Brayton Cycle

Open Cycle Gas Turbine Engines

- after compression, air enters a combustion chamber into which fuel is injected
- the resulting products of combustion expand and drive the turbine
- combustion products are discharged to the atmosphere
- compressor power requirements vary from 40-80% of the power output of the turbine (remainder is net power output), i.e. back work ratio = 0.4 → 0.8
- high power requirement is typical when gas is compressed because of the large specific volume of gases in comparison to that of liquids

Idealized Air Standard Brayton Cycle

- closed loop
- constant pressure heat addition and rejection
- ideal gas with constant specific heats
Brayton Cycle Efficiency

The Brayton cycle efficiency can be written as

\[ \eta = 1 - (r_p)^{(1-k)/k} \]

where we define the pressure ratio as:

\[ r_p = \frac{P_2}{P_1} = \frac{P_3}{P_4} \]
Maximum Pressure Ratio

Given that the maximum and minimum temperature can be prescribed for the Brayton cycle, a change in the pressure ratio can result in a change in the work output from the cycle.

The maximum temperature in the cycle ($T_3$) is limited by metallurgical conditions because the turbine blades cannot sustain temperatures above 1300 K. Higher temperatures (up to 1600 K can be obtained with ceramic turbine blades). The minimum temperature is set by the air temperature at the inlet to the engine.

\[ W_{\text{net,max}} \Rightarrow r_p = \left( \frac{T_{\max}}{T_{\min}} \right)^{\frac{k}{2(k-1)}} \]

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Brayton Cycle with Reheat

- $T_3$ is limited due to metallurgical constraints
- excess air is extracted and fed into a second stage combustor and turbine
- turbine outlet temperature is increased with reheat ($T_6 > T_4'$), therefore potential for regeneration is enhanced
- when reheat and regeneration are used together the thermal efficiency can increase significantly
Compression with Intercooling

- the work required to compress in a steady flow device can be reduced by compressing in stages

- cooling the gas reduces the specific volume and in turn the work required for compression

- by itself compression with intercooling does not provide a significant increase in the efficiency of a gas turbine because the temperature at the combustor inlet would require additional heat transfer to achieve the desired turbine inlet temperature

- but the lower temperature at the compressor exit enhances the potential for regeneration i.e. a larger $\Delta T$ across the heat exchanger
Brayton Cycle with Regeneration

- A regenerator (heat exchanger) is used to reduce the fuel consumption to provide the required \( \dot{Q}_H \).
- The efficiency with a regenerator can be determined as:

\[
\eta = \frac{\dot{W}_{net}}{\dot{Q}_H} = 1 - \frac{\dot{Q}_L}{\dot{Q}_H}
\]
\[
\begin{align*}
&= 1 - \frac{c_p(T_6 - T_1)}{c_p(T_3 - T_5)} \Rightarrow (\text{for a real regenerator}) \\
&= 1 - \frac{c_p(T_6' - T_1)}{c_p(T_3 - T_5')} \Rightarrow (\text{for an ideal regenerator}) \\
&= 1 - \frac{c_p(T_2 - T_1)}{c_p(T_3 - T_4)}
\end{align*}
\]

and

\[
\eta = 1 - \left(\frac{T_{\text{min}}}{T_{\text{max}}}\right)^{(k-1)/k}
\]

- for a given \(T_{\text{min}}/T_{\text{max}}\), the use of a regenerator above a certain \(r_p\) will result in a reduction of \(\eta\)
Regenerator Effectiveness

$$\epsilon = \frac{\dot{Q}_{\text{reg,actual}}}{\dot{Q}_{\text{reg,ideal}}} = \frac{h_5 - h_2}{h_5' - h_2} = \frac{h_5 - h_2}{h_4 - h_2} = \frac{T_5 - T_2}{T_4 - T_2}$$

Typical values of effectiveness are $\leq 0.7$

Repeated intercooling, reheating and regeneration will provide a system that approximates the Ericsson Cycle which has Carnot efficiency $\left( \eta = 1 - \frac{T_L}{T_H} \right)$.

Brayton Cycle With Intercooling, Reheating and Regeneration
Compressor and Turbine Efficiencies

Isentropic Efficiencies

(1) \[ \eta_{\text{comp}} = \frac{h_{2,s} - h_1}{h_2 - h_1} = \frac{c_p(T_{2,s} - T_1)}{c_p(T_2 - T_1)} \]

(2) \[ \eta_{\text{turb}} = \frac{h_3 - h_4}{h_3 - h_{4,s}} = \frac{c_p(T_3 - T_4)}{c_p(T_3 - T_{4,s})} \]

(3) \[ \eta_{\text{cycle}} = \frac{W_{\text{net}}}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} \]

Given the turbine and compressor efficiencies and the maximum \((T_3)\) and the minimum \((T_1)\) temperatures in the process, find the cycle efficiency \((\eta_{\text{cycle}})\).

(4) Calculate \(T_{2,s}\) from the isentropic relationship,

\[ \frac{T_{2,s}}{T_1} = \left( \frac{P_2}{P_1} \right)^{(k-1)/k} \]

Get \(T_2\) from (1).

(5) Do the same for \(T_4\) using (2) and the isentropic relationship.

(6) substitute \(T_2\) and \(T_4\) in (3) to find the cycle efficiency.