wb1224 - Thermodynamics 2

Lecture 10 – Energy Conversion Systems

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Lecture 10 - overview

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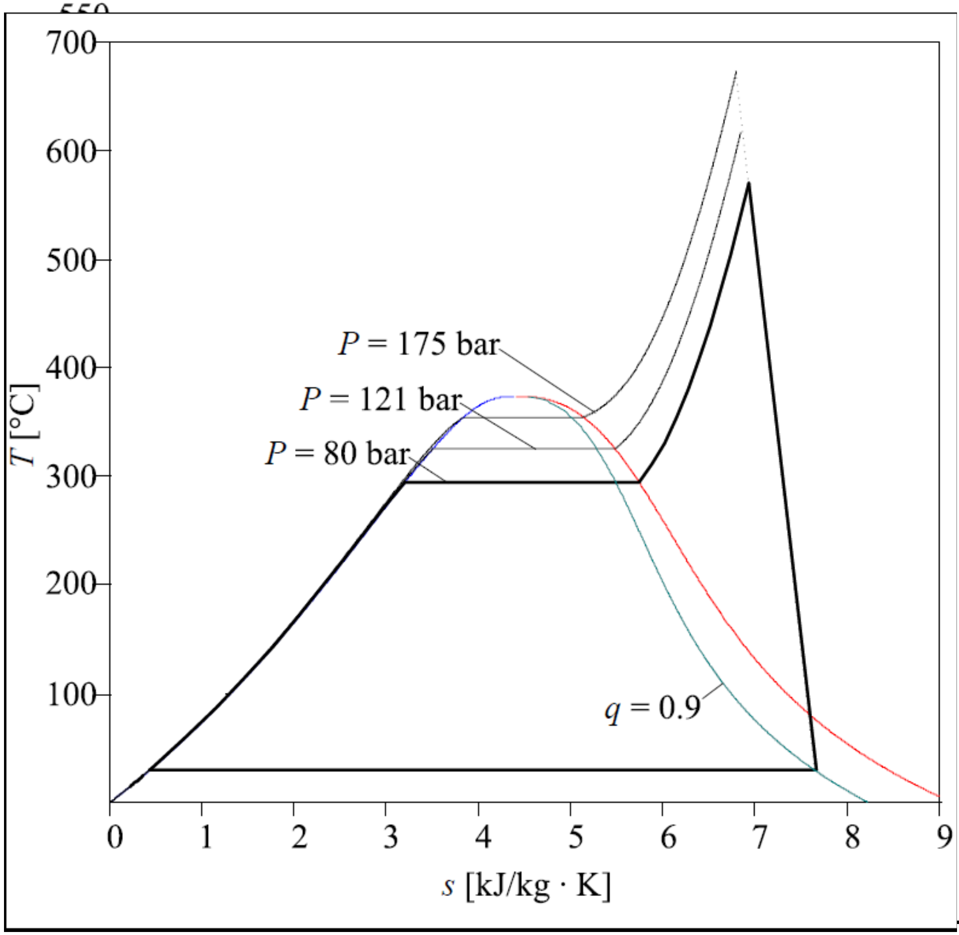
- Brayton cycle (Gas Turbines)
- Ideal vs real Brayton air cycle
- Regeneration
- Closed Brayton Cycle

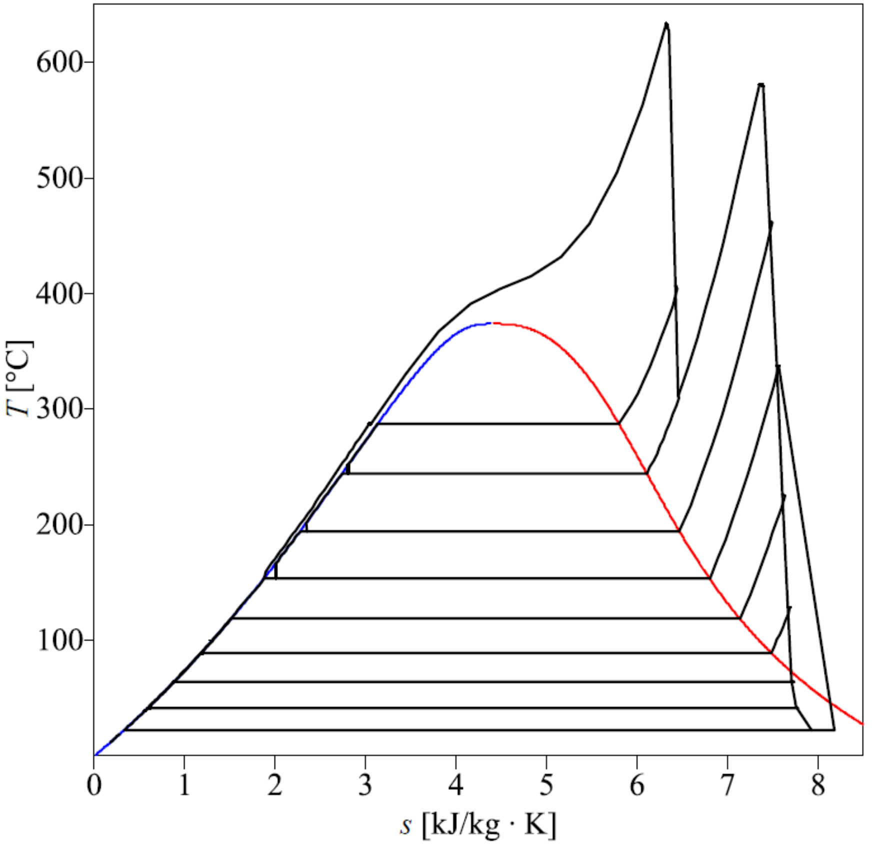
Superheating and reheating

- The steam turbine: high expansion ratio (β_P=1884) and problem of condensation
- Our example: quality q_4=0.81. Max for current turbines q_4=0.9
- From Carnot: increase of P is beneficial: thermal energy introduced at higher T
- Reheating



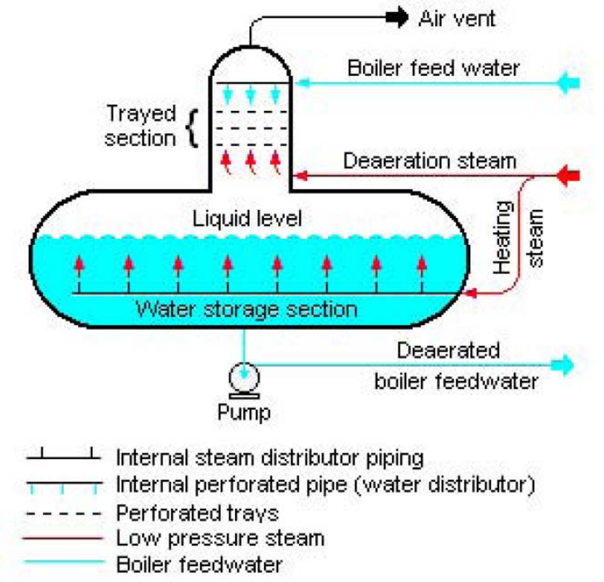
Supercritical cycle

- Efficiency: $\eta_{\text{cycle}} \propto \dfrac{T_{\max}}{T_{\min}}$
- Limit: materials
- Best steam power plants: (ultra) supercritical
- 300 bar and 630 °C, η_{cycle} = 48 %

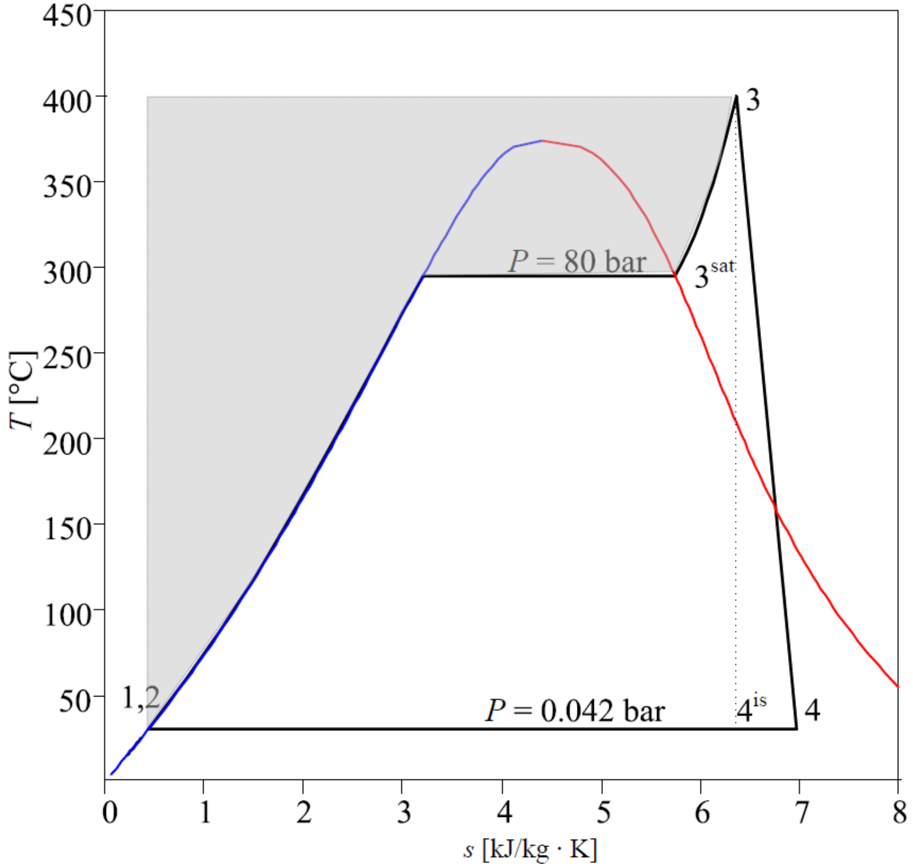


Regeneration (1)

