COMBINED CYCLE ENGINE CASCADES ACHIEVING HIGH EFFICIENCY

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OUTLINE

- Introduction
- Supercritical CO_2 Heat Exchanger and Cycle Analysis
- Combined Cycle Engine Cascades
- Conclusions

INTRODUCTION

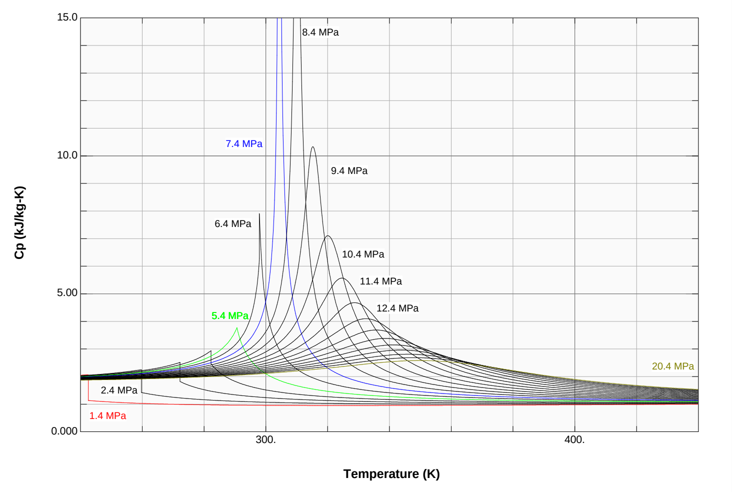
INTRODUCTION

- Supercritical Carbon Dioxide (S-CO_2) Power cycles can possess some favorable qualities of both the Rankine and Brayton cycles.
- S-CO_2 Power cycles are typically proposed as an alternative or compliment to traditional Rankine and Brayton cycle engines.
- Because of their complexity, a S-CO_2 engine has not yet been installed into production use.
- Ongoing research and development aims to make such engines a reality. The present work seeks to help those efforts and understand if these engines can provide an advantage in combined cycle configurations.

ABOUT SUPERCRITICAL CO_2 (S-CO_2) POWER CYCLES

- Closed loop configuration.
- Main compressor inlet temperature and pressure are at or near the critical point.
- Carbon dioxide is the proposed working fluid because it is cheap, inert, and has a critical temperature of 304K (31°C), which is near typical ambient temperatures of $\sim$ 294K (21°C).
- High system pressures occur due to the high critical pressure of carbon dioxide (7.4 MPa).

CARBON DIOXIDE – C_p VS TEMPERATURE

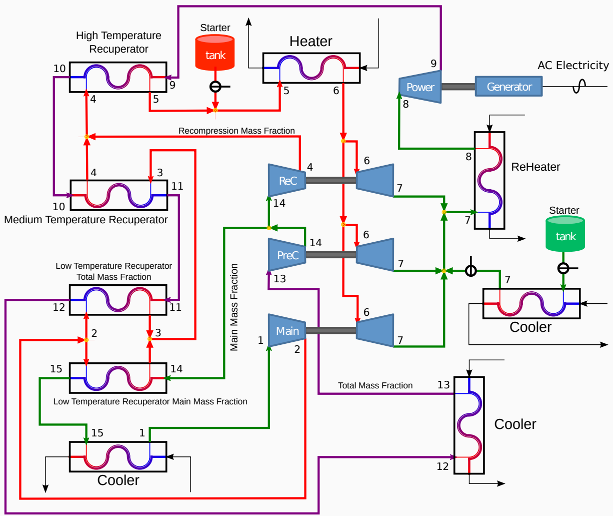


- Low Pressure Ratio
- Large amounts of recuperation possible.
- Low back work ratio: Decreased sensitivity of compressor/turbine efficiency on cycle efficiency.
- High Power Density
  - High pressure and high molecular weight.
  - Fluid densities range from $\sim$23 kg/m^3 to $\sim$788 kg/m^3.
- High exergy efficiencies.

