Supercritical CO2 Brayton Cycles and Their Application as a Bottoming Cycle

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Introduction

- Recently, there has been a flurry of research activity aimed toward implementing a closed Brayton cycle using supercritical carbon dioxide (sCO2) as the working fluid
- The possible advantages of an sCO2 cycle include
  - A marginally higher thermal efficiency than a Rankine steam cycle operating within the same temperature range
  - Lower capital cost than a Rankine cycle due to higher power density
    - smaller turbo-machinery → lower weight → lower cost
- Most sCO2 cycle research to date concerns its application to nuclear power generation as a topping cycle, but the purpose of this project is to examine the possible benefits of using an sCO2 cycle as the bottoming cycle for a natural gas turbine topping cycle.

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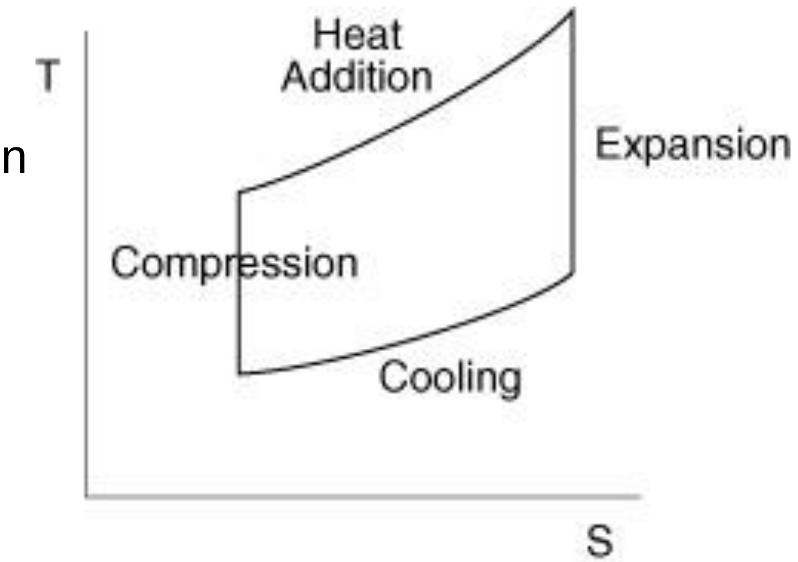
Short Discussion of Brayton Cycle

- The ideal Brayton Cycle consists of:

1. Isentropic (constant entropy) compression
2. Isobaric (constant pressure) heating
3. Isentropic (constant entropy) expansion
4. Isobaric (constant pressure) cooling



- Irreversibilities that occur during compression and expansion reduce the efficiency of real Brayton cycles
- Pressure drops through heat exchangers and recuperators also reduce the efficiency of real Brayton cycles

Assumptions

Unless otherwise noted, these assumptions were used for all of the following sCO2 cycle modeling efforts

- The terminal temperature difference (TTD) of each recuperator and heat exchanger is assumed to be 20°C
- Compressors have an assumed 85% isentropic efficiency
- Turbines have an assumed 90% isentropic efficiency
- Pressure drops through recuperators and heat exchangers have an assumed value of 0.5%
- Steady-state operation, no ramping up or down
- Perfectly insulated ducting, no heat loss to environment, except through precoolers/intercoolers

Design Constraints

- The minimum precooled stream temperature will be 37°C

- To keep the pipe and flange size low, the maximum pressure is limited to 276 bar (4000 PSI).

- The maximum cycle temperature is limited to 20°C below the exhaust temperature of the topping cycle.

- The terminal temperature difference (TTD) of each recuperator is limited to 20°C .

Benchmarks

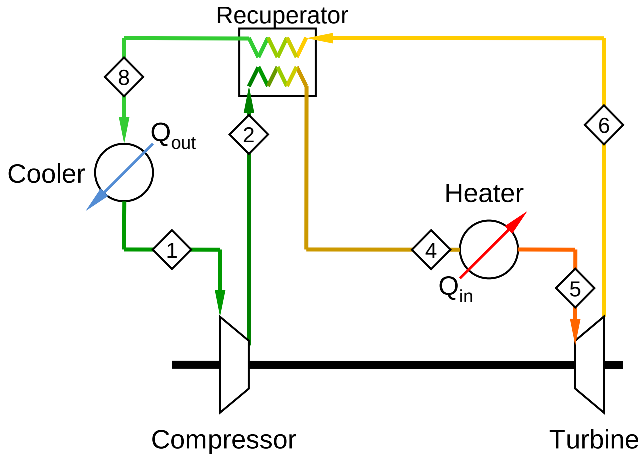
- For the purposes of this study, two modern combined cycles were used as benchmarks, the Siemens H class and the GE LM6000-PH

Combined Cycle	Siemens H class	GE LM6000-PH
Bottoming Cycle Power	195 MW	14 MW
Exhaust Flow Rate	820 kg/s	138.8 kg/s
Exhaust Temperature	625 °C	471 °C

- The exhaust properties of each topping cycle were used to model each possible sCO2 cycle configuration, and the predicted sCO2 bottoming cycle power output was recorded
- The power output of the current bottoming cycle on these plants can be compared to the theoretical sCO2 power output under the same exhaust conditions in order to gauge their performance

Initial Cycle Modeling and Analysis

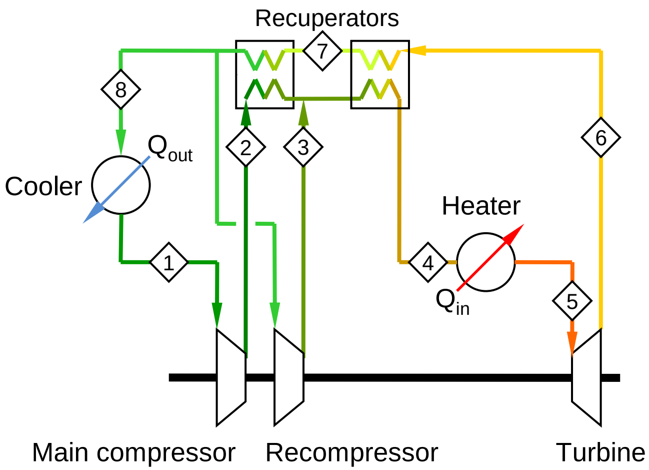
- At the start of the project, 3 commonly proposed sCO2 Brayton cycles were modeled, using the NIST fluid properties database, Refprop, in conjunction with MATLAB software.



