

Brayton cycle with regeneration

Since the temperature of the flow exiting the turbine (T_4) is higher than the temperature exiting the compressor (T_2), an amount of heat can be transferred from T_4 to T_2 and utilized to heat the air flow before entering the combustion chamber. To this effect, a counterflow heat exchanger or a regenerator is used.

For an ideal regenerator, the temperature T_5 will be equal to T_4 and similarly T_2 will be equal to T_6 .

Since less energy is rejected from the cycle (Q_L decreases), the thermal efficiency is expected to increase.

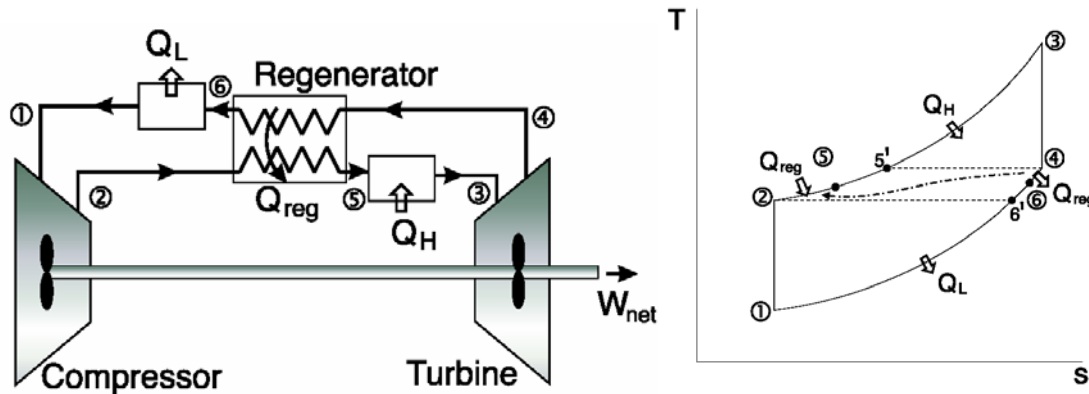


Figure.8.19. Brayton cycle with regeneration.

Thermal efficiency of a Brayton cycle with regeneration:

$$\eta = \frac{W_{turbine} - W_{compressor}}{q_{in}}$$

$$q_{in} = C_p (T_3 - T_5) \text{ and } w_{turb} = C_p (T_3 - T_4)$$

For an ideal regenerator in which we have: $T_5 = T_4$

We get:

$$q_{in} = w_{turb}$$

$$\text{Therefore, } \eta = 1 - \frac{w_c}{w_t} = 1 - \frac{C_p (T_2 - T_1)}{C_p (T_3 - T_4)} = 1 - \frac{T_1 \left(\frac{T_2}{T_1} - 1 \right)}{T_3 \left(1 - \frac{T_4}{T_3} \right)} \quad (I)$$

Using isentropic relations, we have:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} = r_p^{\frac{k-1}{k}}$$

and

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4} \right)^{\frac{k-1}{k}} = r_p^{\frac{k-1}{k}} \text{ therefore } \frac{T_4}{T_3} = r_p^{\frac{1-k}{k}}$$

If we replace in (I)

$$\eta = 1 - \frac{T_1 r_p^{\frac{k-1}{k}} - 1}{T_3 1 - r_p^{\frac{1-k}{k}}}$$

And finally;

$$\eta = 1 - \frac{T_1}{T_3} r_p^{\frac{k-1}{k}}$$

You can compare this efficiency to the efficiency of a simple Brayton cycle

$$\eta = 1 - r_p^{\frac{1-k}{k}}$$

You can notice that the difference between the expression of the Brayton cycle with regeneration and the simple Brayton cycle is the presence of the ratio between the lowest temperature (T_1) and the lowest temperature (T_3), and the exponent of the pressure ratio.

Therefore, for a Brayton cycle with regeneration, the thermal efficiency depends not only on the pressure ratio, but also on the temperature ratio.

A most important point to notice is that contrary to a simple Brayton cycle, the thermal efficiency of a Brayton cycle with regeneration decreases with the increase in pressure ratio.

For r_p =Constant	$\eta \uparrow$ with $(T_1/T_3) \downarrow$
For (T_1/T_3) =Constant	$\eta \downarrow$ with $r_p \uparrow$

Therefore, not all the combinations of pressure and temperature ratios induce an increase in thermal efficiency. The figure below shows the limits of using regeneration.

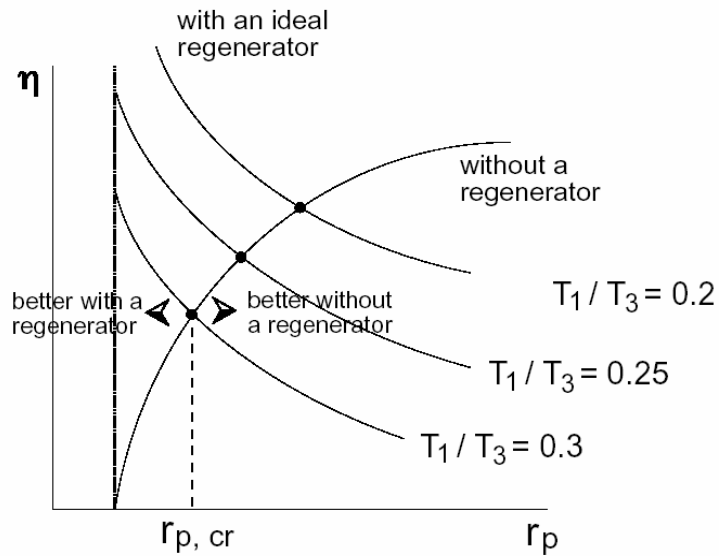


Figure.8.20. Effect of pressure and temperature ratios on thermal efficiency.

