Thermodynamic process and cycle

SNU NAOE
Youngsub Lim

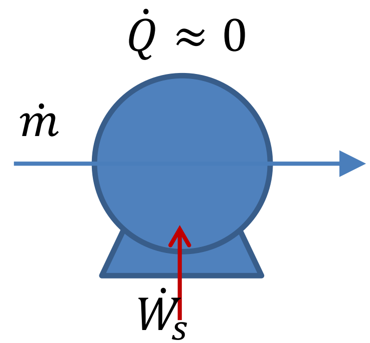
Efficiency

- $\dot{W}_s$ from energy balance is isentropic work.
- Real turbine or pump(compressor) is not reversible(isentropic)
- Use the efficiency

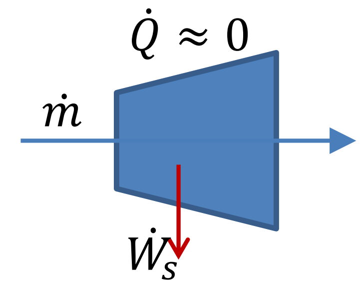
$$\mathbf{0 = \dot{Q} + \dot{W}_s - \dot{m}\Delta h}$$

$$\eta_{turbine} = \frac{\dot{W}_{s,real}}{\dot{W}_{s,isentropic}}$$

$$\eta_{compressor} = \frac{\dot{W}_{s,isentropic}}{\dot{W}_{s,real}}$$

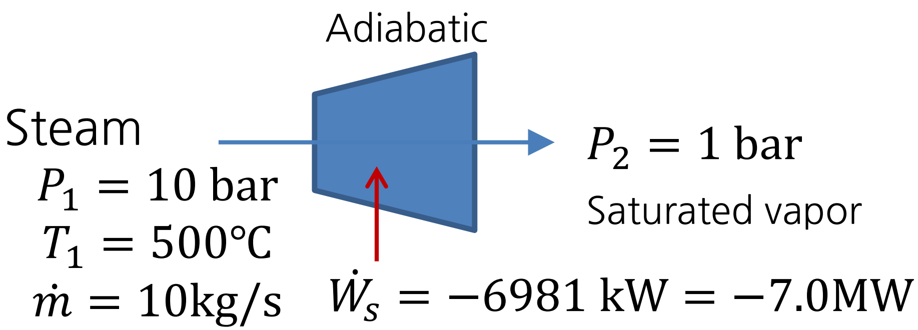


$$\dot{W}_s = \dot{m}\Delta h$$
$$w = \Delta h$$



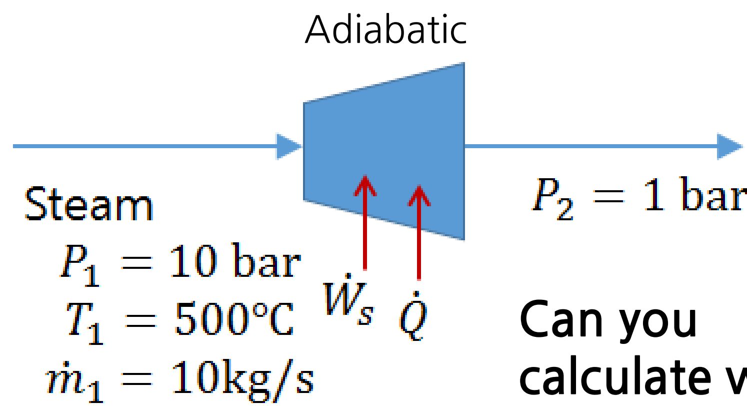
$$\dot{W}_s = \dot{m}\Delta h$$
$$w = \Delta h$$

Example 2.5



	Enthalpy (kJ/kg)	
	Steam table	Hysys
Stream 1	3373.6	-12550.1
Stream 2	2675.5	-13249.5
Δh(=w)	-698.1	-699.4
$\dot{W}_s$(MW)	-6.98	-6.99

$$\dot{W}_s = w \cdot \dot{m}$$



Can you calculate work?

Degree of freedom

- **The number of variables which can vary freely in given condition.**
  - A variable increase DOF by 1, and an independent relation(equation) decrease DOF by 1
  - DOF=number of variables -number of equations

A system defined with
2 variables and 1 equation:

$$x + y = 1$$

DOF=2-1=1
One variable is still free.
(We need to specify one more variable; If we decide x, y is decided. If we decide y, x is decided)
We call this system "underdetermined."
→**<u>No unique solution</u>**.

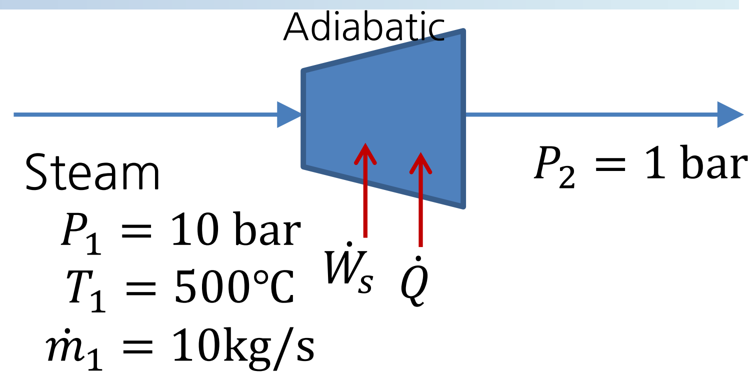
A system defined with
2 variables and 3 equation:

$$x + y = 1$$
$$2x + y = 2$$
$$x + 2y = 4$$

DOF=2-3=-1
We call this system "overdetermined" or "inconsistent"
→**<u>No feasible solution.</u>**
<u>Or no consistency</u>

⇨ If you want to specify all variables (unique solution), you must make the DOF=0 in your system!

