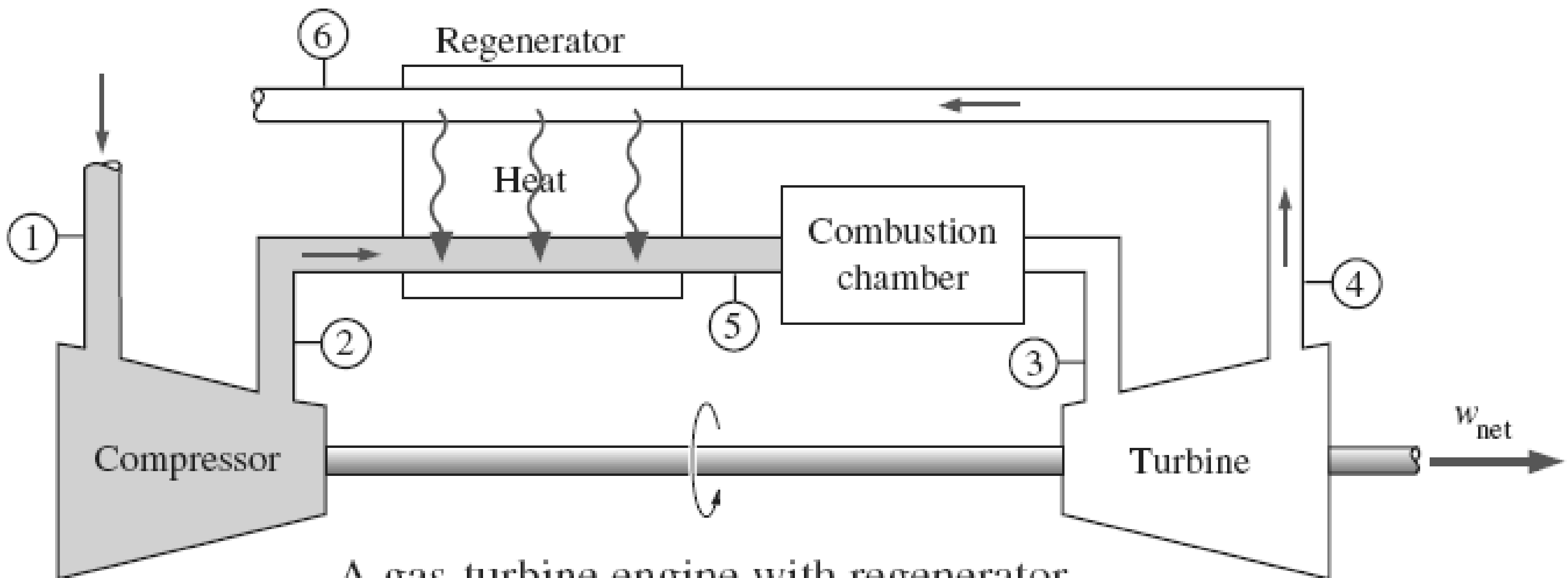
- Recap: Lecture 29, 25th March 2014, 0830-0930 hrs.
  - Stirling cycle
  - Operation of a Stirling cycle
  - Ericsson cycle
  - Stirling, Ericsson and Carnot cycles
  - Brayton cycle
  - Brayton cycle performance with pressure ratio and Tmax
  - Performance improvement of the Brayton cycle

- Applications of gas turbine engines
  - Aircraft engines
  - Marine engines
  - Power generation
  - Racing cars
- Improve gas turbine efficiency
  - Increasing turbine inlet temperature
  - Limitation: materials that withstand high temperatures
  - Increasing efficiency of turbomachinery and other components
  - Adding modifications to the basic cycle
  - Regeneration, intercooling etc.

