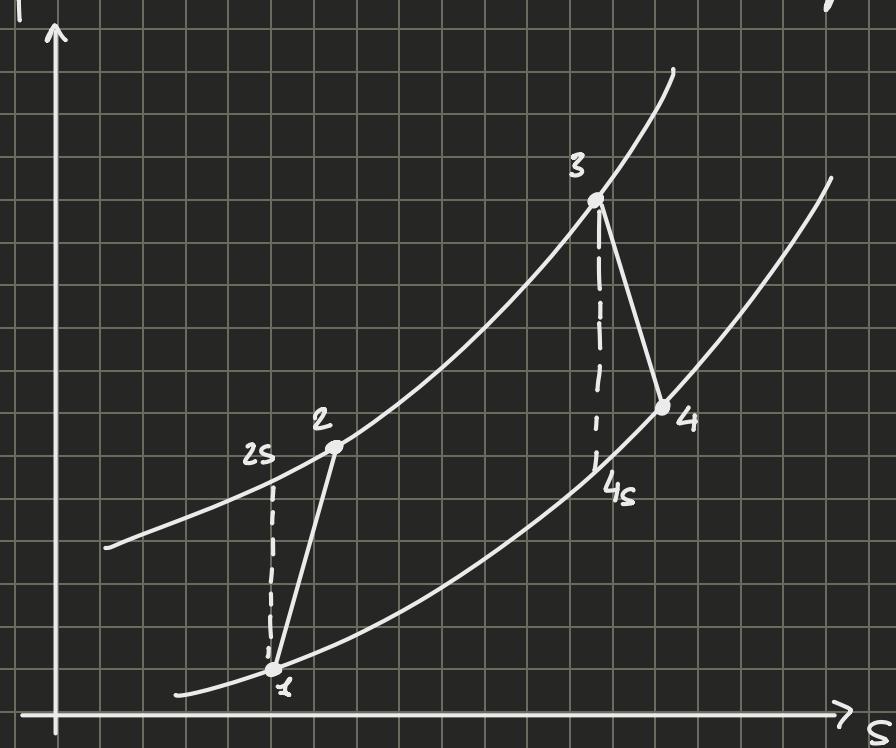


Lesson 28 - Real performance, energy balance of combustion chamber and other machines.

Real Joule-Brayton Cycle → Real heat point of view of transformations.



$$\dot{L}_u \rightsquigarrow \dot{L}_u = \frac{\dot{L}_u^0}{\eta} = |\dot{L}_E| - \dot{L}_C = \eta_E |\dot{L}_{ES}| - \frac{\dot{L}_{CS}}{\eta_C}$$

Now real ones not ideal

we ignore change in \dot{m} ,
since qualitatively result
does not change

$$= \eta_E \dot{L}_{CS} \left(\frac{|\dot{L}_{ES}|}{\dot{L}_{CS}} - \frac{1}{\eta_C \eta_E} \right)$$

$$\dot{L}_u = \eta_E c_p T_1 \left(\beta^{\frac{1-\gamma}{\gamma}} - 1 \right) \left(\frac{T_3}{T_1} \cdot \beta^{\frac{1-\gamma}{\gamma}} - \frac{1}{\eta_C \eta_E} \right)$$

