

Thermodynamics and energetics 1

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Summary last lecture

- Demonstrate and understand the basic principles of vapor power systems, i.e. power systems using a working fluid which is alternately vaporized and condensed
- Develop and analyze thermodynamic models of vapor power plants based on Rankine cycle and its modifications
 - Sketch T - s -, p - v -diagrams
 - Evaluate properties at states of cycle
 - Apply mass, energy and entropy balances to the processes
 - Determine performance
- Discuss and analyze the performance and optimization approaches

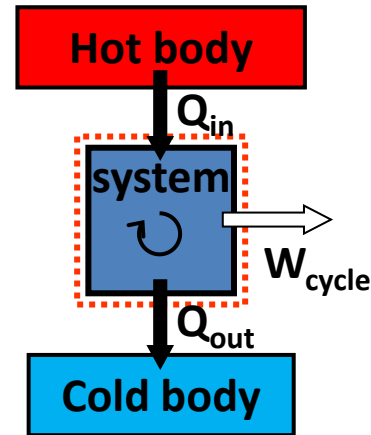
Learning outcomes of today's lecture

- Demonstrate and understand the basic principles of air-standard cycles of
 - Internal combustion engines (Otto, Diesel)
 - Gas turbine power plants
- This includes:
 - Sketch T - s -, p - v -diagrams
 - Evaluate properties at states of cycle
 - Apply mass, energy and entropy balances to the processes
 - Determine performance
- Discuss and analyze the performance and optimization approaches

Moran book: chp. 9

Power systems

- Power generation systems:
 - Produce net power output from a energy source, such as fossil fuel, nuclear, or solar power



- Three major types of systems:
 - Vapor power plants (working fluid alternately vaporizes and condenses)
 - Gas turbine power plants (working fluid gas, series of components)
 - Internal combustion engines (working fluid gas, reciprocating)

Internal combustion engines

- Internal combustion engines:
 - Specifically *reciprocating* internal combustion engines, e.g. used in cars, buses, etc.
 - Two types:
 - Spark ignition: fuel and air mixture is ignited by spark plug
 - Compression ignition: air is compressed to high p and T in order to spontaneously ignite when fuel is added

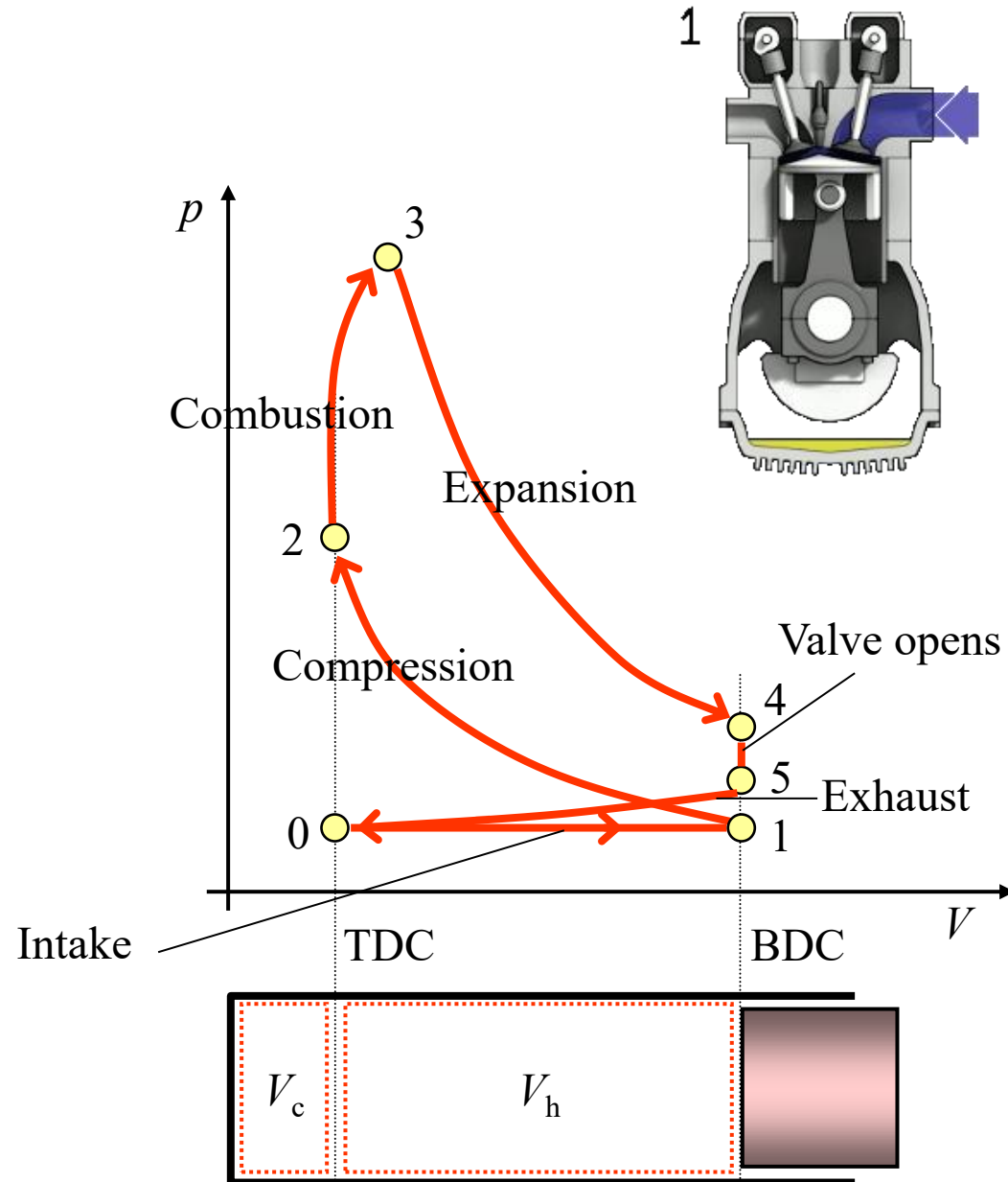
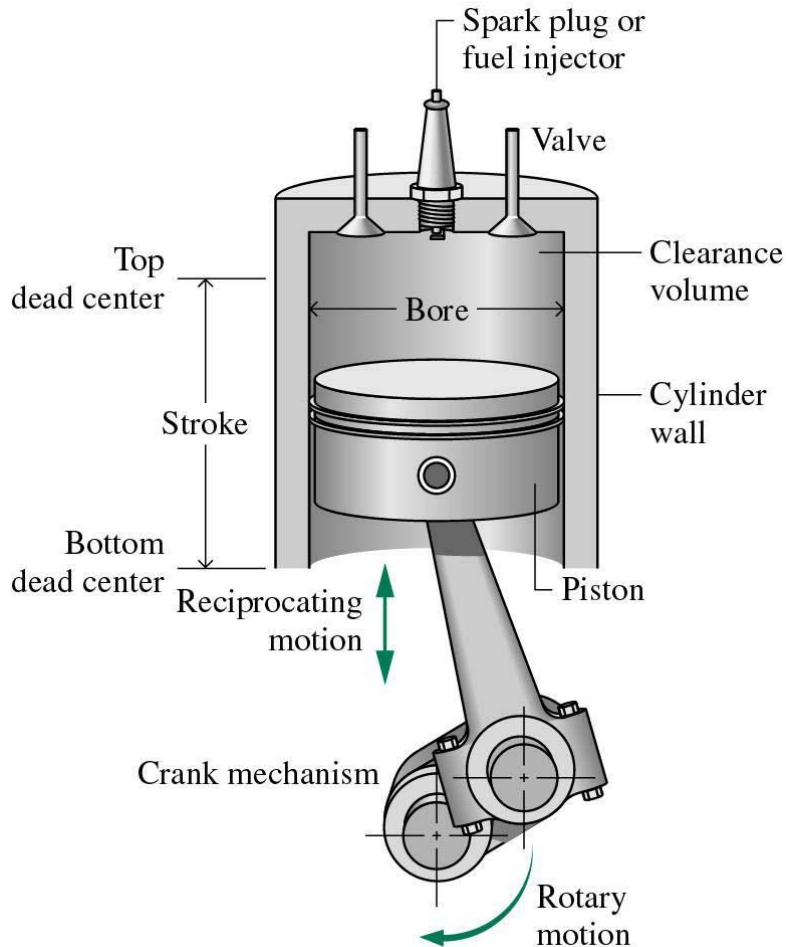
KTM, 125 EXC,
spark ignited,
two stroke