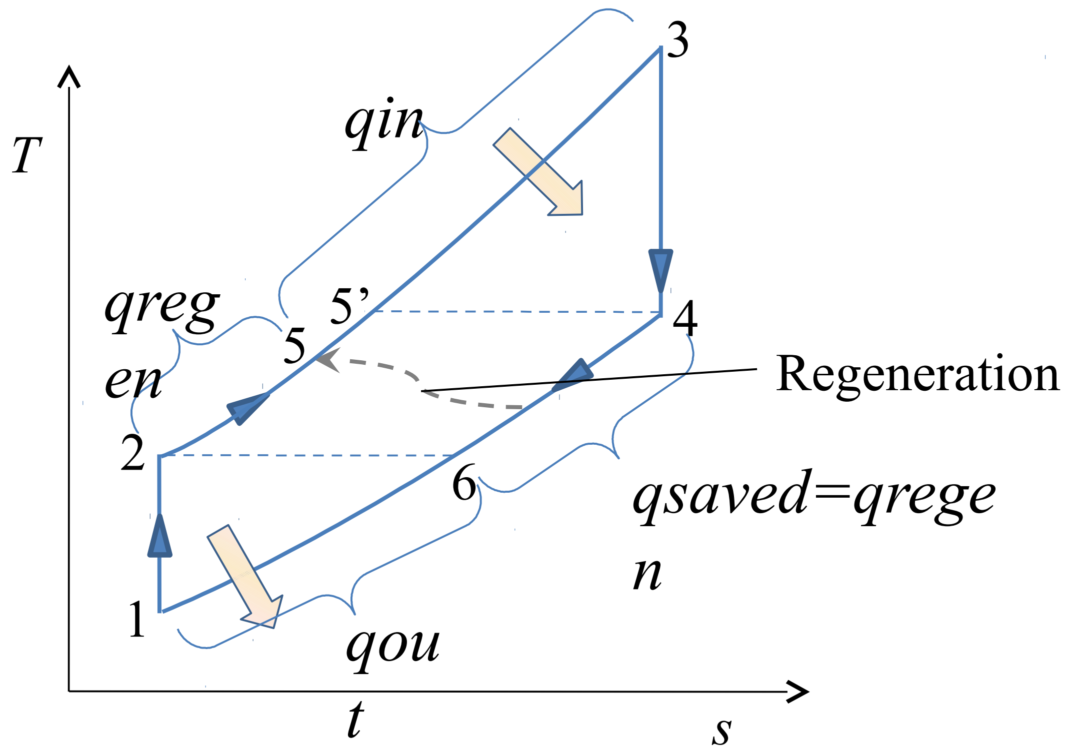
Brayton cycle with regeneration

- 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.
- Regeneration is also sometimes referred to as recuperation.



A gas-turbine engine with regenerator.

Brayton cycle with regeneration



T-s diagram of a Brayton cycle with regeneration

Brayton cycle with regeneration

- The highest temperature occurring within the regenerator is $T4$.
- Air normally leaves the regenerator at a lower temperature, $T5$.
- In the limiting (ideal) case, the air exits the regenerator at the inlet temperature of the exhaust gases $T4$.
- The actual and maximum heat transfers are:

$$q_{regen,act} = h5 - h2 \quad \text{and} \quad q_{regen,max} = h5' - h2 = h4 - h2$$

