Heat Transfer Opportunities for Supercritical CO_2 Power Systems

Pathways to Cost-Effective Heat Exchangers and Thermal Management

Matthew Searle
NETL Support Contractor

University Turbine System Review and Advanced Turbines Program Review Meeting
Oct. 30 – Nov. 1, 2023

Disclaimer

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Authors and Contact Information

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Matthew Searle[1,2]; Owen Grabowski[1,2]; Andrew Tulgestke[1,2]; Justin Weber[1]; Doug Straub[1]

[1]National Energy Technology Laboratory, 3610 Collins Ferry Road, Morgantown, WV 26505, USA

[2]NETL Support Contractor, 3610 Collins Ferry Road, Morgantown, WV 26505, USA

sCO_2 Field Work Proposal

sCO_2 Heat Transfer (Task 2)

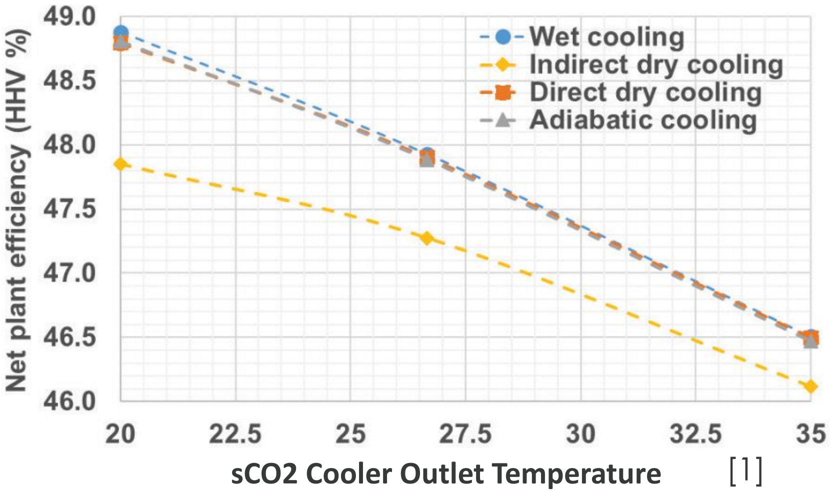
Objective

- Advance the understanding of sCO_2 heat transfer for net-zero power cycles
- Design and test novel concepts for cycle and turbomachinery components

Benefits

- **Increased efficiency**
  - Coolers: (2-4% pts increase) [1-2]
  - Turbine cooling (3% pt increase)*[3]
- **Compact heat exchange equipment**
- **Reduced cost of electricity**
  - Coolers: (3-8% reduction) [1-2]

*Advanced cooling strategies are required to optimize turbine performance



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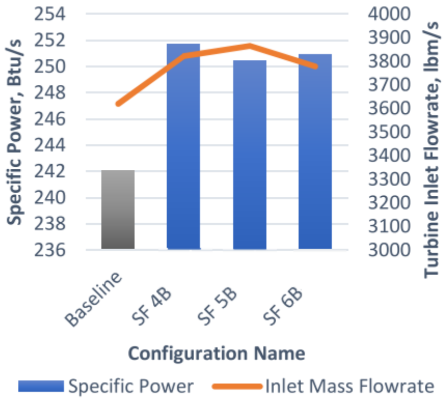


[3]

Design optimization for single flow turbine

[1] Pidaparti, et al., 2020, "Cooling System Cost and Performance Models To Minimize Cost of Electricity of Direct SCO2 Power Plants," 7th Int. Supercrit. CO2 Power Cycles Symp
[2] Ahmed et al., 2023, Int. Commun. Heat Mass Transf., **142**(February), p. 106675.
[3] Uysal, S. C., et al. (2022). "Cooling analysis of an axial turbine for a direct fired sCO2 cycle and impacts of turbine cooling on cycle performance." Energy Conversion and Management **263: 115701.**

sCO_2 FWP Task 2

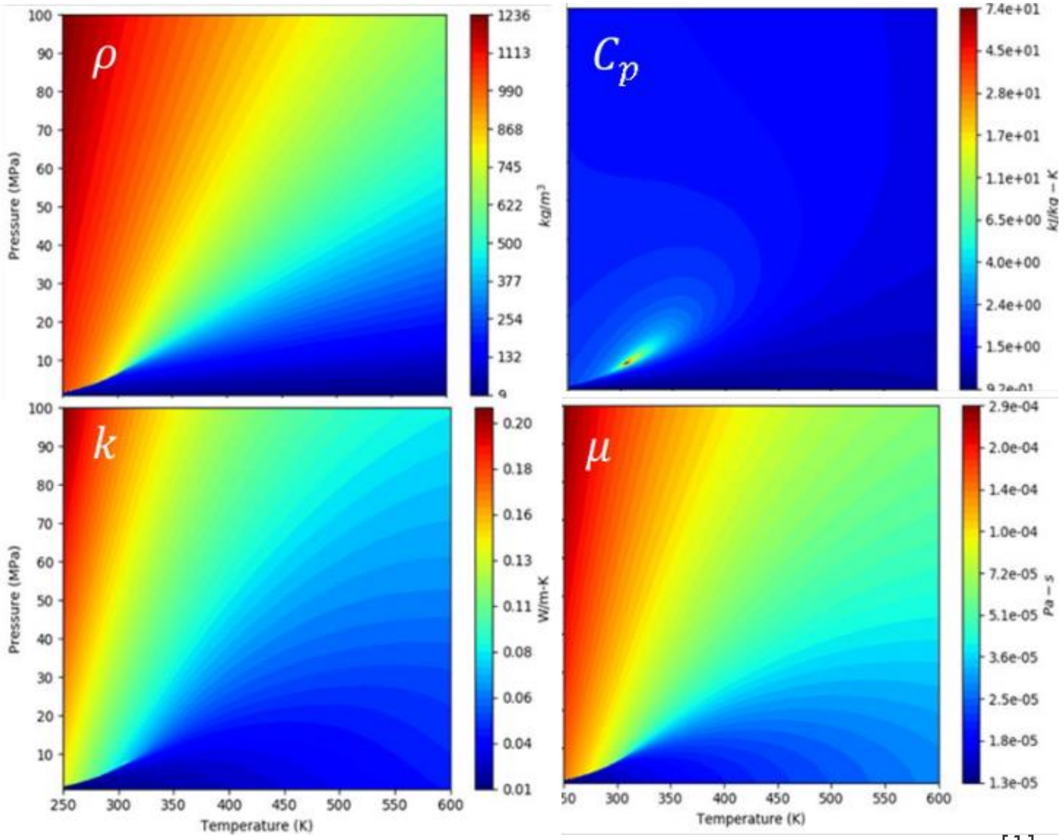
sCO_2 Heat Transfer

Challenges

- Property gradients, small approach temperatures, buoyancy and secondary flows, phase change, working fluid mixtures, non-linear rig behavior, dataset size