Simple Recuperated Bottoming Cycle

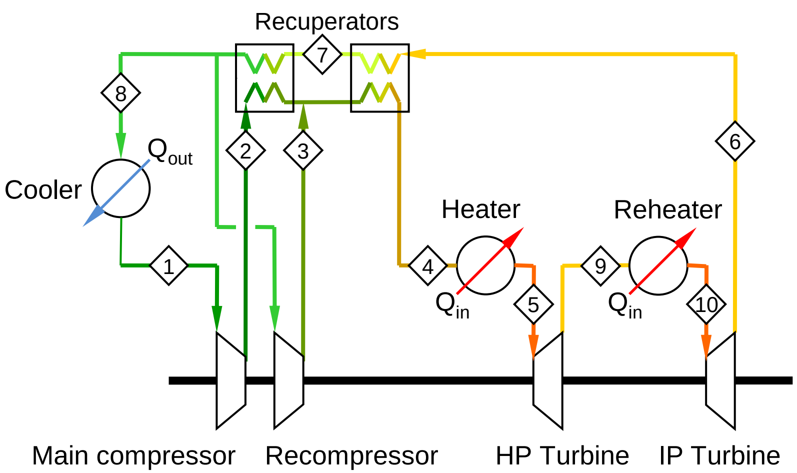
Thermal Efficiency = 40.3%

Commonly Proposed sCO2 Cycles (Cont.)



Bottoming Cycle with Recompression

Thermal Efficiency = 45.4%



Bottoming Cycle with Recompression and Reheat

Thermal Efficiency = 49.3%

Problems With Initial Modeling

- After modeling the 3 commonly proposed cycles, doubts arose concerning the performance of these cycles in a bottoming cycle application.

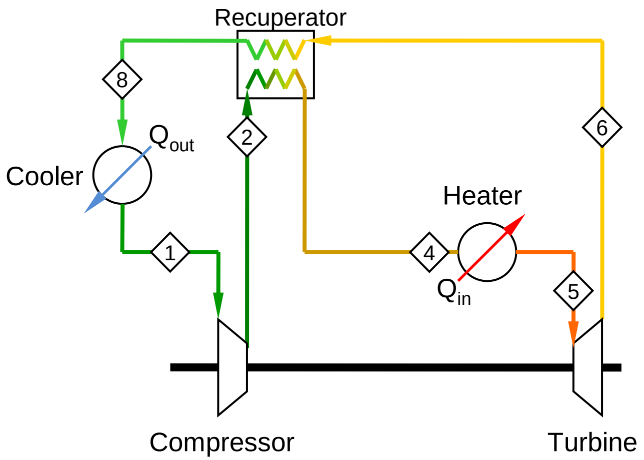
- A presentation by Echogen Power Systems explained the problem: a high thermal efficiency does not necessarily mean that the cycle will generate the maximum amount of power.

- A high performing bottoming cycle must balance thermal efficiency with the ability of the cycle to extract the maximum amount of heat from the exhaust gases.

- The 3 cycles that were initially modeled, while boasting high efficiency, do not adequately utilize the heat available to them.

An Example of the Problem

This simple recuperated bottoming cycle can be used to illustrate the problem



While this cycle can reach 40.3% thermal efficiency, there is a severely limited amount of heat available that can be converted into useful work. The heat exchanger can only recover heat from the exhaust gases if the exhaust gases have a higher temperature than the working fluid. This means that the total input heat from the exhaust gases is

$$Q_{in} = m_{exhaust} * \left(h|_{T=T_{exhaust,in}} - h|_{T=T_4+TTD}\right)$$

Due to the recuperator, T4 can be pretty high, around 400°C if this cycle was used as a bottoming cycle for the H class turbine. Once the topping cycle exhaust is cooled to nearly this temperature, no more heat can be recovered, and the exhaust leaves the combined cycle carrying a significant fraction of its initial energy, which is undesirable. A more effective configuration would utilize this wasted heat and produce more shaft power.

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Development of a Performance Metric

- Using thermal efficiency to describe the performance of an sCO2 bottoming cycle is not sufficient
- The ideal cycle will find the balance between thermal efficiency and high heat recovery
- Specifically, the ideal bottoming cycle will maximize the value of:

$$\eta_{cycle} * \Delta T_{exhaust}$$

- In order to judge the relative performance of an sCO2 bottoming cycle against a Rankine steam cycle, analysis should compare the power output, rather than the efficiency

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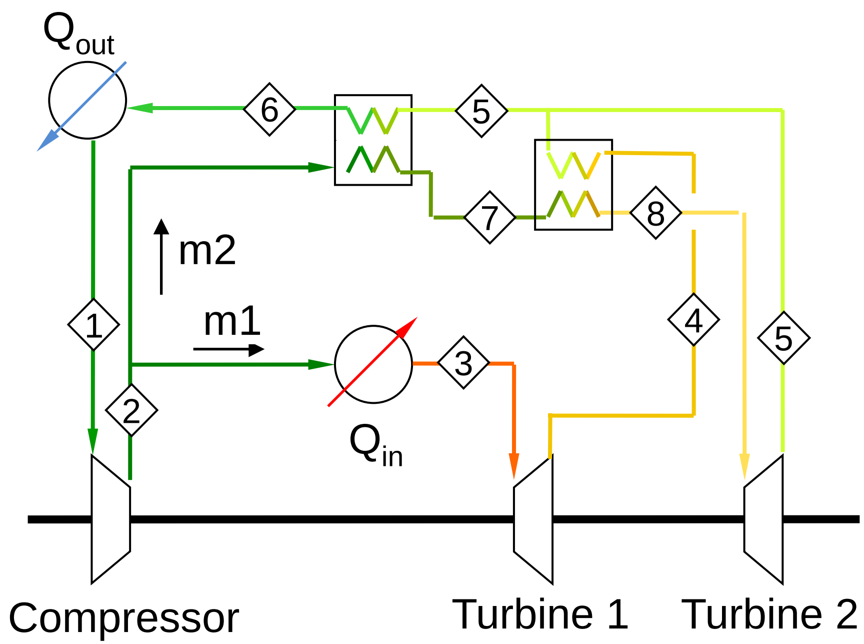
Echogen’s Solution

- In a presentation by Echogen, a cascade style configuration was proposed



- At the cost of efficiency, the heat recovery of this configuration is significantly improved, cooling the exhaust gases to marginally above the compressor outlet temperature.