Brayton cycle with regeneration

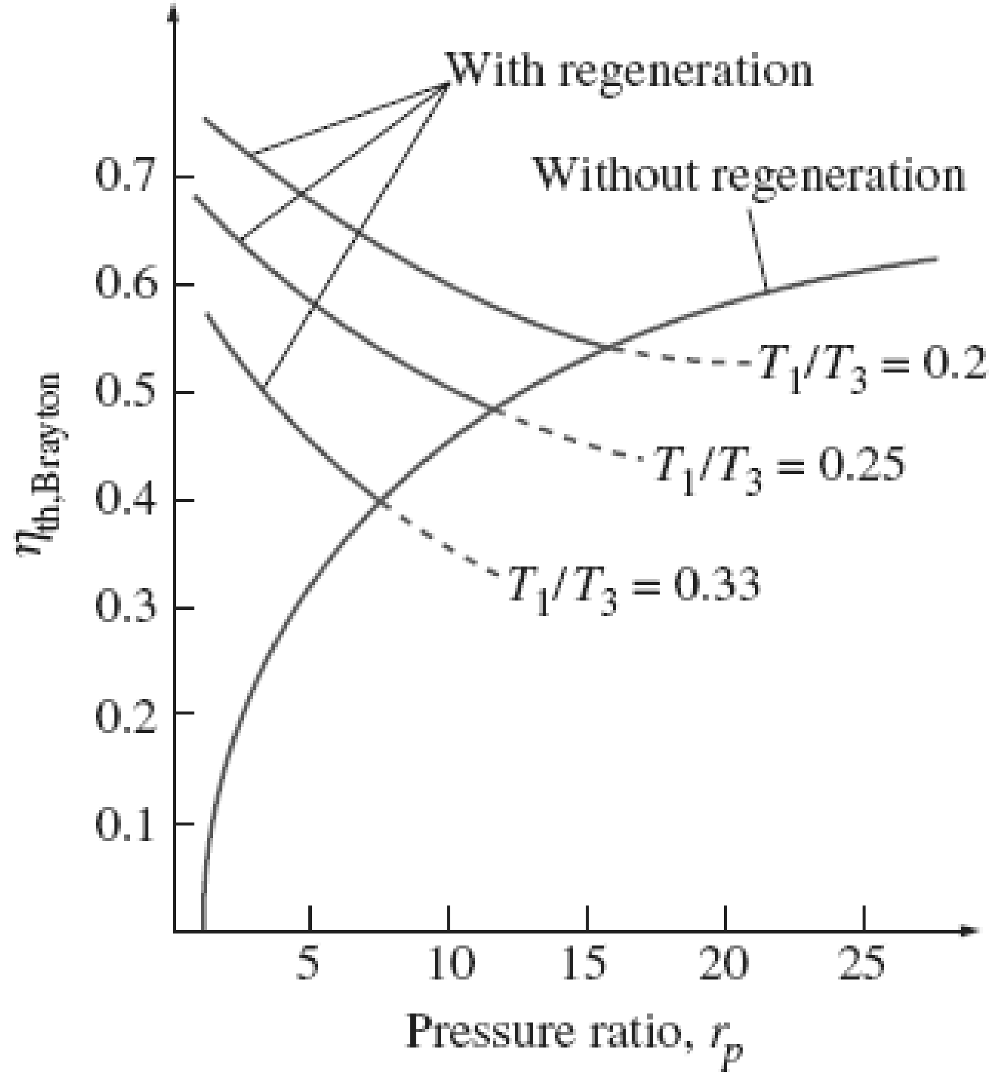
- The extent to which a regenerator approaches an ideal regenerator is called the effectiveness, ε and is defined as

$$\varepsilon = q_{regen,act} / q_{regen,max} = (h5 - h2)/(h4 - h2)$$

- 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.



Thermal efficiency of the ideal Brayton cycle with and without regeneration.

