Increasing Main Cooler Thermal Performance for sCO_2 Power Cycles

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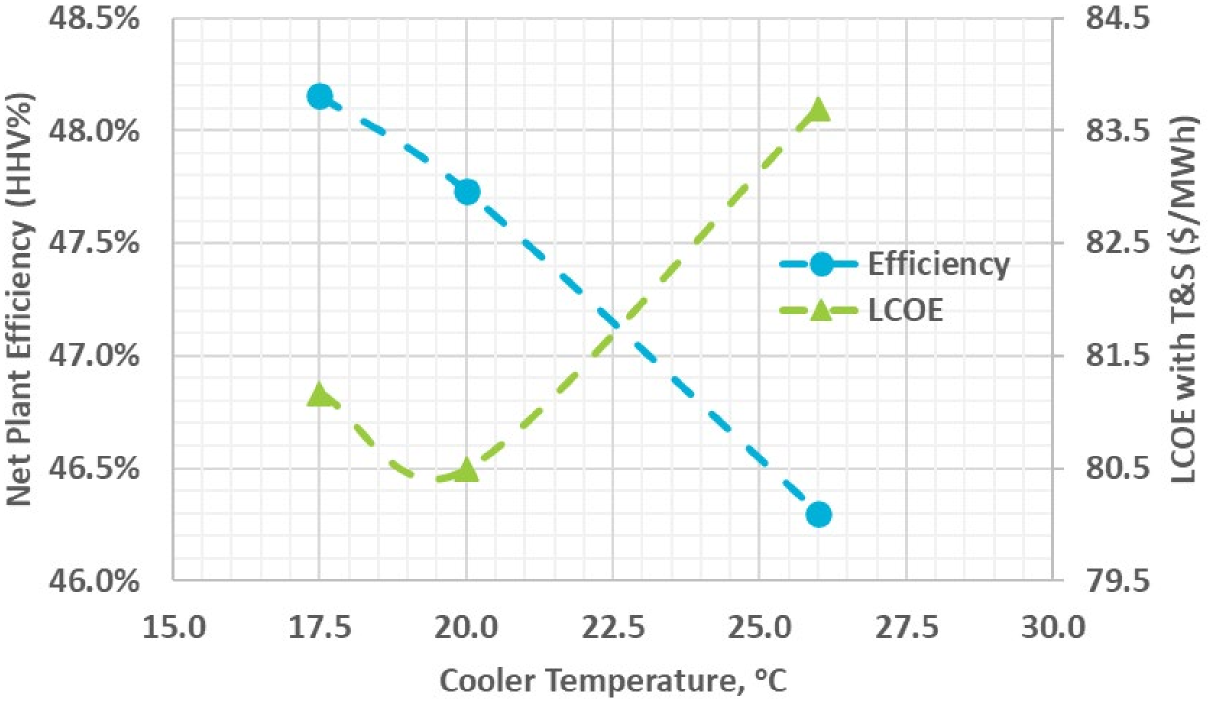
Introduction and Motivation

- sCO_2 power cycle performance is highly dependent on ambient temperature (Wright, 2011; Conboy, 2015).
- Reducing CO_2 cooler outlet temperature increases cycle efficiency and lowers levelized cost of electricity (LCOE) (Pidaparti, 2020).
- Heat transfer enhancement integrated via monolithic additive manufacturing (AM), is a pathway to lower cost heat exchangers.
- AM heat exchangers may be cost competitive with printed circuit heat exchangers (PCHE) for small-duty applications (Robey, 2022).



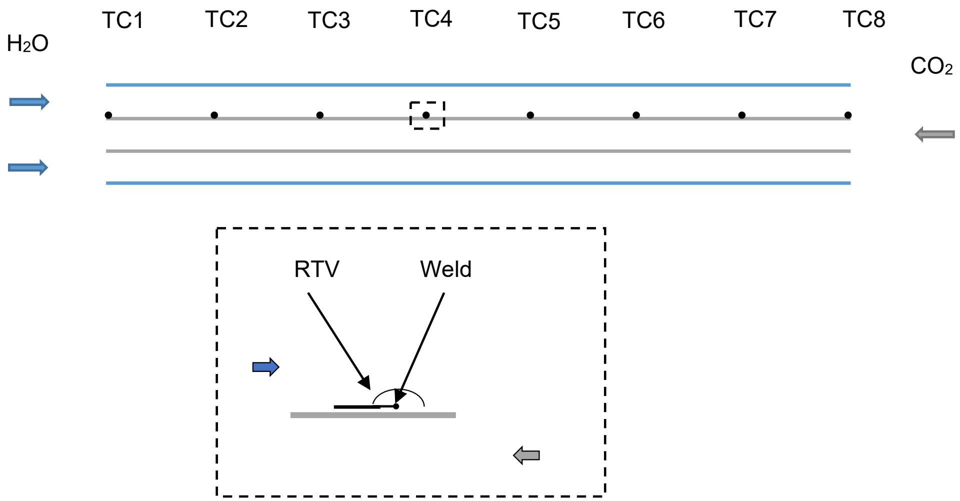
(Pidaparti, 2022)

