Introduction to Aerospace Propulsion

Prof. Bhaskar Roy, Prof. A M Pradeep
Department of Aerospace Engineering, IIT Bombay

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
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.
Regeneration

- 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)
Stirling cycle

Stirling cycle on $P$-$v$ and $T$-$s$ diagrams
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)
Ericsson cycle

Ericsson cycle on $P$-$v$ and $T$-$s$ diagrams
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.
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 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,

\[
\frac{T_1}{T_2} = \left(\frac{P_2}{P_1}\right)^{(\gamma - 1)/\gamma} = \left(\frac{P_3}{P_4}\right)^{(\gamma - 1)/\gamma} = \frac{T_3}{T_4}
\]
Brayton cycle

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

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

where, \( r_p = \frac{P_2}{P_1} \) 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.
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 reused.
• Regeneration decreases the heat input (thus fuel) requirements for the same net work output.
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 $T_4$.
- 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:
  $$q_{\text{regen,act}} = h_5 - h_2 \quad \text{and} \quad q_{\text{regen,max}} = h_5' - h_2 = h_4 - h_2$$
Brayton cycle with regeneration

- The extent to which a regenerator approaches an ideal regenerator is called the effectiveness, $\varepsilon$ and is defined as:
  $$\varepsilon = \frac{q_{\text{regen,act}}}{q_{\text{regen,max}}} = \frac{(h_5 - h_2)}{(h_4 - h_2)}$$

- Under the cold-air-standard assumptions, the thermal efficiency of an ideal Brayton cycle with regeneration is:
  $$\eta_{\text{th,regen}} = 1 - \left( \frac{T_1}{T_3} \right) \left( r_p \right)^{(\gamma-1)/\gamma}$$

- 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.
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

Polytropic process paths

Work saved as a result of intercooling

Isothermal process path

Intercooling

Work inputs to a single-stage compressor (process: 1AC) and a two-stage compressor with intercooling (process: 1ABD).
Brayton cycle with intercooling, reheating and regeneration

T-s diagram of an ideal gas-turbine cycle with intercooling, 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 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.
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
Rankine cycle

The ideal Rankine cycle
Rankine cycle

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

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

Pump: \[w_{pump,in} = h_2 - h_1 = \nu(P_2 - P_1)\]

Boiler: \[q_{in} = h_3 - h_2\]

Condensor: \[q_{out} = h_4 - h_1\]

Turbine: \[w_{out} = h_3 - h_4\]
Rankine cycle

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

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

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