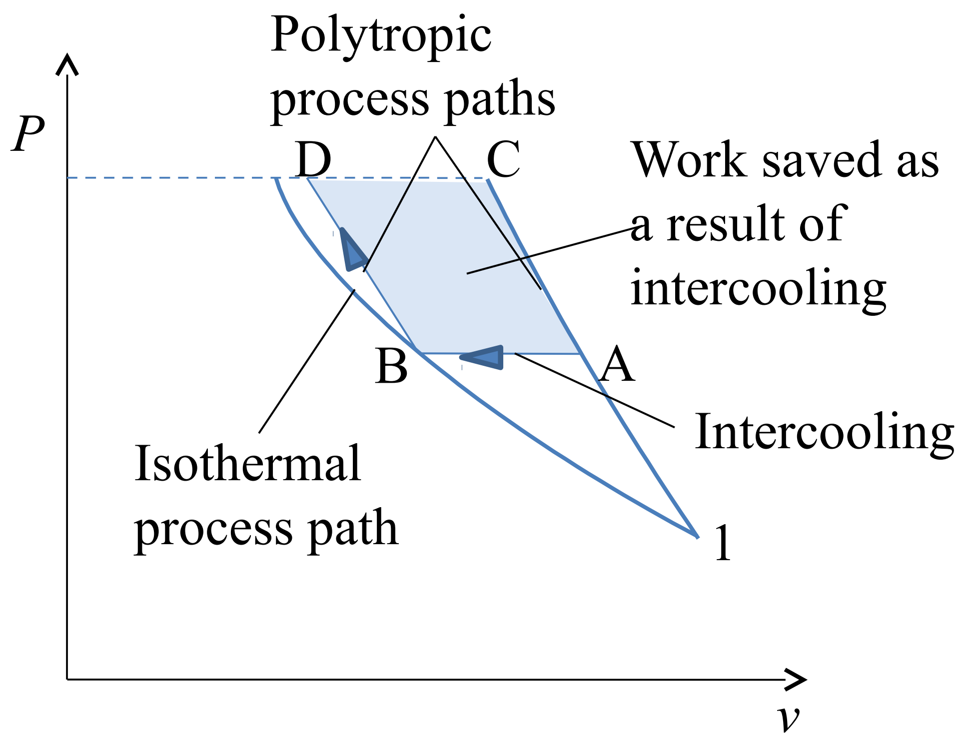
Brayton cycle with intercooling, reheating and regeneration

- 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.

Brayton cycle with intercooling, reheating and regeneration

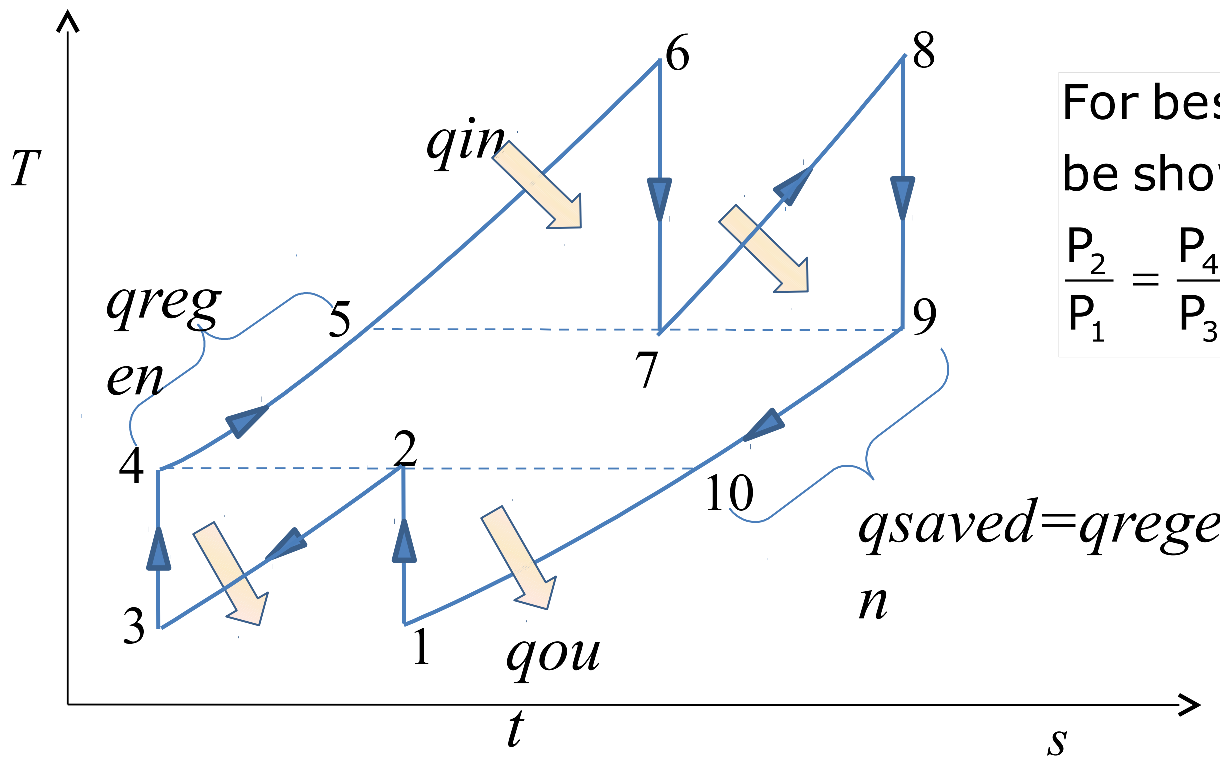
- Similarly the work output of a turbine can be increased by: multi-stage expansion with reheating.
- As the number of stages of compression and expansion are increased, the process approaches an isothermal process.
- A combination of intercooling and reheating can increase the net work output of a Brayton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

