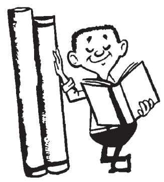
Brayton Cycle



Reading	Problems
12.2 $\rightarrow$ 12.4	12.16, 12.17, 12.18, 12.29, 12.36, 12.116, 12.117

Introduction

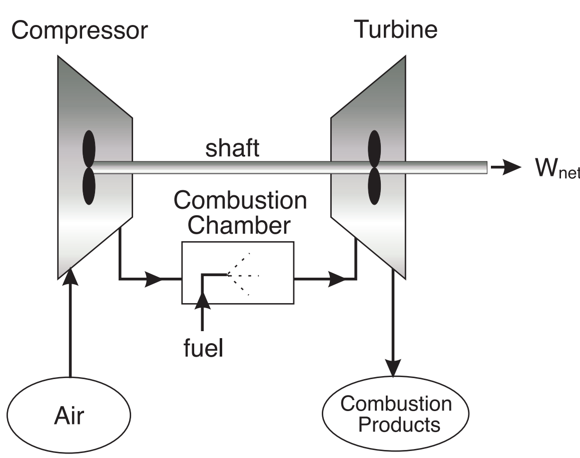
The gas turbine cycle is referred to as the Brayton Cycle or sometimes the Joule Cycle. The actual gas turbine cycle is an open cycle, with the intake and exhaust open to the environment.

- can use different fuels
- simple in construction, easy to maintain
- can handle large volumes of gases
- small weight-to-power ratio

Definitions

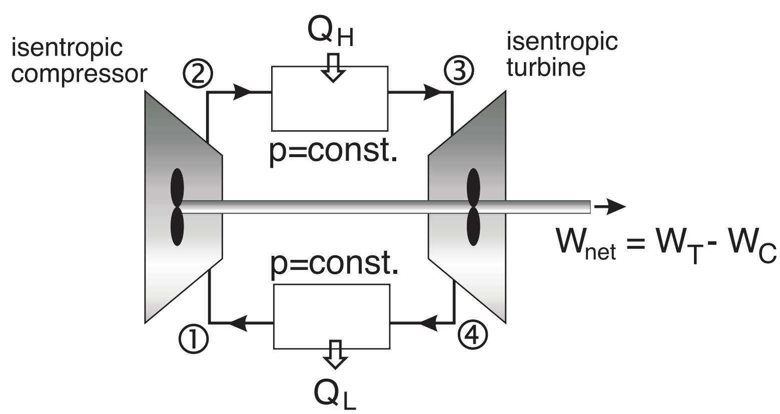
Back Work Ratio: the ratio of the compressor work to the turbine work

Open Cycle Gas Turbine Engines

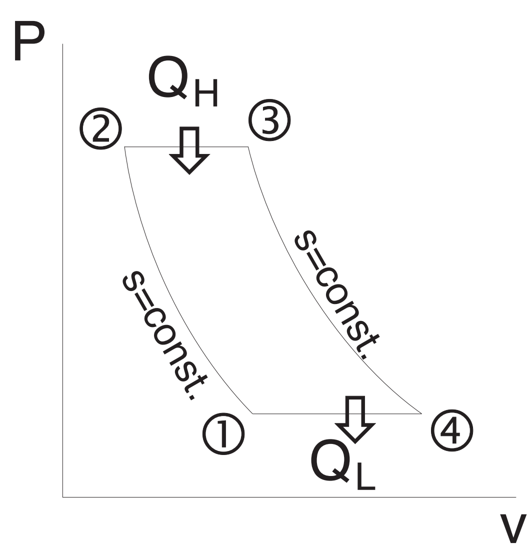


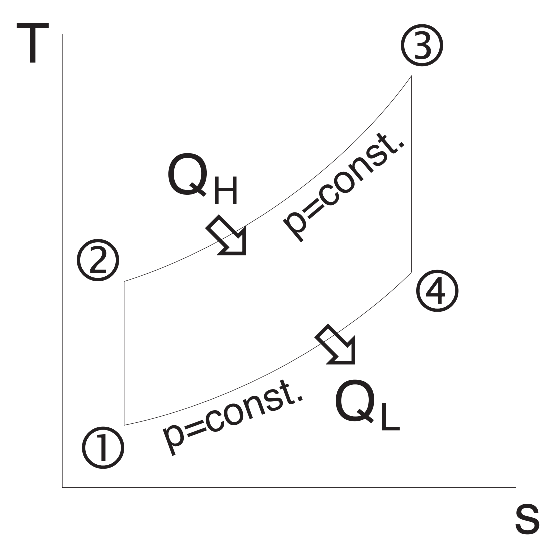
- compressor power requirements vary from 40-80% of the power output of the turbine (remainder is net power output), i.e. back work ratio = 0.4 $\rightarrow$ 0.8
- high power requirement is typical when gas is compressed because of the large specific volume of gases in comparison to that of liquids

