Exergoeconomic Analyses of different sCO_2 Cycle Configurations

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Contents

Introduction

- Future power generation processes requires high-efficiency, flexible, and economically competitive processes
- Emerging field of sCO_2 power cycles
- Applications in fossil-fuel, nuclear, CSP, waste heat recovery
- Advantages: high efficiencies, increased flexibility, lower capital costs
- Vast collection of possible cycle configurations and layouts
- Identification of important cycle features considering economic and thermodynamic efficiencies necessary
- What are the important aspects of a cost-efficient sCO_2 cycle?

Modeling and Simulation

- Data is taken from the literature (reviews of Ahn et al.[1] and Crespi et al.[2])
- Only indirect closed brayton cycles with generic heat source studied here
- Parameters are specified using best practice modeling and benchmark guidelines (DOE/NETL[3], Weiland/Thimsen[4])
- Property data: REFPROP for pure CO_2
- Environment conditions: Midwest-ISO (15 °C and 1.01325 bar)
- Cost estimation based on paper by Carlson et al.[5]

[1] Ahn et al., Nuclear Engineering and Technology 47.6 (2015), pp. 647–661

[2] Crespi et al., Applied Energy 195 (2017), pp. 152–183

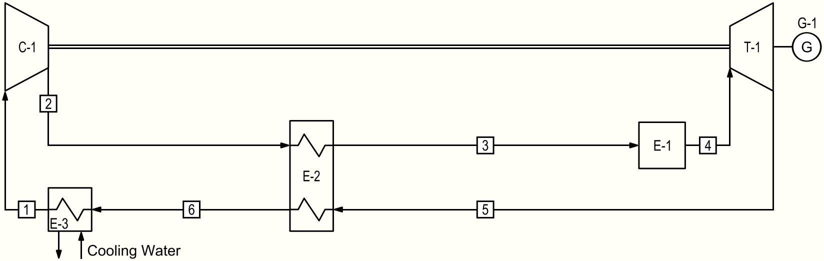
[3] DOE/NETL, QGESS: Process Modeling Design Parameters, 2014

[4] Weiland and Thimsen, A Practical Look at Assumptions and Constraints for Steady State Modeling of sCO_2 Brayton Power Cycles, 5th International Symposium – Supercritical CO_2 Power Cycles, 2016

[5] Carlson et al., ASME 11th International Conference on Energy Sustainability, ES2017-3590, 2017

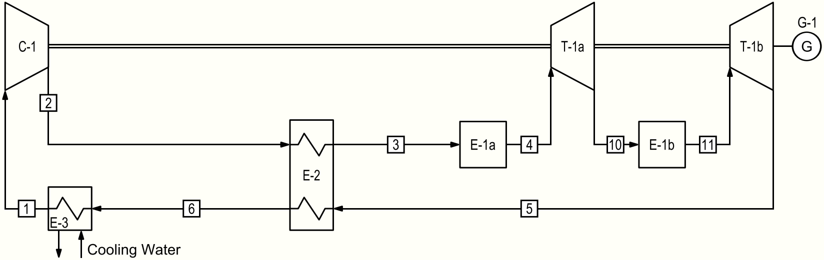
Simple Recuperation Cycle (a)

- Reference cycle
- Single-flow configuration
- Recuperator for high-temperature heat recovery
- Temperature pinch point inside recuperator



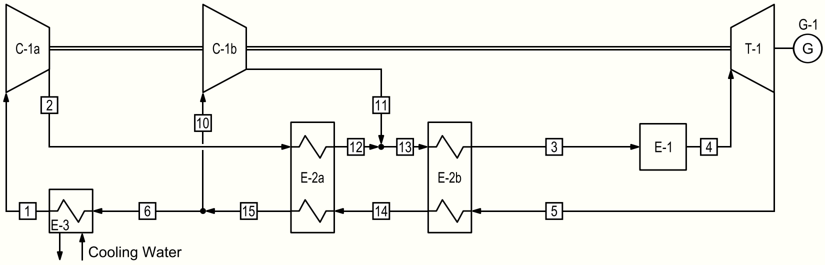
Reheating, Recuperation Cycle (b)

- Single-flow configuration
- General thermodynamic improvement strategy for power cycles
- Additional heat exchanger for heat supply to the cycle
- Increases specific work of the cycle



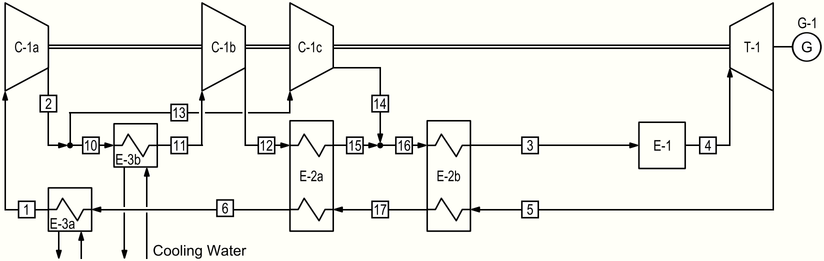
Recompression, Recuperation Cycle (c)