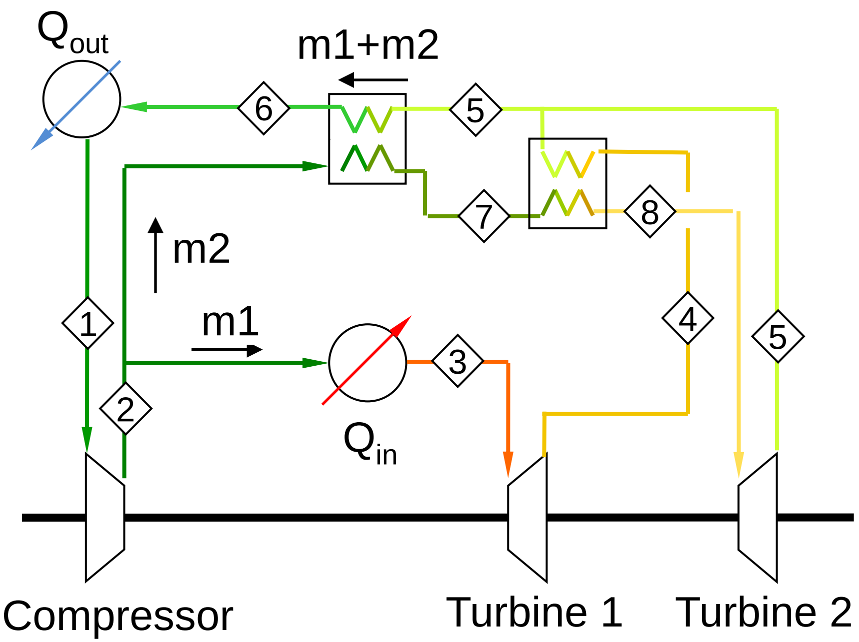
Performance of the Echogen Baseline Configuration

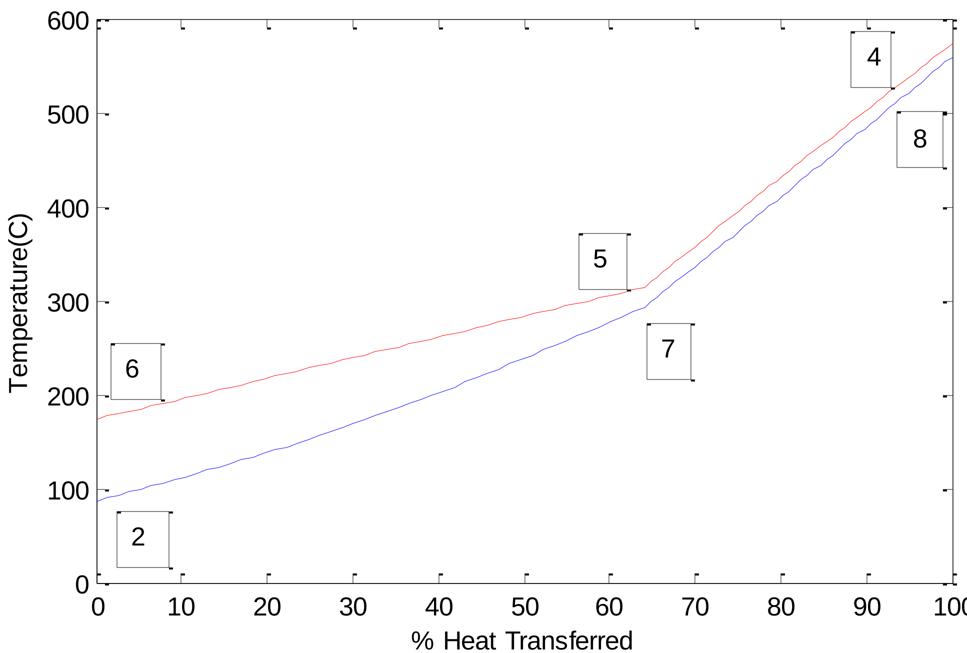
- The Echogen cycle is a definite improvement upon the initial 3 cycles modeled, due to its ability to recover a large amount of heat from the exhaust gases of the topping cycle.

	H Class	LM6000
Bottoming Cycle 1 Power	**133 MW**	**14.2 MW**
Current Steam Bottoming Cycle Power	195 MW	14.0 MW

- This cycle has marginally improved power output compared to the current LM6000 bottoming cycle, but falls short of the high efficiency steam bottoming cycle in place on the H Class.

Recuperator Temperature Profile of Cycle 1

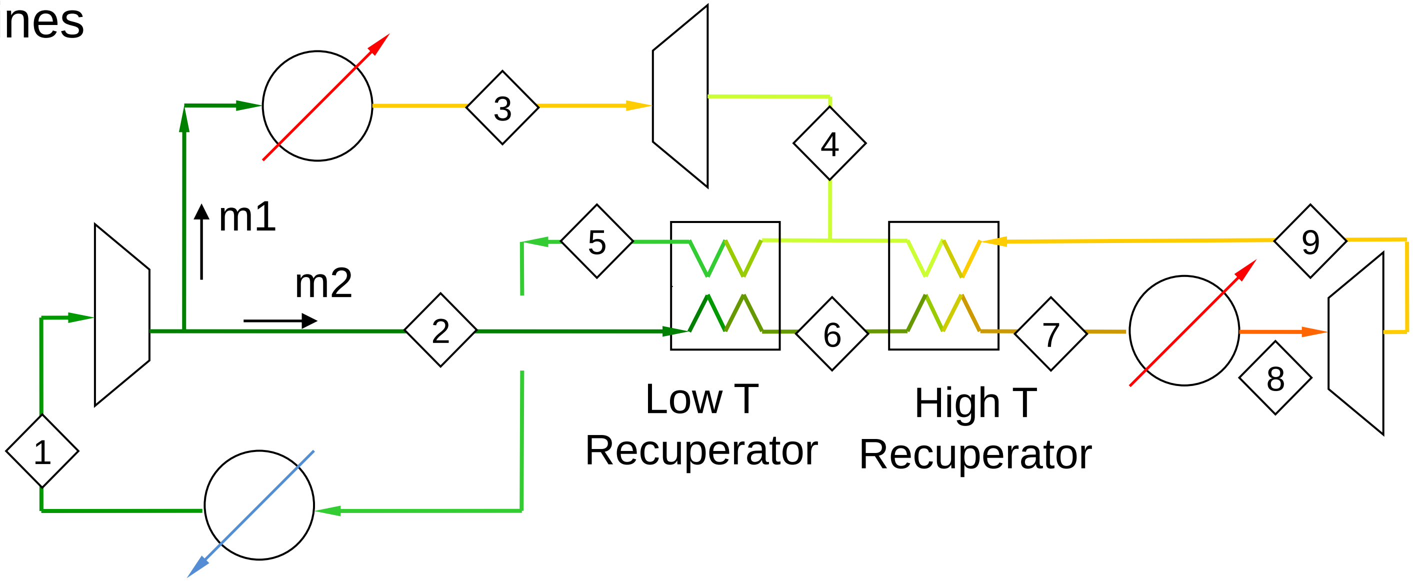




- The low temperature recuperator in this design is ineffective because of the difference in mass flow through the hot and cold side.
- The precooler rejects a lot of heat because the low temperature recuperator does not recover it.