Underdetermined (DOF>0)



Variables (8)

Any two intensive property in stream 1

Any two intensive property in stream 2

Extensive property: $\dot{m}_1, \dot{m}_2$

$\dot{Q}, \dot{W}_s$

Equations (7)

Stream condition(intensive):

$$P_1 = 10 \text{ bar},$$
$$T_1 = 500℃,$$
$$P_2 = 1 \text{ bar}$$

Stream condition(extensive):

$$\dot{m}_1 = 10\text{kg/s}$$

Mass balance

$$\dot{m}_1 = \dot{m}_2$$

Energy balance

$$0 = \dot{Q} + \dot{W}_s - \dot{m}_1 h_1 - \dot{m}_2 h_2$$

Process condition (adiabatic)

$$\dot{Q} = 0$$

State Postulate:
→If you specify any two intensive properties of a stream, you can decide all other intensive properties.

DOF=8-7=1 →underdetermined.

You must have one more relationship(equation) to specify this system.

Overdetermined (DOF<0)

Variables (8)

Any two intensive property in stream 1

Any two intensive property in stream 2

$$\dot{m}_1, \dot{m}_2, \dot{Q}, \dot{W}_s$$

Equations (9)

Stream condition(intensive):

$$P_1 = 10 \text{ bar}$$
$$T_1 = 500℃$$
$$P_2 = 1 \text{ bar}$$
$$s_1 = s_2$$

Stream 2=saturated vapor

Stream condition(extensive):

$$\dot{m}_1 = 10\text{kg/s}$$

Mass balance

$$\dot{m}_1 = \dot{m}_2$$

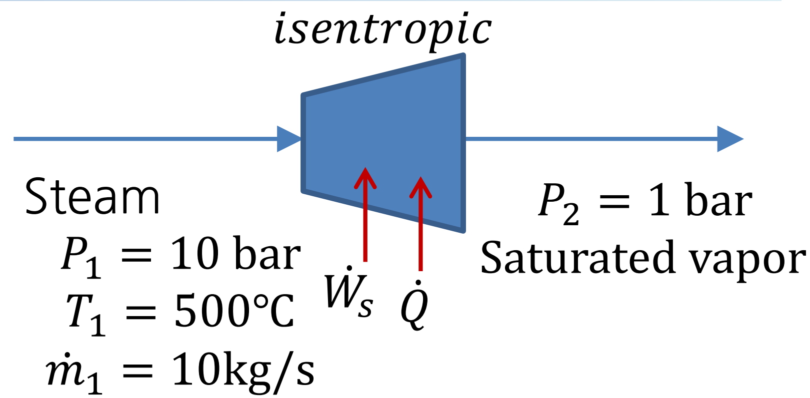
Energy balance

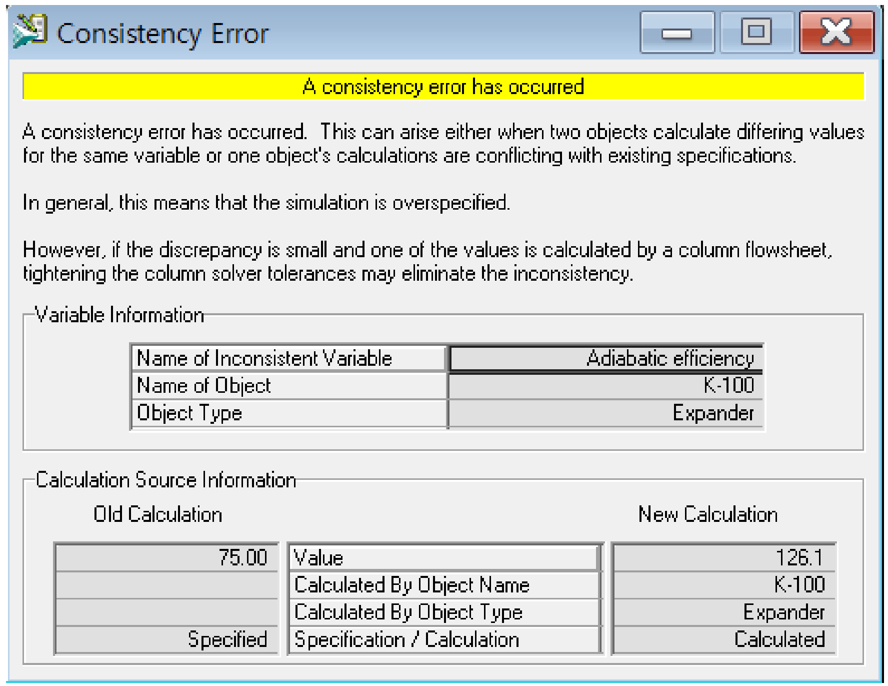
$$\mathbf{0 = \dot{Q} + \dot{W}_s - \dot{m}_1 h_1 - \dot{m}_2 h_2}$$

Process condition (adiabatic)

$$\mathbf{\dot{Q} = 0}$$

DOF=8-9=-1





Consistency Error

A consistency error has occurred

A consistency error has occurred. This can arise either when two objects calculate differing values for the same variable or one object's calculations are conflicting with existing specifications.

In general, this means that the simulation is overspecified.

However, if the discrepancy is small and one of the values is calculated by a column flowsheet, tightening the column solver tolerances may eliminate the inconsistency.

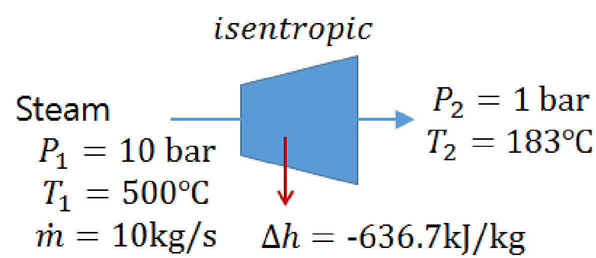
Variable Information

Name of Inconsistent Variable	Adiabatic efficiency
Name of Object	K-100
Object Type	Expander