In practice, to allow heat transfer, the temperature of the air leaving the regenerator at state 5 must be less than the temperature at state 4. In the same way, the temperature at state 6 must be higher than the temperature at state 2.

The efficiency of a regenerator is defined as:

$$\eta_{reg} = \frac{h_5 - h_2}{h_4 - h_2} \text{ which is equal (under air-standard assumptions) to } \eta_{reg} = \frac{T_5 - T_2}{T_4 - T_2}$$

A regenerator with a higher efficiency will obviously save a greater amount of fuel since it will preheat the air to a higher temperature prior combustion. However, a very efficient regenerator is not justified since the price will be very high and it will include significant pressure losses.

The choice is justified unless the savings from fuel costs exceed the additional expenses involved.

The efficiency of most regenerators used in practice is below 85%.

Example

Air enters the compressor of a gas turbine with regeneration at 100 kPa and 15°C. The pressure at the outlet of the compressor is 0.5 MPa and the maximal temperature of the cycle is 900°C.

Determine:

- 1- The thermal efficiency.

Now suppose that the efficiency of the regenerator is 80%. Compute the new thermal efficiency?

Brayton cycle with intercooling; reheat and regeneration

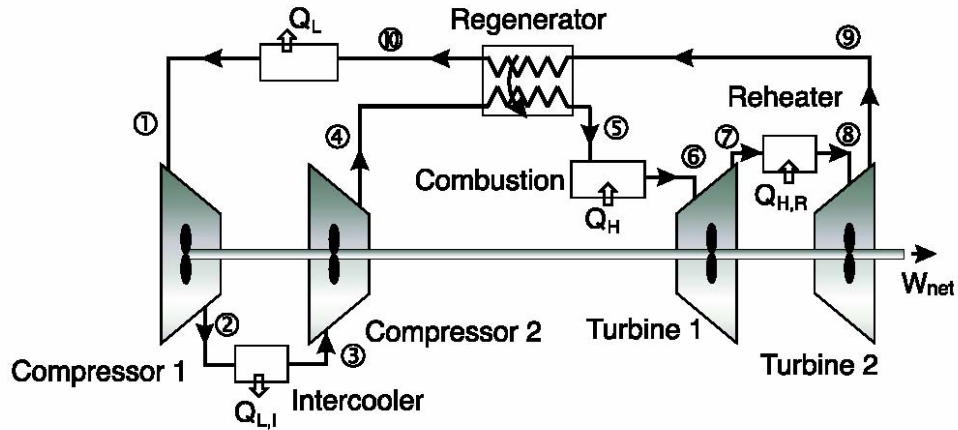


Figure.8.19. Brayton cycle with regeneration

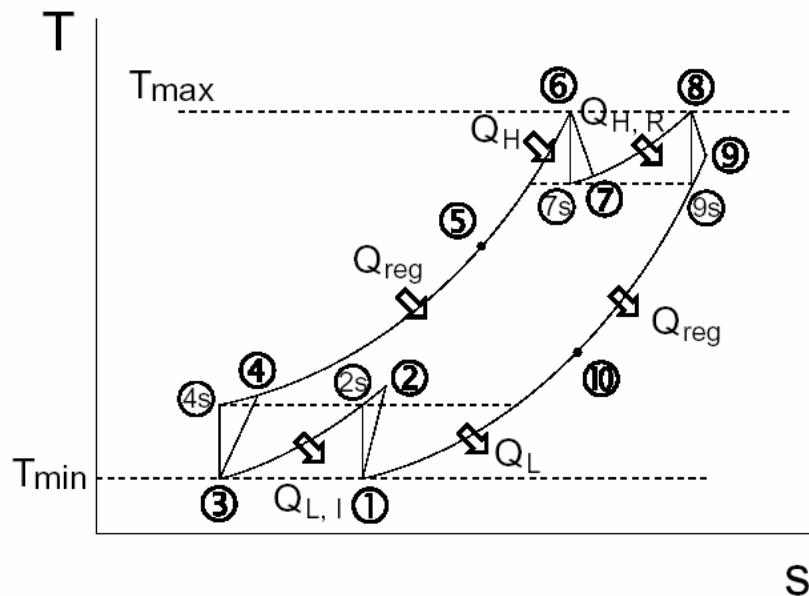


Figure.8.21. Brayton cycle with intercooling, reheating and regeneration.

With increasing the number of stages, the compression process becomes nearly isothermal and the compression inlet temperature and the compression work decrease. The same thing for the turbine, the work of the turbine can be increased by a multistage expansion.

