Lecture 7: ME 8493 Thermal Engineering-I

Topic to be covered	Brayton cycle – Air standard efficiency, Effect of friction, regeneration, reheating and intercooling in Brayton cycle

Learning Outcomes

LO	At the end of the lecture students will be able to	CO	BL
LO1	Comprehend the Brayton cycle	CO1	L2
LO2	Compares the effect of friction, regeneration, reheating and intercooling in Brayton cycle	CO1	L2
Bloom's Level: 1-Remembers, 2-Understand, 3-Apply, 4-Analyse, 5-Evaluate, 6-Create			

Brayton Cycle

The Brayton cycle (first proposed by George Brayton, 1870) is the air standard cycle for gas turbine plant.

The various operations are as follows:

Operation 1-2. The air is compressed isentropically from the lower pressure p_1 to the upper pressure p_2, the temperature rising from T_1 to T_2. No heat flow occurs.

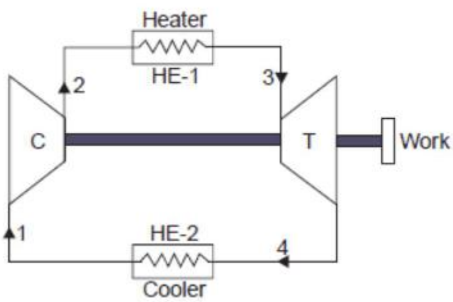
Operation 2-3. Heat flows into the system increasing the volume from V_2 to V_3 and temperature from T_2 to T_3 whilst the pressure remains constant at p_2.

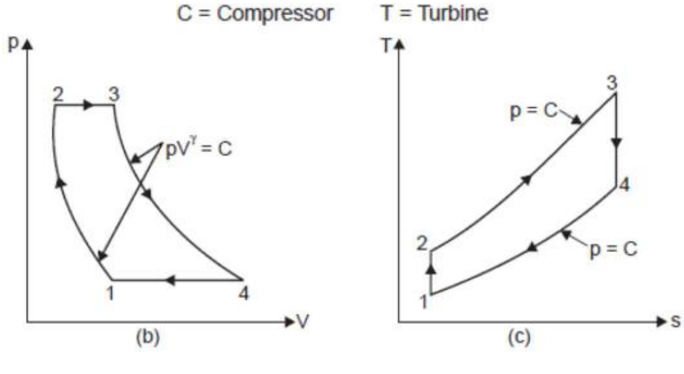
Heat received = $mc_p\,(T_3 - T_2)$.

Operation 3-4. The air is expanded isentropically from p_2 to p_1, the temperature falling from T_3 to T_4. No heat flow occurs.

Operation 4-1. Heat is rejected from the system as the volume decreases from V_4 to V_1 and the temperature from T_4 to T_1 whilst the pressure remains constant at p_1.

Heat rejected = $mc_p(T_4 - T_1)$.

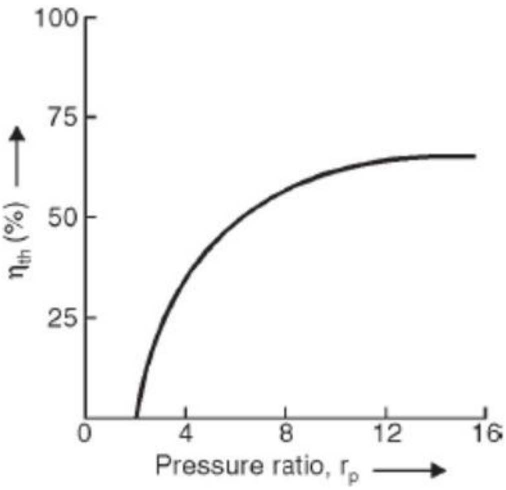




The efficiency of Brayton cycle

$$\eta_B = \frac{W_{net}}{Q_s} = \frac{Q_s - Q_r}{Q_s} = 1 - \frac{Q_r}{Q_s} = 1 - \frac{mc_p(T_4 - T_1)}{mc_p(T_3 - T_2)} = 1 - \frac{(T_4 - T_1))}{(T_3 - T_2))}$$

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



The efficiency of the ideal joule cycle increases with the pressure ratio. The absolute limit of upper pressure is determined by the limiting temperature of the material of the turbine at the point at which this temperature is reached by the compression process alone, no further heating of the gas in the combustion chamber would be permissible and the work of expansion would ideally just balance the work of compression so that no excess work would be available for external use.