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)*.

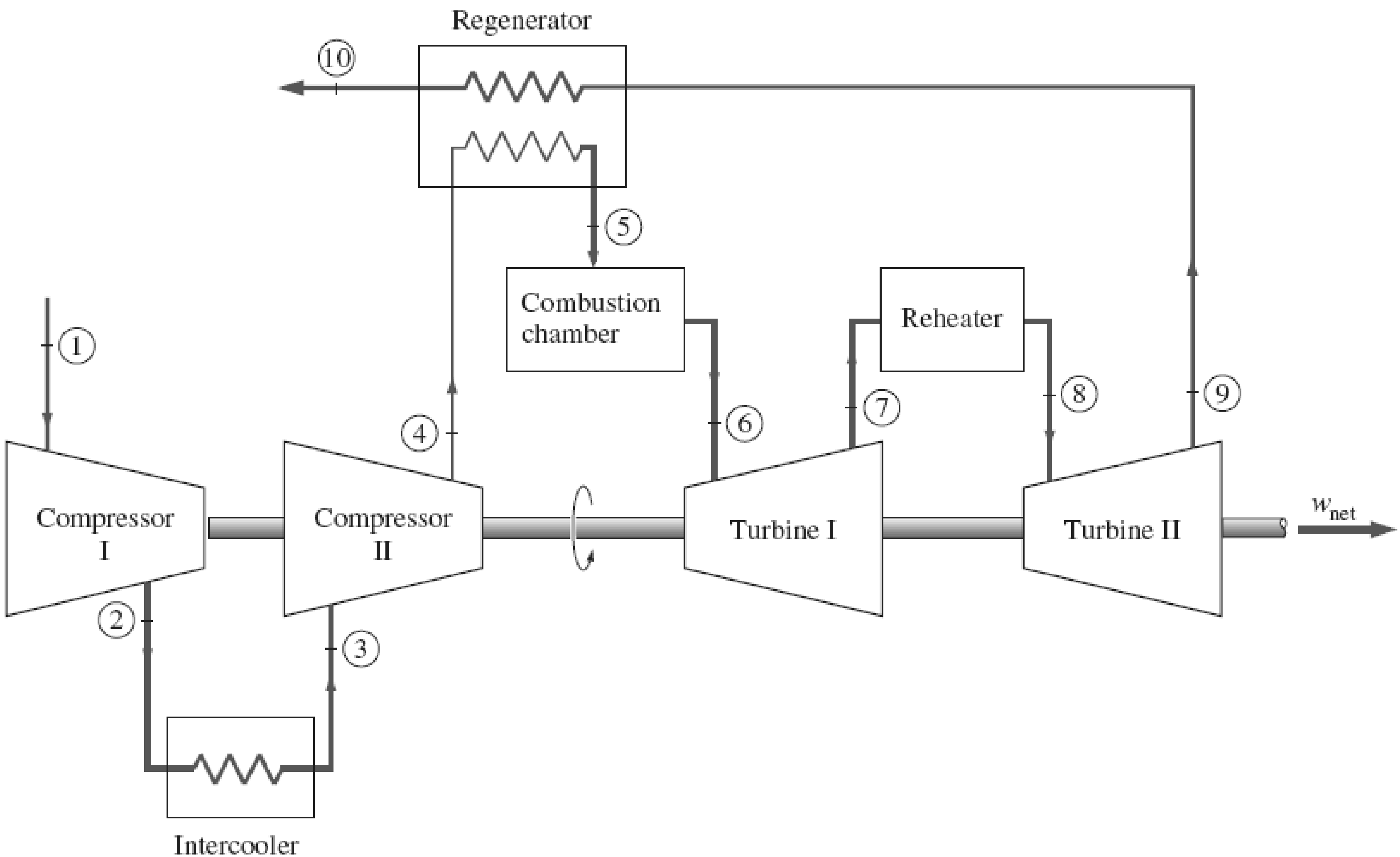
Brayton cycle with intercooling, reheating and regeneration