Idealized Air Standard Brayton Cycle



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





Brayton Cycle Efficiency

The efficiency of the cycle is given by the benefit over the cost or

$$\eta = \frac{W_{net}}{Q_H} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{\dot{m}c_p(T_4 - T_1)}{\dot{m}c_p(T_3 - T_2)} = 1 - \frac{T_1}{T_2}\frac{\left(\frac{T_4}{T_1} - 1\right)}{\left(\frac{T_3}{T_2} - 1\right)}$$

If we use the isentropic equations with the ideal gas law, we see that

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4} \Rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

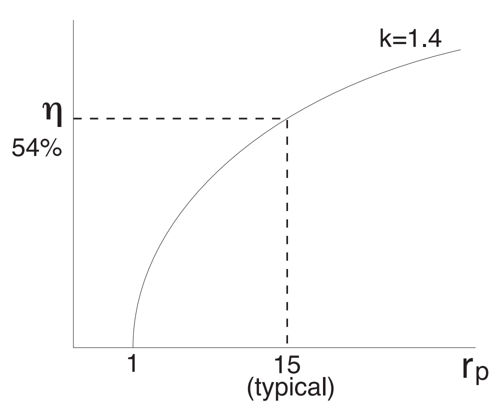
and

$$\eta = 1 - \frac{T_1}{T_2} = 1 - \frac{T_4}{T_3}$$

If we define the pressure ratio as:

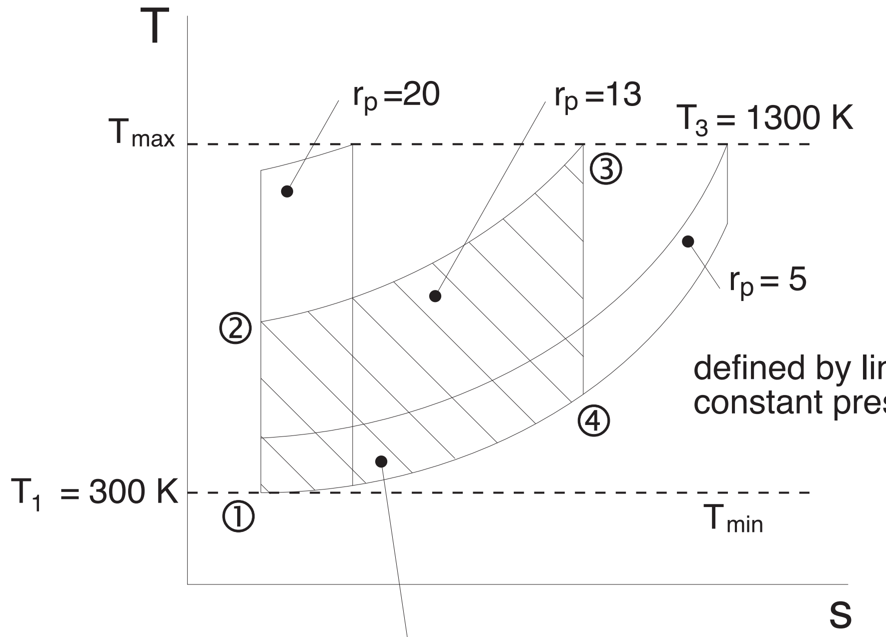
$$r_p = \frac{P_2}{P_1} = \frac{P_3}{P_4}$$

