Introduction to Aerospace Propulsion

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Lecture No - 18

In this lecture ...

- Stirling and Ericsson cycles
- Brayton cycle: The ideal cycle for gas-turbine engines
- The Brayton cycle with regeneration
- The Brayton cycle with intercooling, reheating and regeneration
- Rankine cycle: The ideal cycle for vapour power cycles

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Stirling and Ericsson cycles

- The ideal Otto and Diesel cycles are internally reversible, but not totally reversible.
- Hence their efficiencies will always be less than that of Carnot efficiency.
- For a cycle to approach a Carnot cycle, heat addition and heat rejection must take place isothermally.
- Stirling and Ericsson cycles comprise of isothermal heat addition and heat rejection.

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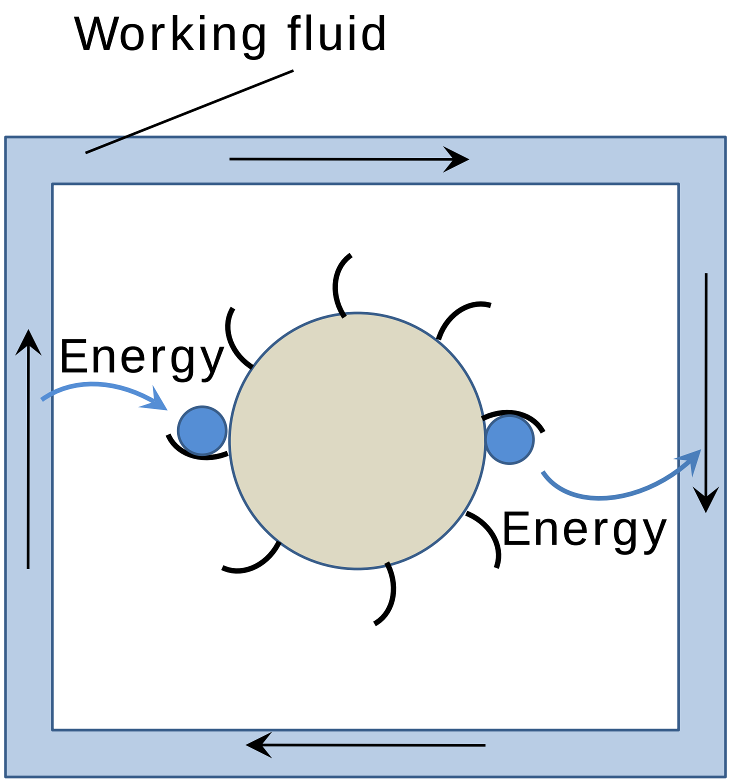
Regeneration



Concept of a regenerator

- Both these cycles also have a regeneration process.
- Regeneration, a process during which heat is transferred to a thermal energy storage device (called a regenerator) during one part of the cycle and is transferred back to the working fluid during another part of the cycle.

Stirling cycle

- Consists of four totally reversible processes:
  - 1-2 T = constant, expansion (heat addition from the external source)
  - 2-3 v = constant, regeneration (internal heat transfer from the working fluid to the regenerator)
  - 3-4 T= constant, compression (heat rejection to the external sink)
  - 4-1 v = constant, regeneration (internal heat transfer from the regenerator back to the working fluid)