- Need for dearation

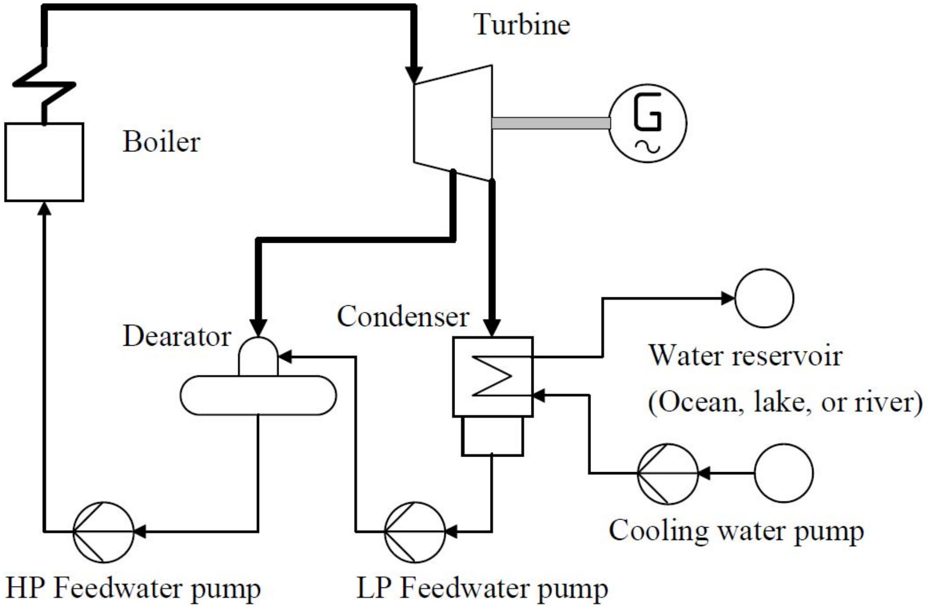


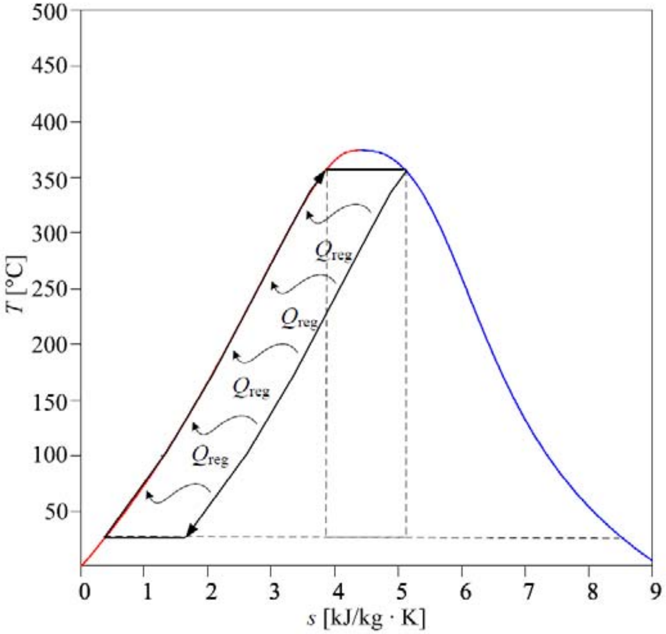
- Large inefficiency ➔ liquid preheating with steam spilled from the turbine



Difference from Carnot Cycle

Regeneration (2)

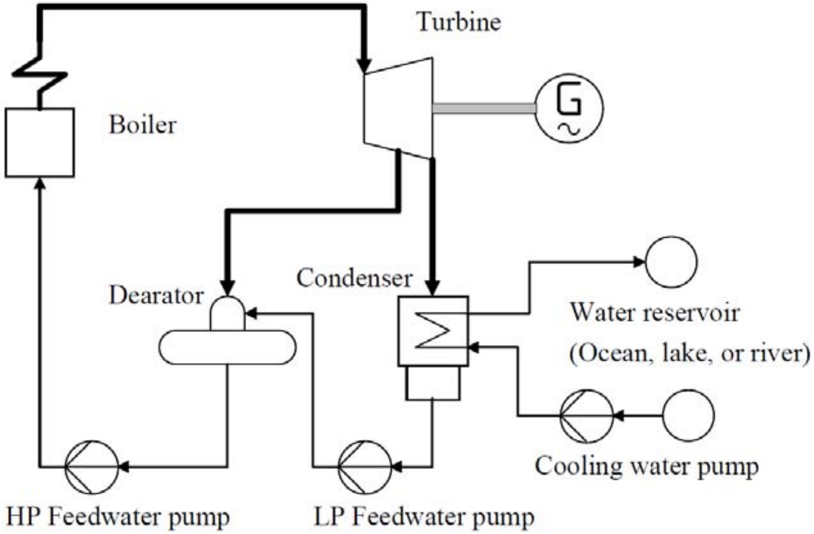


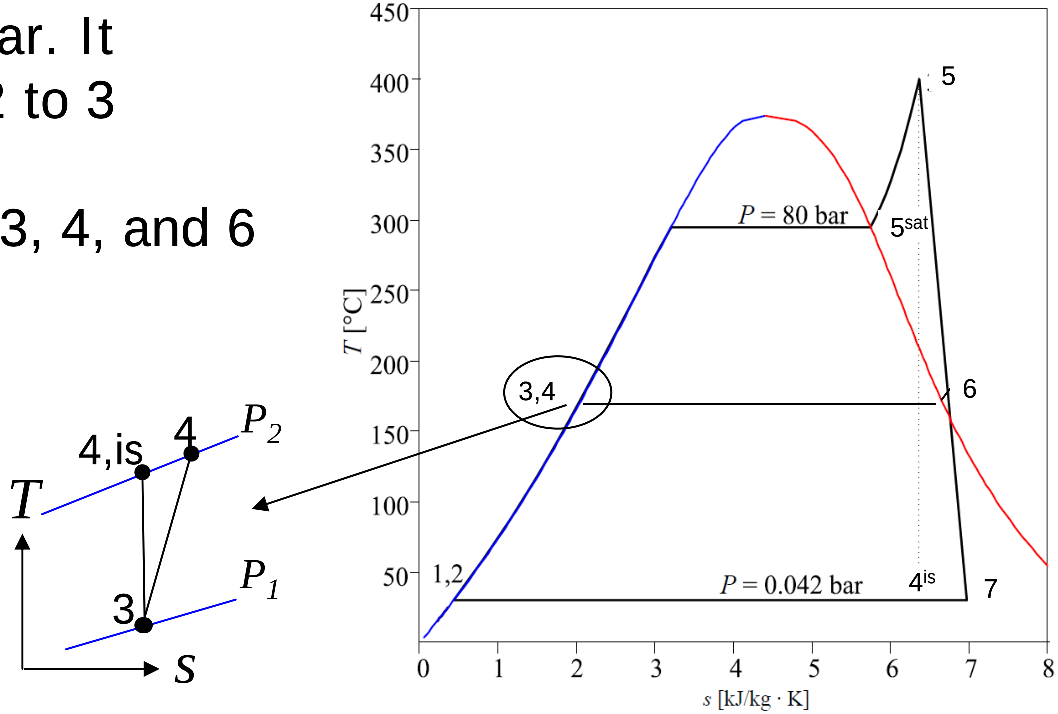


- Positive and negative effect
- Ideal: continuous regeneration = Carnot (“Arab phoenix”)
- Common to all modern ECS and processes (heat integration)

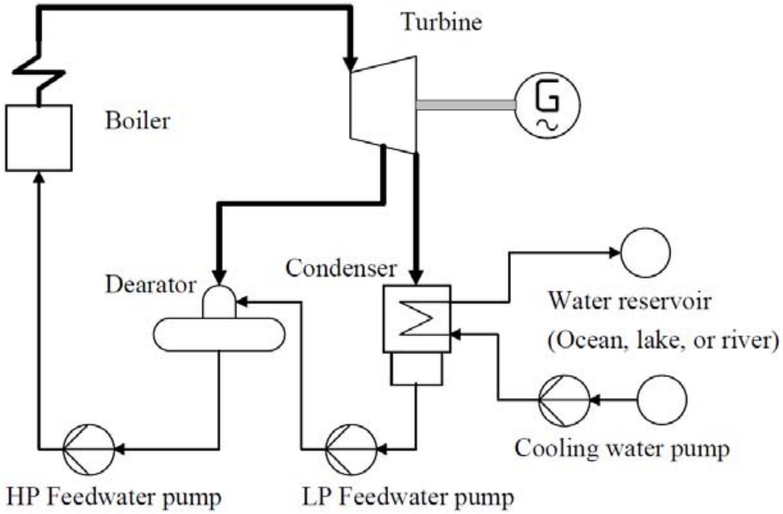
Example: evaluation of regeneration

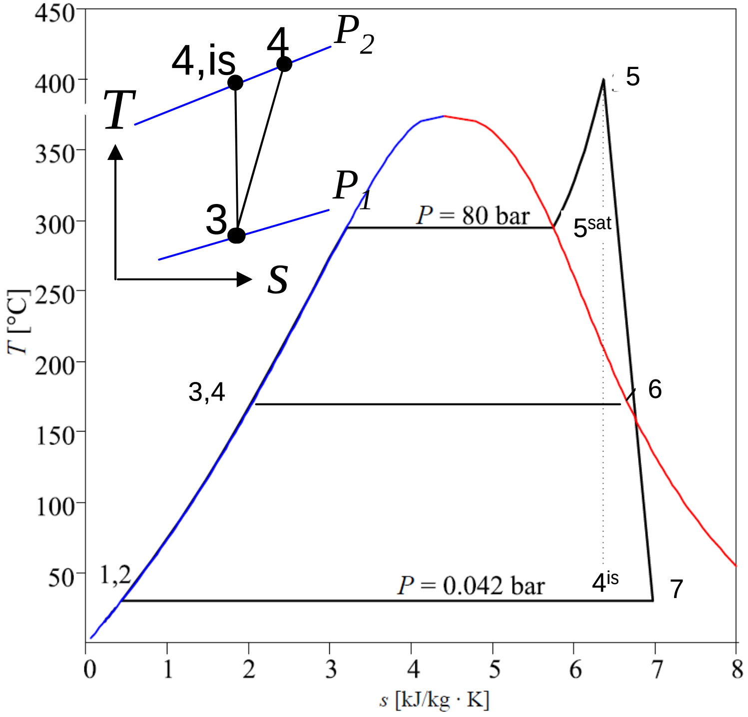
- Data as in the superheated cycle
- Steam extraction at 7 bar. It provides heating from 2 to 3
- Need to calculate state 3, 4, and 6