Approach

- Develop technologies for effective recuperators, primary coolers, and blade/vane thermal management
- Leverage machine learning and advanced manufacturing technologies
- Utilize experimental and computational capabilities at NETL



[1]

[1] S. Ramesh, and D. Straub, DOE/NETL-2021/2842

NETL sCO_2 Test Capabilities

HEET

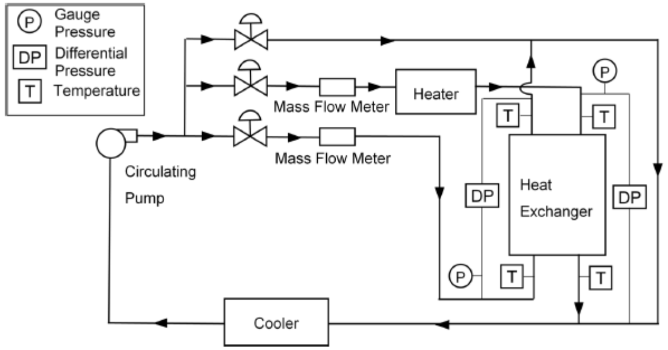
- Heat Exchange and Experimental Testing
- *Coolers, blade/vane internal cooling, low temperature recuperators*

SCORPION

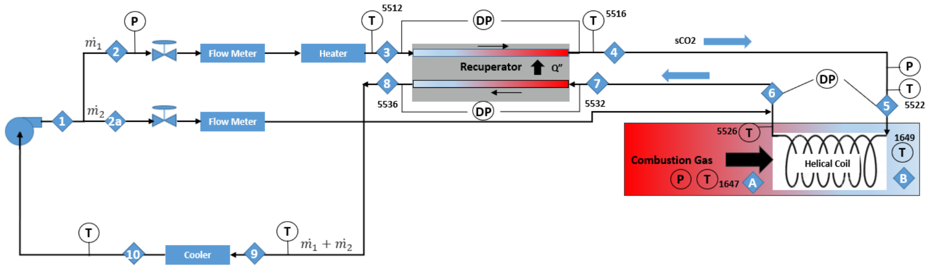
- Supercritical CO2 at Realistic Pressure, Intensity, and OperatioNs
- *High temperature recuperators, primary heaters*

CONDENSE

- CarbON Dioxide ENergy StoragE
- *Heat exchangers for trans-critical power cycles, energy storage, and waste heat recovery*

