PHY555 Energy & Environment
PC 4 Heat engines - guidelines

1 Orders of magnitude

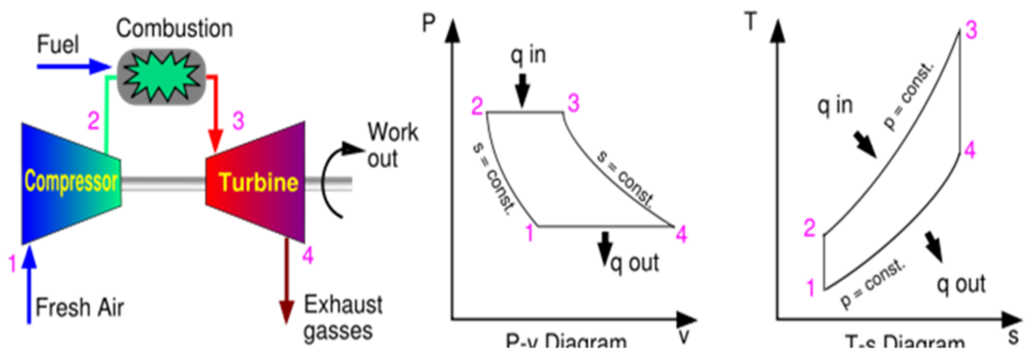
Compare the Carnot estimate and the Curzon Alhborn estimate, which actually much close to real values !

If investiment are more important than running expenditures (CAPEX > OPEX), then you'd better try and have as much has much production as possible, even if it means wasting a bit of the fuel energy.

If fuel is expensive (OPEX > CAPEX), you'd better take all the energy you can from the fuel and work at higher efficiency, even if it means lower power production.

2 Gas turbine - the Joule-Brayton cycle

1. PV Diagrams: pV^γ = cste or p = cste. TS Digrams: s = cste or $T = T_0 \exp\left(\frac{\gamma-1}{\gamma}\frac{S-S_0}{NR}\right)$ because $dH = C_p dT = Vdp + TdS$ et $dp = 0$ so $dS = \frac{NR\gamma}{\gamma-1}\log\frac{T}{T_0}$



2. The efficiency of the cycle is the ratio between what we are interested in (net work provided by the gas on the shaft, ie $\Delta H_{12} + \Delta H_{34}$) to the heat provided to the system Q_{23}. Over the cycle, $\sum \Delta H_i = 0$ and $\Delta H_{23} = Q_{23}$ and $\Delta H_{41} = Q_{41}$ so

$$\eta = -\frac{\Delta H_{12} + \Delta H_{34}}{Q_{23}} = \frac{Q_{23} + Q_{41}}{Q_{23}} = 1 + \frac{Q_{41}}{Q_{23}} = 1 + \frac{T_1 - T_4}{T_3 - T_2}$$

Temperatures ratios can be related to the compression ration (it takes a bit of work !), leading to

$$\eta = 1 - \frac{1}{r^{1-\frac{1}{\gamma}}}$$

Carnot efficiency would be $1 - \frac{T_1}{T_3} \geq \eta$ since $T_2 \leq T_3$

3. Largest efficiency for largest T_2. Since T_3 is fixed, T_2 max = T_3 - ie the system is heated by compression, and combustion adds 0 input. Efficiency is then as good as Carnot = 80%, but the amount of work actually produced is 0. In this case, $r = (T_1/T_3)^{\frac{\gamma}{\gamma-1}} = 268$

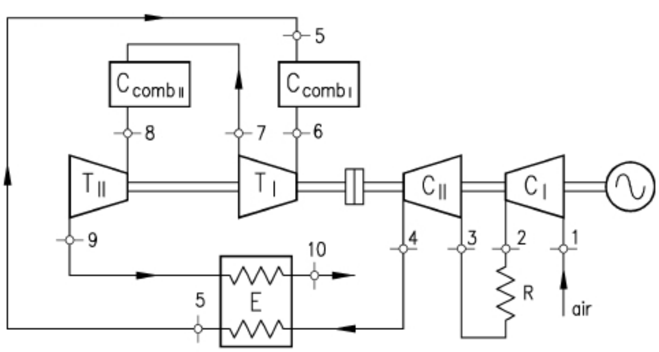
4. Net work on the shaft: $W = \eta Q_{23} = \left(1 - \frac{T_1}{T_2}\right) \times C_P(T_3 - T_2)$. T_1 and T_3 being fixed, optimal for $\partial_{T_2} W = 0$ which allows estimate $T_2 = \sqrt{T_1 T_3}$, and recover the CA efficiency

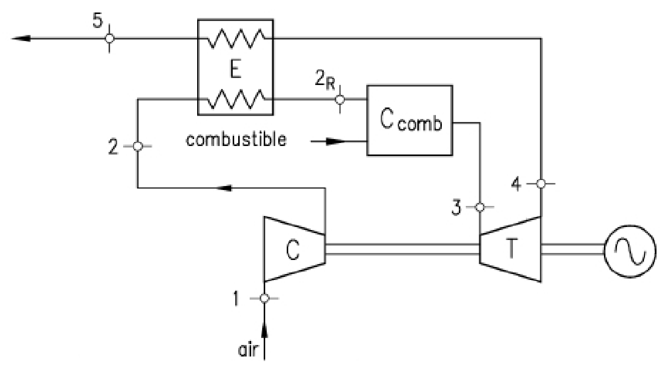
5. If the compression ratio is small (r=10 for instance), the output gas are significantly hotter ($T_4 = 490\,°\mathrm{C}$) than air before combustion ($T_2 = 300\,°\mathrm{C}$). Instead of wasting output heat to the atmosphere, use it to preheat the air before combustion $\rightarrow$ need less combustion heat (ie less fuel) to reach the same T_3. However, can't pass the whole energy surplus. As air heats up and exhaust cool down, temperatures cross and can't give heat from cold to hot. Rough estimation : use the hot source so that both system reach $(T_2 + T_4)/2$. Energy given to air : $C_p\left(\frac{T_2+T_4}{2} - T_2\right) = C_p\frac{T_4-T_2}{2}$. Fraction of energy saving :

$$\frac{Q_{regen}}{Q_{total}} = \frac{1}{2}\frac{T_4 - T_2}{T_3 - T_2} = 10\% \qquad (1)$$

Not as efficient for increasing r, because $T_4 - T_2 = T_3\frac{1}{r^{\frac{\gamma-1}{\gamma}}} - T_1 r^{\frac{\gamma-1}{\gamma}}$ decreases with r.

6. Instead of performing one single adiabatic compression (resp. decompression), break it in several steps. Aim = try and make the transformation isothermal, instead of adiabatic. Motivation: during adiabatic compression, gas heats up, making it harder to further compress.





3 Steam turbine – Cycle of Clausius-Rankine

1. .

2. During isobaric transformations, $Q = \Delta H$. During adiabatic transformations, $W_{\neq p} = \Delta H$. Efficiency can be estimated as the ratio of relevant lengths.

3. Yield slightly improved: 45%. But above all, the end of expansion is dry vapour phase, hence less wear of blades

4 Combined cycle

$$\eta = \eta_{Joule} + \beta_{\text{heat exchange}}\left(1 - \eta_{Joule}\right)\eta_{Rankine}$$