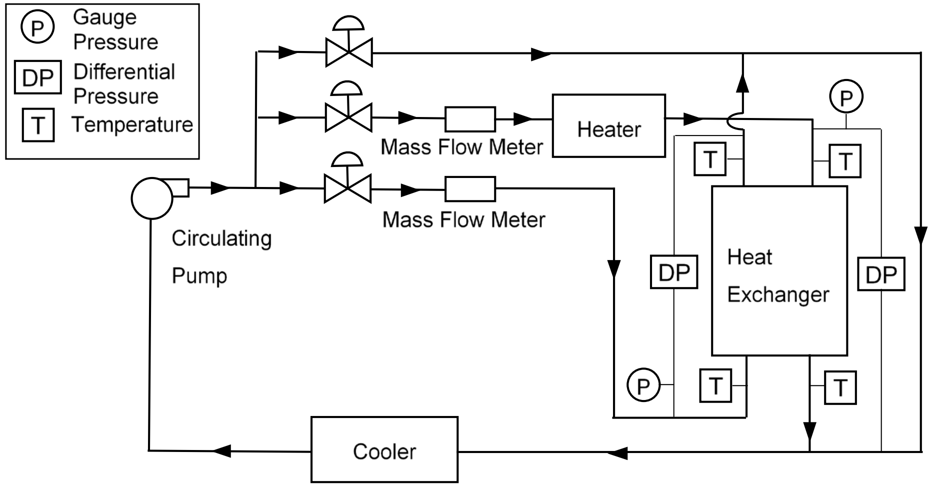
6 °C reduction* -> + 1.4% point in efficiency
- 3.8% in LCOE

* *Provided effective cooler and heat rejection temperature*

Materials and Methods

- Shell and tube heat exchanger constructed with conventional tube.
- Inlet flows instrumented with mass flow, pressure, and temperature.
- Outlet flows instrumented with temperature and differential pressure.
- Wall temperature measurements on shell side.



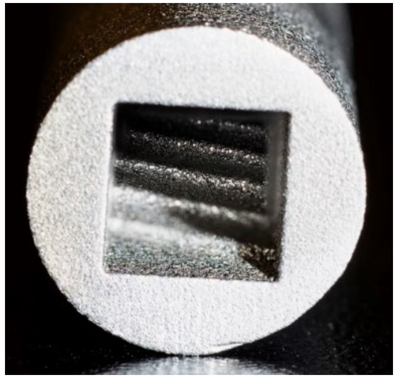


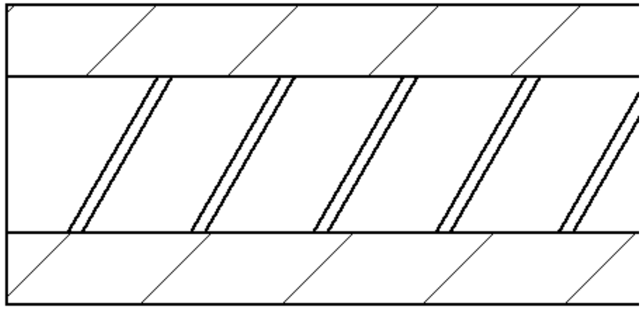
CO_2 (Tube)		
Inlet Temperature (K)	$T_{t,i}$	349.8
Inlet Pressure (MPa)	$P_{t,i}$	8
Mass Flow Range (kg/s)	$\dot{m}_t$	0.0089 to 0.015
Reynolds Number Range, (-)	Re_t	8×10^4 to 1.3×10^5
Water (Shell)		
Inlet Temperature (K)	$T_{s,i}$	289
Inlet Pressure (MPa)	$P_{s,i}$	0.136
Mass Flow Range (kg/s)	$\dot{m}_s$	0.016–0.126

Test Articles

- Script reduces data to determine local heat transfer coefficients.
  - Assumption of uniform heat flux (see the following slide on approach verification).
  - Heat duty calculated from inlet and outlet conditions. Friction factor from pressure drop.
  - Uncertainty analysis by Kline and McClintock approach.
- Two test articles:
  - Conventional commercial tubing.
  - Additively manufactured (AM) tubing with square cross-section and rib turbulators.

Parameter	Symbol	Value
Heat Exchanger Length	L	1.04 m
Conventional Tube Outer Diameter	OD	9.5 mm
Conventional Tube Hydraulic Diameter	D_h	7.04 mm
Square Tube Inner Hydraulic Diameter (side wall length)	D_h	4.98 mm
Rib Height	e	0.39 mm
Rib Angle	α	60°
Rib Pitch to Height	P/e	10
Rib Height to Hydraulic Diameter	e/D_h	0.078

