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 

\[ P_2 = P_3 \text{ and } P_4 = P_1. \]

Therefore,

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

$q_{in}$

$q_{regen}$

$q_{saved} = q_{regen}$

$q_{out}$
Ideal 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.
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.
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Ideal Brayton cycle with intercooling, reheating and regeneration

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

\[
\eta_C = \frac{\text{Isentropic work}}{\text{Actual work}} \approx \frac{h_{2s} - h_1}{h_{2a} - h_1}
\]

\[
\eta_T = \frac{\text{Actual work}}{\text{Isentropic work}} \approx \frac{h_3 - h_{4a}}{h_3 - h_{4s}}
\]

- 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
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  - 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