Week 7: GAS POWER CYCLES

Energy Systems and Conversion

EGR3030

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Outline

- Types of gas turbine engines
- Methods of improving turbine efficiencies
  - With regeneration
  - with Intercooling, Reheating, and Regeneration.

Brayton Cycle

Recall:

The thermal efficiency of Brayton cycle is

$$\eta_{\text{th},Brayton} = 1 - \frac{1}{r_p^{\frac{k-1}{k}}}$$

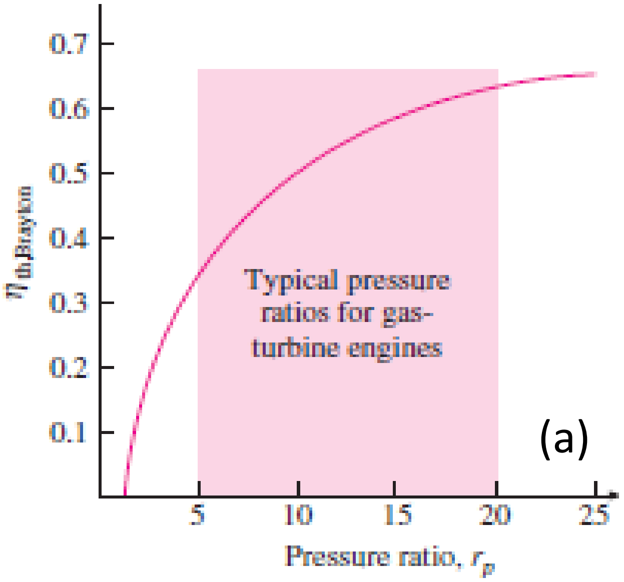
where: $r_p = \frac{P_2}{P_1}$ is the pressure ratio and k is the specific ratio.

The thermal efficiency of an ideal Brayton cycle depends on the pressure ratio of the gas turbine and the specific heat ratio of the working fluid.

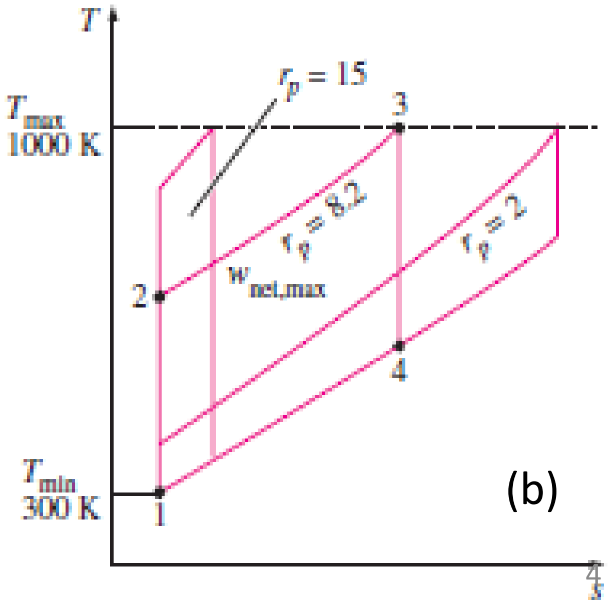
Brayton Cycle

The highest temperature that the turbine blades can stand limits the cycle's maximum temperature, which occurs at the end of the combustion process (state 3).

For a fixed turbine inlet temperature T_3, the net work out-put per cycle increases with the pressure ratio, reaches a maximum, and then decreases, as shown in figure (b).



(a)



(b)

Types & applications of gas turbine engines

Gas-Turbine Engines

Aircraft propulsion

- The gas turbine produces enough power to drive the compressor and a small generator to power the auxiliary equipment.
- The high-velocity exhaust gases produces the required thrust to propel the air-craft.

Electric power generation

- Gas turbine are used as stationary power plant to generate electricity as a stand-alone units or in conjunction with steam power plants on the high-temperature side.
- Also. The exhaust gases of the gas turbine serves as the heat source for the steam

Back work ratio: the ratio of the compressor work to the turbine work in a gas-turbine power plant, which is very high. With high back work ratios, a larger turbine is needed to provide the additional power requirements of the compressor.

Methods of increasing gas turbine efficiencies

Since its successful development in the 1930s, the gas turbine has undergone outstanding advancement and development. The early gas turbines developed in the 1940s and 1950s had simple-cycle efficiencies of about 17% due to low compressor and turbine efficiencies and low turbine inlet temperatures due to metallurgical limitations when initially developed.