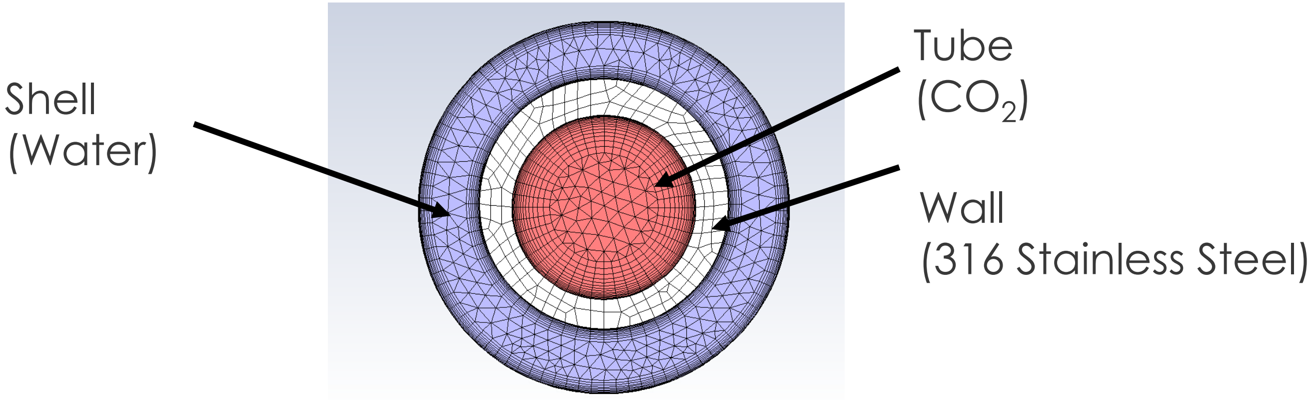


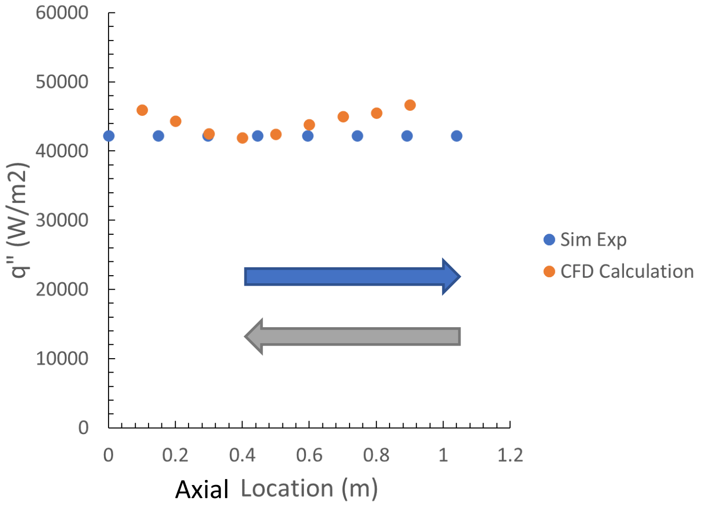


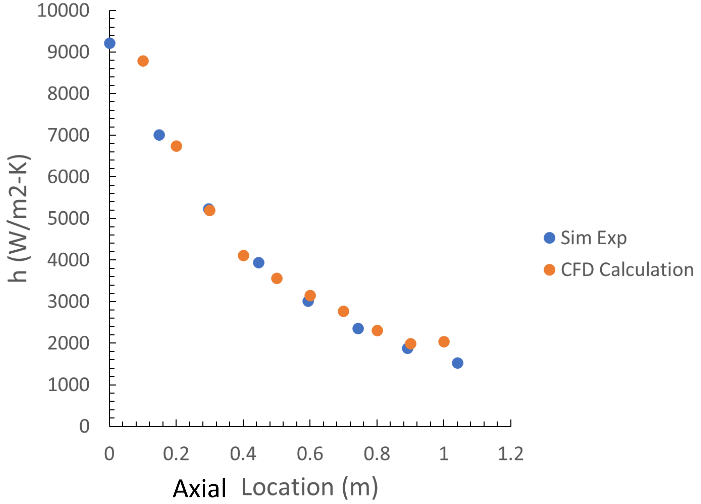
Verification of Test Approach

Uniform Heat Flux Assumption

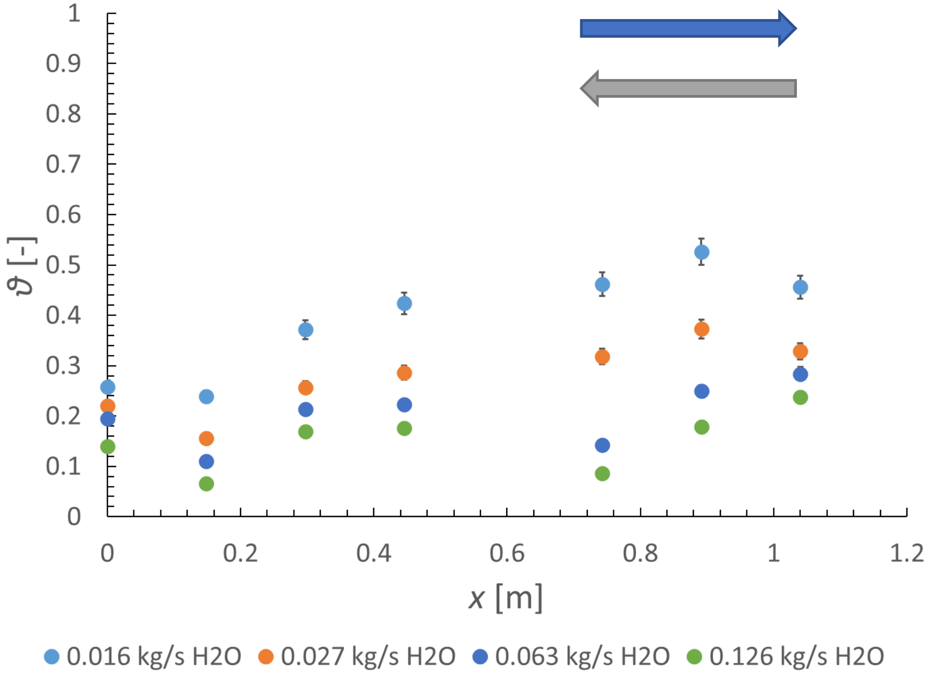
- Full conjugate model: convection in shell (water) and tube (CO_2) and conduction in wall (316 Stainless Steel).
- Reynolds averaged Navier Stokes (RANS).
- k-ω shear stress transport (SST) turbulence model.
- REFPROP 10.0 property data provided at 50 points spanning temperature range in CO_2.
- 0.5 mm mesh (heat transfer coefficient resolved to within 1.6%).
- Inlet/outlet conditions and geometry match experiments.
- Adiabatic shell outer wall. No axial heat flux in pipe at inlet/outlet.