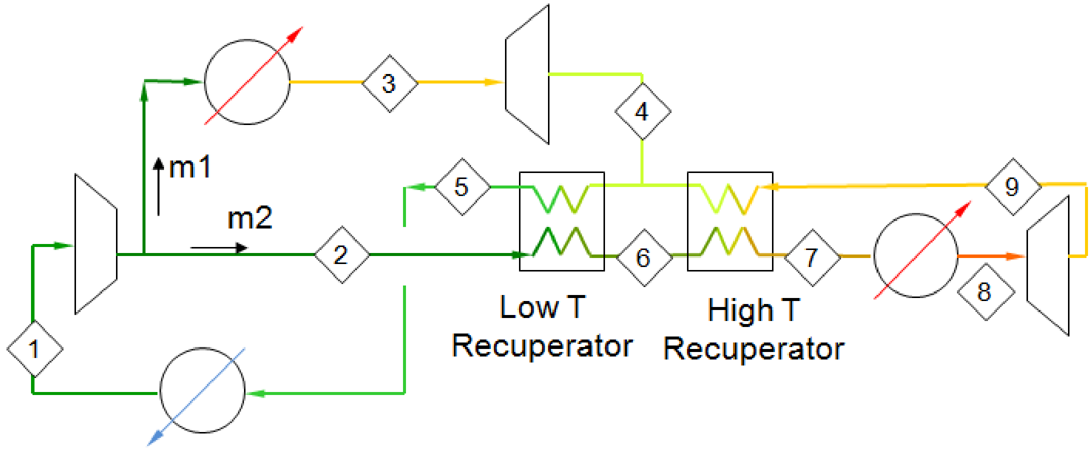
Alternative to Echogen Cycle

- In an attempt to reduce the amount of heat rejection in the precooler, I designed an alternative cycle that heats the CO2 on the way to both turbines

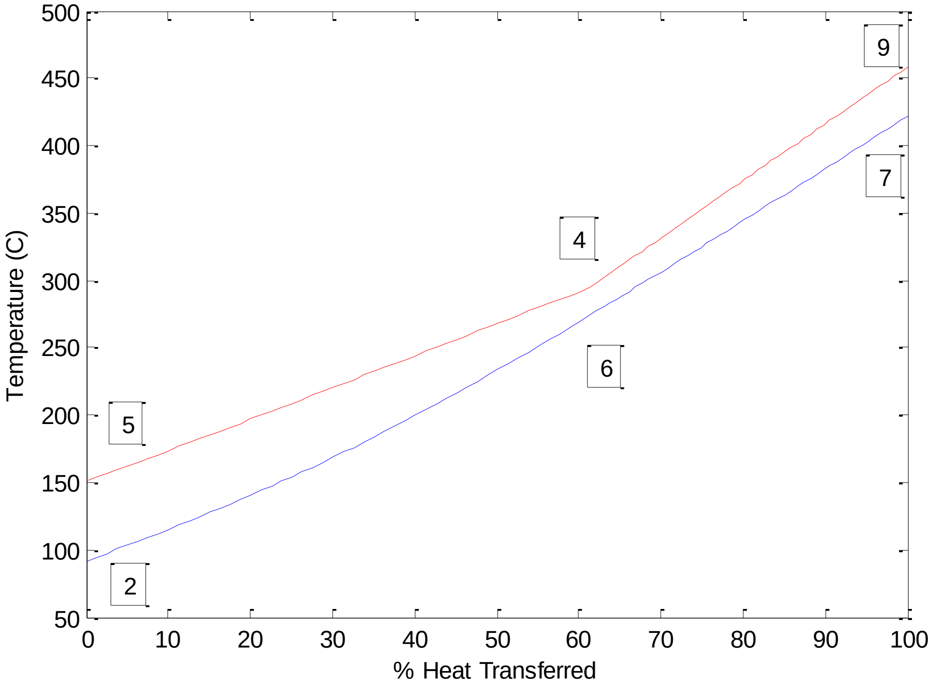


- In this configuration, m2 can be increased. This lowers the precooler inlet temperature, which means that less heat is rejected from the precooler
- This cycle will be referred to as Cycle 2 for the remainder of this presentation

Recuperator Temperature Profile of Cycle 2



- In this configuration, the precooler inlet temperature is lowered to 151°C, whereas in Cycle 1, the precooler inlet temperature was 174°C
- This means that slightly more heat was recuperated, while still maintaining the heat recovery advantages of Cycle 1



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Performance of Cycle 2

- Cycle 2 shows a slightly higher performance than Cycle 1 as a bottoming cycle for the H Class, but Cycle 1 yields a higher output than Cycle 2 when used with the LM6000

	H Class	LM6000
Cycle 1 Power	133 MW	14.2 MW
Cycle 2 Power	**145 MW**	**13.4 MW**
Current Steam Bottoming Cycle Power	195 MW	14.0 MW

- The power output of Cycle 2 is lower than the benchmark power in both cases

Effect of Intercooling on Cycle Performance

- One possibility for improving the net power output of these bottoming cycles is to utilize an intercooler
- Multistage compression decreases the compression work, improving the net power output of the cycle
- The effects of intercooling on each bottoming cycle are shown below

Cycle 1	H Class	LM6000
W/O intercooler	133 MW	14.2 MW
W/ intercooler	149 MW	14.4 MW

Cycle 2	H Class	LM6000
W/O intercooler	145 MW	13.4 MW
W/ intercooler	161 MW	14.8 MW