BMW, 760Li V12, 400kW (544 PS), spark ignited

Internal combustion engines

- Piston-cylinder systems:
 - 4-stroke engine:



Internal combustion engines

- *Air-standard analysis* allows for elementary thermodynamic analysis of internal combustion engines
- Simplifications:
 - Fixed amount of air modeled as ideal gas
 - Combustion modeled by heat transfer from external source
 - No exhaust and intake strokes. Constant volume heat rejection
 - Internally reversible processes
- In *cold air-standard* also specific heats are assumed constant
- With air-standard we considerably simplify the process, especially the complex combustion (reaction, composition change)
- Results might differ from reality but give a qualitative insight

Internal combustion engines

- Reminder: ideal gas model (chapter 5 and 7)

$$pvM = \tilde{R}T$$

$$u_2(T_2) - u_1(T_1) = \int_{T_1}^{T_2} c_v(T) dT$$

$$h_2(T_2) - h_1(T_1) = \int_{T_1}^{T_2} c_p(T) dT$$

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{c_v(T) dT}{T} + \tilde{R} / M \ln \left(\frac{v_2}{v_1} \right)$$

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{c_p(T) dT}{T} - \tilde{R} / M \ln \left(\frac{p_2}{p_1} \right)$$

Internal combustion engines

- New: only valid for Air and isentropic process:

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{c_p(T) dT}{T} - \tilde{R} / M \ln \left(\frac{p_2}{p_1} \right) = s_2^0 - s_1^0 - \tilde{R} / M \ln \left(\frac{p_2}{p_1} \right) \stackrel{!}{=} 0$$

$$\frac{p_2}{p_1} = \frac{\exp(s_2^0 / (\tilde{R} / M))}{\exp(s_1^0 / (\tilde{R} / M))} = \frac{p_{2,r}}{p_{1,r}}$$

Only function of temperature

$$\frac{v_2}{v_1} = \left(\frac{\tilde{R} / MT_2}{p_2} \right) \left(\frac{p_1}{\tilde{R} / MT_1} \right) = \left(\frac{\tilde{R} / MT_2}{p_{2,r}} \right) \left(\frac{p_{1,r}}{\tilde{R} / MT_1} \right) = \frac{v_{2,r}}{v_{1,r}}$$

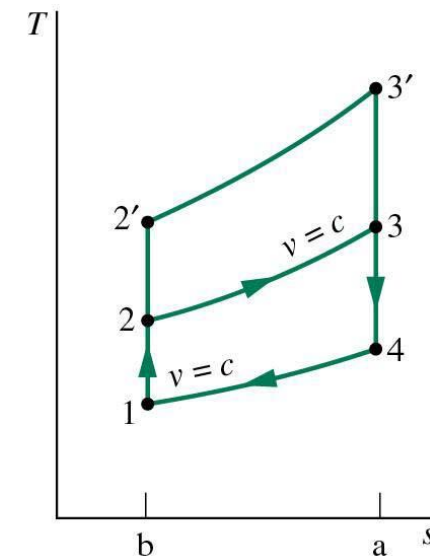
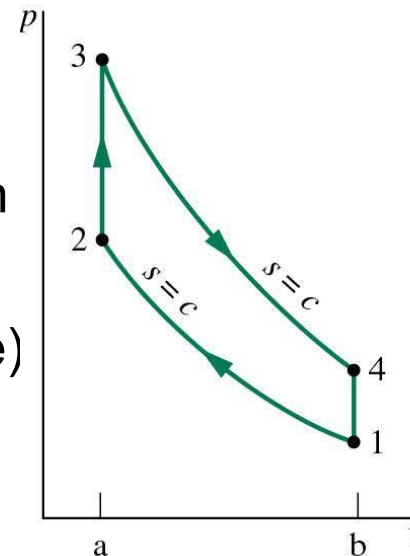
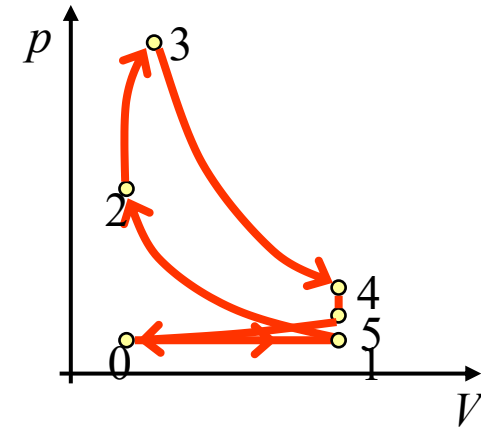
Only function of temperature