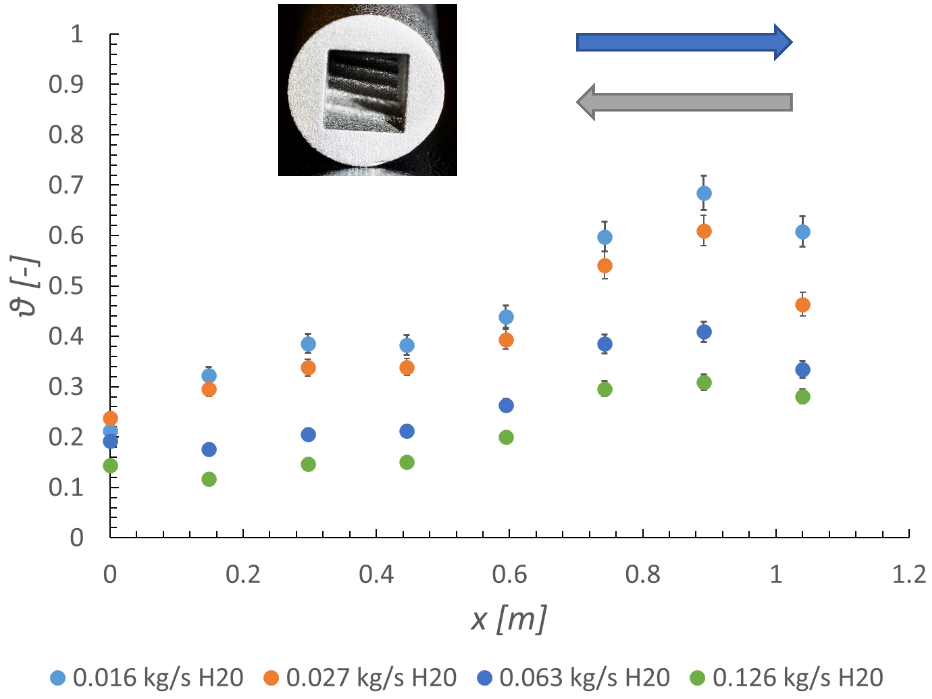




Local Surface Temperatures



Smooth conventional tube



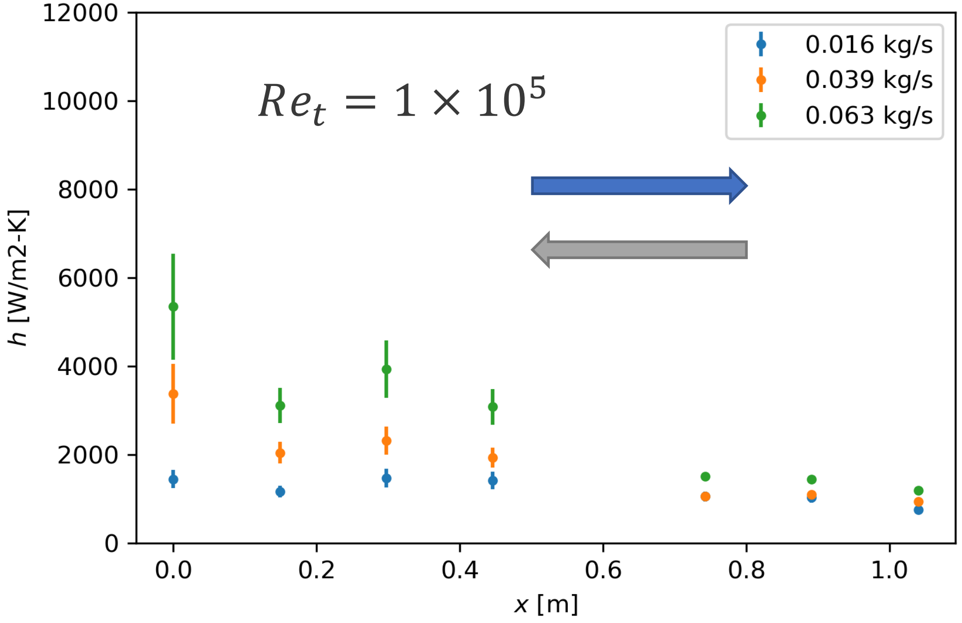
Square tube with ribs

$$\theta_w = \frac{T_w - T_{s,i}}{T_{t,i} - T_{s,i}}$$

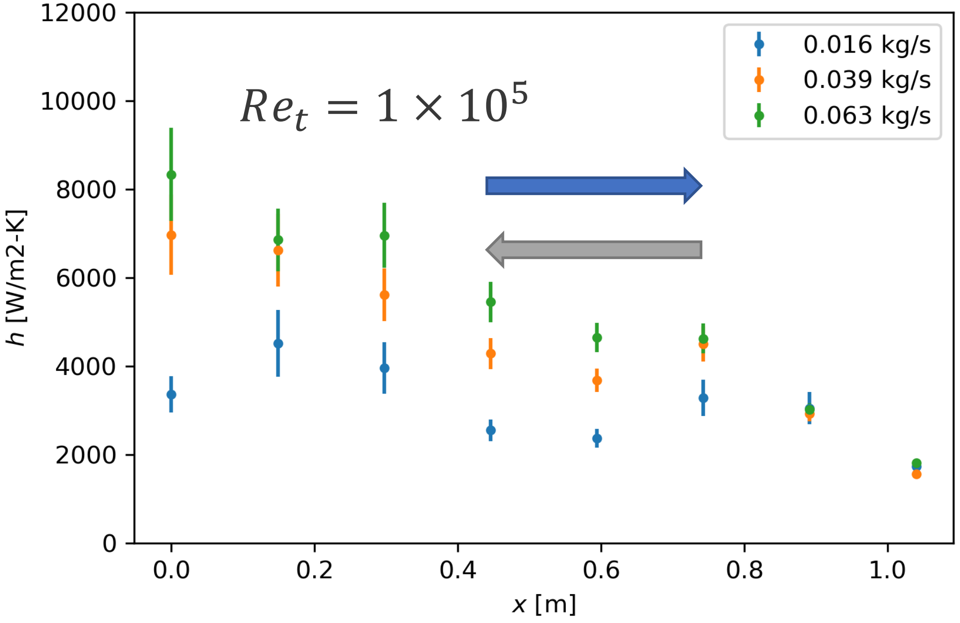
$$Re_t = 1 \times 10^5$$

30% increase in θ_w (decrease in T_w) for $x > 0.6$ m