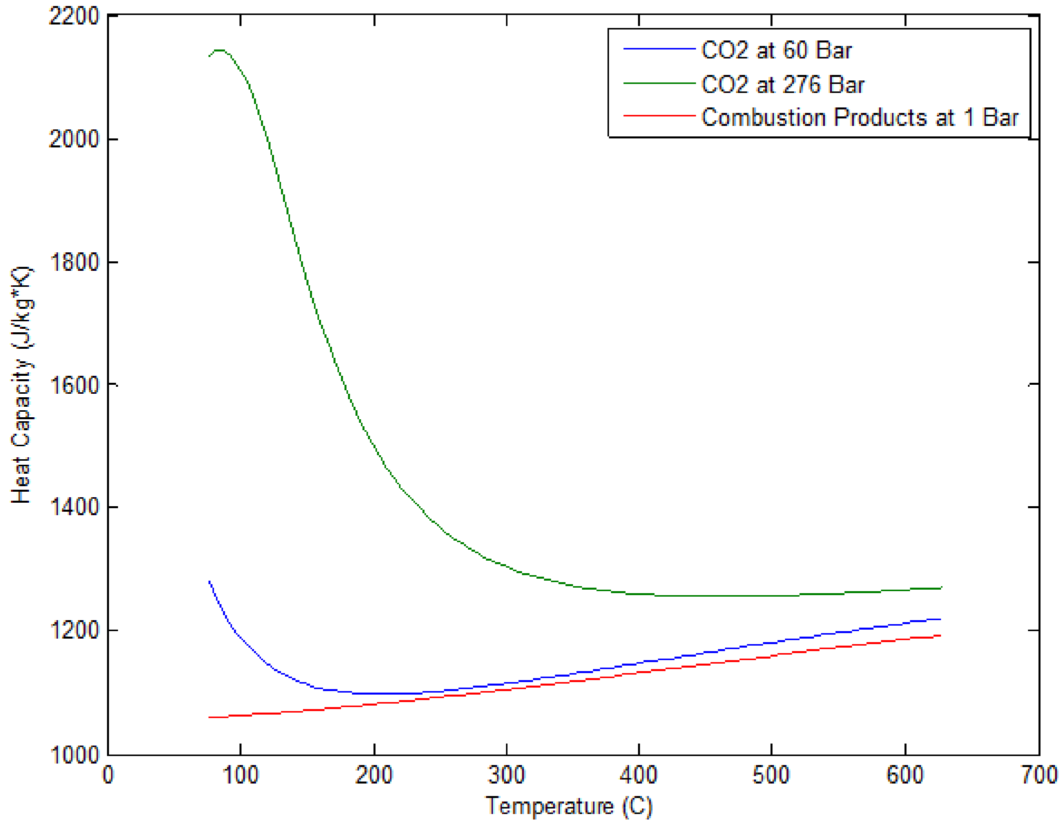
Maximizing Heat Transfer

- Both Cycle 1 and Cycle 2 reject too much heat through the precooler, rather than utilizing this heat in the recuperator.
- This effect is caused by differing stream heat capacities and mass flow rates.
- To fix this problem, a complete redesign was required, borrowing features from both the Echogen Cycle, and Cycle 2.
- The key to maximizing both external heat transfer and recuperator effectiveness can be understood by graphically examining the specific heat capacity of the high pressure and low pressure streams as the temperature changes

Heat Capacity as a Function of Temperature

Key Properties

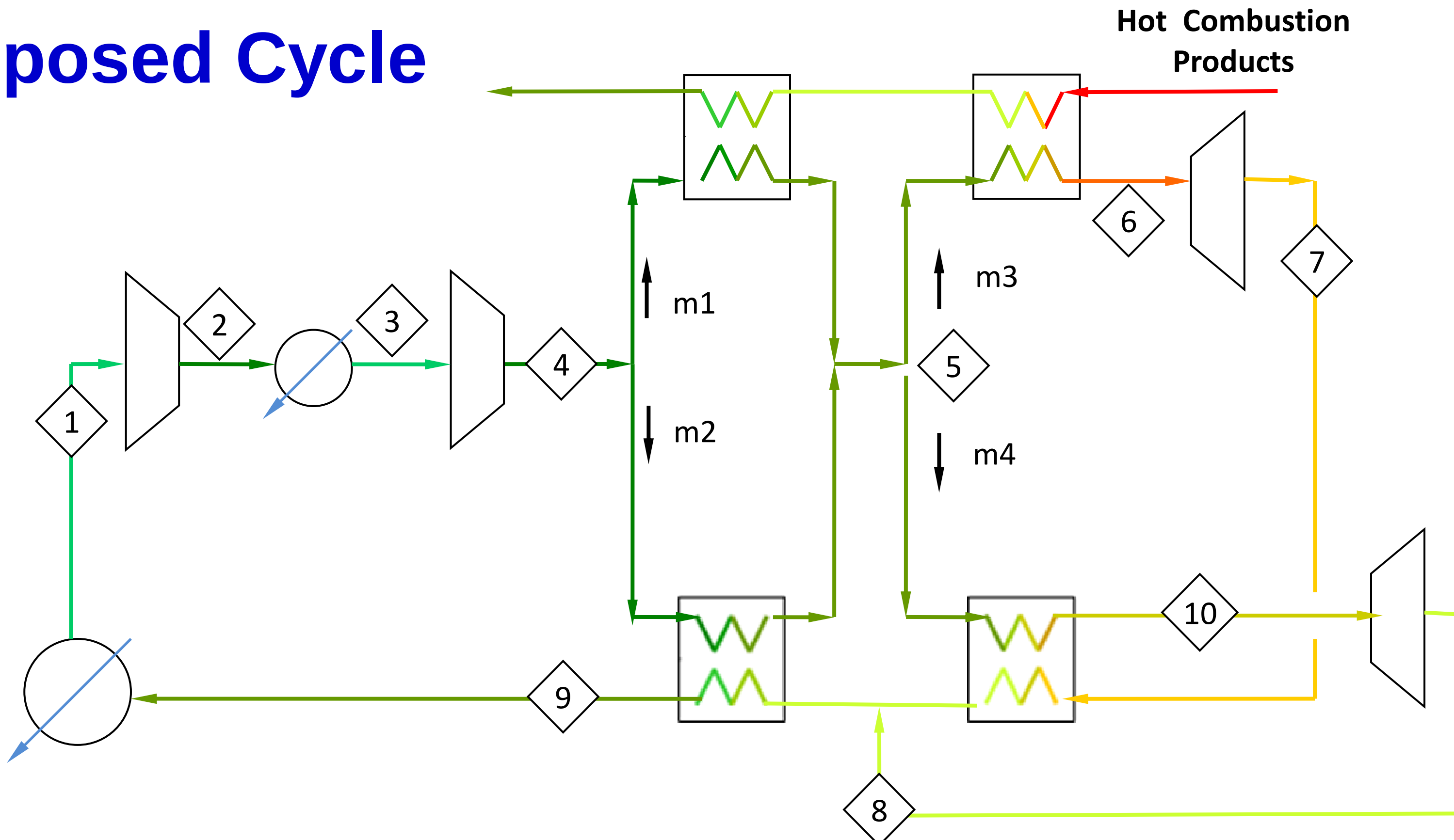
- At all relevant temperatures, CO_2 at high pressure has a significantly higher heat capacity than at low pressure.
- The heat capacity of the high pressure CO_2 drops rapidly with rising temperature.
- The low pressure CO_2 and combustions products track fairly closely, except at very low temperatures.
- The differences in heat capacity at different temperatures cause problems within the heat exchangers.
- The solution is to vary the mass flow rates according to heat capacity.