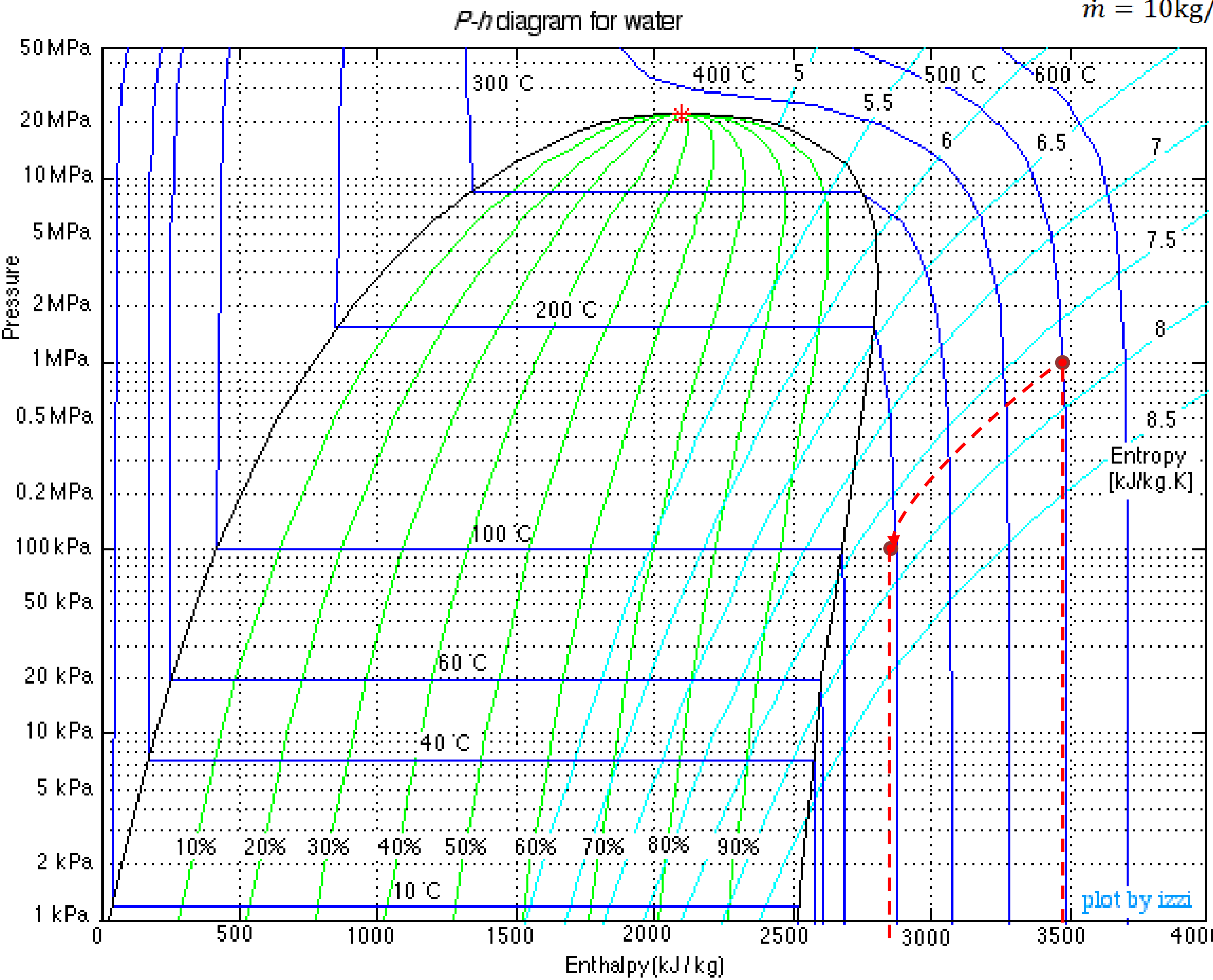
Calculation Source Information

Old Calculation		New Calculation
75.00	Value	126.1
	Calculated By Object Name	K-100
	Calculated By Object Type	Expander
Specified	Specification / Calculation	Calculated

Ph diagram



isentropic
Steam
$P_1 = 10$ bar
$T_1 = 500°C$
$\dot{m} = 10kg/s$
$P_2 = 1$ bar
$T_2 = 183°C$
$\Delta h =$ -636.7kJ/kg

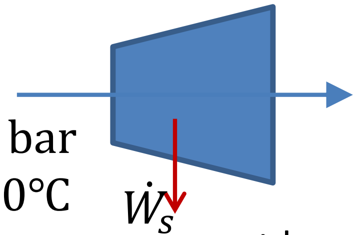


P-h diagram for water
Pressure
50 MPa
20 MPa
10 MPa
5 MPa
2 MPa
1 MPa
0.5 MPa
0.2 MPa
100 kPa
50 kPa
20 kPa
10 kPa
5 kPa
2 kPa
1 kPa
300 °C
400 °C
500 °C
600 °C
200 °C
100 °C
60 °C
40 °C
10 °C
5
5.5
6
6.5
7
7.5
8
8.5
Entropy [kJ/kg.K]
10%
20%
30%
40%
50%
60%
70%
80%
90%
plot by izzi
0
500
1000
1500
2000
2500
3000
3500
4000
Enthalpy (kJ / kg)

examples

isentropic

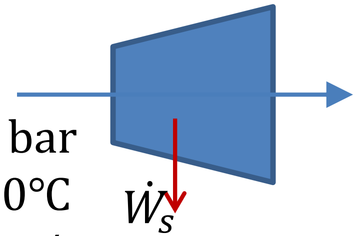
Steam
$P_1 = 10\text{ bar}$
$T_1 = 500℃$
$\dot{m} = 10\text{kg/s}$



$P_2 = 1\text{ bar}$
T_2= 183℃
w=Δh= -637

isentropic

Steam
$P_1 = 10\text{ bar}$
$T_1 = 500℃$
$\dot{m} = 10\text{kg/s}$



$P_2 = 2\text{ bar}$
T_2= 264℃

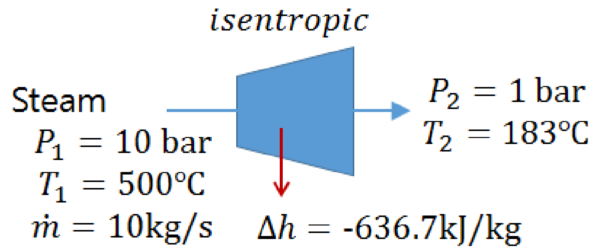
Δh= -479

	Enthalpy (kJ/kg)		Entropy (kJ/kgK)		T (C)	
	Steam table		Steam table		Steam table	
Stream 1	3478.4		7.7621		500	
Stream 2	2843.0		7.7621		183.7	
Δh(=w)	-635.4					

