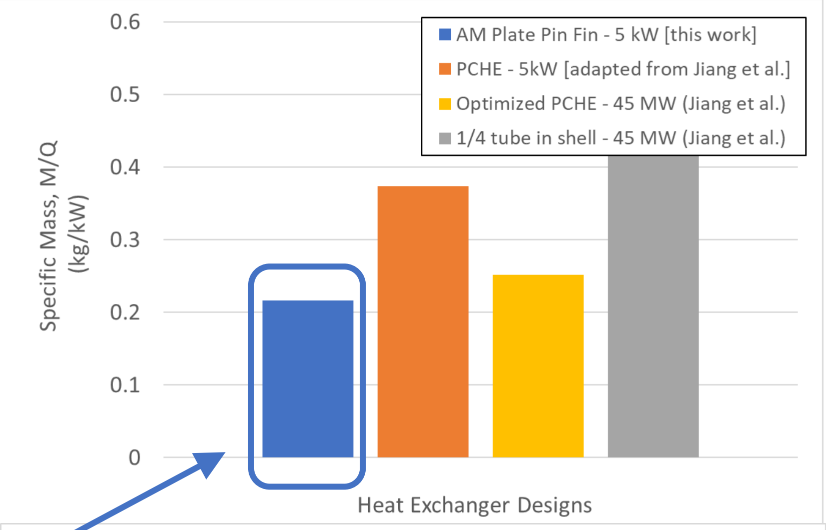


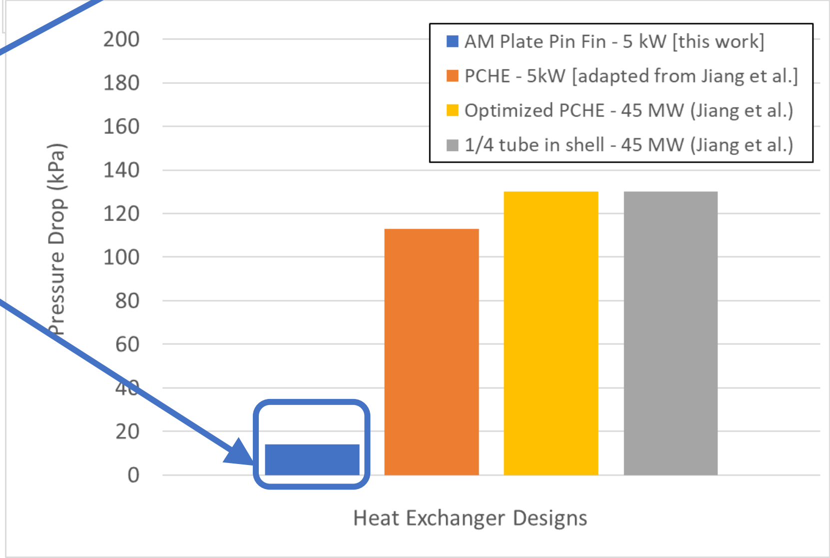


Performance Constraints
- 97% Effectiveness
- Pressure drop < 0.13 bar

Add high density pin-fin arrays to channels
- Pins diameters < 1 mm
- Manufacturing feasibility?

Anticipated Benefits:
- 20-40% less material relative to PCHE
- Lower pressure drop than PCHE
- Fabrication and prototype testing is planned

