Lezione 27 - Gas Turbine Engine

Final point on axial turbine analysis:

As we discussed, the last rotors on the last stage we create a twist to allow the blade to not break and it takes different form depending on the distance to the hub. It has a seal (shrouding element) at the top.
High pressure blades are much much smaller.

General consideration on the mechanical design.

↳ Using impulse stages reduces the number of reaction stage.
In general though, we try to maximise the number of reaction stages to maximise efficiency.

Impulse rotors → if designed well the $\Delta P = 0$, and $F_{axial,x} = 0$, we can make the rotor lighter, we use BLISK (bladed-disks)

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With impulse stages we use disk and diagram technology, meaning the we keep the hub thin and increase the radius where the rotors stay. There will be some losses, so if not designed well lose impulse status.
In reaction stages we use drum technology, thus has some leakage so seals between stages need to be strong.

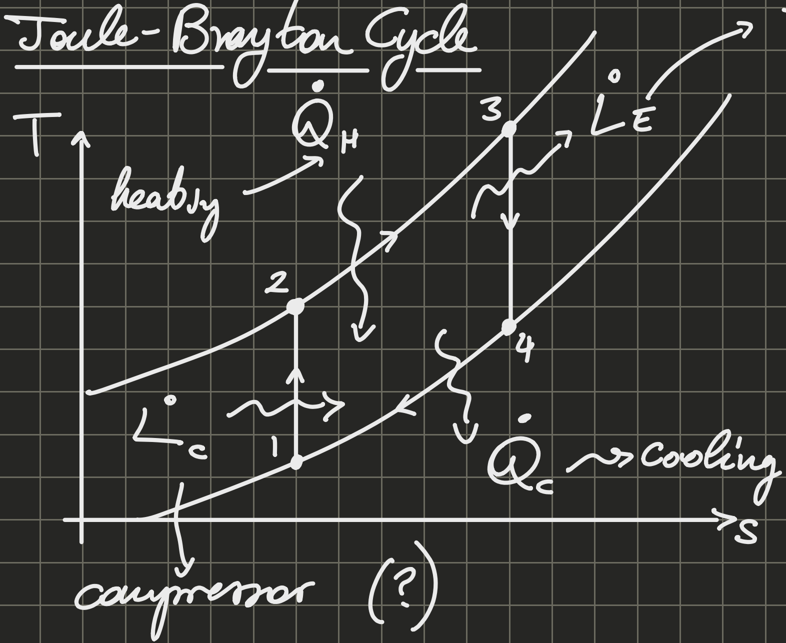
Energy Systems
- Gas turbine
- ICE

Gas Turbine Engines

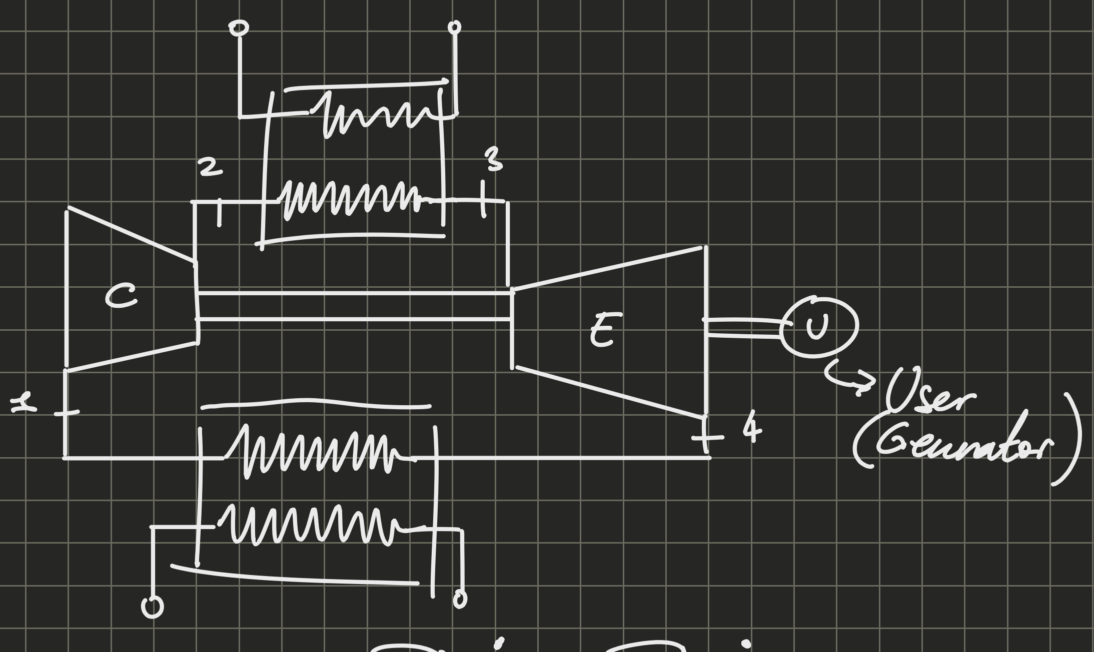
→ Gas turbine engines operate through the Joule-Brayton cycle.
  → 2 isobaric + 2 isoentropic transformations.