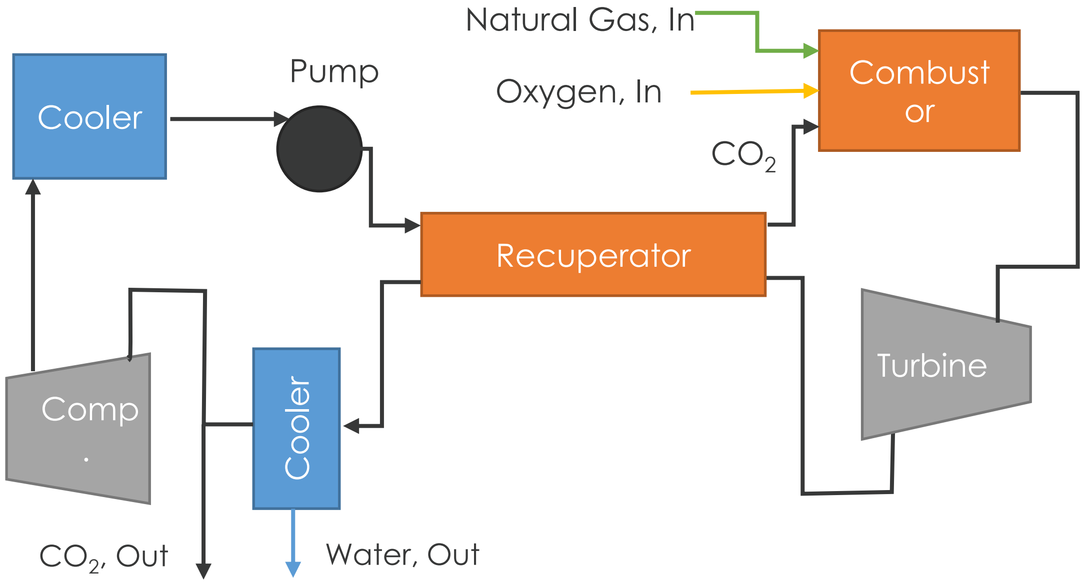


NETL HEET

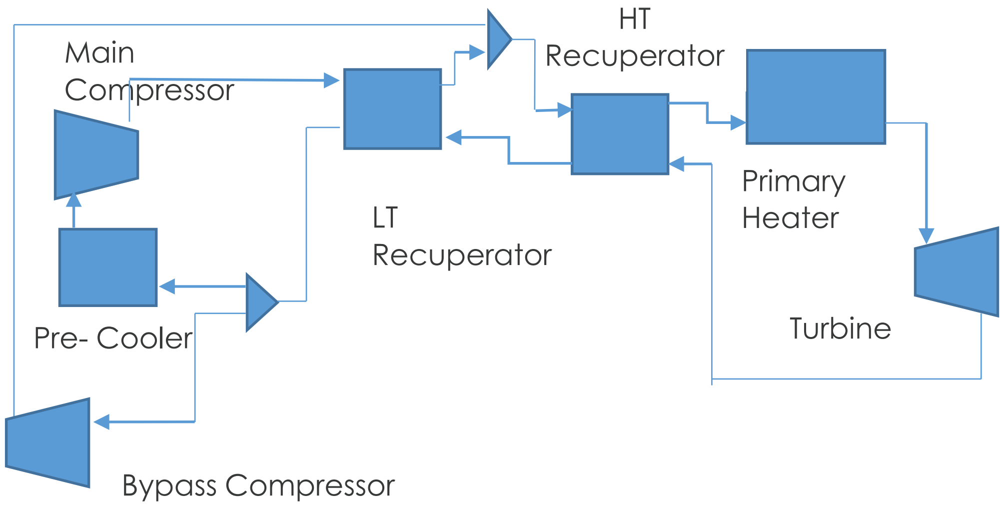


NETL SCORPION

sCO_2 Power Cycles and Heat Transfer



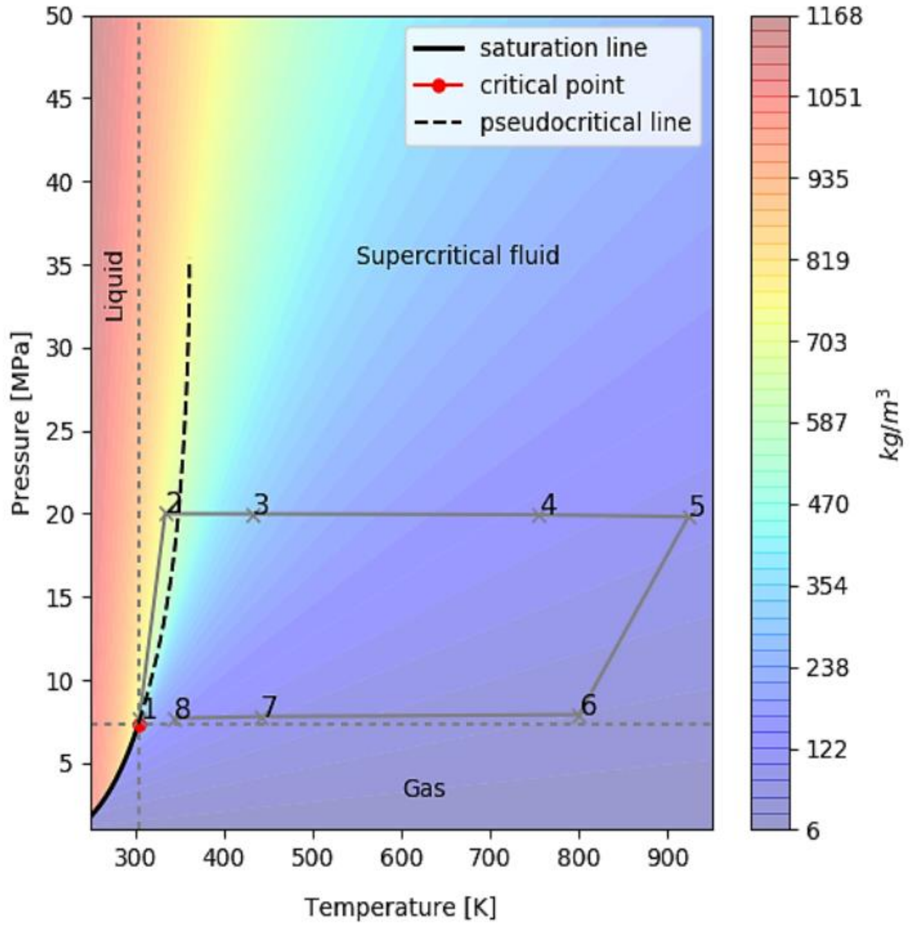
Direct: Simple, Recuperated Brayton Cycle



Indirect: Recompression Brayton Cycle

Outline

- sCO_2 cycle coolers
- sCO_2 turbine cooling technology
- Advanced manufacturing and recuperator heat transfer
- Machine learning applications
- Two-phase heat transfer in trans-critical CO_2 cycles



[1]

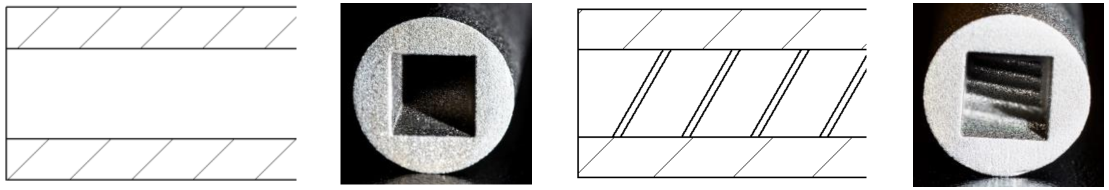
[1] S. Ramesh, and D. Straub, DOE/NETL-2021/2842

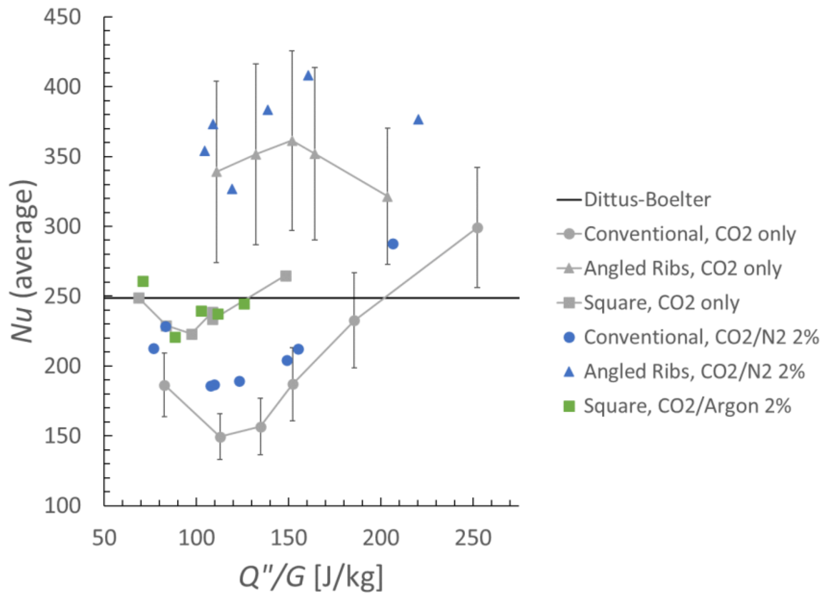
sCO_2 Cycle Coolers

Heat Transfer Enhancement and Impact of Working Fluid Impurities

Background

- Heat transfer degradation due to buoyancy [1]
- Argon and nitrogen may be present as minor impurities in direct cycles due to inefficiencies in the air separation unit [2]
- Impact of impurities (if any) was expected to be large near the pseudo-critical line (coolers)