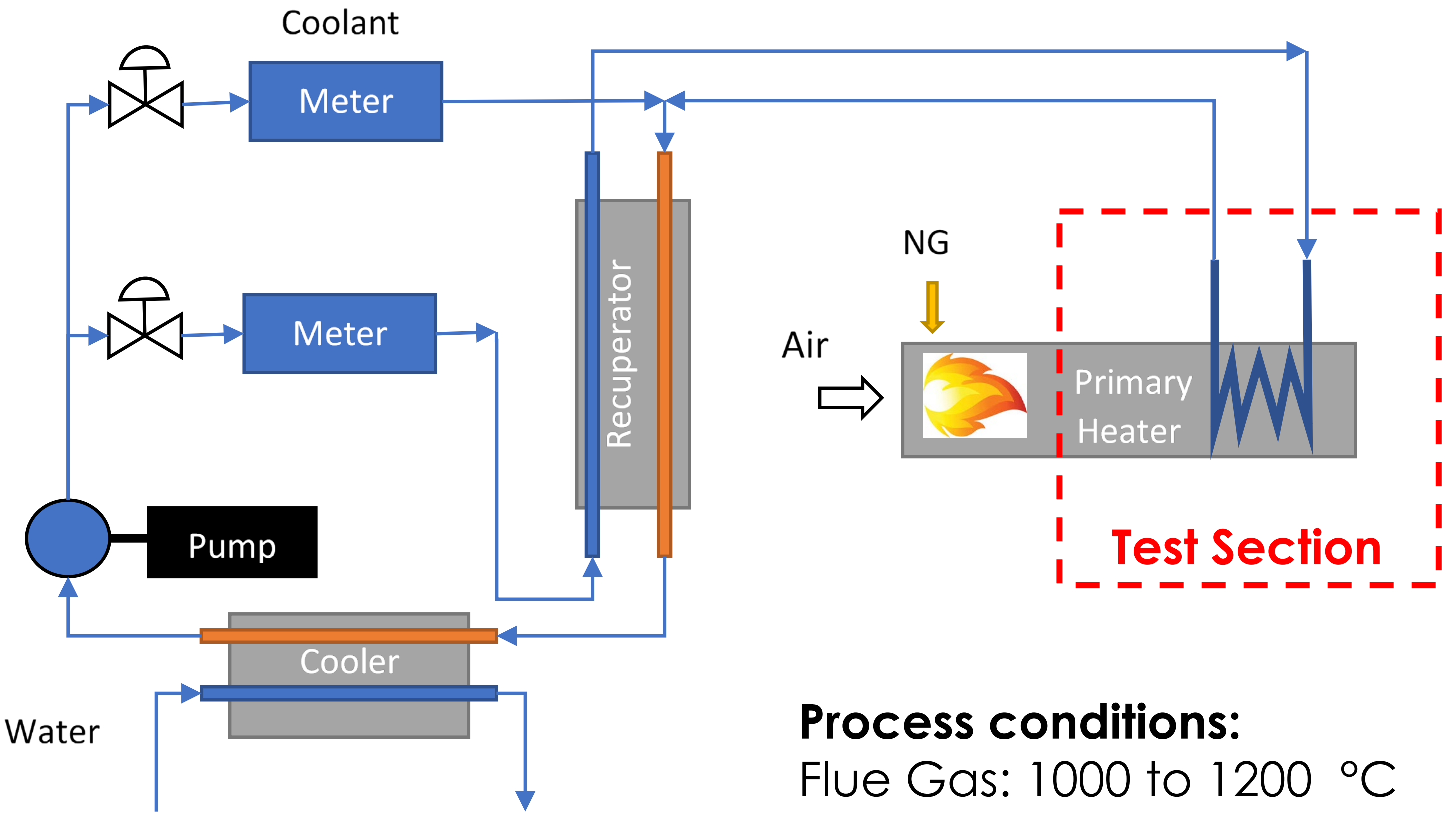




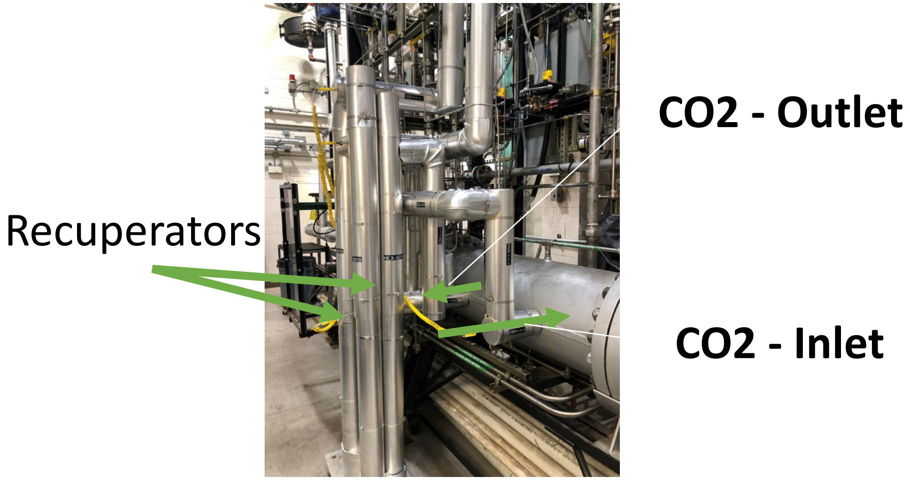
Robey, E. H., Ramesh, S., Sabau, A. S., Abdoli, A., Black, J. B., Straub, D. L., and Yip, M. J., 2021, "Design Optimization of an Additively Manufactured Prototype Recuperator for Supercritical CO2 Power Cycles," *45th Clean Energy Conference*, Clearwater, FL, p. 12.