- Split-flow configuration
- Well-known cycle for improvement, suggested by Dostal
- Shifts pinch point temperature in recuperator
- Increases specific work of the cycle



Modified Recompression, Recuperation Cycle (d)

- Split-flow configuration
- Low pinch point temperature in recuperator
- Increases specific cycle work
- Small compression work required due to intercooling



Thermodynamic Analysis

- sCO_2 cycle simulation with AspenPlus
- Application of energy and mass balances
- Known principle: high-temperature heat source and low-temperature heat sink results in high efficiency
- Definition of thermal efficiency as parameter for comparison:

$$\eta = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{Supply}}}$$

- High influence of modeling assumptions, use of quality and benchmark guidelines for comparison

Economic Analysis

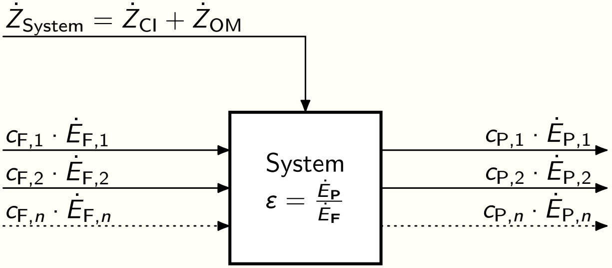
- Following TRR-methodology, calculating Cost of Electricity (COE)
- Cost estimation based on baseline values
- Assumption of total plant investment for cycle
- Generic heat is assumed at zero cost, varied in sensitivity analysis

Exergy Analysis

- Exergy is the maximum theoretical useful work obtainable as the system is brought into complete thermodynamic equilibrium with its thermodynamic environment.
- Exergy can be destroyed in contrast to energy
- Quantification of the different qualities of energy (heat, work)
- Quantification of the real thermodynamic losses
- Calculation of meaningful efficiencies
- Cost assignment to energy carriers and to thermodynamic inefficiencies

Exergoeconomics Analysis

- Combination of exergetic and economic analyses
- Intention to lower product costs of the system
- Identification of main design features and their impact on the system performance
- Cost formation process is revealed
- Monetary values are assigned to thermodynamic irreversibilities



Thermodynamic Analysis

ID	Cycle Configuration	Thermal Efficiency (%)
a	Simple Recuperation Cycle	37.85
b	Reheating Cycle	38.31
c	Recompression Cycle	40.61
d	Modified Recompression Cycle	42.58

- Large power requirement for recompression cycle
- Smaller power requirement for modified recompression cycle
- High pinch point temperatures for cycles (a)/(b)/(c)
- Lower pinch point temperature for cycle (d)

Economic Analysis I

(a) Simple Recuperated Cycle

ID	Z (\$)	Z/Z_{tot} (%)	$Z/\dot{W}_{Net}$ (\$/kW_e)
C-1	36,641,694	30.6	366.4
E-1	36,987,181	30.9	369.9
E-2	11,001,614	9.2	110.0
E-3	7,333,066	6.1	73.3
T-1	27,658,320	23.1	276.6
Total	119,621,876	100.0	1196.2

(b) Reheating Cycle

ID	Z (\$)	Z/Z_{tot} (%)	$Z/\dot{W}_{Net}$ (\$/kW_e)
C-1	36,068,350	30.2	360.7
E-1	36,536,508	30.6	365.4
E-1A	27,093,795	22.7	270.9
E-1B	9,442,713	7.9	94.4
E-2	12,222,226	10.2	122.2
E-3	7,187,489	6.0	71.9
T-1	27,525,631	23.0	275.3
T-1A	10,937,230	9.1	109.4
T-1B	16,588,401	13.9	165.9
Total	119,540,205	100.0	1195.4

Economic Analysis II

(c) Recompression Cycle

ID	Z (\$)	Z/Z_{tot} (%)	$Z/\dot{W}_{Net}$ (\$/kW$_e$)
C-1	52,090,694	32.1	520.9
C-1A	29,065,430	17.9	290.7
C-1B	23,025,265	14.2	230.3
E-1	34,466,642	21.2	344.7
E-2	38,204,642	23.5	382.0
E-2A	24,389,962	15.0	243.9
E-2B	13,814,680	8.5	138.1
E-3	6,398,035	3.9	64.0
T-1	31,315,257	19.3	313.2
Total	162,475,270	100.0	1624.8

