Thermoeconomic Modeling and Analysis of sCO_2 Brayton Cycles

Mathias Penkuhn, George Tsatsaronis

Technische Universität Berlin

mathias.penkuhn@tu-berlin.de

September 19–20, 2019, Paris, France

3rd European Supercritical CO_2 Conference

Contents

mathias.penkuhn@tu-berlin.de

Introduction

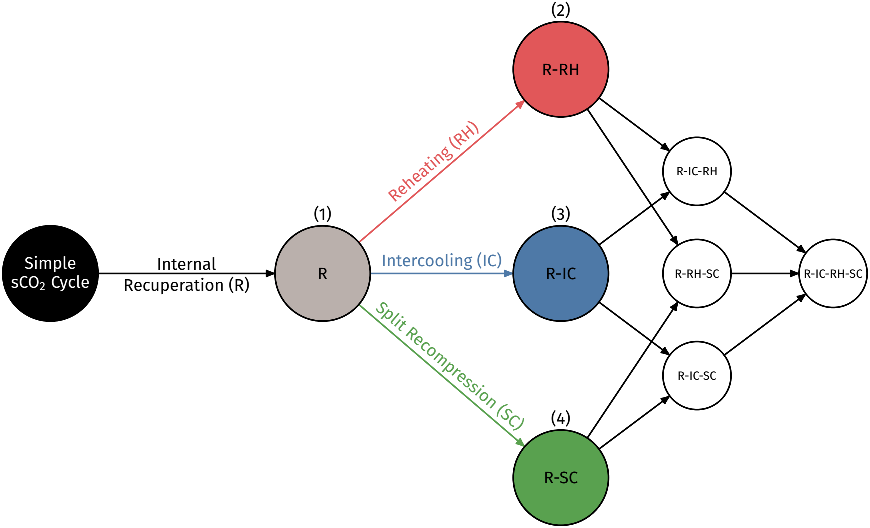
- Last decade has seen substantial interest in sCO_2 applications as high-efficiency, low-emission power generation technology
- Applications in fossil, nuclear, renewables, and waste heast based power generation
- Prospects of higher efficiency and flexibility, with lower capital costs and smaller footprint
- New technologies are entering markets in niches or in areas offering substantial economical or operational advantages
- Conflicting objectives of economic and thermodynamic performance, and highly uncertain data make it difficult to assess different technologies/designs

sCO_2 Cycle Design

- Critical point at 30.98 °C and 73.77 bar
- High-temperature, high-pressure, but low-pressure ratio, and highly-recuperative designs
- Cycle design options follow general guidelines known from conventional Rankine/Brayton cycles
- Low temperature compression, high-temperature expansion
- Large set of potential cycle configurations using reheating, intercooling, and split-recompression
- Large variety of different cycle layouts available in literature with goal of high thermal efficiency
- Unknown cost basis with high inherent uncertainty for economic analyses in open literature