expander (axial turbine

Joule-Brayton Cycle



$$\beta = \frac{P_2}{P_1} = \frac{P_3}{P_4}$$



Power Balance: $\sum_i \dot{Q}_i + \sum_j \dot{L}_j = 0$

$\Rightarrow \dot{Q}_H + \dot{Q}_c + \dot{L}_c + \dot{L}_E = 0$

$$\dot{Q}_H - |\dot{Q}_C| + \dot{L}_C - |\dot{L}_E| = 0$$ → considering the signs they will always have

$$\Longrightarrow \dot{Q}_H - |\dot{Q}_C| = |\dot{L}_E| - \dot{L}_C$$

Mechanical Balance at the shaft:

$$\dot{L}_C + \dot{L}_E + \dot{L}_U = 0$$ → If not 0, the shaft accelerates, and there will be an inertial term.

$$\dot{L}_C - |\dot{L}_E| + \dot{L}_U = 0$$

$$\Longrightarrow \dot{L}_U = |\dot{L}_E| - \dot{L}_C$$

Efficiency:

$$\boxed{\eta_{TD}} = \frac{\dot{L}_U}{\dot{Q}_H} = \frac{|\dot{L}_E| - \dot{L}_C}{\dot{Q}_H} = \frac{\dot{Q}_H - |\dot{Q}_C|}{\dot{Q}_H} = \boxed{1 - \frac{|\dot{Q}_C|}{\dot{Q}_H}}$$

↳ Thermodynamic

J–B cycle performance → Effective performance

↳ only representative of the real cycle.

$$\eta_{JB} = 1 - \frac{|\dot{Q}_C|}{\dot{Q}_H} = 1 - \frac{\cancel{\dot{m}_C}\,\cancel{c_p}(T_4 - T_1)}{\cancel{\dot{m}_H}\,\cancel{c_p}(T_3 - T_2)} = 1 - \frac{T_1}{T_2} \cdot \frac{\cancel{\left(\frac{T_4}{T_1} - 1\right)}}{\cancel{\left(\frac{T_3}{T_2} - 1\right)}} = 1 - \frac{T_1}{T_2} = 1 - \beta^{\frac{1-\gamma}{\gamma}}$$

≈ 0

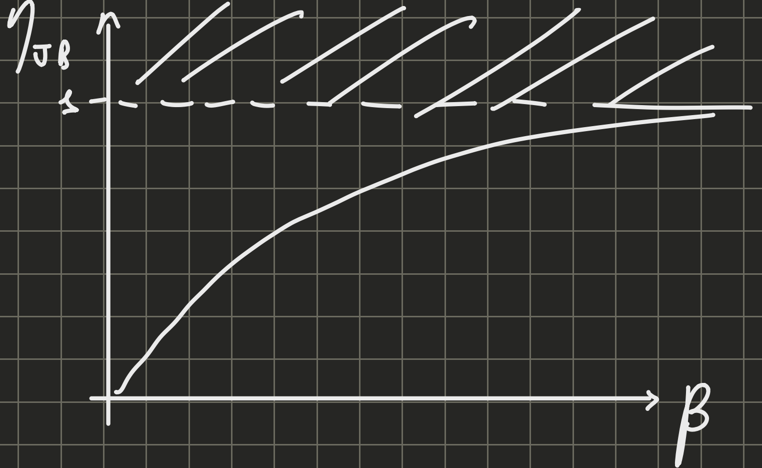
$$\underbrace{l}_{0} + q = \Delta h + \frac{\Delta v^2}{2} + \cancel{g\Delta z} = c_p \Delta T$$

↳ heat exchangers have $l = 0$

↳ ≈ 0, at our level (for us as students), in reality this is not neglected.

