# Jet Aircraft Propulsion

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Lect-6

# In this lecture…

- Brayton cycles
  - Ideal Brayton cycle
  - Variants of Brayton cycle
  - Actual/real Brayton cycle

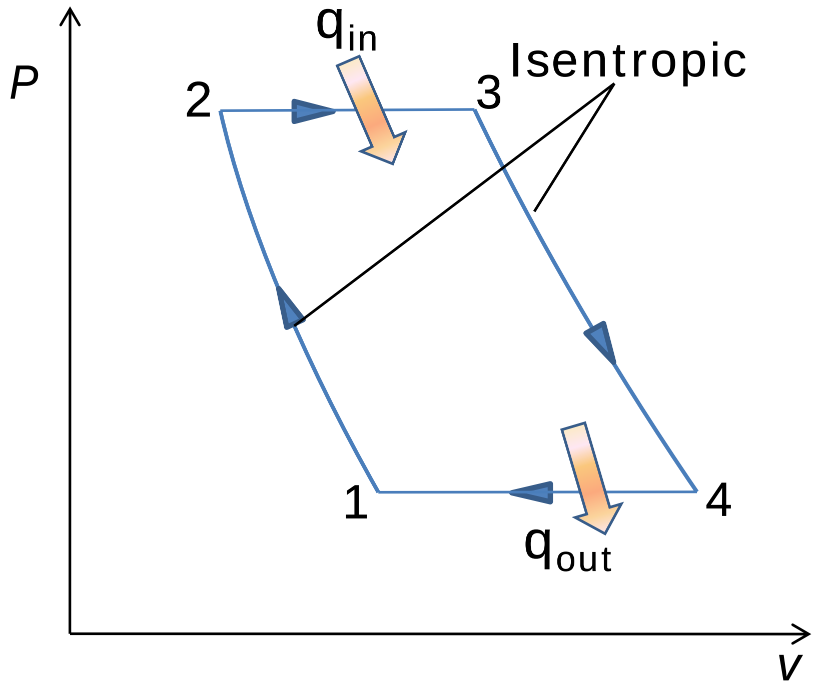
# Brayton cycle

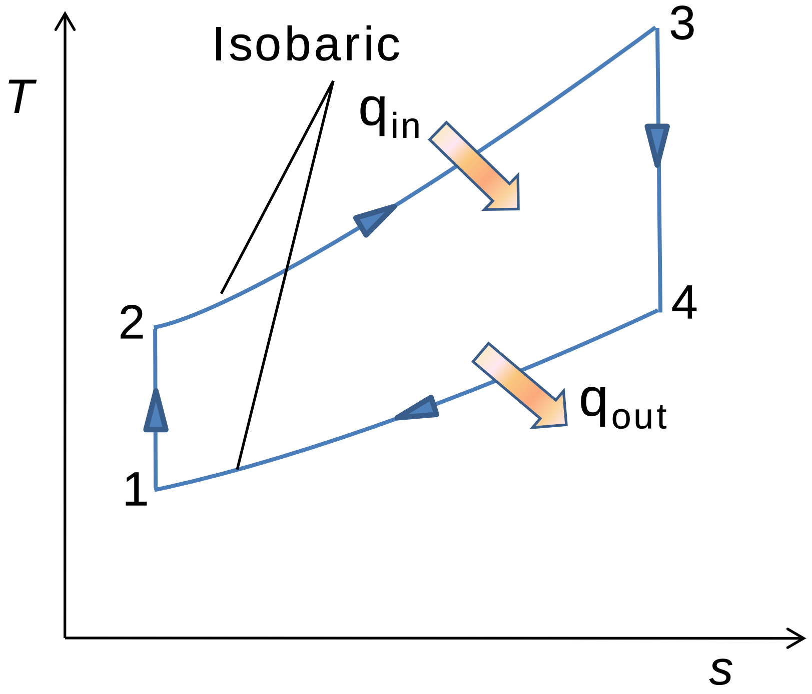
- The Brayton cycle was proposed by George Brayton in 1870 for use in reciprocating engines.
- Modern day gas turbines operate on Brayton cycle and work with rotating machinery.
- Gas turbines operate in open-cycle mode, but can be modelled as closed cycle using air-standard assumptions.
- Combustion and exhaust replaced by constant pressure heat addition and rejection.

