Power and Refrigeration Systems – Gaseous Working Fluids

(Lecture 12)

2021년 1학기

열역학 (M2794.001100.002)

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(*) Some texts and figures are borrowed from Sonntag & Borgnakke unless noted otherwise.

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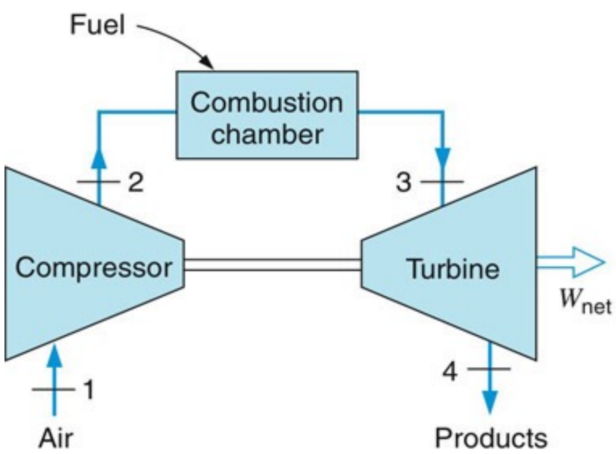
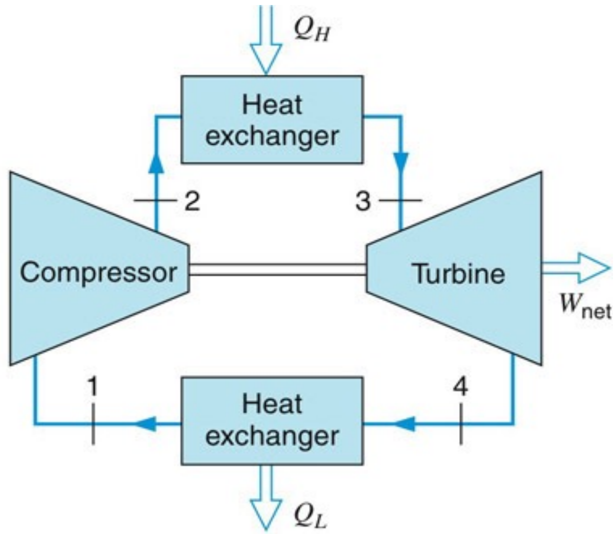
10.1 Air-Standard Power Cycles

- Air-standard cycle is devised to approximate an open (or actual) cycle.
- Assumptions:
  - A fixed mass of air is used as working fluid throughout the cycle.
  - Ideal gas, internally reversible processes.
  - The combustion process is replaced by heat transfer from an external source.



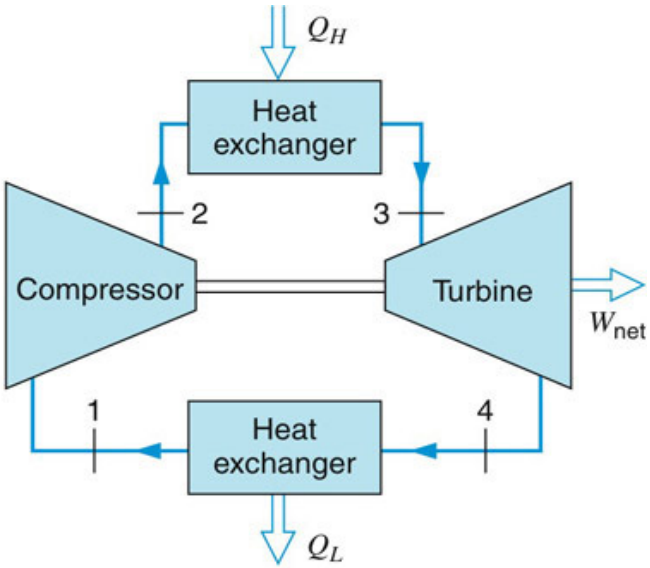
Open (or actual cycle)