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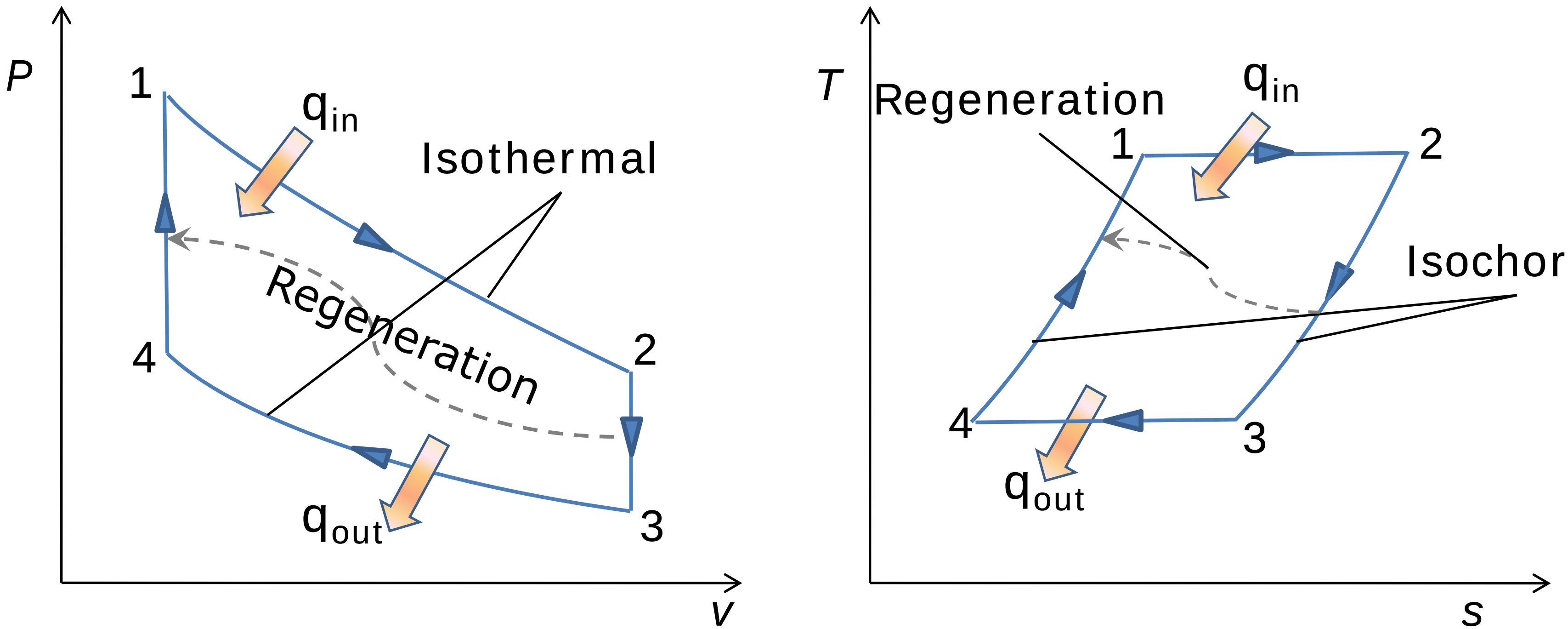
Stirling cycle



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

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Ericsson cycle

- Consists of four totally reversible processes:
  - 1-2 T = constant, expansion (heat addition from the external source)
  - 2-3 P = constant, regeneration (internal heat transfer from the working fluid to the regenerator)
  - 3-4 T= constant, compression (heat rejection to the external sink)
  - 4-1 P = constant, regeneration (internal heat transfer from the regenerator back to the working fluid)

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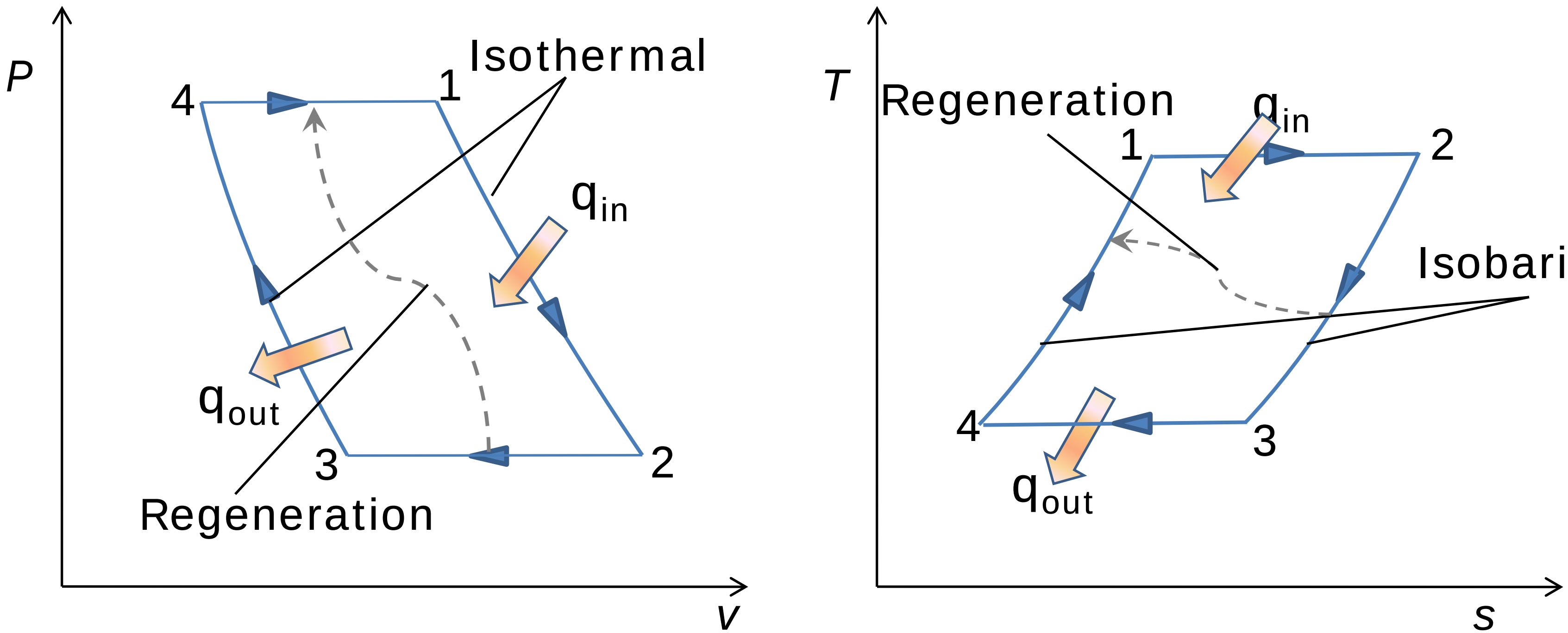
Ericsson cycle



