Analysis of Supercritical CO_2 Brayton Cycle Recuperative Heat Exchanger Size and Capital Cost with Variation of Layout Design

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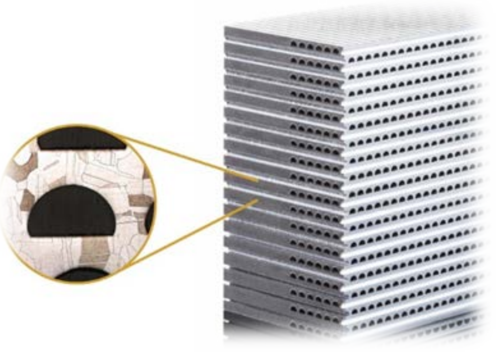
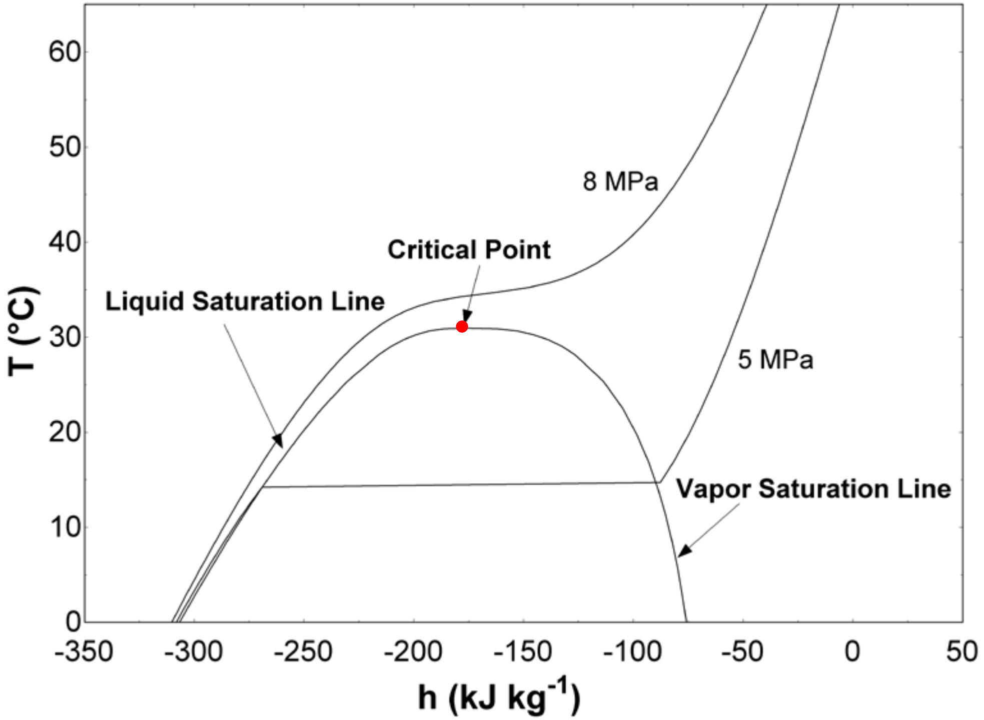
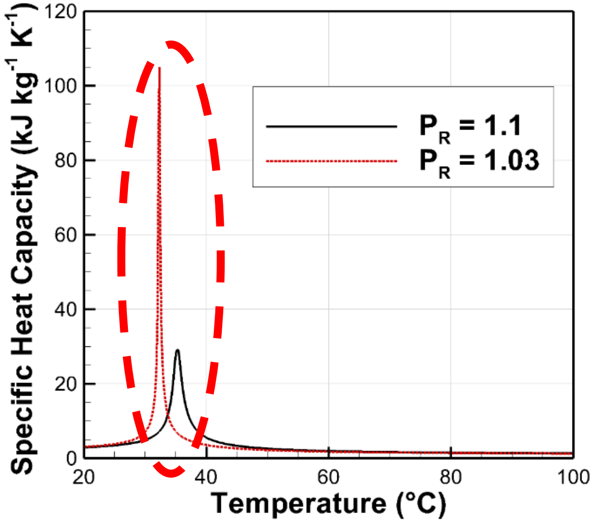


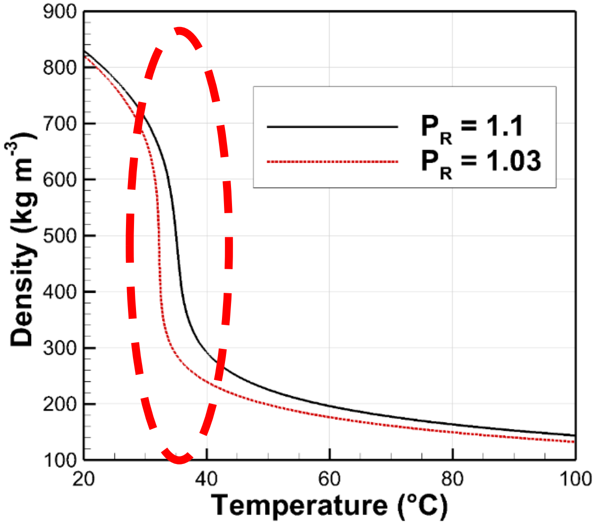
What is Supercritical CO_2?

$T_{critical}$ (°C/°F)	$P_{critical}$ (MPa/kPSI)
31.0 / 87.9	7.4 / 1.1



Span and Wagner (1996)