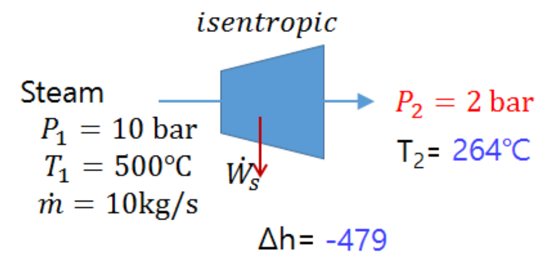
	h (kJ/kg)
Stream 1	-12446.4
Stream 2	-12925.4
Δh(=w)	-479

P=1bar	T	h	s
Steam Table	150	2776.4	7.6133
	200	2875.3	7.8342
Interpolation	183.6804	2843.02	7.7621

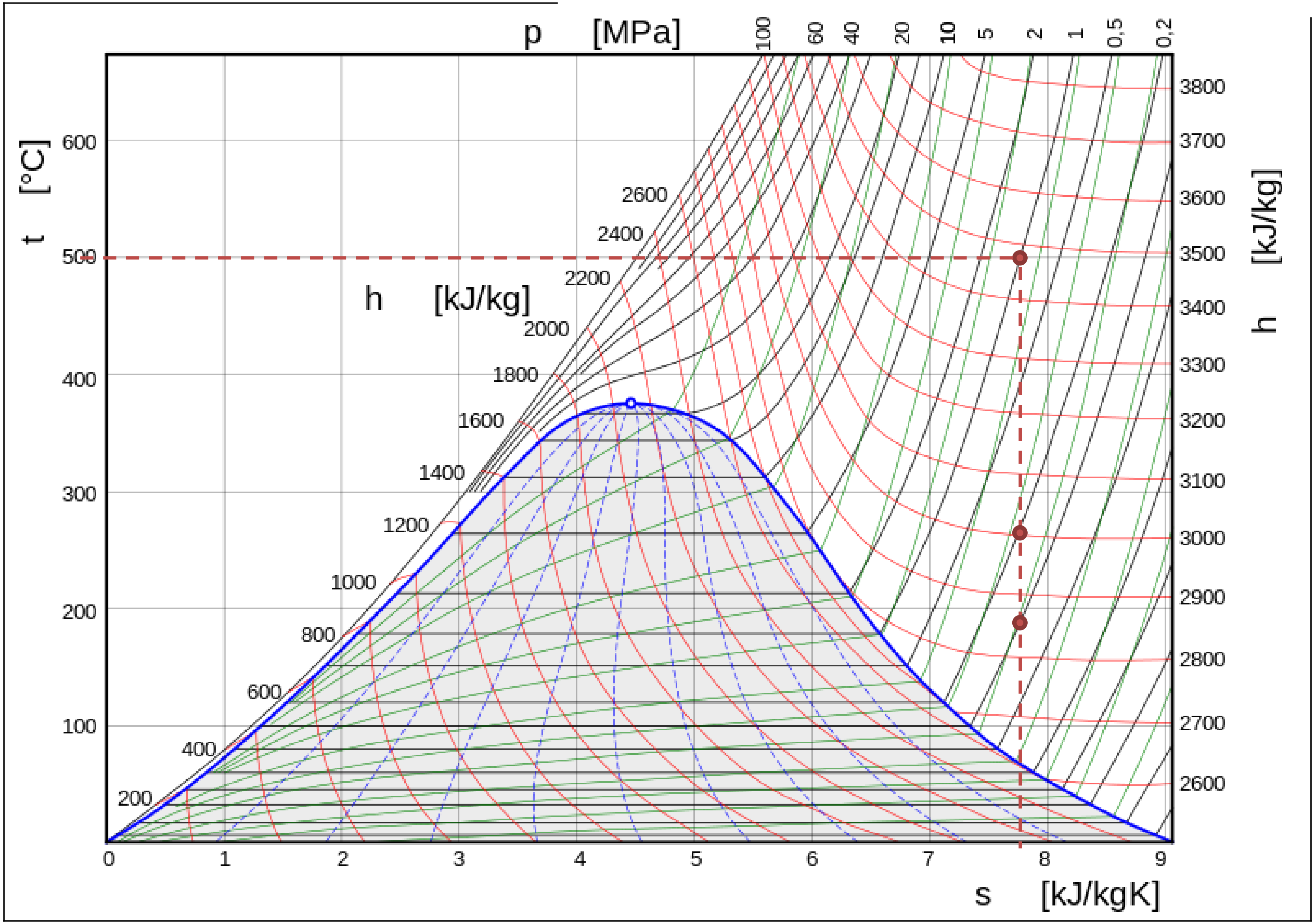
Ts diagram



isentropic
Steam
$P_1 = 10$ bar
$T_1 = 500°C$
$\dot{m} = 10$kg/s
$P_2 = 1$ bar
$T_2 = 183°C$
$\Delta h =$ -636.7kJ/kg

