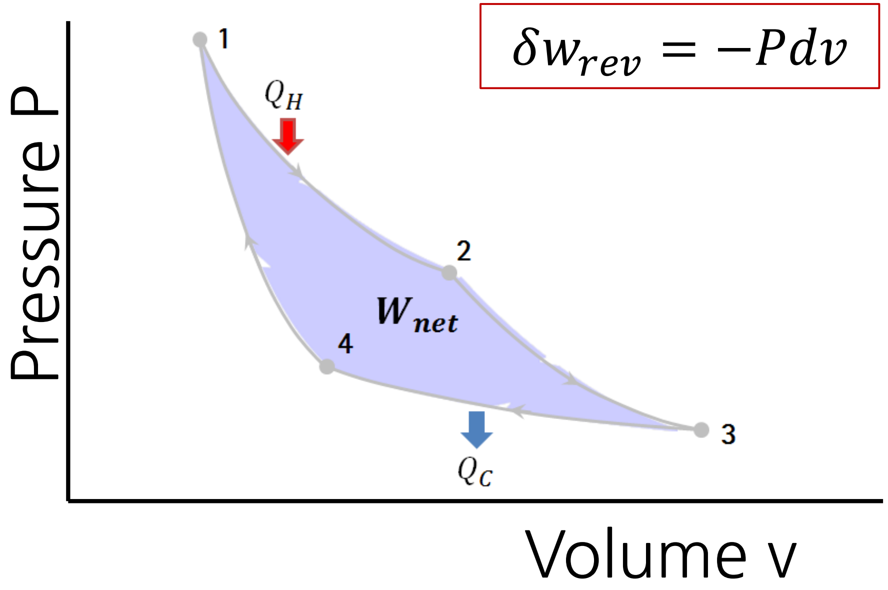
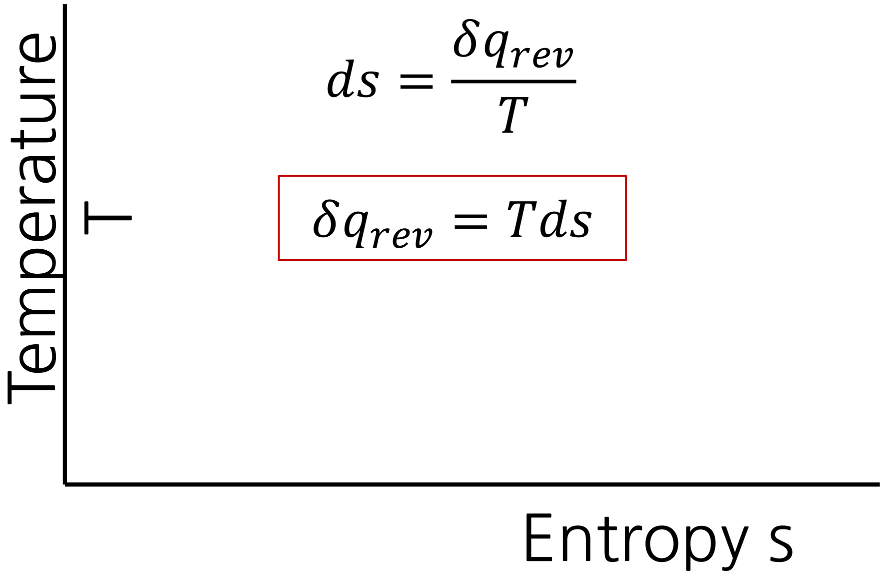
Thermodynamic cycles

Carnot cycle on T-s diagram



$$\boxed{\delta w_{rev} = -P dv}$$



$$ds = \frac{\delta q_{rev}}{T}$$

$$\boxed{\delta q_{rev} = T ds}$$

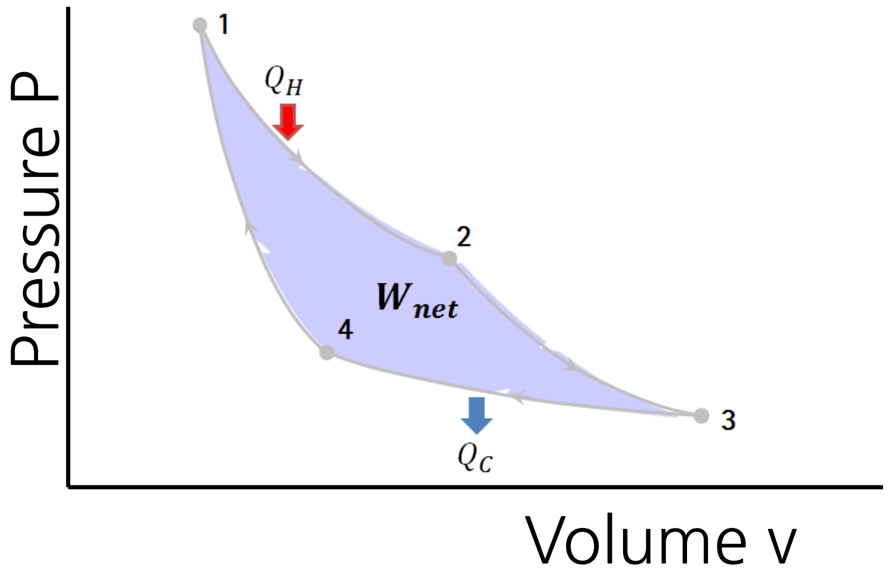
1→2 Isothermal Expansion at T_H

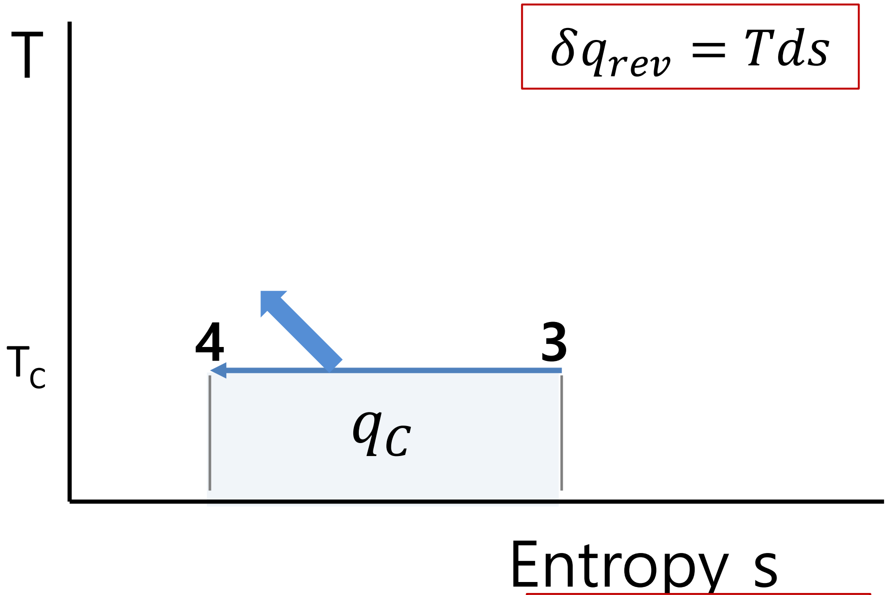
2→3 Adiabatic Expansion T_H→T_C

3→4 Isothermal Compression at T_C

4→1 Adiabatic Compression T_C→T_H

Carnot cycle on T-s diagram

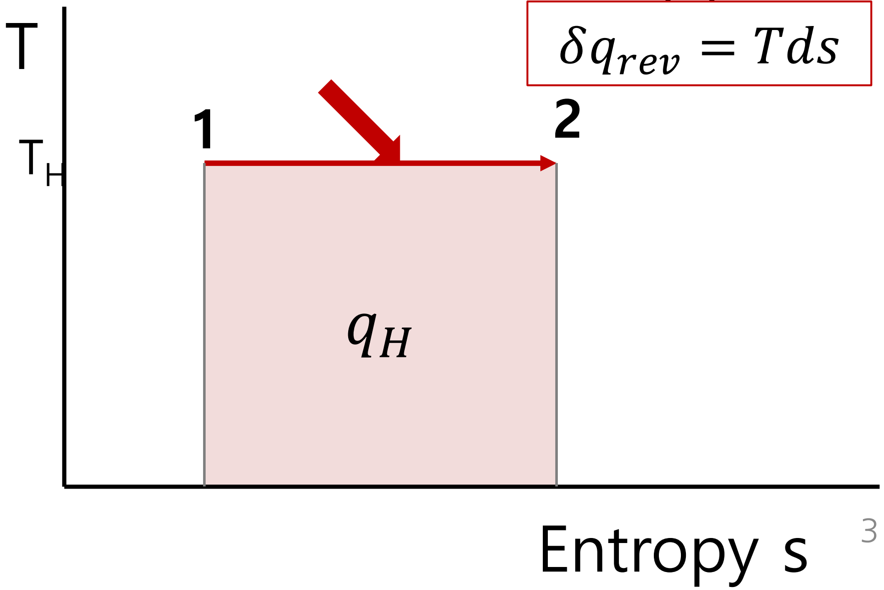



$$\delta q_{rev} = Tds$$

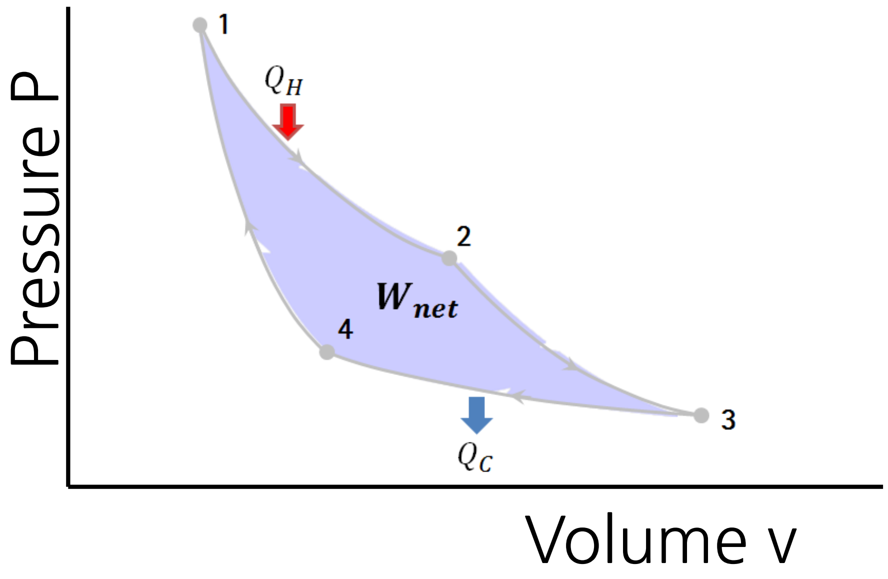
Isothermal (ΔT=0)

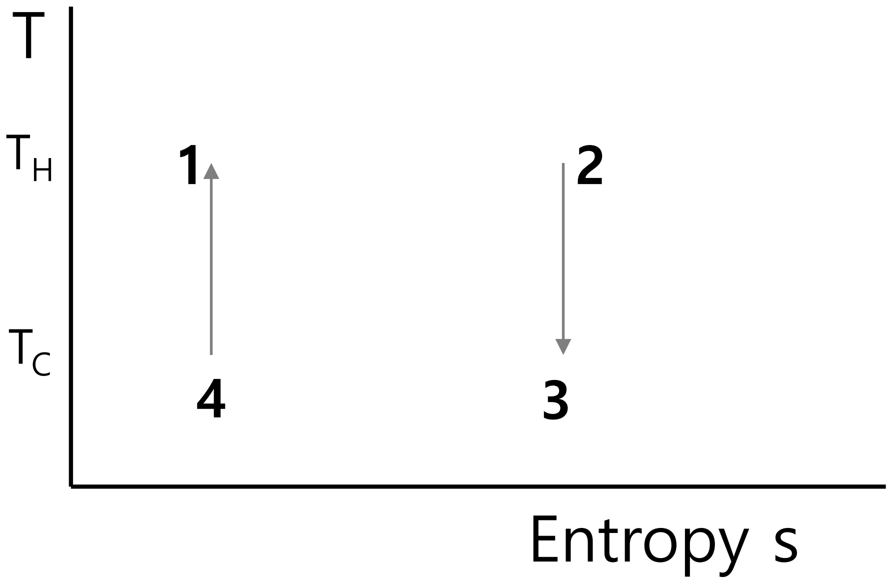
1→2 Isothermal Expansion at T_H

3→4 Isothermal Compression at T_C


$$\delta q_{rev} = Tds$$

Carnot cycle on T-s diagram





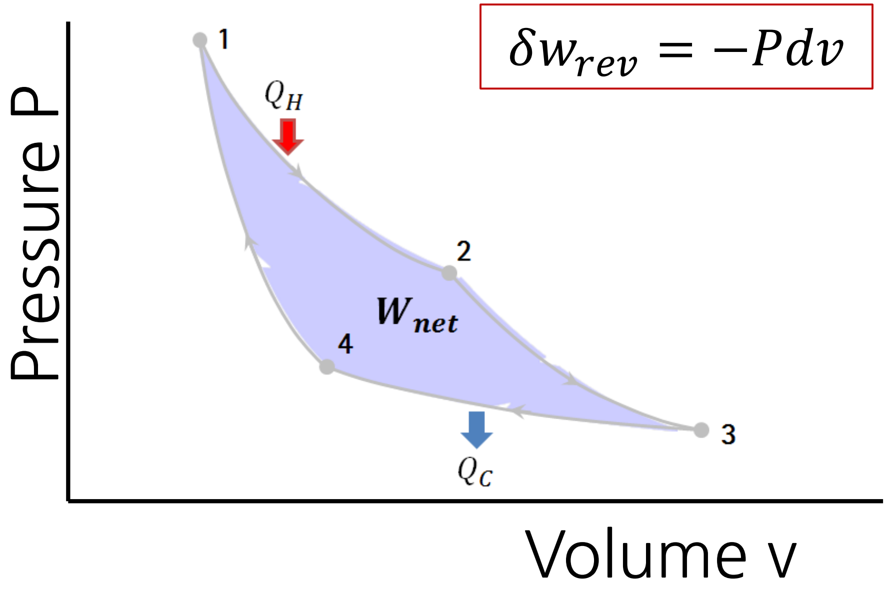
Adiabatic and reversible → isentropic

(q_{rev}=0→Δs=0)