Proposed Cycle

m2>m1

m4<m3



The flow from the compressor can be heated in one of two ways:

1. Heated externally by the topping cycle exhaust gases
2. Heated internally through recuperated heat from the turbine outlet streams

Changing the mass flow rates at state 4 and 5 exercises greater control over the recuperator and heat exchanger temperature profiles, maximizing heat recovery from both the topping cycle exhaust and from the turbine outlet streams.

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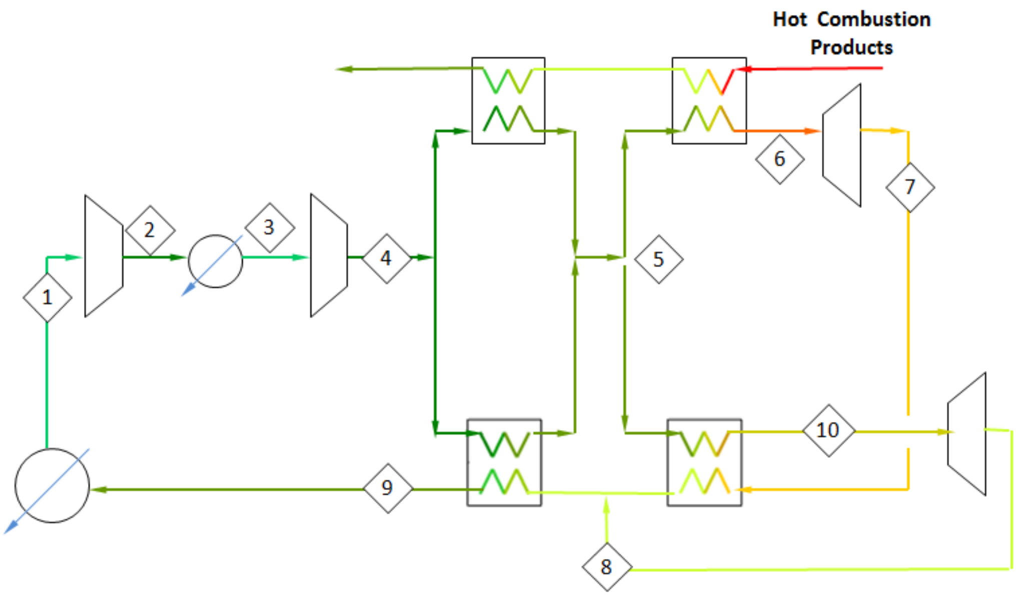
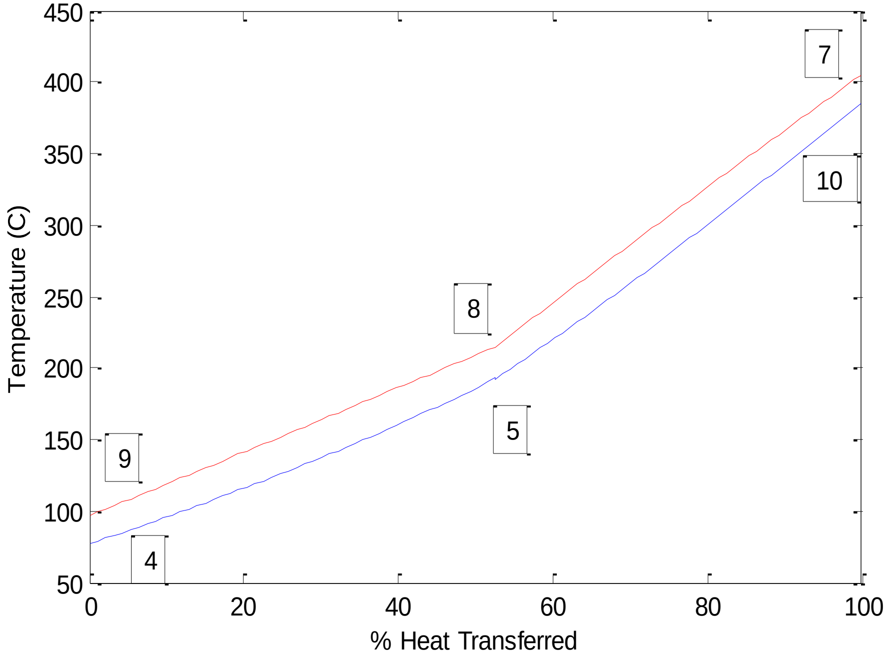
Recuperator Temperature Profile of Cycle 3





- The hot and cold side temperature track each other better in Cycle 3 than either Cycle 1 or Cycle 2.
- The precooler inlet temperature reaches a temperature nominally above the main compressor outlet temperature.
- This signifies that Cycle 3 is recuperating as much heat as possible under the design constraints, while still maintaining high heat recovery.

Cycle 3 Performance

- Cycle 3 outperforms all of the other proposed sCO2 bottoming cycles, both on the H Class and the LM6000

	H Class	LM6000
Cycle 1 Power	133 MW	14.2 MW
Intercooled Cycle 1 Power	149 MW	14.4 MW
Cycle 2 Power	145 MW	13.4 MW
Intercooled Cycle 2 Power	161 MW	14.8 MW
Intercooled Cycle 3 Power	**169 MW**	**15.2 MW**
Current Steam Bottoming Cycle Power	195 MW	14.0 MW

- Cycle 3 does not meet the power output of the H Class steam bottoming cycle.

Summary and Recommendations

- In developing a bottoming cycle, the overall power output is a more valuable description of performance than thermal efficiency.
- An effective CO2 bottoming cycle will balance thermal efficiency with the ability to recover a large portion of heat from the exhaust gases of the topping cycle.
- None of the 3 bottoming cycles modeled met the performance of the current steam bottoming cycle in place on the Siemens H class combined cycle system, although all 3 surpassed the performance of the steam bottoming cycle in place on the GE LM6000 combined cycle system.
- This suggests that an sCO2 bottoming cycle may be better suited to low-temperature applications.

Summary and Recommendations (cont.)

- Despite having lower power output than the current H class steam bottoming cycle, an sCO2 cycle may still be justified economically by the possibility of a lower capital cost.

- Future research should include a cost-benefit analysis of the cycles featured in this presentation. Although Cycle 3 boasts the highest power output of the 3 cycles in this presentation, its design is of higher complexity, which is likely to make it more costly to implement.