SUPERCRITICAL CO_2 POWER CYCLE - WEAKNESSES

- Nonlinear specific heat mismatch causes difficulties exchanging heat between high and low pressure sides at lower temperatures.
- Heating power in recuperators can be 350% of the net output power and 180% of the input heating power.
- Closed loop design presents additional system complexities.
- High pressures present increased structural loading and seal leakage issues.
- Nonlinear property variations near the critical point present turbomachinery design complications as well as challenges maintaining off design operability.
- High working fluid densities prohibit efficient low power, low speed, low cost prototypes to be developed.

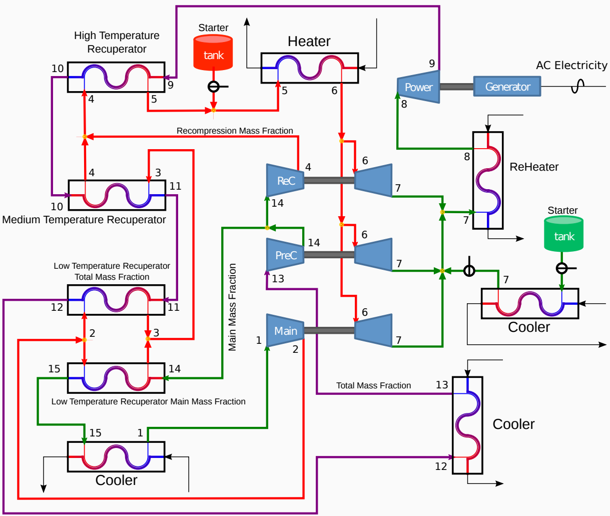
SUPERCRITICAL CO_2 HEAT EXCHANGER AND CYCLE ANALYSIS

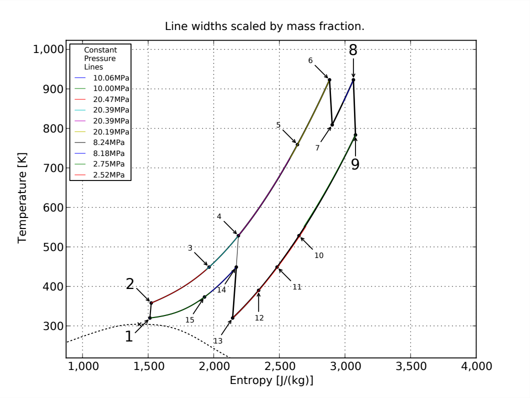


- Three compressors and several flow splits are used to help mitigate heat transfer issues due to specific heat mismatches.
- Four shafts are utilized to better match optimal operating speeds of each turbomachinery component.
- Due to the small size of the turbomachinery, as well as the use of multiple shafts, each assembly (except for the power turbine and generator) can be placed inside a pressure vessel to avoid the need for high speed, high pressure seals.
- Tanks and a blow down startup procedure are used to eliminate the need to attach a motor to the higher speed shafts.

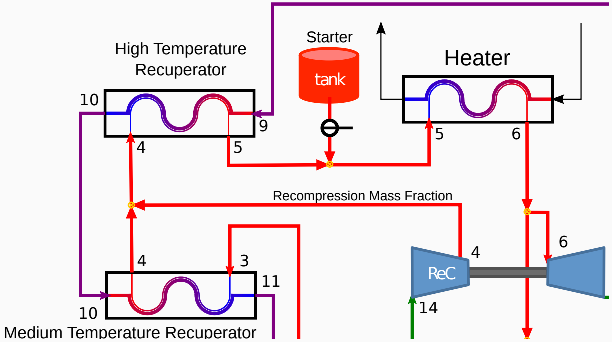
Thermal Efficiency	49.6%
Exergy Efficiency	75.9%