$$\boxed{\eta = 1 - (r_p)^{(1-k)/k}}$$



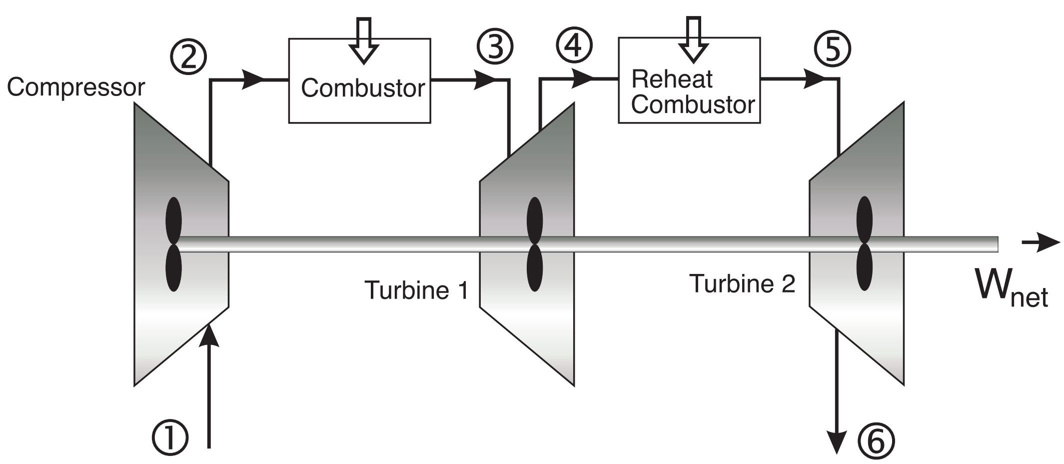
Maximum Pressure Ratio

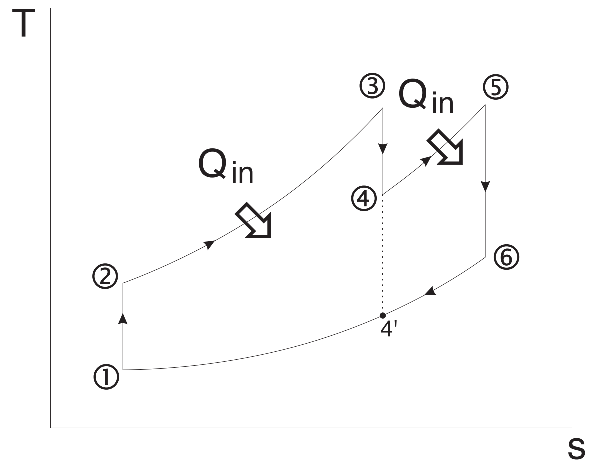
Given that the maximum and minimum temperature can be prescribed for the Brayton cycle, a change in the pressure ratio can result in a change in the work output from the cycle.



$$W_{net,max} \Rightarrow \quad r_p = \left(\frac{T_{max}}{T_{min}}\right)^{\frac{k}{2k-2}}$$