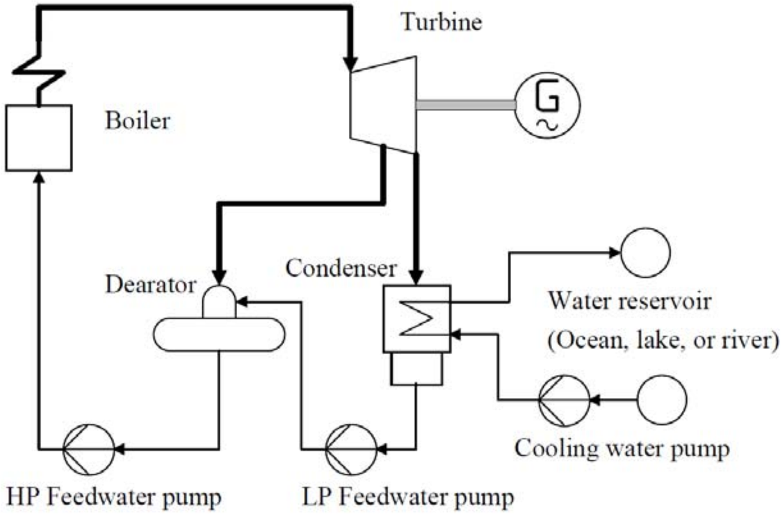


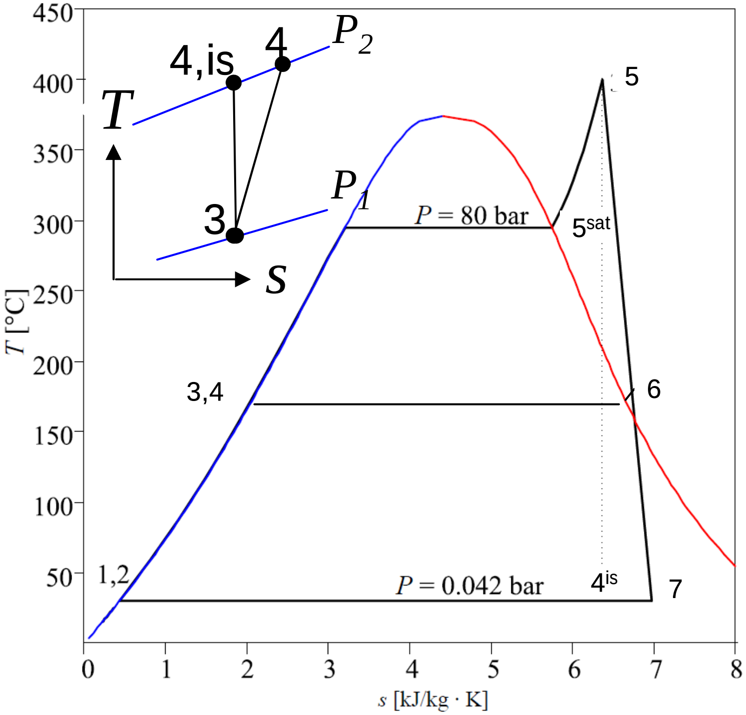


State 3 (dearator)



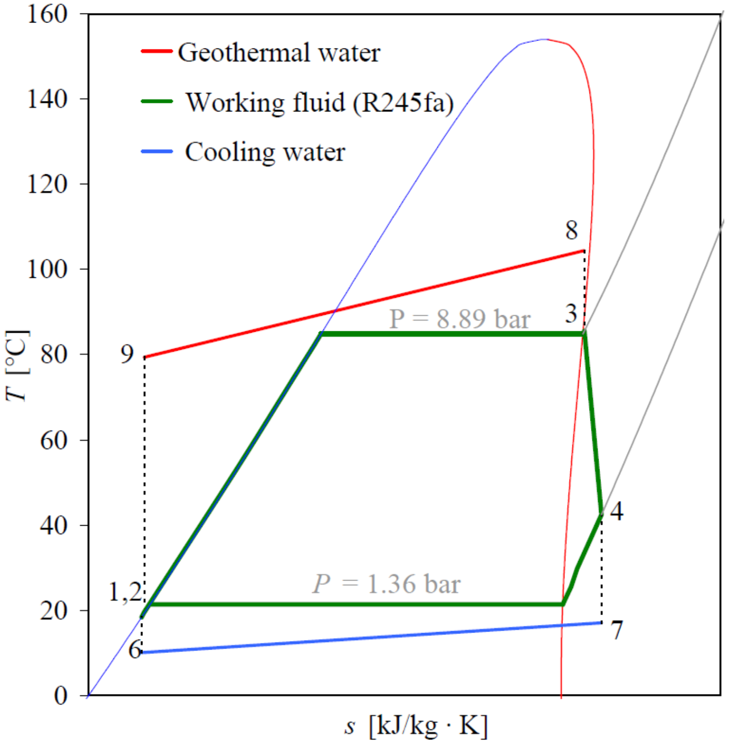



Turbine
Boiler
Dearator
Condenser
Water reservoir
(Ocean, lake, or river)
Cooling water pump
HP Feedwater pump
LP Feedwater pump


4,is
4
P_2
3
P_1
T
s
5
5^{sat}
P = 80 bar
3,4
6
1,2
P = 0.042 bar
4^{is}
7
T [°C]
s [kJ/kg · K]
450
400
350
300
250
200
150
100
50
0
1
2
3
4
5
6
7
8

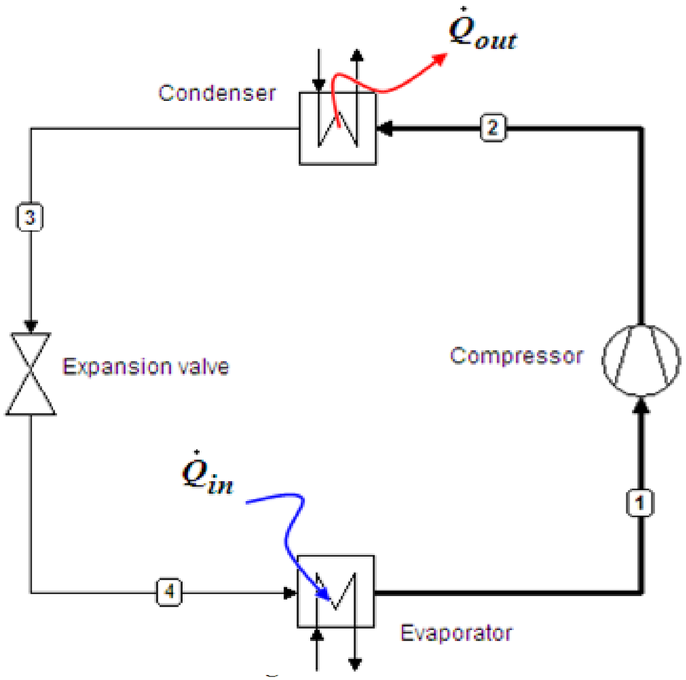
Organic Rankine Cycle turbogenerator

- Small capacity: from few kW up to 1-2 MW_e (optimal turbine)
- Renewable energy!
- Good for low-temperature heat sources (geothermal)
- Dry expansion
- Analysis: the same as steam cycle, but different fluid

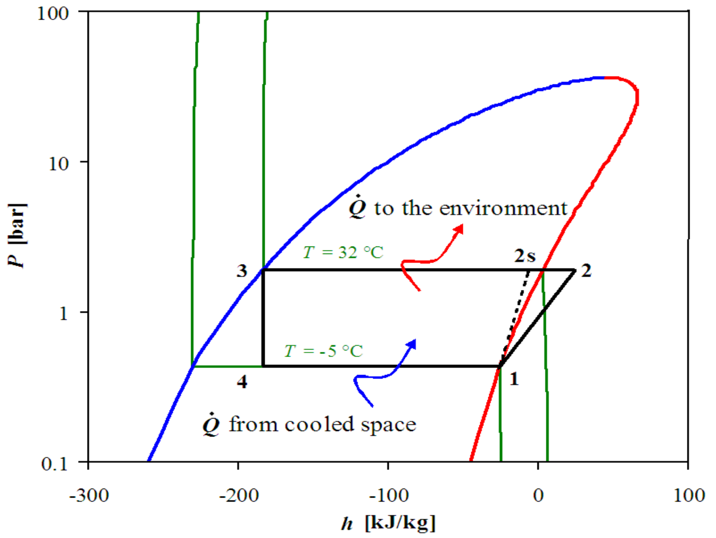


Refrigeration

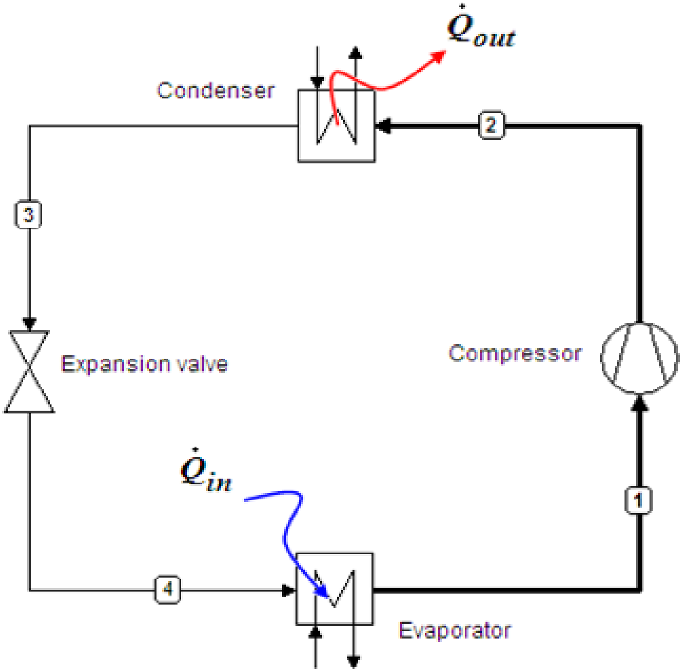
Vapor compression cycle



- Objective: cooling, thermal energy transfer (food, home,..)
- Inverse Rankine cycle (same cycle shape in the T-s and P-h diagrams)
- Thermal power transfer is obtained by means of mechanical power (compression)
- Working fluid: refrigerant to match environment conditions