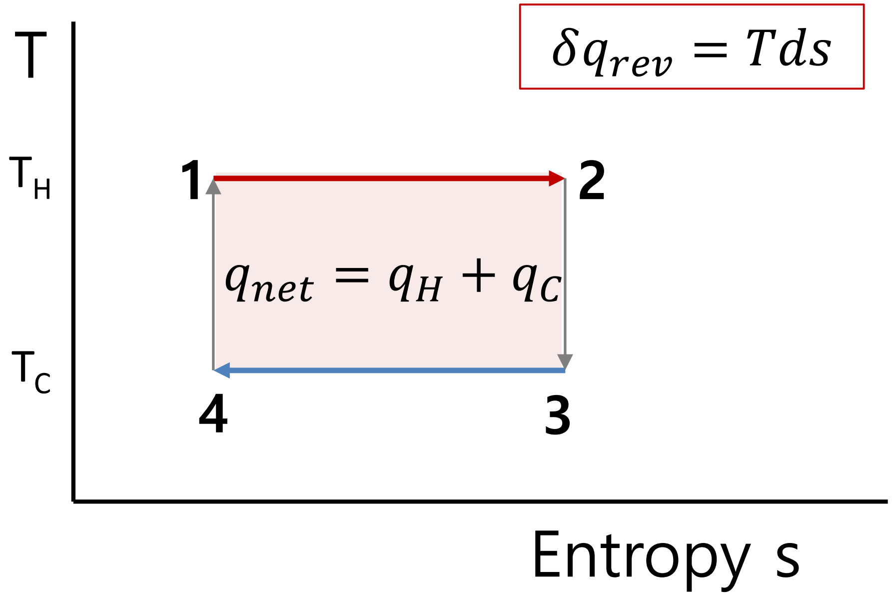
2→3 Adiabatic Expansion T_H→T_C

4→1 Adiabatic Compression T_C→T_H

Carnot cycle on T-s diagram



$$\delta w_{rev} = -Pdv$$

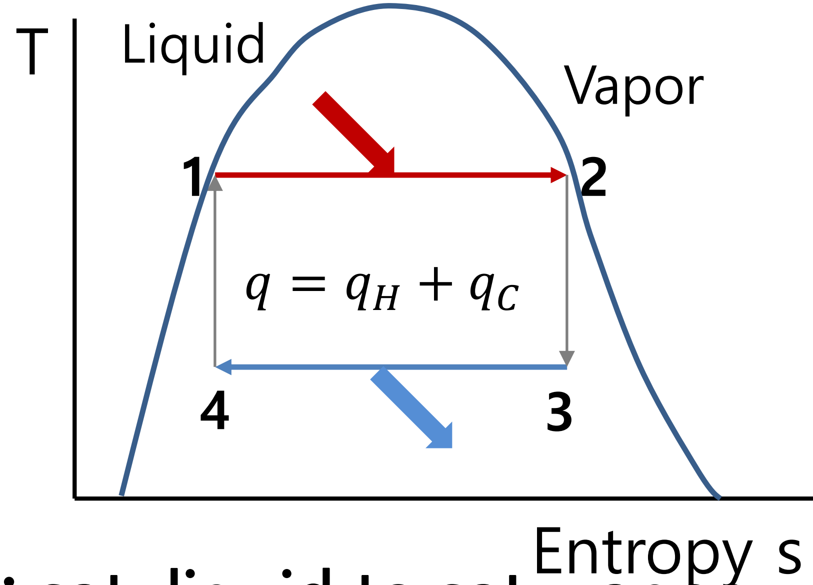


$$\delta q_{rev} = Tds$$

$$q_{net} = q_H + q_C$$

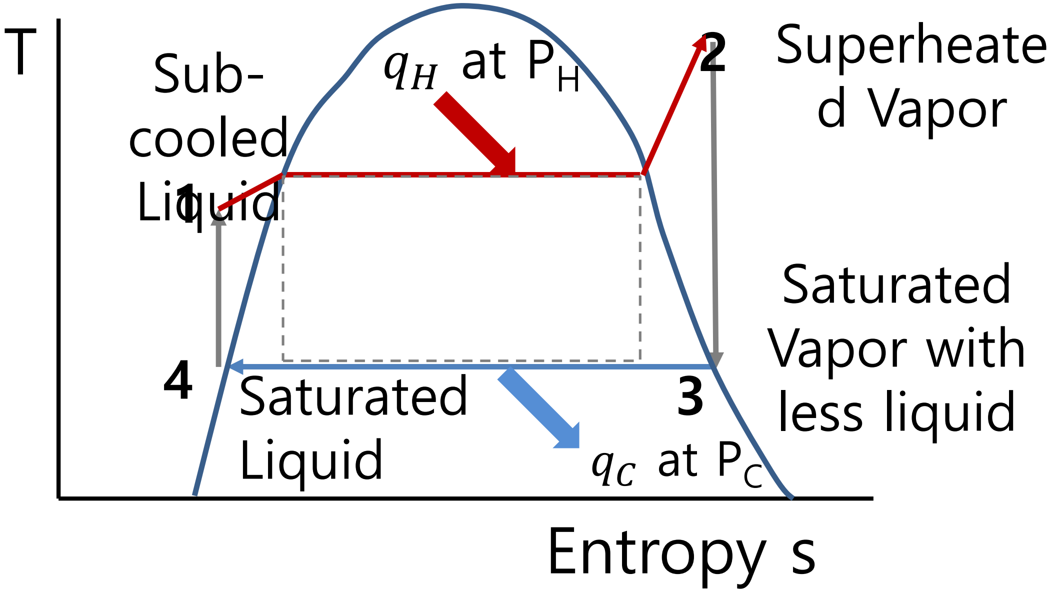
1→2 Isothermal Expansion at T_H
2→3 Adiabatic Expansion $T_H \rightarrow T_C$
3→4 Isothermal Compression at T_C
4→1 Adiabatic Compression $T_C \rightarrow T_H$

Practical problems of Carnot cycle



- 1→2 boiler: sat. liquid to sat. vapor
- 2→3 turbine: maybe OK but large amount of liquid flowing into the turbine can cause physical damage
- 3→4 condenser: how to stop at 4?
- 4→1 compressor: how to compress L/G mixture?

Rankine cycle



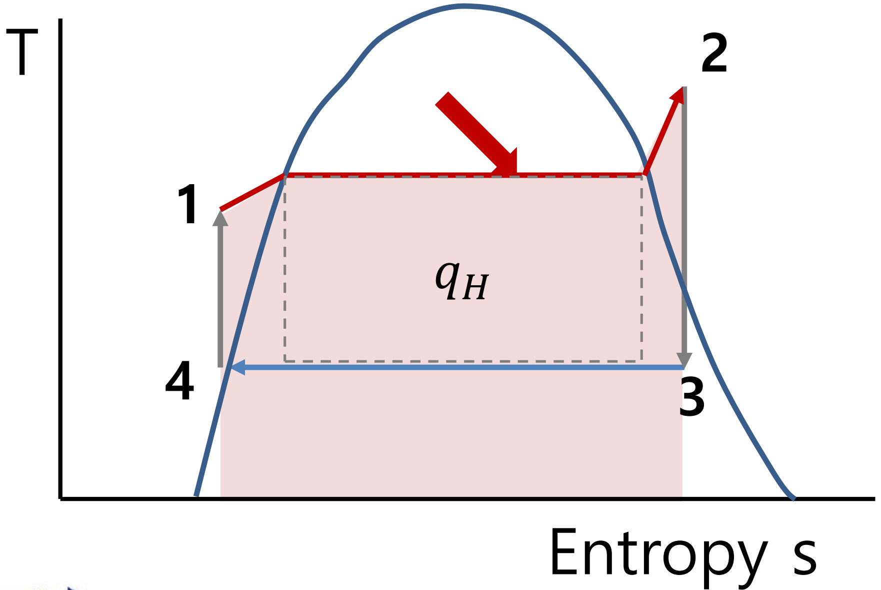
William JM Rankine (1820 -1872)

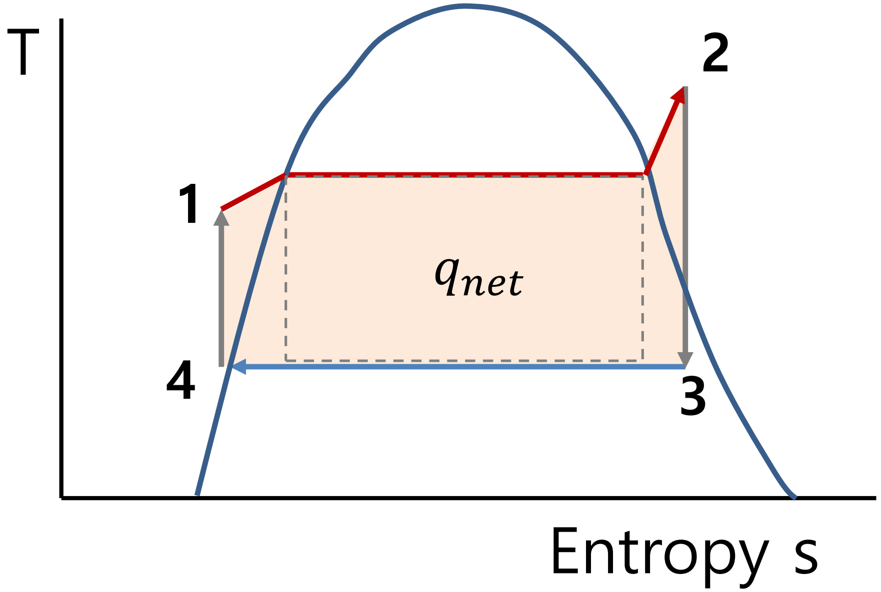
- 1→2 Isobaric expansion at P_H (T change): boiler
- 2→3 Adiabatic expansion: turbine
- 3→4 Isobaric and isothermal compression:
- 4→1 Adiabatic compression: pump (for 100% liquid)

http://en.wikipedia.org/wiki/Rankine_cycle

Efficiency of Rankine cycle

- $\Delta u_{cycle} = q_{net} + w_{net}$
- $\eta = \dfrac{|w_{net}|}{|q_H|} = \dfrac{|q_{net}|}{|q_H|}$





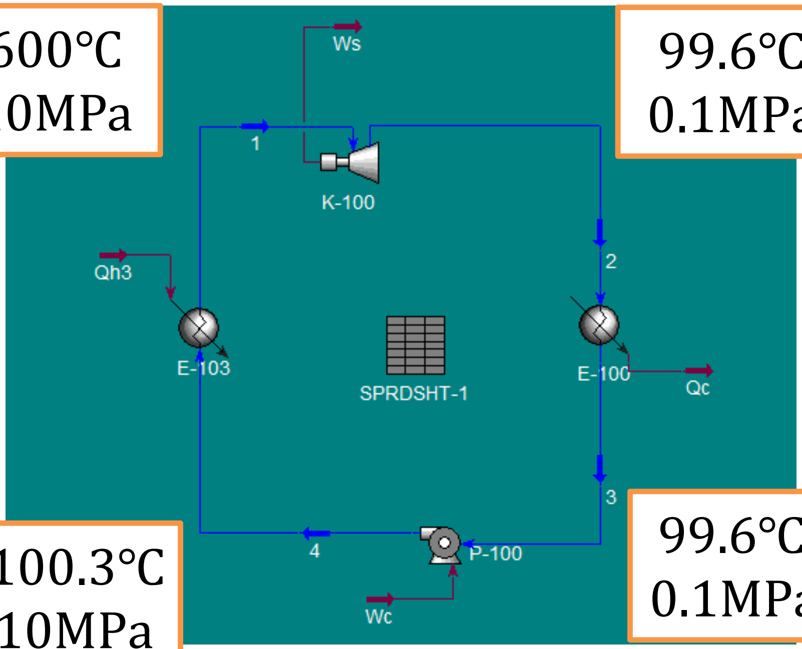
Ideal Rankine cycle example 3.14

- **Ideal Rankine cycle**

(100% efficiency turbine and pump)