For best performance, it can be shown that

$$\frac{P_2}{P_1} = \frac{P_4}{P_3} \text{ and } \frac{P_6}{P_7} = \frac{P_8}{P_9}$$

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

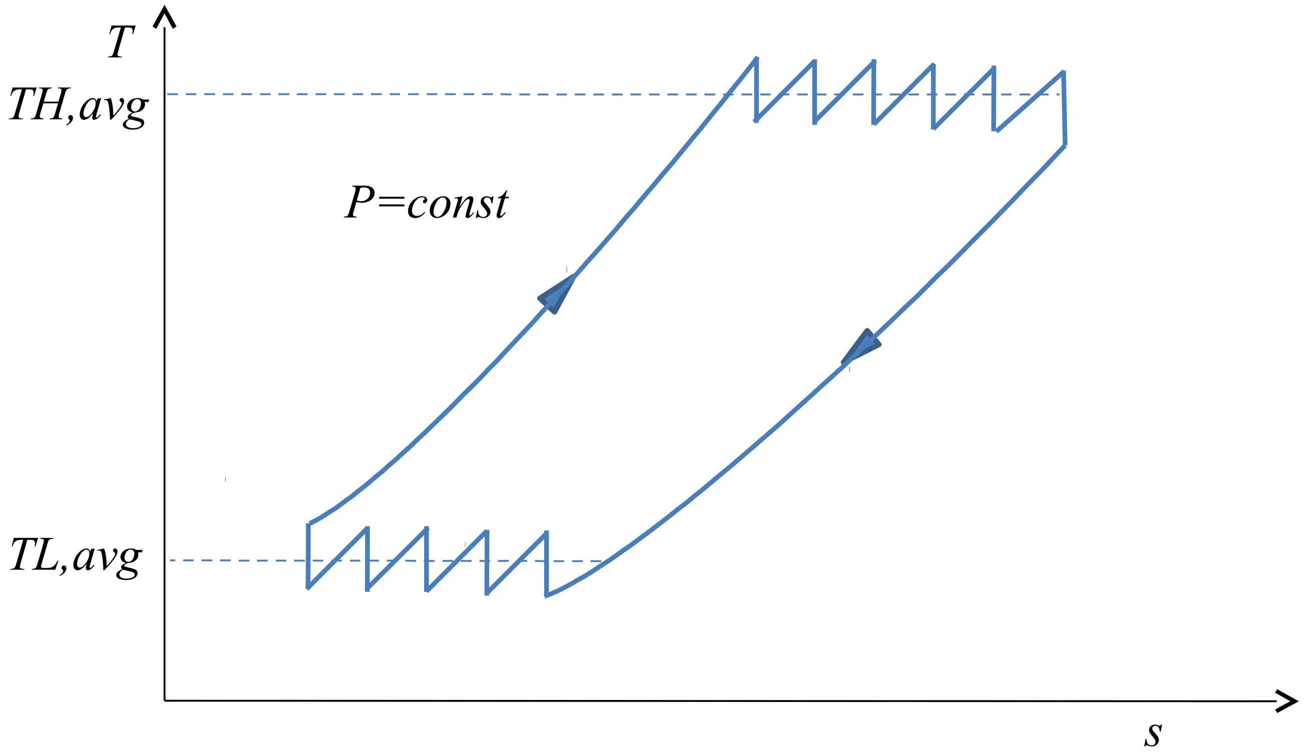


A gas-turbine engine with two-stage compression with intercooling, two-stage expansion with reheating, and regeneration.