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

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Stirling and Ericsson cycles

- Since both these engines are totally reversible cycles, their efficiencies equal the Carnot efficiency between same temperature limits.
- These cycles are difficult to realise practically, but offer great potential.
- Regeneration increases efficiency.
- This fact is used in many modern day cycles to improve efficiency.

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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.

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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

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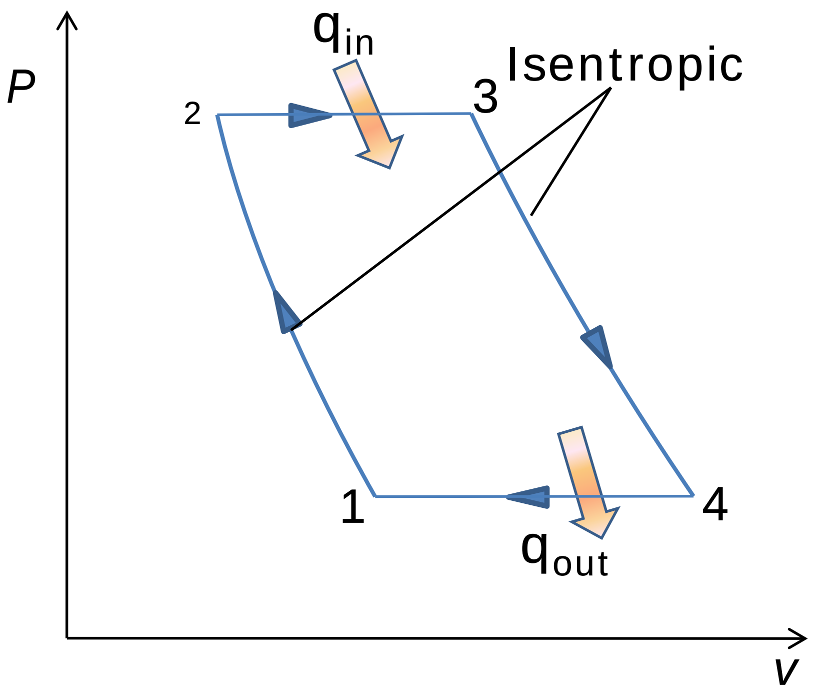
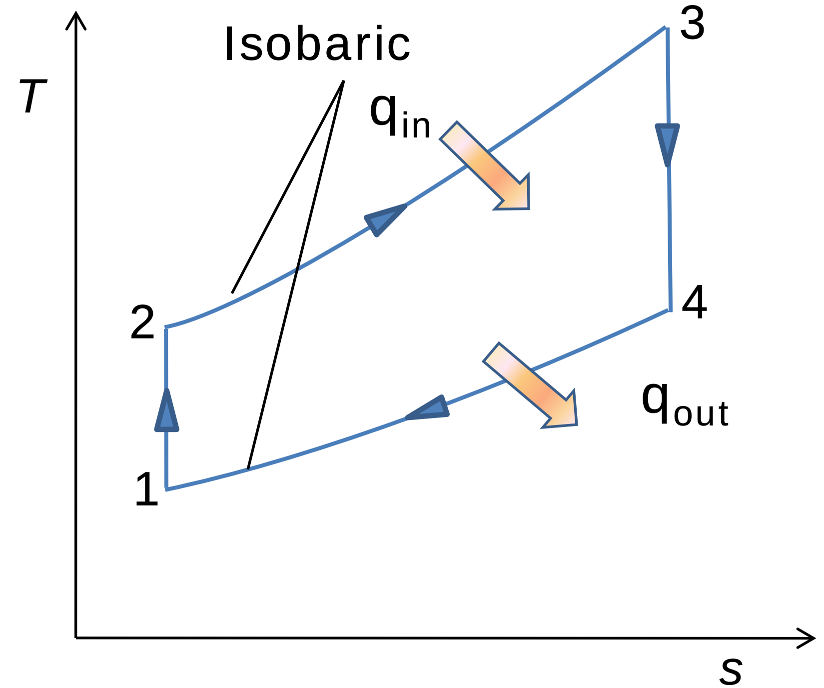
Brayton cycle