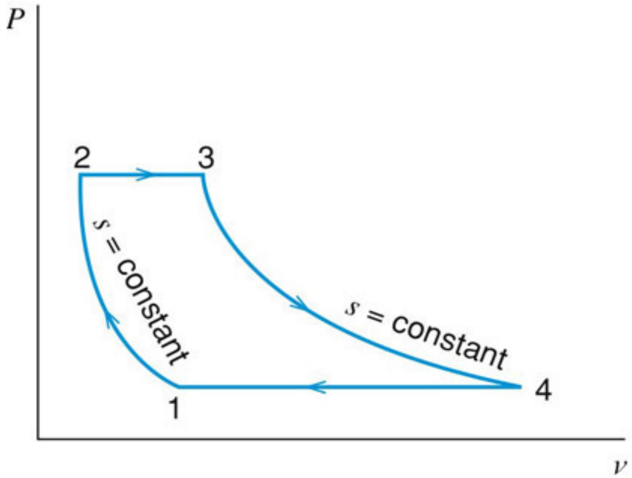


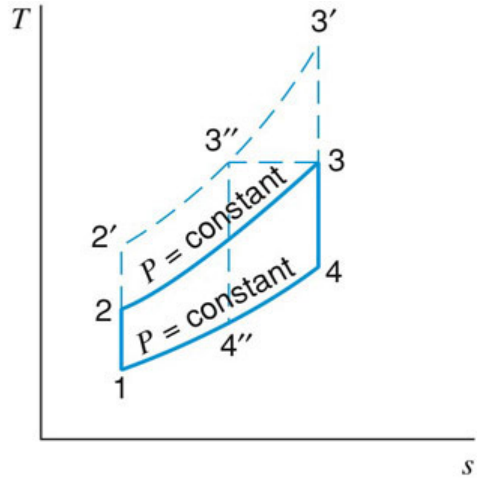
Air-standard cycle

10.2 The Brayton Cycle

- Brayton cycle is an ideal cycle for the simple gas turbine.
- The cycle consists of two constant-pressure heat transfer and two isentropic work transfer processes (same as in Rankine cycle).







Brayton cycle

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

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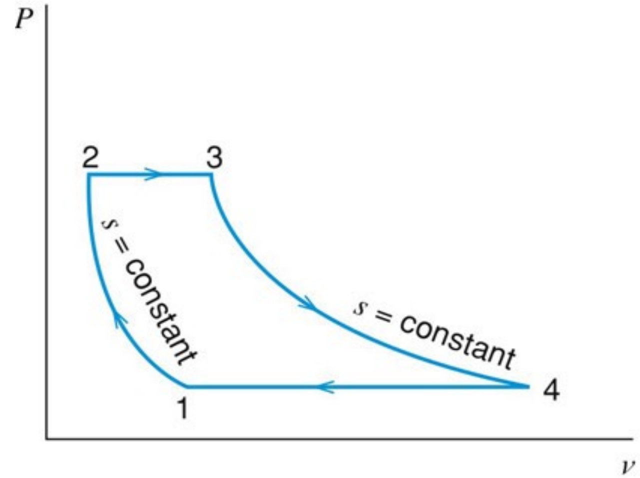
➔ For constant specific heats,

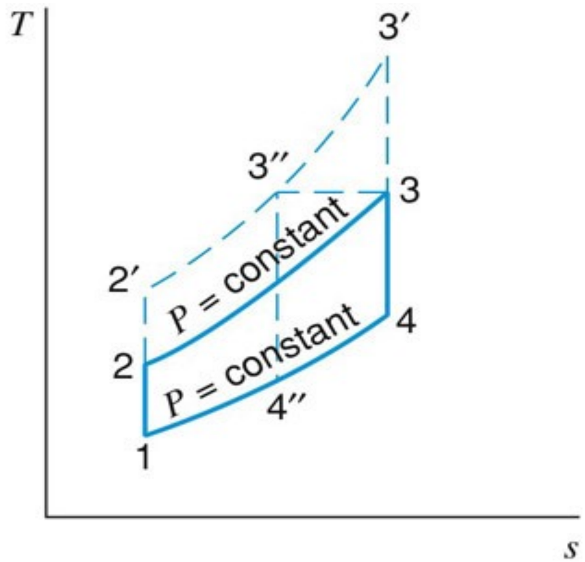
$$\eta_{\text{th}} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{C_p\left(T_4 - T_1\right)}{C_p\left(T_3 - T_2\right)} = 1 - \frac{T_1\left(T_4 / T_1 - 1\right)}{T_2\left(T_3 / T_2 - 1\right)}$$

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

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

$$\therefore \eta_{th} = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{P_1}{P_2}\right)^{\frac{k-1}{k}} = 1 - \frac{1}{\left(P_2 / P_1\right)^{\frac{k-1}{k}}}$$