(d) Modified Recompression Cycle

ID	Z (\$)	Z/Z_{tot} (%)	$Z/\dot{W}_{Net}$ (\$/kW$_e$)
C-1	27,497,767	23.5	275.0
C-1A	4,254,808	3.6	42.5
C-1B	11,011,405	9.4	110.1
C-1C	12,231,554	10.4	122.3
E-1	32,878,218	28.1	328.8
E-2	18,653,397	15.9	186.5
E-2A	9,311,439	8.0	93.1
E-2B	9,341,958	8.0	93.4
E-3	12,442,879	10.6	124.4
E-3A	5,677,140	4.9	56.8
E-3B	6,765,740	5.8	67.7
T-1	25,580,072	21.9	255.8
Total	117,052,332	100.0	1170.5

Exergy Analysis I

(a) Simple Recuperated Cycle

ID	$\dot{E}_F$ (MW)	$\dot{E}_P$ (MW)	$\dot{E}_D$ (MW)	ε (%)	y_D (%)
C-1	54.5	46.1	8.4	84.6	4.7
E-1	166.6	163.3	3.3	98.0	1.8
E-2	178.4	159.3	18.6	89.3	10.3
E-3	25.6	–	24.0	–	13.3
T-1	164.7	154.5	10.1	93.8	5.6
Total	180.1	100.0	75.4	55.5	41.9

(b) Reheating Cycle

ID	$\dot{E}_F$ (MW)	$\dot{E}_P$ (MW)	$\dot{E}_D$ (MW)	ε (%)	y_D (%)
C-1	53.4	45.2	8.2	84.6	4.6
E-1	168.0	165.0	3.1	98.2	1.7
E-1A	124.4	122.2	2.3	98.2	1.3
E-1B	43.6	42.8	0.8	98.2	0.5
E-2	215.5	194.1	20.8	90.1	11.7
E-3	25.0	–	23.5	–	13.2
T-1	162.9	153.4	9.4	94.2	5.3
T-1A	64.7	61.0	3.7	94.3	2.1
T-1B	98.2	92.5	5.7	94.2	3.2
Total	177.9	100.0	73.3	56.2	41.2

Exergy Analysis II

(c) Recompression Cycle

ID	$\dot{E}_F$ (MW)	$\dot{E}_P$ (MW)	$\dot{E}_D$ (MW)	ε (%)	y_D (%)
C-1	85.3	73.1	12.1	85.8	7.2
C-1A	47.6	40.2	7.3	84.6	4.4
C-1B	37.7	32.9	4.8	87.3	2.9
E-1	158.0	155.1	2.9	98.2	1.7
E-2	213.1	205.4	7.6	96.4	4.6
E-2A	73.9	70.0	3.9	94.8	2.3
E-2B	139.2	135.4	3.8	97.3	2.2
E-3	22.3	–	20.9	–	12.5
T-1	197.4	185.3	12.2	93.8	7.3
Total	167.7	100.0	63.6	59.6	37.9

(d) Modified Recompression Cycle

ID	$\dot{E}_F$ (MW)	$\dot{E}_P$ (MW)	$\dot{E}_D$ (MW)	ε (%)	y_D (%)
C-1	37.8	31.6	6.2	83.5	3.9
C-1A	5.9	4.8	1.0	82.2	0.7
C-1B	15.2	12.6	2.6	82.8	1.6
C-1C	16.8	14.2	2.6	84.6	1.6
E-1	148.1	145.2	2.9	98.0	1.8
E-2	173.6	156.8	16.8	90.3	10.5
E-2A	15.6	14.2	1.4	91.3	0.9
E-2B	158.1	142.6	15.5	90.2	9.7
E-3	12.5	–	10.9	–	6.8
E-3A	7.8	–	7.1	–	4.4
E-3B	4.7	–	3.8	–	2.4
T-1	146.9	137.8	9.0	93.8	5.7
Total	159.7	100.0	55.7	62.6	34.9

Exergoeconomic Analysis I

(a) Simple Recuperated Cycle

ID	c_F ($/GJ)	c_P ($/GJ)	$\dot{C}_D$ ($/h)	r (–)	f (–)
C-1	5.97	9.87	180.59	0.65	0.72
E-1	0.04	0.84	0.49	19.35	1.00
E-2	4.40	5.18	293.99	0.18	0.32
E-3	7.82	–	675.51	–	0.12
T-1	5.01	5.97	182.83	0.19	0.66
Total	0.97	5.97	262.18	5.19	0.85

