- Recap: Lecture 28, 24th Mar 2014, 1130-1230 hrs.
  - Otto cycle
  - 2-stroke engines
  - Wankel engine
  - Otto cycle efficiency and compression ratio
  - Diesel cycle
  - Thermodynamic cycle
  - Efficiency
  - Diesel cycle efficiency and compression ratio
  - Dual cycle
  - Stirling cycle
  - Regeneration

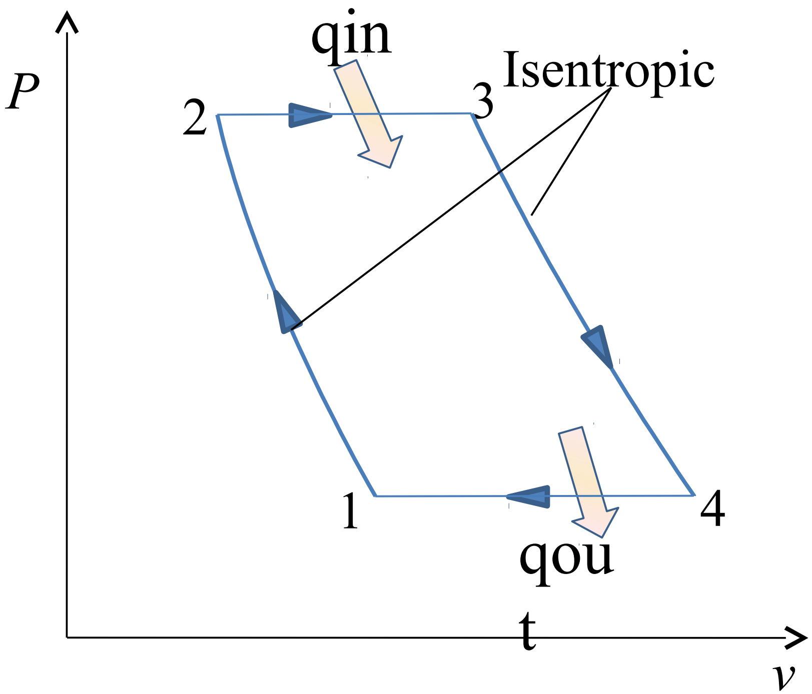
Brayton cycle

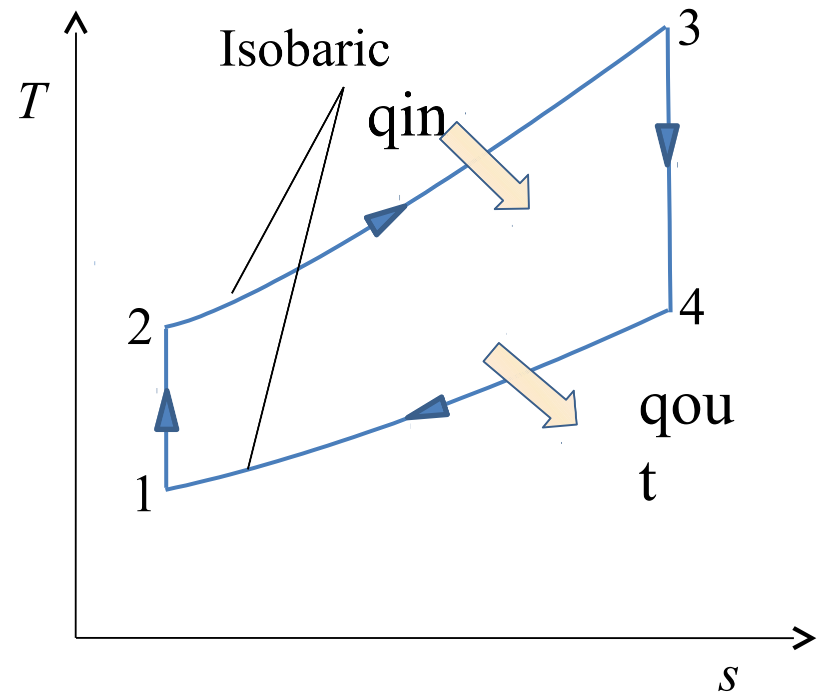
- The Brayton cycle was proposed by George Brayton in 1870 for use in reciprocating engines.
- Modern day gas turbines operate on Brayton cycle and work with rotating machinery.
- Gas turbines operate in open-cycle mode, but can be modelled as closed cycle using air-standard assumptions.
- Combustion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