# Ideal Brayton cycle

- The Brayton cycle consists of four internally reversible processes:
  - 1-2 Isentropic compression (in a compressor)
  - 2-3 Constant-pressure heat addition
  - 3-4 Isentropic expansion (in a turbine)
  - 4-1 Constant-pressure heat rejection

# Ideal Brayton cycle





Brayton cycle on *P*-*v* and *T*-*s* diagrams

# Ideal Brayton cycle

- The energy balance for a steady-flow process can be expressed as:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = \Delta h$$

The heat transfer to and from the working fluid can be written as:

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2)$$

$$q_{out} = h_4 - h_1 = c_p(T_4 - T_1)$$

# Ideal Brayton cycle

- The thermal efficiency of the ideal Brayton cycle under the cold air standard assumptions becomes:

$$\eta_{th,Brayton}=\frac{w_{net}}{q_{in}}=1-\frac{q_{out}}{q_{in}}=1-\frac{T_4-T_1}{T_3-T_2}=1-\frac{T_1(T_4/T_1-1)}{T_2(T_3/T_2-1)}$$

Processes 1-2 and 3-4 are isentropic and

$P_2=P_3$ and $P_4=P_1$.

Therefore, $\dfrac{T_2}{T_1}=\left(\dfrac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}=\left(\dfrac{P_3}{P_4}\right)^{(\gamma-1)/\gamma}=\dfrac{T_3}{T_4}$

# Ideal Brayton cycle

- Substituting these equations into the thermal efficiency relation and simplifying:

$$\eta_{th,Brayton} = 1 - \frac{1}{{r_p}^{(\gamma-1)/\gamma}}$$

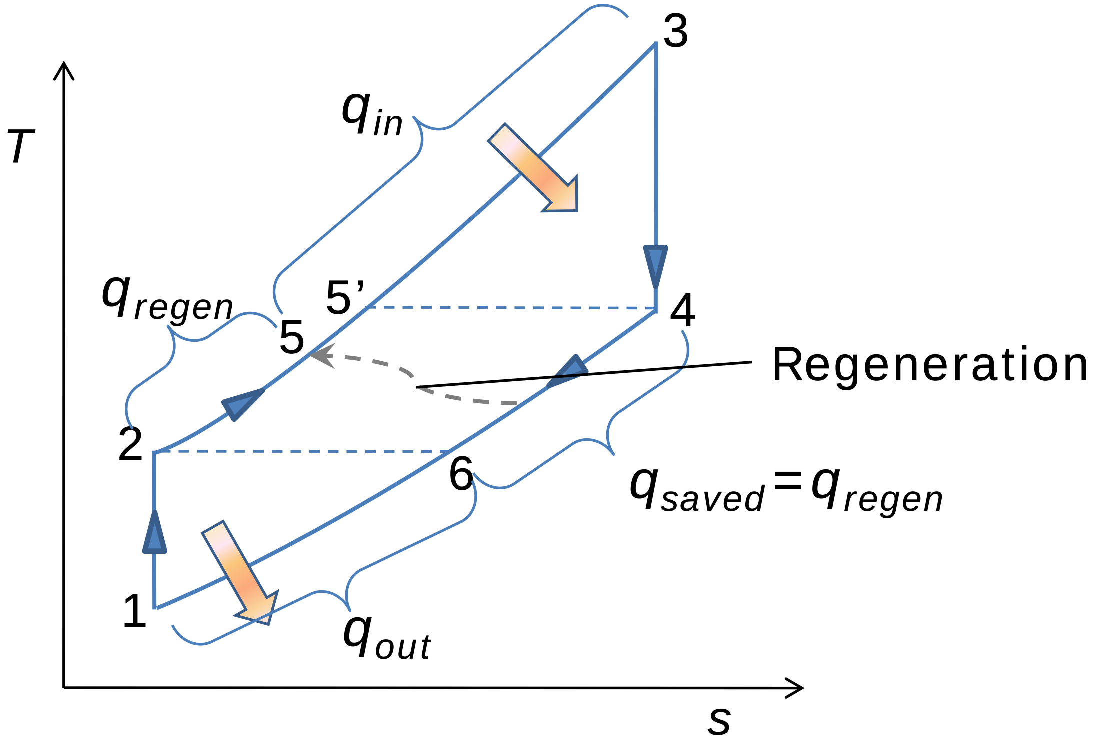
$$\text{where, } r_p = \frac{P_2}{P_1} \text{ is the pressure ratio.}$$

- The thermal efficiency of a Brayton cycle is therefore a function of the cycle pressure ratio and the ratio of specific heats.