NETL SCORPION Test Rig

SCORPION (SCO_2 at Realistic Pressure, Intensity, and OperatioNs)



HEET rig (sCO2 source and circulating pump)



Process conditions:
Flue Gas: 1000 to 1200 °C
sCO2: 540 to 700 °C,
sCO2 Pressure: 21 MPa

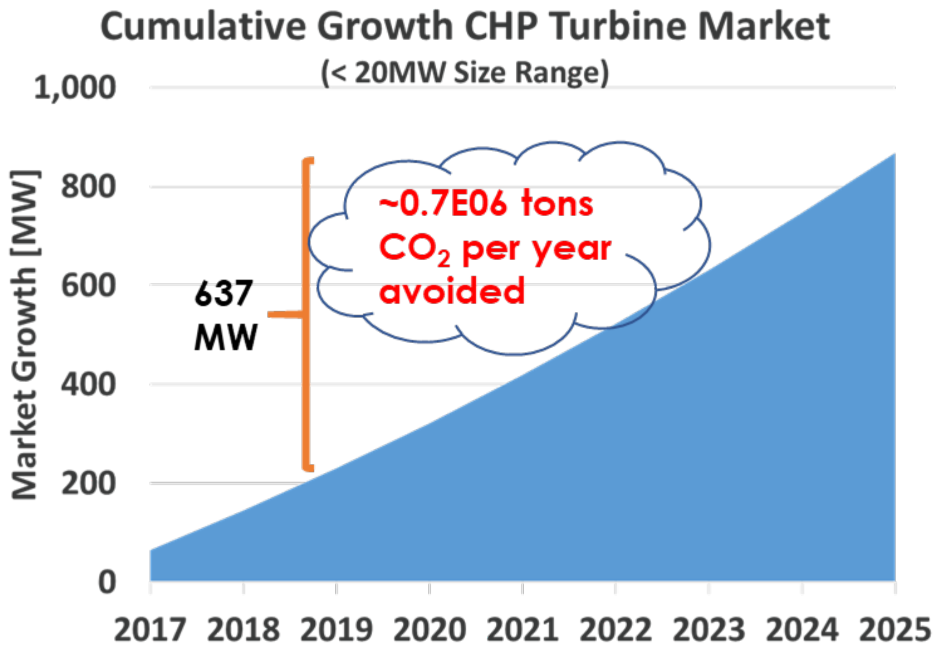
Motivation For Cooling Improvements For Small GT's (CHP Systems)

Why focus on small GT's for CHP systems?

- Currently > 2 GW of small GT-CHP in U.S.
  - 30-40% lower fuel use and lower CO_2 emissions
    - Relative to separate power + boiler sources
- >0.5GW growth by 2025
  - <20MW GT size range

	Baseline Engine (TIT-2000F)	Baseline +100C (TIT-2180F)	6% Increase in η_c	13% Increase in η_c
Power (kW)	6100	7214	7416	7592
Pressure Ratio	14.7	16.4	16.4	16.4
Thermal Efficiency	33.1%	34.0%	34.7%	35.3%
Coolant Fraction	9.6%	14.1%	13.5%	12.9%