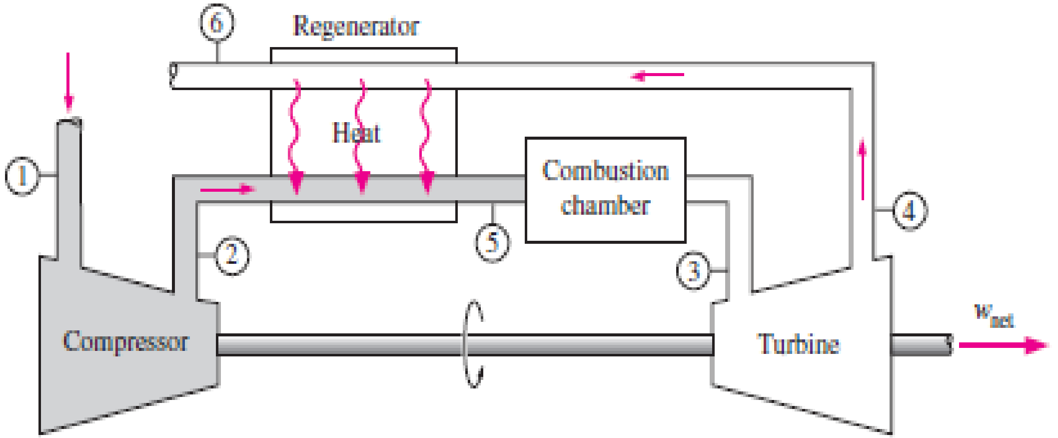
The low efficiency of the gas turbine cycle are improved by;

- Increasing the turbine inlet (or firing) temperatures.
- Increasing the efficiencies of turbomachinery components (the use of computer aided design tool to design and optimize turbomachinery components aerodynamically with minimal losses).
- Adding modifications to the basic cycle (by incorporating intercooling, regeneration/recuperation, and reheating)

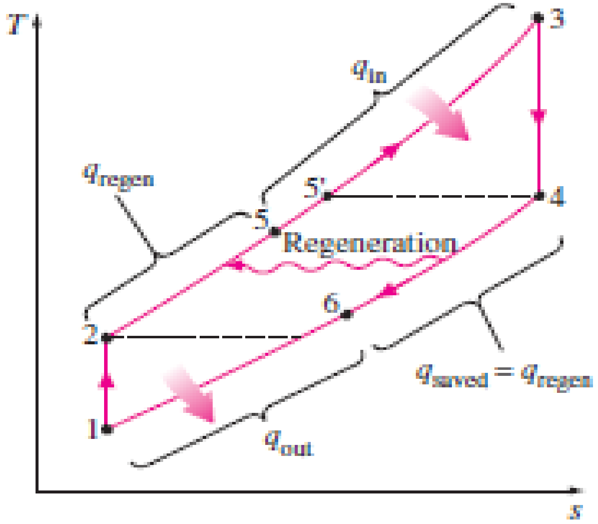
The Brayton cycle with regeneration

Regeneration or recuperation is where the high-pressure air leaving the compressor can be heated by transferring heat to it from the hot exhaust gases in a counter-flow heat exchanger. i.e., the hot exhaust gases leaving the turbine is used to preheat the gas exiting the compressor before it enters the combustion chamber.

As a result, the thermal efficiency of the Brayton cycle increases. This in turn decreases the heat input (fuel) requirements for the same net work output.



Note: Regeneration only works when the gas (temperature) at the turbine exit is higher than the gas (temperature) at the compressor exit.



The Brayton cycle with regeneration Cont.

Assuming the regenerator to be well insulated and any changes in kinetic and potential energies to be negligible, the actual and maximum heat transfers from the exhaust gases to the air is:

$$q_{regen,act} = h_5 - h_2$$

And

$$q_{regen,max} = h_{5`} - h_2 = h_4 - h_2$$

The extent to which a regenerator approaches an ideal regenerator is called the effective;