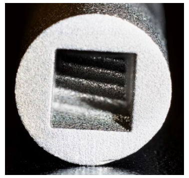
Local Heat Transfer Coefficients



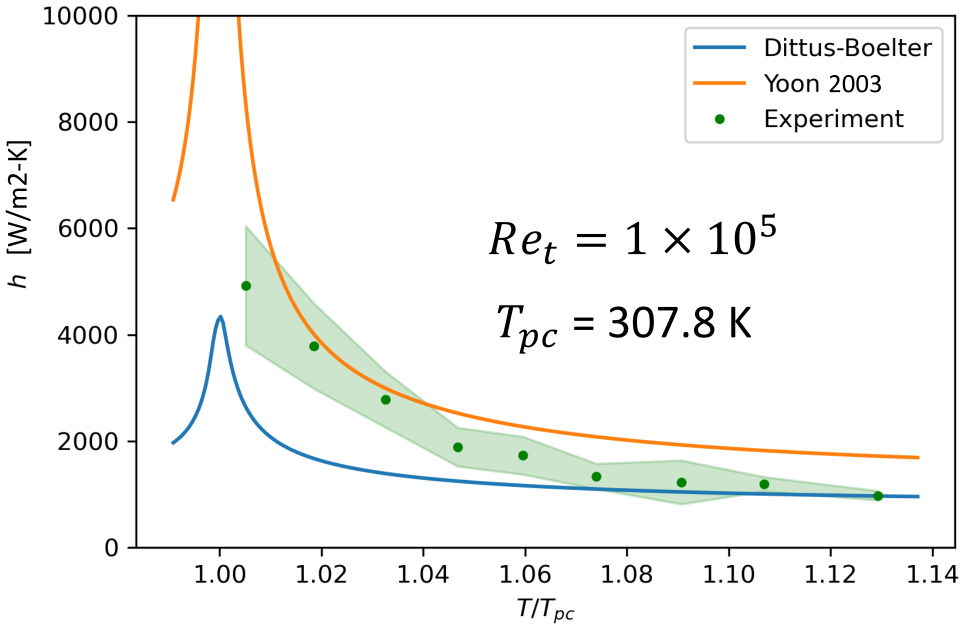
Smooth conventional tube



Square tube with ribs



Comparison to Correlation



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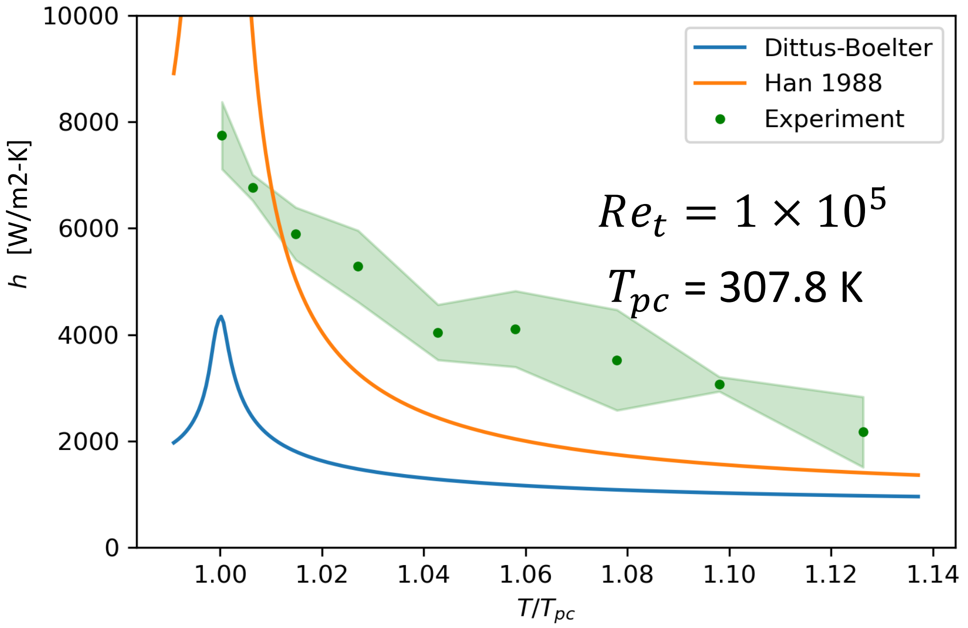
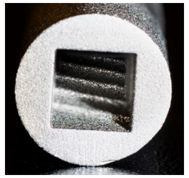


Square tube with ribs