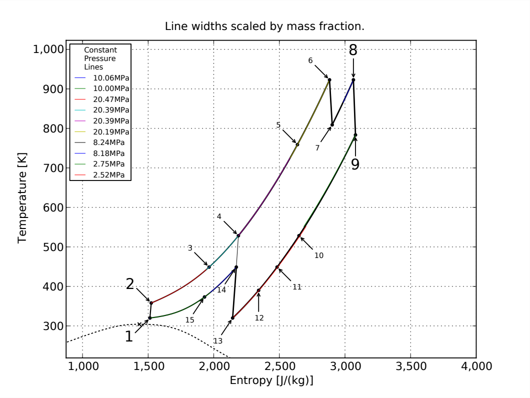
LAYOUT FOR A STAND ALONE CYCLE (WITH REHEAT)





HEAT EXCHANGER MASS FLOW DIFFERENCES

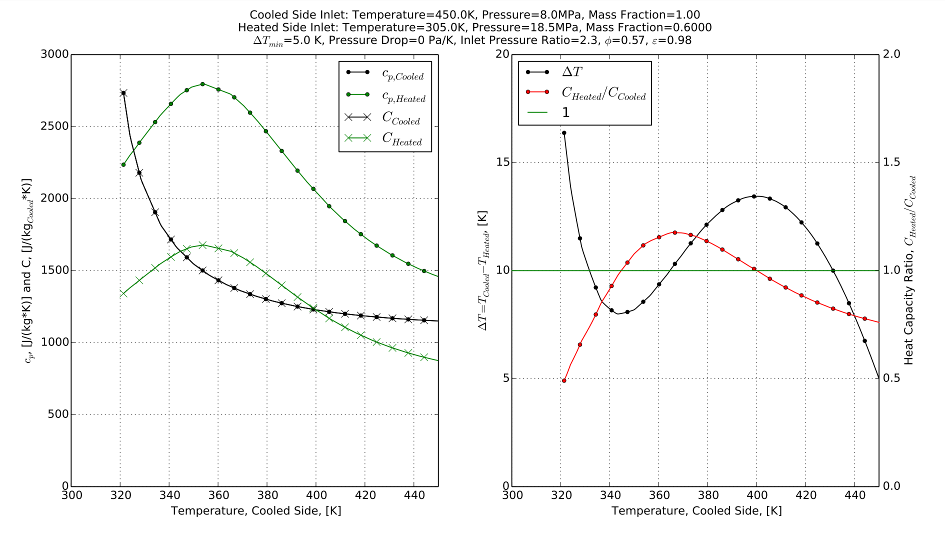




VARIABLE PROPERTY HEAT ENGINE CYCLE ANALYSIS CODE

- A thermodynamic cycle analysis code was created from scratch using Python.
- Variable fluid properties are implemented as a function of both temperature and pressure using REFPROP.
- 0-D counterflow heat exchanger model was developed to account for variable fluid properties, yet maintaining high solution speed.
- Design space for the inputs is explored in parallel and can run on as many processors as are available.

- Minimum temperature difference is defined instead of an effectiveness or surface area and convection coefficients.
- Pressure drop is not computed based on an assumed geometry, but is approximated to be linearly dependent upon temperature drop in the heat exchanger.
- Initial guess for the location of the minimum temperature difference and the corresponding unknown boundaries is made by comparing heat capacities of each fluid stream.
- A root finding technique is used with the initially guessed heat exchanger minimum temperature difference and unknown boundaries in order to find the actual minimum temperature difference and unknown boundaries.