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 reduces the thermal efficiency unless they are accompanied by regeneration.
- This is because
  - intercooling reduces the average temperature at which heat is added,
  - reheating increases the average temperature at which heat is rejected.

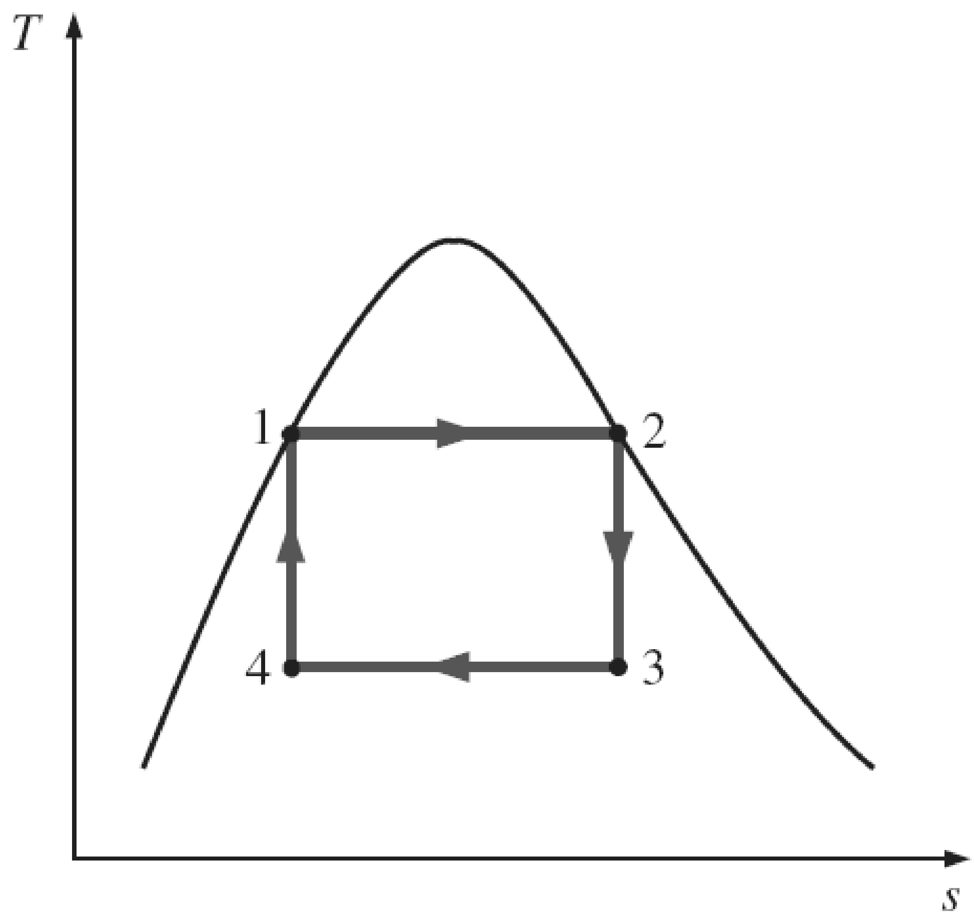
Brayton cycle with intercooling, reheating and regeneration