# Ideal Brayton cycle with regeneration

- Regeneration can be carried out by using the hot air exhausting from the turbine to heat up the compressor exit flow.
- The thermal efficiency of the Brayton cycle increases as a part of the heat rejected is re-used.
- Regeneration decreases the heat input (thus fuel) requirements for the same net work output.

# Ideal Brayton cycle with regeneration



T-s diagram of a Brayton cycle with regeneration

# Ideal Brayton cycle with regeneration

- The extent to which a regenerator approaches an ideal regenerator is called the effectiveness, ε and is defined as

  $\varepsilon = q_{regen,act} \ / \ q_{regen,max} = (h_5 - h_2)/(h_4 - h_2)$
- Under the cold-air-standard assumptions, the thermal efficiency of an ideal Brayton cycle with regeneration is:

$$\eta_{th,regen} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(\gamma-1)/\gamma}$$

- The thermal efficiency depends upon the temperature as well as the pressure ratio.

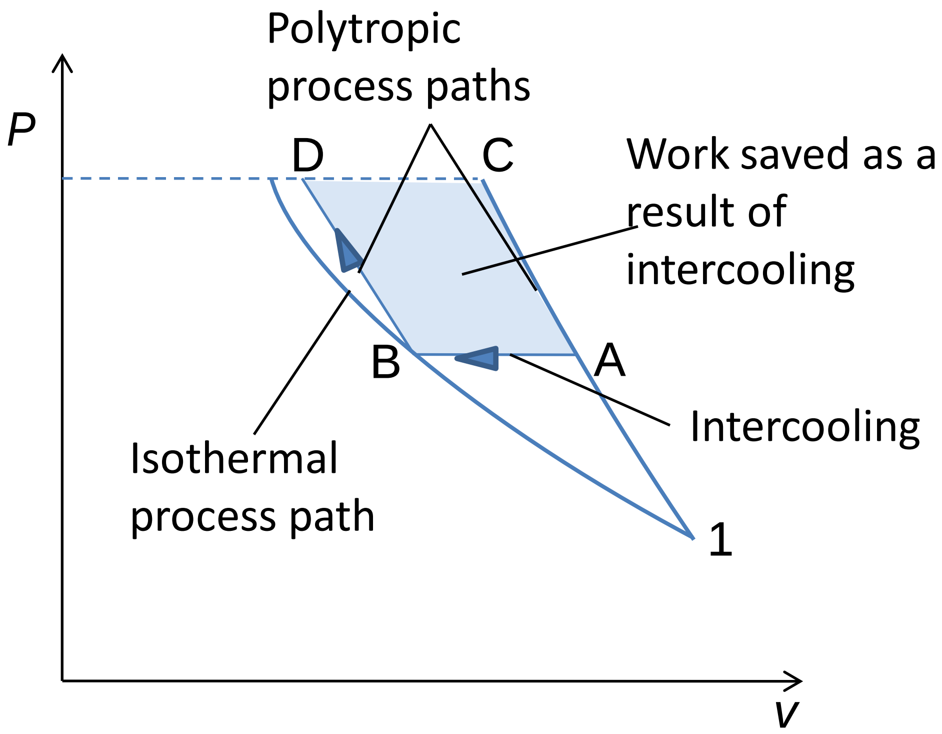
# Ideal Brayton cycle with intercooling, reheating and regeneration

- The net work of a gas-turbine cycle is the difference between the turbine work output and the compressor work input.
- It can be increased by either decreasing the compressor work or increasing the turbine work, or both.
- The work required to compress a gas between two specified pressures can be decreased by carrying out the compression process in stages and cooling the gas in between: multi-stage compression with intercooling.