Cooled Side Inlet: Temperature=450.0K, Pressure=8.0MPa, Mass Fraction=1.00
Heated Side Inlet: Temperature=305.0K, Pressure=18.5MPa, Mass Fraction=0.6000
ΔT_{min}=5.0 K, Pressure Drop=0 Pa/K, Inlet Pressure Ratio=2.3, ϕ=0.57, ε=0.98
$c_{p,Cooled}$
$c_{p,Heated}$
C_{Cooled}
C_{Heated}
c_p, [J/(kg*K)] and C, [J/(kg$_{Cooled}$*K)]
Temperature, Cooled Side, [K]
ΔT
C_{Heated}/C_{Cooled}
1
$\Delta T = T_{Cooled} - T_{Heated}$, [K]
Heat Capacity Ratio, C_{Heated}/C_{Cooled}
Temperature, Cooled Side, [K]

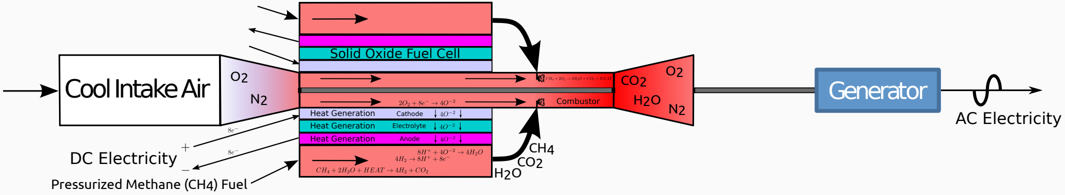
CYCLE OPTIMIZATION CONSTRAINTS

Parameter	Minimum	Maximum
PreCompressor Pressure Ratio	1.0	4.0
Main Compressor Pressure Ratio	1.1	4.1
Recompression Fraction	0.000	0.991
Low Temperature Recuperator Main Fraction High Pressure Component Mass Fraction	0.001	0.991
Main Compressor Outlet Pressure	2 MPa	35 MPa
Maximum Temperature	923 K [650°C]	923 K [650°C]
Minimum Temperature	306 K [33°C]	306 K [33°C]
Main Compressor Isentropic Efficiency	0.850	0.850
PreCompressor Isentropic Efficiency	0.875	0.875
ReCompressor Isentropic Efficiency	0.875	0.875
Power Turbine Isentropic Efficiency	0.930	0.930
Main/Re/Pre Compressor Turbine Isentropic Efficiency	0.890	0.890
Heat Exchanger Minimum Temperature Difference	5 K	5 K
Heat Exchanger Pressure Drop	500 Pa/K	500 Pa/K

COMBINED CYCLE ENGINE CASCADES

GENERAL TOPPING CYCLE WITH OPTIONAL FUEL CELL

NET REACTION: $CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 +$ ELECTRICAL WORK + HEAT



$\eta_c = 84.0\%$

$\eta_t = 90.0\%$

$PR_c =$ fixed at 37.15 (with fuel cell), optimized but limited to 45.00 (without fuel cell)

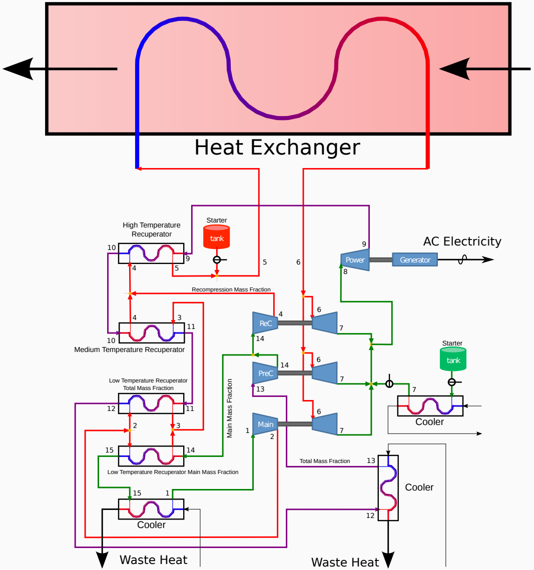
Turbine Inlet Temperature = 1,500 K [1,227°C] (with fuel cell), 1,890K [1,617°C] (without fuel cell)