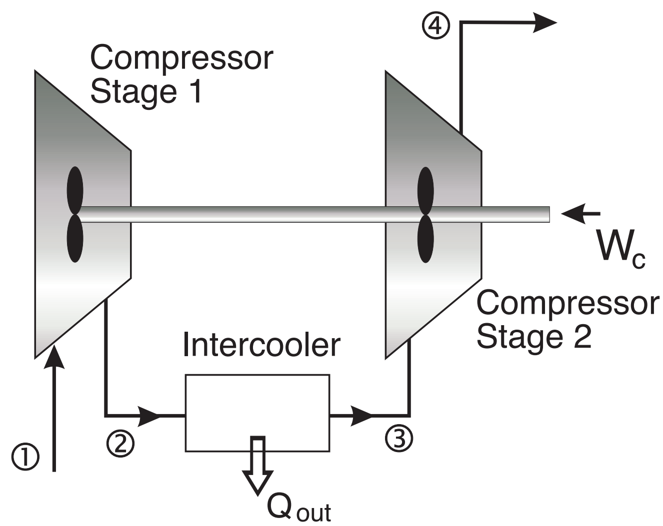
Brayton Cycle with Reheat



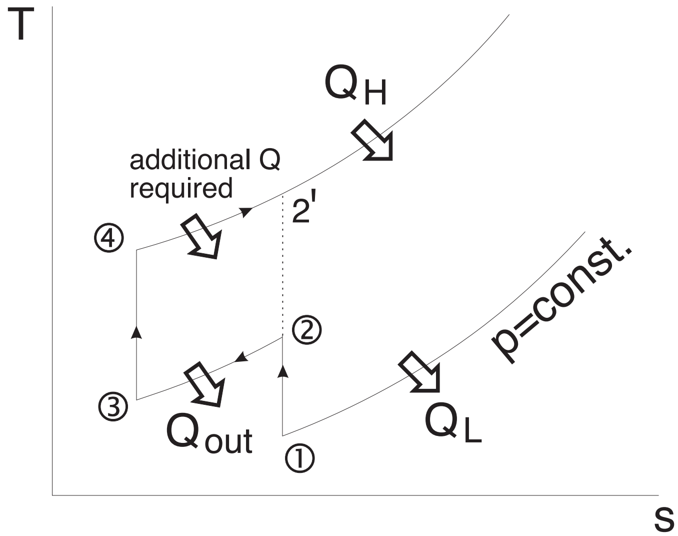


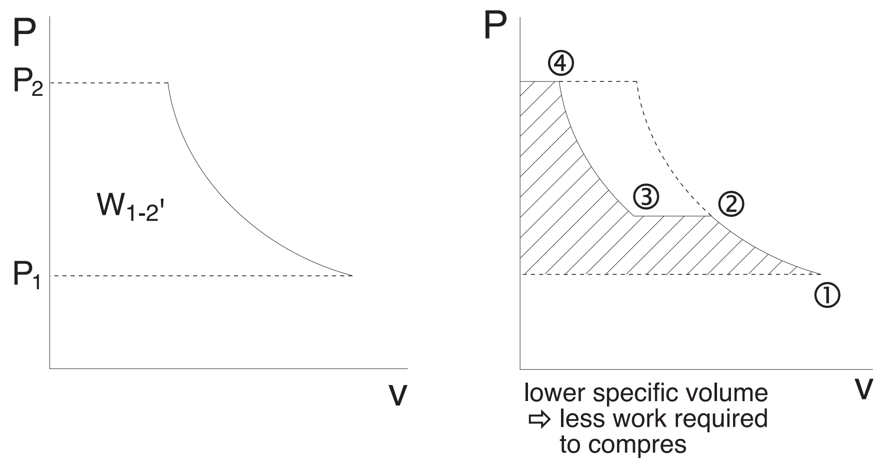
- total work is increased
- but additional heat input is required
- net efficiency may or may not increase

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





How Can We Improve Efficiency?

We know the efficiency of a Brayton cycle engine is given as

$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{W}_{turbine} - \dot{W}_{compressor}}{\dot{Q}_H}$$

There are several possibilities, for instance we could try to increase $\dot{W}_{turbine}$ or decrease $\dot{W}_{compressor}$.

Recall that for a SSSF, reversible compression or expansion

$$\frac{\dot{W}}{\dot{m}} = \int_{in}^{out} v\, dP \quad \Rightarrow \quad \textbf{keep } v \uparrow \textbf{ in turbine, keep } v \downarrow \textbf{ in compressor}$$

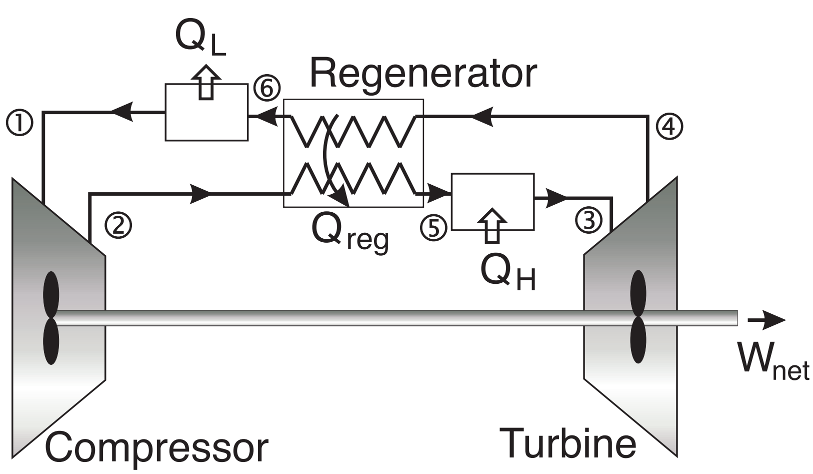
This can be achieved through the use of intercooling and reheating.