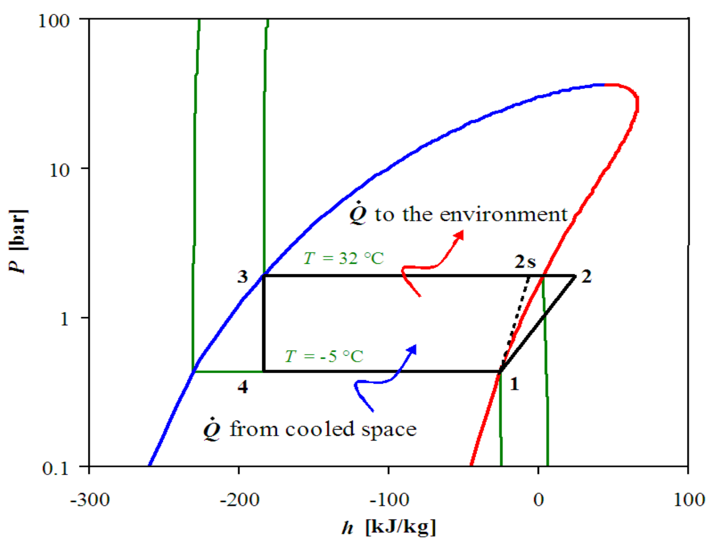
Vapor comp. cycle analysis:
Input data

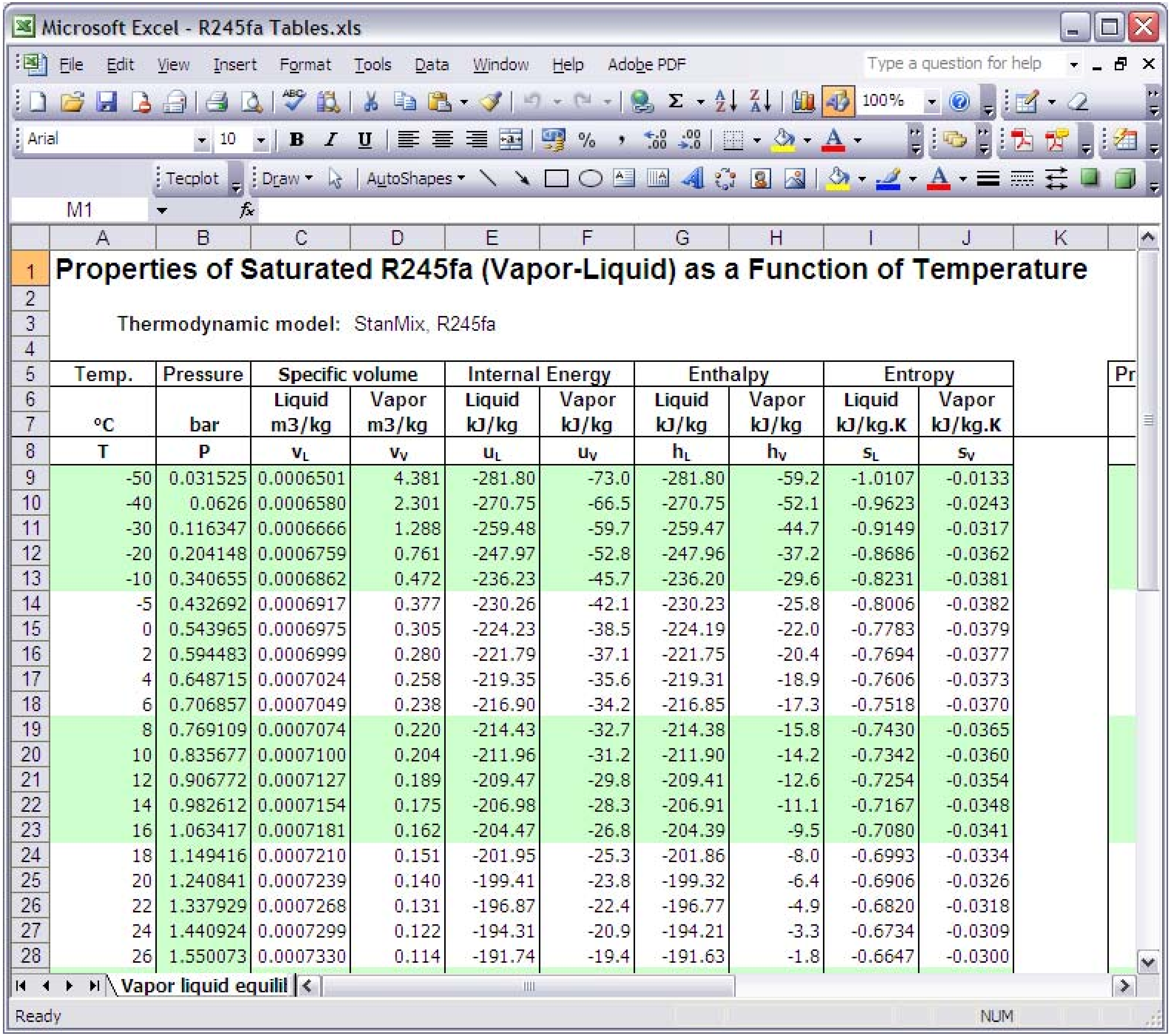


INPUT DATA

- Working fluid: R245fa
- Evaporation temperature: $T = 268.15$ K
- Condensation temperature $T = 305.15$ K
- Compressor: $\eta_{\text{is, compr}} = 0.75$

log *P*-*h* chart



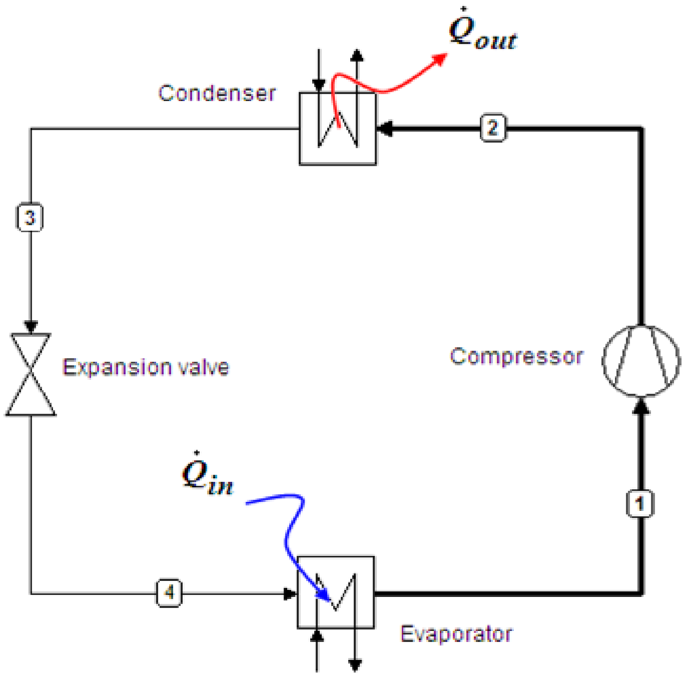


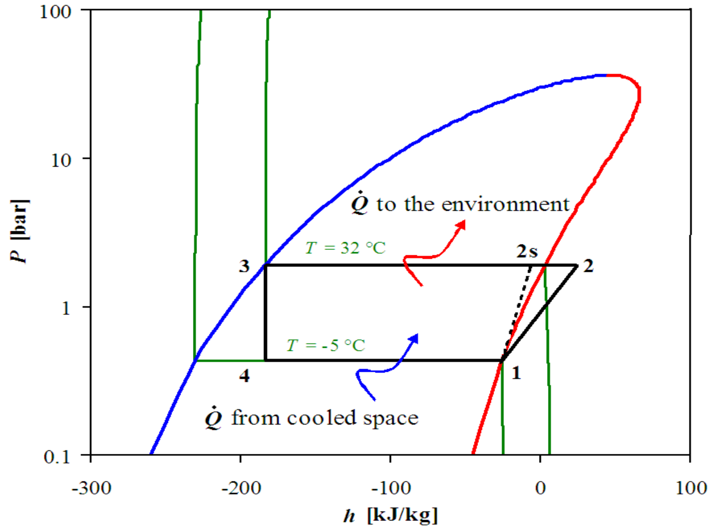
Properties of Saturated R245fa (Vapor-Liquid) as a Function of Temperature

Thermodynamic model: StanMix, R245fa

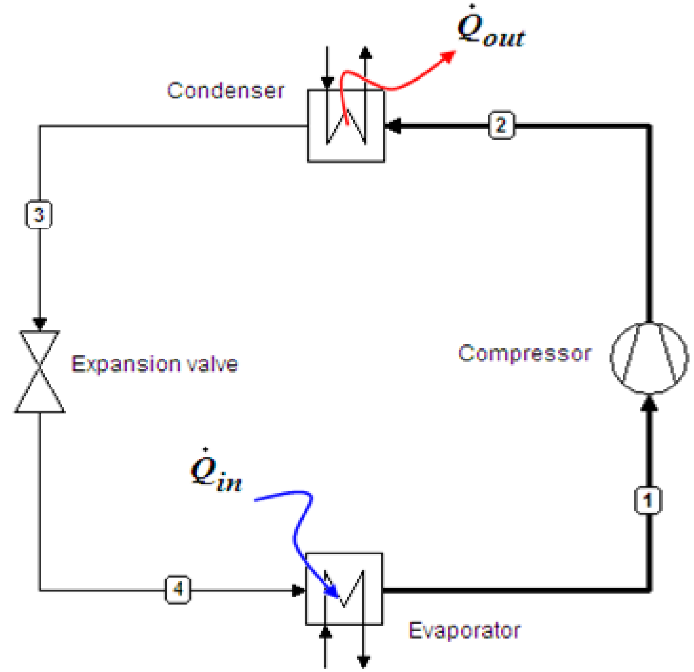
Temp.	Pressure	Specific volume		Internal Energy		Enthalpy		Entropy		Pr
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	
°C	bar	m3/kg	m3/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg.K	kJ/kg.K	
T	P	v_L	v_V	u_L	u_V	h_L	h_V	s_L	s_V	
-50	0.031525	0.0006501	4.381	-281.80	-73.0	-281.80	-59.2	-1.0107	-0.0133	
-40	0.0626	0.0006580	2.301	-270.75	-66.5	-270.75	-52.1	-0.9623	-0.0243	
-30	0.116347	0.0006666	1.288	-259.48	-59.7	-259.47	-44.7	-0.9149	-0.0317	
-20	0.204148	0.0006759	0.761	-247.97	-52.8	-247.96	-37.2	-0.8686	-0.0362	
-10	0.340655	0.0006862	0.472	-236.23	-45.7	-236.20	-29.6	-0.8231	-0.0381	
-5	0.432692	0.0006917	0.377	-230.26	-42.1	-230.23	-25.8	-0.8006	-0.0382	
0	0.543965	0.0006975	0.305	-224.23	-38.5	-224.19	-22.0	-0.7783	-0.0379	
2	0.594483	0.0006999	0.280	-221.79	-37.1	-221.75	-20.4	-0.7694	-0.0377	
4	0.648715	0.0007024	0.258	-219.35	-35.6	-219.31	-18.9	-0.7606	-0.0373	
6	0.706857	0.0007049	0.238	-216.90	-34.2	-216.85	-17.3	-0.7518	-0.0370	
8	0.769109	0.0007074	0.220	-214.43	-32.7	-214.38	-15.8	-0.7430	-0.0365	
10	0.835677	0.0007100	0.204	-211.96	-31.2	-211.90	-14.2	-0.7342	-0.0360	
12	0.906772	0.0007127	0.189	-209.47	-29.8	-209.41	-12.6	-0.7254	-0.0354	
14	0.982612	0.0007154	0.175	-206.98	-28.3	-206.91	-11.1	-0.7167	-0.0348	
16	1.063417	0.0007181	0.162	-204.47	-26.8	-204.39	-9.5	-0.7080	-0.0341	
18	1.149416	0.0007210	0.151	-201.95	-25.3	-201.86	-8.0	-0.6993	-0.0334	
20	1.240841	0.0007239	0.140	-199.41	-23.8	-199.32	-6.4	-0.6906	-0.0326	
22	1.337929	0.0007268	0.131	-196.87	-22.4	-196.77	-4.9	-0.6820	-0.0318	
24	1.440924	0.0007299	0.122	-194.31	-20.9	-194.21	-3.3	-0.6734	-0.0309	
26	1.550073	0.0007330	0.114	-191.74	-19.4	-191.63	-1.8	-0.6647	-0.0300	

