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Lecture 21

Topic 4

Power & Refrigeration Cycles

Topic

– 4.5 Brayton Cycle pt 2

Reading:

Ch 10: 10.1 – 10.5 Borgnakke & Sonntag Ed. 8

Ch 9: 9-9 – 9-12 Cengel and Boles Ed. 7

4.5 Brayton Cycle

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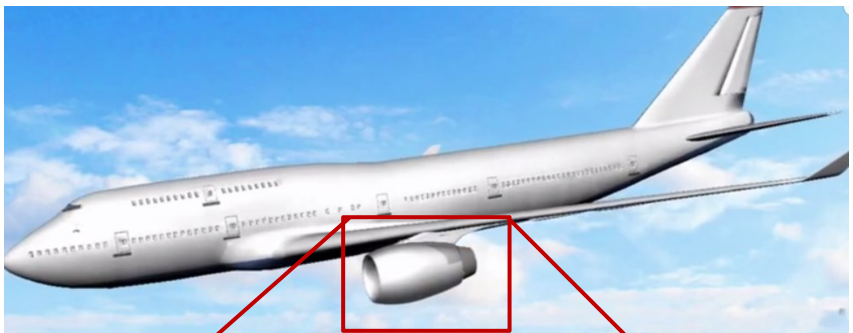
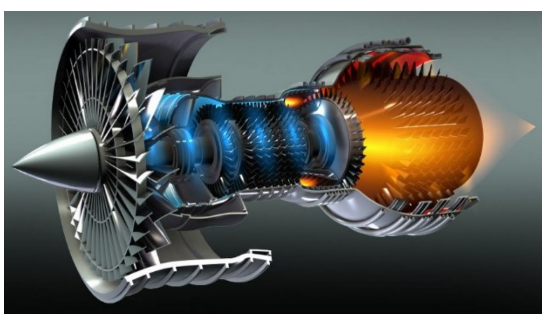
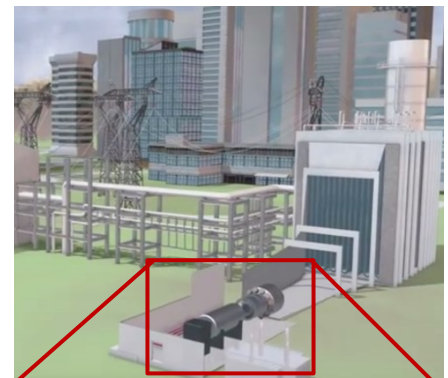
Brayton Cycle – transfer of heat to useful work out (e.g. electricity to grid or propel an aircraft).