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Supplemental Slides

- Exhaust Composition
- Power Output of Simple Recuperated Bottoming Cycle
- Cycle Fluid Property Tables

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Exhaust Composition for Natural Gas

Component	% by mass
Argon	1.2%
CO2	6.3%
N2	73.4%
O2	13.5%
H2O	5.7%

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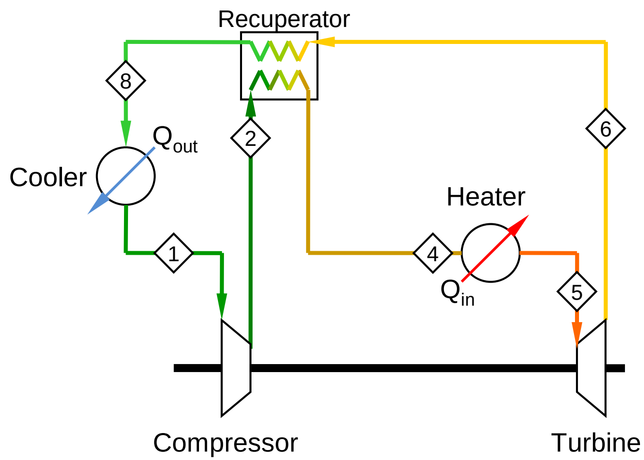
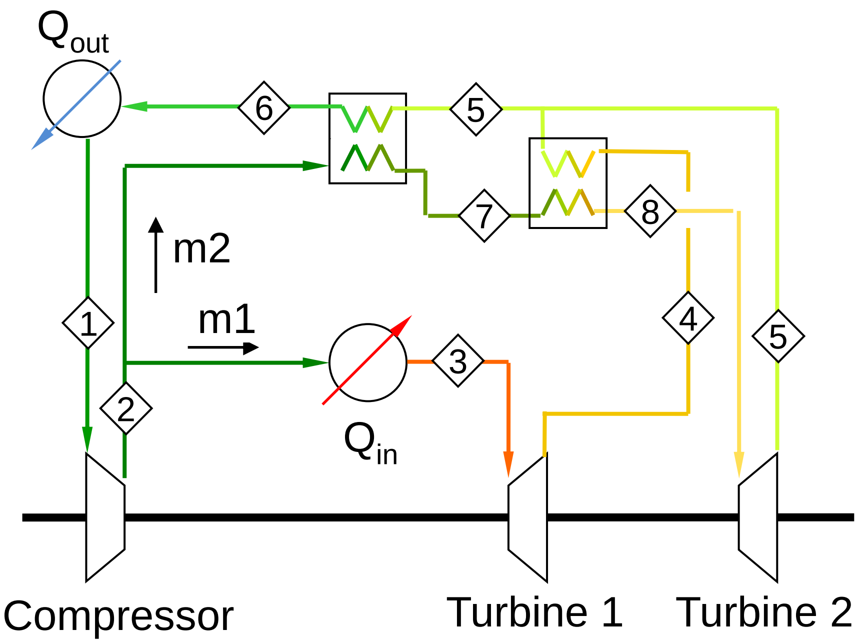
Power Output of Simple Recuperated Bottoming Cycle



	Power
H Class	94.9 MW
LM6000	11.1 MW

Cycle 1



H-class

Power Output=133 MW
Efficiency = 28.38%
m1 = .525
m2 = .475

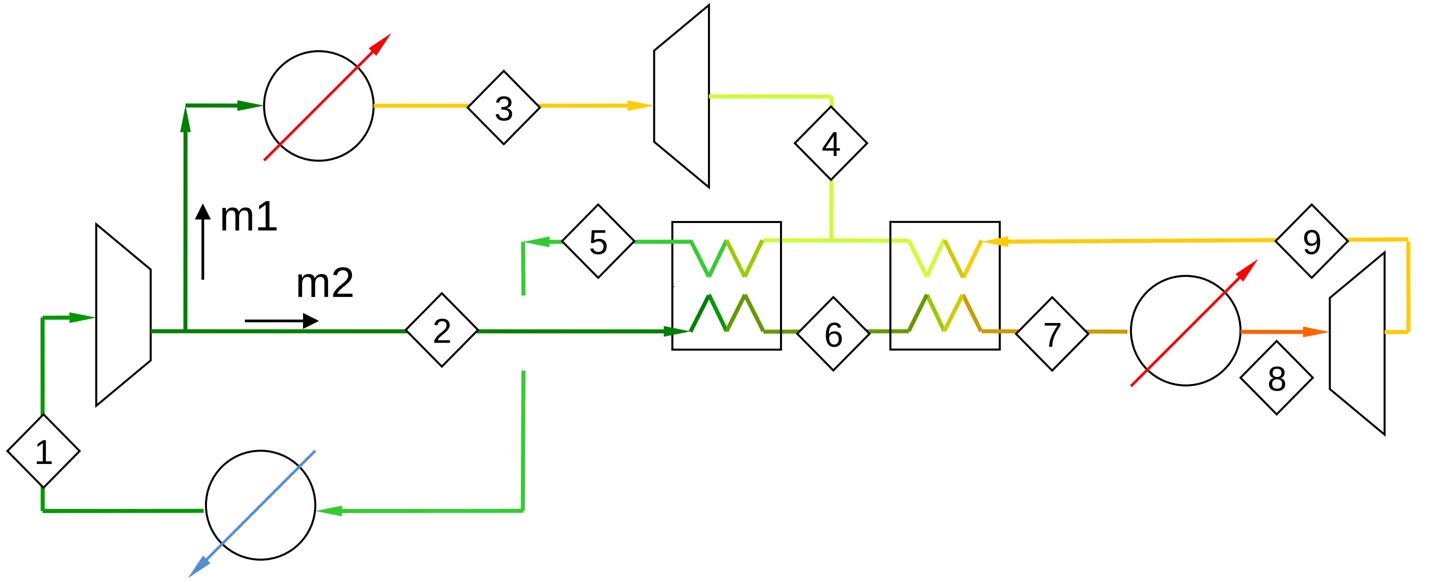
State	1	2	3	4	5	6	7	8
Pressure(Bar)	85	276	274.62	85.85642	85.42714	85.42714	274.62	273.2469
Temperature (°C)	36.85	86.368	604.85	461.2494	313.7194	173.6727	292.7264	441.2494
Enthalpy(J/kg)	332124	367957	1099625	938234	767185.1	607230	704704.8	893758.8
Entropy(J/kg*K)	1425.818	1440.82	2754.284	2778.958	2520.066	2208.536	2197.987	2495.847

LM6000

Efficieny = 25.92%
Power = 14.2 MW
m1 = .556
m2 = .444

State	1	2	3	4	5	6	7	8
Pressure(Bar)	85	276	274.62	85.85642	85.42714	85.42714	274.62	273.2469
Temperature (°C)	36.85	86.36867	450.85	322.3767	187.6403	129.0114	167.5142	302.3767
Enthalpy(J/kg)	332123.9	367957.2	905684.2	776987.3	623450.4	553607.4	525261.1	717528
Entropy(J/kg*K)	1425.818	1440.821	2511.451	2535.718	2244.283	2082.024	1837.842	2221.372