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

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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:

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

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

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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 $P_4 = P_1$.

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

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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.

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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.

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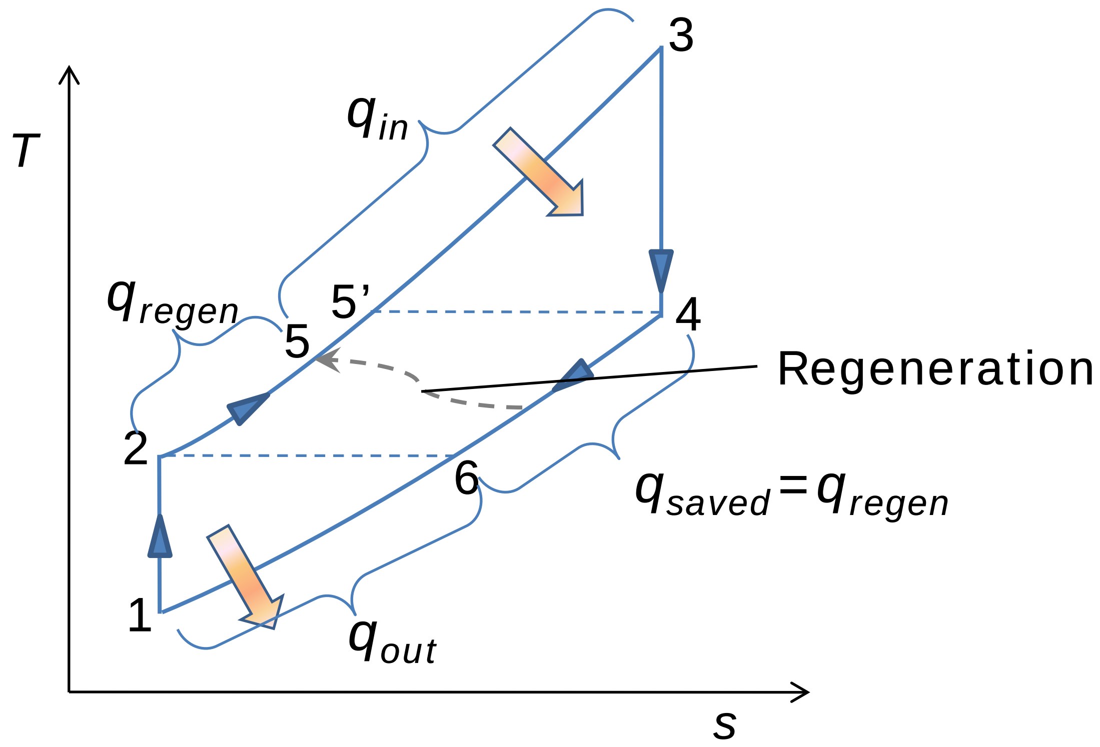
Brayton cycle with regeneration



T-s diagram of a Brayton cycle with regeneration

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Brayton cycle with regeneration

- The highest temperature occurring within the regenerator is T_4.
- Air normally leaves the regenerator at a lower temperature, T_5.
- In the limiting (ideal) case, the air exits the regenerator at the inlet temperature of the exhaust gases T_4.
- The actual and maximum heat transfers are:

$$q_{regen,act} = h_5 - h_2 \quad and \quad q_{regen,max} = h_{5'} - h_2 = h_4 - h_2$$

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.