- Air standard ideal cycle approximation for gas-turbine engine





Aircraft: Power → Thrust

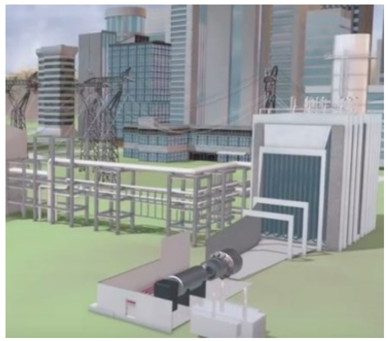


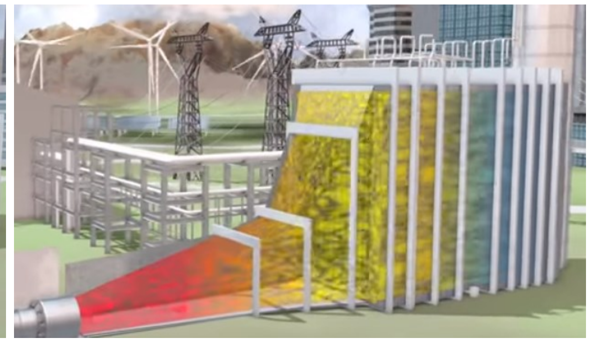
Power Plant: Power → Electricity

4.5 Brayton Cycle

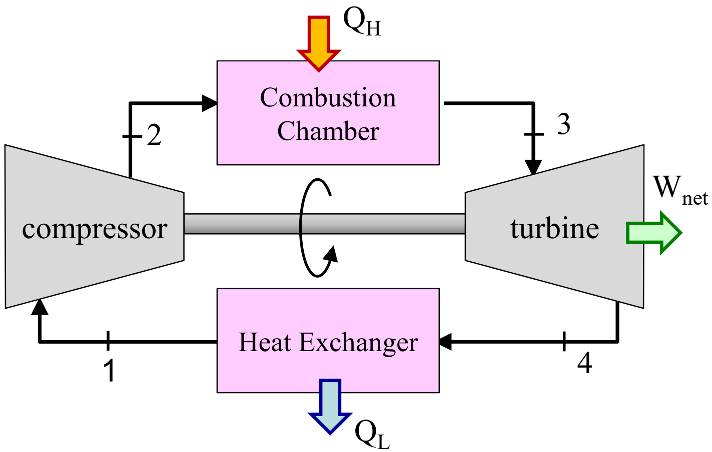
Brayton Cycle – gas-turbine engine air power plant

Combined (Dual) Cycle Power Plant: Power → Electricity

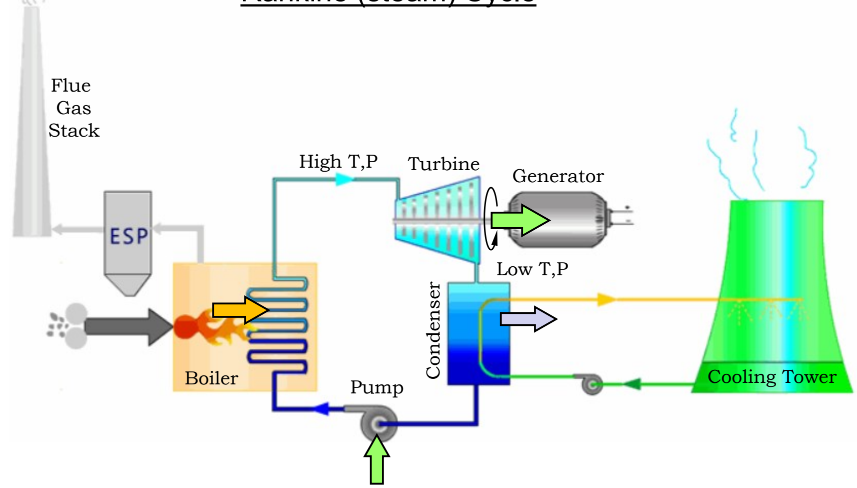




<u>Closed Brayton Cycle</u>



<u>Rankine (steam) Cycle</u>



https://www.youtube.com/watch?v=eeiu-wcyEbs

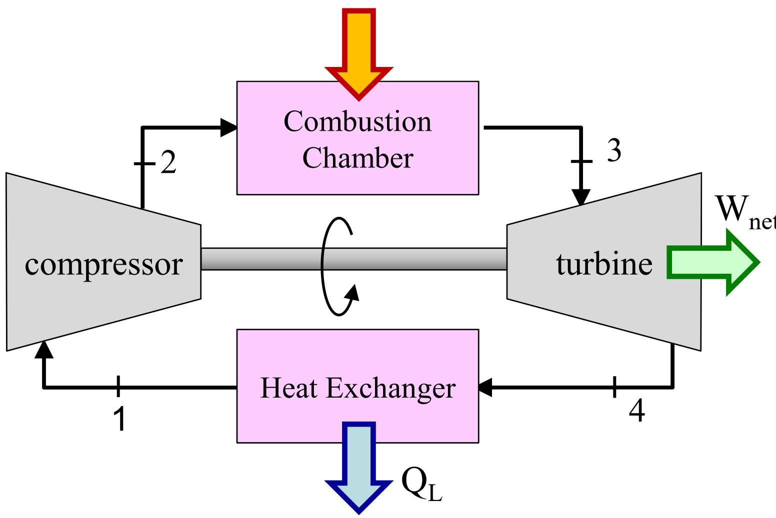
4.5 Brayton Cycle - Basics

Process 1-2: air enters the compressor where; P & T increase.

Process 2-3: high-P air enters combustion chamber. Heat addition at constant pressure.

Process 3-4: high-T gases enter the turbine and expand to atmospheric pressure while producing power.