↳ this is only important in aeroengines since after turbine there is a nozzle. → jet engine + turbofan.

since $\frac{T_2}{T_1} = \beta^{\frac{\gamma}{\gamma-1}}$



As we increase the stages, the efficiency (This is a theoretical result)

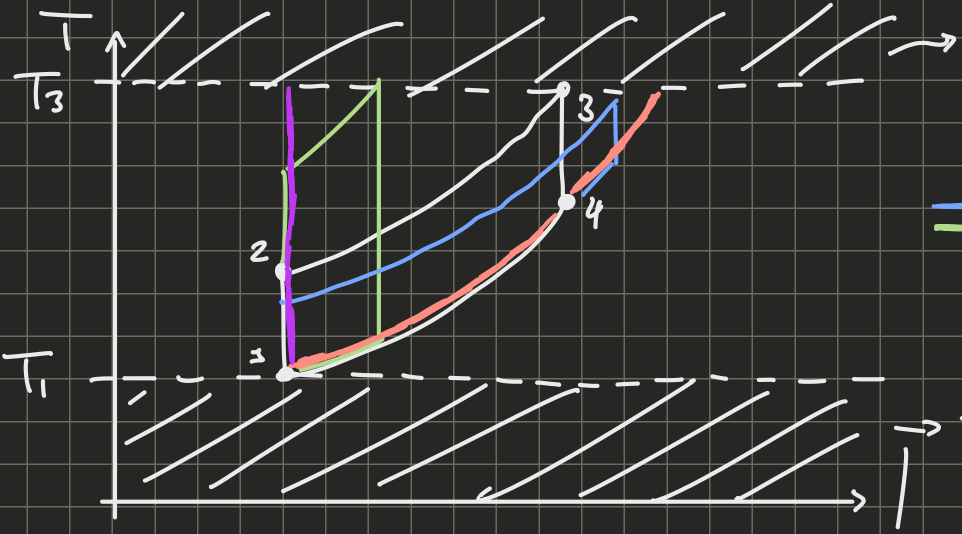
$$l_u = \frac{\dot{L}_u}{\dot{m}} = |l_E| - l_c = c_p(T_3 - T_4) - c_p(T_2 - T_1) =$$

since $q = 0$ in expander and compressor

T_4 and T_2 should be T_{4s} and T_{2s}, but we have no introduced any losses that occur in reality, but we will have to clarify later.

$$= c_p(T_2 - T_1)\left(\frac{T_3 - T_4}{T_2 - T_1} - 1\right) = c_p T_1\left(\beta^{\frac{\gamma-1}{\gamma}} - 1\right)\left(\frac{T_3}{T_2}\,\frac{\cancel{1 - T_4/T_3}}{\cancel{1 - T_1/T_2}} - 1\right)$$

$$\boxed{= c_p T_1\left(\beta^{\frac{\gamma-1}{\gamma}} - 1\right)\left(\underbrace{\frac{T_3}{T_1}\beta^{\frac{1-\gamma}{\gamma}}}_{T_3/T_2} - 1\right) = l_u}$$



The technologies we choose set a limit on T_3.

= possible cycles based on technological choices

We impose a limit on T_1, since

The work depends on T_1, T_3 and β.

it depends on the heatsink system.
Our environmental rules also set this kind of.

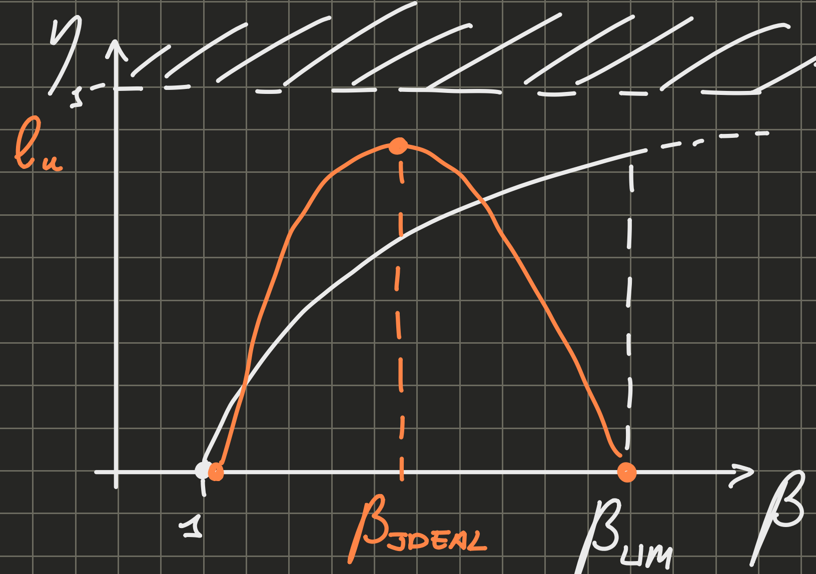
$$l_u = 0 \rightarrow \beta = 1 \Rightarrow \eta = 0$$

$$l_u = 0 \rightarrow \frac{T_3}{T_1}\beta^{\frac{1-\gamma}{\gamma}} = 1 \Rightarrow \beta = \left(\frac{T_3}{T_1}\right)^{\gamma/\gamma-1} \triangleq \beta_{LIM} \Rightarrow \eta = 1 - \frac{T_1}{T_3}$$

since l_u is twice-dependent on β.