$$Nu_b = 0.023\, Re^{0.8}\, Pr^{n}$$

Dittus-Boelter

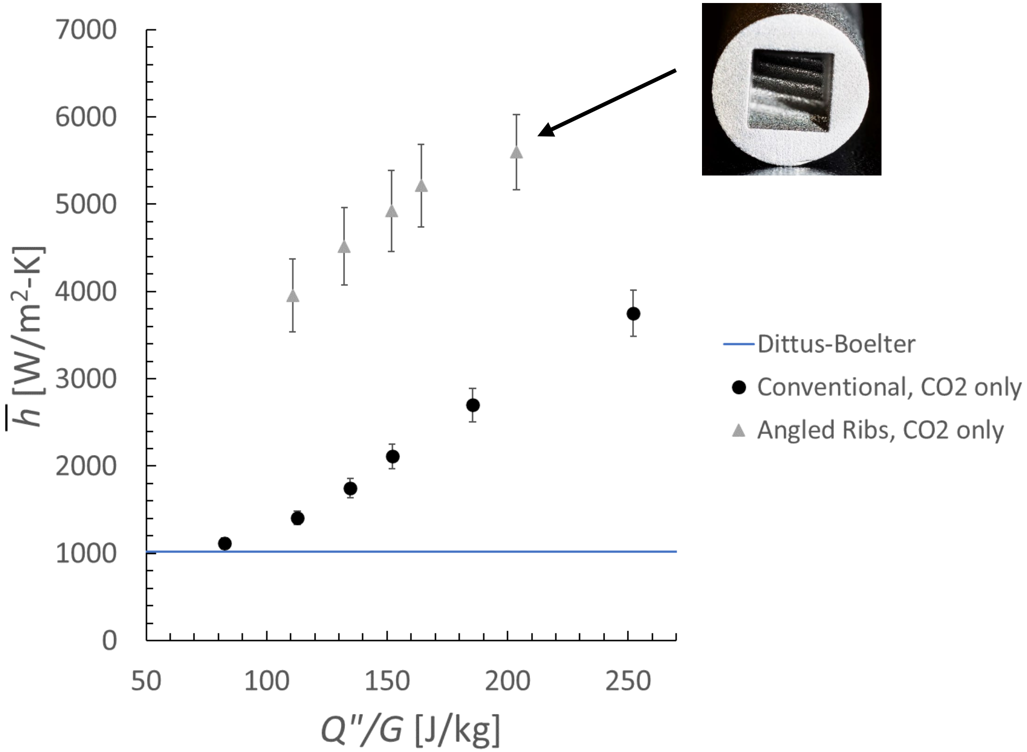
$$\mathrm{Nu_b} = \begin{cases} 0.14\, \mathrm{Re_b}^{0.69}\, \mathrm{Pr_b}^{0.66}, \dfrac{\mathrm{T_{pc}}}{\mathrm{T_b}} < 1 \\ 0.013\, \mathrm{Re_b}\, \mathrm{Pr_b}^{-0.05} \left(\dfrac{\rho_{pc}}{\rho_b}\right)^{1.6}, \dfrac{\mathrm{T_{pc}}}{\mathrm{T_b}} \geq 1 \end{cases}$$