Internal combustion engines

- Air-standard Otto cycle:

Ideal cycle, which assumes heat addition occurs instantaneously while piston is at top dead center

- 1-2: Isentropic compression of air as piston moves from bottom to top dead center
- 2-3: constant-volume heat transfer from external source while piston is at top dead center (represents fuel addition and combustion)
- 3-4: Isentropic expansion (power stroke)
- 4-1: Constant-volume heat rejection while piston is at bottom dead center (replaces exhaust/intake)



Internal combustion engines

- Air-standard Otto cycle: Cycle analysis

- 1-2 and 3-4: work, no heat
- 2-3 and 4-1: no work, heat

- First law:

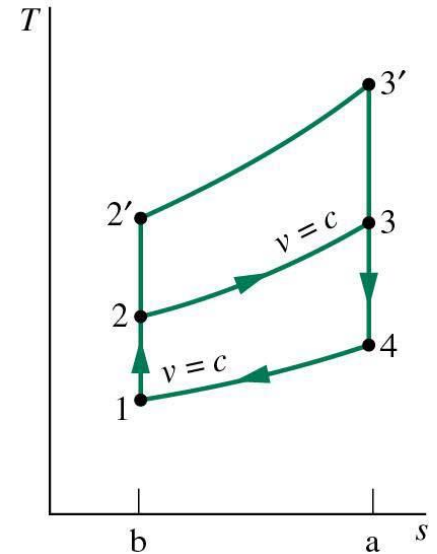
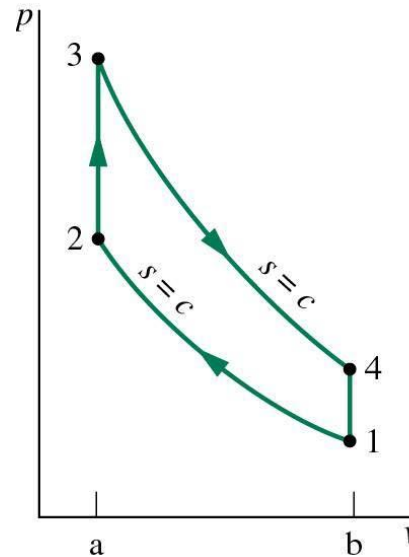
$$\frac{W_{12}}{m} = u_1 - u_2 \qquad \frac{W_{34}}{m} = u_3 - u_4$$

$$\frac{Q_{23}}{m} = u_3 - u_2 \qquad \frac{Q_{41}}{m} = u_1 - u_4$$

- Cycle:

$$\frac{W_{\text{cycle}}}{m} = \frac{W_{34}}{m} + \frac{W_{12}}{m} = u_3 - u_4 + u_1 - u_2$$

$$\frac{W_{\text{cycle}}}{m} = \frac{Q_{23}}{m} + \frac{Q_{41}}{m} = u_3 - u_2 + u_1 - u_4$$



$$\left. \begin{array}{l} \frac{W_{\text{cycle}}}{m} = u_3 - u_4 + u_1 - u_2 \\ \frac{W_{\text{cycle}}}{m} = u_3 - u_2 + u_1 - u_4 \end{array} \right\} \eta = \frac{W_{\text{cycle}}}{Q_{23}} = \frac{u_3 - u_4 + u_1 - u_2}{u_3 - u_2}$$

Internal combustion engines

- Air-standard Otto cycle: Cycle analysis

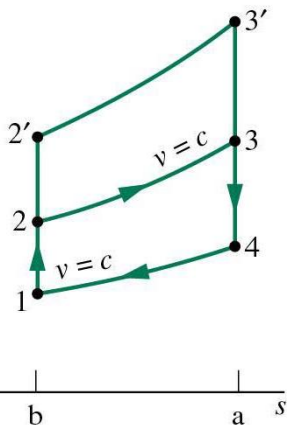
- Compression ratio, r :

$$r = \frac{V_1}{V_2} = \frac{V_4}{V_3} \quad r = \frac{v_{1,r}}{v_{2,r}} = \frac{v_{4,r}}{v_{3,r}}$$

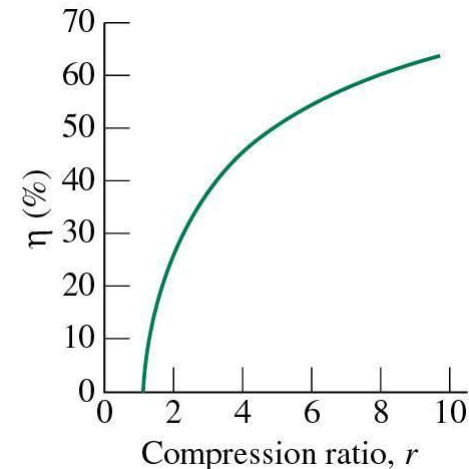
- For cold air-standard ($c_p/c_v = \text{const.}$):

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2} \right)^{k-1} = r^{k-1} \quad \frac{T_4}{T_3} = \left(\frac{V_3}{V_4} \right)^{k-1} = \frac{1}{r^{k-1}}$$

- Effect of compression ratio on performance (cold air-standard analysis):



$$\begin{aligned} \eta &= \frac{W_{\text{cycle}}}{Q_{23}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1}{T_2} \left(\frac{T_4 / T_1 - 1}{T_3 / T_2 - 1} \right) \\ &= 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r^{k-1}} \end{aligned}$$