Superheated steam

v.f. 0.924



600℃
10MPa

99.6℃
0.1MPa

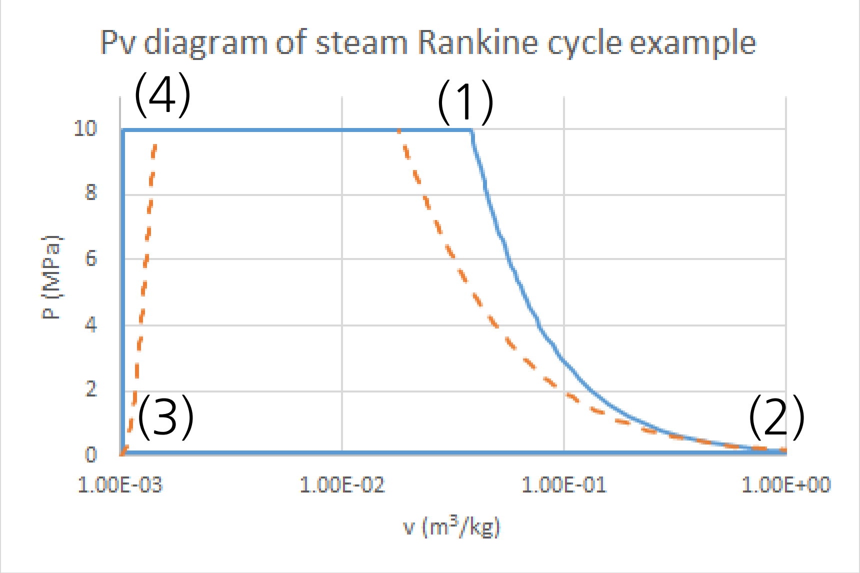
100.3℃
10MPa

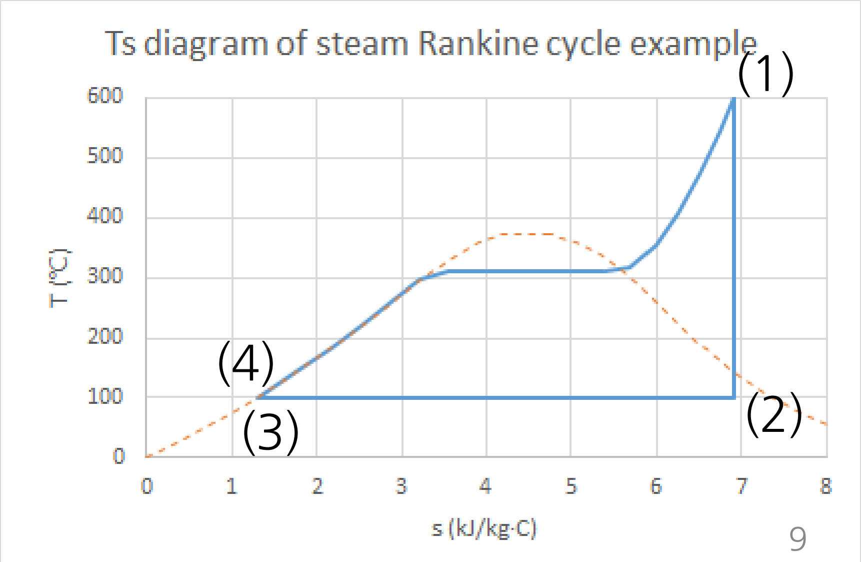
99.6℃
0.1MPa

Subcooled water

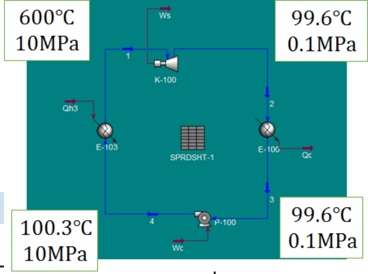
Saturated water

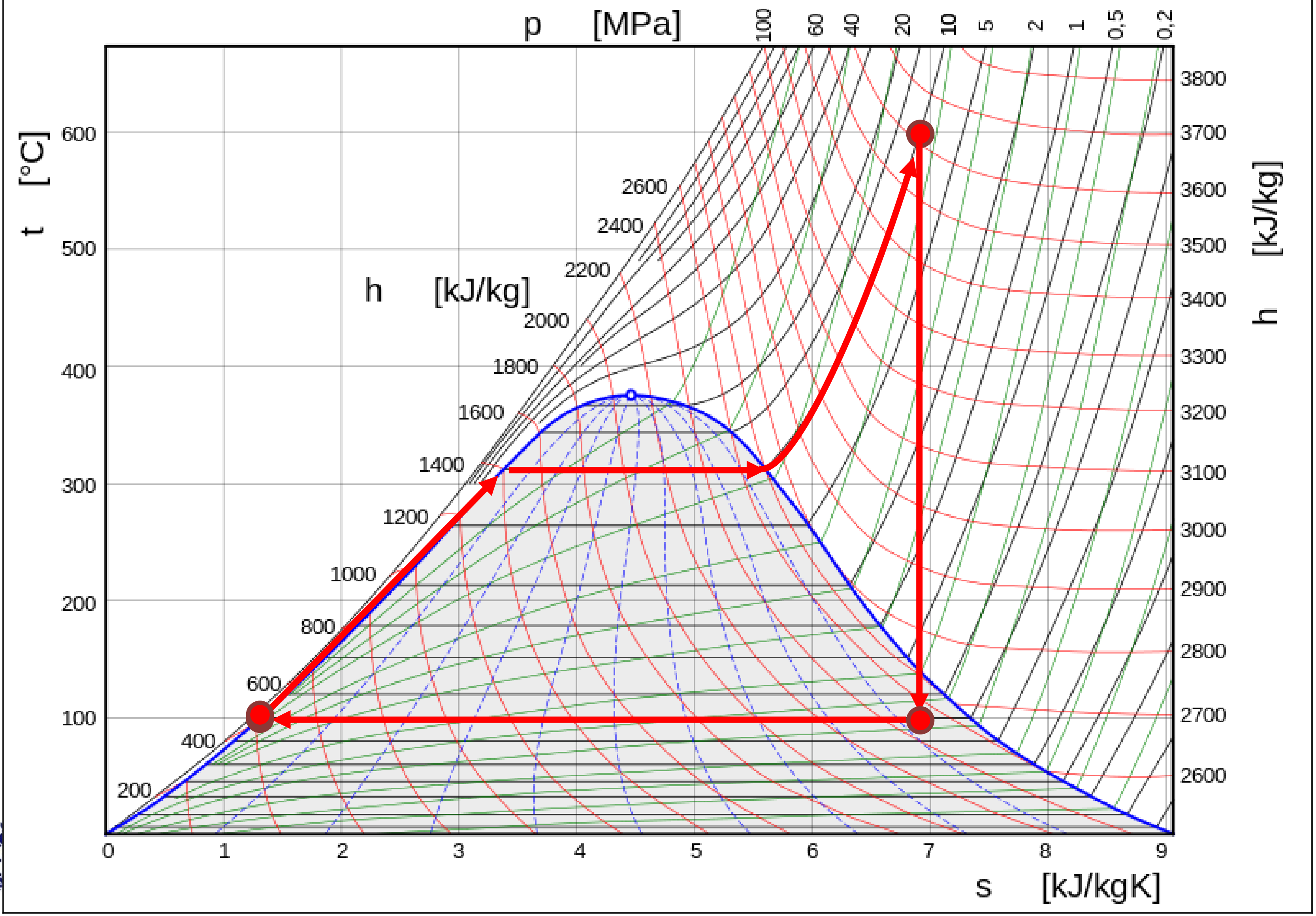
$$\eta_{Rankine} = \frac{|w|}{q_H} = \frac{1108}{3196} = 34.7\%$$





Ts diagram


600℃
10MPa
99.6℃
0.1MPa
Ws
1
K-100
Qh3
E-103
SPRDSHT-1
2
E-100
Qc
3
4
P-100
Wc
100.3℃
10MPa
99.6℃
0.1MPa

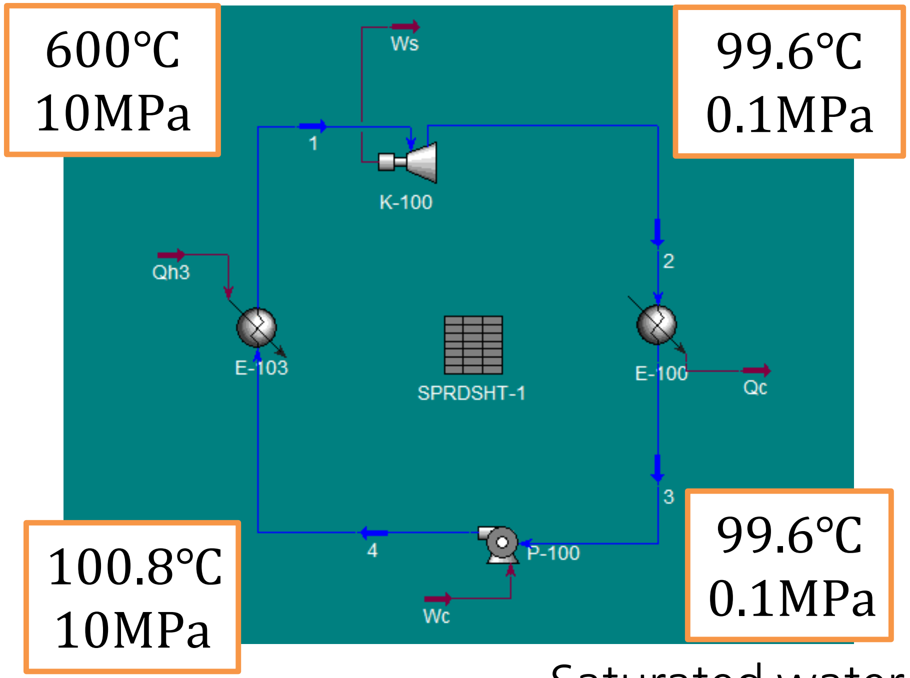

p [MPa]
100
60
40
20
10
5
2
1
0,5
0,2
t [°C]
600
500
400
300
200
100
h [kJ/kg]
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
3800
3700
3600
3500
3400
3300
3200
3100
3000
2900
2800
2700
2600
h [kJ/kg]
0
1
2
3
4
5
6
7
8
9
s [kJ/kgK]

Real Rankine cycle example 3.15

- Rankine cycle with 85% efficiency turbine and pump

Superheated steam

v.f. 0.999



600°C
10MPa

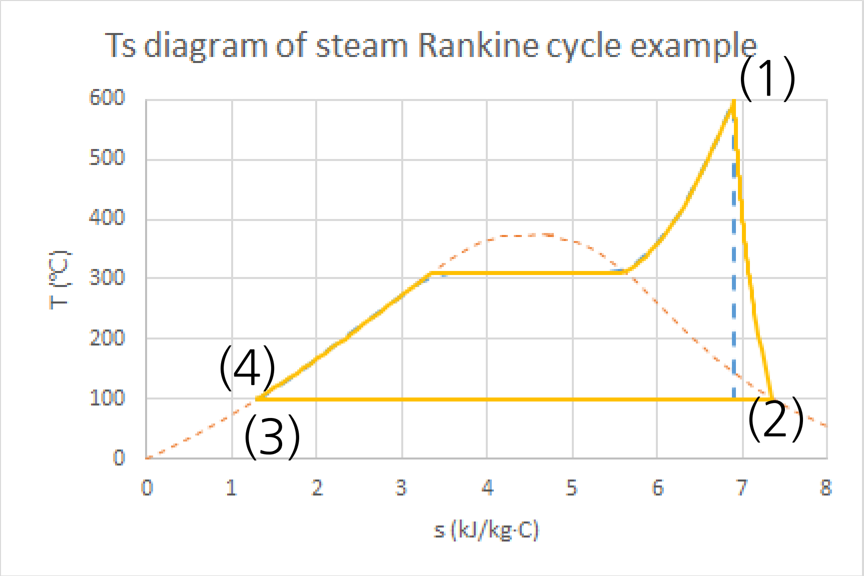
99.6°C
0.1MPa

100.8°C
10MPa

99.6°C
0.1MPa

Subcooled water

Saturated water



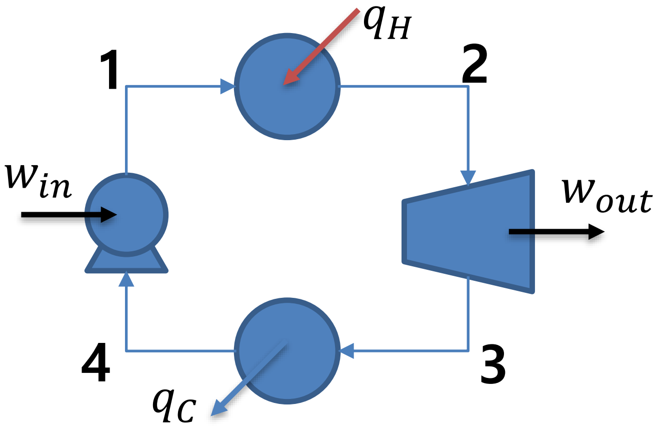
$$\eta_{Rankine} = \frac{|w|}{q_H} = \frac{1108}{3196} = 34.7\%$$