# Ideal Brayton cycle with intercooling, reheating and regeneration

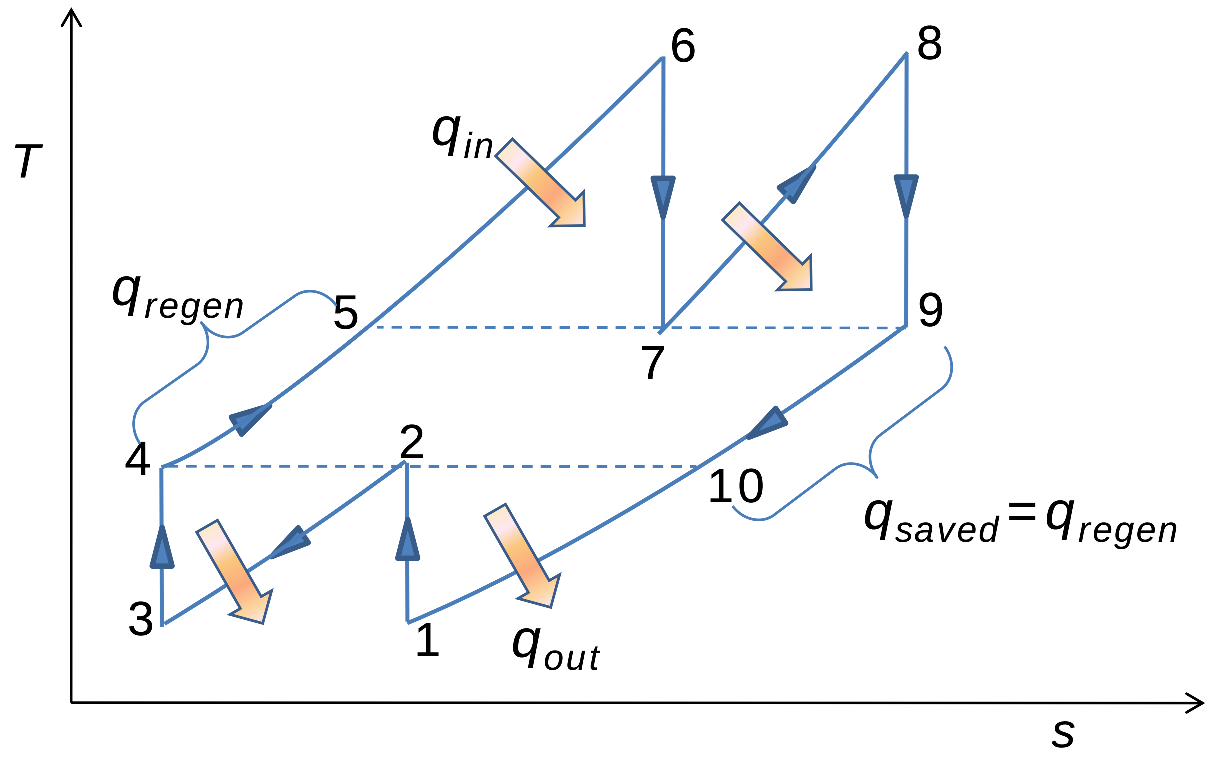
- Similarly the work output of a turbine can be increased by: multi-stage expansion with reheating.
- As the number of stages of compression and expansion are increased, the process approaches an isothermal process.
- A combination of intercooling and reheating can increase the net work output of a Brayton cycle significantly.

# Ideal Brayton cycle with intercooling, reheating and regeneration



Work inputs to a single-stage compressor (process: 1*AC*) *and a* two-stage compressor with intercooling (process: 1*ABD*).