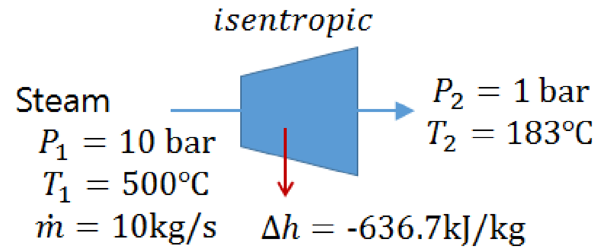


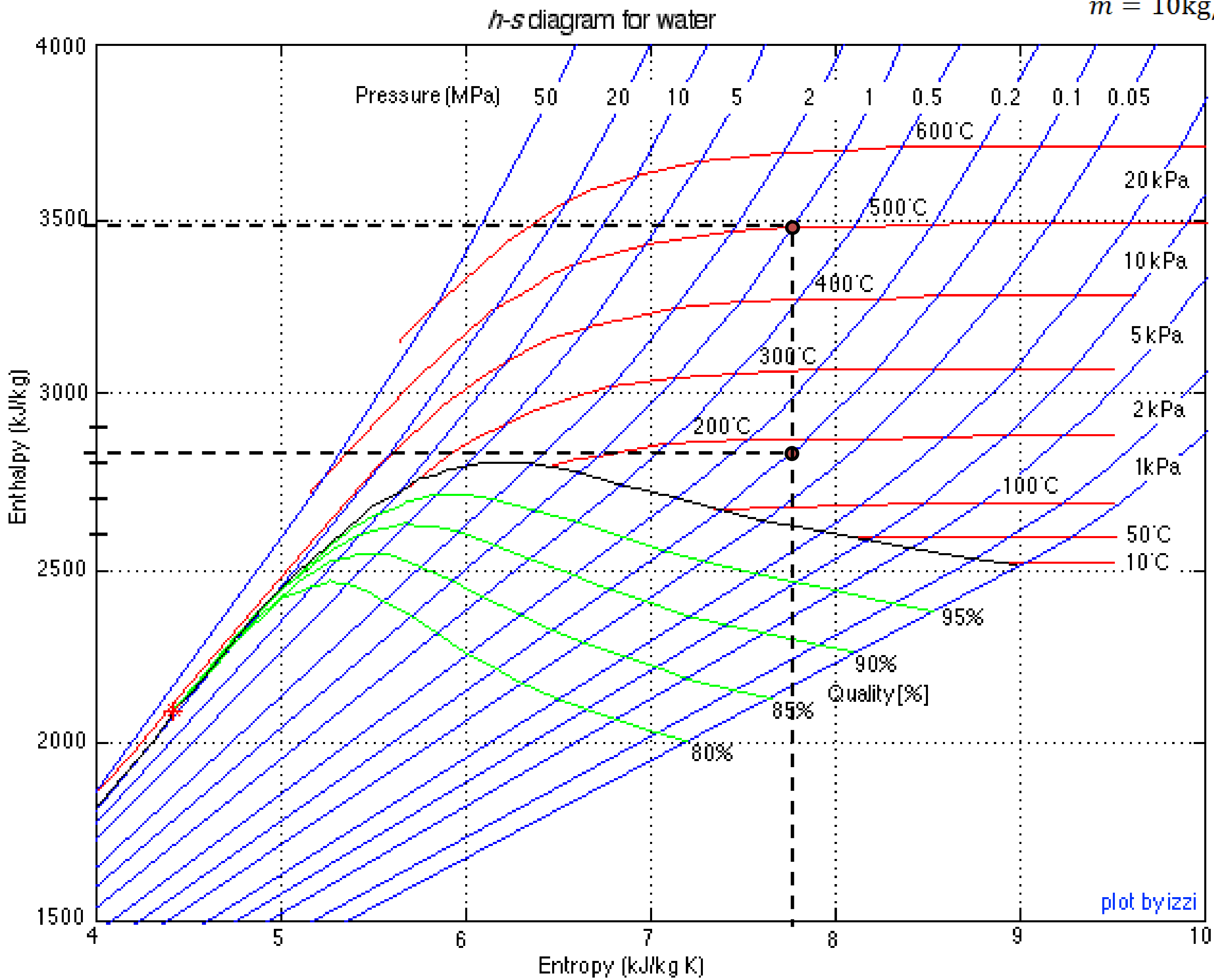
isentropic
Steam
$P_1 = 10$ bar
$T_1 = 500°C$
$\dot{m} = 10$kg/s
$\dot{W}_s$
$P_2 = 2$ bar
$T_2 = 264°C$
$\Delta h = -479$



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]

hs diagram


isentropic
Steam
$P_1 = 10$ bar
$T_1 = 500$°C
$\dot{m} = 10$kg/s
$\Delta h =$ -636.7kJ/kg
$P_2 = 1$ bar
$T_2 = 183$°C


h-s diagram for water
Pressure (MPa)
50
20
10
5
2
1
0.5
0.2
0.1
0.05
600°C
500°C
400°C
300°C
200°C
100°C
50°C
10°C
20 kPa
10 kPa
5 kPa
2 kPa
1kPa
95%
90%
85%
80%
Quality [%]
plot by izzi
Enthalpy (kJ/kg)
4000
3500
3000
2500
2000
1500
Entropy (kJ/kg K)
4
5
6
7
8
9
10