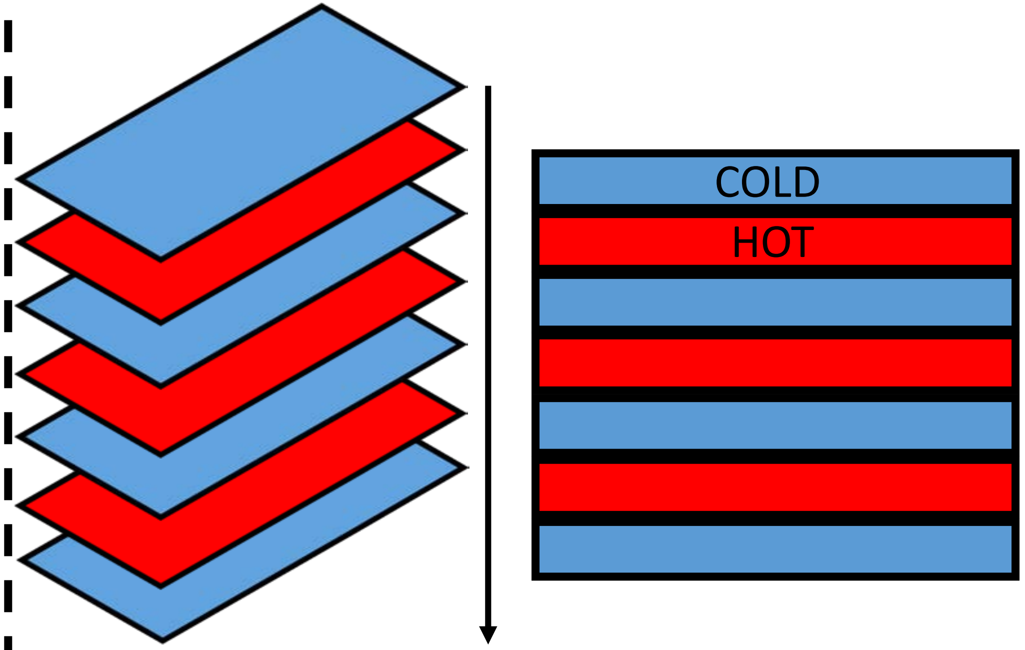
Brayton Cycle Heat Exchangers

Cycle Type	Compressors	Turbines	Recuperators	Coolers	IHXs
Simple Recuperative	1	1	1	1	1
Pre-Compression	2	1	2	1	1
Partial Cooling w/Improved Regen.	3	1	3	1	1
Cascaded Reheat	1	2	2	1	1
Recompression	1	1	2	1	1

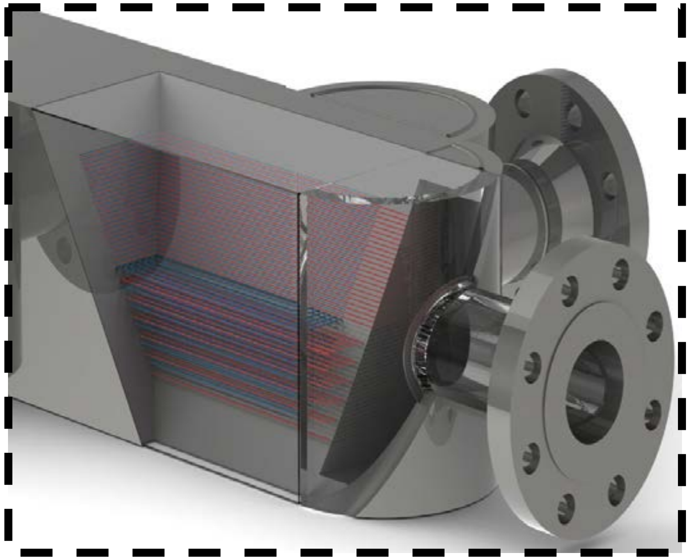
- Cycle layout variations can improve efficiency
- Can increase complexity and budget
- ***Size and capital cost of recuperative heat exchangers***

Angelino (1969)
Dostal *et al.* (2004)
Wright *et al.* (2010)
Conboy *et al.*(2012)
Iverson *et al.* (2013)
Ahn *et al.* (2015)

Printed-Circuit Heat Exchangers



Stack Platelets
ABAB . . . BABA



Diffusion Bonding Fabrication Technology

What:

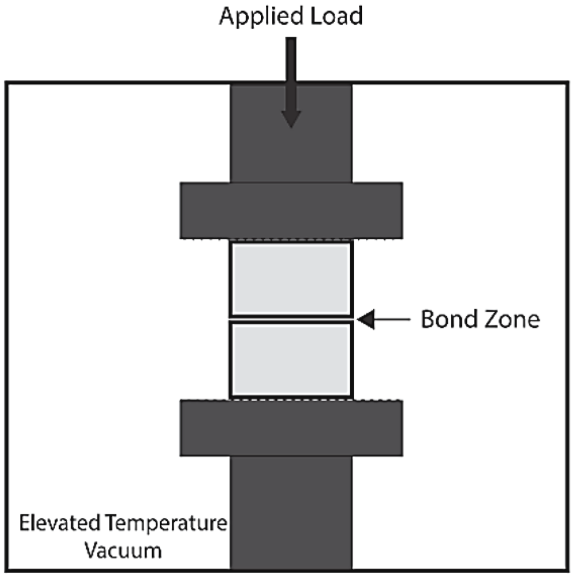
- Highly reliable, solid-state welding process
- No interface filler material needed

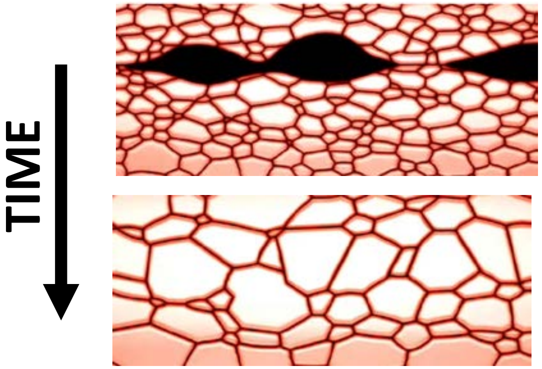
How:

- Controlled environment furnace promotes grain growth
- Dynamic, time-dependent load applied

Outcome:

- Achieved parent material strength
- ‘Welds’ all interfaces while preserving geometry