$$\epsilon = \frac{q_{regen,act}}{q_{regen,max}} = \frac{h_5 - h_2}{h_4 - h_2}$$

When the cold-air-standard assumption are utilized, it reduces to,

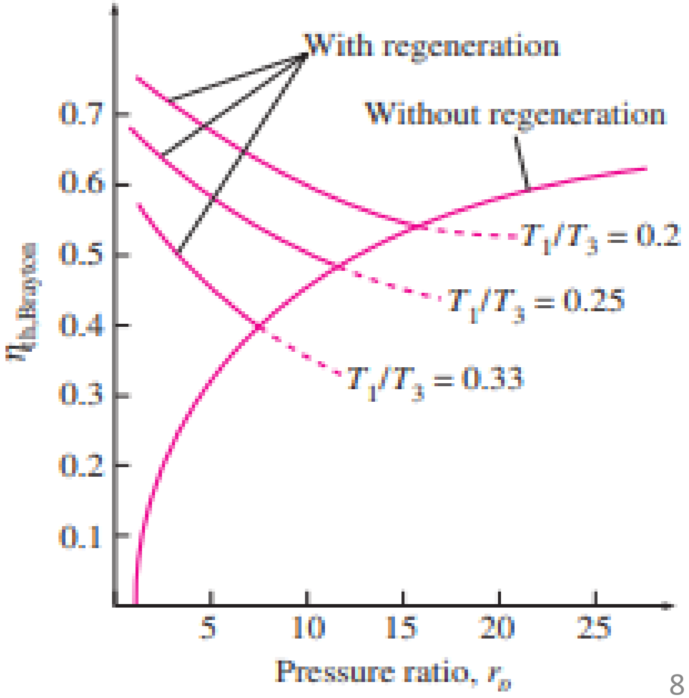
$$\epsilon = \frac{T_5 - T_2}{T_4 - T_2}$$

Note: the effectiveness of most regenerators used in practice is below 0.85.

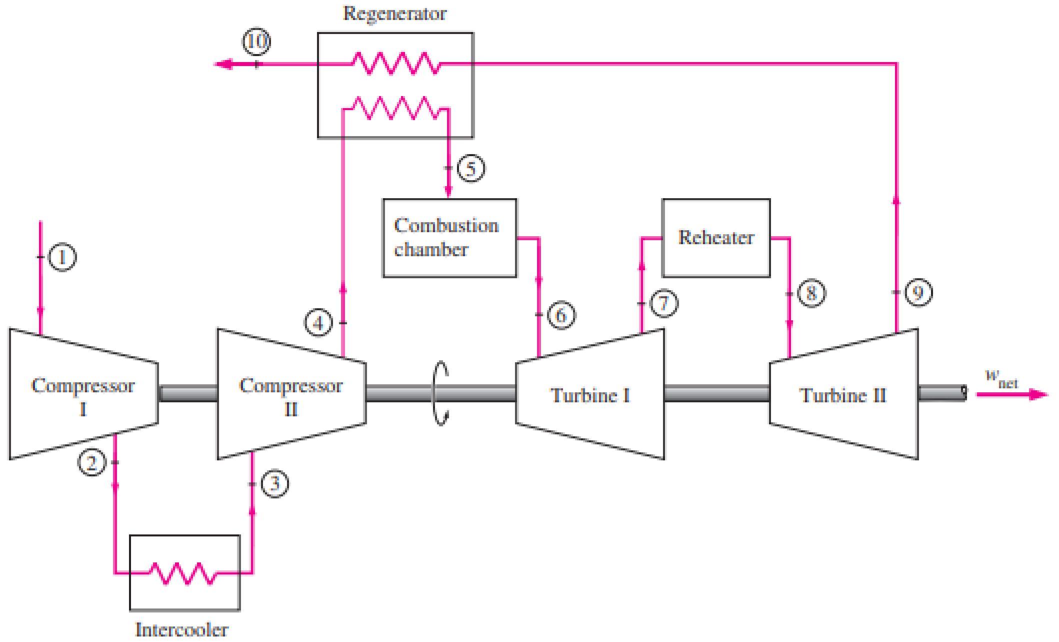
Under the cold-air-standard assumptions, the thermal efficiency of an ideal Brayton cycle with regeneration is;

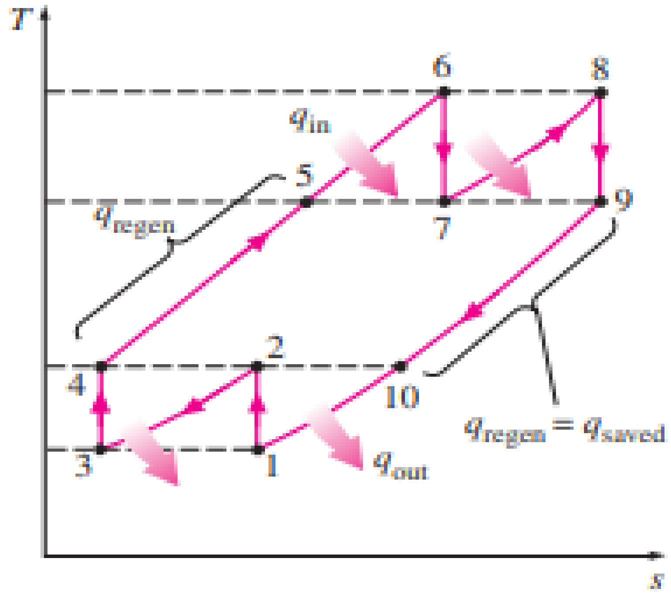
$$\eta_{\text{th},regen} = 1 - \left(\frac{T_1}{T_3}\right) r_p^{(k-1)/k}$$