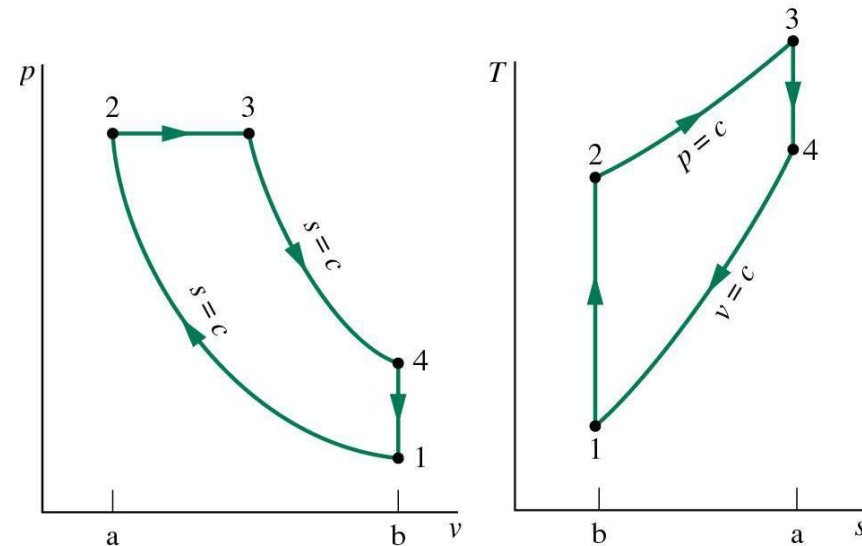
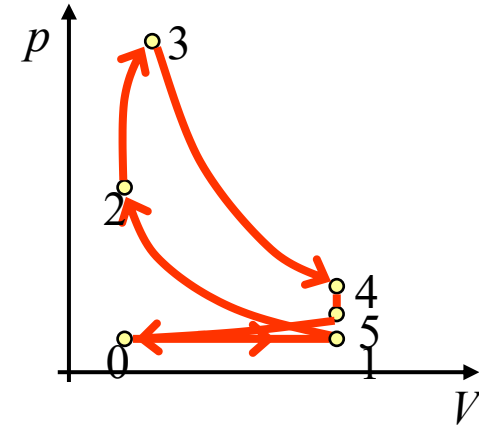


Internal combustion engines

- Air-standard Diesel cycle:

Ideal cycle, which assumes heat addition occurs at a constant pressure, which starts with piston position at top dead center

- 1-2: Isentropic compression of air as piston moves from bottom to top dead center
- 2-3: constant-pressure heat transfer from external source while piston starts at top dead center (represents fuel addition, combustion, and part of power stroke)
- 3-4: Isentropic expansion (remaining power stroke)
- 4-1: Constant-volume heat rejection while piston is at bottom dead center



Internal combustion engines

- Air-standard Diesel cycle: Cycle analysis

- 1-2 and 3-4: work, no heat
- 2-3 and 4-1: (no) work, heat

- First law:

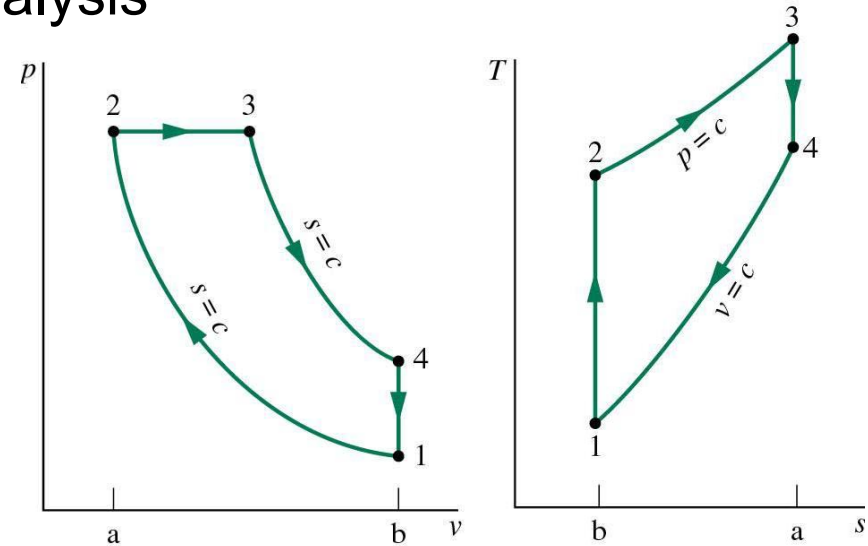
$$\frac{W_{12}}{m} = u_1 - u_2 \quad \frac{W_{34}}{m} = u_3 - u_4$$

$$\frac{W_{23}}{m} = p_2(v_3 - v_2) \quad \frac{Q_{23}}{m} = u_3 - u_2 + \frac{W_{23}}{m}$$

$$\frac{Q_{41}}{m} = u_1 - u_4$$

- Cycle:

$$\eta = \frac{W_{\text{cycle}}}{Q_{23}} = \frac{h_3 - h_2 - u_4 + u_1}{h_3 - h_2} = 1 - \frac{u_4 - u_1}{h_3 - h_2}$$



Internal combustion engines

- Air-standard Diesel cycle: Cycle analysis

- Compression ratio, r : and cutoff ratio, r_c :

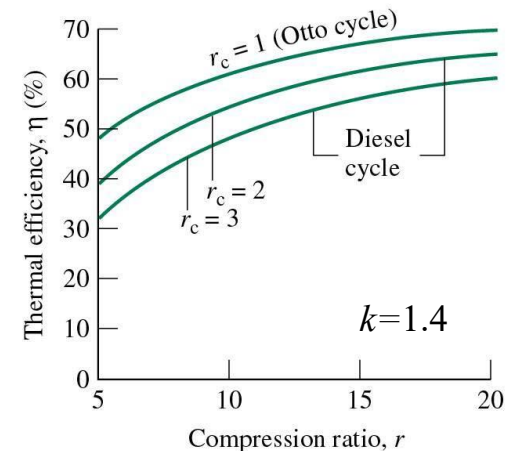
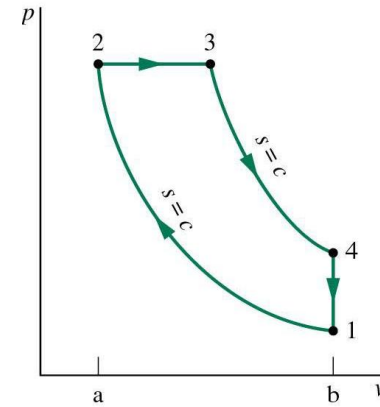
$$r = \frac{V_1}{V_2} = \frac{v_{1,r}}{v_{2,r}} \quad r_c = \frac{V_3}{V_2}$$

- For cold air-standard ($c_p/c_v = \text{const.}$):

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2} \right)^{k-1} = r^{k-1} \quad \frac{T_4}{T_3} = \left(\frac{V_3}{V_4} \right)^{k-1} = \left(\frac{r_c}{r} \right)^{k-1}$$

- Effect of compression ratio on performance (cold air-standard analysis):

$$\begin{aligned} \eta &= \frac{W_{\text{cycle}}}{Q_{23}} = 1 - \frac{c_v(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{1}{k} \frac{T_1}{T_2} \left(\frac{T_4 / T_1 - 1}{T_3 / T_2 - 1} \right) \\ &= 1 - \frac{1}{k} \frac{1}{r^{k-1}} \left(\frac{T_3 / T_2 r_c^{k-1} - 1}{T_3 / T_2 - 1} \right) = 1 - \frac{1}{k} \frac{1}{r^{k-1}} \left(\frac{r_c^k - 1}{r_c - 1} \right) \end{aligned}$$