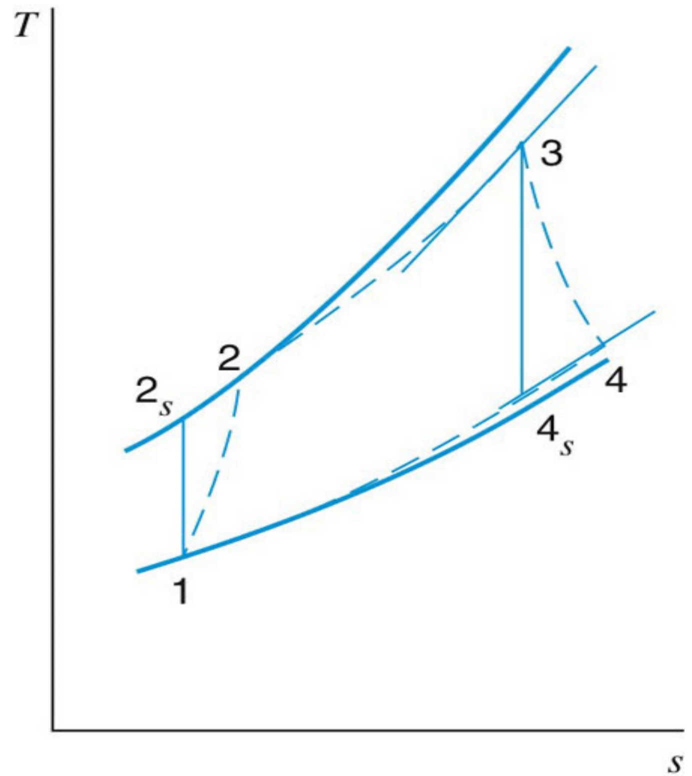
Higher P₂: $1 - 2' - 3' - 4 - 1$: $\mathrm{T}_{\mathrm{H,avg}} \uparrow \rightarrow \eta \uparrow$

T_3”=T_3: $1 - 2' - 3'' - 4'' - 1$: $\mathrm{T}_{\mathrm{H,avg}} \uparrow \rightarrow \eta \uparrow$, work decrease per kg

- For real cycle, we need to consider isentropic efficiencies.

$$\eta_{comp} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

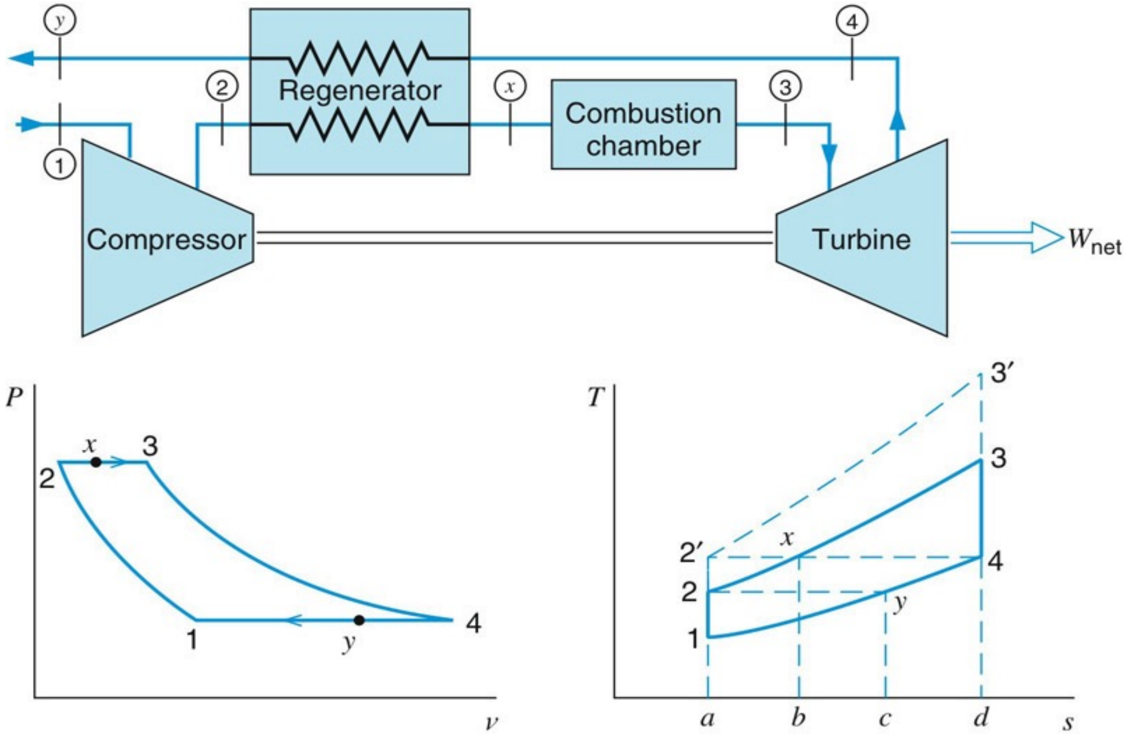
$$\eta_{turb} = \frac{h_3 - h_4}{h_3 - h_{4s}}$$