$\Rightarrow T_2 \to T_3$ & $T_4 \to T_1$

Once we identify an environmental limit of T_1 and technological limit to T_3, we have our β_{LIM}.



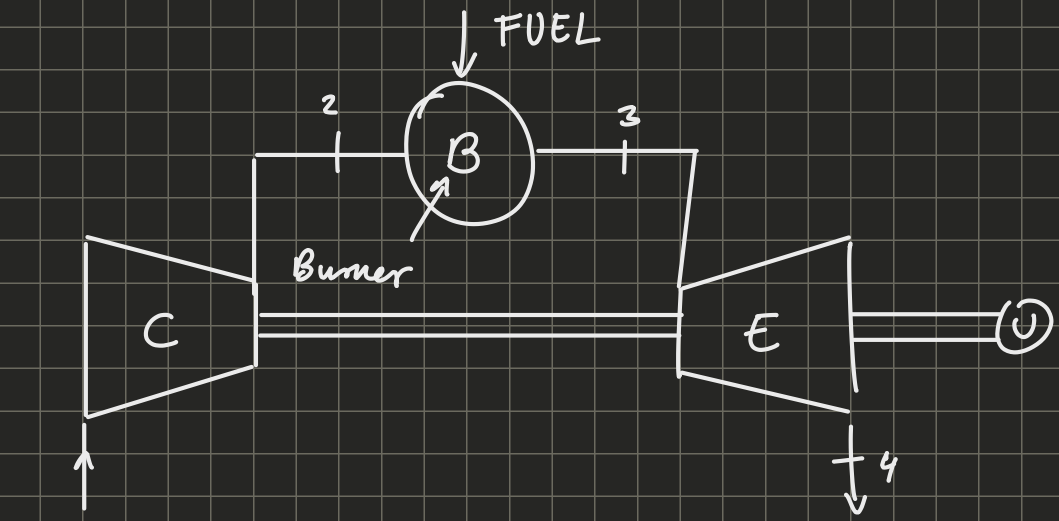
This is not true in the real case but that's fine for now.

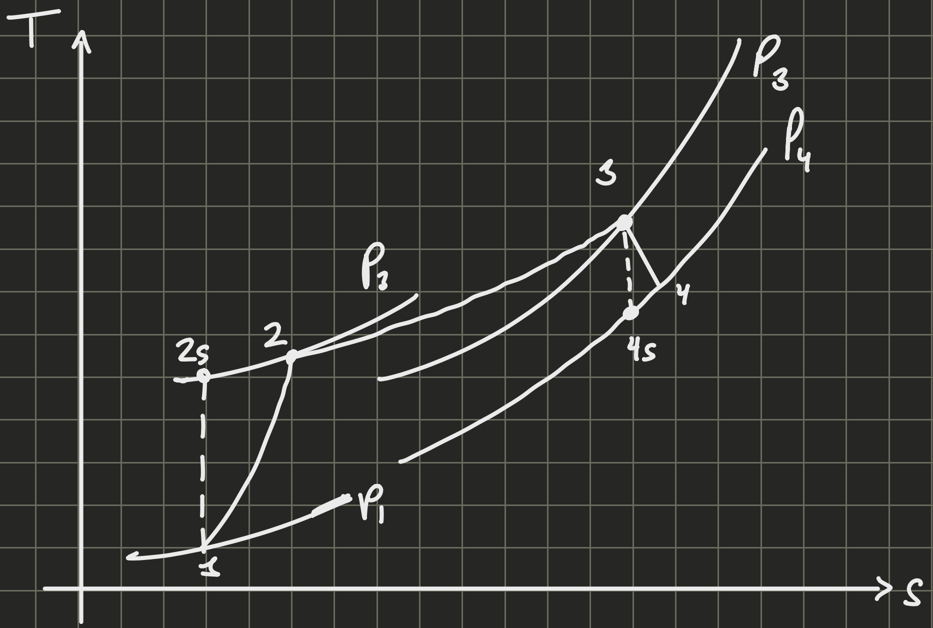
$\beta = \beta_{IDEAL}$ when $T_2 = T_4 \rightarrow$ this will be true for the real system.

Military systems work at max l_u rather than max η.

Real Gas Turbine Cycle

The high temp. heater is a waste of energy, we can replace it with a combustion chamber which mixed the fluid with the gas and send it to the turbine to leave the system. Since the fluid leaves we can also remove the heat exchanger.





Differences:

- Open, not closed cycle:
  - Consequences:
    - Fluid at compressor and turbine is not the same, a compressor we have air, at turbine we have air + fuel.
    - Flow-rate changes, since we add fuel flow rate.
    - Different values of c_p (we keep the same)
    - Conclusions are not significantly different.
    - $\beta_C \neq \beta_E$, but the scenario is not too different
- Compression and expansion are not isoentropic, will have

big consequences.