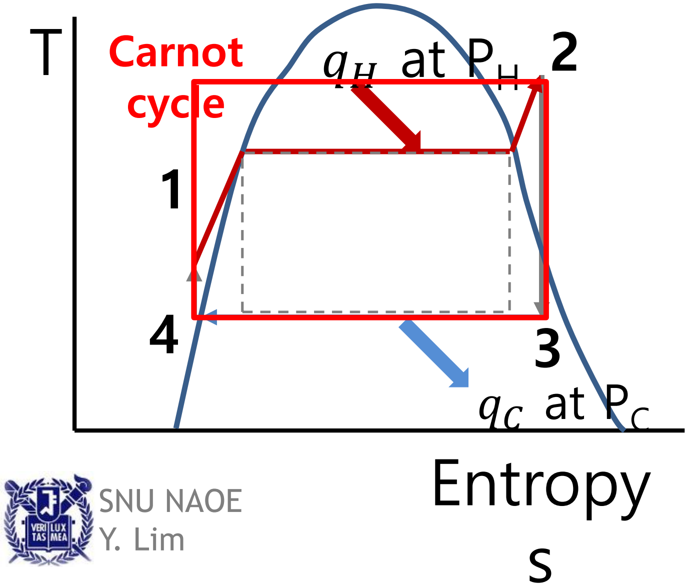
⇩

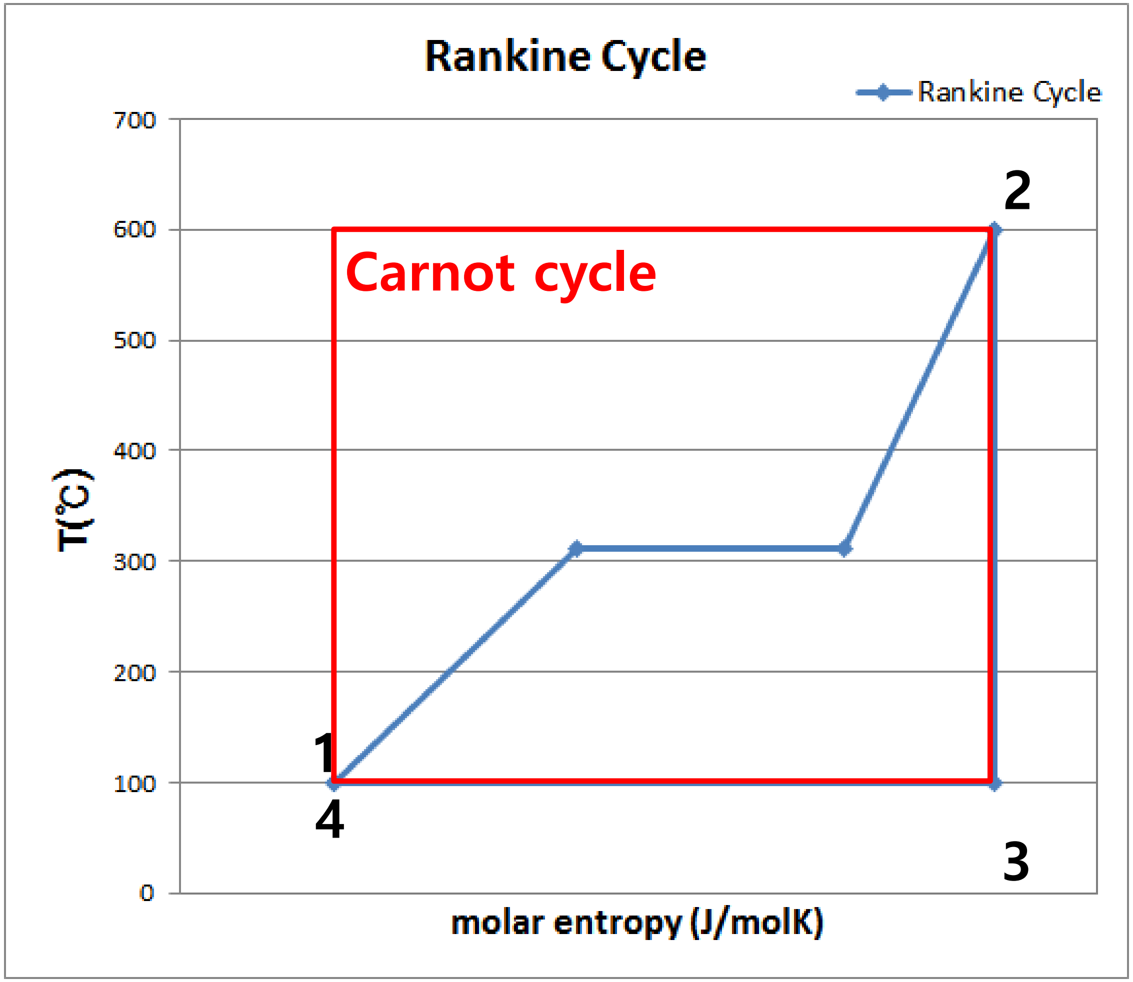
$$\eta_{Rankine} = \frac{|w|}{q_H} = \frac{938.5}{3194} = 29.4\%$$

Carnot cycle and Rankine cycle

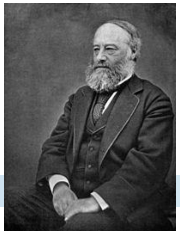
- **Ex 3.14**



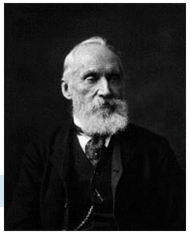




Joule-Thomson effect(expansion)

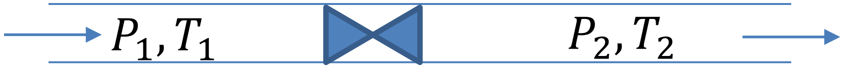


JP Joule
(1818-1889)



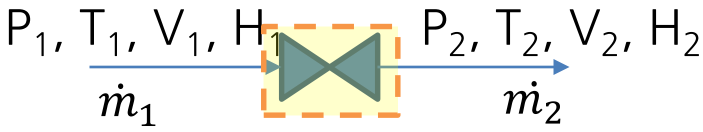
W Thomson
(Lord Kelvin)
(1824-1907)

- How does the temperature of gas change when it is forced through a valve or porous plug while kept insulated so that no heat is exchanged with the environment?



(throttling process or Joule-Thomson process)

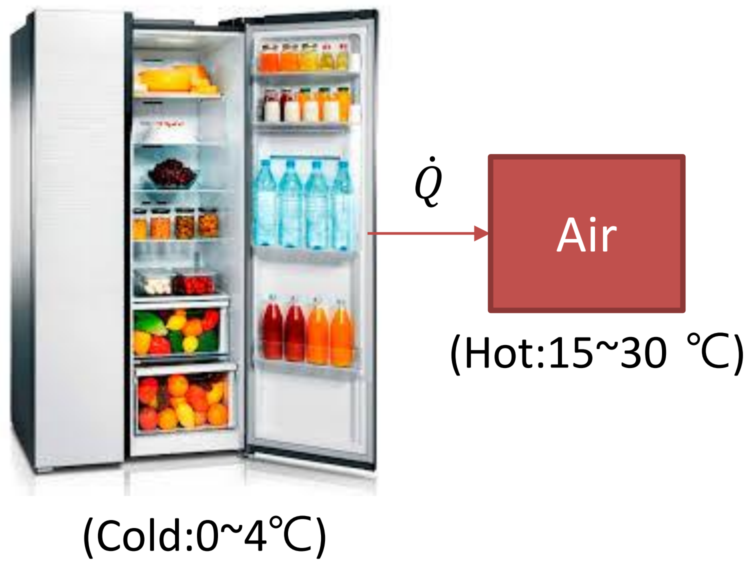
JT process ≈ isenthalpic process



(Assume steady-state, KE&PE small, adiabatic)

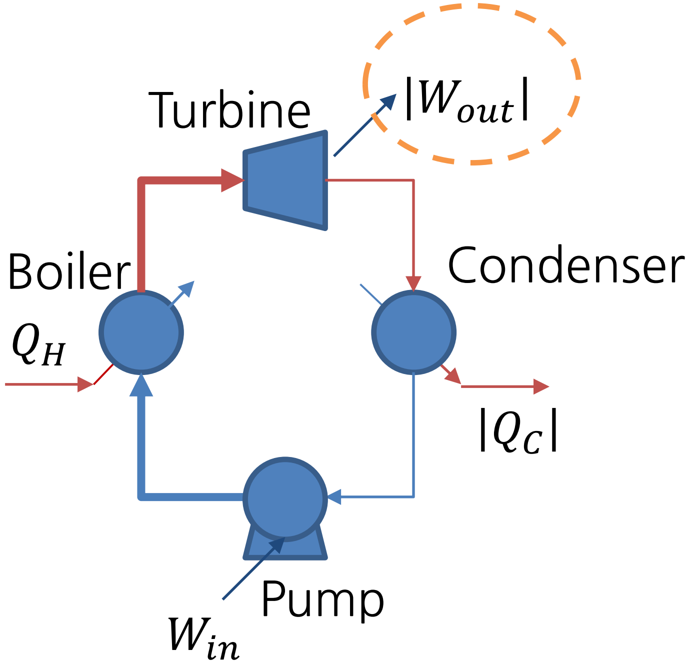
- **Energy Balance (1st law, Open system)**
  - $\frac{dU}{dt} = \dot{Q} + \dot{W}_s + \sum_{in} \dot{m}_i h_i - \sum_{out} \dot{m}_o h_o$
  - Since the gas spends so little time in the valve, there is no time for heat transfer. Since there is no component, the shaft work is near zero. If the kinetic energy difference is negligible, for st-st,
  - $0 = 0 + 0 + \dot{m}_1 h_1 - \dot{m}_2 h_2$
  - $h_1 = h_2$ (isenthalpic)