Fuel Cell Excess Air = 26.3%

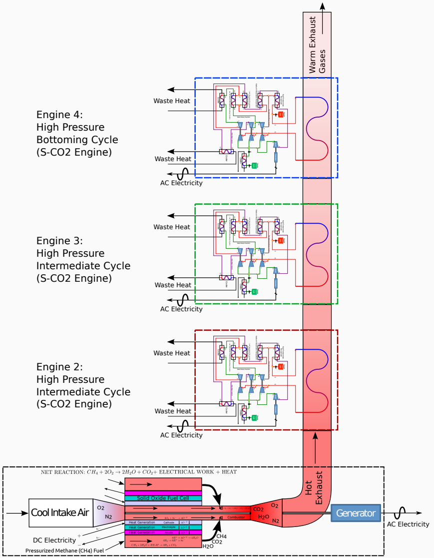
Fuel Cell Fuel Utilization = 80.0%

Fuel Cell Electrochemical Efficiency = 58.5% (HHV), 65.0% (LHV)

INTERMEDIATE AND BOTTOMING ENGINES (NO REHEAT)

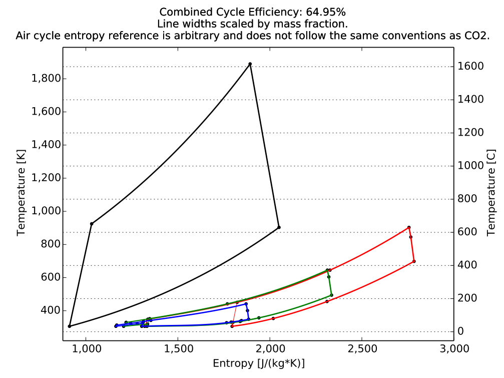


GENERAL COMBINED CYCLE ENGINE



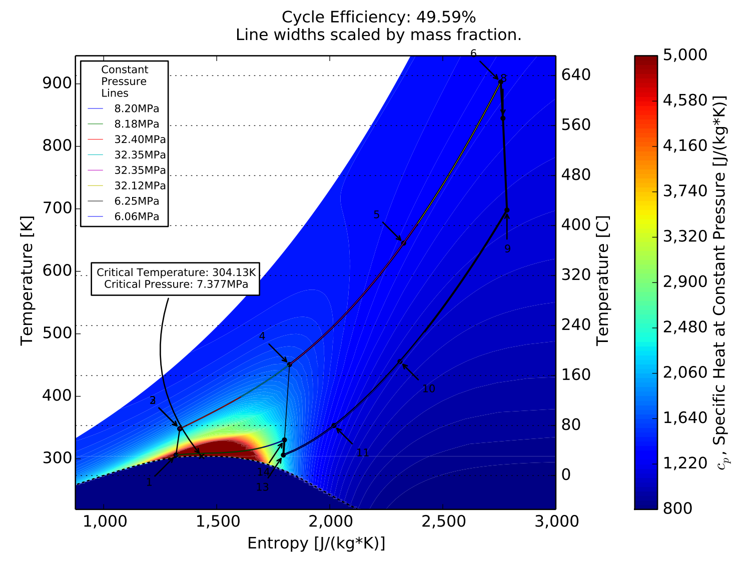
Engine 1: Low/Medium Pressure Topping Cycle (Airbreathing Gas Turbine with Fuel Cell)