Work output during the Brayton cycle

W = Heat received/cycle – heat rejected/cycle

$W = mc_p (T_3 - T_2) - mc_p (T_4 - T_1)$

$W = mc_p (T_3 - T_4) - mc_p (T_2 - T_1)$

$$W = mc_p \left[T_3 \left(1 - \frac{T_4}{T_3} \right) - T_1 \left(\frac{T_2}{T_1} - 1 \right) \right]$$

For isentropic processes, $\frac{T_3}{T_4} = \frac{T_2}{T_1} = r_p^{\left(\frac{\gamma-1}{\gamma}\right)} = r_p^z$

where $z = \frac{\gamma - 1}{\gamma}$

$$W = mc_p \left[T_3 \left(1 - \frac{1}{r_p^z} \right) - T_1 \left(r_p^z - 1 \right) \right]$$

For maximum work output, $\frac{dW}{dr_p} = 0$; gives $\frac{T_3}{T_1} = r_p^{2z} = r_p^{2\left(\frac{\gamma-1}{\gamma}\right)}$, $r_p = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}}$

The work output per unit mass of gas

$W = c_p (T_3 - T_4) - c_p (T_2 - T_1) = c_p (T_3 - T_4 - T_2 + T_1)$

$$W = c_p\left(T_3 - \frac{T_1T_3}{T_2} - T_2 + T_1\right)$$

For maximum work output $\frac{dW}{dT_2} = 0$, gives $T_2 = \sqrt{T_1T_3}$

Therefore $W_{max} = c_p\left(\sqrt{T_3} - \sqrt{T_1}\right)^2$

Maximum efficiency of Brayton cycle $\eta_{max} = 1 - \frac{1}{\left(r_p\right)^{\frac{\gamma-1}{\gamma}}} = 1 - \sqrt{\frac{T_1}{T_3}}$

Effect of friction in turbine and compressor on Brayton cycle

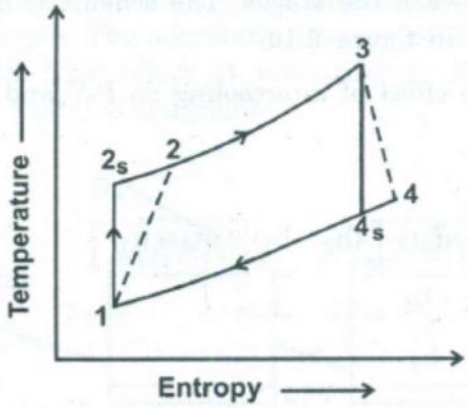


Fig. 2.15: Effect of turbine and compressor efficiency on Brayton cycle

Heat supplied $Qs = mc_p\left(T_3 - T_2\right)$

Heat rejected $Qr = mc_p\left(T_4 - T_1\right)$

Turbine work $W_T = mc_p\left(T_3 - T_4\right)$

Compressor work $W_C = mc_p\left(T_2 - T_1\right)$

Efficiency of the cycle $\eta = \frac{W_T - W_C}{Qs}$

Turbine efficiency

$$\eta_T = \frac{W_{act}}{W_{isen}} = \left(\frac{T_3 - T_4}{T_3 - T_{4s}}\right)$$

