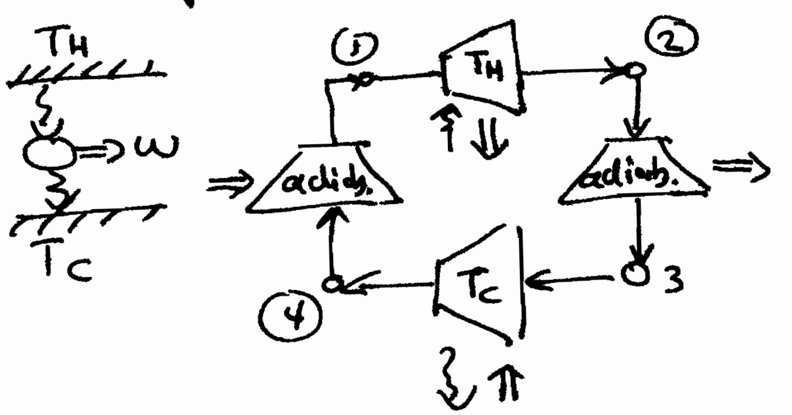
Ch. 4 Power Generation + Cooling

How are power generation / refrigeration cycles implemented in practice?

Ideal-Gas Heat Engines

(not practical, but instructional to analyze)

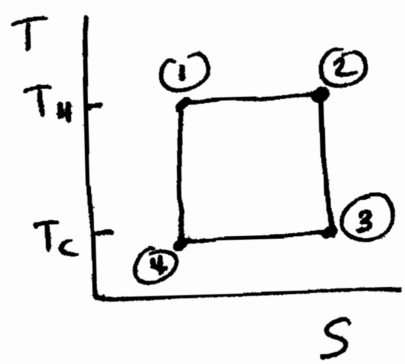


① → ② isoth. expansion, T_H

② → ③ adiab. compression

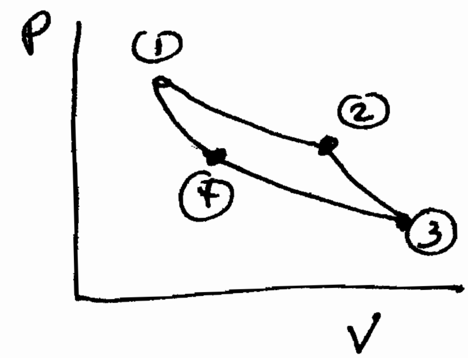
③ → ④ isoth. compression T_C

④ → ① adiab. compression



↻ power generation

↺ cooling



When analyzed using adiabatic ideal gas expressions + 1st Law balances (see Example 4.1) $\Rightarrow$ $\eta = \dfrac{-W}{Q_H} = \dfrac{T_H - T_C}{T_H}$

Theoretical maximum (Carnot) efficiency

∴ Ideal-gas T is the same as Carnot T

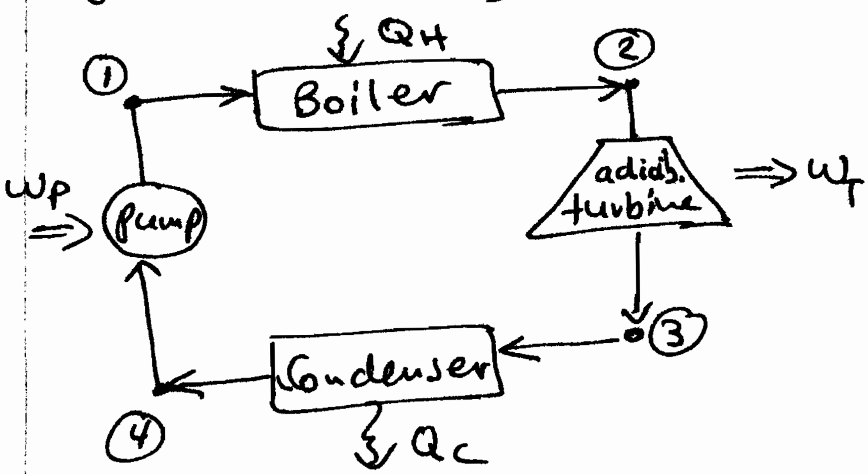
⇒ Thermodynamic Temperature ⇐

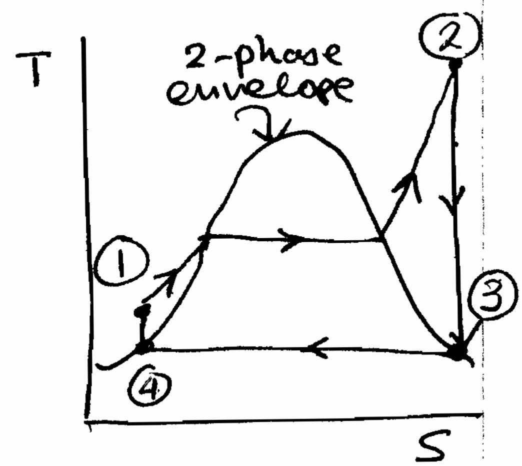
Practical issues preventing implementation:

* Isothermal turbines / compressors cannot be constructed
* Need huge equipment sizes (low ρ of I.G.)
* Cost of compression

Rankine Cycle

Practical power generation using a working fluid (usually steam). Industrial Revolution.