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

Brayton cycle





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

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 :

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

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

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

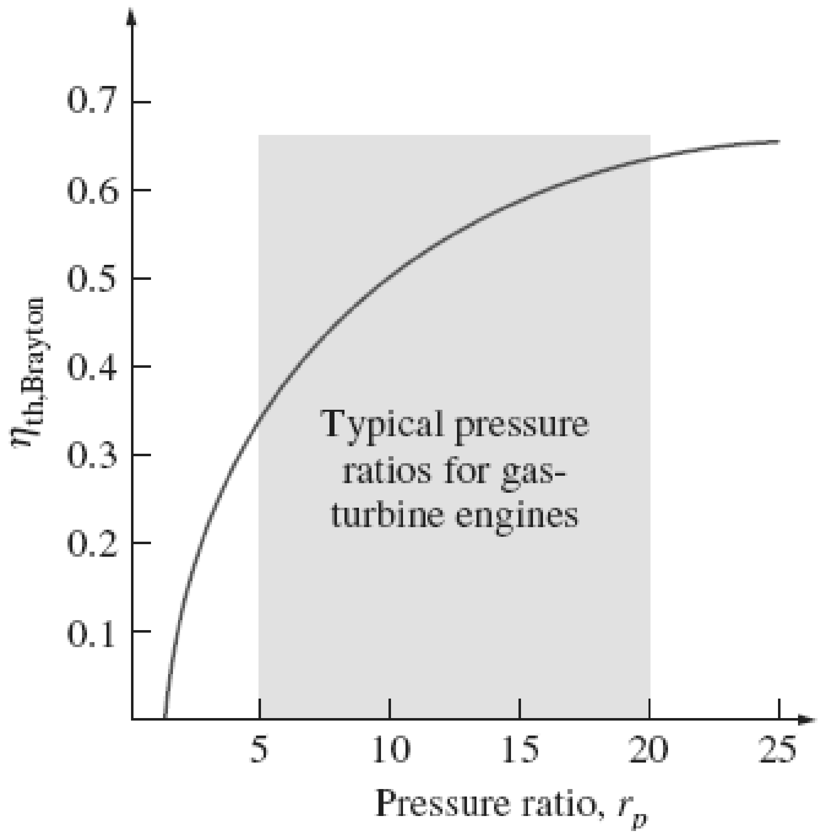
Brayton cycle

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

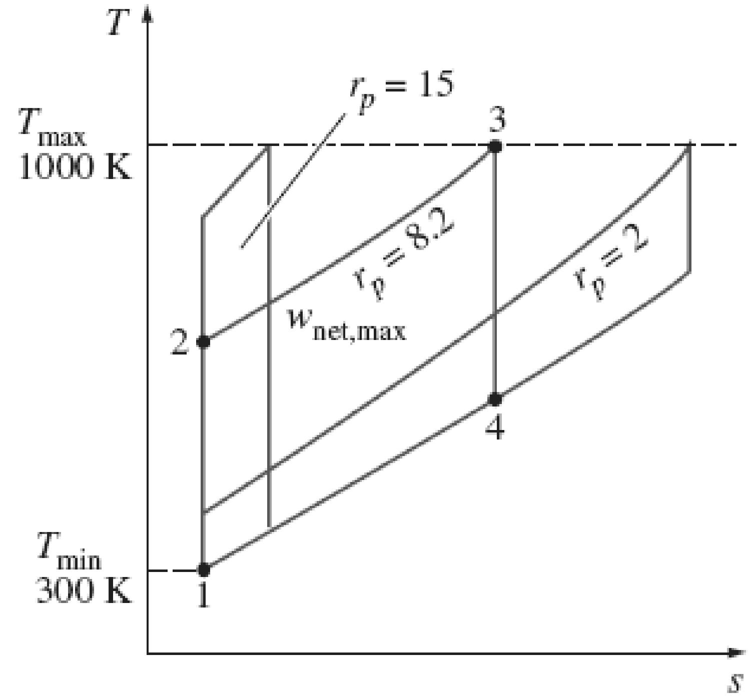
$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$

where, $r_p = \dfrac{P_2}{P_1}$ 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.