Refrigeration cycle



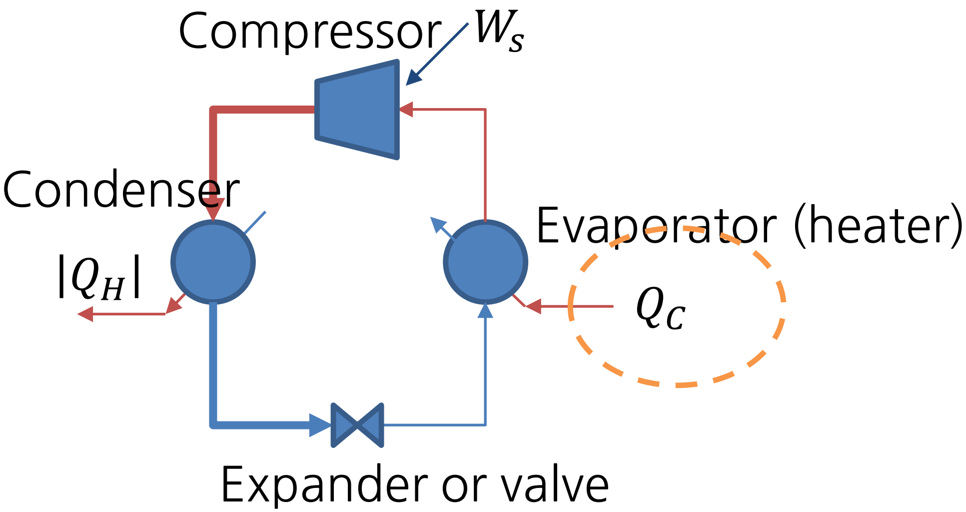
Refrigeration process

- Carnot cycle



$$efficiency\ \eta \equiv \frac{|W|}{|Q_H|}$$

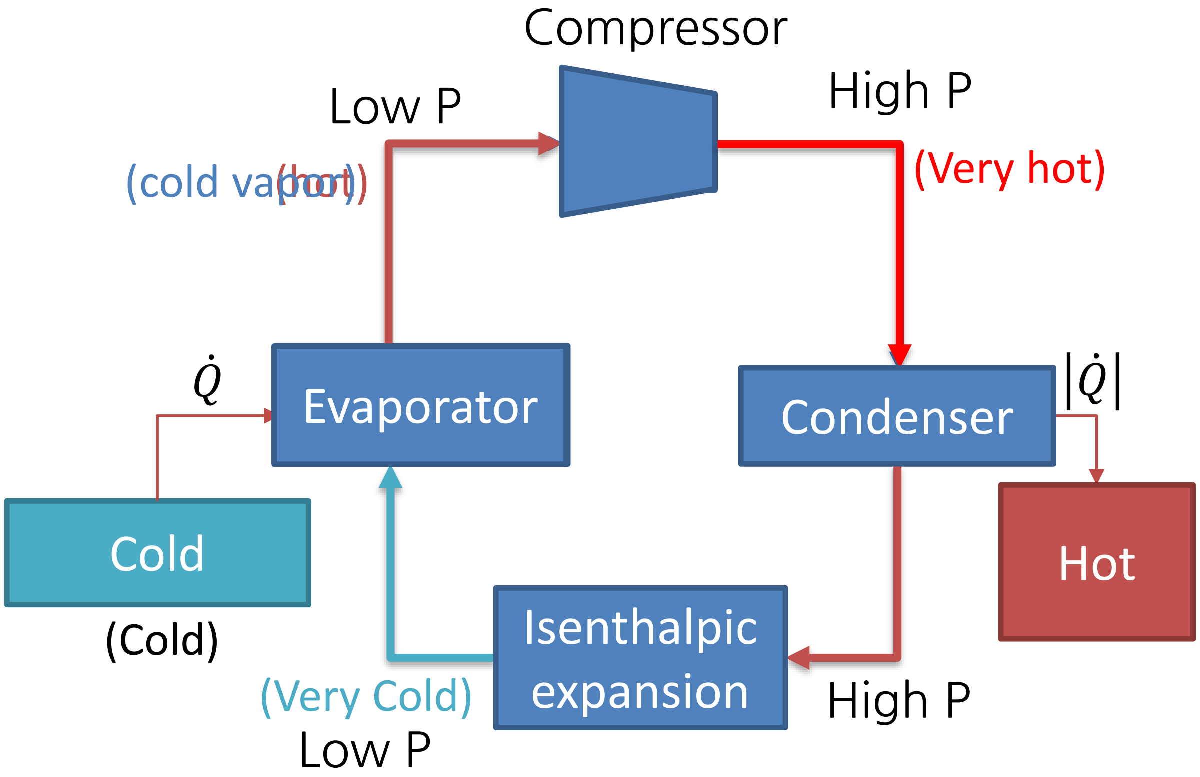
Refrigeration cycle

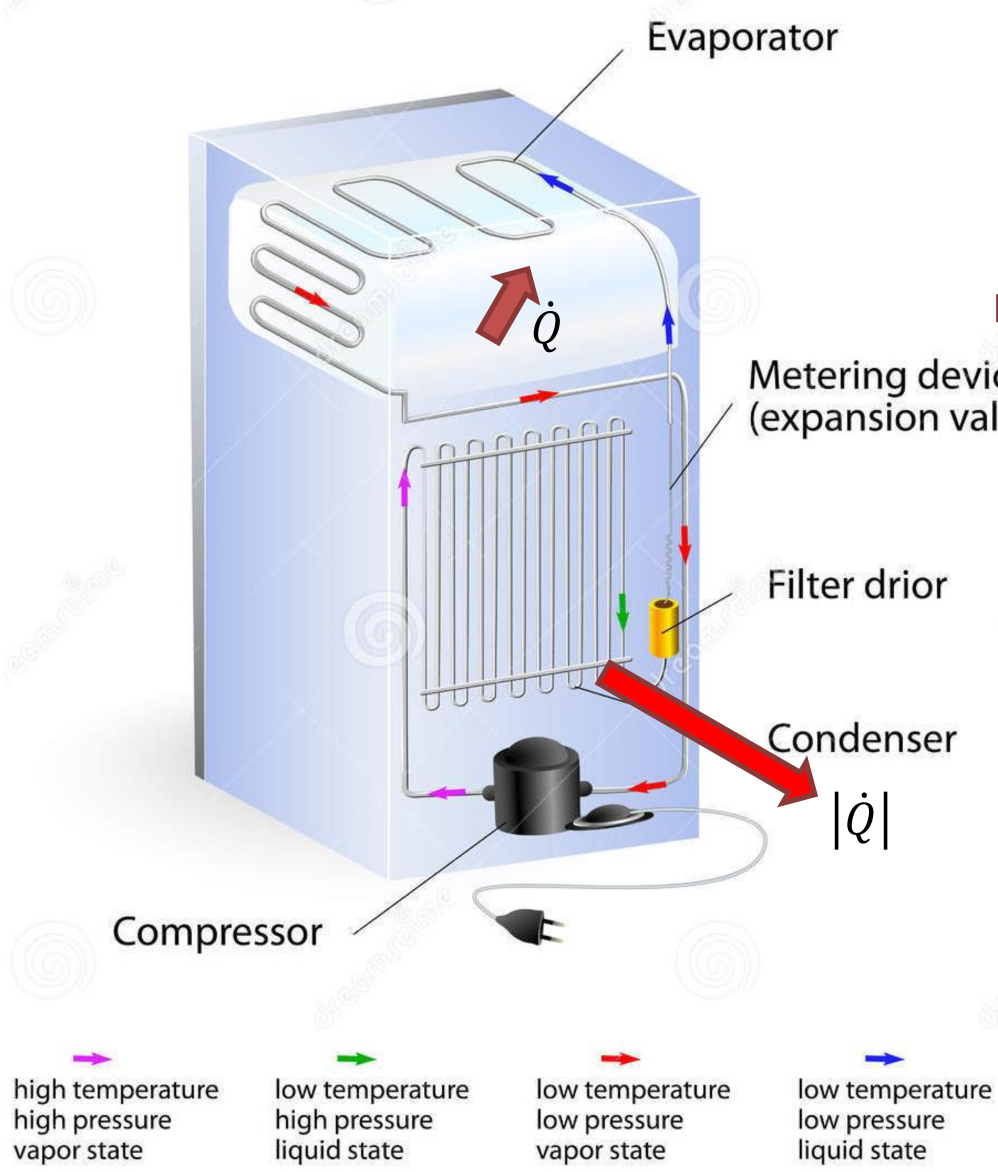


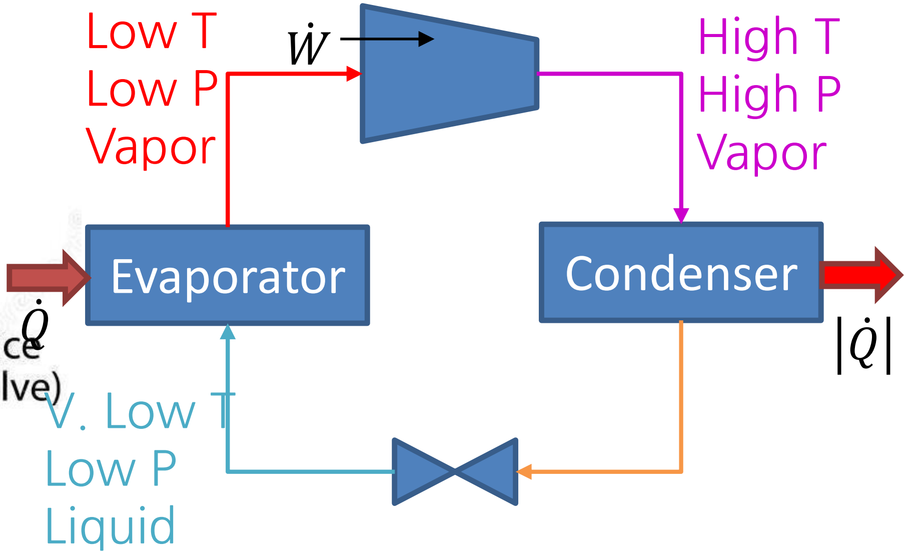
$$coefficient\ of\ performance$$

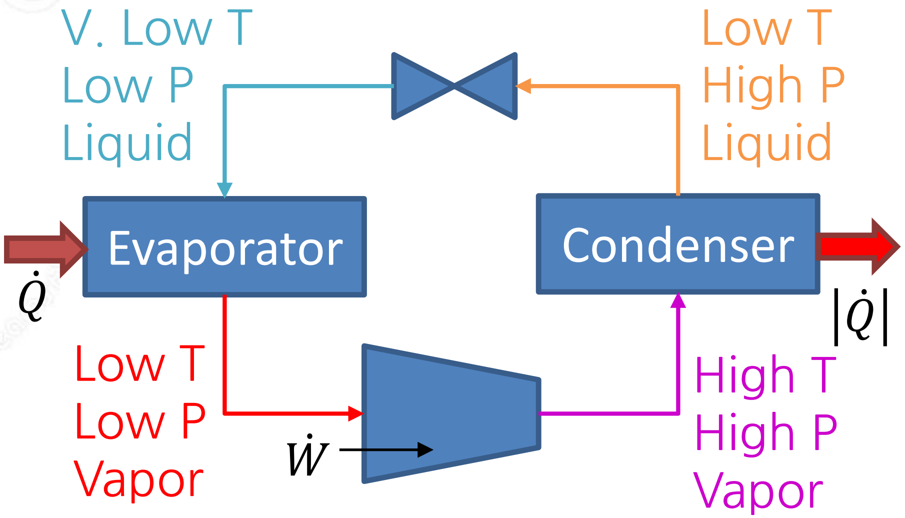
$$\mathrm{COP} = \frac{Q_C}{W}$$

Refrigeration cycle

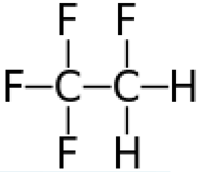



Evaporator
$\dot{Q}$
Metering device
(expansion valve)
Filter drior
Condenser
$|\dot{Q}|$
Compressor
high temperature high pressure vapor state
low temperature high pressure liquid state
low temperature low pressure vapor state
low temperature low pressure liquid state


Low T
Low P
Vapor
$\dot{W}$
High T
High P
Vapor
Evaporator
Condenser
$\dot{Q}$
$|\dot{Q}|$
V. Low T
Low P
Liquid


V. Low T
Low P
Liquid
Low T
High P
Liquid
Evaporator
Condenser
$\dot{Q}$
$|\dot{Q}|$
Low T
Low P
Vapor
$\dot{W}$
High T
High P
Vapor

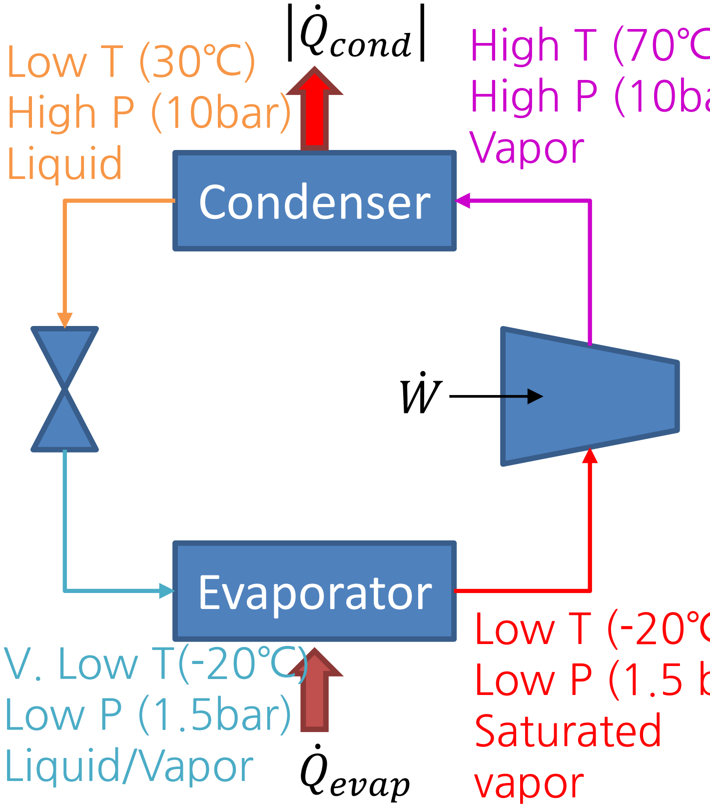
Example



1,1,1,2-Tetrafluoroethane

Boiling point of −26.3 °C at 1 atm

- R134a (Refrigerant 134a)