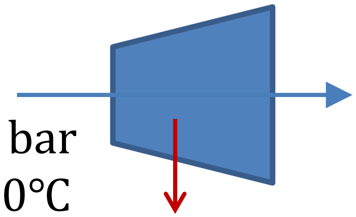
isentropic

Steam

$P_1 = 10\text{ bar}$

$T_1 = 500°\text{C}$

$\dot{m} = 10\text{kg/s}$



$P_2 = 1\text{ bar}$

$T_2 = 183°\text{C}$

$\Delta h = -636.7\text{kJ/kg}$

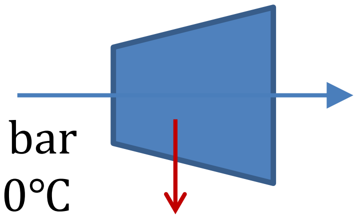
isentropic

Steam

$P_1 = 10\text{ bar}$

$T_1 = 500°\text{C}$

$\dot{m} = 10\text{kg/s}$



$P_2 =$ 3.8 bar

$T_2 = 300°\text{C}$

$\Delta h =$ -308 kJ/kg

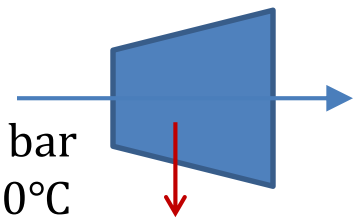
isentropic

Steam

$P_1 = 10\text{ bar}$

$T_1 = 500°\text{C}$

$\dot{m} = 10\text{kg/s}$



$P_2 = 2\text{ bar}$

$T_2 = 264°\text{C}$

$\Delta h = -479\text{ kJ/kg}$

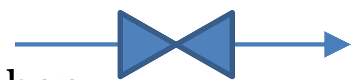
isenthalpic

Steam

$P_1 = 10\text{ bar}$

$T_1 = 500°\text{C}$

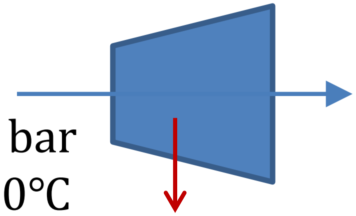
$\dot{m} = 10\text{kg/s}$



$P_2 = 1\text{ bar}$

$T_2 =$ 495.4℃

$isentropic$

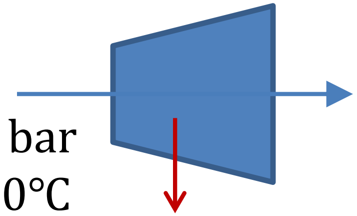


Steam
$P_1 = 10$ bar
$T_1 = 500°C$
$\dot{m} = 10kg/s$

$P_2 = 1$ bar
$T_2 = 183°C$

$\Delta h = -636.7 kJ/kg$

η = 63.4%

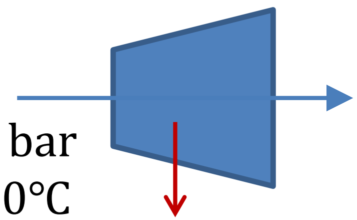


Steam
$P_1 = 10$ bar
$T_1 = 500°C$
$\dot{m} = 10kg/s$

$P_2 = 1$ bar
$T_2 = 300°C$

Δh = -403.9

$\eta = 50\%$

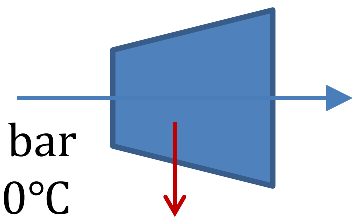


Steam
$P_1 = 10$ bar
$T_1 = 500°C$
$\dot{m} = 10kg/s$

$P_2 = 1$ bar
T_2 = 342.3°C

Δh = -318.3

η = 120%

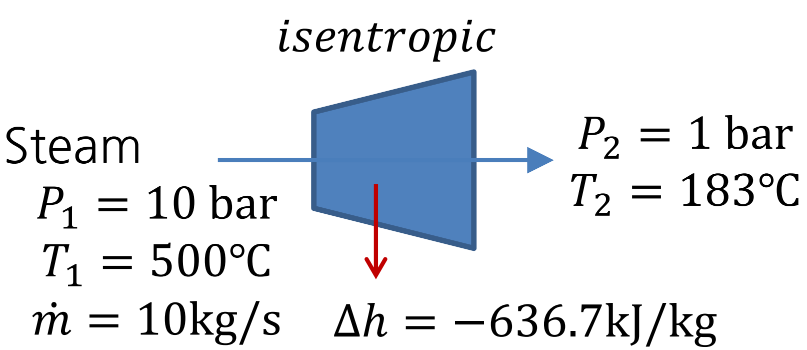


Steam
$P_1 = 10$ bar
$T_1 = 500°C$
$\dot{m} = 10kg/s$

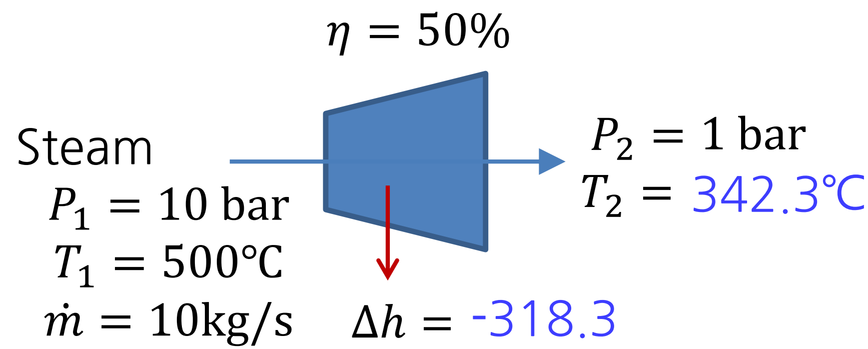
$P_2 = 1$ bar
$T_2 = 120°C$

Δh = -762.0

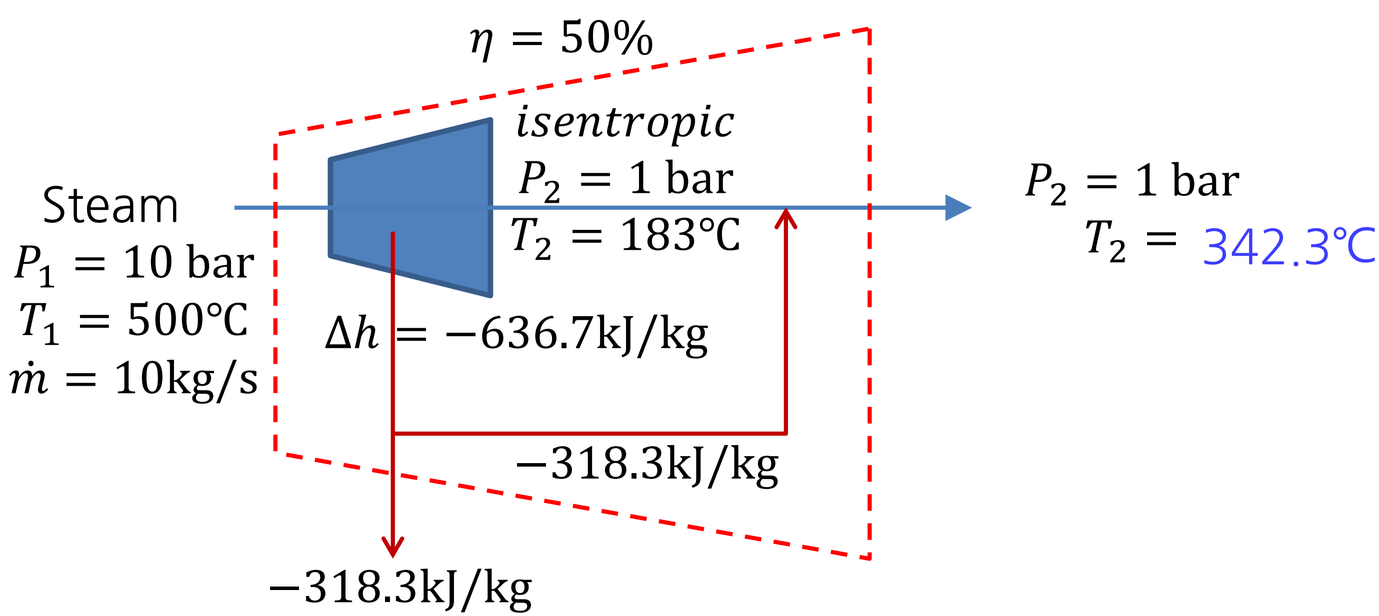
Impossible!
(wrong design)