Process 4-1: Closed: exhaust gases (modelled as air) enter heat exchanger were heat is lost. Air returns back to state 1.



4.5 IDEAL Brayton Cycle

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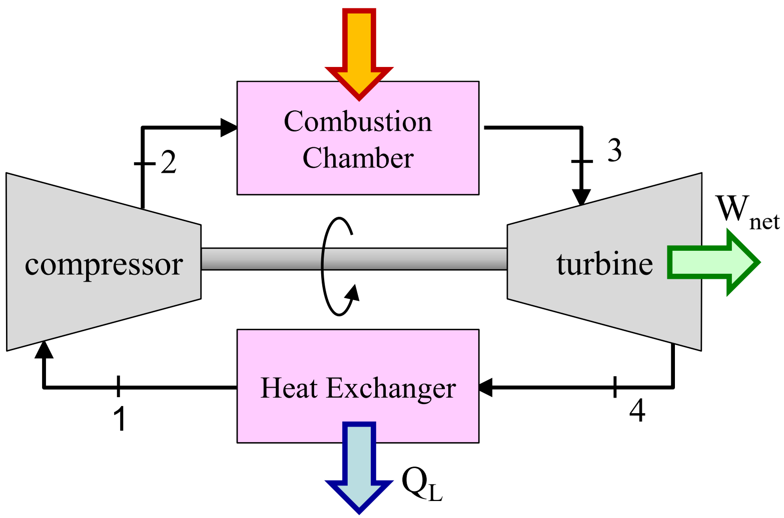
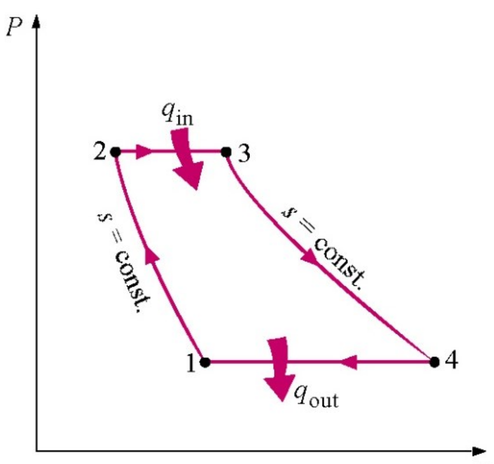
Processes in an air-standard closed Brayton cycle

- Working fluid is air (ideal gas)
- Closed cycle is represented to provide a closed loop in the P-v and T-s diagrams

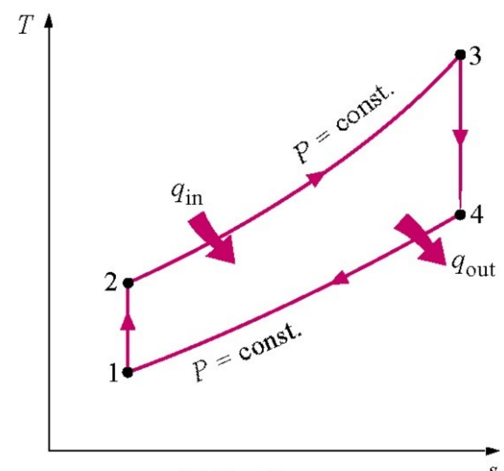
Closed Brayton Cycle



Process	Description
1-2	Isentropic compression
2-3	Constant pressure heat addition
3-4	Isentropic expansion
4-1	Constant pressure heat rejection