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

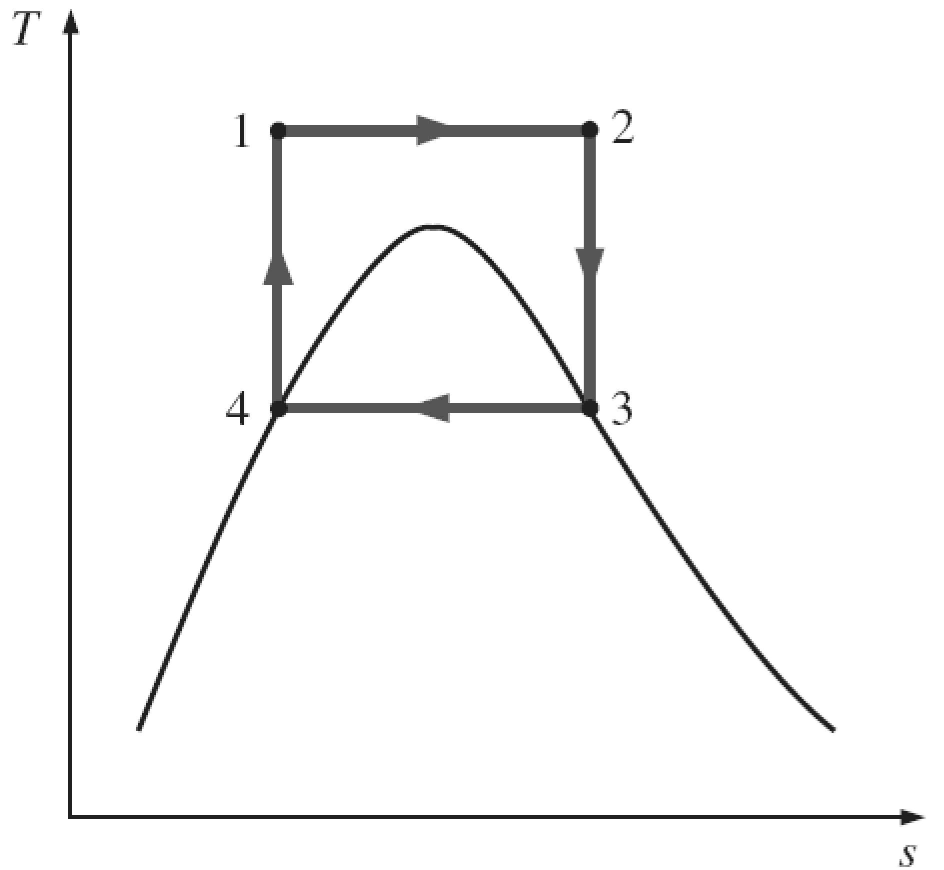
Carnot Vapour Cycle

- Carnot cycle is the most efficient cycle between given temperature limits.
- Let us extend a Carnot cycle for a vapour cycle with steam as the working fluid.
- Though theoretically such a cycle seems feasible, there are severe practical limitations.
- Carnot vapour cycle needs to have the following processes
  - Isothermal heat addition
  - Isentropic expansion
  - Isothermal heat rejection
  - Isentropic compression



Case 1: Carnot cycle within the saturation dome

- Two-phase heat transfer, severely limits the maximum temperature that can be used in the cycle (it has to remain under the critical-point value) limits max efficiency.
- Raising the maximum temperature in the cycle involves heat transfer to the working fluid in a single phase, which is not easy to accomplish isothermally.
- Isentropic expansion: Leads to very low quality steam turbine operation is severely affected.
- Isentropic compression: Control the condensation process during 4-1, Compressor to handle two-phase flow.



Case 2: Carnot cycle partially outside the saturation dome

- Isentropic compression to extremely high pressures □ difficult to achieve
- Not possible to have isothermal heat transfer at variable pressures.
- Therefore Carnot cycle cannot form a realistic model for vapour power cycles.
- The ideal cycle for vapour is the Rankine cycle.