Internal combustion engines

- Example (8.1): At the beginning of a compression process of an air-standard diesel cycle operating with compression ratio of 18, temperature 300 K, pressure 0.1 MPa, and cutoff ratio of 2. Determine:
 - Temperature and pressure at each state of the process
 - Thermal efficiency

$$\eta_{\text{th}} = 58\%$$

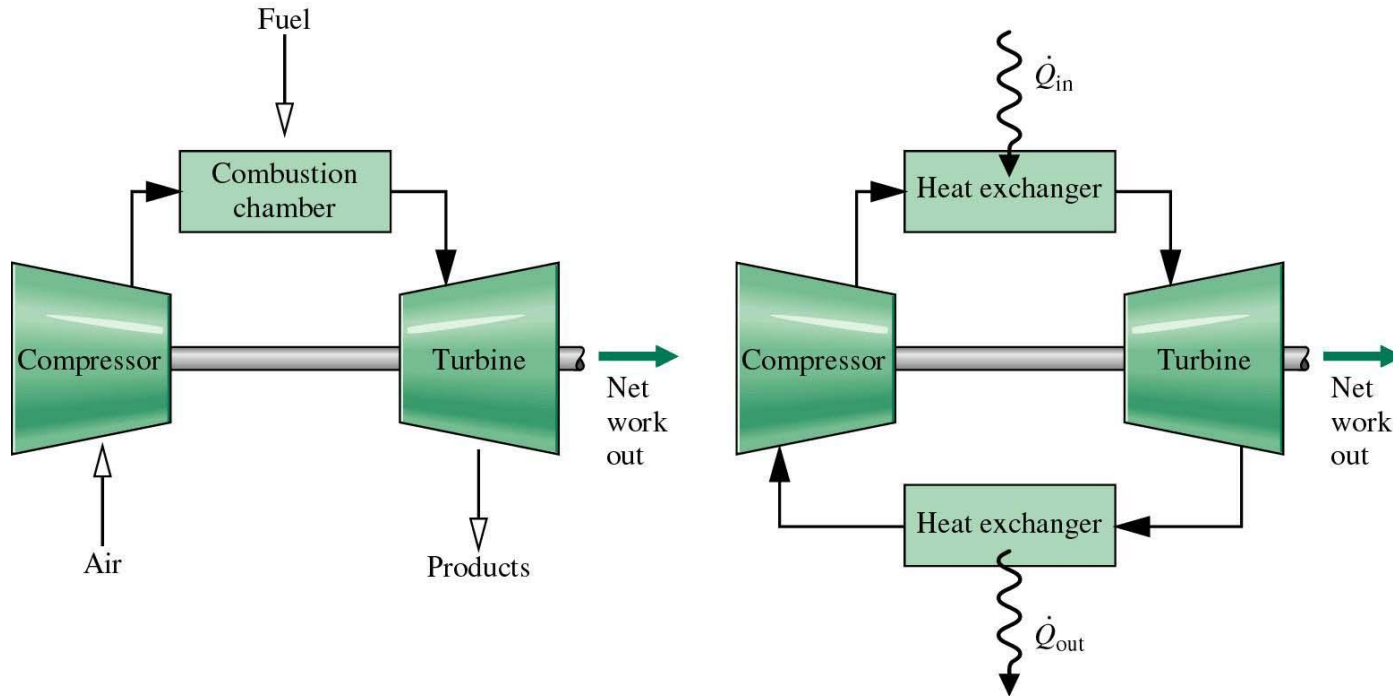
Internal combustion engines

- Example (8.2): At the beginning of a compression process of an air-standard dual cycle with a compression ratio of 18, temperature is 300 K, and pressure 0.1 MPa. The pressure ratio for the constant volume part of the heating process is 1.5:1. The volume ratio for the constant pressure part is 1.2:1. Determine:
 - Thermal efficiency
 - The mean effective pressure

$$\eta_{\text{th}} = 63.5\%$$
$$\text{MEP} = 0.56 \text{ MPa}$$

Gas turbine power plants

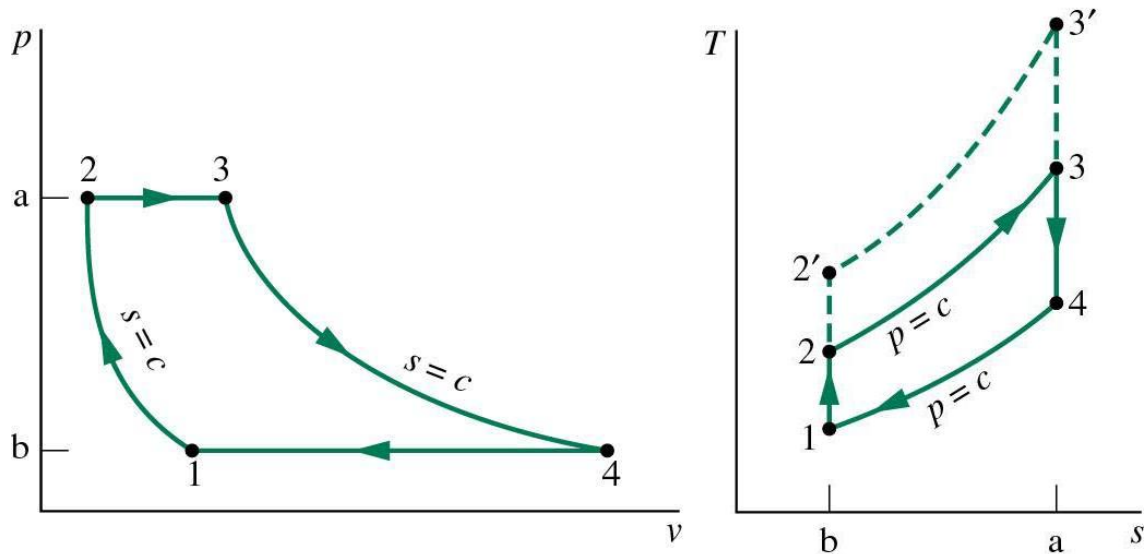
- Gas turbine cycles can be open or closed systems:



- Assumptions for air-standard analysis:
 - Working fluid is air, which behaves as an ideal gas
 - Temperature increase during combustion is modeled by heat transfer from an external source