Outcomes

- Impact of 2% N_2 and 2% Argon is small
- Additive manufacturing (AM) roughness and rib patterning are effective enhancement technologies for coolers, achieving 40% and 110% improvement, respectively

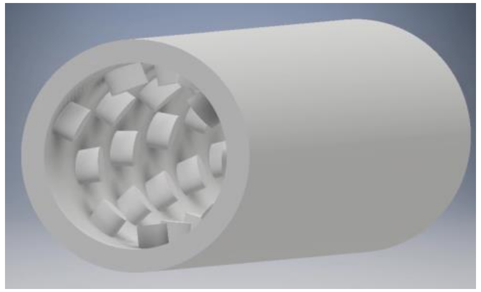
[1] Jackson, J. D. (2017). "Models of heat transfer to fluids at supercritical pressure with influences of buoyancy and acceleration." Applied Thermal Engineering 124: 1481-1491.
[2] White et al., 2020, *Cooling Technology Models for Indirect SCO2 Cycles, sCO2 Symposium*

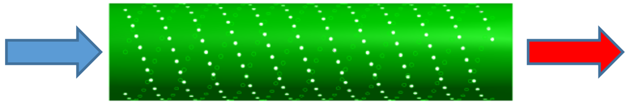
Parametric Optimization

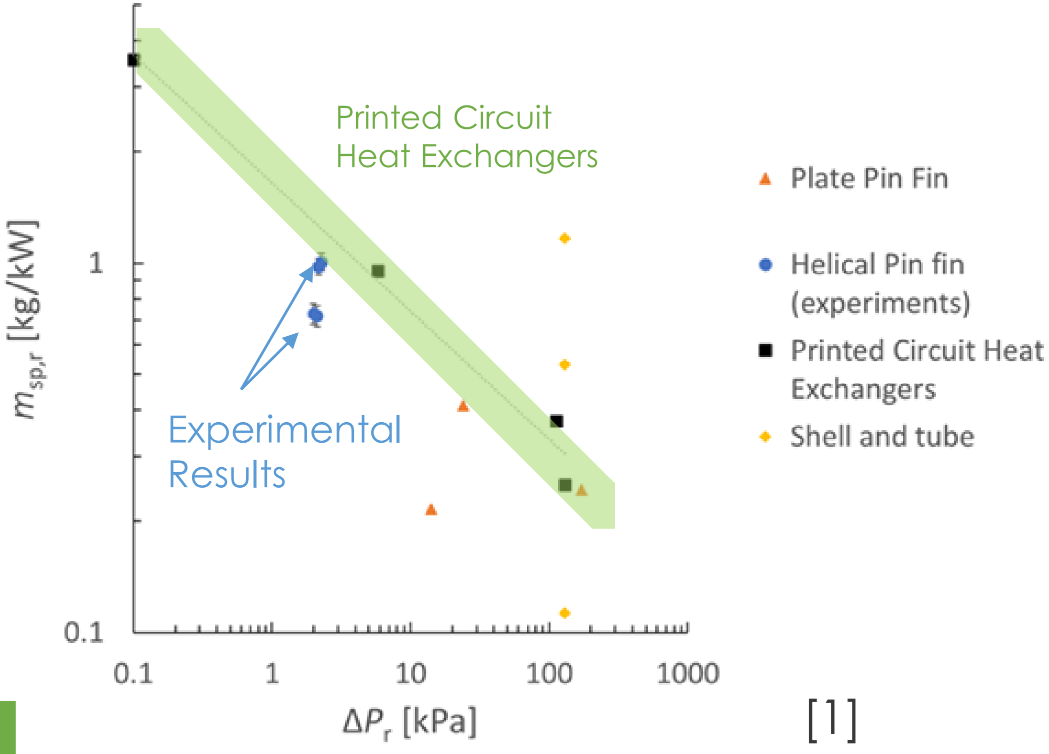
AM Enabled Geometry Optimized using Computational Fluid Dynamics (CFD)

Internal Tube Helical Pin Arrays

- CO_2 @ 155 bar, 400 K
- Reynold's Number: 120,000
  - Based on smooth tube dia.
- Prandtl Number: 1.1
- Concept: Elliptical pins on helical paths angled with respect to the flow







[1]

Major Pin-fin Diameter	Minor Pin-fin Diameter	Pin-fin Length	Pin-fin Helical Spacing	Wall Angle	Flow Angle	No. Helix Paths	Helix Pitch
0.25-0.75 mm	0.25-0.75 mm	1.0-3.0 mm	$2d_{pin}$-$6d_{pin}$	20-45 deg	15-75 deg	3–7	1D-5D mm

[1] Robey, E. H., Ramesh, S., Sabau, A. S., Abdoli, A., Black, J. B., Straub, D. L., & Yip, M. J. (2022). Design Optimization of an Additively Manufactured Prototype Recuperator for Supercritical CO2 Power Cycles. *Energy*, *251*, 12.