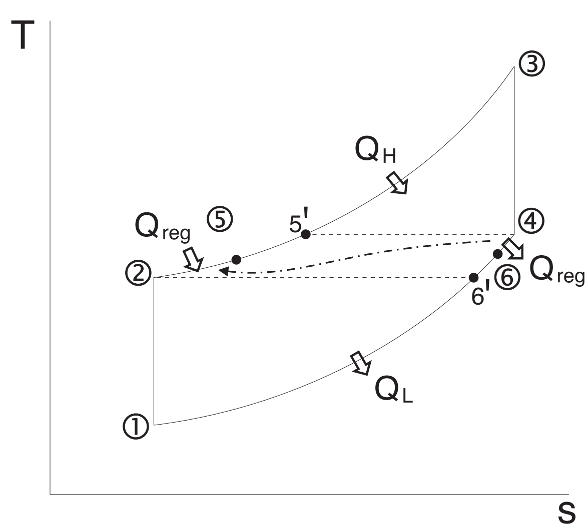
$$\text{Compressor} \quad \longrightarrow \quad \eta = \frac{\dot{W}_T - \dot{W}_C(\downarrow)}{\dot{Q}_{H,Total}(\uparrow)}\ ,\ \text{overall } (\downarrow)$$

$$\text{Turbine} \quad \longrightarrow \quad \eta = \frac{\dot{W}_T(\uparrow) - \dot{W}_C)}{\dot{Q}_{H,Total}(\uparrow)}\ ,\ \text{overall } (\downarrow)$$

The conclusion is the intercooling and/or reheating by themselves will lower η. We have to find a way to reduce $\dot{Q}_H$