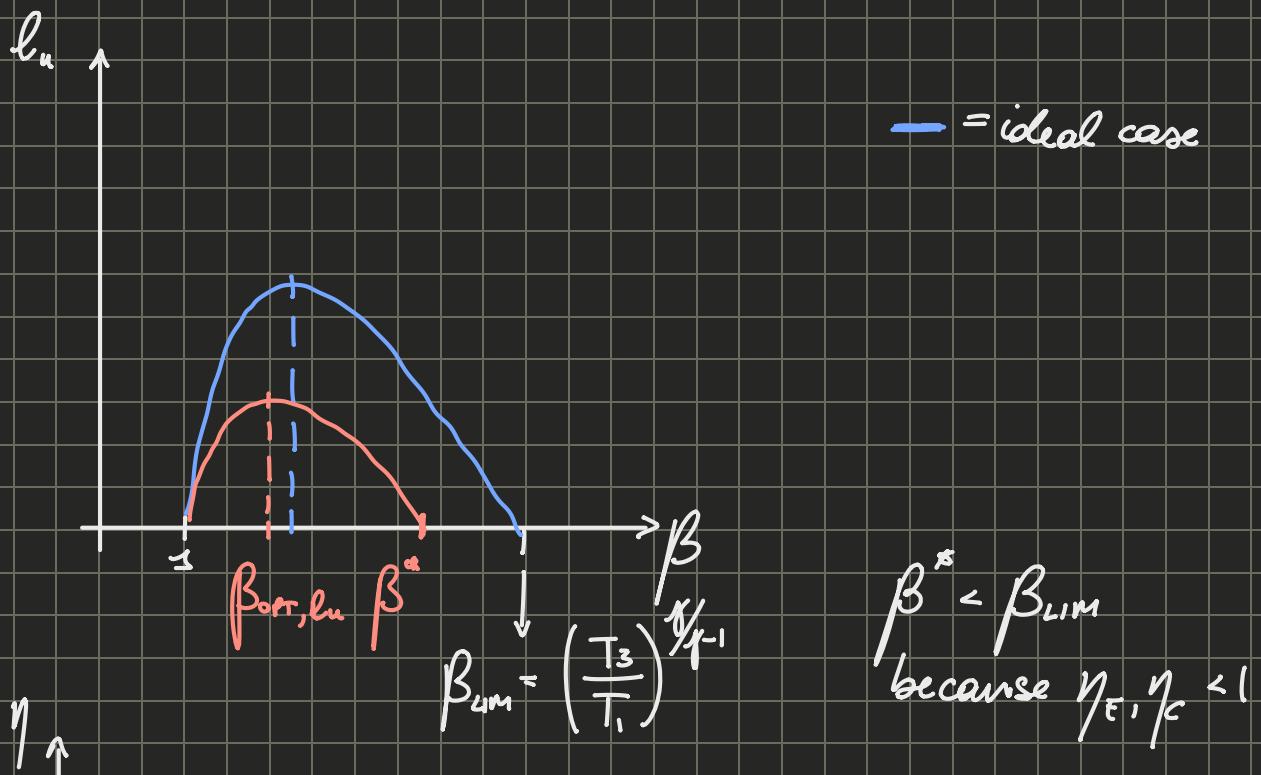
We have already known-ideal cycle

$$\left(\frac{T_{2s}}{T_1} \right)^{\frac{1-\gamma}{\gamma}}$$

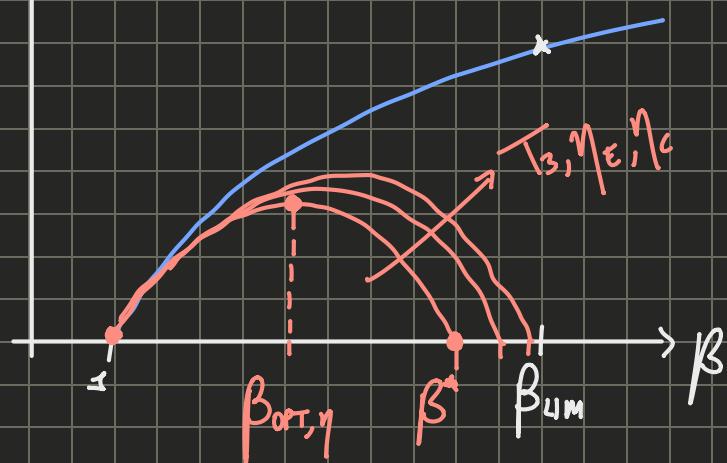
First term $\beta = 1$

$$\dot{L}_u = 0 \rightarrow \frac{T_3}{T_1} \beta^{\frac{1-\gamma}{\gamma}} = \frac{1}{\eta_E \eta_C} \rightarrow \text{Same as ideal, but in ideal } \eta_E = 1 \text{ and } \eta_C = 1$$