Gas turbine power plants

- Air-standard Brayton cycle (ideal):
 - 1-2: Isentropic compression of air in the compressor
 - 2-3: Isobaric heat transfer from external source
 - 3-4: Isentropic expansion in turbine
 - 4-1: Isobaric heat transfer to the surrounding



Gas turbine power plants

- Air-standard Brayton cycle: Cycle analysis

- 1-2 and 3-4: work, no heat
- 2-3 and 4-1: no work, heat

- First law:

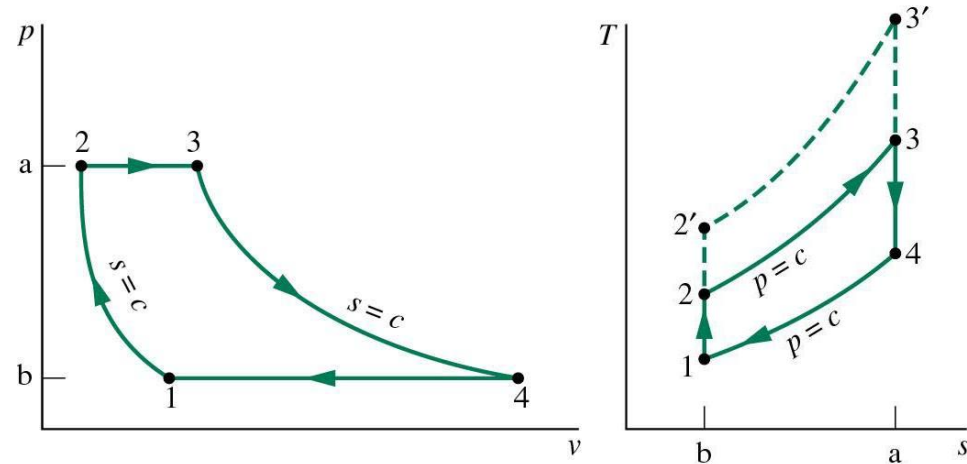
$$\frac{\dot{W}_{12}}{\dot{m}} = h_1 - h_2 \quad \frac{\dot{W}_{34}}{\dot{m}} = h_3 - h_4$$

$$\frac{\dot{Q}_{23}}{\dot{m}} = h_3 - h_2 \quad \frac{\dot{Q}_{41}}{\dot{m}} = h_1 - h_4$$

- Cycle:

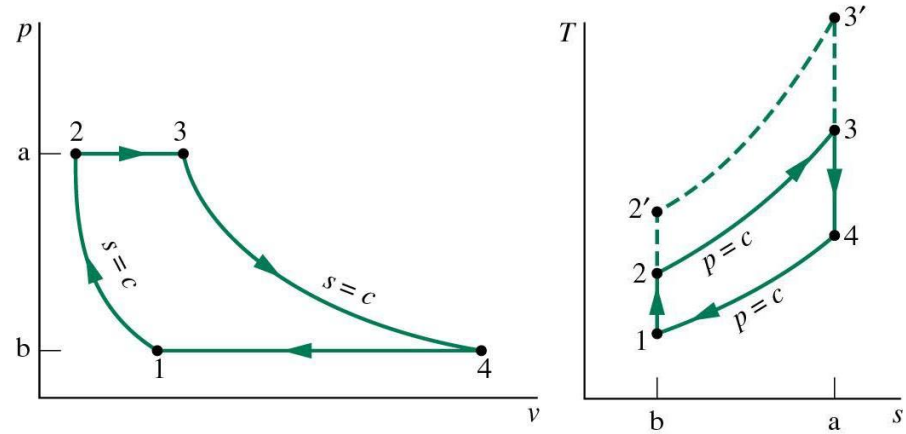
$$\eta = \frac{W_{\text{cycle}}}{Q_{23}} = \frac{h_3 - h_4 + h_1 - h_2}{h_3 - h_2}$$

$$\text{back work ratio} = \frac{|\dot{W}_c / \dot{m}|}{\dot{W}_t / \dot{m}} = \frac{h_2 - h_1}{h_3 - h_4}$$



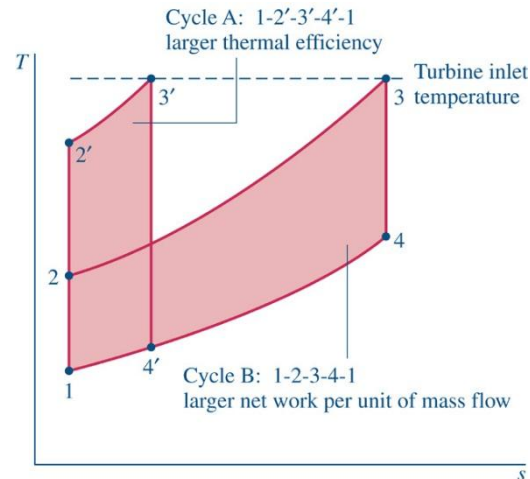
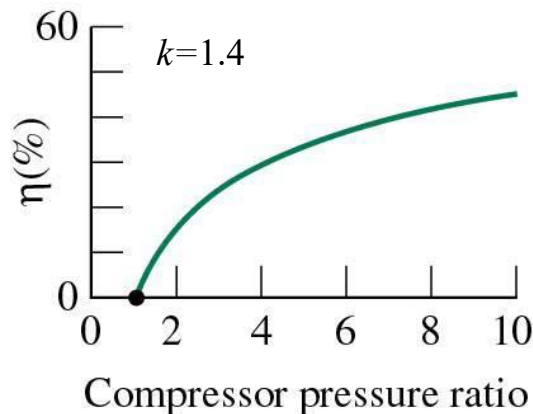
Gas turbine power plants

- Air-standard Brayton cycle: pressure ratio effect on performance
 - Efficiency increases with increasing pressure ratio



- Cold air-standard analysis ($c_p/c_v = \text{const.}$):

$$\eta = \frac{W_{\text{cycle}}}{Q_{23}} = \frac{h_3 - h_4 + h_1 - h_2}{h_3 - h_2} = \frac{c_p(T_3 - T_4 + T_1 - T_2)}{c_p(T_3 - T_2)} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{(p_2 / p_1)^{(k-1)/k}}$$



Internal combustion engines

- Example (8.3): Air enters the compressor of an ideal air-standard Brayton cycle at 100 kPa, 300K, with a volumetric flow rate of 5 m³/s. The compressor pressure ratio is 10. the turbine inlet temperature is 1400 K. Determine:
 - Thermal efficiency
 - The back-work-ratio
 - The net power

