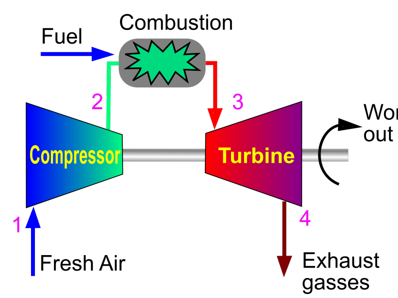
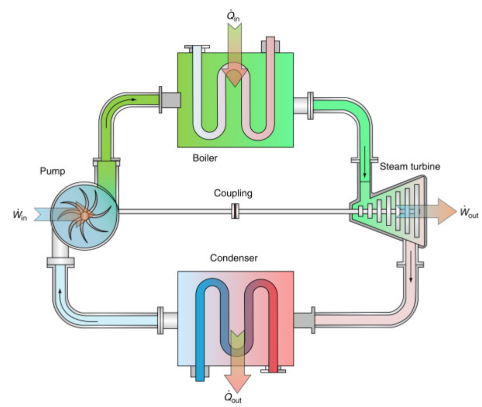
PHY555 Energy & Environment
PC 4 Heat engines

At present, most of the electric power in the world is produced in thermal power plants using fossil fuels (gaz, oil, coal). In a context of liberalization of the electricity market and integration of renewable energy in intermittent production, the internal combustion turbine (primarily natural gaz) have grown remarkably. Coal plants and nuclear power plants use steam turbines (external combustion). We will analyse the performance of these two types of thermal into mechanical energy converters. Then we will study the performance gain in gas stations known as "combined cycle" that combine the two cycles one after the other.





Reminders

1. The Carnot efficiency correponds to the optimal energy conversion ($W_{\text{out}}/Q_{\text{in}}$). The Curzon Alhborn efficiency corresponds to the optimal output power ($\dot{W}_{\text{out}}$)

$$\eta_{\text{Carnot}} = 1 - \frac{T_{\text{cold}}}{T_{\text{hot}}} \qquad \eta_{\text{C-A}} = 1 - \sqrt{\frac{T_{\text{cold}}}{T_{\text{hot}}}}$$

2. An ideal gas obeys the following laws:

   (a) Thermodynamic identity

$$pV = nRT \tag{1}$$

   (b) Joule's laws: the internal energy and the enthalpy of an idean gas depend *only* on the gas temperature (not on pressure)

$$dU = C_v dT \qquad dH = C_p dT \tag{2}$$

   (c) Mayer relation: heat capacities are related as

$$C_p - C_V = nR \tag{3}$$

   (d) Introducing the heat capacity ratio $\gamma = C_p/C_v$ ($= 1 + 2/f$ where f is the number of degree of freedom of a molecule), we recall useful relations for an ideal gas

      i. By definition, heat capacities can be expressed as

$$C_V = \frac{nR}{\gamma - 1} \qquad C_p = \frac{\gamma nR}{\gamma - 1}$$

      ii. Laplace laws: during an adiabatic and reversible transformation

$$pV^{\gamma} = \text{cste} \qquad TV^{\gamma-1} = \text{cste} \qquad T^{\gamma}p^{1-\gamma} = \text{cste}$$

1 Orders of magnitude

The table below gives the properties of three different power plants. Comment the results

	Cold source	Hot source	Measured η
West Thurrock (U.K.) coal fired steam plant	25	565	0.36
CANDU (Canada) PHW nuclear reactor	25	300	0.3
Larderello (Italy) geothermal steam plant	80	250	0.16

Reference: Esposito et al., Efficiency at Maximum Power of Low-Dissipation Carnot Engines, PRL 105, 150603 (2010)

2 Gas turbine - the Joule-Brayton cycle

The operation of a gaz turbine is based on the Joule (or Brayton) Cycle:

- $1 \to 2$: adiabatic compression of air in an axial compressor (turbine engine)
- $2 \to 3$: fuel continuous inlet (gaz) and combustion at constant pressure
- $3 \to 4$: adiabatic expansion in a turbine
- $4 \to 1$: exhaust of hot gases at atmospheric pressure

We will perform an *air standard* analysis, based upon the following assumptions

- The working fluid is always treated as ideal air. Chemical changes are neglected.
- A fixed mass of air is taken as the working fluid throughout the entire cycle. Intake and exhaust processes are not considered.
- The combustion process is replaced by heat input, as if coming from an external source.

1. Draw the Clapeyron diagram (P-V) and entropy diagram (T-S) of the cycle.
2. Express the efficiency of the cycle as function of the temperatures involved, then as function of the compression ratio r. What is then the relationship between the temperature of combustion end and the temperature of the exhaust gazes ? Discuss the difference with the Carnot cycle efficiency.
3. The end temperature combustion $T_3 = 1200\,°\mathrm{C}$ is constrained by used material strength considerations (in particular the blades). The air enters the compressor at a temperature $T_1 = 25\,°\mathrm{C}$. Under which conditions is the yield the highest and what is its value? What is the consequence for the work per mole of intake air? What is the corresponding compression ratio?
4. How can we maximize the work done by the turbine per mole of intake air? What is the corresponding yield and the compression ratio for the same temperature at end of combustion T_3 and at intake T_1?
5. A possible way to improve the Brayton cycle is to introduce a "regenerator" which allows heat exchange between the exhaust step and the compression step. Show the role of this step on the T-S diagram. Explain the interest and limitation of this strategy.
6. Another possible improvement is to introduce intercoolers and/or reheaters which allow to split the compression and/or expansion phases in several steps. Show the role of these steps on the T-S diagram. Explain the interest and limitation of this strategy.