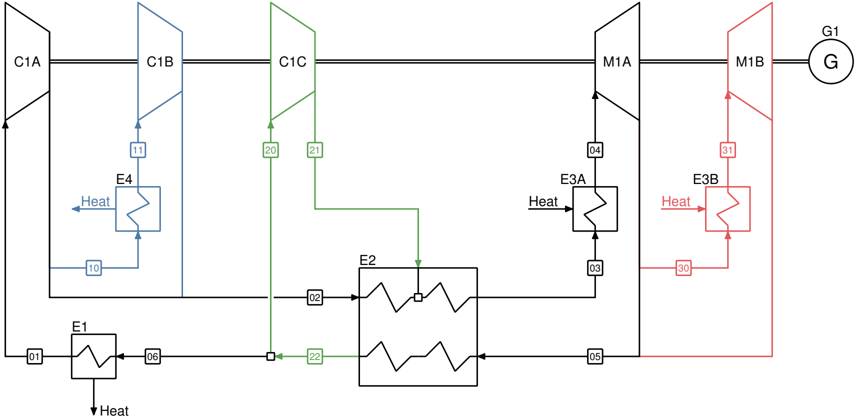
mathias.penkuhn@tu-berlin.de

sCO$_2$ Cycle Design and Improvement Options



sCO_2 Cycle Flowsheets

Modeling and Simulation using AspenPlus and REFPROP



sCO_2 Cycle Design Simulation Parameters

Unit ID	Parameter	Value
M1 A/B	Turbine Inlet Temperature	600 °C
M1 A	Turbine Inlet Pressure	250 bar
M1 A/B	Turbine Isentropic Efficiency	90 %
M1 A/B	Turbine Mechanical Efficiency	99 %
C1 A/B/C	Compressor Inlet Pressure	75 bar
C1 A	Precompressor Inlet Pressure	50 bar
C1 A/B/C	Compressor Isentropic Efficiency	85 %
C1 A/B/C	Compressor Mechanical Efficiency	99 %
G1	Electric Generator Efficiency	99 %
E1, E4	Cooler Outlet Temperature	32 °C
E1, E4	Cooler Pressure Drop	15 kPa
E2	Max. Recuperator Cold Side Outlet Temperature	400 °C
E2	Max. Recuperator Effectiveness	0.9
E2	Recuperator Hot-Side Pressure Drop	280 kPa
E2	Recuperator Cold-Side Pressure Drop	140 kPa
E3 A/B	Primary Heat Exchanger Pressure Drop	200 kPa
E3 A/B	Primary Heat Exchanger Min. Temperature Diff.	50 K

Based on good-practice guidelines by Weiland and Thimsen (2016), and Crespi et al. (2017)

mathias.penkuhn@tu-berlin.de

System Thermodynamic Analysis

- Thermal (energetic) efficiency based on overall cycle energy balance:

$$\eta = \frac{\dot{W}_{\mathrm{net}}}{\dot{Q}_{\mathrm{supply}}}$$

- Suitable framework for comparing different cycles necessary as site environment conditions have huge impact; related to heat sink temperature

mathias.penkuhn@tu-berlin.de

System Economic Analysis I – Preliminaries

- Literature provides various methodologies for conducting economic analyses; significant differences in results possible
- TRR method used here; assumptions on capital investment, economic, financial, and operating parameters

$$\begin{aligned} TRR = \quad & Carrying\ Charges_{\mathrm{L}} + Fuel\ Cost_{\mathrm{L}} \\ & + Operation/Maintenance\ Cost_{\mathrm{L}} \end{aligned}$$

- Determination of cost rate $\dot{Z}_k$ for each component

$$\dot{Z}_k = \dot{Z}_k^{\mathrm{CI}} + \dot{Z}_k^{\mathrm{OM}}$$

- Cost rate of fuel $\dot{C}_{\mathrm{F}}$
- Levelized cost rates are suitable for conducting analyses on component level

mathias.penkuhn@tu-berlin.de

System Economic Analysis II – Exergoeconomics

- Cost allocation for fuels and products based on exergoeconomics, exergoeconomic analyses put cost tags on individual streams like heat and power
- Here, simplified to thermoeconomics as different value of heat and power is not accounted for

$$\dot{C}_\mathrm{q} = c_\mathrm{q} \cdot \dot{Q}$$
$$\dot{C}_\mathrm{w} = c_\mathrm{w} \cdot \dot{W}$$

- Evaluate cost balance on overall cycle and component level

$$\sum_i^n \dot{C}_{i,\mathrm{out}} = \sum_i^n \dot{C}_{i,\mathrm{in}} + \sum_k^n \dot{Z}_k$$

- On overall cycle level follows

$$\dot{C}_\mathrm{w} = \dot{Z} + \dot{C}_\mathrm{q,heat} + \dot{C}_\mathrm{q,cool}$$

mathias.penkuhn@tu-berlin.de

System Economic Analysis III – Problems

- Productive system equation for heat input and power output

$$\dot{C}_{\mathrm{P}} = \dot{Z} + \dot{C}_{\mathrm{F}}$$

- Specific levelized cost of electricity $c_{\mathrm{w,P}}$

$$c_{\mathrm{w,P}} = \frac{\dot{Z}}{\dot{W}_{\mathrm{net}}} + c_{\mathrm{q,F}} \frac{\dot{Q}_{\mathrm{F}}}{\dot{W}_{\mathrm{net}}}$$

- Problem: large amount of highly uncertain data for parametric component cost estimation, financial project parameters, etc.