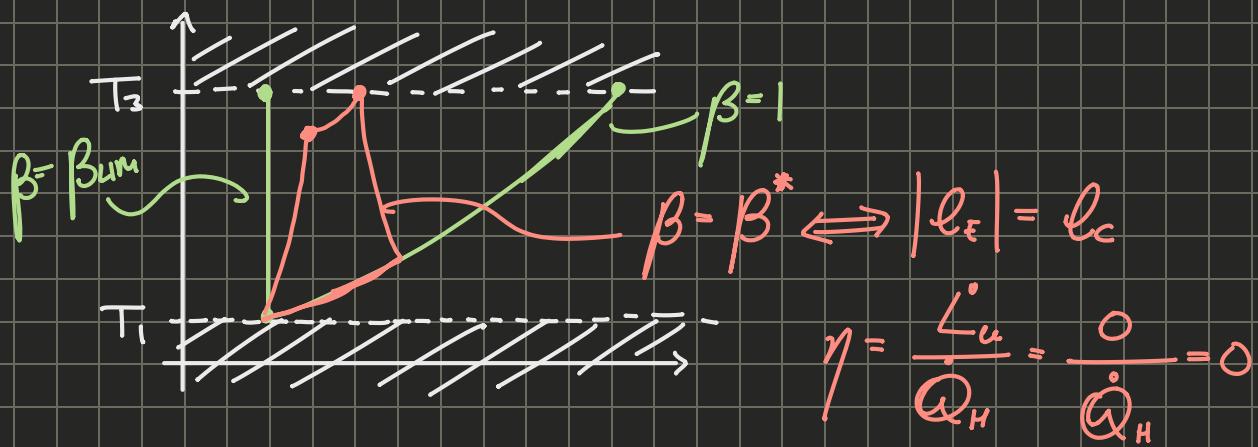
$$\hookrightarrow \beta = \left(\eta_{\varepsilon} \eta_c \frac{T_3}{T_1} \right)^{\frac{1}{q-1}} = \beta^*$$



$\beta^* < \beta_{lim}$
because $\eta_{\varepsilon}, \eta_c < 1$



Effects of β^* on η :



$$\eta = \frac{\dot{Q}_u}{\dot{Q}_H} = \frac{0}{\dot{Q}_H} = 0$$

↪ in the real case we need \dot{Q}_H

The higher will T_3 , η_E and η_c be, the closer will β^* get to β_{lim} .

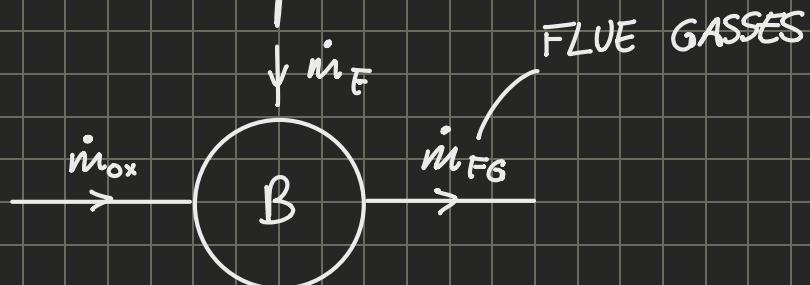
Since \dot{Q}_H is no longer 0 when $\beta = \beta^*$, the efficiency will be 0, so we cannot push β , we have to maximize T_3 , η_E and η_c to increase η .

There have been many ways which have been used to increase T_3 , by finding different ways to cool the blades.

↳ we can reach $T_3 \approx 2000\text{ K}$.