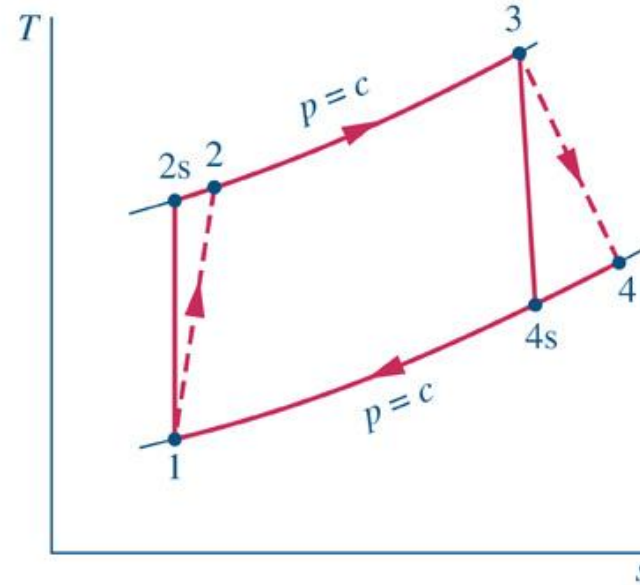
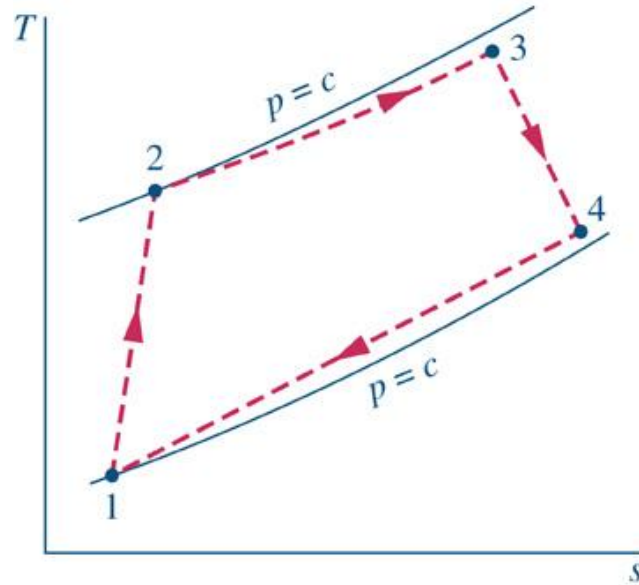
$$\eta_{\text{th}}=47.5\%$$

$$\text{bwr}=39.6\%$$

$$\dot{W}_{\text{cycle}}=2.48\text{MW}$$

Gas turbine power plants

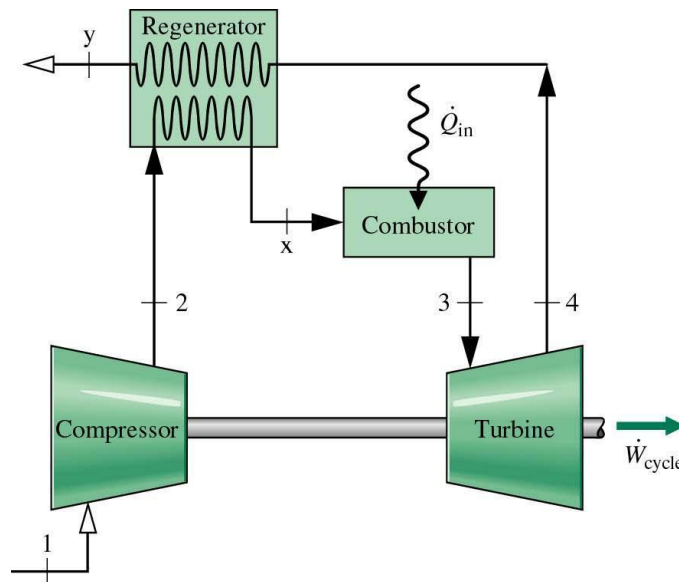
- Air-standard Brayton cycle: irreversibilities



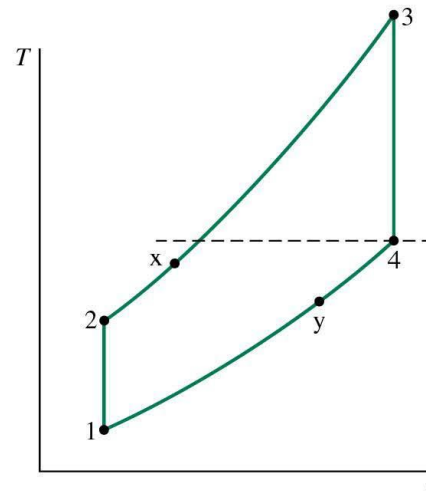
- Friction effects in turbine and compressor increase specific entropy
 - isentropic compressor and turbine efficiencies
- Frictional effects in heat exchangers lead to reduction in pressure, usually much smaller than losses in turbine and compressor

Gas turbine power plants

- Air-standard Brayton cycle: regeneration
 - Exhaust gas has temperature well above ambient and therefore work potential (exergy)
 - Using this potential via heat exchangers to pre-heat the gas before it enters combustion chamber
 - Heat transfer from external source only from x to 3:

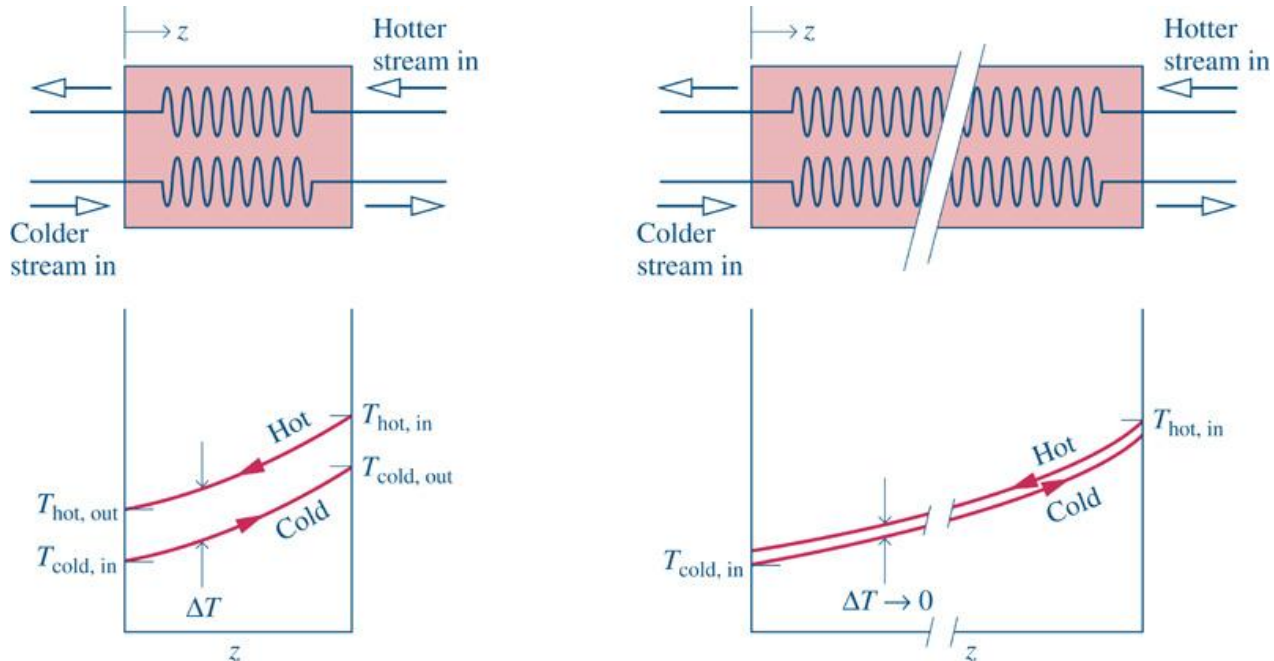


$$\frac{\dot{Q}_{23}}{m} = \frac{\dot{Q}_{in}}{m} = h_3 - h_x$$



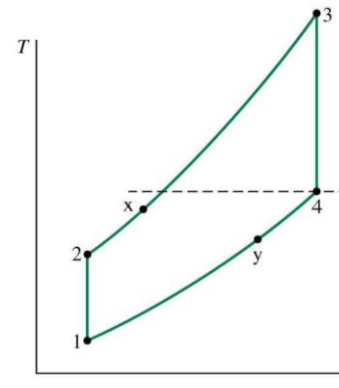
Gas turbine power plants

- Air-standard Brayton cycle: regeneration
 - Regenerator has also internal irreversibilities:



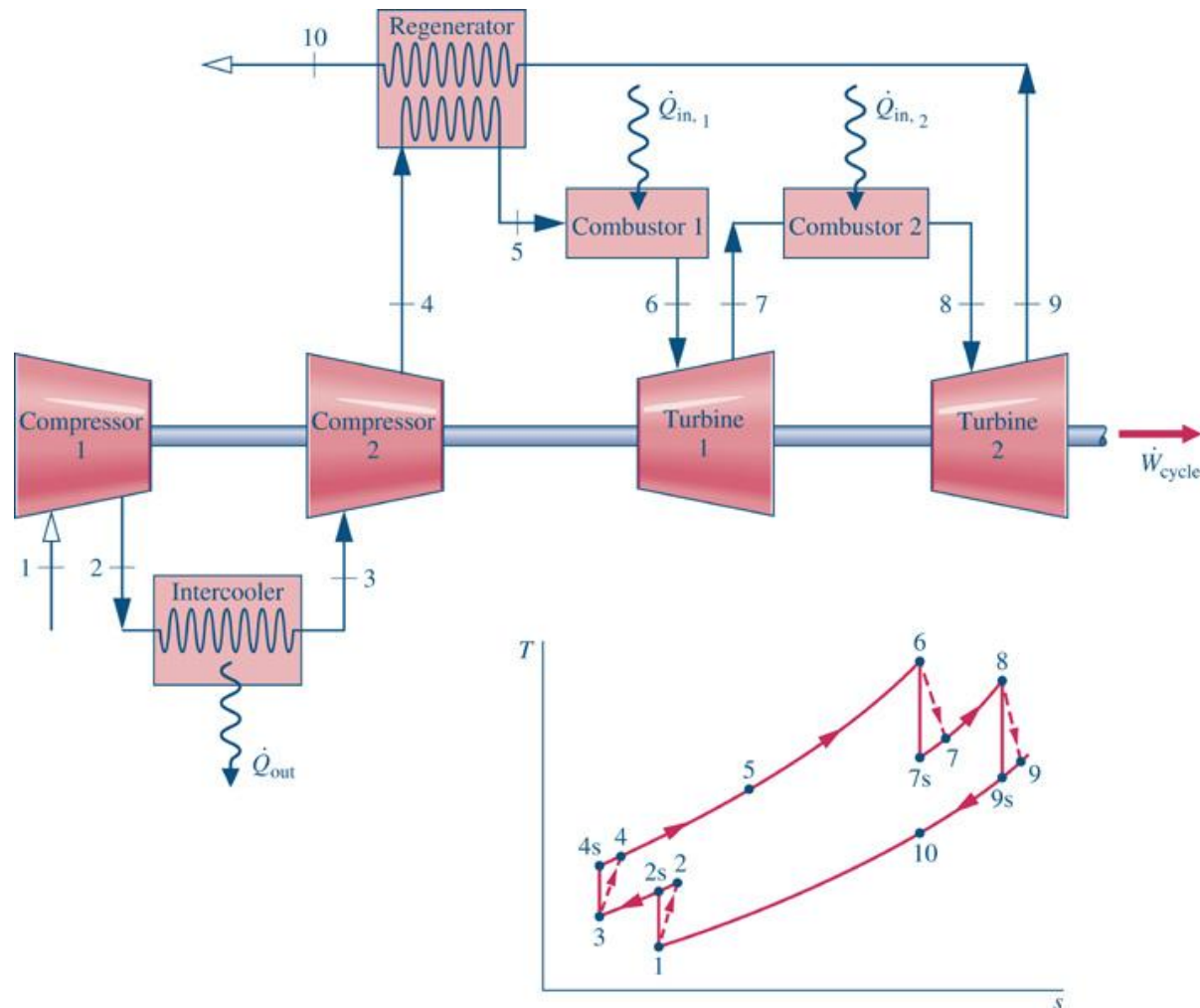
- Regenerator effectiveness:

$$\eta_{reg} = \frac{h_x - h_2}{h_4 - h_2}$$



Gas turbine power plants

- Air-standard Brayton cycle: regeneration, reheating and intercooling
 - Combination of reheating and intercooling most effective:



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