Ref: Uysal et al., ASME Paper GT2021-58718

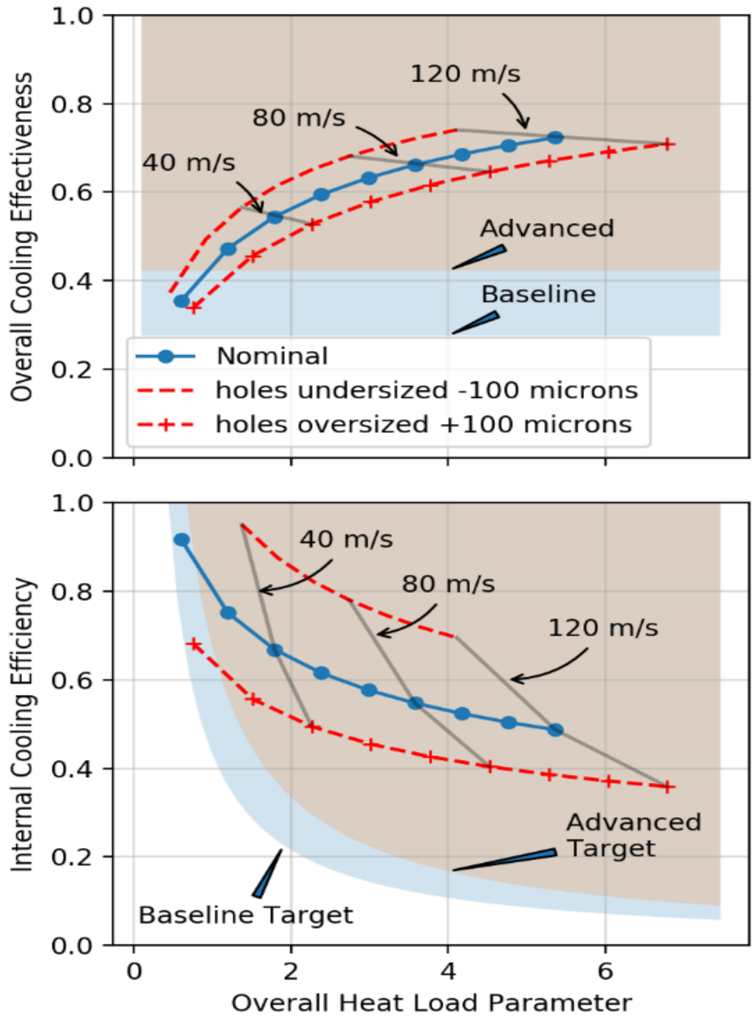


Anticipated Benefits:
- Reduce heat rate by 6% and increase power output by 24%
- Reduce payback period by ~25%
- Reduce CO_2 by 35% relative to non-CHP system

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*.

What differentiates this effort from others?

- Focus on small gas turbines
  - Internal cooling only (no film cooling)
- Define generic baseline
  - Engine model (Uysal et al., 2021)
  - Symmetric airfoils with internal cooling features
- Develop simplified cooling models
- Measure cooling performance curves for each design
  - Including internal cooling efficiency
- Extension of prior UTSR projects
  - Enable AM materials with better creep performance than cast alloys (WVU/Pitt)
  - Validate incremental impingement cooling design (UND)



Straub, D., Ramesh, S., Searle, M., Roy, A., and Black, J., 2021, "Baseline Airfoil Cooling Designs for a 5-10 MW Combined Heat and Power Turbine Application," *ASME Paper GT2021-59114*, pp. 1–14.

Motivation Film Cooling Improvements

Simple Cycle Sensitivity Study of Uysal et al. (2018)

- Internal cooling efficiency
  - By increasing cooling efficiency from 0.75 to 0.85
    - 5% improvement in efficiency
    - 8% improvement in power
- Film cooling effectiveness
  - By increasing film cooling effectiveness from 0.4 to 0.5
    - 10% improvement in efficiency
    - 15% improvement in power
- Film cooling concepts to consider
  - Tripod hole designs
  - Momentum preserved film cooling holes (Shih et al.)
  - Vortex control concepts (Shih et al.)

Internal Cooling Efficiency

$$\eta_{th} = \frac{T_{c_e} - T_{c_i}}{T_{w_e} - T_{c_i}}$$

Adiabatic Film Cooling Effectiveness

$$\eta = \frac{(T_g - T_{aw})}{(T_g - T_{c_e})}$$

Uysal, S. C., Liese, E., Nix, A. C., and Black, J., 2018, "A Thermodynamic Model to Quantify the Impact of Cooling Improvements on Gas Turbine Efficiency," J. Turbomach., **140**(3), pp. 1–11.