Refrigeration cycle:
Anaysis (1)

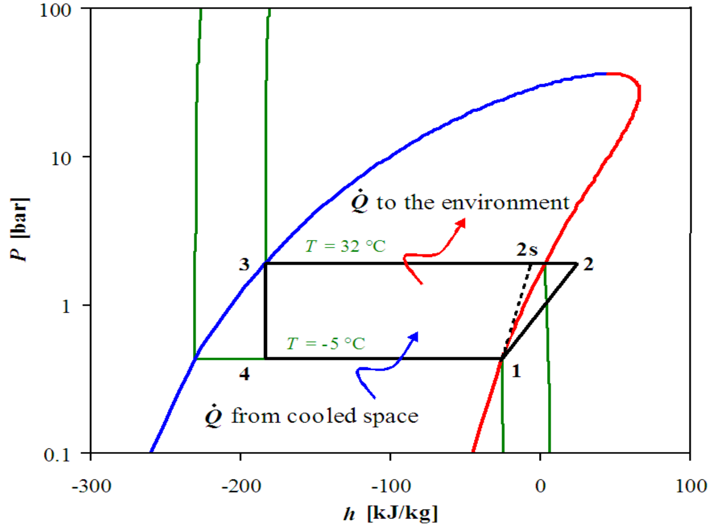




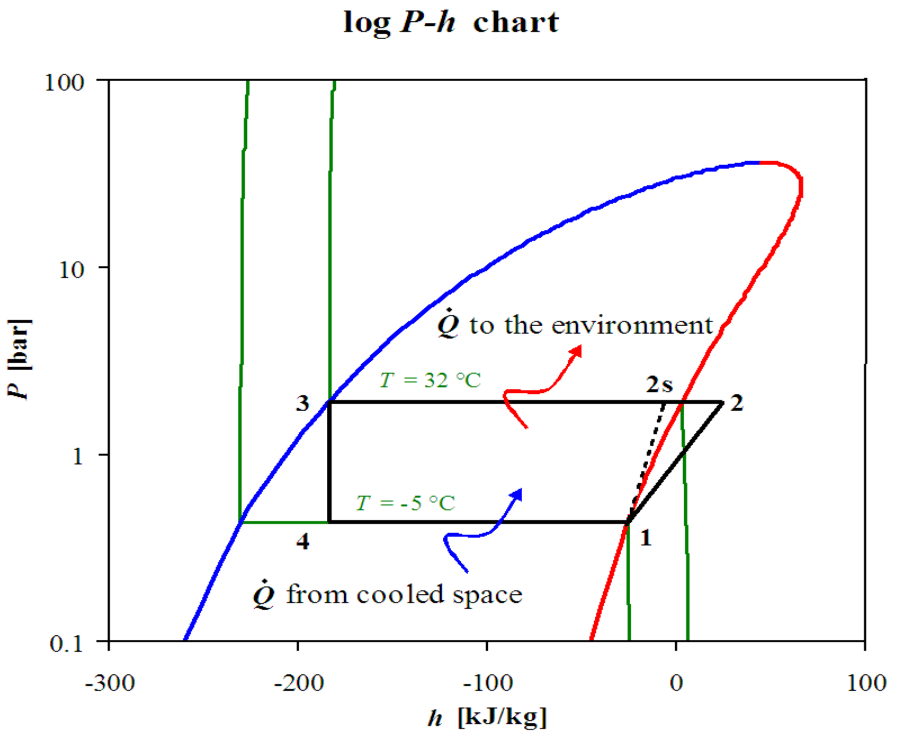
Refrigeration cycle:
Anaysis (2)



log *P*-*h* chart

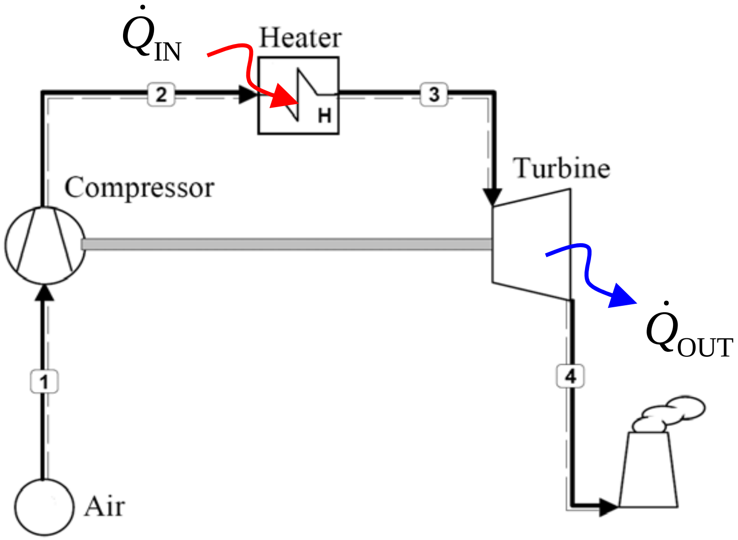


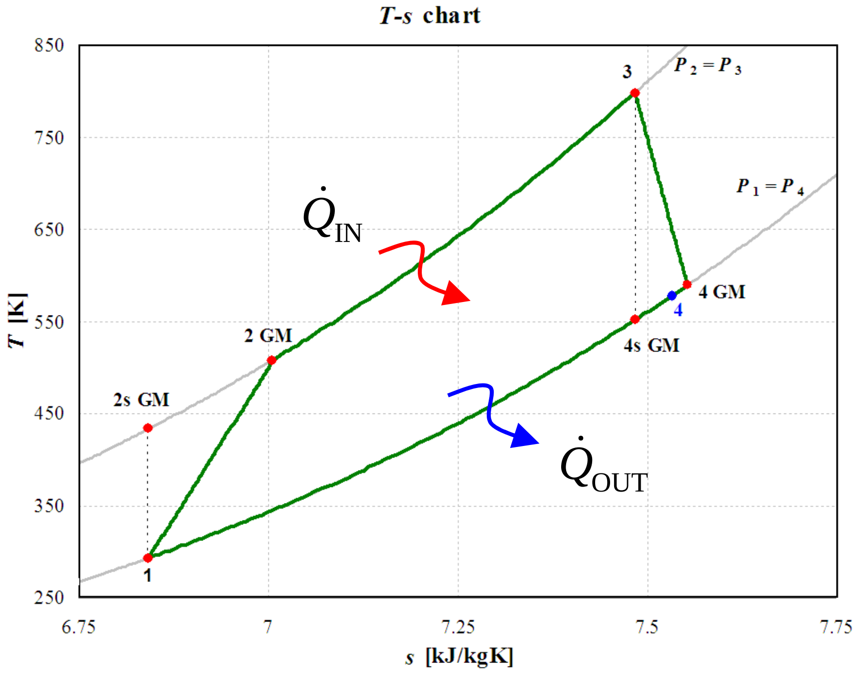
Calculation of the COP



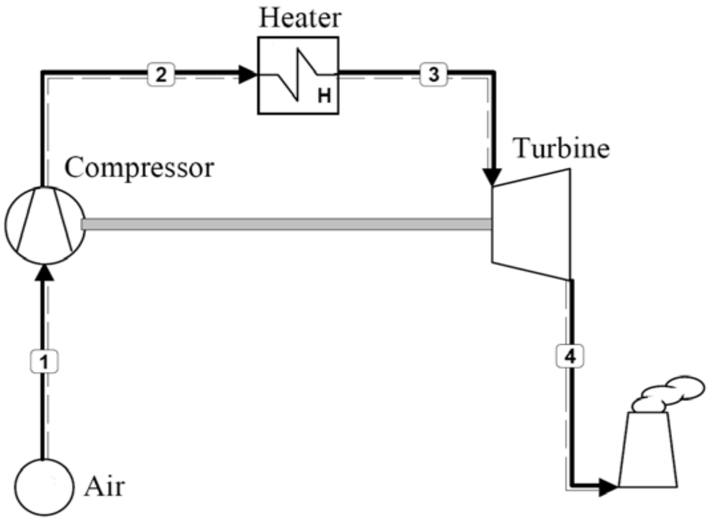
Brayton cycle

- Advantage of a gas cycle (simple, light)
- Why gas turbine came after steam engines
- Working fluid: air (ideal gas)
- Operating principle
- Processes