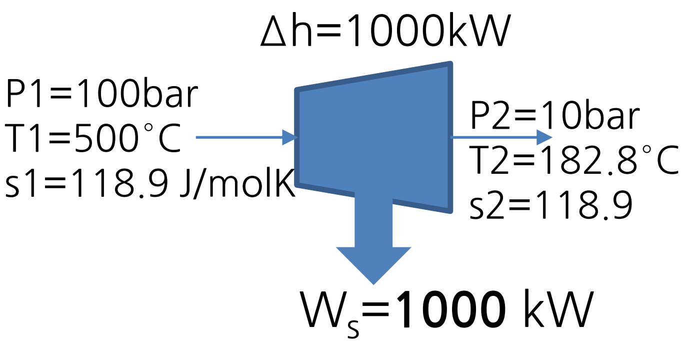
isentropic
Steam
$P_1 = 10$ bar
$T_1 = 500$℃
$\dot{m} = 10$kg/s
$P_2 = 1$ bar
$T_2 = 183$℃
$\Delta h = -636.7$kJ/kg

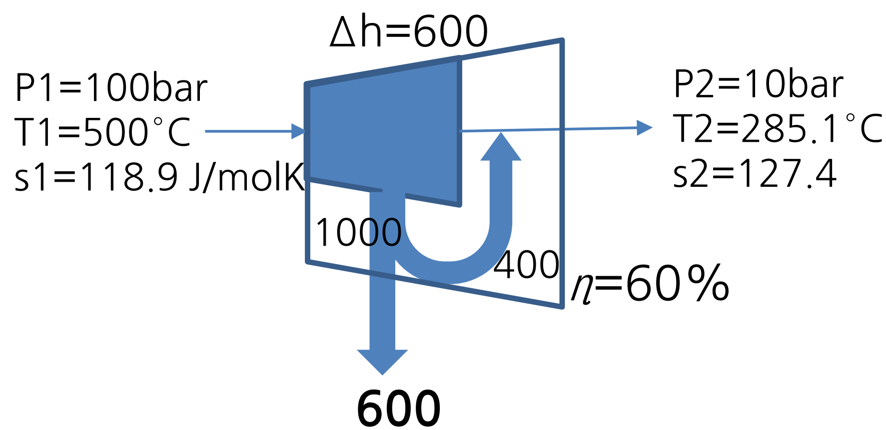


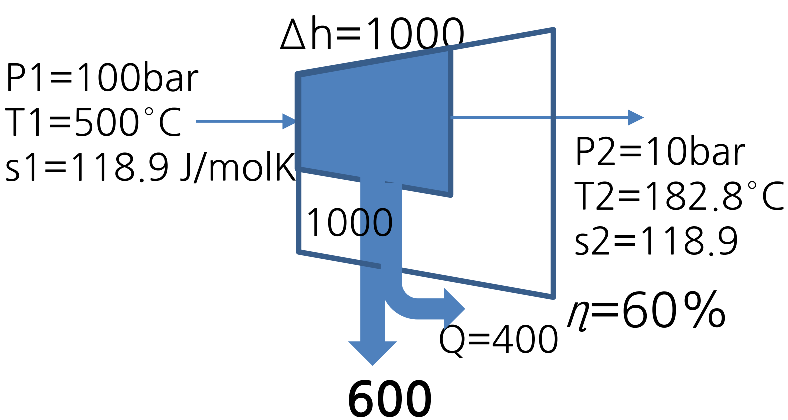
$\eta = 50\%$
Steam
$P_1 = 10$ bar
$T_1 = 500$℃
$\dot{m} = 10$kg/s
$P_2 = 1$ bar
$T_2 = 342.3$℃
$\Delta h = -318.3$

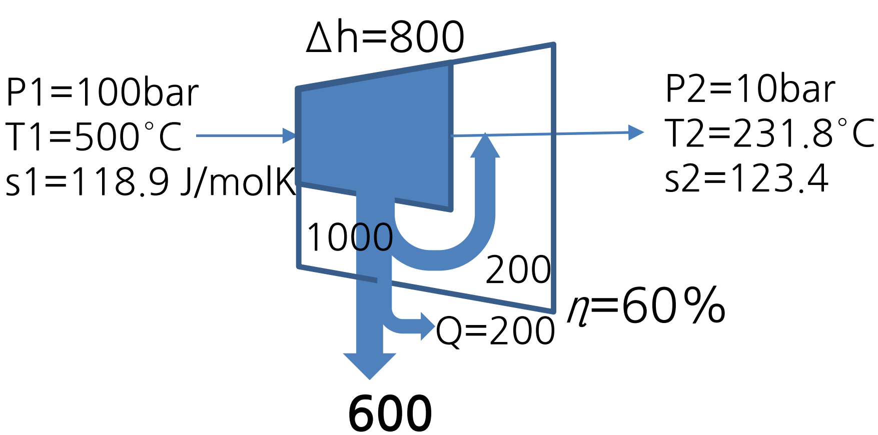


$\eta = 50\%$
isentropic
Steam
$P_1 = 10$ bar
$T_1 = 500$℃
$\dot{m} = 10$kg/s
$P_2 = 1$ bar
$T_2 = 183$℃
$\Delta h = -636.7$kJ/kg
-318.3kJ/kg
$P_2 = 1$ bar
$T_2 = 342.3$℃
-318.3kJ/kg