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.

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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.

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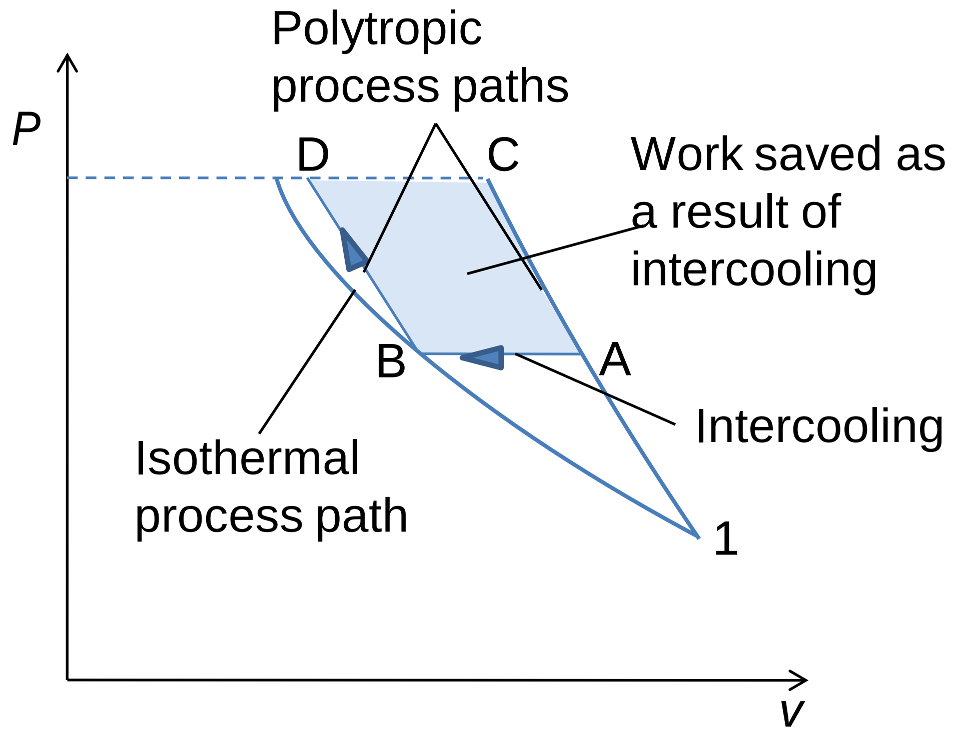
Brayton cycle with intercooling, reheating and regeneration