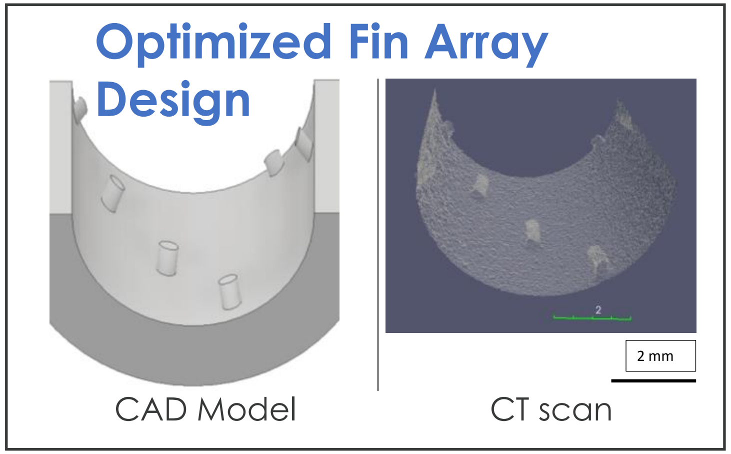
Parametric 3D-CFD Optimization

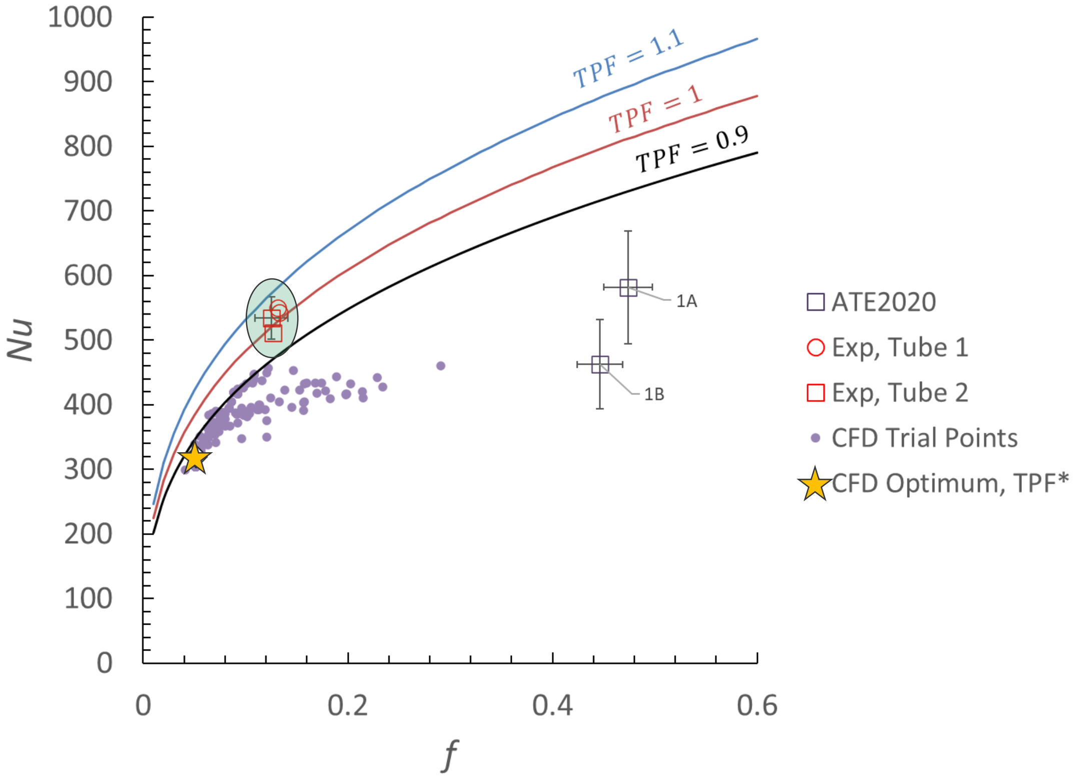
Heat Transfer Performance Details

AM "optimization-inspired" design tested at condition

- 14% improvement in Nu relative to CFD
- Friction factor decreased 4x relative to baseline

$$TPF = (Nu/Nu_0)/(f/f_0)^{1/3} \qquad TPF^* = \frac{TPF}{\frac{fin\ volume}{length}}$$





Machine Learning Application

sCO_2 Turbine Cooling

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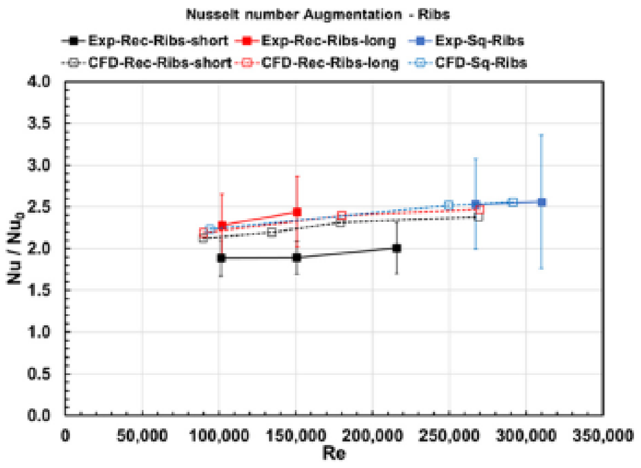
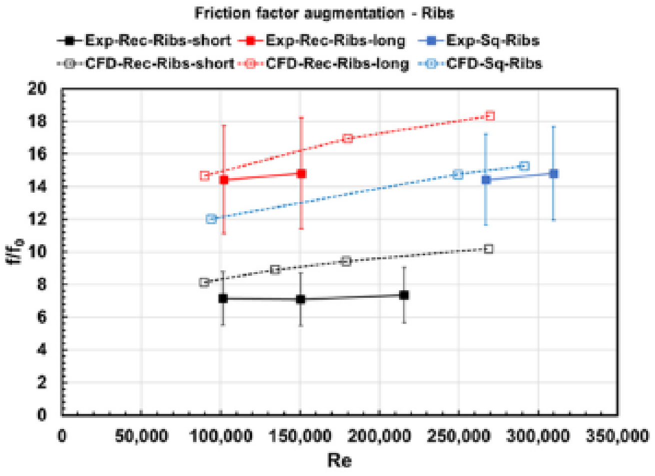
Background

- Blade/vane cooling is required in direct-fired cycle [1]
- Classic rib cooling technologies perform better in CO_2 than in air*[2]
- New datasets and correlations are needed
- ML models can guide and supplement the experimental approac'-

  * at matched conditions





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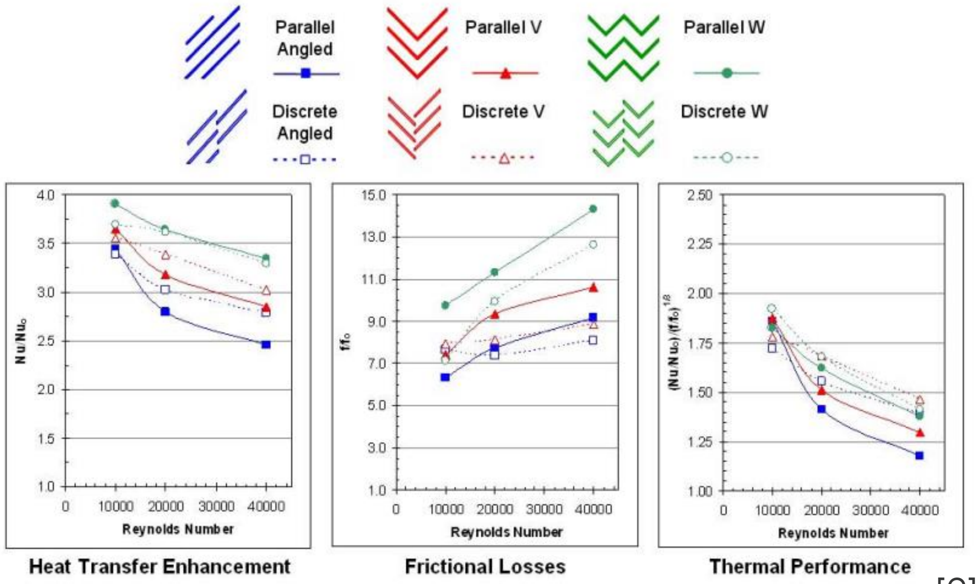