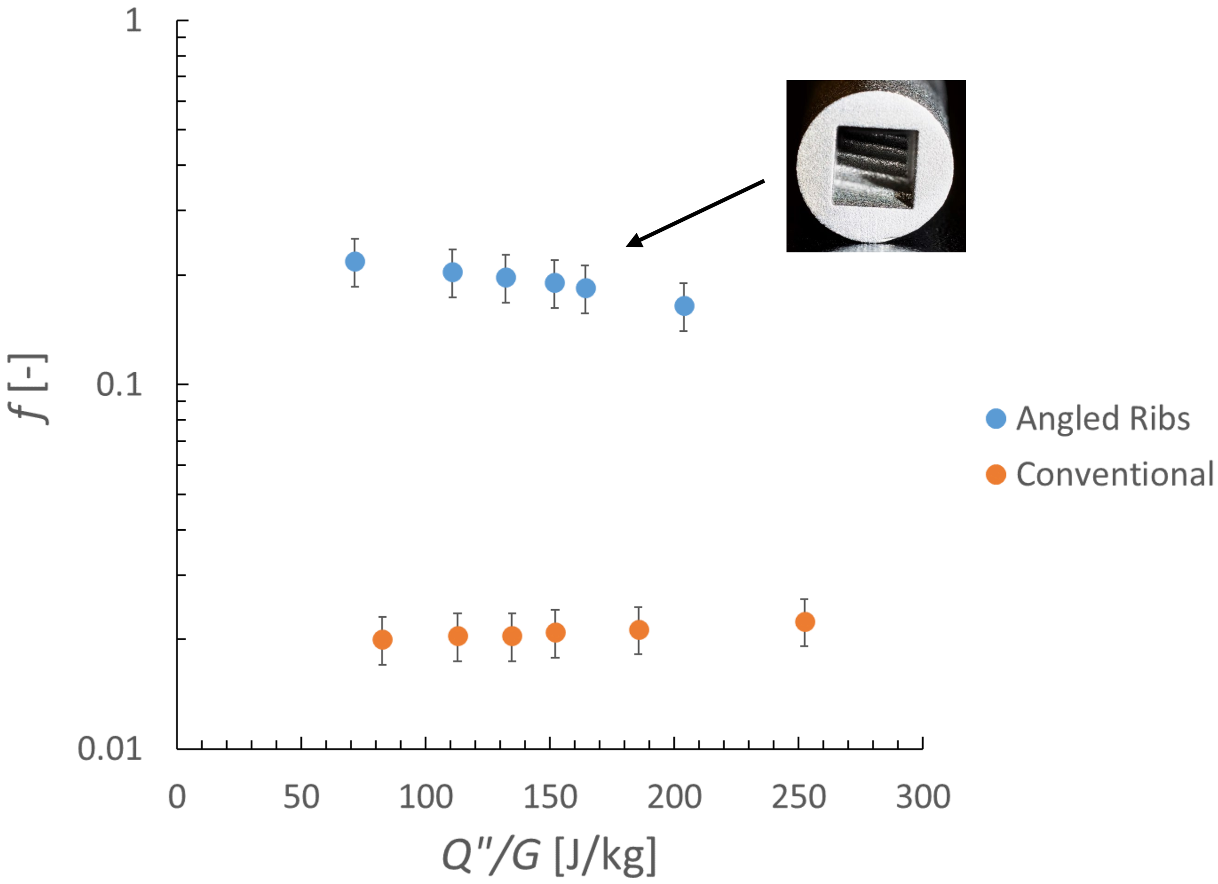
Yoon (2003)

$$St_{r2} = \frac{f_{r4}}{2 \cdot \left\{ \left[G(e^{+}) - R(e^{+}) \right] \cdot \sqrt{\dfrac{f_{r4}}{2}} + 1 \right\}}$$

Han & Park (1988)