Cycle 2



H-class

m1=.45
m2=.55
Power = 145 MW
Efficiency = 31.18%

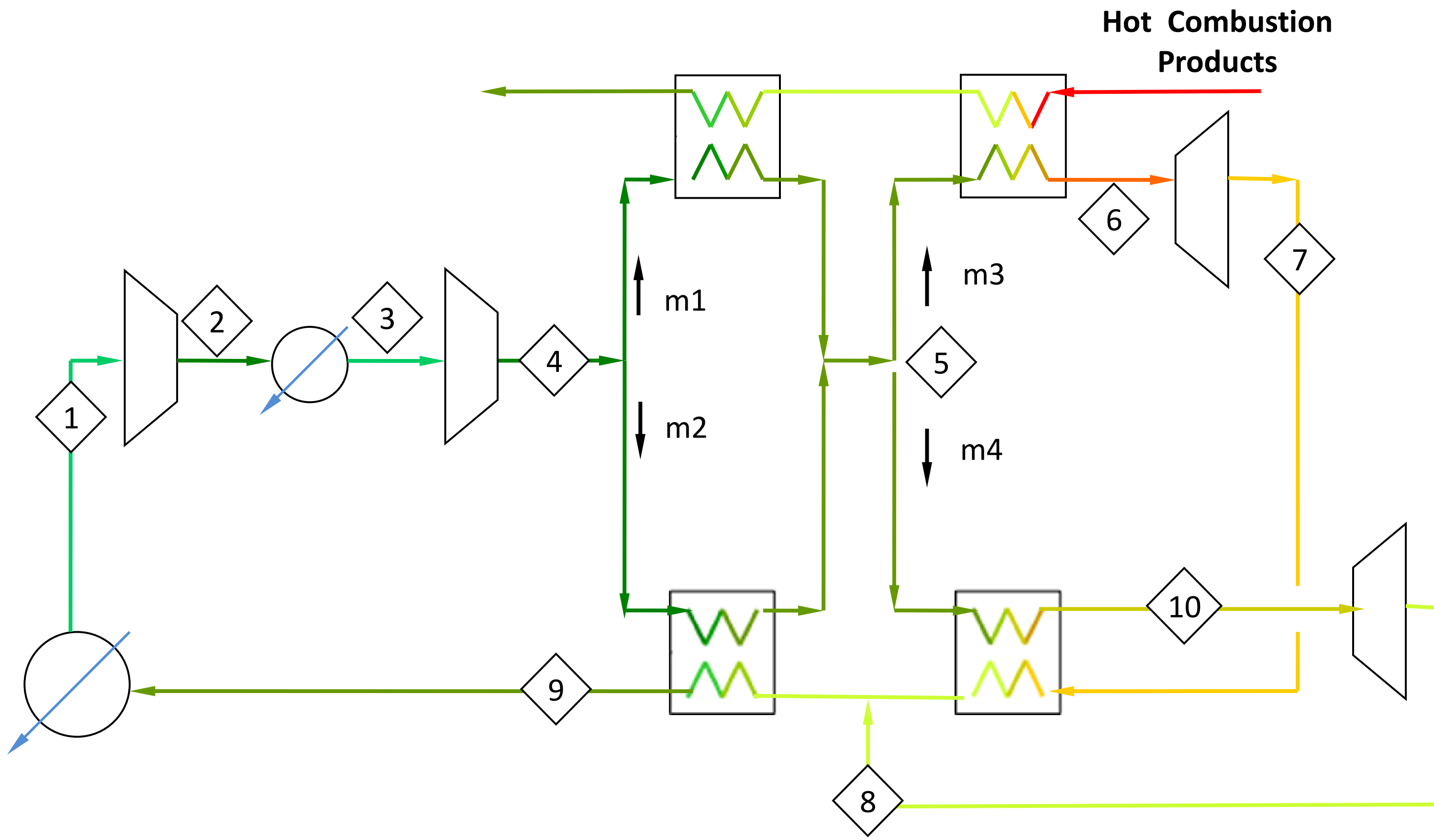
State	1	2	3	4	5	6	7	8	9
Pressure(Bar)	84	276	274.62	84.84634	84.42211	277.3869	278.7808	280.1817	85.2727
Temperature (°C)	36.85	91.75647	421.85	294.9499	150.6635	274.528	421.85	604.85	458.106
Enthalpy(J/kg)	341601.2	379495.2	869268.1	745921.6	580542.8	680183.8	868859	1099368	934596.
Entropy(J/kg*K)	1457.04	1472.67	2460.11	2484.50	2149.20	2152.12	2456.61	2749.98	2775.28

LM-6000

m1=.55
m2=.45
Efficiency = 24.78%
Power = 13.4 MW

State	1	2	3	4	5	6	7	8	9
Pressure(Bar)	84	276	274.62	84.84634	84.42211	277.3869	278.7808	280.1817	85.27271
Temperature (°C)	36.85	91.75647	246.85	136.49	117.6021	116.8103	246.85	451.15	319.8199
Enthalpy(J/kg)	341601.2	379495.2	643304.8	563183.7	539801.5	431455.7	642457	905574	774185.1
Entropy(J/kg*K)	1457.042	1472.676	2084.794	2106.72	2049.073	1609.84	2080.546	2507.378	2532.267

Cycle 3



H-class
m1 = .37
m2 = .63
m3 = .55
m4=.45
Power = 169 MW
Efficiency = 35.20%

State	1	2	3	4	5	6	7	8	9	10
Temp(C)	36.85	70.69	36.85	75.08	232.28	604.85	424.14	247.92	90.98	404.1
Pressure(bar)	50	89	88.555	276.	274.62	273.2469	50.75756	50.50378	50.25126	27324.69
Enthalpy(J/kg)	462412.5	492223.7	314865.2	345636.3	565030.8	1099688	877533.4	666540	528321.5	822911.6
Entropy(J/kg*K)	1904.897	1914.054	1368.1	1377.819	1925.654	2755.359	2792.355	2428.741	2101.43	2392.544

LM6000
m1 = .42
m2 = .58
m3 = .60
m4 = .40
Efficiency = 27%
Power = 15.2 MW

State	1	2	3	4	5	6	7	8	9	10
Pressure(Bar)	60	89	88.555	276	274.62	273.247	60.9091	60.6045	60.3015	273.247
Temperature	36.85	69.7224	36.85	76.6209	105.034	451.11	289.718	129.116	98.5531	269.718
Enthalpy(J/kg)	445743	464593	314865	347084	407980	906132	745670	567974	532655	674524
Entropy(J/kg*K)	1827	1835.27	1368.1	1381.96	1549.94	2513.05	2545.18	2174.25	2083.74	2144.44