Combustion

Oxidation process



Mass Balance

$$\sum_i \dot{m}_{in,i} = \sum_j \dot{m}_{out,j}$$

Power Balance

$$L + \dot{Q} = \sum_j h_j \dot{m}_{out,j} - \sum_i h_i \dot{m}_{in,i}$$

$$\Rightarrow \dot{m}_{ox} + \dot{m}_F = \dot{m}_{FG}$$

$$L + \dot{Q} = \dot{m}_{FG} \cdot h_{FG} - \dot{m}_{ox} h_{ox} - \dot{m}_F h_F$$

→ This is the thermal power exchanged through solid boundaries.

Since above net power, we need to introduce the reference for each enthalpy, and we hide in each the formation energy, and from here we get the energy released through the oxidation.

$$h_{FG} = h_{FG}(T) = h_{f,FG}(T_{ref}) + \int_{T_{ref}}^{T_{FG}} \overline{C_{p,FG}}(T) dT$$

↳ Formation enthalpy,
energy used to create links

$$= h_{f,FG}(T_{ref}) + \overline{C_{p,FG}}(T_{FG} - T_{ref})$$

in
average

Technically free since we get air ↑ from outside we don't integrate

$$h_{ox} = h_{f,ox} + \overline{C_{p,ox}}(T_{ox} - T_{ref})$$

$$h_F = h_{f,F} + \overline{C_{p,F}}(T_F - T_{ref})$$

$$\dot{m}_{FG} h_{f,FG} + \dot{m}_{FG} \overline{C_{p,FG}}(T_{FG} - T_{ref}) = \dot{m}_{ox} h_{f,ox} + \dot{m}_{ox} \overline{C_{p,ox}}(T_{ox} - T_{ref}) + \dot{m}_F h_{f,F} + \dot{m}_F \overline{C_{p,F}}(T_F - T_{ref})$$

Fuel is preheated

$$\underbrace{\dot{m}_{F,FG} \overline{C_{p,FG}}(T_{FG} - T_{ref})}_{\text{Excess enthalpy due to heating from combustion}} = \underbrace{\dot{m}_{ox} \overline{C_{p,ox}}(T_{ox} - T_{ref})}_{\text{Excess enthalpy from compression}} + \underbrace{\dot{m}_F \overline{C_{p,F}}(T_F - T_{ref})}_{+ \dot{m}_{ox} h_{f,ox} + \dot{m}_F h_{f,F} - \dot{m}_{FG} h_{f,FG}}$$

Energy needed to generate the molecules,
also energy produced in chemical reaction.

$$= \dot{m}_F LHV_F$$

\hookrightarrow Low Heat Value of Fuel

If we provided \dot{m}_x and T at T_{ref} ,

the change in FG would be the result of the combustion.

All the energy released due to the chemical reaction becomes change in \bar{h} for FG, so we consider it a candidate to replace it. Therefore it's a property of the fuel, this is why we use \dot{m}_F

So we can consider:

$$\overline{T}_{FG} \rightarrow T_3$$

$$\overline{T}_{ox} \rightarrow T_2$$

$$\overline{T}_F \cong \overline{T}_2$$

Since $\dot{m}_{ox} \gg \dot{m}_F$, we can say:

$$\overline{Cp}_F \approx \overline{Cp}_{ox}$$

$$\Rightarrow \dot{m}_{FG} \overline{Cp}_{FG} \cdot (T_3 - T_{ref}) = (\dot{m}_{ox} + \dot{m}_F) \overline{Cp}_{ox} (T_2 - T_{ref}) + \dot{m}_F LVH_F$$

We introduce a new parameter:

$$\alpha = \frac{\dot{m}_{ox}}{\dot{m}_F}$$

\hookrightarrow Helps us determine the mix and cost

$$\dot{m}_{FG} = \dot{m}_{ox} + \dot{m}_F = \dot{m}_F (\alpha + 1)$$

$$\dot{m}_{ox} + \dot{m}_F = \dot{m}_F (\alpha + 1)$$

Applying this to the equation:

$$(\alpha + 1) \overline{Cp}_{FG} (T_3 - T_{ref}) = (\alpha + 1) \overline{Cp}_{ox} (T_2 - T_{ref}) + LVH_F$$