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

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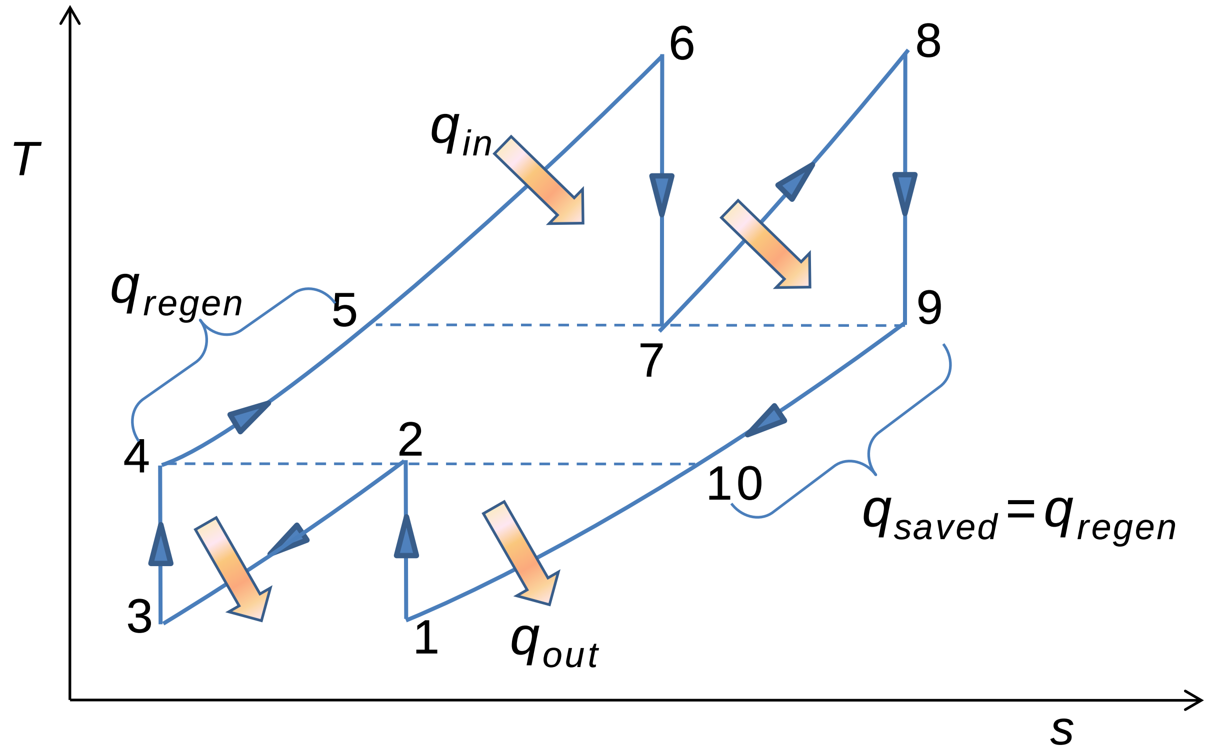
Brayton cycle with intercooling, reheating and regeneration



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

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Brayton cycle with intercooling, reheating and regeneration

- The net work output of a gas-turbine cycle improves as a result of intercooling and reheating.
- However, intercooling and reheating decreases the thermal efficiency unless they are accompanied by regeneration.
- This is because intercooling decreases the average temperature at which heat is added, and reheating increases the average temperature at which heat is rejected.

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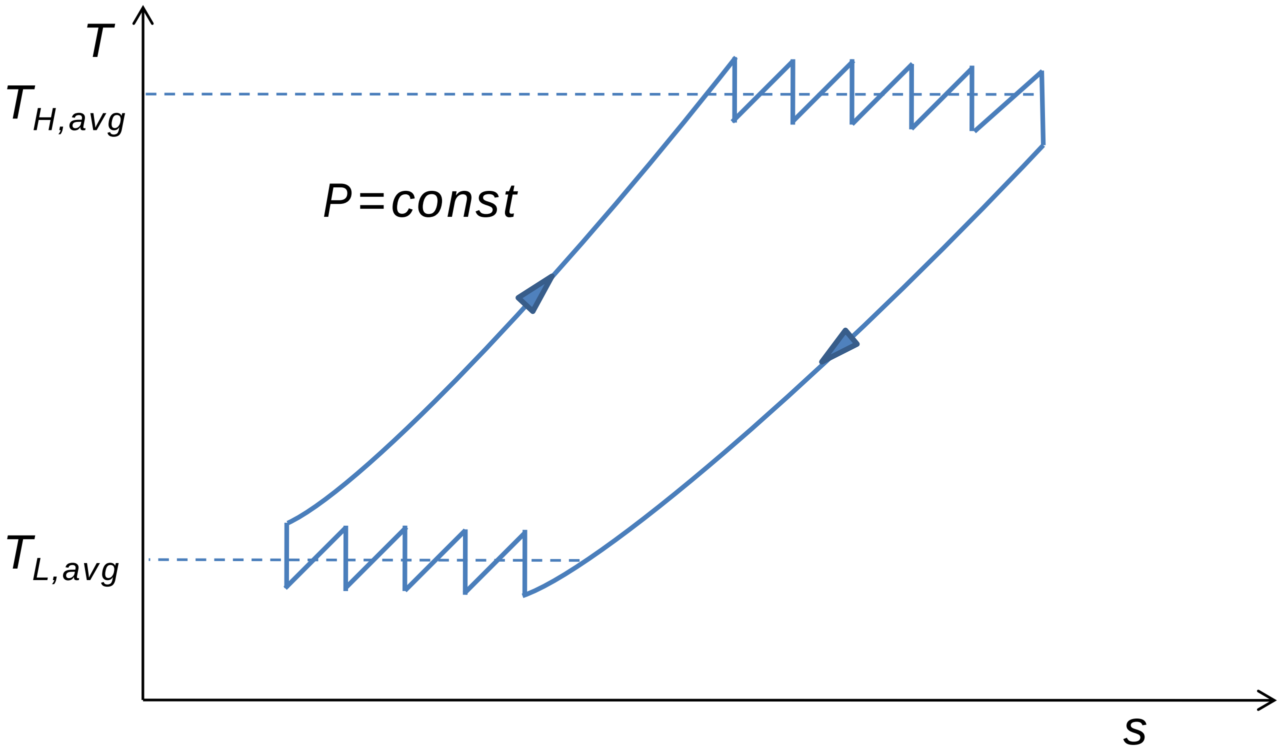
Brayton cycle with intercooling, reheating and regeneration