[2]

[1] Uysal, S. C., et al. (2022). "Cooling analysis of an axial turbine for a direct fired sCO2 cycle and impacts of turbine cooling on cycle performance." Energy Conversion and Management **263: 115701.**
[2] A. Roy, M. Searle, S. Ramesh, D. Straub. "Investigation of Gas Turbine Internal Cooling Using Supercritical CO2—Effect of Surface Roughness and Channel Aspect Ratio," Journal of Engineering for Gas Turbines and Power, 144(November 2022) 111019.
[3] J-C Han, L. M. Wright, 4.2.2.2 "Enhanced Internal Cooling of Turbine Blades and Vanes," Gas Turbine Handbook. NETL. 2006

Machine Learning Applications

sCO_2 Turbine Cooling

HEET ML heat exchanger model

- Large dataset: 4,000+ operational hours

Screened

- Gaussian process regressor
- Gradient boosting regressor
- **Multi-layer perceptron regressor (selected)**

Implementation

- Scikit-learn in Python
- Five layers with 100 neurons

Applications

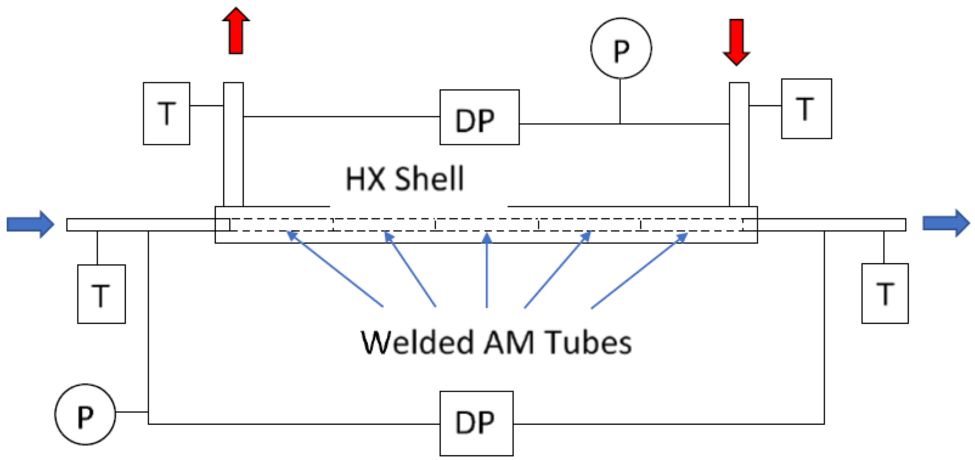
- Test plan development
- Virtual experiments
- Surrogate model for optimization

Inputs

- Tube and shell inlet temperature and pressure
- Tube and shell mass flow rates
- Tube feature parameters

Outputs

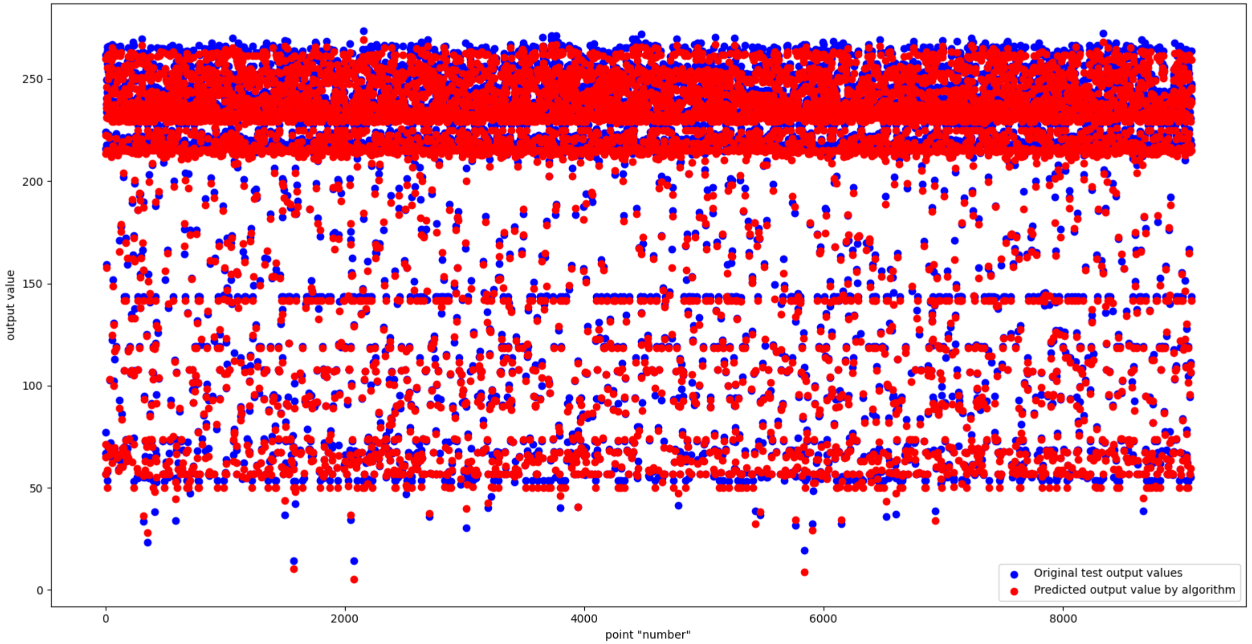
- Tube and shell outlet temperature
- Tube pressure drop