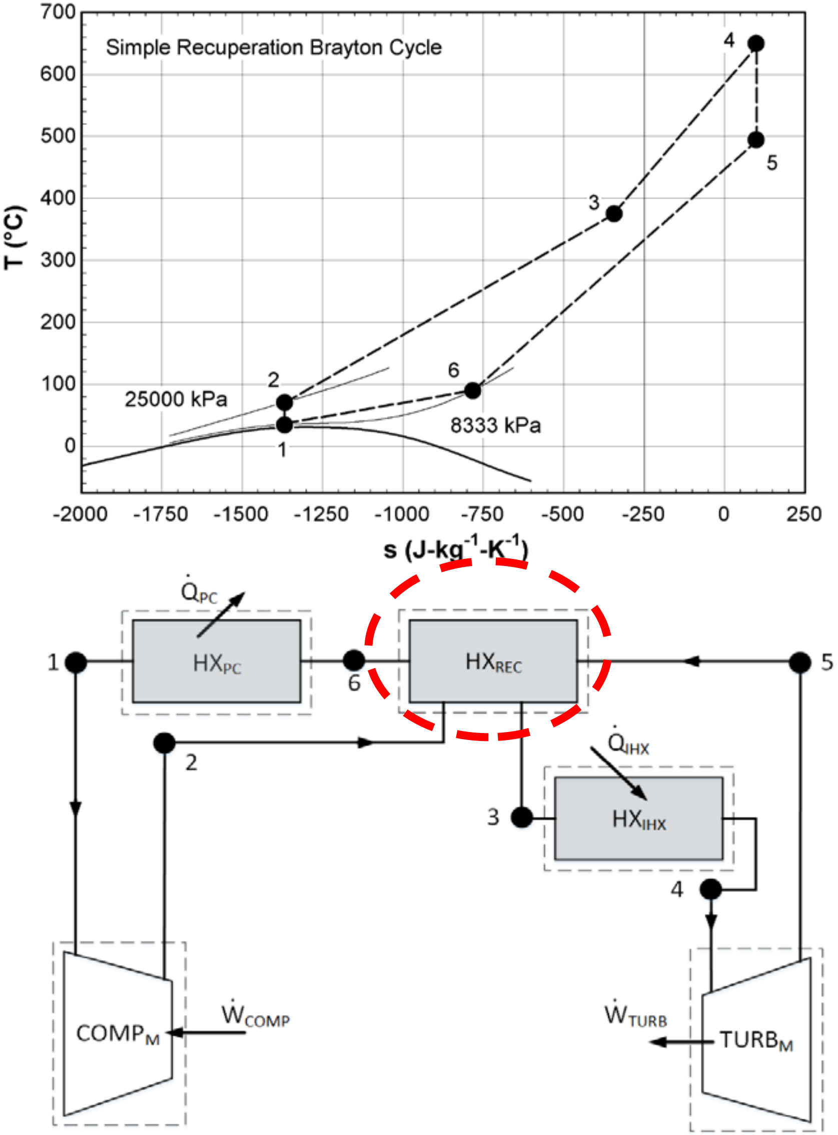




Agenda

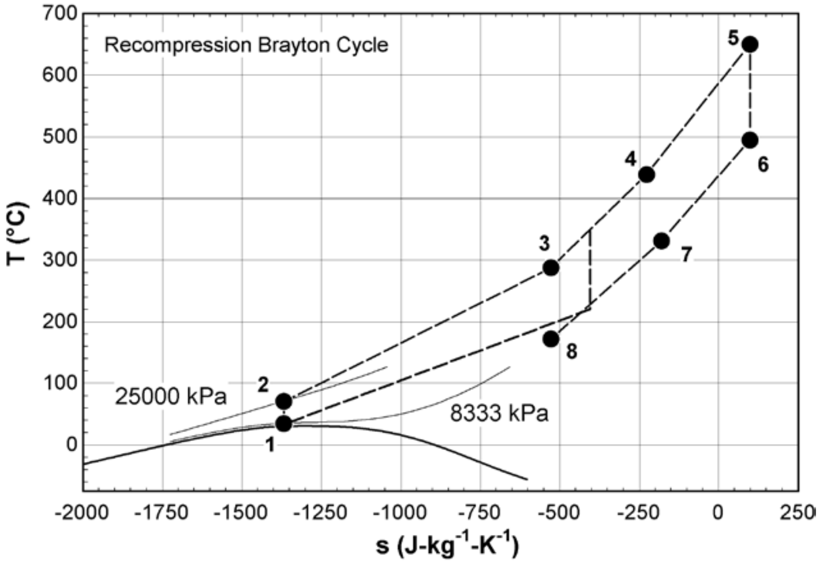
1. Introduction
2. Power Cycle Layouts
3. Modeling Approach and Methodology
4. Recuperative Heat Exchanger Cost Variables
5. Results and Discussion
6. Conclusions and Future Work

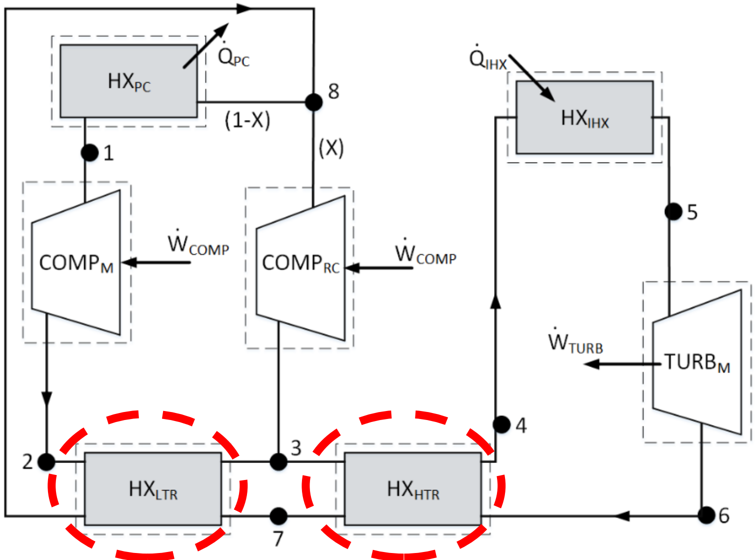
Simple Recuperative Brayton Cycle



- Simple layout
- Single recuperator
- Latent heat energy sources or heat flux sources