3 Steam turbine – Cycle of Clausius-Rankine

Steam turbines generally use the Clausius-Rankine cycle with overheating (also called Hirncycle), characterized by phase change of the working fluid, generally water:

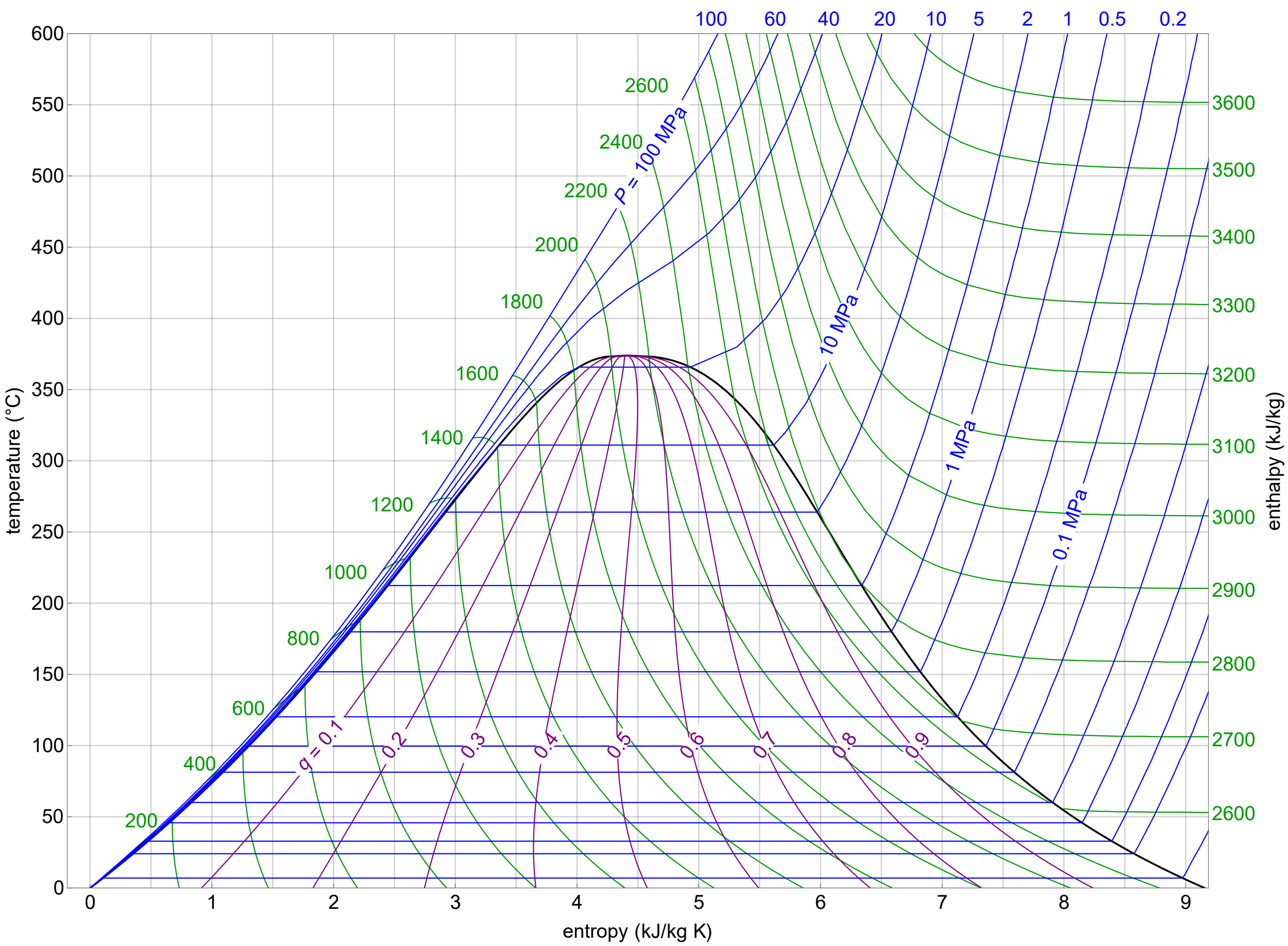
- isentropic compression of the liquid water
- isobaric heating of the liquid water until its complete evaporation

- isobaric super-heating of steam
- isentropic expansion of the "dry" vapour isobaric
- condensation of steam until complete liquefaction

1. The figure below gives the isochoric and isobaric lines of water (liquid and vapour) in an entropic chart. Using this diagram, determine the latent heat of evaporation of water at 100 °C. Determine the shape of the isobars in the mixed phase (water-vapour) in an enthalpy chart (h–s), also known as "Mollier diagram".
2. Draw the cycle with and without overheating on the provided T-s and Mollier diagrams
3. Using the Mollier diagram, calculate and comment the efficiency of a steam turbine considering that steam enters the turbine at 530°C and 150 bar, and that the condenser pressure is 0.1 bar.
4. To limit the erosion of the blades, the expansion phase has to take place with only dry steam. To do this, the expansion is performed in two steps separated by isobaric heating of the steam (recalorification) from the time the steam reaches the dew point. Trace the corresponding cycle in the Mollier diagram and determine the yield considering that reheating brings the fluid back to the same temperature as the incoming steam (530°C). What is the phase of the fluid at the turbine outlet?

4 Combined cycle

The two cycles are combined using the turbine exhaust gaz to generate steam, which feeds a steam turbine. Draw an entropy diagram using both idealized cycles. Calculate the total return based on individual yields of the two cycles. What is the efficiency of a combined cycle when the gaz turbine has a yield of 35% and the steam one a yield of 40%?



Mollier H-S Diagram for Water-Steam