COMBINED CYCLE ENGINE

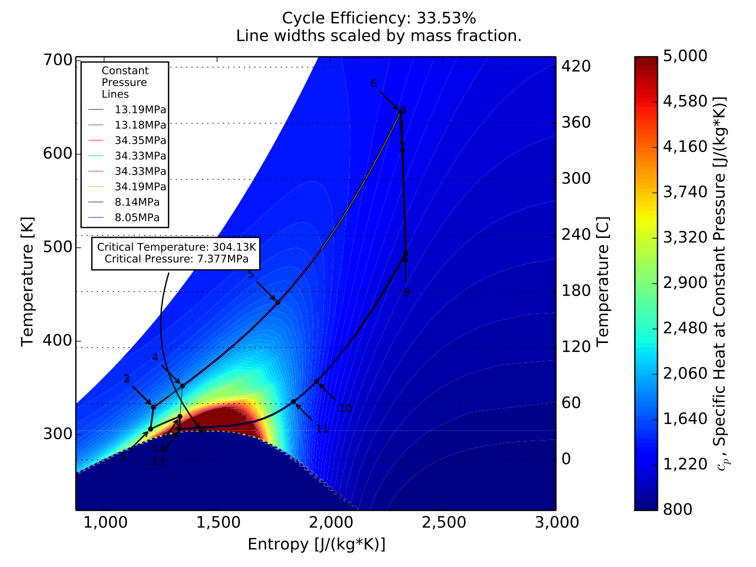


Engine		Work Fraction	Marginal Combined Cycle Efficiency	Engine Efficiency	Engine Exergy Efficiency
Type	Number	%	%	%	%
Gas Turbine	1	70.05	45.49	45.49	54.28
$S-CO_2$ Engine	2	18.60	12.08	49.59	75.02
$S-CO_2$ Engine	3	9.45	6.14	33.53	63.79
$S-CO_2$ Engine	4	1.90	1.23	14.14	46.10
Combined		100.00	64.95	64.95	77.5

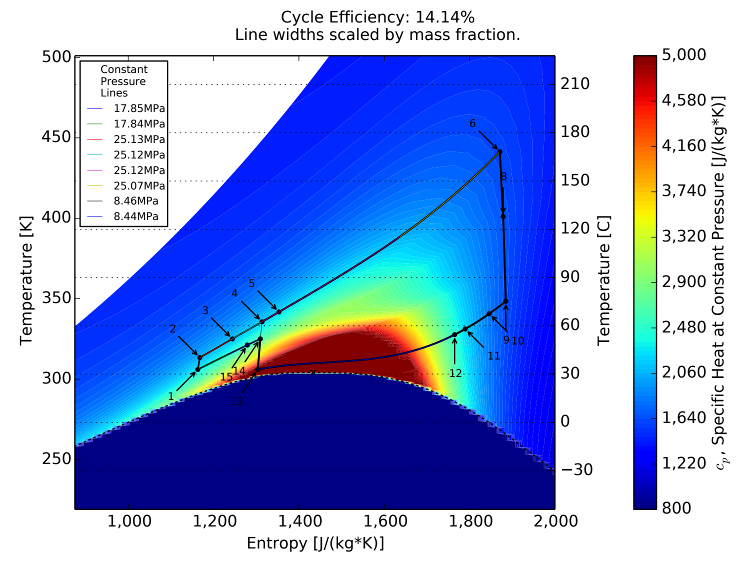
ENGINE NUMBER 2: $s - CO_2$ CYCLE, TEMPERATURE ENTROPY DIAGRAM



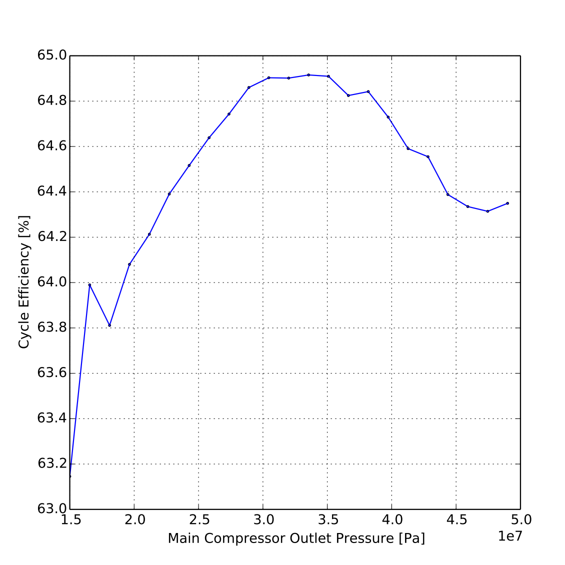
ENGINE NUMBER 3: $s - CO_2$ CYCLE, TEMPERATURE ENTROPY DIAGRAM