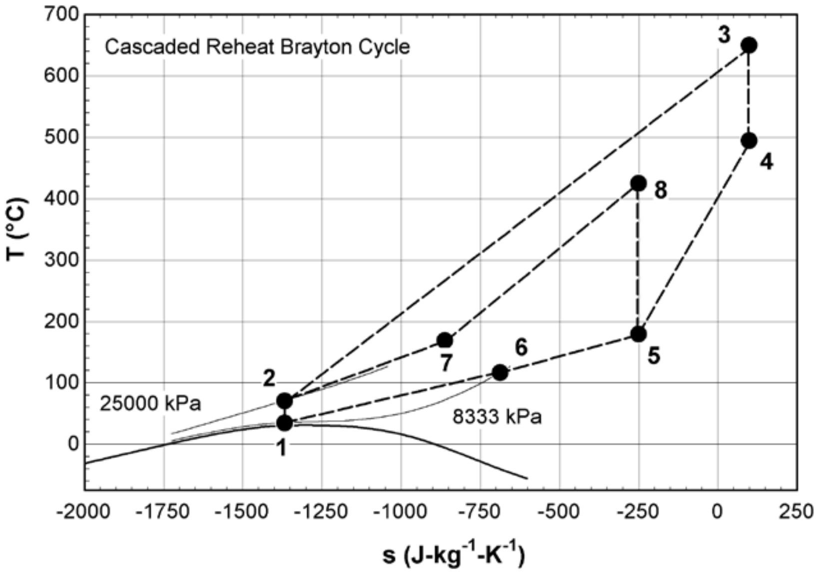
Recompression Brayton Cycle

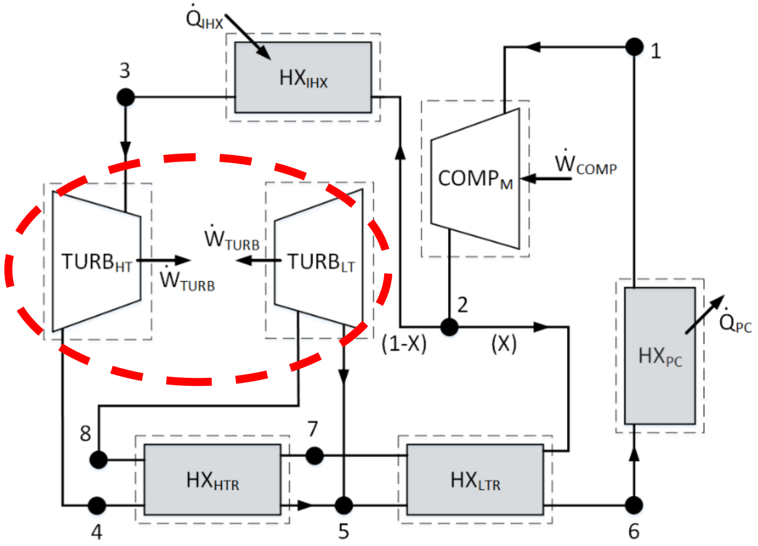




- Compression through two stages of compressors
- HTR and LTR heat recovery by splitting vastly different Cp
- Nuclear or solar thermal based heat flux sources

Cascaded Reheat Brayton Cycle





- Expansion through two stages of turbines
- Attempts to utilize all heat source energy
- Fossil fuel or waste heat

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Summary of Cycle Conditions and Assumptions

Variable	Simple	Recomp.	Casc. Reheat
Power Output (MW_{th})	50 MW_{th}		
Turbine Power Percentage (%)	100%	Split & Varied	
Thermal Efficiency (%)	Calc., 45%		
sCO_2 Flow Rate ($kg\text{-}s^{-1}$)	Calculated		
Turbine Inlet Temperature (^oC)	650 ^oC		
Compressor Inlet Temperature (^oC)	35 ^oC		
Compressor Outlet Pressure (MPa)	25 MPa		
Compressor Ratio (-)	3.0		

- *Engineering Equation Solver* (EES) platform V.10.295-3D (Klein 2017)
- EOS for CO_2 as developed by Span and Wagner (1996)
- Negligible: ΔP, *PE*, *KE*
- Isentropic efficiency = 100% (ideal)

Methodology

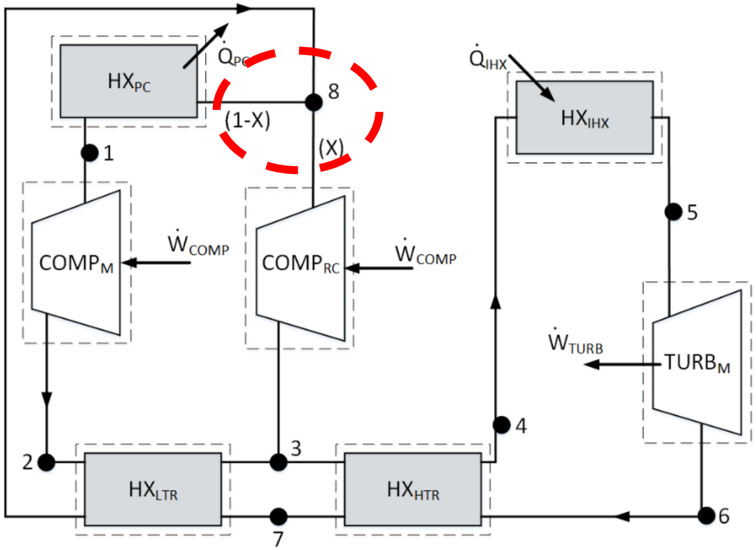
$$\eta_{cycle} = 100 \times \left(\frac{\sum \dot{W}_{TURB} - \sum \dot{W}_{COMP}}{\dot{Q}_{IHX}} \right)$$

$$\cancel{\frac{dE_{CV}}{dt}} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum \dot{m} \left(h_i + \cancel{\frac{V_i^2}{2}} + \cancel{gZi} \right) - \sum \dot{m} \left(h_o + \cancel{\frac{V_o^2}{2}} + \cancel{gZ_o} \right)$$

$$\dot{W}_{TURB} = \dot{m} \times (h_i - h_o)$$

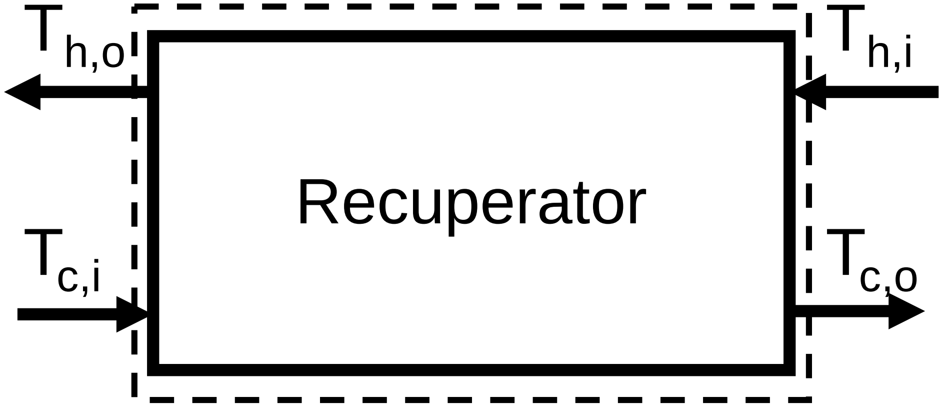
$$\dot{W}_{COMP} = \dot{m} \times (h_o - h_i)$$

$$\dot{Q}_{IHX} = \dot{m} \times (h_o - h_i)$$



Methodology Cont'd

$$\dot{Q}_{REC,h} = \dot{m} \times (hi - ho)$$
$$\dot{Q}_{REC,c} = \dot{m} \times (ho - hi)$$
$$\dot{Q}_{REC,h} = \dot{Q}_{REC,c}$$



$$\dot{Q}_{REC} = UA_{REC} \times LMTD$$

$$\dot{Q}_{REC} = UA_{REC} \times \left(\frac{(T_{h,o} - T_{c,i}) - (T_{h,i} - T_{c,o})}{\ln\left(\frac{(T_{h,o} - T_{c,i})}{(T_{h,i} - T_{c,o})}\right)} \right)$$

$$\varepsilon = \frac{\dot{Q}_{actual}}{\dot{Q}_{maximum}} = \frac{h_{h,i} - h_{h,o}}{h_{h,i} - \boxed{h^*_{c,i}}} \longrightarrow h^*_{c,i} = f(T_{c,i}, P_h)$$