We solve for α :

$$\Rightarrow \alpha = \frac{LVH_F}{\bar{C}_p^{\text{FG}}(\bar{T}_3 - T_{\text{ref}}) - \bar{C}_p^{\text{ox}}(\bar{T}_2 - T_{\text{ref}})} - 1$$

We introduce an average \bar{C}_p :

$$\bar{C}_p = \frac{\bar{C}_p^{\text{FG}} + \bar{C}_p^{\text{ox}}}{2}$$

$$\Rightarrow \alpha = \frac{LVH_F}{\bar{C}_p (\bar{T}_3 - T_{\text{ref}} - (\bar{T}_2 - T_{\text{ref}}))} - 1 = \frac{LVH_F}{\bar{C}_p (\bar{T}_3 - \bar{T}_2)} - 1$$

Expression we will use in exercises.

We can calculate the stoichiometric α , to be able to use the minimum amount of oxidizer possible



we can calculate α , then from \bar{T}_2 find T_3 and LVH_F

→ Prohibitive since start to produce NO_x , so we add more air to reduce the temperature T_3 to point less.



→ CO₂ carbon emission, but since we have air, NO_x will still be used, so we still have pollution.

Turbogas Machines

Joule - Brayton cycles are very technologically dependent

It's possible to have more complex layout that have machines that work at different pressures and angular speeds

Combustion Chamber Technology:

↳ Annular, Turbulent or Multi-channel

Generally part of the flow of the oxidizer is sent to the primary duct to combust and other part is sent outside to cool down the fluid on the way to the expander, as it is mixed different parts in the combustion chamber.

With hydrogen dilution need to be one with nitrogen so there is no more reaction, and so we can keep temperature low.

Co-combustion is very useful since it removes many elements like the stator, but it's bulky so it's not used in planes.

Cooled Blades:

↳ We can actively cool blades to be able to limit the temperature of blades so the surrounding air can reach even higher temperatures.

<!Graph of evolution of cooling blisks and temperature which has been reached at different points. $TBC \rightarrow$ ceramic thermal barrier coating >

The materials also improved, as well as the cooling systems.

Performance

↳ The maximum efficiency is reached for $\beta \approx 30 - 40$

The optimal β to maximise η is smaller than that for maximising γ .

↳ Which β we choose.

Performance has improved, η , B_{max} and C_a have all increased through time.

layouts for aero-engines

Turbo propeller

↳ Gas turbine power propeller

Turbo-jet

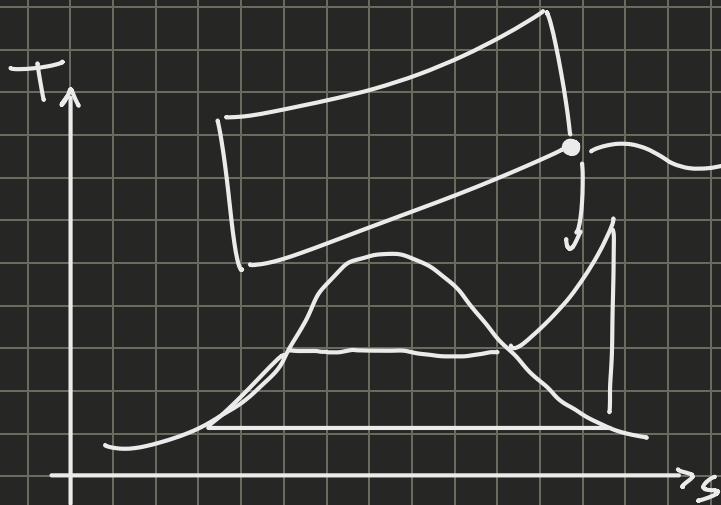
↳ Gas greater exit nozzle to generate thrust
↳ Create huge amount of thrust