$|\dot{Q}_{cond}|$

Low T (30℃)
High P (10bar)
Liquid

High T (70℃)
High P (10bar)
Vapor

Condenser

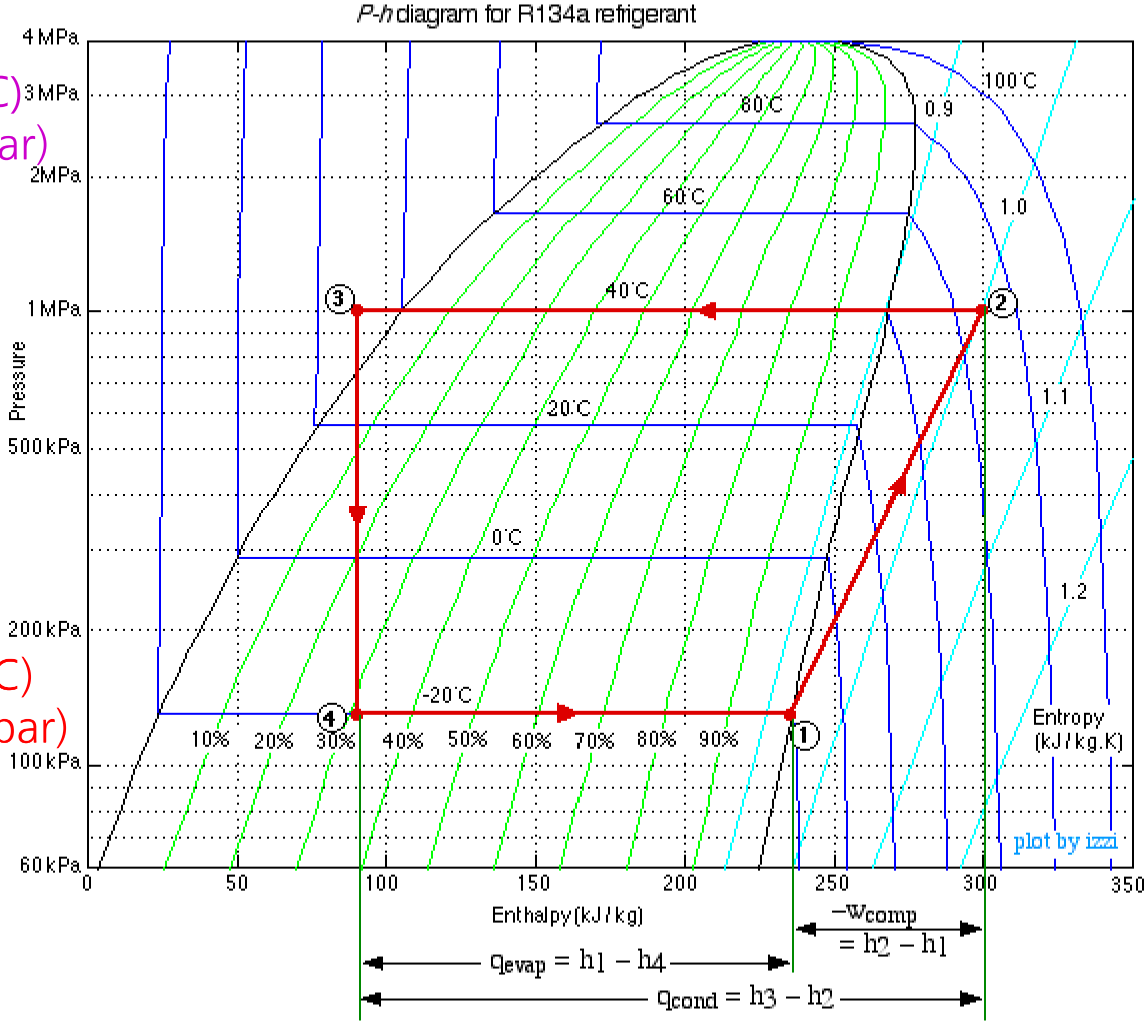
$\dot{W}$

Evaporator

V. Low T(-20℃)
Low P (1.5bar)
Liquid/Vapor

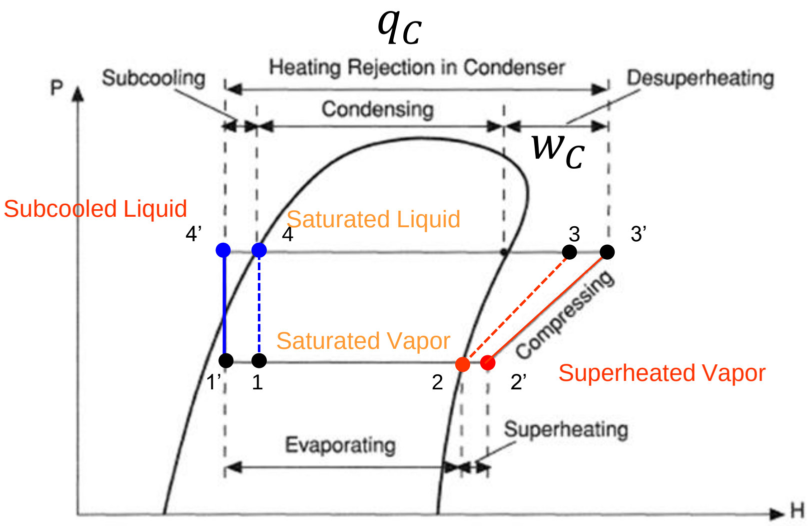
$\dot{Q}_{evap}$

Low T (-20℃)
Low P (1.5 bar)
Saturated
vapor



SNU NAOE
Y. Lim

Subcooling & Superheating

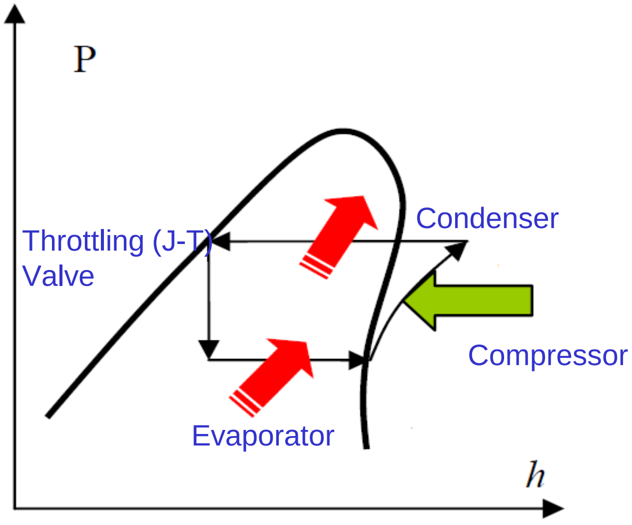


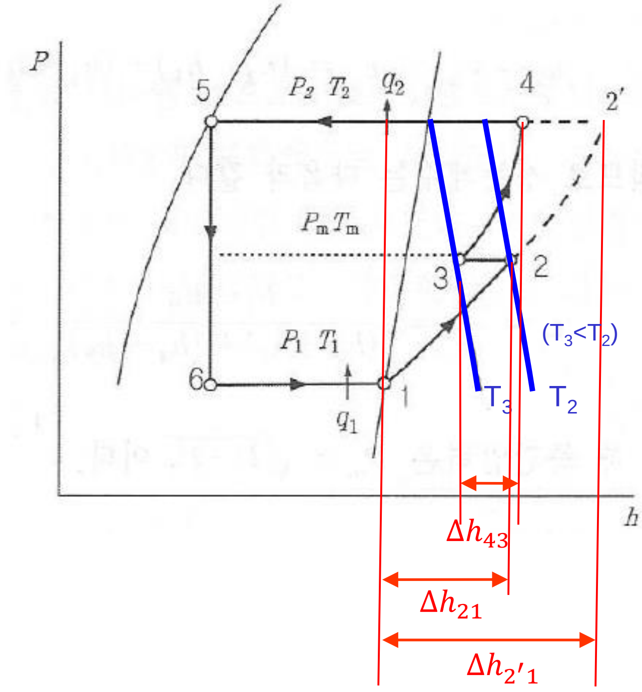
$$\therefore COP = \frac{\dot{Q}_C}{\dot{W}_c} = \frac{q_C}{w_C}$$

- Subcooling (Point 4→4')
- Superheating (Point 2→2')

Multi Compression

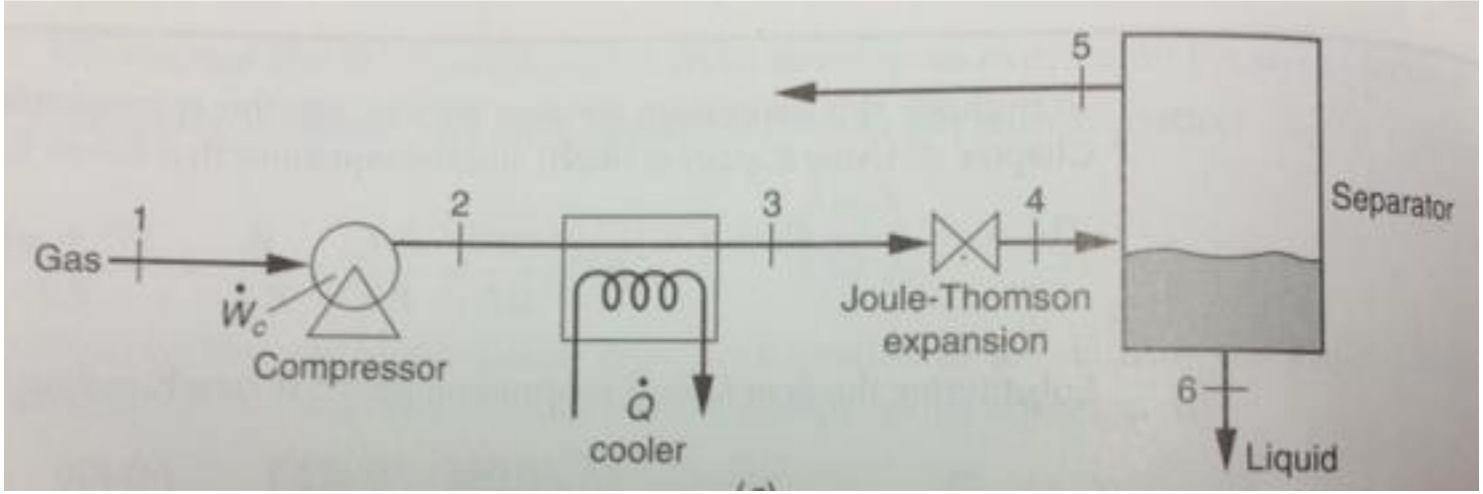
- Multi Compression
  - $\Delta h_{2'1} > \Delta h_{21} + \Delta h_{43}$