Brayton Cycle with Regeneration

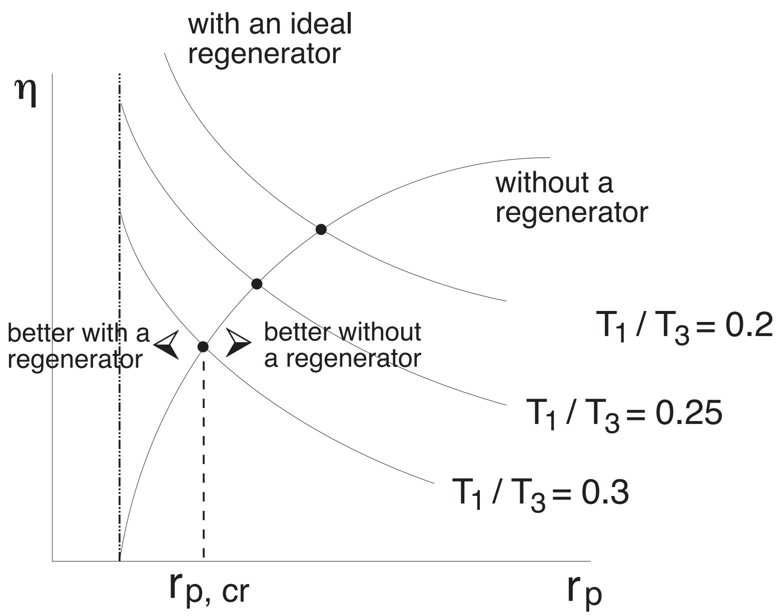




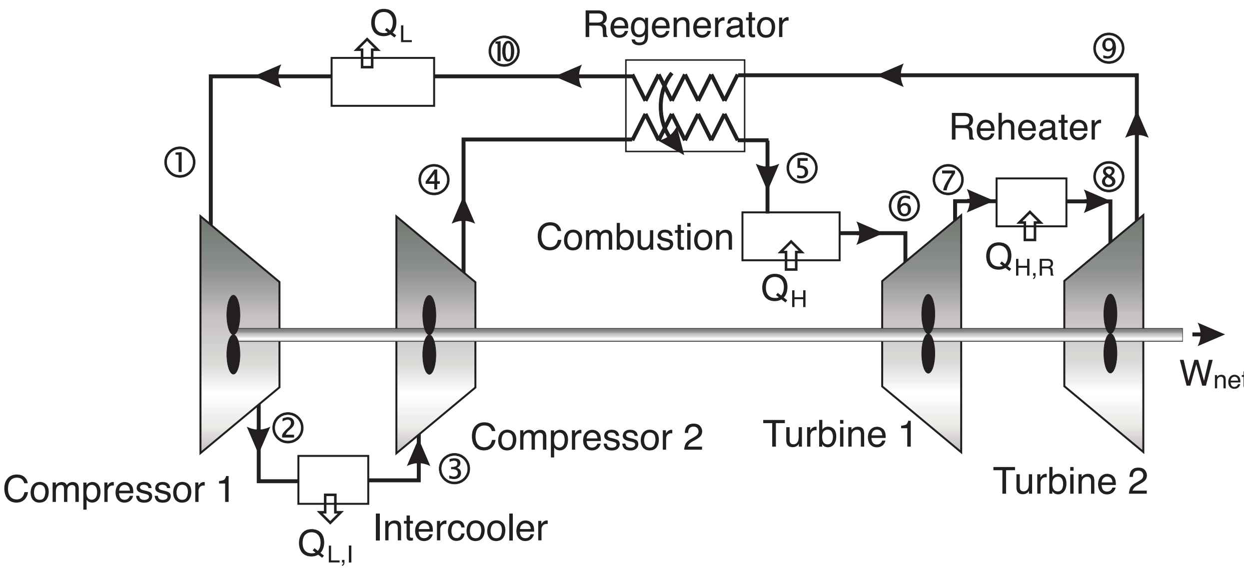
- a regenerator is used to reduce the fuel consumption to provide the required $\dot{Q}_H$
- the efficiency with a regenerator can be determined as:

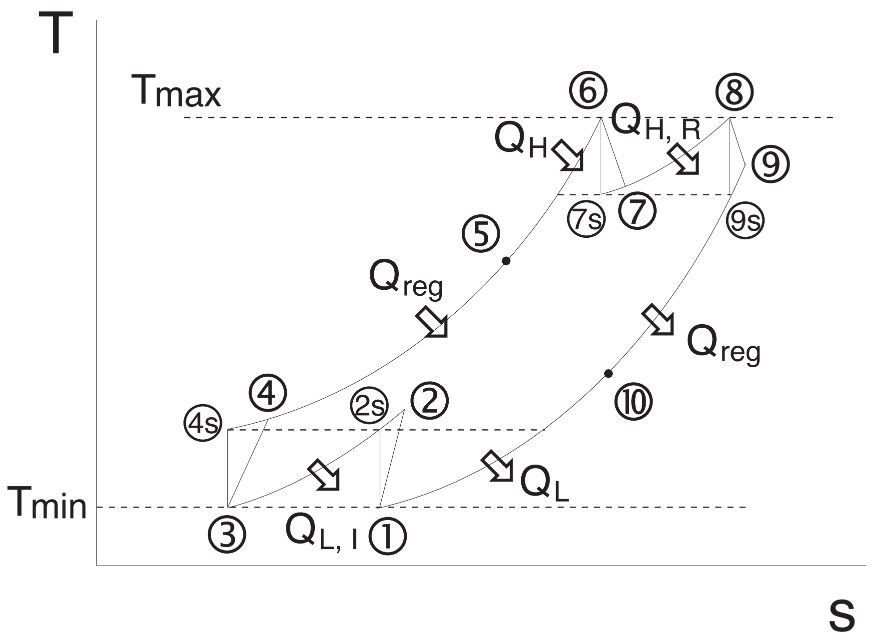
$$\boxed{\eta = 1 - \left(\frac{T_{min}}{T_{max}}\right)(r_p)^{(k-1)/k}}$$

- for a given T_{min}/T_{max}, the use of a regenerator above a certain r_p will result in a reduction of η



Brayton Cycle With Intercooling, Reheating and Regeneration





Compressor and Turbine Efficiencies

Isentropic Efficiencies

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

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

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

(4) Calculate T_{2s} 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.

PROBLEM STATEMENT:

Air enters the compressor of a gas-turbine power plant, at $290\ K,\ 0.1\ MPa$. The ratio of the maximum to minimum pressure in the cycle is 4.0 and the maximum cycle temperature is $1200\ K$. Compressor and turbine isentropic efficiencies are 0.85. The compression process occurs in two stages, each having a pressure ratio of 2.0 with intercooling to $300\ K$ in between. A 75% effective regenerator reduces fuel costs.

a) Determine the net work transfer $[kJ/kg]$
b) Determine the thermal (first law) efficiency.