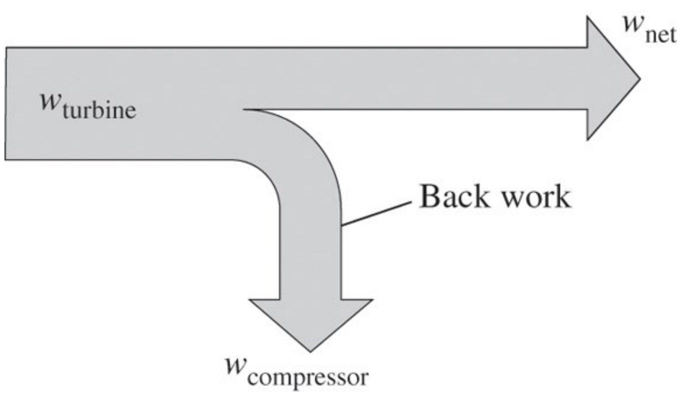
(b) P-υ diagram



(a) T-s diagram

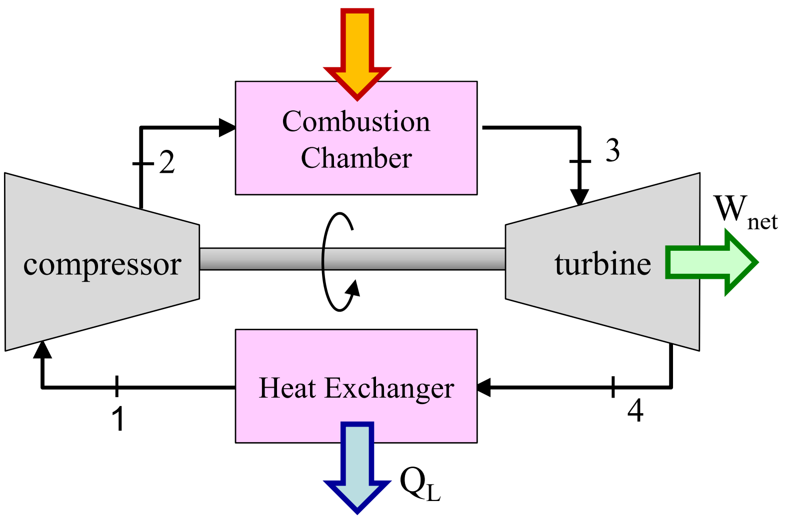
4.5 Brayton Cycle - Basics

- Turbine is connected to compressor via a shaft.
- A fraction of turbine work is used to power the compressor.
- Ratio of compressor to turbine work is called the back work ratio.



$$BWR = \frac{w_{compressor}}{w_{turbine}}$$

Closed Brayton Cycle



- For open Brayton cycle (jet engine): $BWR = 1$
  - 100% turbine work powers compressor
- For closed Brayton cycle: $BWR < 1$

4.5 Brayton Cycle – Basic Equations

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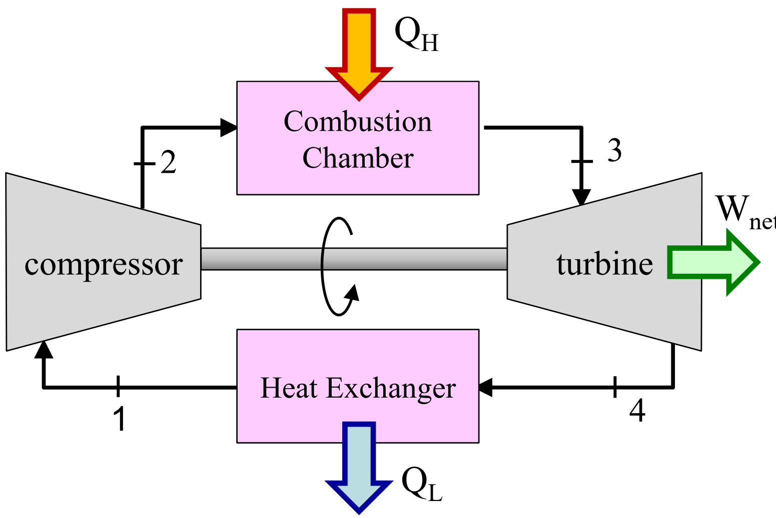
Ideal Brayton cycle

- Air treated as an ideal gas

Process 1-2: Isentropic Compression

- 1st Law:
  - $0 = \dot{Q} - \dot{W} + \sum \dot{m}_i(h_i + ke + pe) - \sum \dot{m}_e(h_e + ke + pe)$
  - $\dot{W}_{21,IN} = \dot{m}(h_2 - h_1) = \dot{m}C_P(T_2 - T_1)$
- 2nd Law:
  - $s_2 - s_1 = \int \frac{\delta d}{T} + s_{gen} \rightarrow s_2 - s_1 = 0$
  - Isentropic relations
  - $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{V_1}{V_2}\right)^{k-1}$ & $\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{k}$