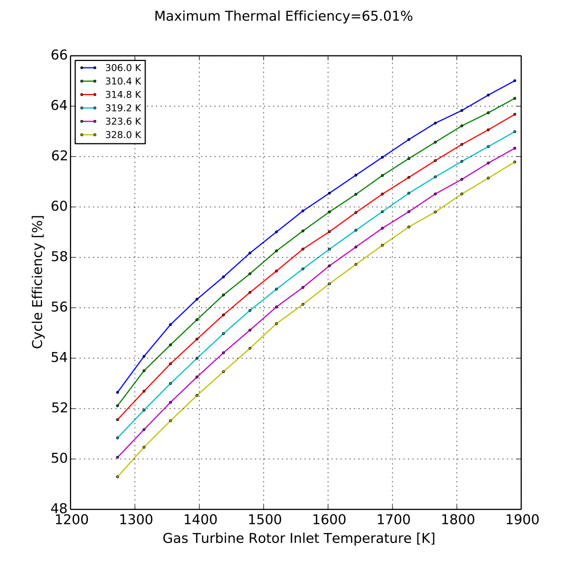


ENGINE NUMBER 4: $s-CO_2$ CYCLE, TEMPERATURE ENTROPY DIAGRAM

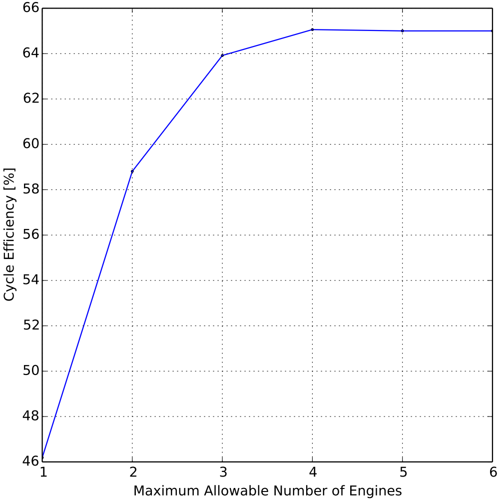


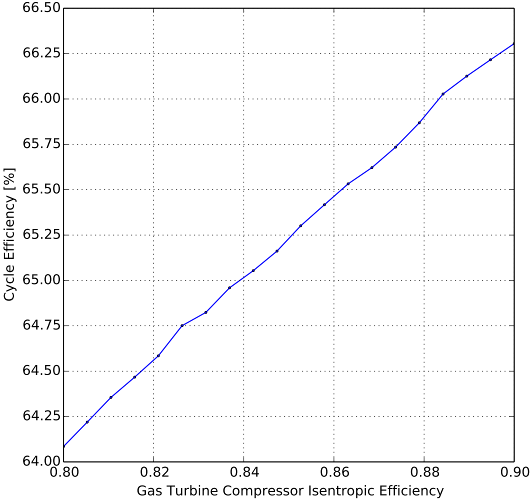
EFFICIENCY VS $S-CO_2$ ENGINE PEAK PRESSURE & TOPPING CYCLE TURBINE INLET TEMP

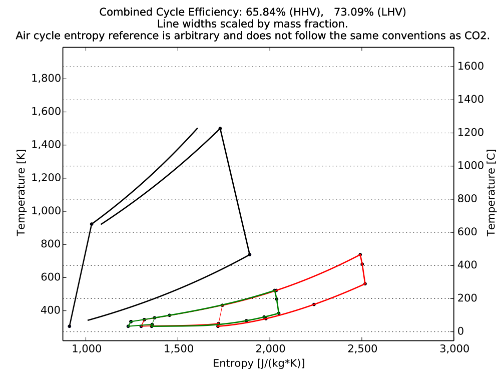




EFFICIENCY VS NUMBER OF ENGINES & TOPPING CYCLE COMP ISENTROPIC EFFICIENCY







Engine		Work Fraction		Marginal Combined Cycle Efficiency				Engine Efficiency		Engine Exergy Efficiency
Type	Number	%		HHV, %		LHV, %		%		%
Fuel Cell	1	71.14	91.15	46.84	60.01	52.00	66.63	52.00 (LHV)	66.63 (LHV)	-
Gas Turbine		20.01		13.17		14.63		30.47 (LHV)		
$S - CO_2$ Engine	2	6.44		4.24		4.71		41.00		69.99
$S - CO_2$ Engine	3	2.41		1.59		1.76		23.02		55.52
Combined		100.00		65.84		73.09%				-

CONCLUSIONS

NOVELTY OF THE CURRENT WORK

- Combined cycle configurations using supercritical carbon dioxide power cycles in conjunction with a fuel cell and gas turbine has been explored and optimized.
- A unique shaft layout and startup procedure are used in conjunction with a series of intermediate and bottoming engines.
- With the multi-shaft configuration, turbomachinery can be placed inside pressure vessels to avoid high pressure ratio seals.
- A custom variable property cycle analysis code was developed and used.
- A combined cycle efficiency of 64.95% was predicted for the combined cycle without a fuel cell with a turbine inlet temperature of 1,890 K [1,617°C] and a rejected heat temperature of 306 K [33°C].
- A combined cycle efficiency of 73.09% was predicted for the combined cycle with a fuel cell with a rejected heat temperature of 306 K [33°C].

CONCLUSIONS

- Supercritical CO_2 Power Cycles have the potential for high efficiencies at low turbine inlet temperatures.