Sharma *et al.* (2017)

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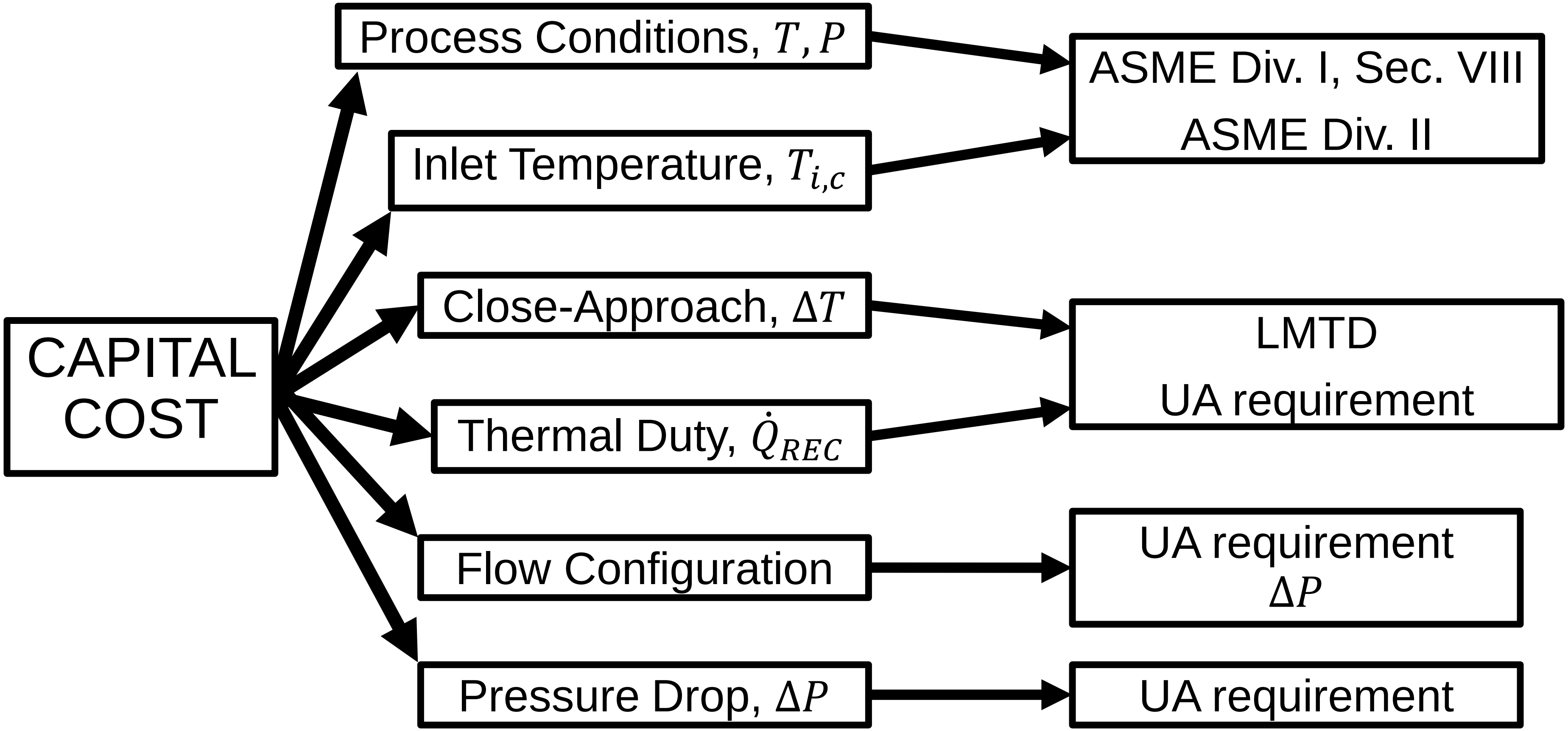
Heat Exchanger Capital Cost Variables



CAPITAL COST

Process Conditions, T, P

Inlet Temperature, $T_{i,c}$

Close-Approach, ΔT

Thermal Duty, $\dot{Q}_{REC}$

Flow Configuration

Pressure Drop, ΔP

ASME Div. I, Sec. VIII

ASME Div. II

LMTD

UA requirement

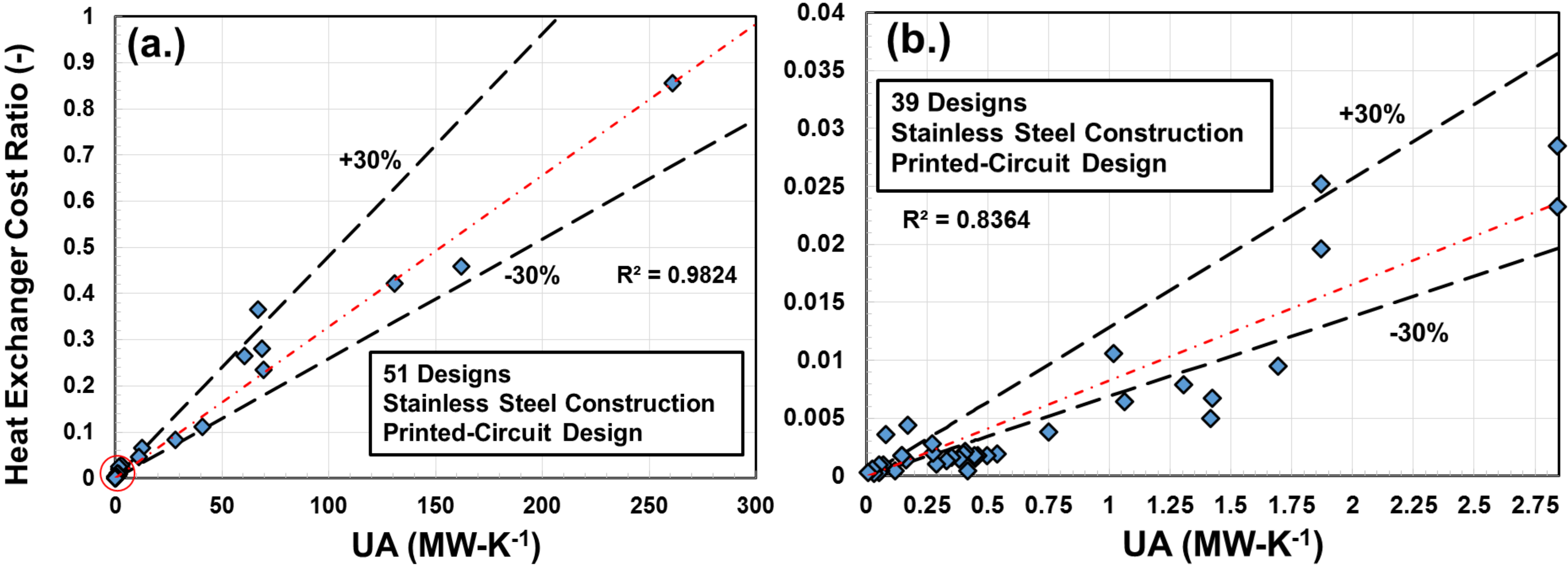
UA requirement

ΔP

UA requirement

$$\dot{Q}_{REC} = UA_{REC} \times LMTD \qquad \Delta P = Lf\frac{\rho}{2}\frac{V}{D_H} + \sum K_{minor}$$