Closed Brayton Cycle



4.5 Brayton Cycle – Basic Equations

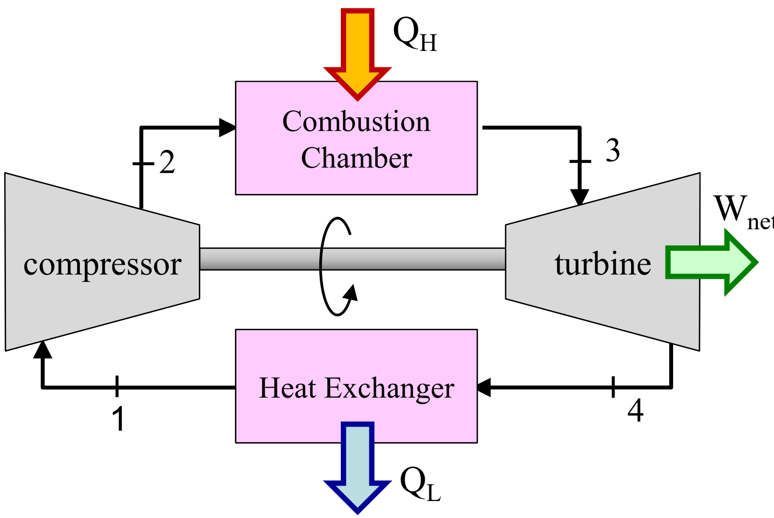
<u>Ideal Brayton cycle</u>

- Air treated as an <u>ideal gas</u>

<u>Process 2-3</u>: Constant pressure heat addition

- 1st Law:
  - $0 = \dot{Q} - \dot{W} + \sum \dot{m}_i(h_i + ke + pe) - \sum \dot{m}_e(h_e + ke + pe)$
  - $\dot{Q}_{32} = \dot{m}(h_3 - h_2) = \dot{m}C_P(T_3 - T_2)$

Closed Brayton Cycle



4.5 Brayton Cycle – Basic Equations

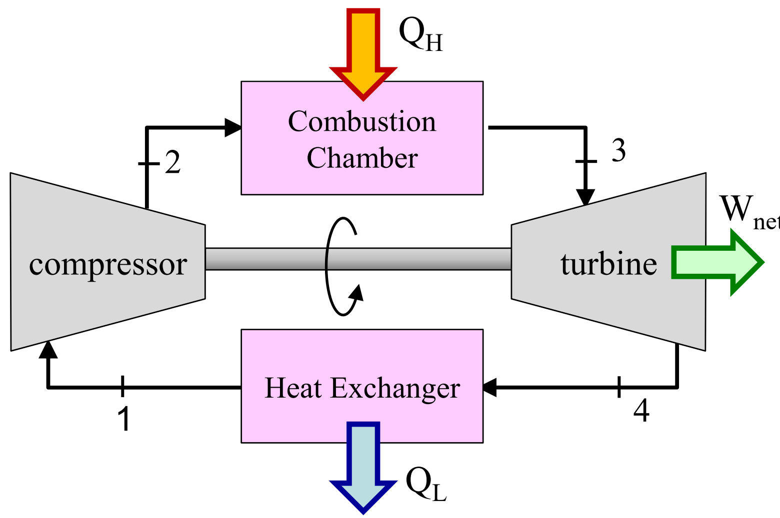
<u>Ideal Brayton cycle</u>

- Air treated as an <u>ideal gas</u>

<u>Process 3-4</u>: Isentropic expansion

- 1st Law:
  - $0 = \dot{Q} - \dot{W} + \sum \dot{m}_i(h_i + ke + pe)\text{-}\sum \dot{m}_e(h_e + ke + pe)$
  - $\dot{W}_{34} = \dot{m}(h_3 - h_4) = \dot{m}C_P(T_3 - T_4)$
- 2nd Law:
  - $s_4 - s_3 = \int \frac{\delta d}{T} + s_{gen} \rightarrow s_4 - s_3 = 0$
  - Isentropic relations
  - $\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{(k-1)/k} = \left(\frac{V_3}{V_4}\right)^{k-1}$ & $\frac{P_4}{P_3} = \left(\frac{V_3}{V_4}\right)^{k}$