- Highly nonlinear fluid properties present significant challenges in cycle and component design.
- Appropriate modeling of heat exchangers is critical in assessing correct cycle performance.
- Supercritical carbon dioxide power cycles can be very beneficial in combined cycle configurations, provided multiple supercritical carbon dioxide power cycles are used and each cycle is optimized individually.

RECOMMENDED FUTURE WORK

- Allow for variable turbomachinery efficiencies which are dependent on the inlet conditions and pressure ratio.
- Improve pressure drop relationships for heat exchangers in the 0-D heat exchanger solver.
- Support condensation and boiling in heat exchangers.
- Further investigate the use of CoolProp as a replacement for REFPROP.
- Incorporate a cost model into the cycle optimization process.
- Conduct preliminary design and numerical simulations of turbomachinery components.

Questions?

Engine		Exhaust Gas Heat Exchanger		Power Turbine	Main Compressor
Type	Number	Inlet Temperature	Outlet Temperature	Exit Temperature	Exit Temperature
		K [°C]	K [°C]	K [°C]	K [°C]
Gas Turbine	1	-	903 [630]	903 [630]	925 [652]
$S-CO_2$ Engine	2	903 [630]	645 [372]	698 [425]	348 [75]
$S-CO_2$ Engine	3	645 [372]	441 [168]	494 [221]	329 [56]
$S-CO_2$ Engine	4	441 [168]	342 [69]	348 [75]	313 [40]

SELECTED TEMPERATURES: COMBINED CYCLE WITH FUEL CELL

Engine		Exhaust Gas Heat Exchanger		Power Turbine	Main Compressor
Type	Number	Inlet Temperature	Outlet Temperature	Exit Temperature	Exit Temperature
		K [°C]	K [°C]	K [°C]	K [°C]
Fuel Cell + Gas Turbine	1	-	739 [466]	739 [466]	923 [650]
$S - CO_2$ Engine	2	739 [466]	523 [250]	563 [289]	346 [73]
$S - CO_2$ Engine	3	523 [250]	373 [99]	385 [111]	334 [61]