- In Brayton cycle, the compressor work is 40~80 % of the turbine work.
(cf. In Rankine cycle, the pump work is 1~2 % of the turbine work.)

10.3 The Simple Gas-Turbine Cycle with a Regenerator

- The efficiency of the gas-turbine cycle can be improved by introducing a regenerator.
- Heat transfer from the turbine exit stream (4) to post-compressor stream (2).



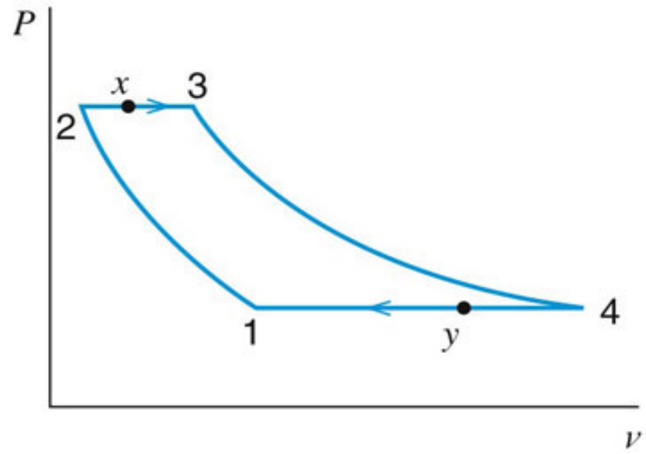
$T_{avg,H}$ increases

→ Efficiency increases.

If P_H increases, there is some point where no more regeneration may occur.

$$\eta_{th} = \frac{w_{net}}{q_H} = \frac{w_t - w_c}{q_H}$$

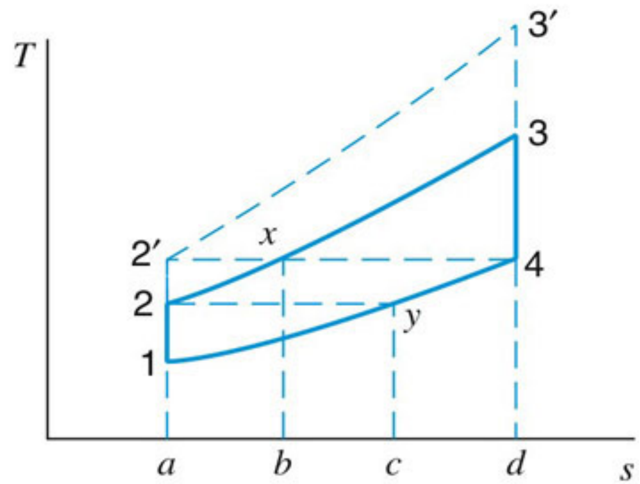
$$q_H = C_p\left(T_3 - T_x\right)$$
$$w_t = C_p\left(T_3 - T_4\right)$$



Ideal case: $T_x = T_4 \rightarrow q_H = w_t$

$$\eta_{th} = \frac{w_t - w_c}{w_t} = 1 - \frac{w_c}{w_t} = 1 - \frac{C_p\left(T_2 - T_1\right)}{C_p\left(T_3 - T_4\right)}$$