System Economic Analysis IV – Possible Solution

- Suitable component cost scaling based on similitude

$$C = C_{\text{ref}} \left(\frac{X}{X_{\text{ref}}} \right)^{n}$$

- Employ reference cycle design with reference characteristics

$$\dot{C}_{\text{w,P}} \frac{\dot{C}_{\text{w,P,ref}}}{\dot{C}_{\text{w,P,ref}}} = \dot{Z} \frac{\dot{Z}_{\text{ref}}}{\dot{Z}_{\text{ref}}} + \dot{C}_{\text{q,F}} \frac{\dot{C}_{\text{q,F,ref}}}{\dot{C}_{\text{q,F,ref}}}$$

- Reordering, and definition of thermoeconomic factor f quantifying contributions of monetary expenses and fuel costs for reference design

$$\frac{c_{\text{w,P}}}{c_{\text{w,P,ref}}} = f \frac{\dot{Z}}{\dot{Z}_{\text{ref}}} + (1 - f) \frac{c_{\text{q,F}} \cdot \eta_{\text{ref}}}{c_{\text{q,F,ref}} \cdot \eta}$$

mathias.penkuhn@tu-berlin.de

System Economic Analysis V – Solution

- With reference components in reference cycle, cost scaling for components is possible, quantifying importance and scaling behavior

$$\frac{\dot{Z}}{\dot{Z}_{\mathrm{ref}}} = \sum_{k}^{n} x_{k,\mathrm{ref}} \frac{\dot{Z}_k}{\dot{Z}_{k,\mathrm{ref}}} = \ldots = \sum_{k}^{n} x_{k,\mathrm{ref}} \left(\frac{X_k}{X_{k,\mathrm{ref}}} \right)^n$$

- Using the following significant parameters X for scaling:
  - Heat exchangers: heat transfer capacity UA
  - Compressors, turbines, generators: power $\dot{W}$

Results

- Fixed power output, generic heat source
- Compare cycle efficiency using energetic efficiency
- Study thermoeconomic results for different sCO_2 cycle designs and improvement options for 100 MW_e cycles

Thermodynamic Results

Design	Cooler $\dot{Q}_{E1/4}$ (MW)	Recup. $\dot{Q}_{E2}$ (MW)	Heater $\dot{Q}_{E3}$ (MW)	Compr. $\dot{W}_{C1}$ (MW)	Turb. $\dot{W}_{M1}$ (MW)	Gen. $\dot{W}_{G1}$ (MW)	η (–)
R (1)	177.58	316.82	280.34	36.14	137.15	100	35.67
R-RH (2)	174.87	360.63	277.59	34.23	135.24	100	36.02
R-IC (3)	168.33	223.78	271.26	44.91	145.92	100	36.87
R-SC (4)	137.52	379.76	240.59	51.49	152.50	100	41.56

mathias.penkuhn@tu-berlin.de

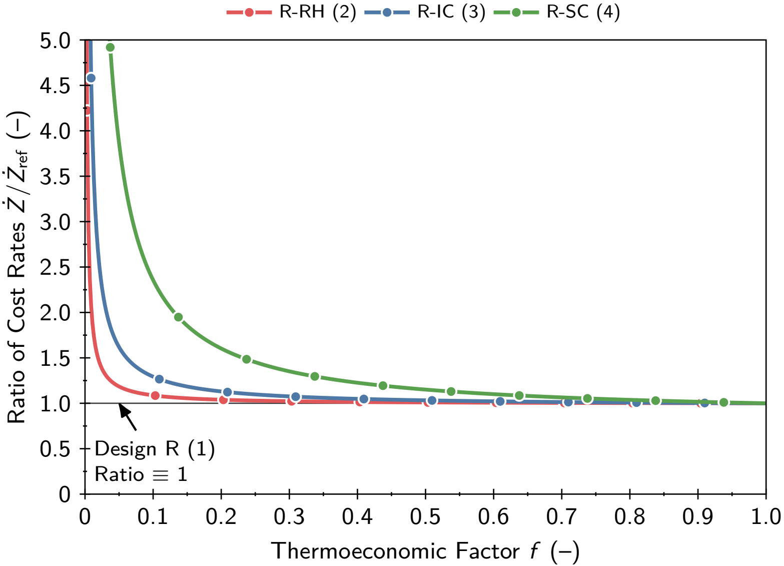
Thermoeconomic Results I

			Design (1) R		Design (2) R-RH	
Design Parameter	n (–)	$x_{k,\mathrm{ref}}$ (–)	Parameter (kW/K; MW)	$\dot{Z}/\dot{Z}_{\mathrm{ref}}$ (–)	Parameter (kW/K; MW)	$\dot{Z}/\dot{Z}_{\mathrm{ref}}$ (–)
$UA_{\mathrm{E1/4}}$	0.9500	0.045	3354.1	0.05	3184.4	0.04
UA_{E2}	0.9500	0.180	4646.5	0.18	4678.5	0.18
UA_{E3}	1.0000	0.180	5606.8	0.18	5551.8	0.18
$\dot{W}_{\mathrm{C1}}$	0.7865	0.270	36.1	0.27	34.2	0.26
$\dot{W}_{\mathrm{M1}}$	0.6842	0.225	137.1	0.23	135.2	0.22
$\dot{W}_{\mathrm{G1}}$	1.0000	0.100	100.0	0.10	100.0	0.10
Cycle		1.000		1.00		0.98