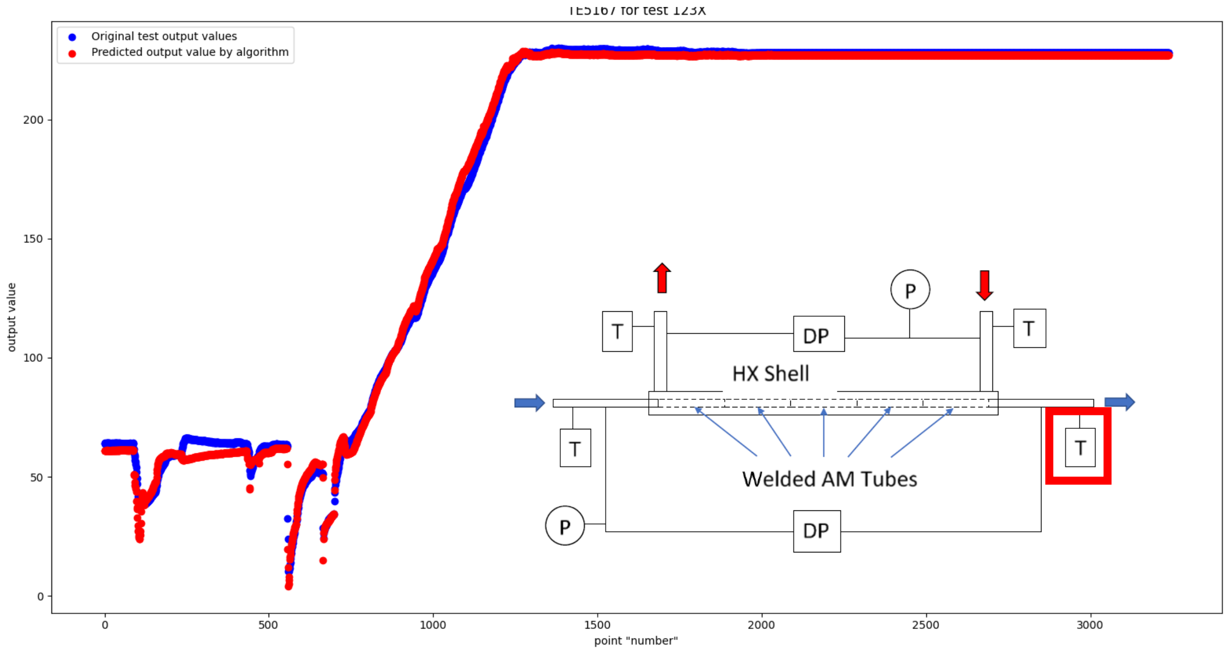
Machine Learning Applications

Tube Outlet Temperature

Training Data



Test Data

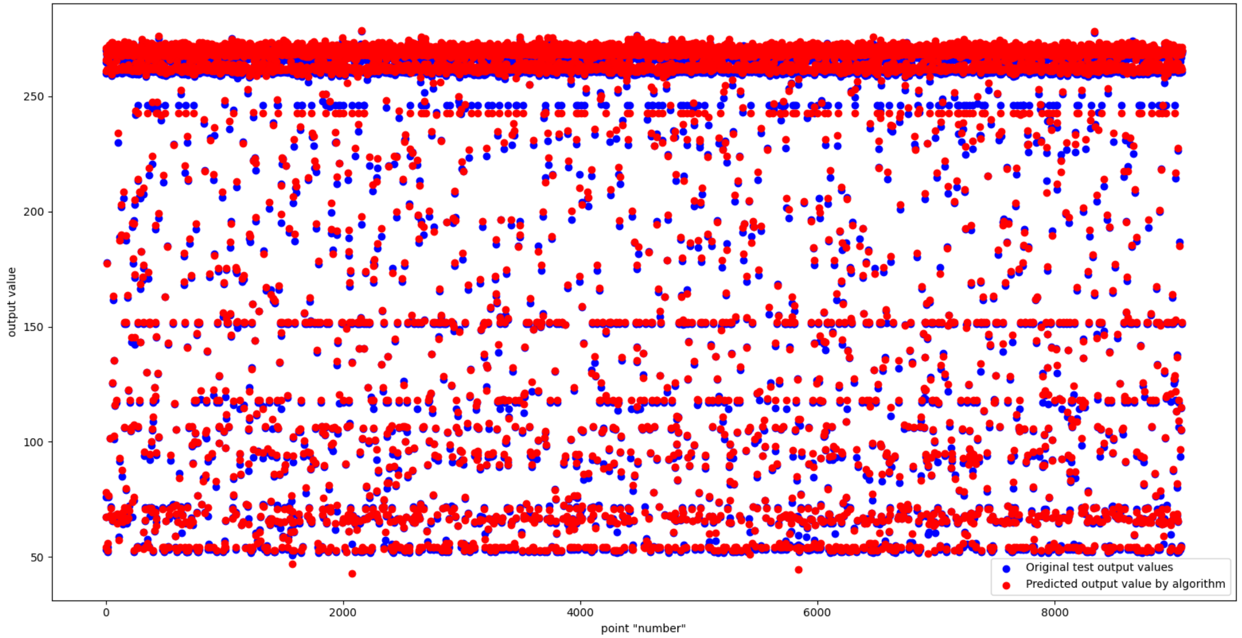


	Training	Test
R^2	0.998	
Mean absolute error	2.2 °F	2.2 °F
Max absolute error	12.9 °F	17.5 °F