Example 4.2

Steam, $T_H = 800K$, $T_C = 373K$ $\eta = ?$

Start from point (3), saturated vapor @ $T_C = 373K$

From WebBook } $P_3 = P_4 = 1$ bar $\underline{H}_3 = 48.2 \frac{kJ}{mol}$ $\underline{S}_3 = 132.5 \frac{J}{mol K}$
saturation T calc. }

$\underline{H}_4 = 7.5 \frac{kJ}{mol}$ $\underline{S}_4 = 23.5 \frac{J}{mol K}$

Adiabatic expansion is – in the best case – isentropic, $\underline{S}_2 = \underline{S}_3$. From $T_2 = 800K$ (isoth. calc.) we can obtain $P_2 = 27.4$ bar, $\underline{H}_2 = 63.4 \frac{kJ}{mol}$

The pumping step (4) → (1) also operates — at best — isentropically, so that: $\underline{S}_1 = \underline{S}_4 = 23.5 \frac{J}{mol\,K}$; from isobaric calculation at $P_1 = P_2 = 27.4$ bar:

$T_1 = 373$ K (no T change) $\quad \underline{H}_1 = 7.6$ kJ/mol

$$\therefore \dot{W}_p = \underline{H}_1 - \underline{H}_4 = 0.1 \frac{kJ}{mol} \quad \text{(very small)}$$

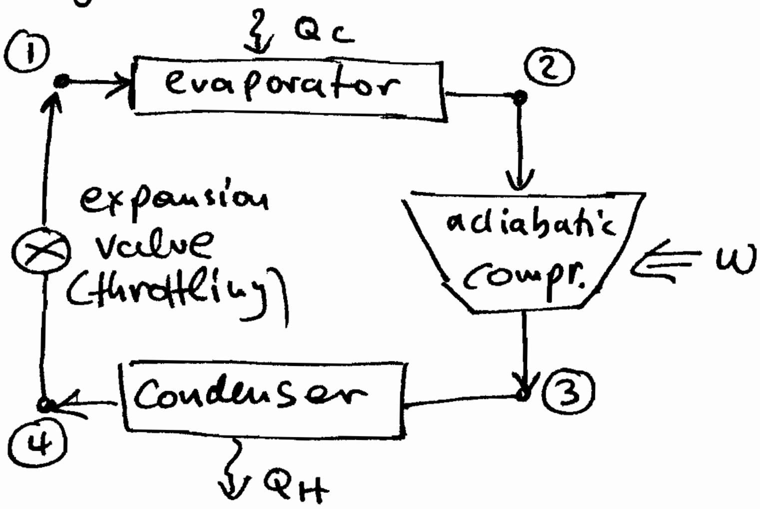
$$\left.\begin{aligned} \dot{W}_T &= \underline{H}_3 - \underline{H}_2 = -15.2 \frac{kJ}{mol} \\ \dot{Q}_H &= \underline{H}_2 - \underline{H}_1 = 55.8 \text{ kJ/mol} \end{aligned}\right\} \eta = \frac{15.2}{55.8} = 27\%$$

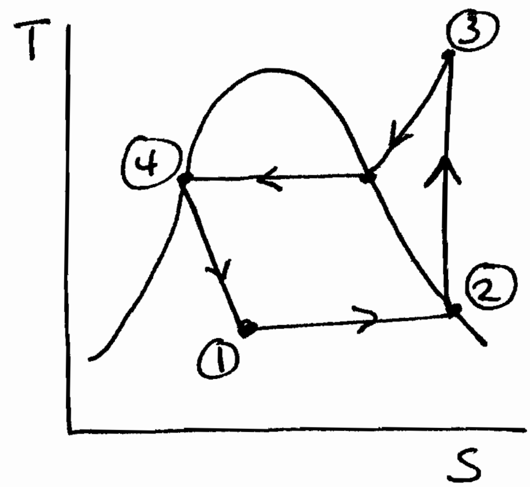
Compare to $\eta^{rev} = \frac{800-373}{800} = 53\%$

Why is efficiency lower than Carnot? } → Non-isothermal operation of boiler

Refrigeration Cycles

Slight modification of "reversed" Rankine Cycle:





E.g. Car air conditioner w/ R134a [Example 4.3]

$\theta_4 = 130\,°F$, $\quad \theta_1 = \theta_2 = 40\,°F$

From the NIST WebBook, saturation properties of R134a @ 40 °F, vapor: $\underline{H}_2 = 401 \frac{kJ}{kg}$ $\underline{S}_2 = 1.72 \frac{J}{kg\,K}$

Point ③ has $\underline{S}_3 = \underline{S}_2$

At $\theta_4 = 130$ °F, sat. liquid ⇒ $P_4 = 14.7$ bar, $\underline{H}_4 = 279 \frac{kJ}{kg}$

Isobaric calculation at $P_3 = P_4$ to match the value of the entropy (1.72 J/kg K) gives:

$\theta_3 = 137$ °F , $\underline{H}_3 = 430$ kJ/kg

Throttling valve is isenthalpic, $\underline{H}_1 = \underline{H}_4$

$\dot{W} = \underline{\dot{H}}_3 - \underline{\dot{H}}_2 = 29$ kJ/kg $\qquad \dot{Q}_c = \underline{H}_2 - \underline{H}_1 = 122 \frac{kJ}{kg}$

$$J = \frac{122}{29} = 4.2$$

Compare to Carnot: $J^{rev} = \dfrac{T_c}{T_H - T_c} = 5.6$

With the use of two 3-way valves, the role of cold + hot coil can be reversed and an air conditioner can operate as a <u>heat pump</u>, bringing heat into a building from the outside (colder) air.