Compressor efficiency

$$\eta c = \frac{W_{isen}}{W_{act}} = \frac{T_{2s} - T_1}{T_2 - T_1}$$

Brayton cycle with intercooling

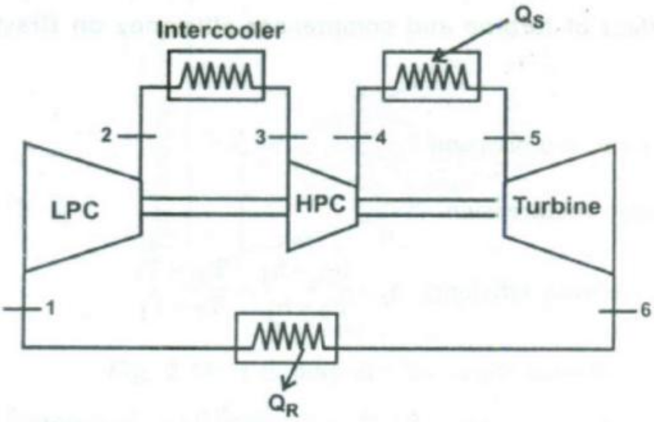


Fig. 2.16: Brayton cycle with Intercooling.

Heat supplied $Qs = mc_p(T_5 - T_4)$ Heat rejected $Qr = mc_p(T_6 - T_1)$

Turbine work $W_T = mc_p(T_5 - T_6)$ Compressor work $W_C = mc_p[(T_2 - T_1) + (T_4 - T_3)]$

Efficiency of the cycle $\eta = \dfrac{W_T - W_C}{Qs}$

Brayton cycle with reheating

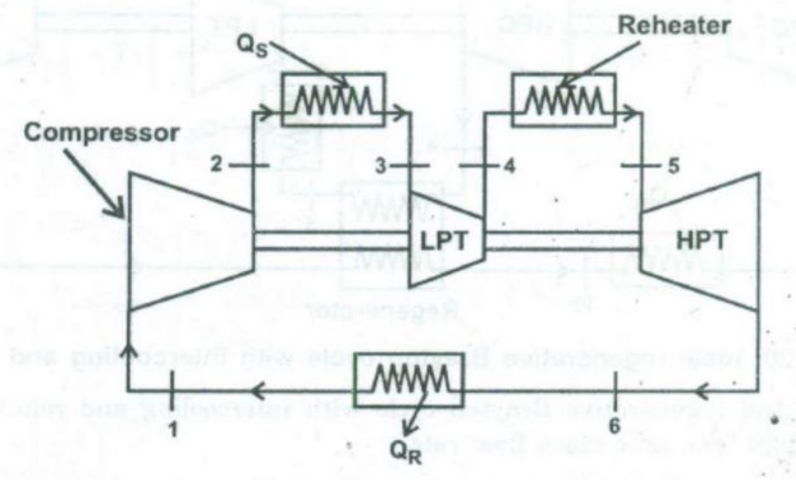


Fig. 2.18: Brayton cycle with reheating.

Heat supplied $Qs = mc_p[(T_3 - T_2) + (T_5 - T_4)]$ Heat rejected $Qr = mc_p(T_6 - T_1)$

Turbine work $W_T = mc_p[(T_3 - T_4) + (T_5 - T_6)]$ Compressor work $W_C = mc_p(T_2 - T_1)$