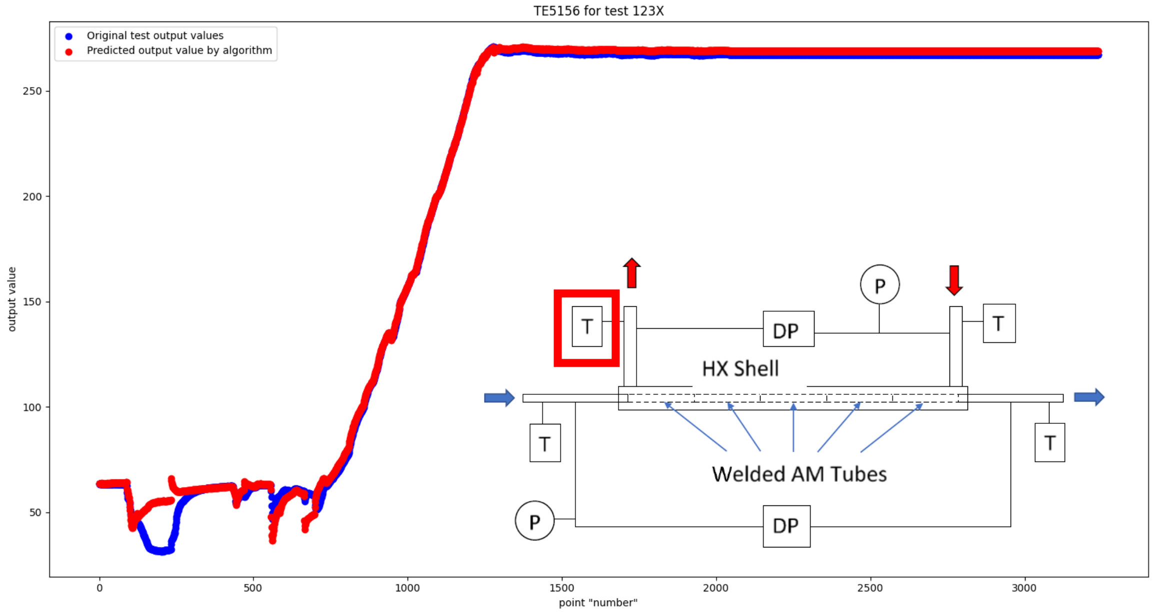
Machine Learning Applications

Shell Outlet Temperature

Training Data



Test Data



	Training	Test
R^2	0.9995	
Mean absolute error	1.38 °F	2.5 °F
Max absolute error	14.9 °F	31.3 °F

Trans-critical CO_2 Cycles

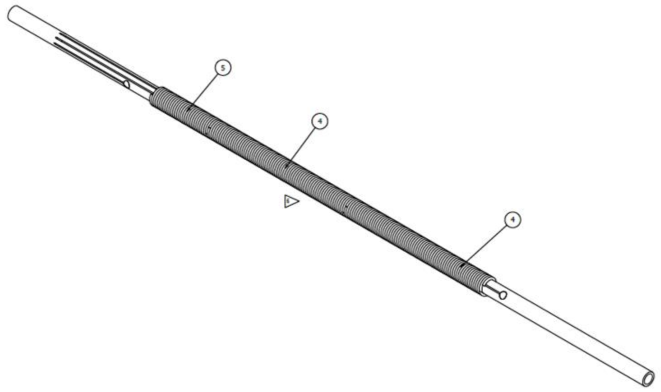
Enabling Higher Efficiency, Flexible Heat Source Power Cycles

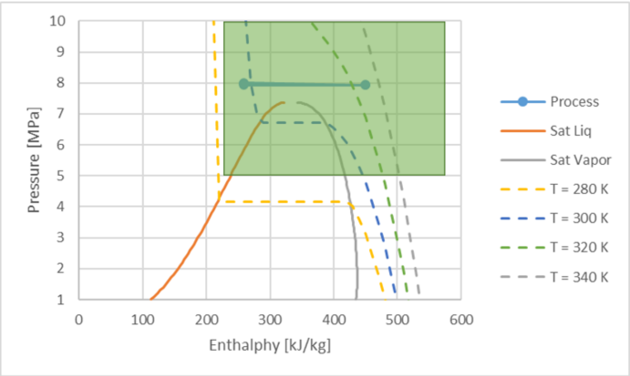
Background

- Condensing operation is an option to minimize cost of electricity (COE) and maximize power generation in sCO_2 cycles [1]
- Heat exchange enhancement technologies may be applied via AM in evaporators/boilers, condensers, and intercoolers

Design Status

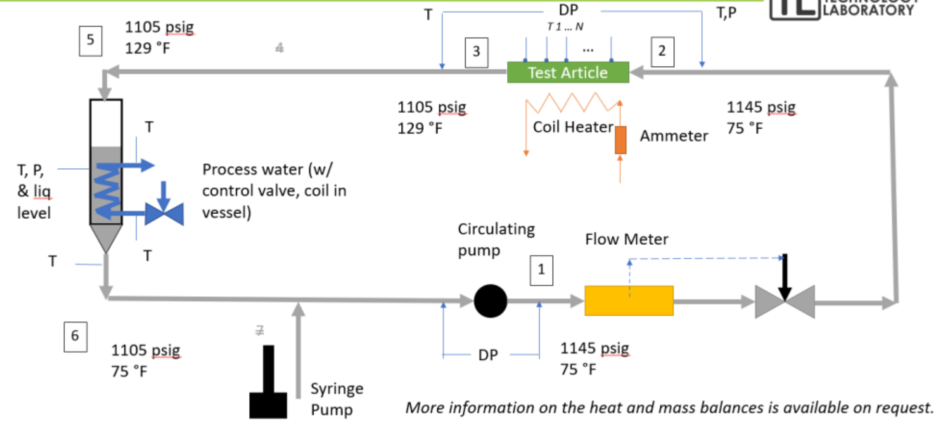
- Rig design underway with contractor
- Phase-change test article design complete





Operational envelope

Concept Drawing



More information on the heat and mass balances is available on request.

[1] Liese, E. and S. Pidaparti (2023). Modeling a water-cooled printed circuit heat exchanger condensing CO2 for use in sCo2 cycle system optimization studies. Proceedings of Turbo Expo 2023, Boston, Massachusetts, ASME, 102269.

Task 2 : EY23 Milestones/Deliverables

sCO_2 Heat Transfer

Expected Completion Date	Description	Status
12/30/2023	2.1.1. Improve design models and correlations for direct cycle main cooler, including gas composition effects	In progress
1/31/2024	2.1.2. Utilize machine learning (CFD and experimental data for training) to design at least one heat transfer enhancement feature for primary cooler application at direct sCO_2 cycle conditions	In progress
3/31/2024	2.1.3. Evaluate liquid CO_2 heat transfer and pressure drop behavior	Rig design and commissioning started

Conclusions

- AM roughness and rib turbulators enable more effective sCO_2 coolers
- Trace argon and nitrogen negligibly impact heat exchanger performance
- Deviation from design intent and surface roughness resulted in a recuperator tube design with 14% increase in Nu relative to CFD. f decreased by a factor of 4.
- A multilayer perceptron regressor has been trained to guide heat exchanger experiments

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