Brayton cycle calculation:
Input data



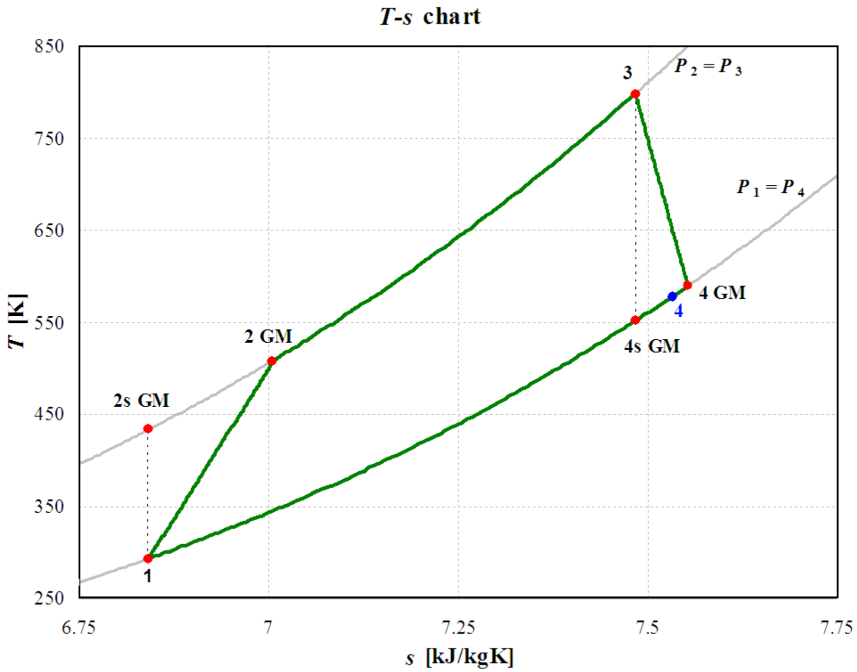
INPUT DATA: operating parameters

- State 1, 293.15K (20 °C), 1.013 bar (atmospheric pressure)
- State 2, 0.4 MPa (4 bar)
- State 3, 798.15 K (525 °C), 0.4 MPa (4 bar)
- State 4, 1.013 bar

INPUT DATA: components efficiencies

- Compressor: $\eta_{\text{is, comp}}$=0.65
- Turbine: $\eta_{\text{is, turb}}$=0.85

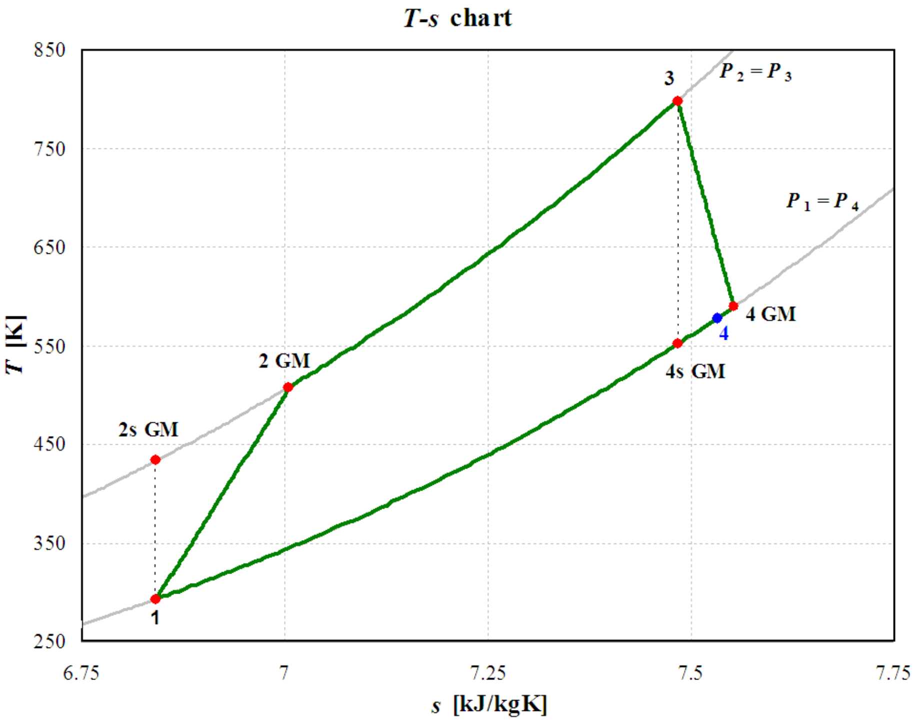
Same as in the Rankine Cycle example



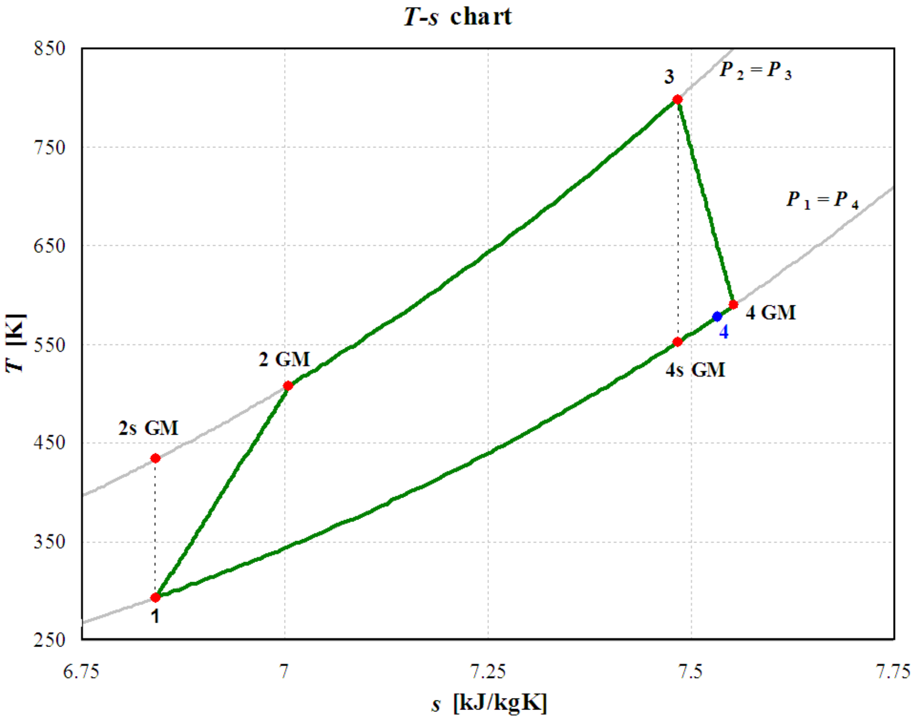
Assumptions

- Kinetic and potential energies negligible at states 1, 2, 3, and 4
- Compressor and turbine adiabatic
- No pressure drop in the heater
- The system is at steady state
- Equilibrium states at 1, 2, 3, and 4
- Air can be modeled as a polytropic ideal gas ($\gamma = 1.4$ $C_p = \text{const} = 1.04\ \text{kJ/kg}\cdot\text{K}$) or as an ideal gas with $C_p = C_p\,(T)$ (FluidProp/GasMix)

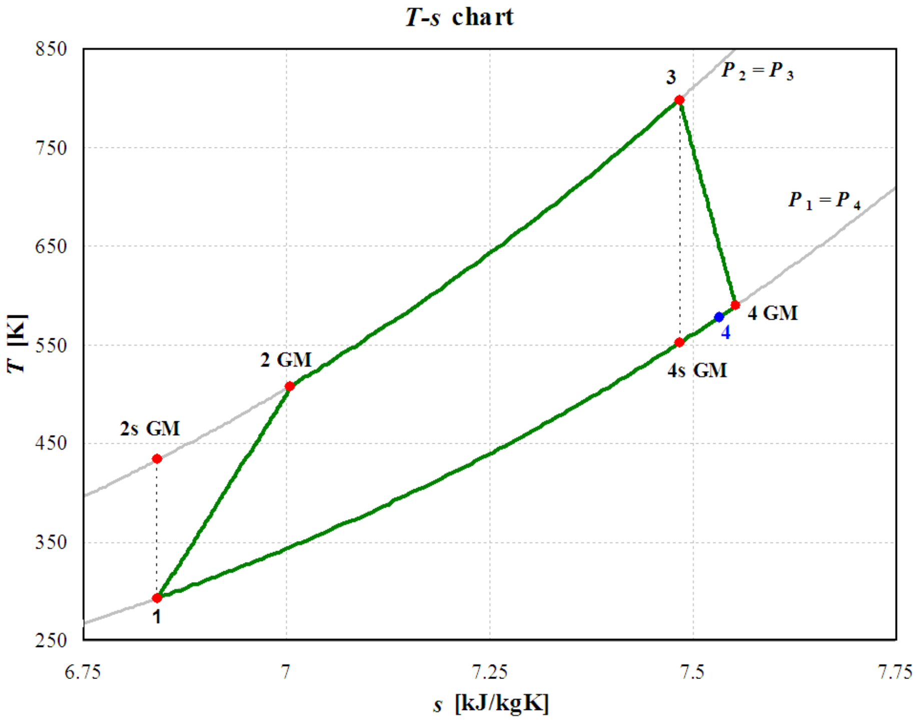
Compressor work (state 1&2)



Air Heating (state 3)



Turbine work (state 4)



Net power output and efficiency

Comparison with Superheated Rankine cycle for similar compression and expansion efficiencies, but higher TIT.

$$\eta_{\mathrm{I,Rankine}} = 0.34$$

$$\eta_{\mathrm{II,Rankine}} = 0.62$$

Efficiency of the ideal Brayton cycle

$Pv = RT, \quad c_P = \text{const.}, \text{ isentropic compression/expansion}$

$$\eta = \frac{w_\text{net}}{q_\text{in}} = 1 - \frac{q_\text{out}}{q_\text{heater}} = 1 - \frac{\overbrace{c_P\left(T_4 - T_1\right)}^{\text{divide and multiply by } T_1}}{\underbrace{c_P\left(T_3 - T_2\right)}_{\text{divide and multiply by } T_2}} = 1 - \frac{T_4/T_1 - 1}{T_3/T_2 - 1} \cdot \frac{T_1}{T_2}$$