Conjugate Heat Transfer Test Rig

Film Cooling with Coolant in Crossflow

- Intermediate temperature (~700K) test rig
- Mass flow (0.5 – 1 kg/s)
- Pressure (~1 atm)
- Develop test method to measure all relevant cooling parameters at each pixel of an IR image

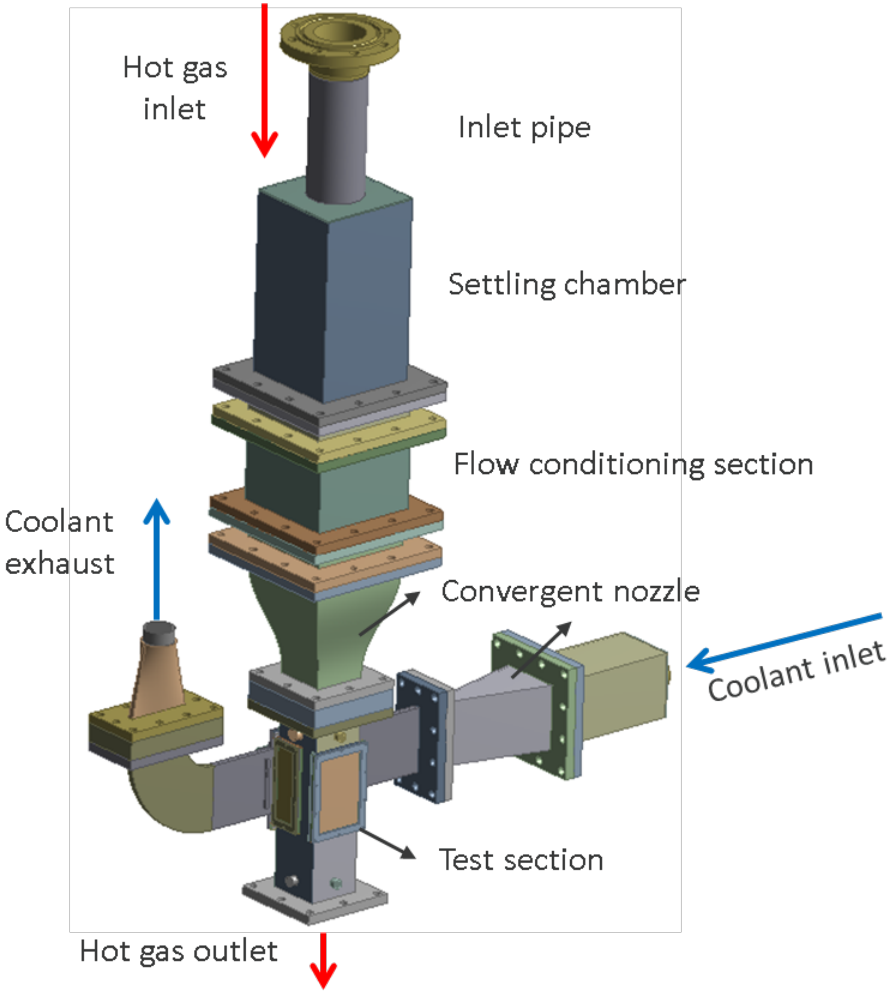
$$\boxed{\Delta q_r = 1 - \frac{q_f}{q_o} = 1 - \frac{h_f}{h_o}\left(1 - \frac{\eta}{\phi}\right)}$$