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

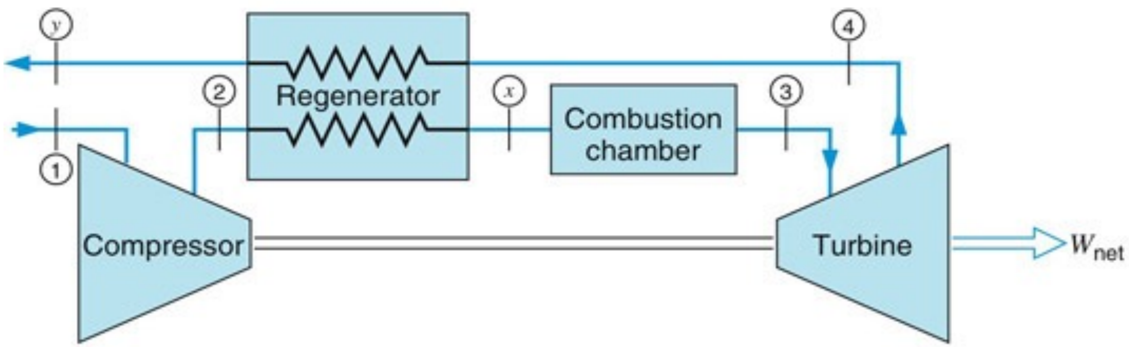


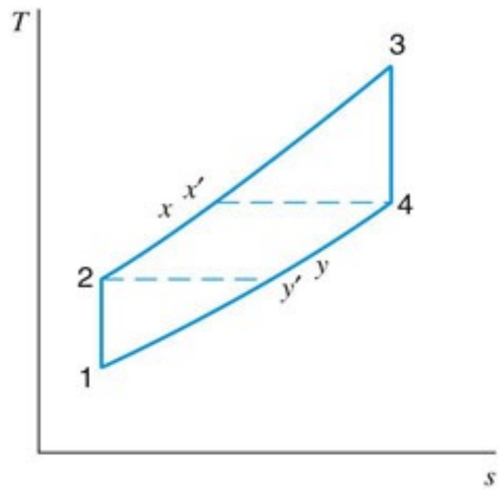
$$= 1 - \frac{T_1}{T_3}\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\left[\frac{1 - \left(P_1/P_2\right)^{\frac{k-1}{k}}}{1 - \left(P_1/P_2\right)^{\frac{k-1}{k}}}\right] = 1 - \frac{T_1}{T_3}\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 1 - \frac{T_2}{T_3}$$

- Regenerator efficiency is defined by,

$$\eta_{reg} = \frac{h_x - h_2}{h_{x'} - h_2}$$

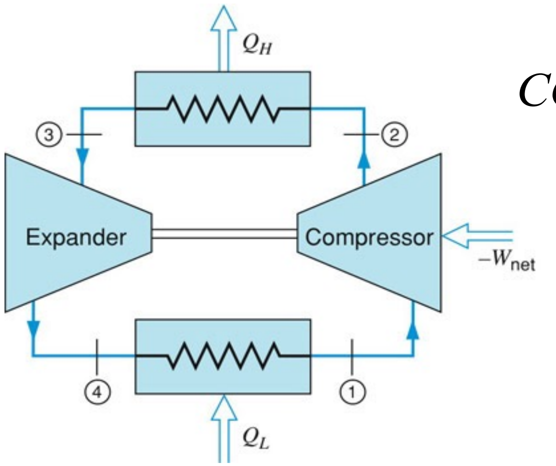
$$\eta_{reg} = \frac{T_x - T_2}{T_{x'} - T_2} \qquad \text{if } C_p = const.$$





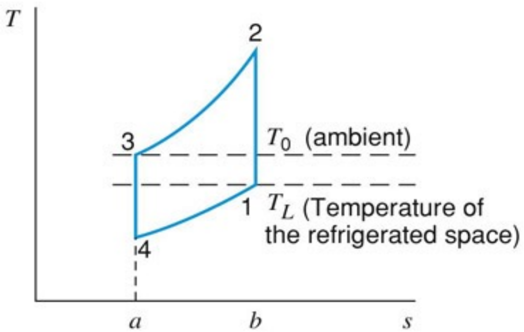
10.6 The Air-Standard Refrigeration Cycle

- The air-standard refrigeration cycle is the reverse Brayton cycle.
  - Expansion work is NOT negligible → Expander.
  - Used in the liquefaction of air, aircraft cooling systems, etc.



$$COP(\beta) = \frac{q_L}{w_{net}} = \frac{q_L}{w_C - w_E} = \frac{h_1 - h_4}{h_2 - h_1 - (h_3 - h_4)} \approx \frac{C_P(T_1 - T_4)}{C_P(T_2 - T_1) - C_P(T_3 - T_4)}$$

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



$$\beta = \frac{T_1 - T_4}{T_2 - T_1 - T_3 + T_4} = \frac{1}{\frac{T_2}{T_1}\frac{1 - T_3/T_2}{1 - T_4/T_1} - 1} = \frac{1}{\frac{T_2}{T_1} - 1} = \frac{1}{r_p^{(k-1)/k} - 1}$$