Thermal efficiency of the ideal Brayton cycle as a function of the pressure ratio.

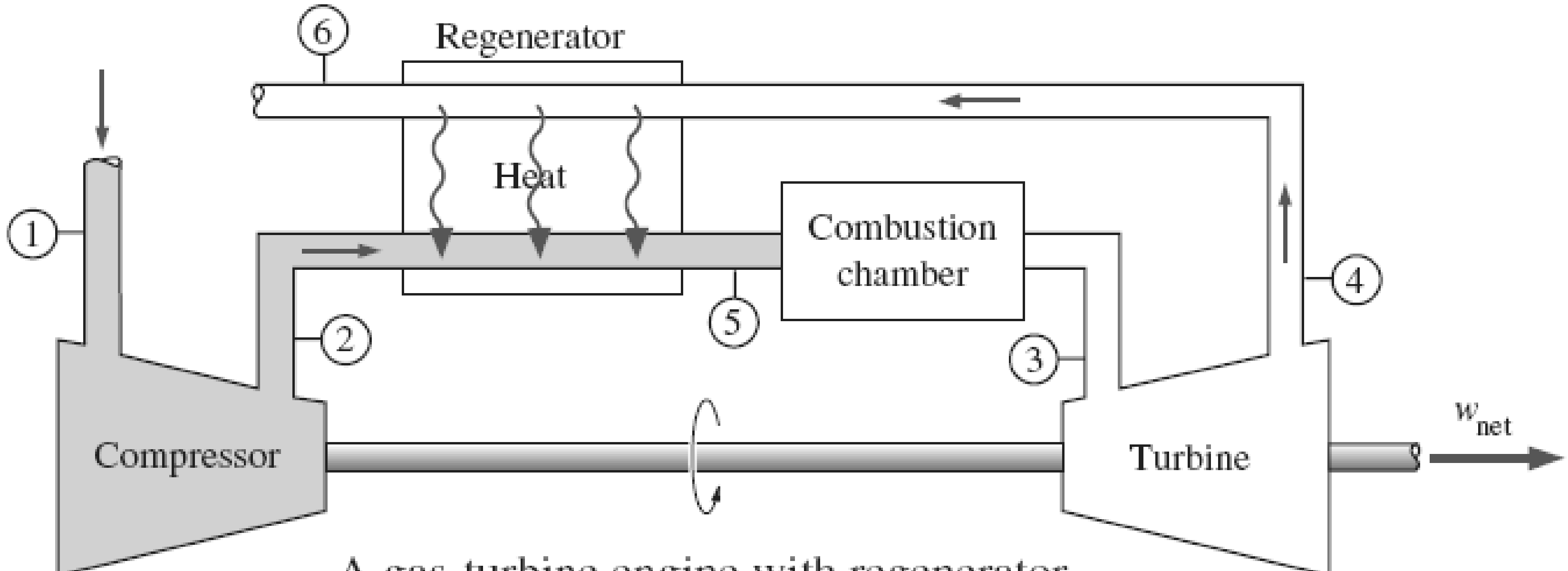


For fixed values of T_{min} and T_{max}, the net work of the Brayton cycle first increases with the pressure ratio, then reaches a maximum at $r_p = (T_{max}/T_{min})^{k/[2(k-1)]}$, and finally decreases.

- 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.