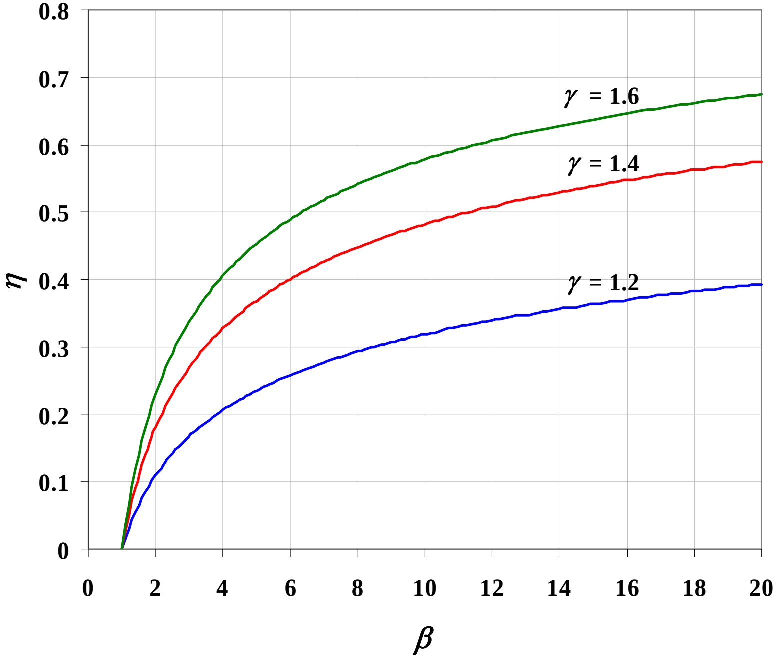
$$\frac{T_4}{T_1} = \frac{T_3}{T_2} \quad \Rightarrow \quad \eta = 1 - \frac{T_1}{T_2}.$$

$$\frac{T_1}{T_2} = \frac{T_3}{T_4} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \qquad \beta = \frac{P_2}{P_1} = \frac{P_3}{P_4}$$

$$\vartheta = \frac{\gamma - 1}{\gamma}$$

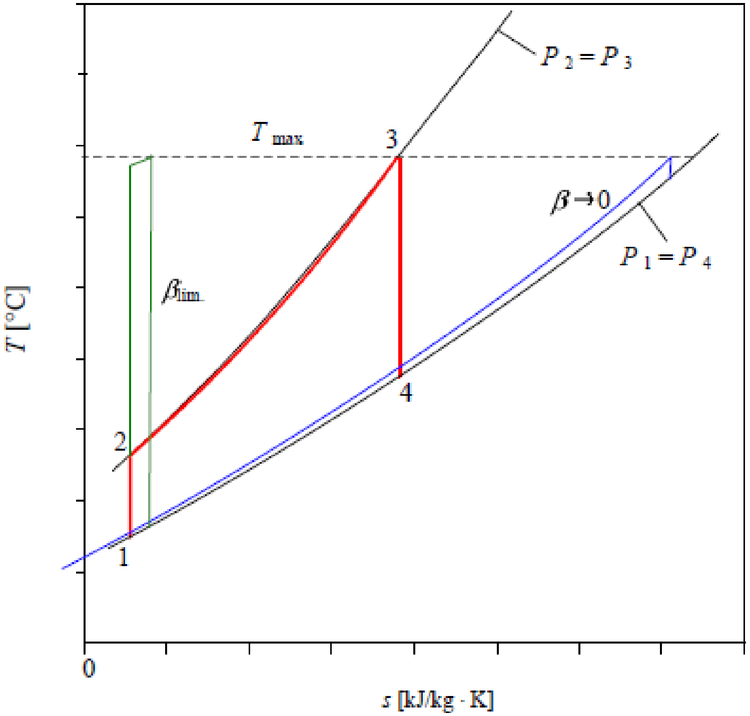
$$\eta = 1 - \beta^{-\vartheta}$$

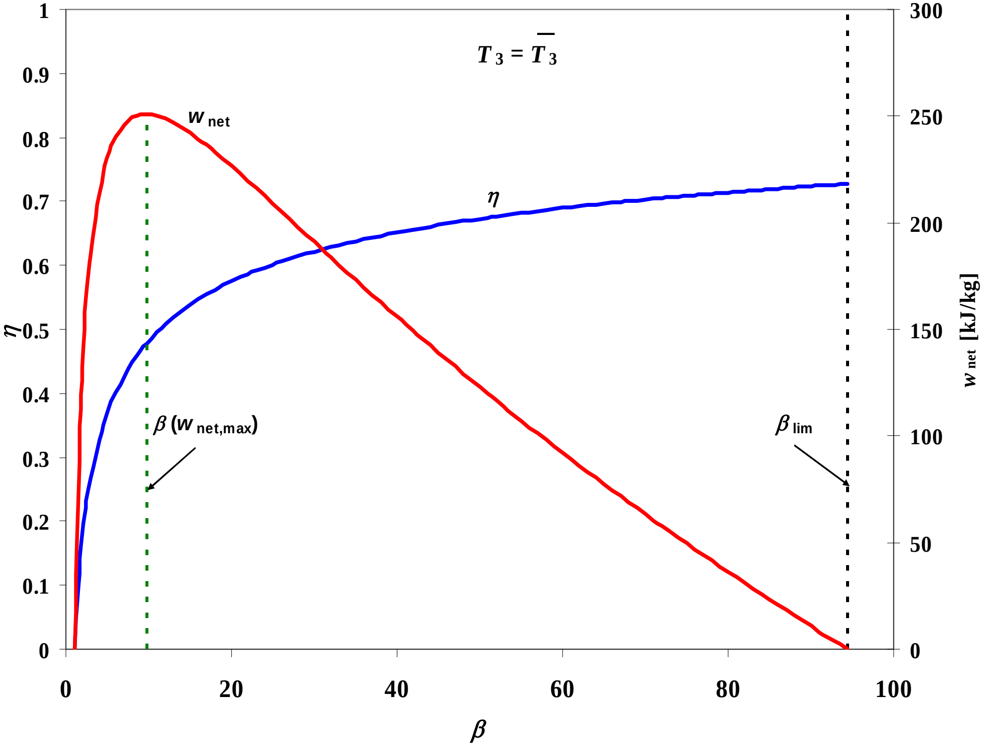
Depends only on β and γ



Ideal gas cycle

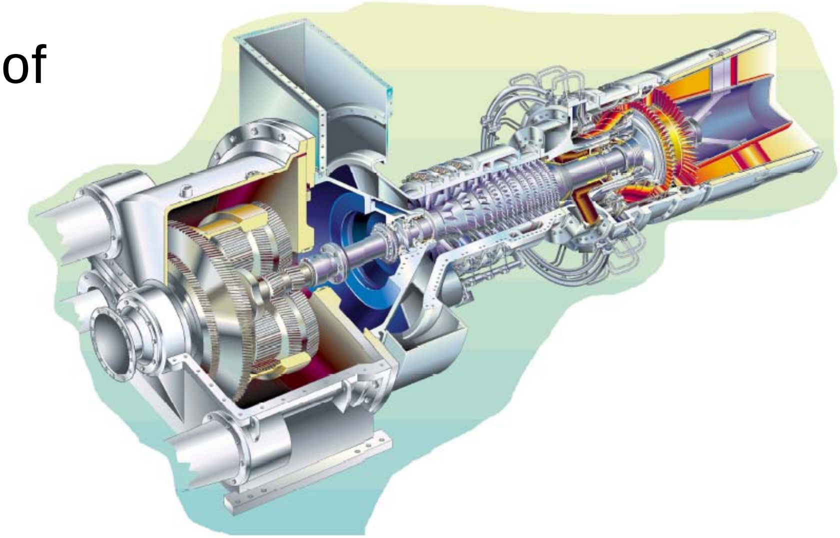
W_{net} max for $T_4 = T_2$





Comparison real vs ideal cycle

- The most relevant losses are in the compressor and turbine: limitation of ideal-gas analysis (β too high is a problem)
- Limit on TIT (blade cooling)
- Fuel issue



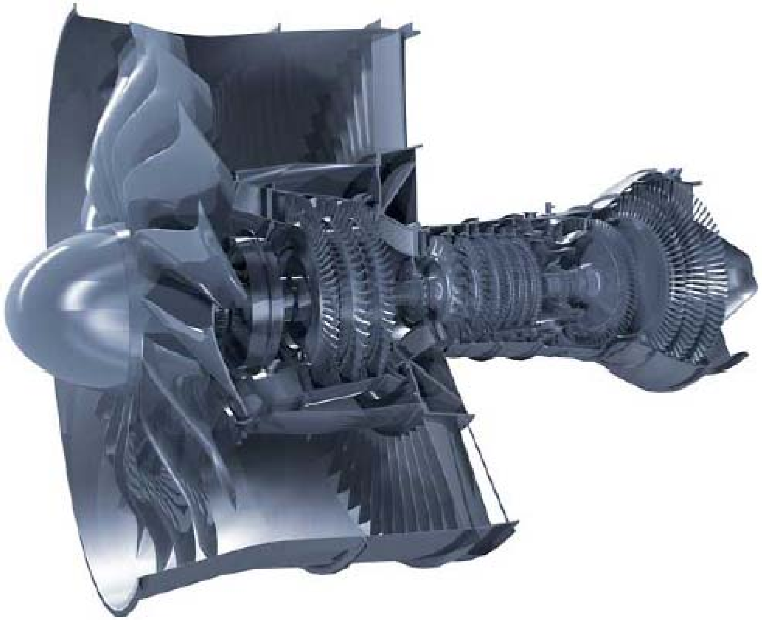
Gas Turbine

Advantages:

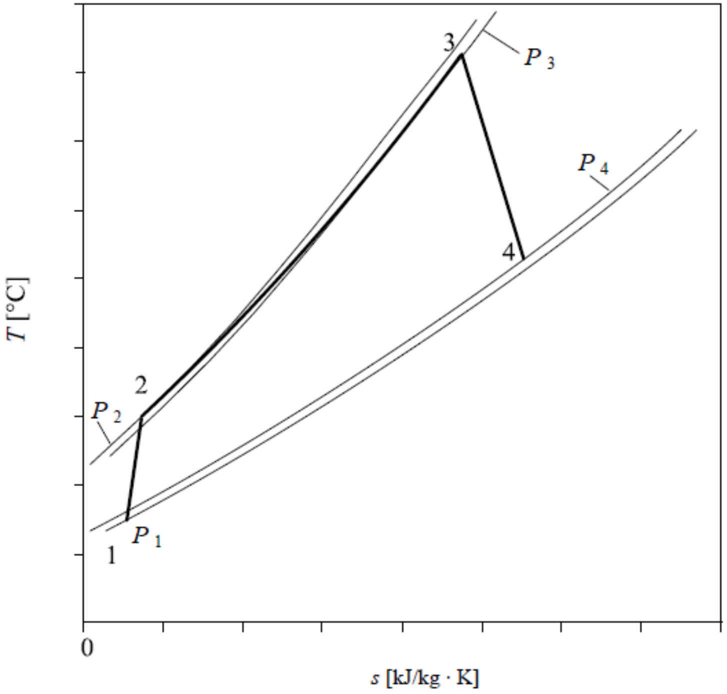
- High temperature & low pressure -> high power/weight
- No blade erosion with high-quality fuel
- Fast load-change

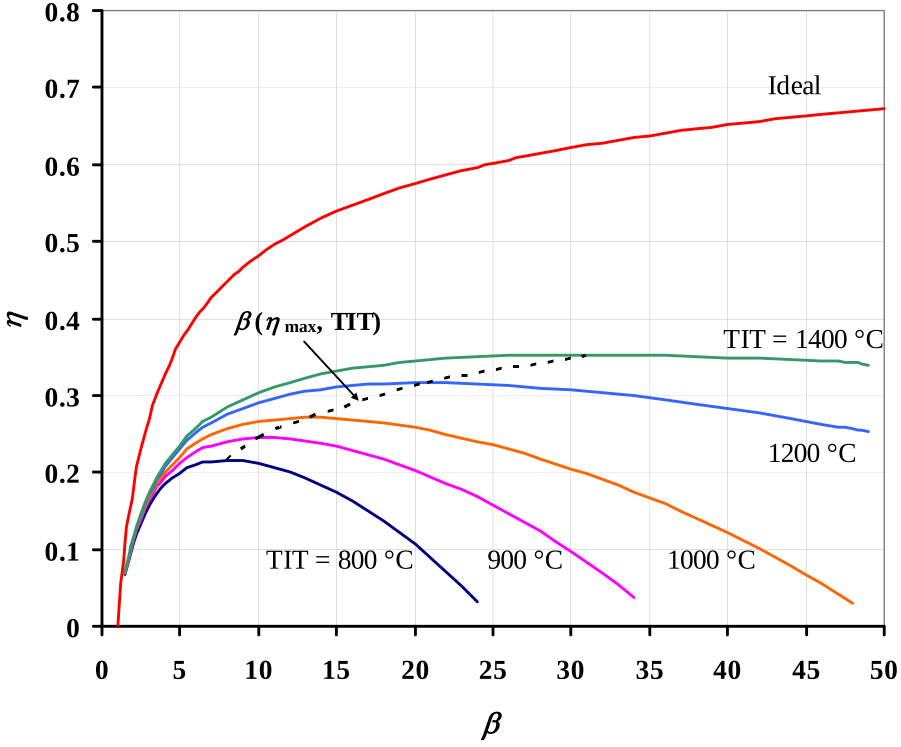
Applications:

- Aircraft propulsion (ships, trains)
- Combined Cycle, Peak-shaving
- Cars (for hybrid engines in the future?)

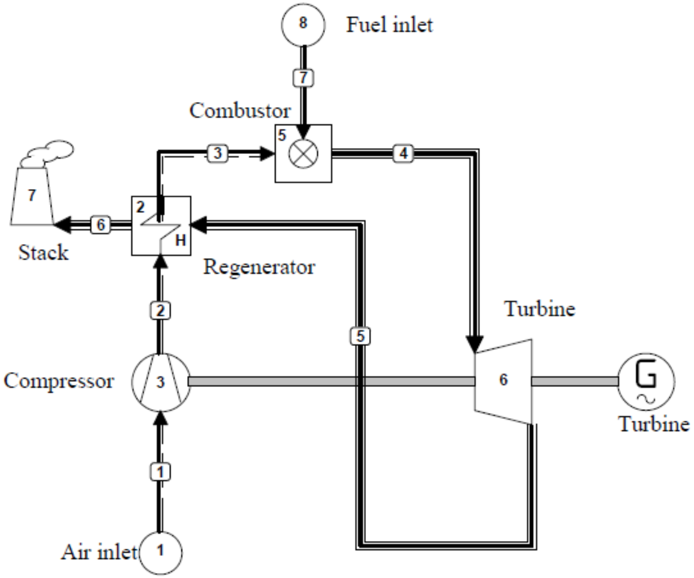


Gas turbine cycle: parameters

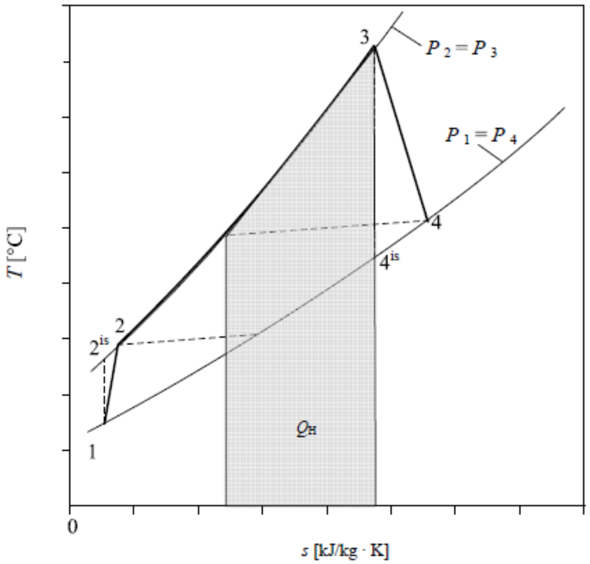




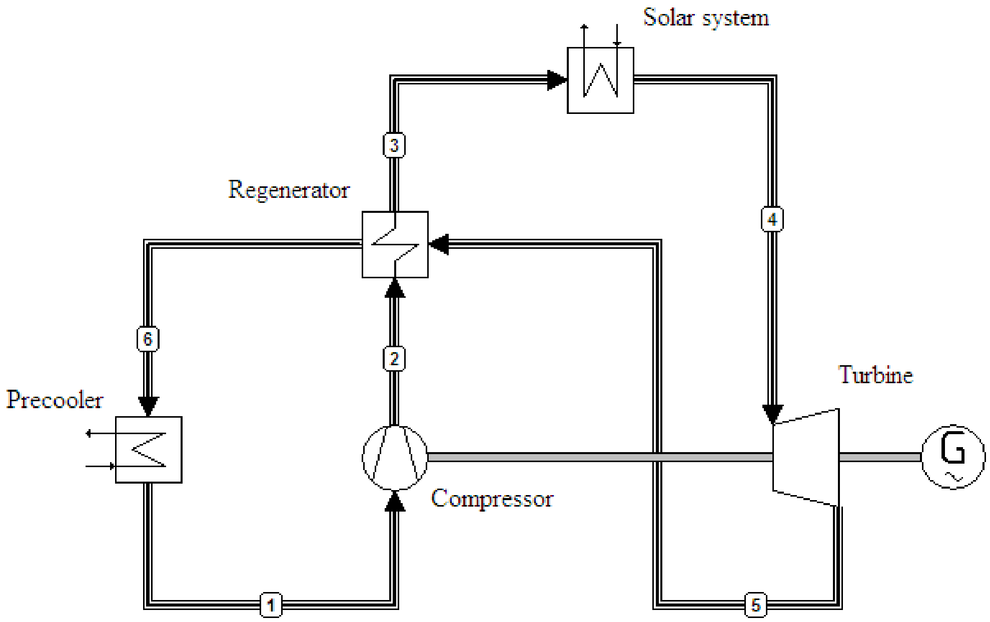
Regeneration

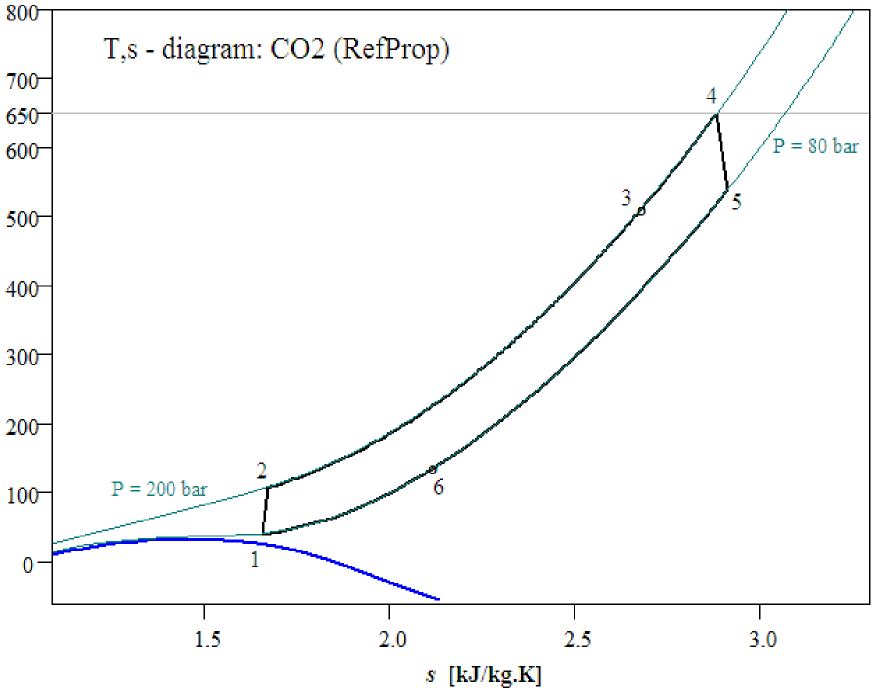


- Reduction of thermal losses
- Note: T_4 often in excess of 450 °C
- For given TIT, maximum efficiency at modest β (increase $T_4 - T_2$)
- Recuperator: technological problem



Closed Brayton cycle gas turbine





Final remarks

- Importance of assumptions
- Always mass and energy balances
- Thermodynamic cycles: comparison with Carnot cycle
- Courses on gas turbines of the Master in Sustainable Energy Technology:
  - WB4420 Gas Turbines and
  - WB4421 Gas Turbines Simulation/Application