Average Heat Transfer Coefficient, $\bar{h}$, and Friction Factor, f, Results



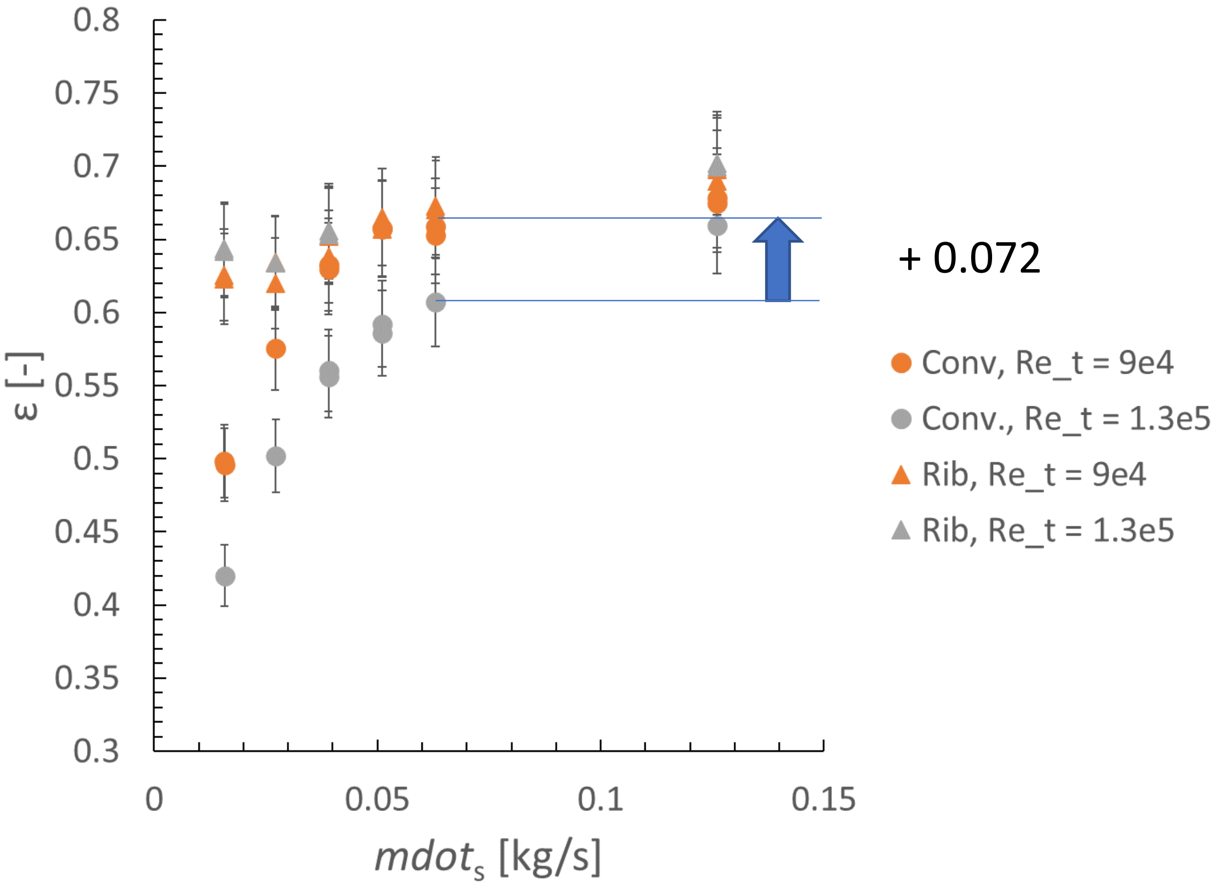


Q'', tube wall heat flux
G, tube mass flux

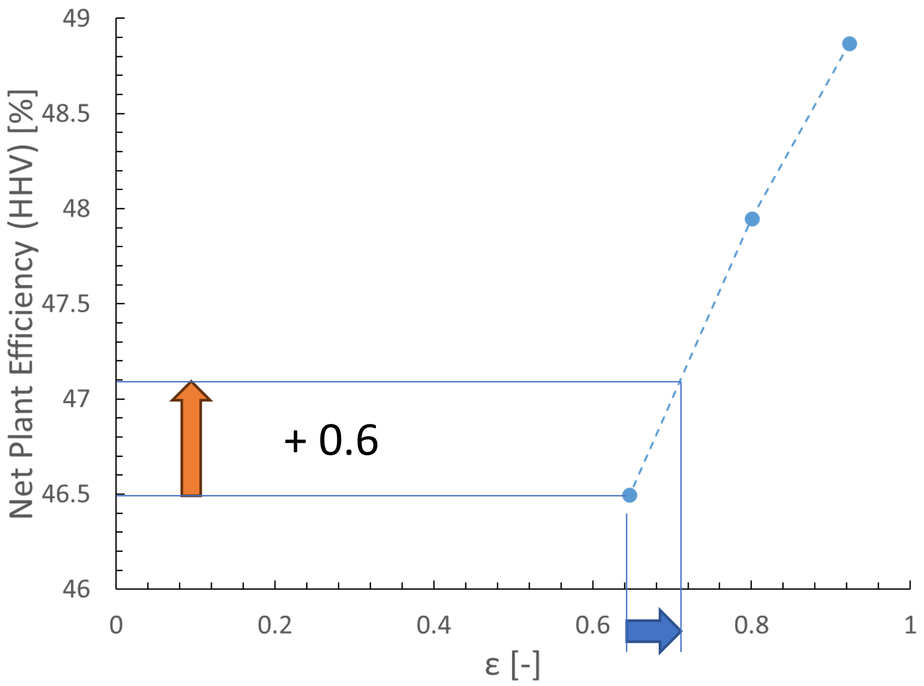
$$Re_t = 1 \times 10^5$$

$\bar{h}$ increases by 70% to 180%

Heat Exchanger Effectiveness and Cycle Efficiency



$$\varepsilon = (T_{t,i} - T_{t,o})/(T_{t,i} - T_{s,i})$$



+ 0.072

Data adapted from Pidaparti (2022)

+13% (0.072) in ε -> + 0.6% point in cycle efficiency

Conclusions

- For $T/T_{pc} < 1.05$, Yoon correlation was more accurate than Dittus-Boelter.
- Angled rib tubes had 70% to 180% larger average heat transfer coefficient than smooth tube.
- Heat exchanger effectiveness due to angled rib turbulators was greater at low water flow rates and high sCO_2 flow rates.
- Angled ribs yielded a 13% increase in heat exchanger effectiveness (0.072 increment) at tube Reynolds number equal to 1.3×10^5.
- The 0.072 increment in effectiveness yields 0.6% point improvement in cycle efficiency.

Acknowledgments

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