The objective of the multistage process is to maintain the specific volume as low as possible during compression and as high as possible during expansion.

This is role of the Brayton cycle with intercooling, reheating and regeneration.

The reheat is performed by spraying additional fuel into the exhaust gases. This is possible since after the first combustion, the exhaust gases still contain enough Oxygen (remember that the mass ratio between air/fuel is > 50).

If the number of stages is indefinitely increased, the Brayton cycle with intercooling, reheating and regeneration approaches an Ericsson cycle (remember that the efficiency of an Ericsson cycle approaches the Carnot efficiency).

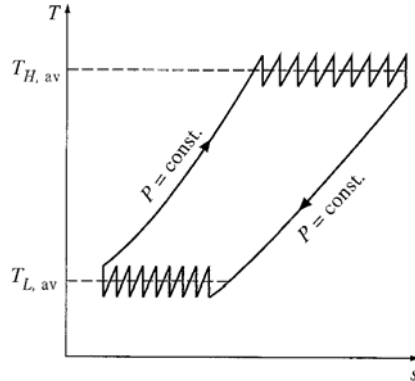


Figure.8.22. Brayton cycle with intercooling, reheating and regeneration with a high number of stages (equivalent to an Ericsson cycle).

However, in practice the number of stages for the compression and the expansion is limited to 2 or 3. This is because, a high number of stages increases the pressure losses.

This configuration of the Brayton cycle makes the regeneration very attractive, since, the fluid leaves the compressor at low temperature and the turbine at high temperature.

How does this configuration affect the thermal efficiency?

The work of the turbine will increase and the work of the compressor will decrease. The net work and back work ratio will both, therefore, increase. However, we decreased the temperature at which the heat is supplied and we increased the temperature at which the heat is rejected. Therefore, this configuration will not necessarily increase the thermal efficiency.

To improve the efficiency, intercooling and reheat are always used with regeneration.

Example

An ideal gas-turbine cycle with two stages of compression and two stages of expansion has an overall pressure ratio of 8. Air enters each stage of the compressor at 300 K and each stage of the turbine at 1300 K. Determine the back work ratio and the thermal efficiency of this gas-turbine cycle, assuming (a) no regenerator and (b) an ideal regenerator with 100% effectiveness.

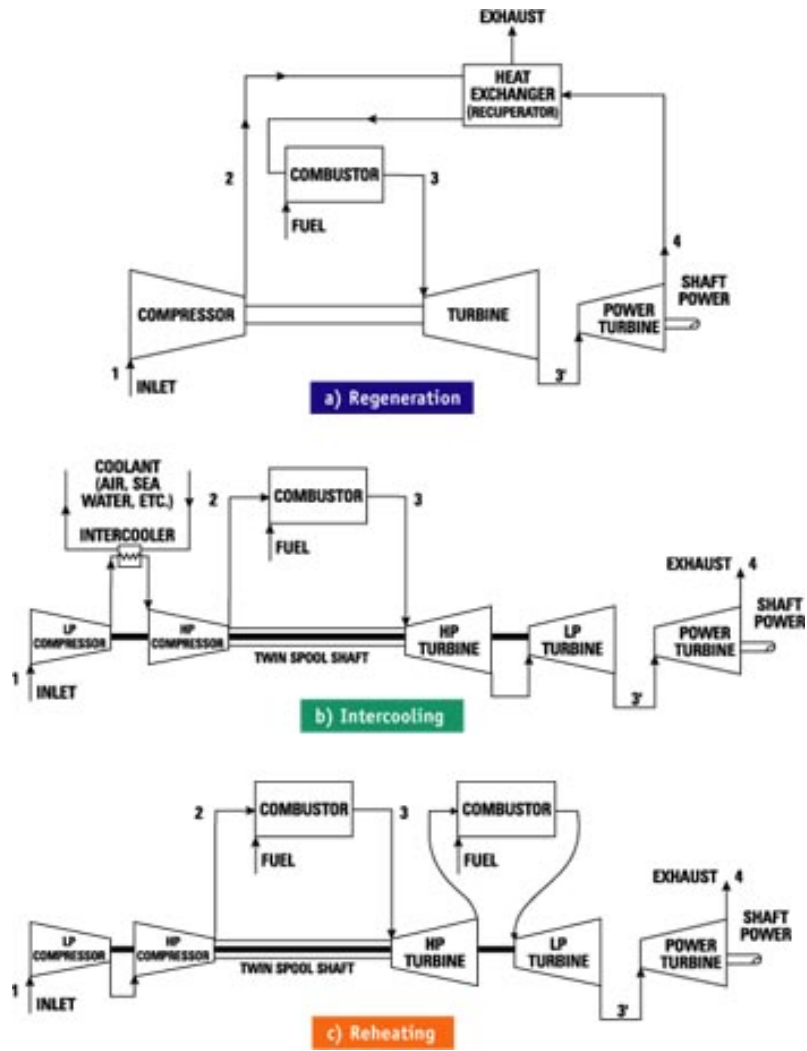


Figure.8.23. Regeneration, intercooling and reheat.