Turbofan:

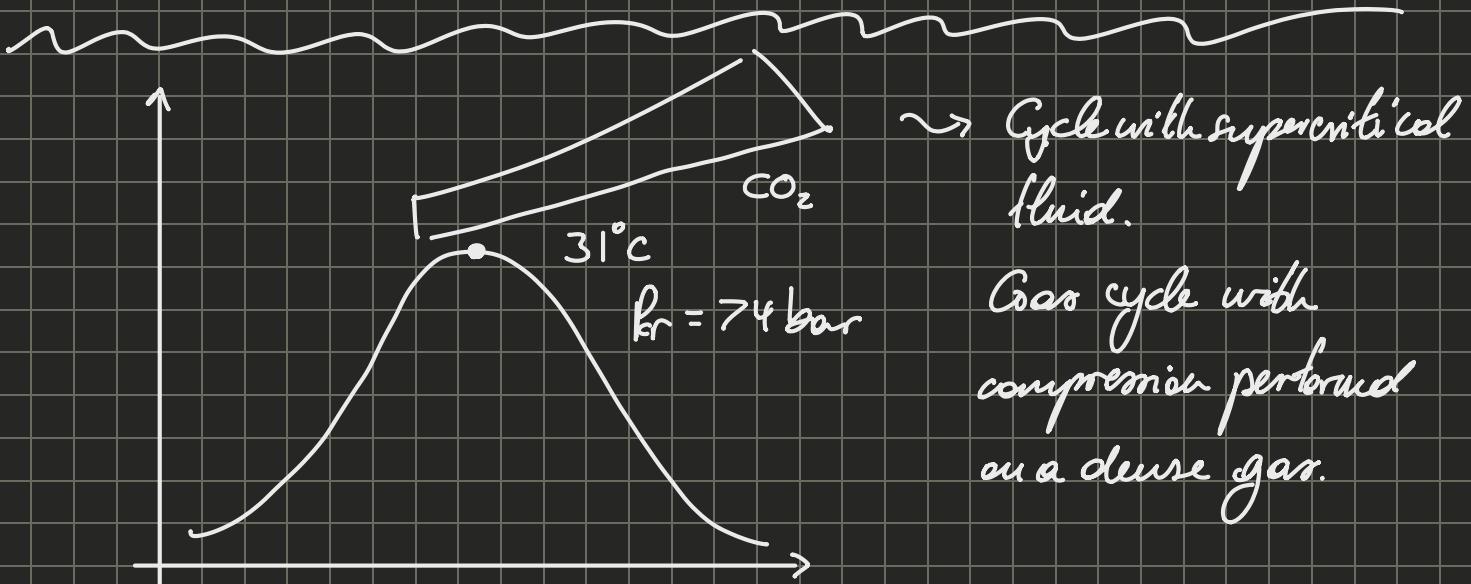
- ↳ Gas turbine powers ducted fan and feeds nozzle 1 and fan feeds nozzle 2.
- ↳ Creates a balance in thrust needed for civil uses.
- ↳ Machine is split in 3 parts.

Layout for starting application

- ↳ Aero-derivative
- ↳ Heavy Duty Gas Turbines $\rightarrow \eta = 53.8\%$
 - ↳ even 60% can be reached.
- ...



we can use the energy here to heat the 2-3 from ramline - cycle,
this is called a combined cycle
 \rightarrow Allows to increase technological efficiency greatly.



Gas cycle with compression performed on a dense gas.

The compression is very cheap (strange for a gas cycle).

This is capable of being more efficient than Rankine and Taft - Brayton cycle.

This is used in nuclear reactors. There is a lot of research on the topic now.

One of the two people who came up with the idea came from Polimi.

Since we work near the saturation line, this is the only case for thermal machine within which we have cavitation and condensation.

It may be okay since the specific volume is already low, so it may not be too much of a problem.