Efficiency of the cycle $\eta = \dfrac{W_T - W_C}{Qs}$

Brayton cycle with regeneration

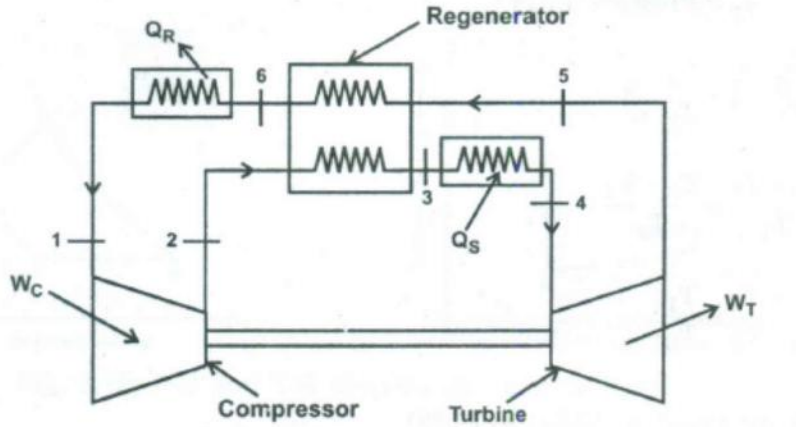


Fig. 2.13: Brayton cycle with regeneration

Heat supplied $Qs = mc_p(T_4 - T_3)$ Heat rejected $Qr = mc_p(T_6 - T_1)$

Turbine work $W_T = mc_p(T_4 - T_5)$ Compressor work $W_C = mc_p(T_2 - T_1)$

Efficiency of the cycle $\eta = \dfrac{W_T - W_C}{Qs}$

Learning Outcome Assessment Questions

1. An ideal Brayton cycle, operating between the pressure limits of 1 bar and 6 bar, as minimum and maximum temperatures of 300 K and 1500 K. The ratio of specific heats of the working fluid is 1.4. The approximate final temperatures in K at the end of compression and expansion processes are respectively
   a. 500 and 900
   b. 900 and 500
   c. 500 and 500
   d. 900 and 900
2. A gas turbine cycle with heat exchanger and reheating improves
   a. Only the thermal efficiency
   b. Only the specific power output
   c. Both thermal efficiency and specific work output
   d. Neither thermal efficiency nor specific power output
3. A gas turbine cycle with infinitely large number of stages during compression and expansion leads to
   a. Stirling cycle
   b. Atkinson cycle
   c. Ericsson cycle
   d. Brayton cycle
4. A cycle consisting of two reversible isothermal processes and two reversible isobaric processes is known as
   a. Atkinson cycle
   b. Stirling cycle
   c. Brayton cycle
   d. Ericsson cycle
5. Air enters a compressor at a temperature of 27°C the compressor pressure ratio is 4. Assuming an efficiency of 80%, the compressor work required in kJ/kg is
   a. 160
   b. 172
   c. 182
   d. 225
6. In a gas turbine, hot combustion products with the specific heat ratio 1.3 enter the turbine at 20 bar, 1500 K and exit at 1 bar. The isentropic efficiency of the turbine is 0.94. The work developed by the turbine per kg of gas flow is
   a. 869.64 kJ/kg
   b. 794.66 kJ/kg
   c. 1009.72 kJ/kg
   d. 1312.00 kJ/kg
7. The pressure ratio of a gas power plant cycle corresponding to maximum work output for the given temperature limits of T_{min} and T_{max} will be

   a. $\left(\frac{T_{\max}}{T_{\min}}\right)^{\frac{\gamma}{2(\gamma-1)}}$
   b. $\left(\frac{T_{\min}}{T_{\max}}\right)^{\frac{2\gamma}{(\gamma-1)}}$
   c. $\left(\frac{T_{\max}}{T_{\min}}\right)^{\frac{\gamma-1}{\gamma}}$
   d. $\left(\frac{T_{\min}}{T_{\max}}\right)^{\frac{\gamma-1}{2\gamma}}$
8. Draw the Brayton cycle in PV and TS diagrams (AU-Nov 2009)
9. Explain the effect of pressure ratio on the net output and efficiency of a Brayton cycle (AU-May 2006)
10. Name the process of heat addition in Brayton cycle. (AU-May 2010)
11. What is relative efficiency of a gas power cycle? (AU-Nov 2012)
12. What is effect of regeneration in Brayton cycle?
    What is the effect of intercooling in Brayton cycle?
    What is the effect of reheating in Brayton cycle?

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14.