As the number of compression and expansion stages increases, the Brayton cycle with intercooling, reheating, and regeneration approaches the Ericsson cycle.

Rankine cycle

- Rankine cycle is the ideal cycle for vapour power cycles.
- The ideal Rankine cycle does not involve any internal irreversibilities.
- The ideal cycle consists of the following:
  - 1-2 Isentropic compression in a pump
  - 2-3 Constant pressure heat addition in a boiler
  - 3-4 Isentropic expansion in a turbine
  - 4-1 Constant pressure heat rejection in a condenser

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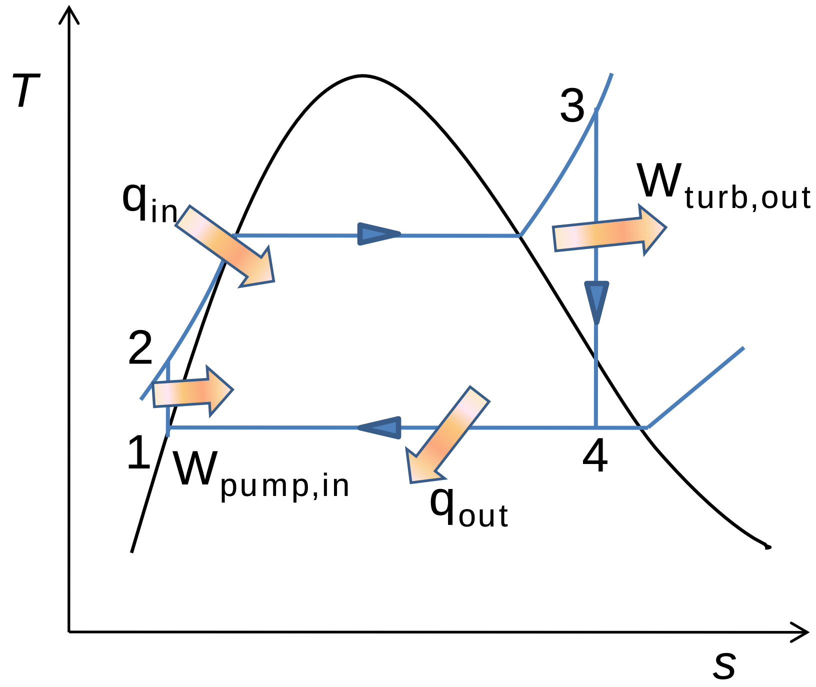
Rankine cycle



The ideal Rankine cycle

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Rankine cycle

- All the components are steady flow systems.
- The energy balance for each sub-system can be expressed as:

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

$$\text{Pump}: w_{pump,in} = h_2 - h_1 = v(P_2 - P_1)$$

$$\text{Boiler}: q_{in} = h_3 - h_2$$

$$\text{Condensor}: q_{out} = h_4 - h_1$$

$$\text{Turbine}: w_{out} = h_3 - h_4$$

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Rankine cycle

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

$$\eta_{th,Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$\text{where, } w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{pump,in}$$

Rankine cycle

- Rankine cycles can also be operated with reheat and regeneration.
- The average temperature during the reheat process can be increased by increasing the number of expansion and reheat stages.
- A Rankine cycle with reheat and regeneration offer substantially higher efficiencies as compared to a simple Rankine cycle.

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In the next lecture …

- Helmholtz and Gibb’s functions
- Legendre transformations
- Thermodynamic potentials
- The Maxwell relations
- The ideal gas equation of state
- Compressibility factor
- Other equations of state
- Joule-Thomson coefficient

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