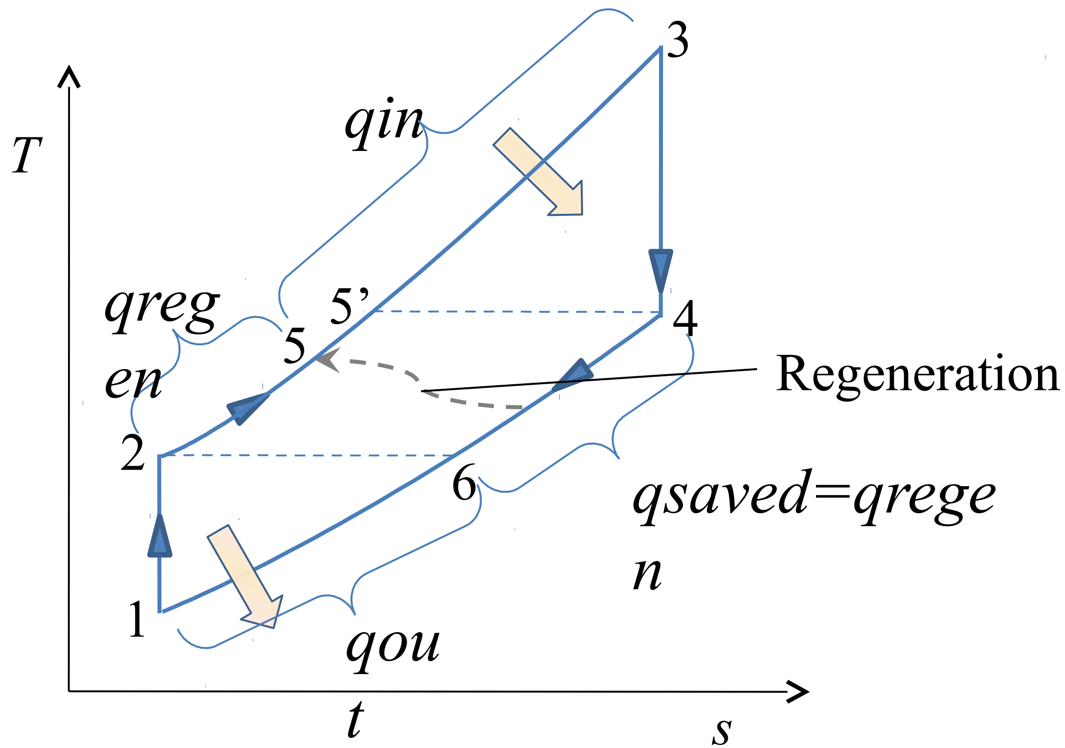
Brayton cycle with regeneration

- 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:

$$qregen,act = h5 - h2 \quad and \quad qregen,max = h5' - h2 = h4 - h2$$

Brayton cycle with regeneration

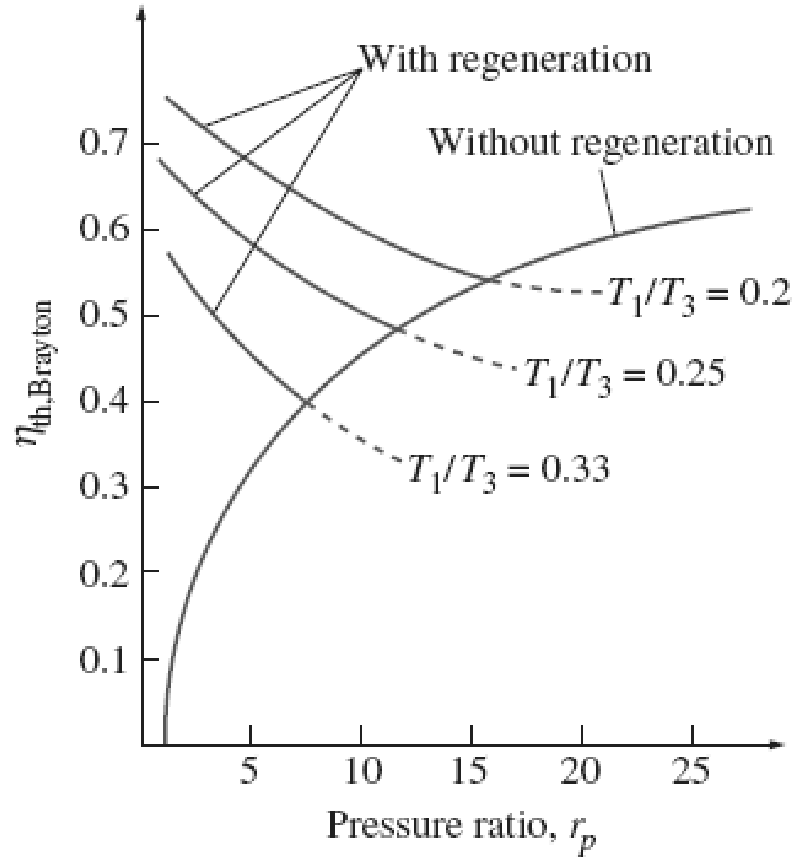
- The extent to which a regenerator approaches an ideal regenerator is called the effectiveness, ε and is defined as

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

- 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.