<u>Closed Brayton Cycle</u>

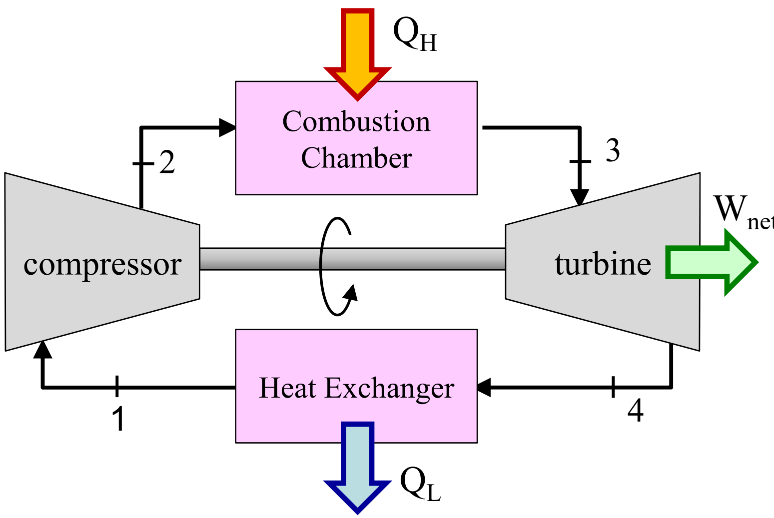


4.5 Brayton Cycle – Basic Equations

Ideal Brayton cycle

- Air treated as an ideal gas

Closed Brayton Cycle



Process 4-1 CLOSED: constant pressure heat rejection (closed cycle)

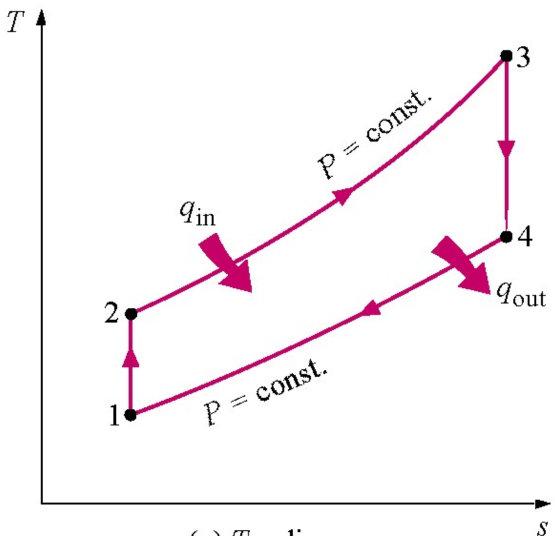
- 1st Law:
  - $0 = \dot{Q} - \dot{W} + \sum \dot{m}_i(h_i + ke + pe) - \sum \dot{m}_e(h_e + ke + pe)$
  - $\dot{Q}_{41} = \dot{m}(h_4 - h_1) = \dot{m}C_P(T_4 - T_1)$

Efficiency:

- $\eta_{th,Brayton} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{out} - \dot{W}_{in}}{\dot{Q}_{in}} = \frac{\dot{Q}_{in} - \dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}}$

4.5 Brayton Cycle – Thermal Efficiency

- Net thermal efficiency of an ***ideal, closed*** Brayton cycle can be expressed as a function of temperatures in the cycle



(a) T-s diagram

- $\eta_{th,Brayton} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{Q}_{in}-\dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}}$
- $\eta_{th,Brayton} = 1 - \frac{mC_p(T_4-T_1)}{mC_p(T_3-T_2)}$
- $\eta_{th,Brayton} = 1 - \frac{(T_4-T_1)}{(T_3-T_2)} = \frac{T_1(T_4/T_1-1)}{T_2(T_3/T_2-1)}$

- Processes 1-2 and 3-4 are isentropic $\rightarrow$ $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{k-1/k}$ and $\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{k-1/k}$
- Since $P_3 = P_2$ and $P_4 = P_1$ $\rightarrow$ $\frac{T_2}{T_1} = \frac{T_3}{T_4}$ and $\frac{T_4}{T_1} = \frac{T_3}{T_2}$
- Brayton cycle efficiency: $\eta_{th,Brayton} = 1 - \frac{T_1}{T_2}$