# Ideal Brayton cycle with intercooling, reheating and regeneration

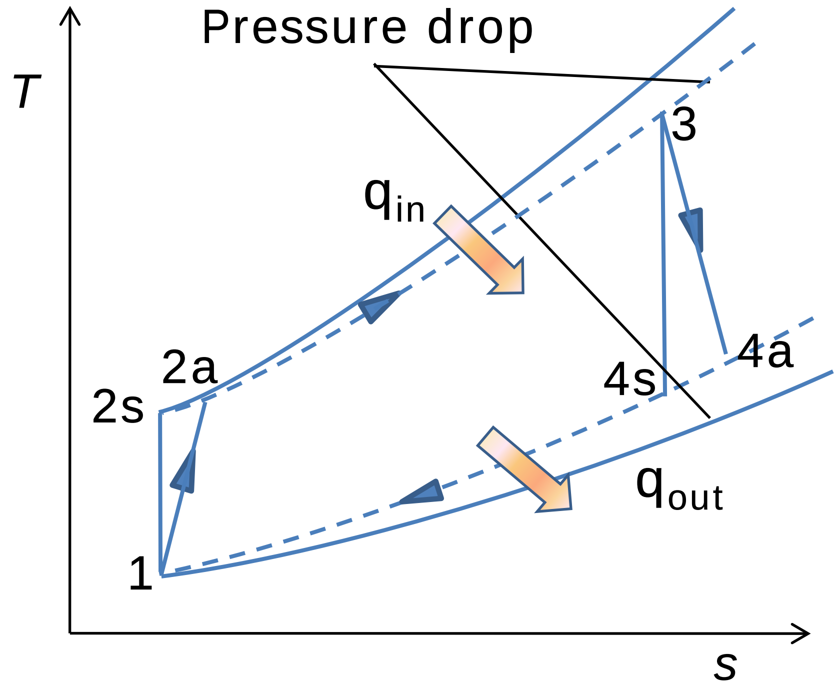


T-s diagram of an ideal gas-turbine cycle with intercooling, reheating, and regeneration

# Actual / Real Brayton cycle

- Actual Brayton cycles differ from the ideal cycles in all the four processes.
- The compression process and expansion processes are non-isentropic.
- Pressure drop during heat addition and heat rejection.
- The presence of irreversibilities causes the above deviations.

# Actual / Real Brayton cycle



Actual Brayton cycle *T-s* diagram

# Actual / Real Brayton cycle

- The deviation of actual compressors and turbines from the isentropic versions can be accounted for by using the isentropic efficiencies.

$$\eta_C = \frac{\text{Isentropic work}}{\text{Actual work}} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{\text{Actual work}}{\text{Isentropic work}} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

- Where, *2a* and *4a* are the actual states at the compressor and turbine exit and *2s* and *4s* are the corresponding isentropic states.

# Actual/Real Brayton cycle

- As a result of non-isentropic compression and expansion, the compressor needs more work than the ideal cycle and turbine generates less work.
- Isentropic efficiencies reflect the amount of deviation of the actual compression/expansion processes from the ideal.
- Total pressure losses in the heat addition/rejection processes also need to be considered.

# Actual / Real Brayton cycle

- Other differences between ideal and actual Brayton cycles
  - Change of specific heats with temperature
  - Heat exchanger effectiveness (in case of regenerative cycles)
  - Mass flow rate of fuel
  - Combustion efficiency
- These parameters are often used in actual cycle analysis.

# Actual / Real Brayton cycle

- Variants of the simple Brayton cycle
  - Reheating
  - Intercooling
  - Regeneration
- Actual cycles with the above will be different from the ideal cycles in terms of the irreversibilities present.
- Isentropic efficiencies, total pressure losses, heat exchanger effectiveness for each additional components of the cycle.

# Actual / Real Brayton cycle

- Actual Brayton cycle with intercooling
  - Isentropic efficiencies of each stage of intercooling
  - Heat exchanger effectiveness of the intercooling duct
- Actual Brayton cycle with reheating
  - Isentropic efficiencies of each stage of reheating
  - Total pressure loss and combustion efficiency during reheating

# Actual / Real Brayton cycle

- Actual Brayton cycle with regeneration
  - Heat exchanger effectiveness
- Actual Brayton cycle with all three of these modifications need to be analysed considering the above discussed irreversibilities.

# In this lecture...

- Brayton cycles
  - Ideal Brayton cycle
  - Variants of Brayton cycle
  - Actual/real Brayton cycle

# In the next lecture...

- Jet engine cycles for aircraft propulsion
  - Turbojet engine
  - Turbojet engine with afterburning
  - Turbofan and its variants
  - Turboprop and turboshaft engines