Adiabatic Film Cooling Effectiveness

$$\eta = \frac{T_g - T_{aw}}{T_g - T_{c_e}}$$

Overall effectiveness

$$\phi = \frac{T_g - T_{w_e}}{T_g - T_{c_i}}$$



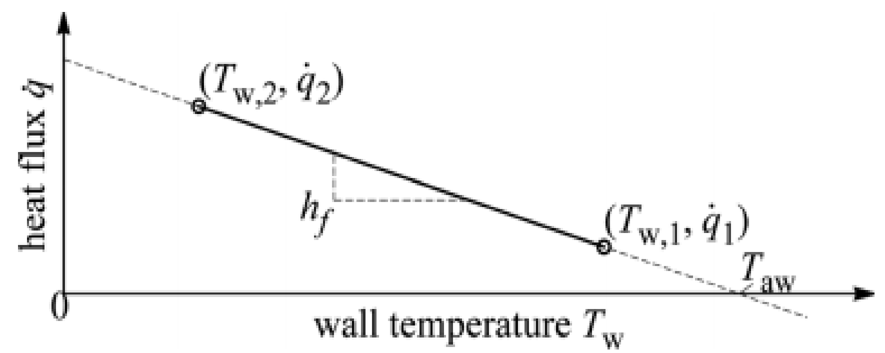
Ramesh, S., Robey, E., Lawson, S. A., Straub, D., and Black, J., 2020, "Design, Flow Field And Heat Transfer Characterization Of The Conjugate Aero-thermal Test Facility At NETL," *ASME Paper GT2020-15644*

Ramesh, S., Robey, E., Straub, D., and Black, J., 2019, "Experimental Evaluation of Heat Transfer in a High Temperature High Pressure Test Facility," *ASME Paper GT2019-91537*

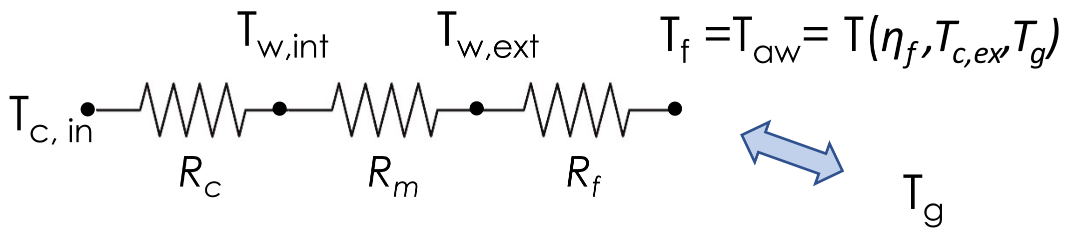
Test Approach

Modified Approach Has Been Developed For Conjugate Film Cooling Tests

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



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



What if wall temperature is not independent of $T_{aw} = T_{film}$?

Modified Approach

$$T_{aw} = \eta T_{c,e} + (1-\eta)T_g$$

$$q_f = -h_f T_w + h_f[T_g - \eta(T_g - T_{c,e})]$$

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

Slope

Intercept

Summary and Future Work

sCO2 Power Cycles

- NETL/HEET rig is sCO2 flow loop for measuring average HTC's and pressure drops
  - 1 kg/s; T_{max} < 500C; P_{max} = 240 bar
- Internal cooling ribs and dimples
  - Thermal Performance Factor does not decay with increasing Re
- Compact Plate Pin-Fin concept has potential to be better than PCHE recuperator (joint project with ORNL)
  - 20-40% less mass → lower cost
  - Lower pressure drop
  - Prototype testing is planned
- NETL/SCORPION rig is a new capability to measure average HTC's at primary heater conditions
  - 500C< T_{max} <800C; P_{max} = 240 bar; < 1 kg/s

Summary and Future Work

NATIONAL ENERGY TECHNOLOGY LABORATORY

Brayton Power Cycles

- AM airfoil internal cooling concepts with higher internal cooling efficiency than SOTA baselines
  - Baseline AM designs have been designed, fabricated and tested
  - Several advanced designs have been designed and fabricated
    - Test incremental impingement concept developed under UTSR (Forrest Ames, UND)
  - Internal cooling efficiency has been measured for baseline designs
  - Can AM materials be produced with better creep resistance than cast superalloys
    - Extend ODS materials work done under UTSR (Bruce Kang, WVU & Minking Chyu, Pitt)
- Film cooling efforts
  - Demonstrate test method to measure q_f, h_f, η_f, ϕ_f and q_o, h_o, η_o, ϕ_o
  - Validation data for novel AM concepts developed at Purdue (Tom Shih, et al.)
    - Vortex control concepts --
    - Momentum preserved concepts