4.5 Brayton Cycle – Thermal Efficiency

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Pressure ratio

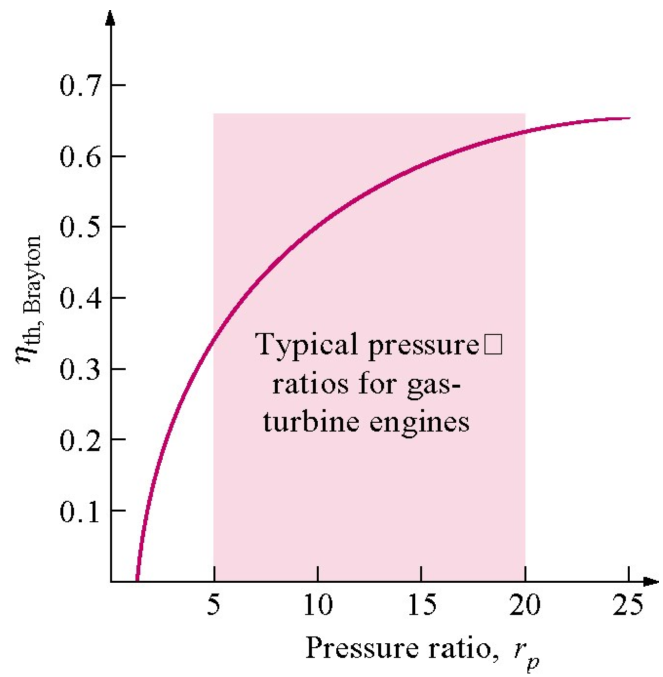
- <u>Closed</u> Brayton cycle efficiency is: $\eta_{th,Brayton} = 1 - \frac{T_1}{T_2}$

- Process 1-2 is isentropic, so $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{k-1/k} = \left(r_p\right)^{(k-1)/k}$

And, hence

$$\boxed{\eta_{th,\,Brayton} = 1 - \frac{1}{r_p^{\,(k-1)/k}}}$$

where the pressure ratio is $r_P = P_2/P_1$



4.5 Compressor and Turbine efficiency

- Compression & expansion processes are not reversible or adiabatic in reality.

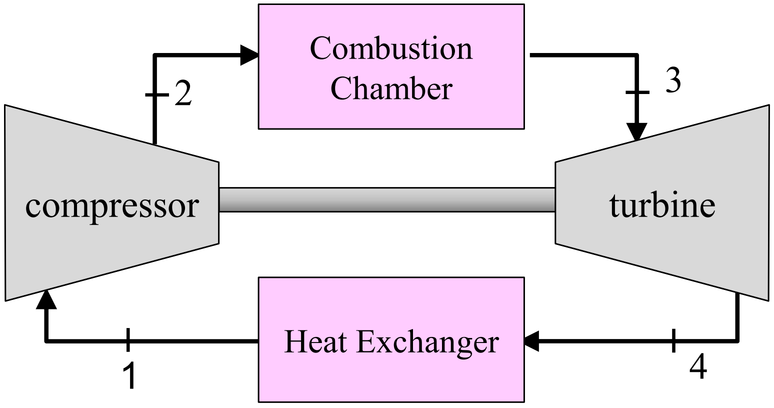
- Isentropic efficiencies:

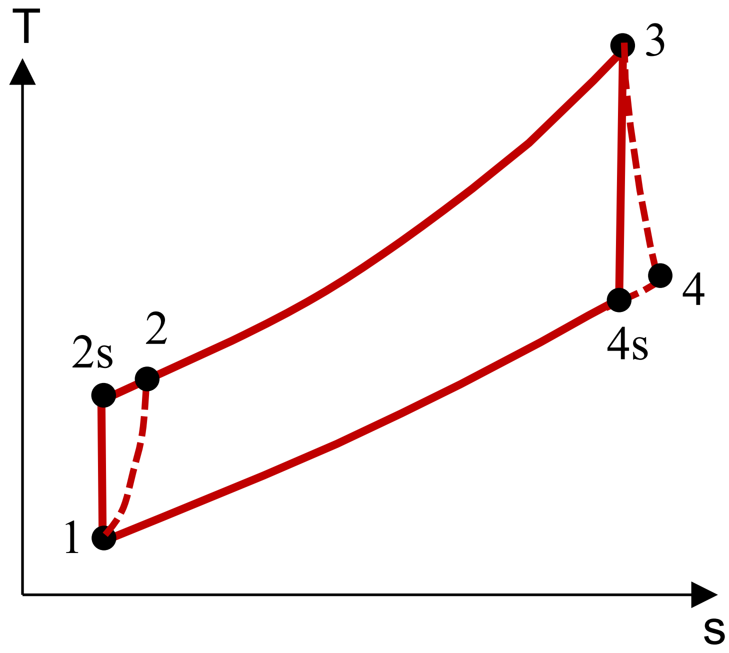
$$\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1} \quad \& \quad \eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}}$$