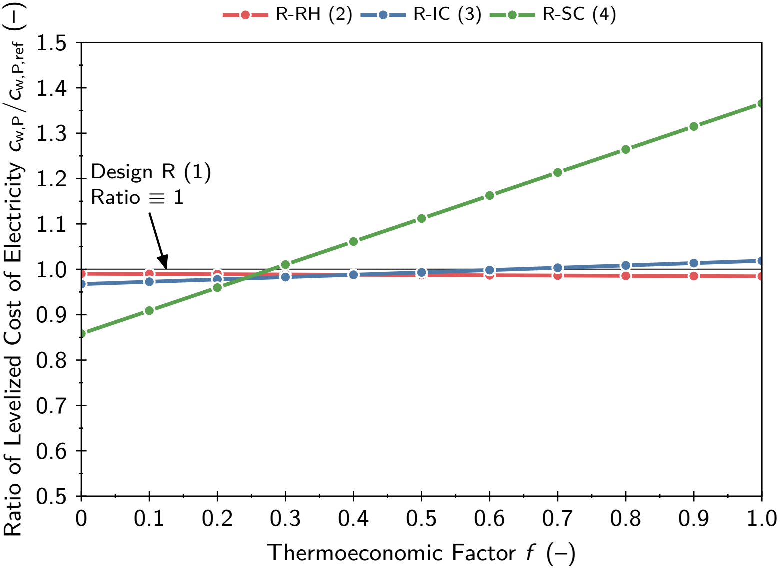
			Design (3) R-IC		Design (4) R-SC	
Design Parameter	n (–)	$x_{k,\mathrm{ref}}$ (–)	Parameter (kW/K; MW)	$\dot{Z}/\dot{Z}_{\mathrm{ref}}$ (–)	Parameter (kW/K; MW)	$\dot{Z}/\dot{Z}_{\mathrm{ref}}$ (–)
$UA_{\mathrm{E1/4}}$	0.9500	0.045	4299.0	0.06	2988.8	0.04
UA_{E2}	0.9500	0.180	3440.4	0.14	11981.8	0.44
UA_{E3}	1.0000	0.180	5425.2	0.17	4811.8	0.15
$\dot{W}_{\mathrm{C1}}$	0.7865	0.270	44.9	0.32	51.5	0.36
$\dot{W}_{\mathrm{M1}}$	0.6842	0.225	145.9	0.23	152.5	0.24
$\dot{W}_{\mathrm{G1}}$	1.0000	0.100	100.0	0.10	100.0	0.10
Cycle		1.000		1.02		1.34

mathias.penkuhn@tu-berlin.de

Thermoeconomic Results II – Isolines



Thermoeconomic Results III – Design Comparison



Results – Summary

- Reference (R), reheating (R-RH), and intercooling (R-IC) designs exhibit only small differences; recompression cycle (R-SC) requires much higher investments compared to reference cycle
- Recuperator, compressor, and turbine are main cost drivers
- Reheating (R-RH) provides a general small benefit,
- Intercooling (R-IC) becoming more favorable if heat sources are more expensive ($f < 0.6$)
- Recompression cycle designs are only advantageous for very expensive heat sources ($f < 0.25$)
- Significant increase in heat exchange capacity UA is highly detrimental for economic performance

Conclusions

Outcomes:

- Study analyzed systematically closed-cycle sCO_2 cycles using a dimensionless approach based on thermoeconomic similitude and scaling
- Large reduction in number of parameters, gain in robustness
- Comparison of available design options in case no cost data is available
- Multiobjective trade-off analysis is possible, sensitivity studies are projected to be easier

Future work:

- Conduct further analysis with actual heat resources (sCO_2 Power Cycles Symposium 2020)
- Incorporating the potential to account for more details at the component level

Thermoeconomic Modeling and Analysis of sCO_2 Brayton Cycles

Mathias Penkuhn, George Tsatsaronis

Technische Universität Berlin

mathias.penkuhn@tu-berlin.de

September 19–20, 2019, Paris, France

3rd European Supercritical CO_2 Conference