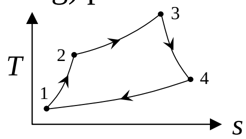
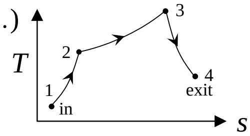
Thermodynamic Cycle Analysis

- One powerful use of TD is study of systems that manipulate energy (original motivation for TD)
  - **heat engines**: thermal energy conversion to work
    - convert ? energy → thermal energy → work (shaft)
  - **thermal transfer systems**: refrig., heat pumps
- These devices typically employ a working substance/fluid that goes through a (repeating) process ⇒ **thermodynamic cycle**
  - **closed cycle** (*steam power plant, refrig,...*)
    - same working fluid continuously circulates through cycle
  - **open cycle** (*jet engine, rocket, car engine,…*)
    - fluid enters and leaves device, but new fluid (at same initial condition) keeps replacing exhausted fluid

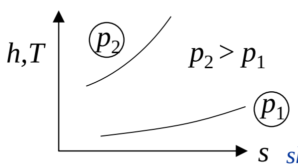
but same analysis used for both



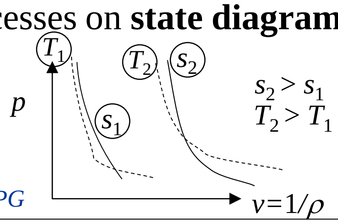


Ideal Cycles and State Diagrams

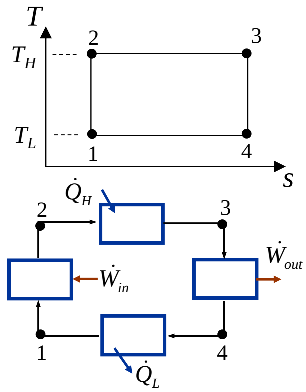
- Simply analysis of many real devices with ideal cycle
  1. ideal fluid, e.g., thermally, calorically perf. gas
  2. simplify processes, e.g., combustor replaced by nonreacting heat exchanger
  3. open → closed, e.g., surroundings (atmos.) = ht xchngr
  4. reversible, i.e., all components internally reversible
- Useful to visualize cycle processes on **state diagrams**



shown for TPG



Carnot Cycle



- Start by examining a completely reversible cycle
- **Carnot cycle**: 4 processes
  - 2 rev. isentropic (1→2, 3→4)
    - work, but no heat transfer
  - 2 rev. isothermal (2→3, 4→1)
    - heat transfer (and work?)
- What is efficiency of a device that follows this cycle?
- For heat engine

cycle or thermal efficiency

$$\eta = \frac{\textit{net work out}}{\textit{energy added as heat}} \quad \text{(II.18)}$$

what we want (net work out)

what we "pay for" (energy added as heat)

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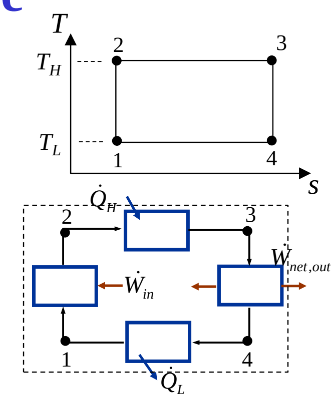
Carnot Cycle



$$\eta = \frac{\textit{net work out}}{\textit{energy added as heat}}$$

- To find η use energy conservation
  - consider C.S. around engine

$$\dot{W}_{net,out} = \dot{Q}_H - \dot{Q}_L$$

  - so $\eta = \dfrac{\dot{Q}_H - \dot{Q}_L}{\dot{Q}_H} = 1 - \dfrac{Q_L}{Q_H}$
  - if rev. $\Delta S = Q/T$ $\quad = 1 - \dfrac{T_L(s_4 - s_1)}{T_H(s_3 - s_2)}$

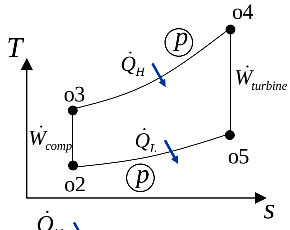
T_L	T_H	η%
300	600	50.0
300	2400	87.5
200	2400	91.7

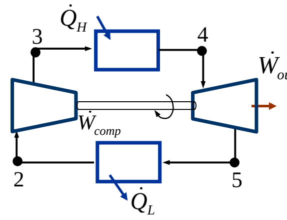
$$\eta_{Carnot} = 1 - \frac{T_L}{T_H} \quad \text{(II.19)}$$

1) get max η for $T_H >> T_L$; add heat at high T as possible (reject heat at low T as possible)
2) even though every process in Carnot cycle is rev., can't get 100% efffic. (unless T_L=0)
3) can show no 2 T heat engine has higher η than Carnot

Brayton Cycle

- Ideal cycle for jet engines, gas turbines
  - 2 rev+adiabatic processes
    - compressor 2→3
    - turbine (expansion) 4→5
  - 2 rev+isobaric processes
    - combustor (heat add) 3→4
    - heat exchanger 5→2





- Efficiency

$$\eta = \frac{\dot{W}_{turb} - \dot{W}_{comp}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_L}{\dot{Q}_H}$$

tpg, cpg

$$= \frac{\dot{m}\left[(h_{04} - h_{05}) - (h_{03} - h_{02})\right]}{\dot{m}(h_{o4} - h_{o3})} = 1 - \frac{T_{05} - T_{02}}{T_{04} - T_{03}}$$

η↑ for high T_{o4}-T_{o3} (material limit) and low T_{o5}-T_{o2} (reduces wasted "heat")

Brayton Cycle

- Efficiency

tpg, cpg

$$\eta = 1 - \frac{T_{05} - T_{02}}{T_{04} - T_{03}}$$

$$= 1 - \frac{\frac{1}{T_{03}}\frac{T_{05}}{T_{04}} - \frac{1}{T_{04}}\frac{T_{02}}{T_{03}}}{\frac{T_{04}}{T_{03}T_{04}} - \frac{T_{03}}{T_{03}T_{04}}}$$

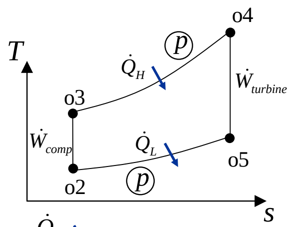
$$\frac{T_{02}}{T_{03}} = \left(\frac{p_{02}}{p_{03}}\right)^{\gamma-1/\gamma} = \frac{T_{05}}{T_{04}}$$

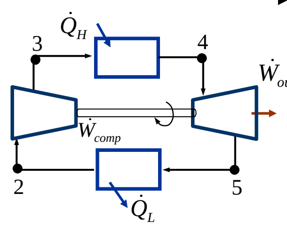
$$\Pr \equiv p_{03}/p_{02}$$

cycle pressure ratio

$$= 1 - \frac{\left(\frac{1}{T_{03}} - \frac{1}{T_{04}}\right)\left(\frac{1}{\Pr}\right)^{\gamma-1/\gamma}}{\frac{1}{T_{03}} - \frac{1}{T_{04}}}$$

(II.20)





Pr	η% (γ=1.4)
2	18
10	48
30	62

$$\eta_{Brayton} = 1 - \left(\frac{1}{\Pr}\right)^{\gamma-1/\gamma}$$

$\eta_{Brayton}$ ↑ for high pressure ratio
– not strictly function of temperature, but Pr limited by max T allowed