  - Subscript "s" denotes the ideal isentropic case.

  - Ideal gas with constant specific heats:

$$\eta_c = \frac{T_{2s} - T_1}{T_2 - T_1} \quad \& \quad \eta_T = \frac{T_3 - T_4}{T_3 - T_{4s}}$$





4.5 Brayton Cycle – Example

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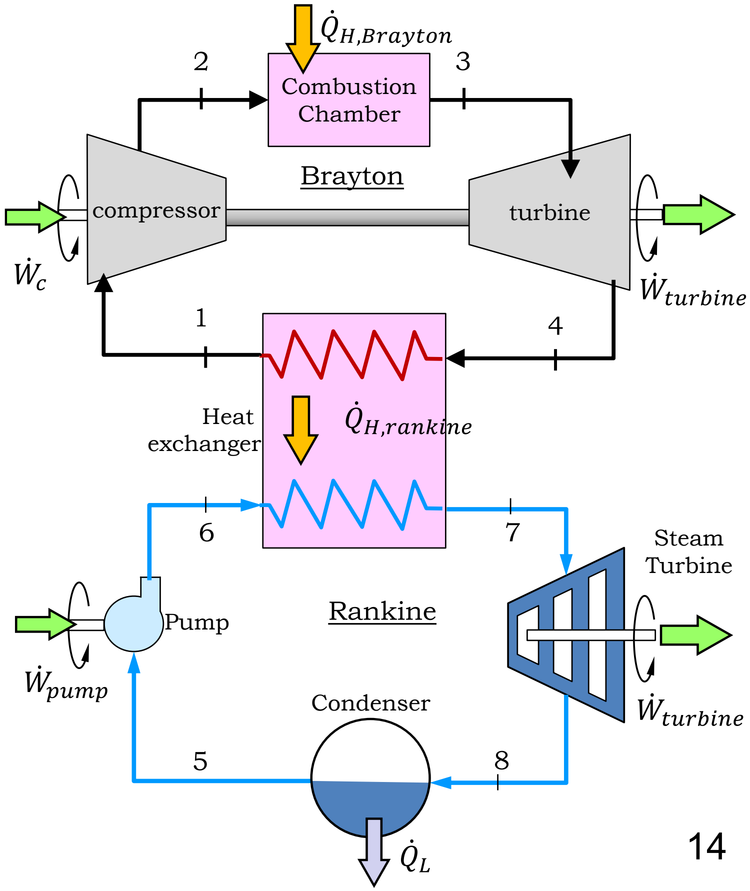
Example 4-8: Consider an ideal closed, air-standard Brayton cycle. Air enters the compressor at 90 kPa, 320K with a flow rate of 50 kg/s. The cycle operates with a pressure ratio of 14 and the maximum temperature reached is 1600 K. The exhaust gas exits the turbine at 90 kPa and sent to a heat exchanger that provides the heat source to operate a Rankine steam power plant. Assume the air exiting the heat exchanger returns to conditions entering the compressor (i.e. state 1).

a) Determine the back work ratio of the Brayton cycle.

b) What is the Brayton cycle efficiency?

c) If the Rankine cycle operates between 10 kPa and 3000 kPa with a highest temperature in the cycle reaching 450°C, determine the mass flow rate of water in the Rankine cycle.



Assume air behaves as an ideal gas with constant specific heats: C_P = 1.004 kJ/kgK, R = 0.287 kJ/kgK