Therefore, the thermal efficiency of an ideal Brayton cycle with regeneration depends on the ratio of the minimum to maximum temperature as well as the pressure ratio.



The Brayton cycle with Intercooling, Reheating, and Regeneration





Another way of increasing the specific work output or net work of a gas turbine cycle is by decreasing the work of compression or increasing the turbine work, or both. i.e., compression in more than one stage and using an intercooler in between the compressor.

The steady-flow compression or expansion work is proportional to the fluid's specific volume. As a result, the working fluid's specific volume should be as low as possible during a compression process and as high as possible during an expansion phase. This is exactly what intercooling and reheating achieve.

The Brayton cycle with Intercooling, Reheating, and Regeneration Cont.

- Combustion in gas turbines typically occurs at 4x the amount of air needed for complete combustion to avoid excessive temperatures. Therefore, the exhaust gases are rich in oxygen, and reheating can be accomplished by simply spraying additional fuel to exhaust gases between 2 expansion states.
- The working fluid leaves the compressor at a lower temperature, and the turbine at a higher temperature, when intercooling and reheating are utilised. This makes regeneration more attractive since a greater potential for regeneration exists
- Also, the gases leaving the compressor can be heated to a higher temperature before they enter the combustion chamber because of the higher temperature of the turbine exhaust.

The Brayton cycle with Intercooling, Reheating, and Regeneration Cont.

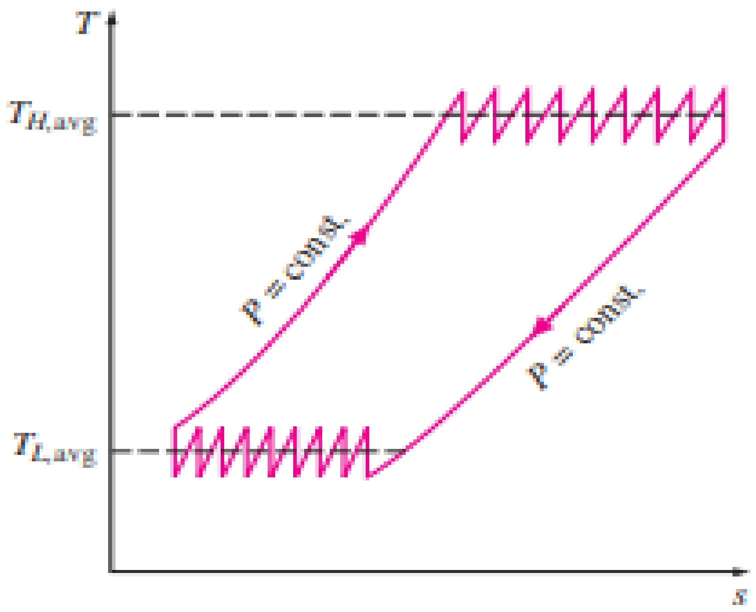
The turbine work output is maximised when the work input to a two-stage compressor is minimised when equal pressure ratios are maintained across each stage. i.e.,

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

NOTE: Intercooling and reheating enhance the back work ratio of a gas-turbine cycle. However, this does not imply that the thermal efficiency also improves. The fact is, intercooling and reheating always reduces the thermal efficiency unless they are accompanied by regeneration.

The Brayton cycle with Intercooling, Reheating, and Regeneration Cont.

This is because intercooling lowers the average temperature at which heat is added while reheating increases the average temperature at which heat is rejected. As a result, intercooling and reheating are always employed in conjunction with regeneration in gas turbine power plants.



Also, The ideal gas-turbine cycle with intercooling, reheating, and regeneration approaches the Ericsson cycle as the number of compression and expansion phases increases, as shown in the figure above, and the thermal efficiency approaches the theoretical limit (the Carnot efficiency).

Summary

- Types of gas turbine engines
- Methods of improving turbine efficiencies
  - With regeneration
  - with Intercooling, Reheating, and Regeneration.