Recuperative Heat Exchanger Capital Cost



$1.49 – $2.21/UA for HTR

$1.19 – $1.77/UA for LTR

NOTE: cost metrics are a function of a limited range of process conditions and should not be universally applied to all heat exchangers

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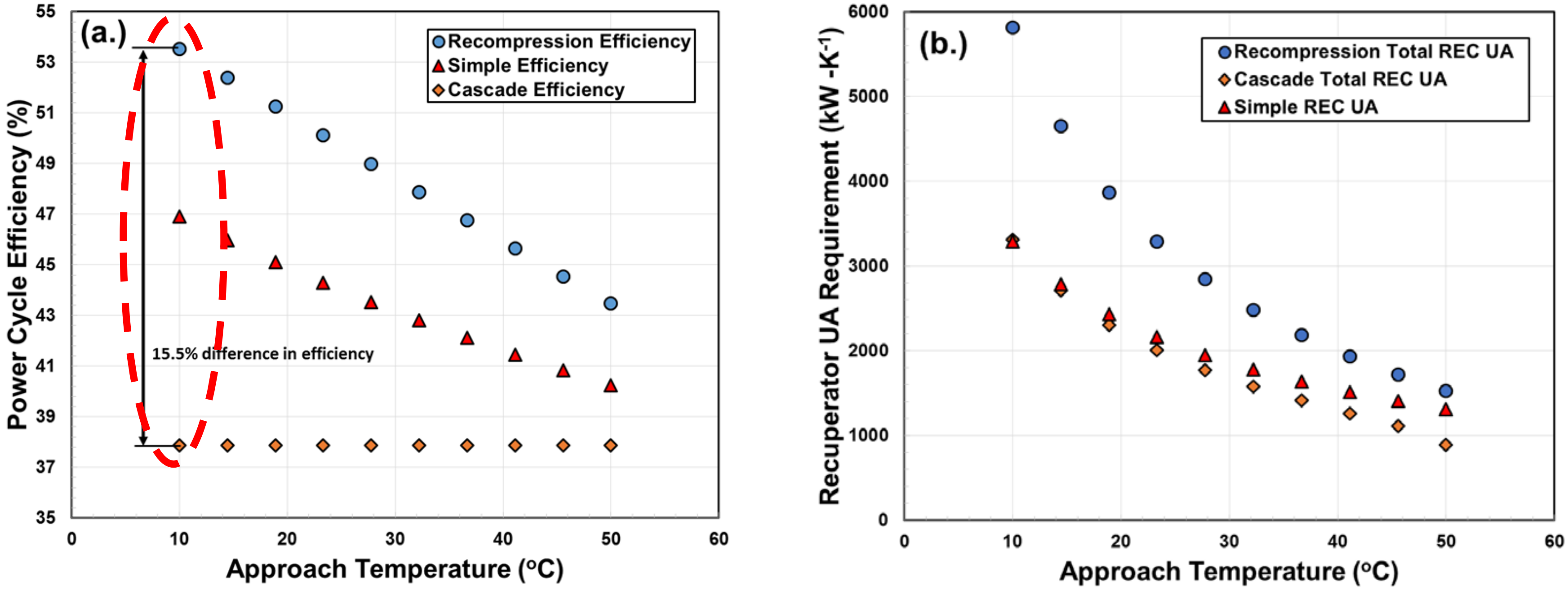
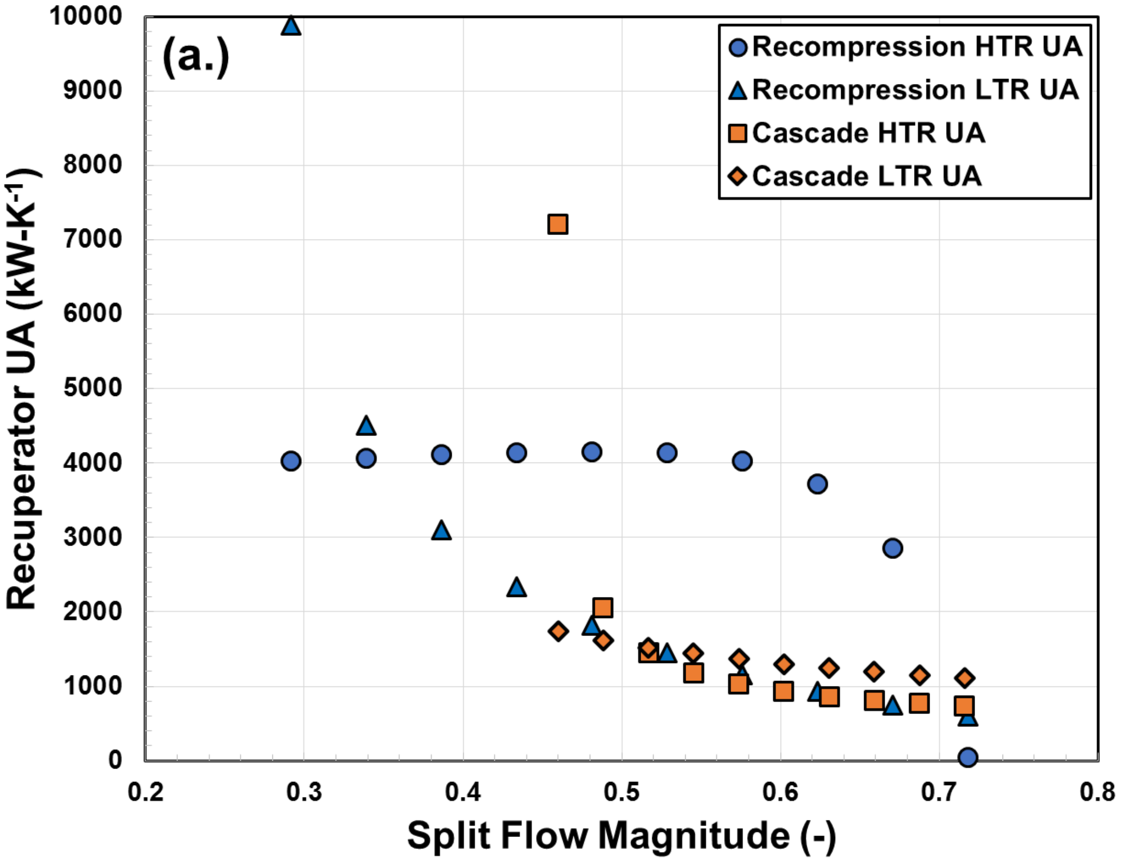
Results and Discussion