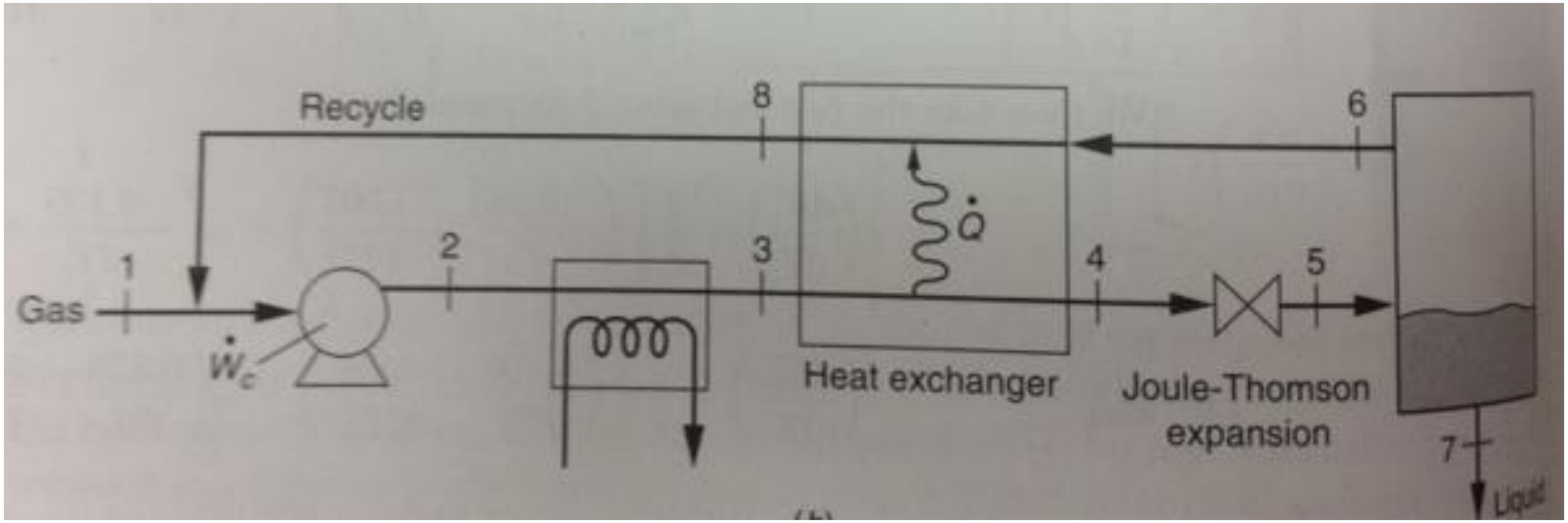




$w_C = \Delta h$

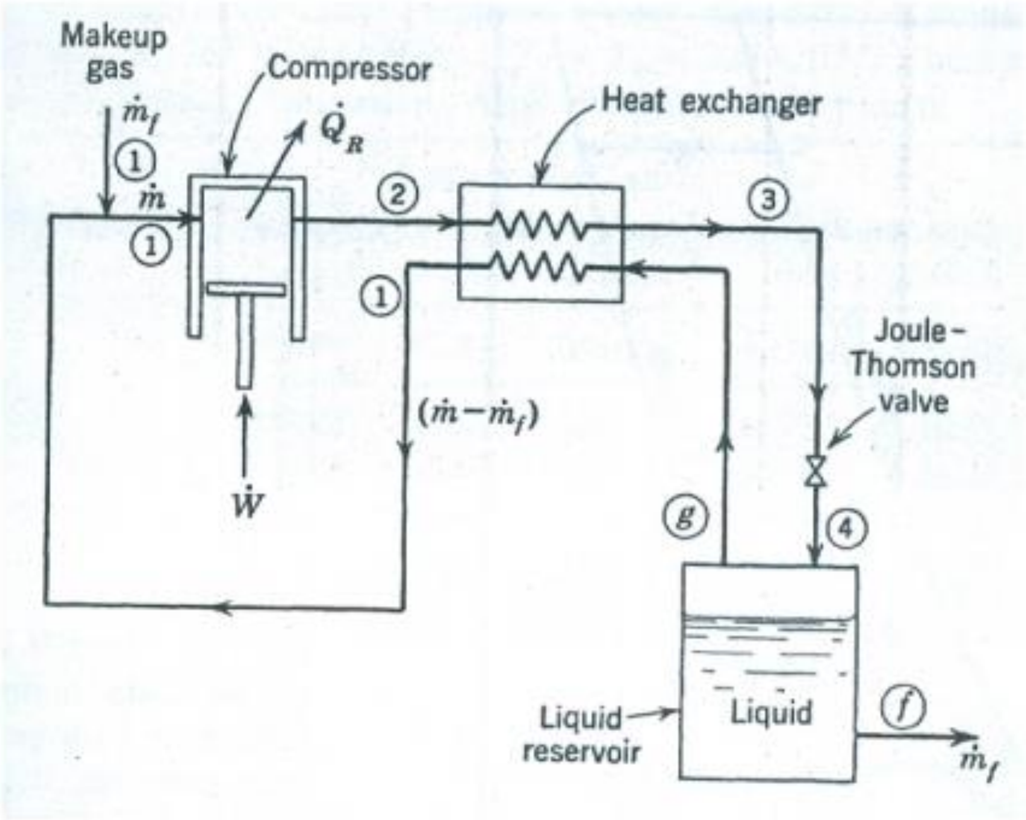
Simple liquefaction process

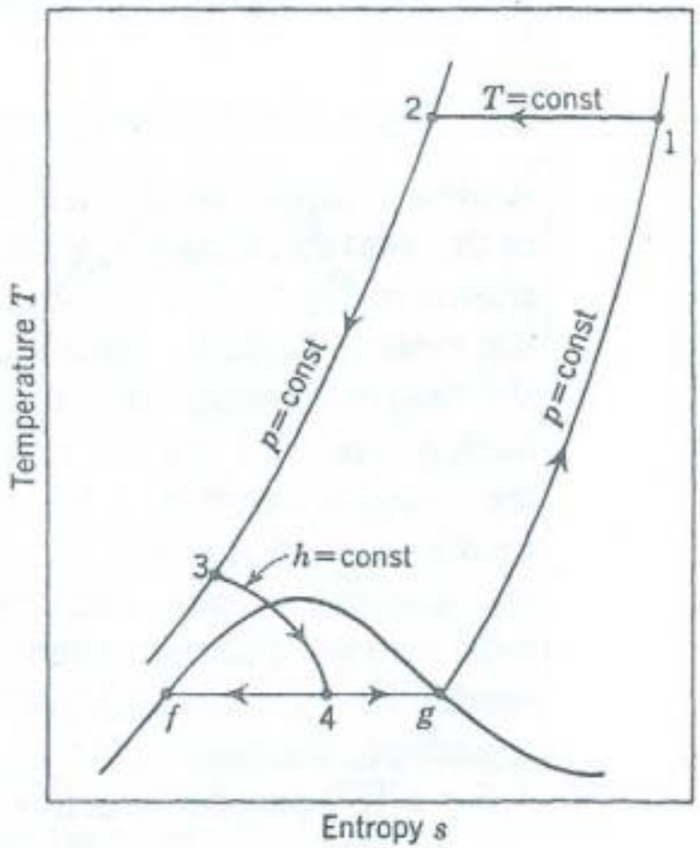




Linde-Hampson liquefaction process

- (1895)





http://ethesis.nitrkl.ac.in/1466/1/PROCESS_DESIGN.pdf

Example 3.16

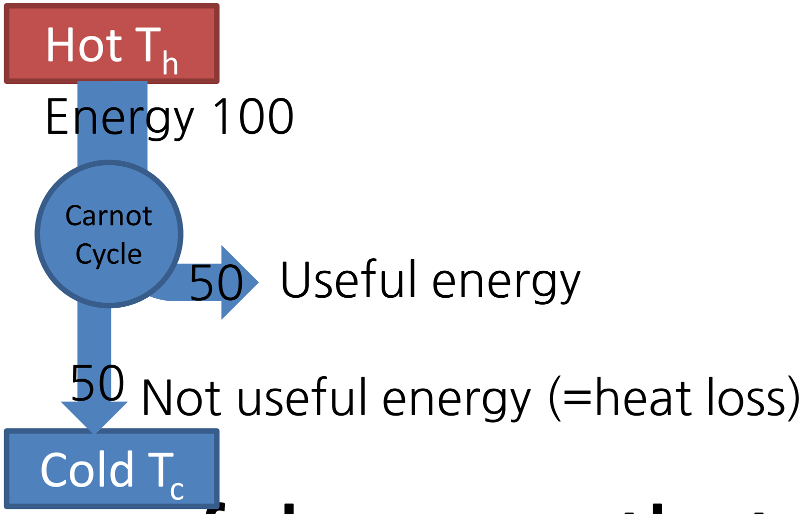
- n=? (0.73 mol/s in textbook)
- COP=? (3.22 in textbook)

PR							

Exergy

- Energy is always conserved, but not all that energy is available to do useful work.

Steam table	Internal energy u	Enthalpy h (kJ/kg)
P=100kPa, T=200℃	2658.0	2875.3
P=10MPa, T=325℃	2610.4	2809.0


Hot T_h

Energy 100

Carnot Cycle

50 Useful energy

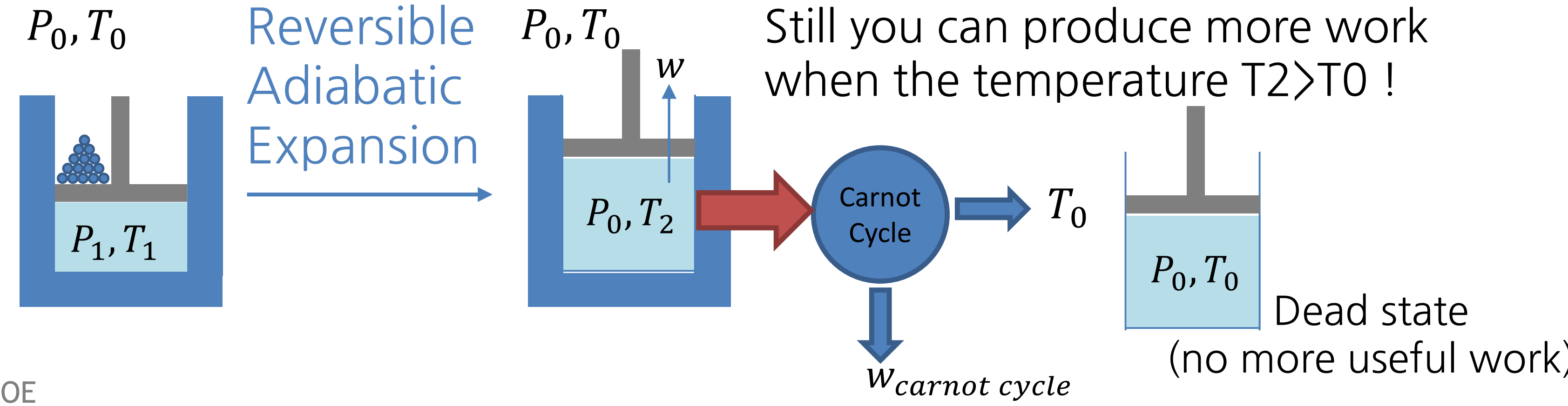
50 Not useful energy (=heat loss)

Cold T_c

- How can we define an useful energy that we can use? →Exergy

Exergy

- **Exergy**
  - Available energy to be used.
  - The maximum useful work possible during a process that brings the system into equilibrium with its surroundings.
  - The useful energy based on the surroundings condition as the reference.



Still you can produce more work when the temperature T2>T0 !

Dead state
(no more useful work

Exergy

- Exergy b at state 1 can be defined as:

$$b_1 \equiv (u_1 - u_0) + P_0(v_1 - v_0) - T_0(s_1 - s_0)$$

Available internal energy (comparing to the dead state)

Available PV work

Entropy loss or heat loss (or Available chemical energy)

- If the macroscopic kinetic energy and potential energy are not negligible:

$$b_1 = (u_1 - u_0) + P_0(v_1 - v_0) - T_0(s_1 - s_0) + \left(\frac{\bar{V}_1^2}{2} - \frac{\bar{V}_0^2}{2}\right) + g(z_1 - z_0)$$

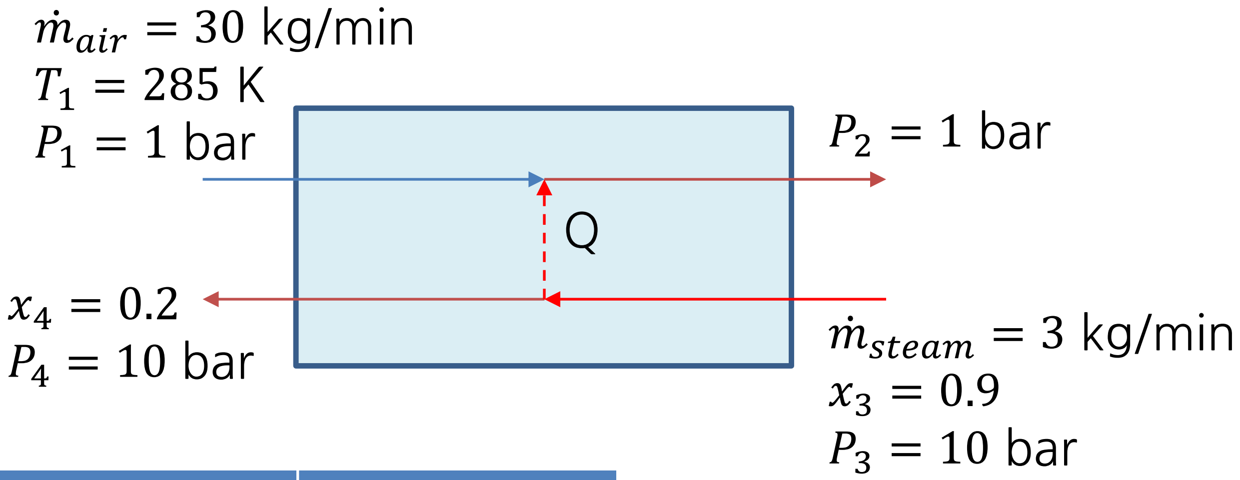
$$= (u_1 - u_0) + P_0(v_1 - v_0) - T_0(s_1 - s_0) + \frac{\bar{V}_1^2}{2} + gz_1$$

Exergy in an open system

$$
\begin{aligned}
b_1 &= (u_1 - u_0) + P_0(v_1 - v_0) - T_0(s_1 - s_0) + (P_1 - P_0)v_1 \\
&= (u_1 + P_1 v_1) - (u_0 + P_0 v_0) - T_0(s_1 - s_0) \\
&= (h_1 - h_0) - T_0(s_1 - s_0)
\end{aligned}
$$

– This exergy in an open system is called as "exthalpy b_f," but many people use just exergy for both meaning.