(b) Reheating Cycle

ID	c_F ($/GJ)	c_P ($/GJ)	$\dot{C}_D$ ($/h)	r (–)	f (–)
C-1	5.93	9.84	175.89	0.66	0.72
E-1	0.08	0.87	0.91	9.53	1.00
E-1A	0.05	0.84	0.44	14.49	1.00
E-1B	0.16	0.95	0.47	4.81	1.00
E-2	4.24	4.93	318.17	0.16	0.33
E-3	7.82	–	662.10	–	0.12
T-1	4.99	5.93	169.56	0.19	0.67
T-1A	5.42	6.38	72.11	0.18	0.66
T-1B	4.71	5.64	97.32	0.20	0.68
Total	0.96	5.93	252.85	5.19	0.86

Exergoeconomic Analysis II

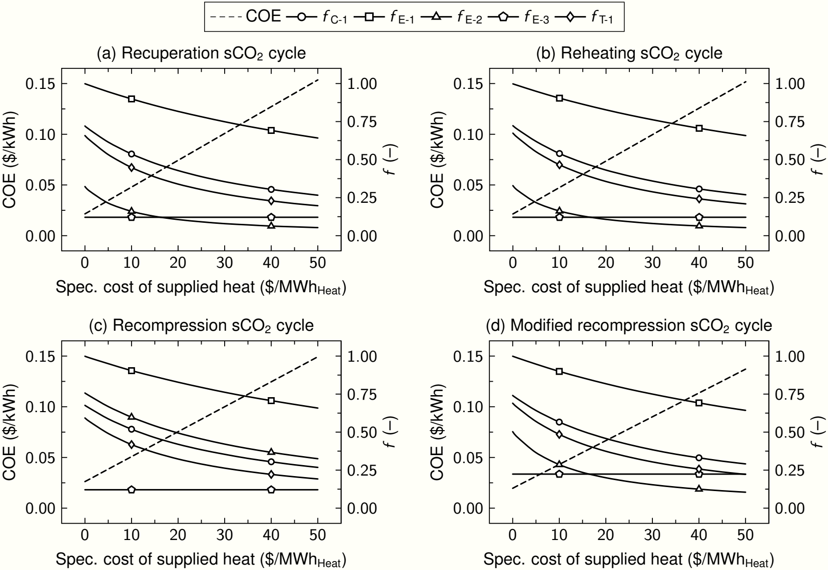
(c) Recompression Cycle

ID	c_F (\$/GJ)	c_P (\$/GJ)	$\dot{C}_D$ (\$/h)	r (–)	f (–)
C-1	7.27	10.99	317.29	0.51	0.68
C-1A	7.27	11.15	191.77	0.53	0.66
C-1B	7.27	10.80	125.53	0.49	0.70
E-1	0.04	0.85	0.45	18.36	1.00
E-2	5.68	6.55	156.03	0.15	0.76
E-2A	5.69	7.24	79.40	0.27	0.80
E-2B	5.67	6.19	76.70	0.09	0.70
E-3	7.82	–	589.45	–	0.12
T-1	6.26	7.27	273.88	0.16	0.59
Total	0.90	7.27	207.13	7.03	0.91

(d) Modified Recompression Cycle

ID	c_F (\$/GJ)	c_P (\$/GJ)	$\dot{C}_D$ (\$/h)	r (–)	f (–)
C-1	5.45	9.61	122.41	0.76	0.74
C-1A	5.45	9.76	20.44	0.79	0.73
C-1B	5.45	9.69	51.06	0.78	0.73
C-1C	5.45	9.48	50.90	0.74	0.75
E-1	0.05	0.71	0.48	14.52	1.00
E-2	3.88	4.72	234.95	0.22	0.50
E-2A	3.93	6.63	19.27	0.69	0.86
E-2B	3.87	4.53	215.66	0.17	0.36
E-3	13.99	–	547.90	–	0.22
E-3A	12.94	–	330.35	–	0.18
E-3B	15.76	–	214.54	–	0.29
T-1	4.50	5.45	146.53	0.21	0.69
Total	0.82	5.45	164.59	5.64	0.90

Sensitivity



Discussion

- Cycle layout influences cycle efficiency and cost
- Recuperator integration is of high importance for the design of a high efficiency/low cost cycle
- Compression is the main cost driver and the most important design decision for cycle cost efficiency
- Primary heat exchanger/turbine section is driven by investment costs
- Cost of upstream processes has a huge influence on cycle design
- Modified recompression design has best metrics of all cycles
- Innovative compression and recuperation integration required

Conclusions

- Importance of economic analysis for different cycle configurations
- Compression and recuperation are the most important cycle features
- Conduct compression at lowest temperature possible
- Importance of an integrated approach for cycle design (exergetic/exergoeconomic analysis) is shown, providing better understanding of cycle features
- Outlook I: complete exergy and exergoeconomic mapping of different cycles
- Outlook II: application of advanced exergy-based methods for improvement quantification and determination of component interaction

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