$\dot{W}_{TURB}$	$\dot{m}_{sCO2}$	$T_{TURB,i}$	$T_{COMP,i}$	Split-Flow	R_{COMP}
50 MW_{th}	278.1 kg-s^{-1}	650 °C	35 °C	0.50 (-)	3.0 (-)

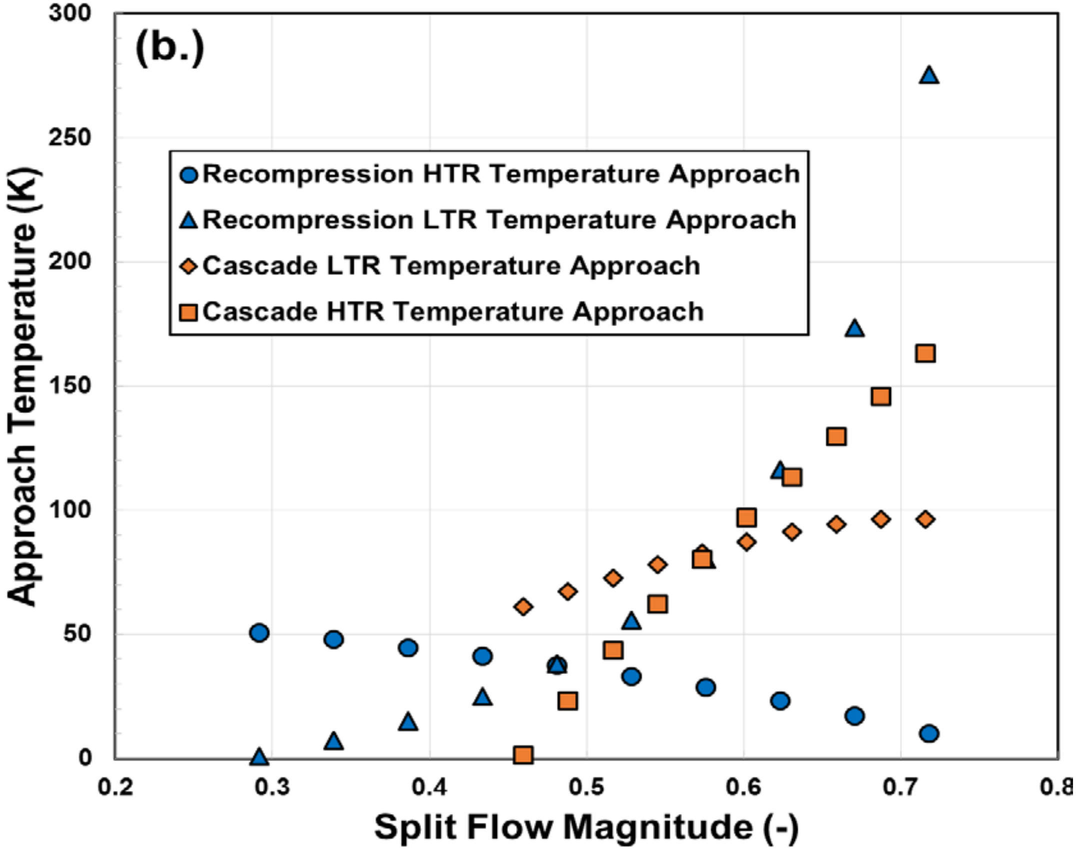
Results and Discussion Cont'd

$\dot{W}_{TURB}$	$T_{TURB,i}$	$T_{COMP,i}$	R_{COMP}	$\Delta T\ HTR/LTR$
50 MW_{th}	650 °C	35 °C	3.0 (-)	10 K



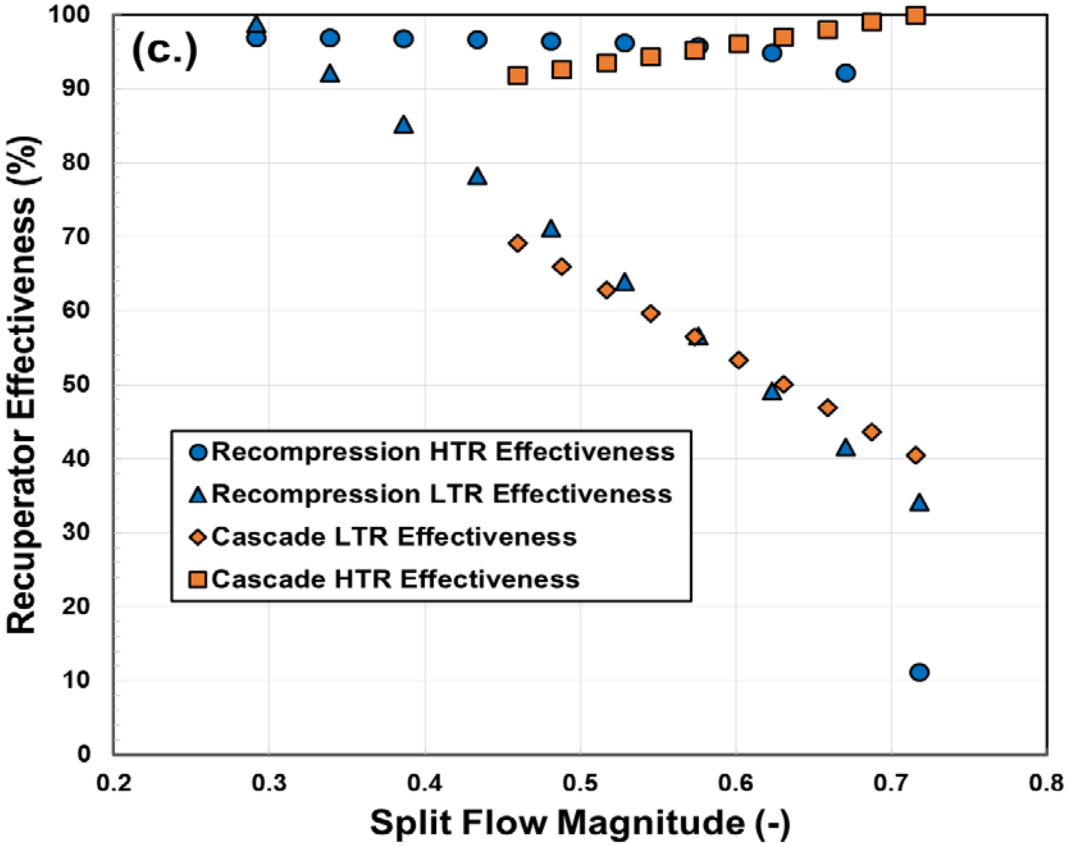
Results and Discussion Cont’d

$\dot{W}_{TURB}$	$T_{TURB,i}$	$T_{COMP,i}$	R_{COMP}	$\Delta T\ HTR/LTR$
50 MW_{th}	650 °C	35 °C	3.0 (-)	10 K