Example 3.18



$\dot{m}_{air} = 30$ kg/min
$T_1 = 285$ K
$P_1 = 1$ bar

$P_2 = 1$ bar

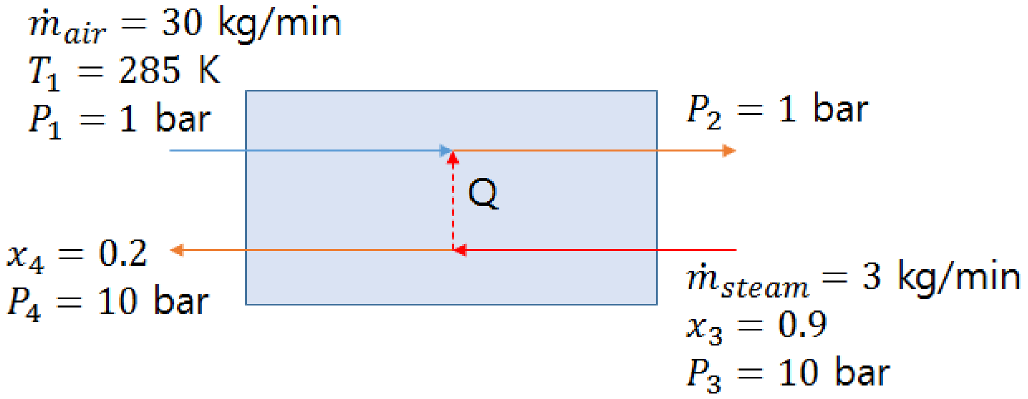
Q

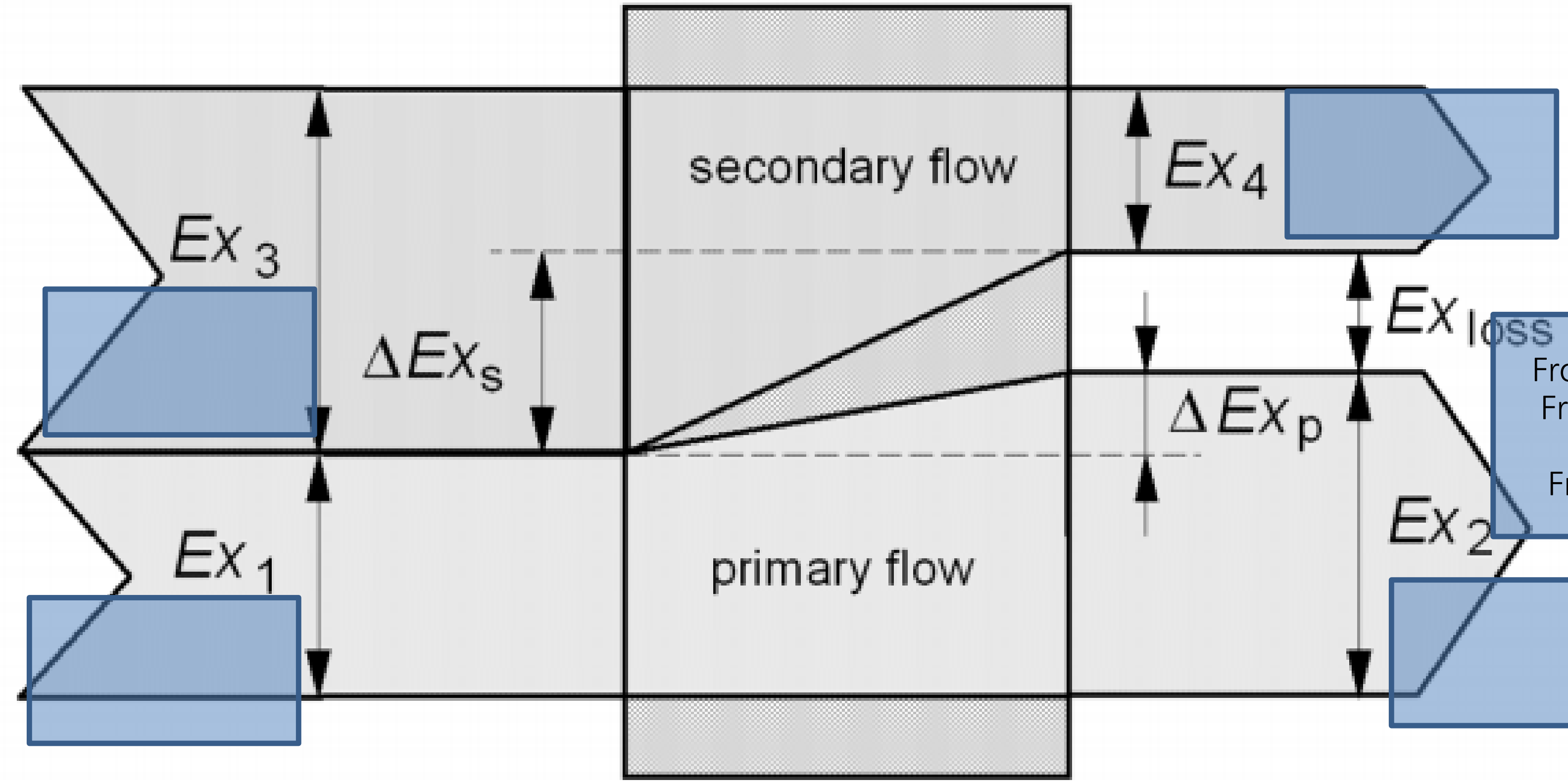
$x_4 = 0.2$
$P_4 = 10$ bar

$\dot{m}_{steam} = 3$ kg/min
$x_3 = 0.9$
$P_3 = 10$ bar

Ex 3.18 (exergy loss)	
814.4 kJ/min (SRK)	

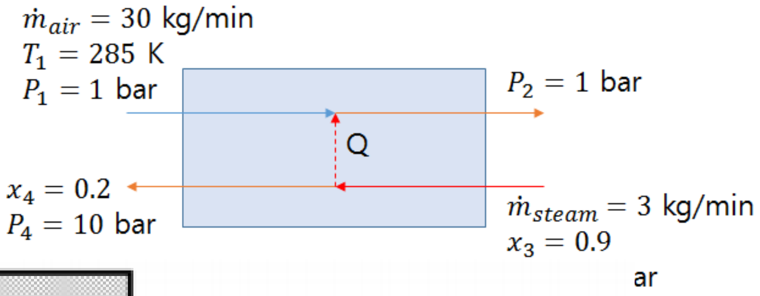
Example 3.18

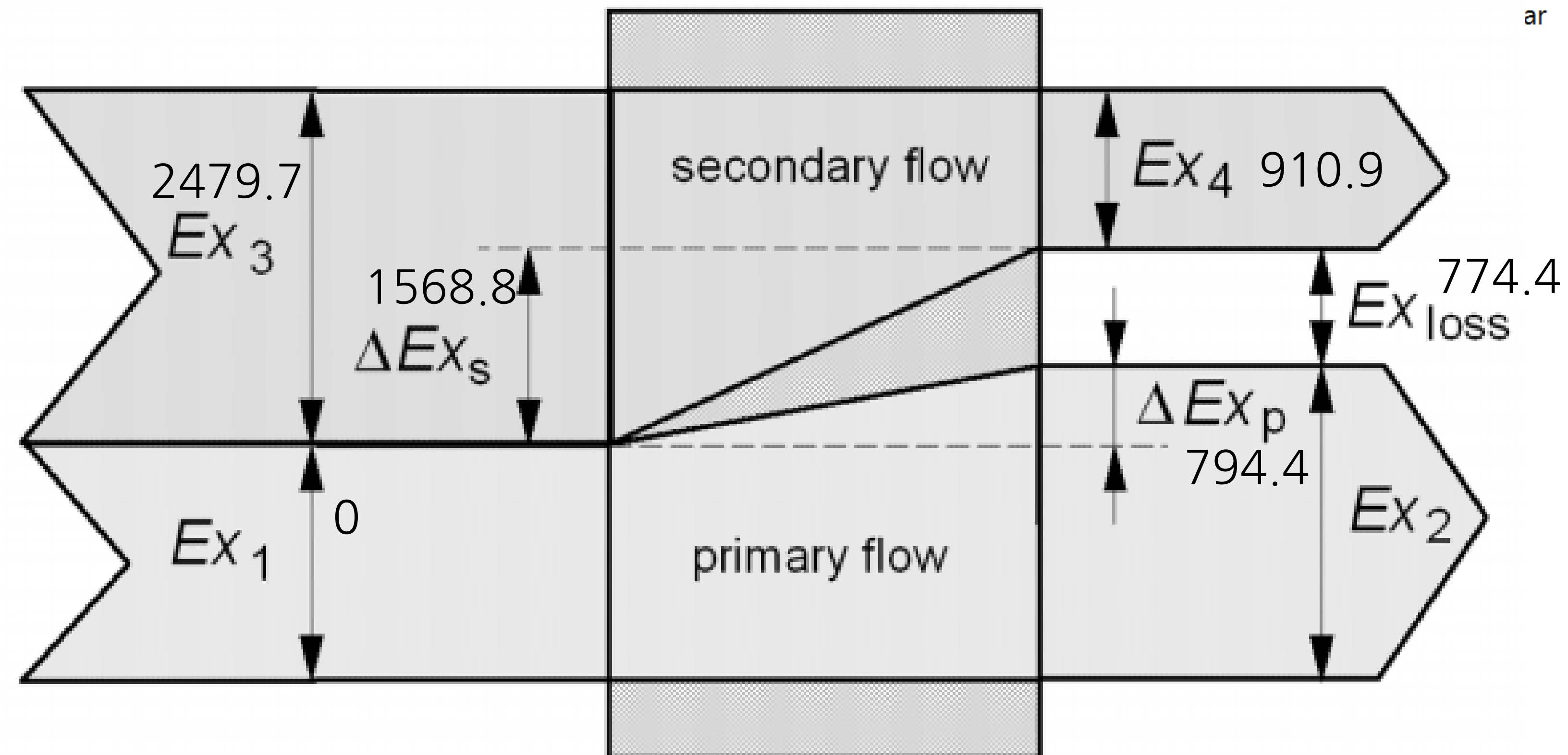


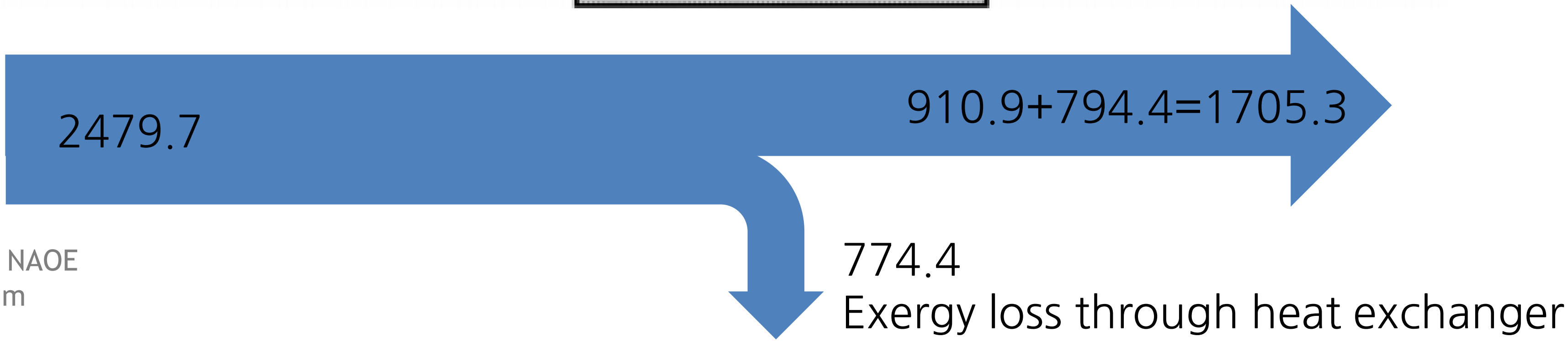


From h,s: -794 kJ/min
From ex: -809kJ/min
From h s:
From ex: -813/-839

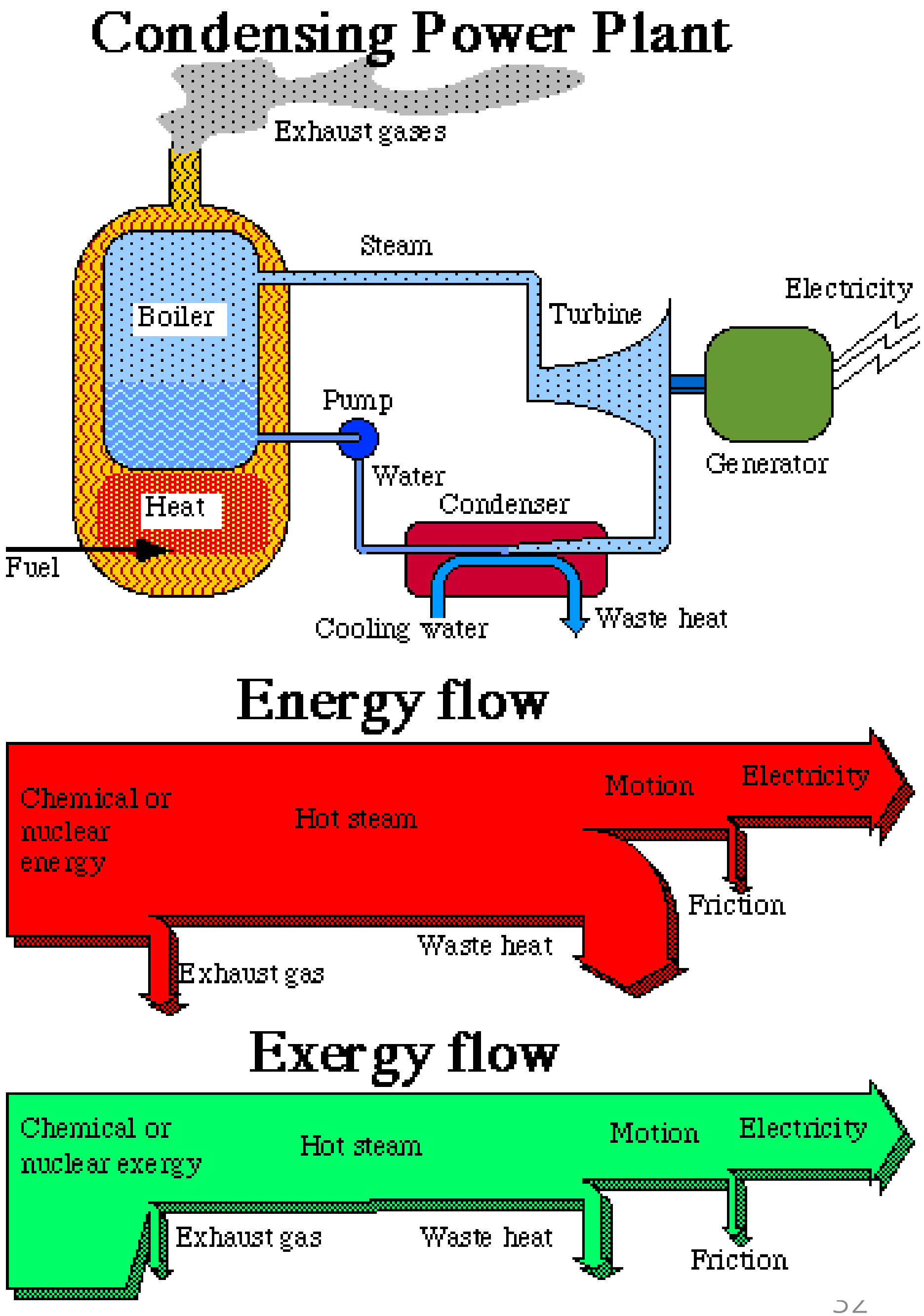
Exergy analysis







Exergy Analysis



http://exergy.se/goran/thesis/paper1/paper1.html