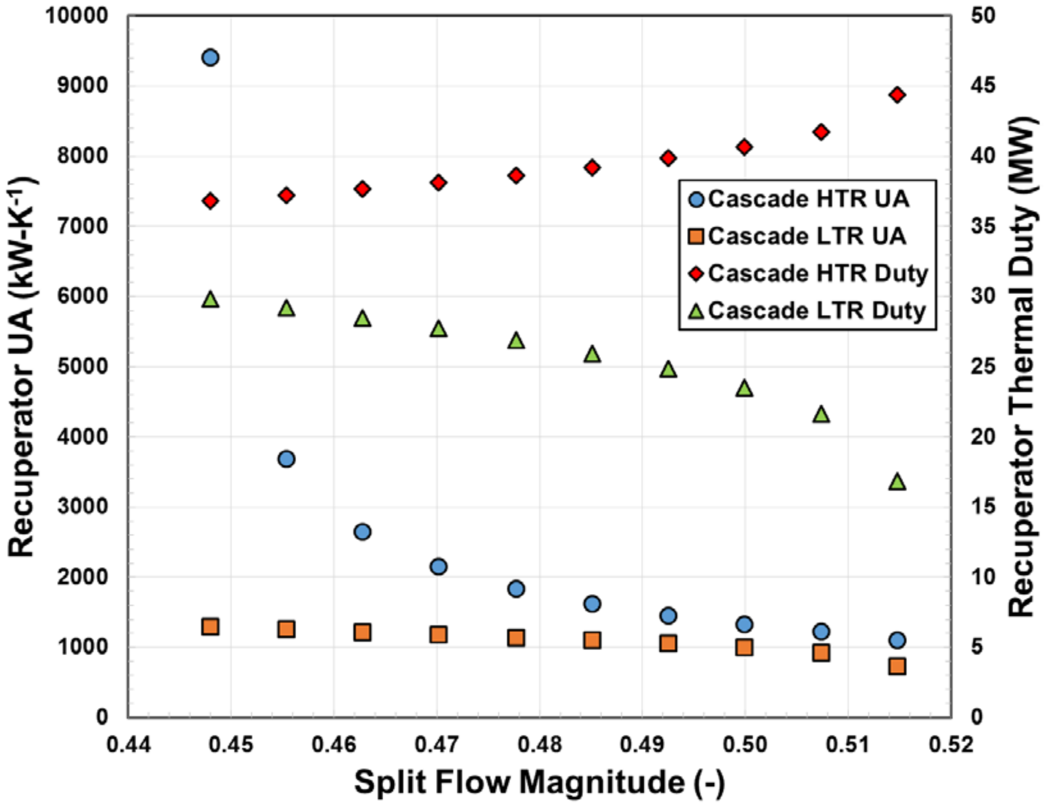


Results and Discussion Cont'd

$\dot{W}_{TURB}$	$T_{TURB,i}$	$T_{COMP,i}$	R_{COMP}	$\Delta T\ HTR/LTR$
50 MW_{th}	650 ^{o}C	35 ^{o}C	3.0 (-)	10 K



Results and Discussion Cont’d



$\dot{W}_{TURB}$	η_{cycle}	$T_{TURB,i}$	$T_{COMP,i}$	R_{COMP}	$\Delta T\ HTR/LTR$
50 MW_{th}	45 (%)	650 ^{o}C	35 ^{o}C	3.0 (-)	10 K

Results and Discussion Cont'd

$\dot{W}_{TURB}$	η_{cycle}	$T_{TURB,i}$	$T_{COMP,i}$	R_{COMP}	$\Delta T\ HTR/LTR$
50 MW_{th}	45 (%)	650 ^{o}C	35 ^{o}C	3.0 (-)	10 K

Parameter	**Recompression**	**Cascaded Reheat**	**Recomp. vs. Cascade**
IHX Duty (MW)	60.9 MW	97.5 MW	+60%
Comp. Work (MW); MC, RC	-2.4 MW, -20.2 MW	-6.1 MW	-73%
Turb. Work (MW); HT, LT	50 MW	21.4 MW, 28.6 MW	0%
X (-)	0.6558	0.5148	-21.5%
Mass Flow ($kg\text{-}s^{-1}$)	278.1 $kg\text{-}s^{-1}$	245.7 $kg\text{-}s^{-1}$	-11.7%

HTR Duty (MW)	45.4 MW	44.4 MW	-2.2%
HTR UA ($kW\text{-}K^{-1}$)	3,235 $kW\text{-}K^{-1}$	1,099 $kW\text{-}K^{-1}$	-66%
HTR Effectiveness (%)	93.4%	90.2%	-3.4%
HTR LMTD (K)	14.0 K	40.4 K	+186%
HTR Cost Ratio (-)	1.00	0.34	-66%
LTR Duty (MW)	41.7 MW	16.8 MW	-59.7%
LTR UA ($kW\text{-}K^{-1}$)	799 $kW\text{-}K^{-1}$	734 $kW\text{-}K^{-1}$	-8.1%
LTR Effectiveness (%)	44%	68%	+54.5%
LTR LMTD (K)	52.2 K	23.0 K	-56%
LTR Cost Ratio (-)	1.00	0.92	-8.1%

Conclusions

- Thermodynamic analysis of recuperative heat exchangers
  - Simple recuperative
  - Recompression
  - Cascaded reheat

- Variation of approach temperature shows limitation of cascaded reheat cycle

- Split flow magnitude show interesting difference in UA requirements between cycles

- Single cost metric will not provide accurate heat exchanger cost
  - Too many variables
  - Case-by-case basis

Future Work

- Discretize recuperative heat exchanger
- Evaluate different cycle parameter sets between cycle
- Complete full heat exchanger cost analysis
  - PCHE layout design
  - Mechanical design
  - Optimization of core blocks
  - Large vs. small furnace diffusion bonding

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Questions?

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