Δh=1000kW
P1=100bar
T1=500°C
s1=118.9 J/molK
P2=10bar
T2=182.8°C
s2=118.9
Ws=1000 kW


Δh=600
P1=100bar
T1=500°C
s1=118.9 J/molK
P2=10bar
T2=285.1°C
s2=127.4
1000
400
η=60%
600


Δh=1000
P1=100bar
T1=500°C
s1=118.9 J/molK
P2=10bar
T2=182.8°C
s2=118.9
1000
Q=400
η=60%
600


Δh=800
P1=100bar
T1=500°C
s1=118.9 J/molK
P2=10bar
T2=231.8°C
s2=123.4
1000
200
Q=200
η=60%
600

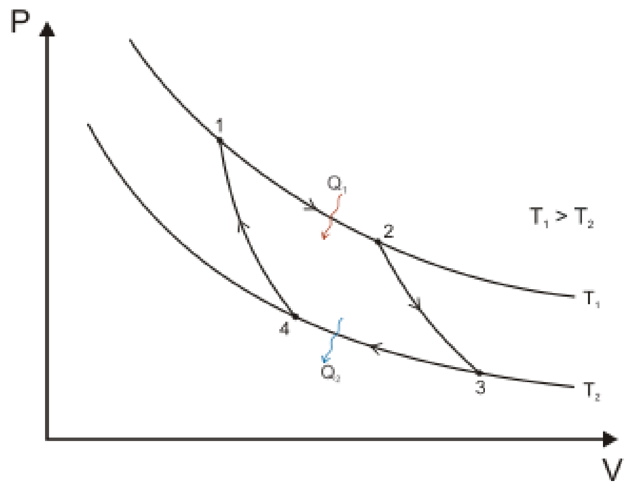
Polytropic efficiency

- Polytropic Process
- Polytropic exponent
- Polytropic efficiency

Thermodynamic cycle

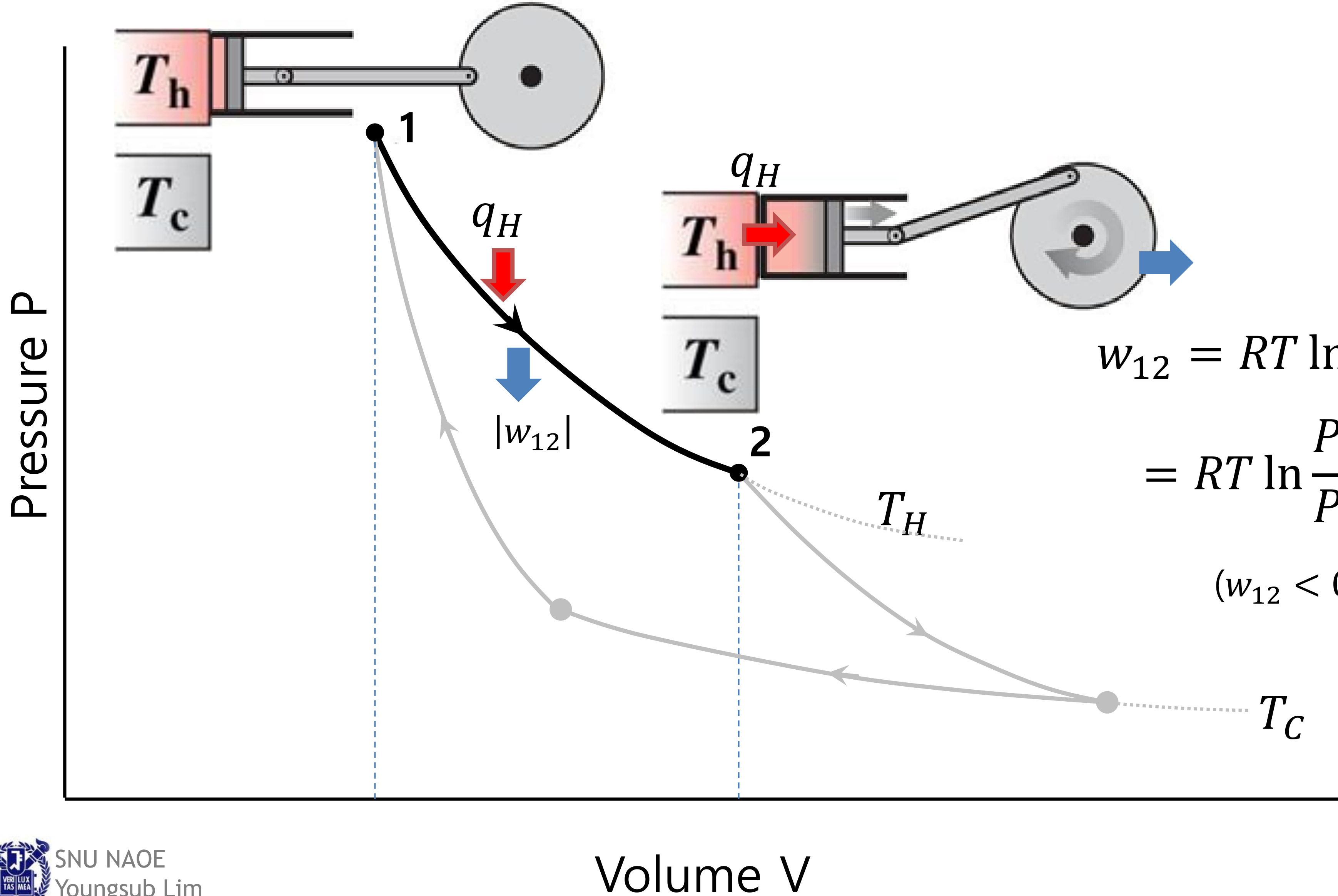
– A set of processes through which a system returns to the same initial state

- **Carnot Cycle**
  – Proposed by NLS Carnot in 1824
  – Reversible cyclic process with Ideal gas
  – Maximum efficiency of a heat engine



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

A: state 1→2 Isothermal Expansion



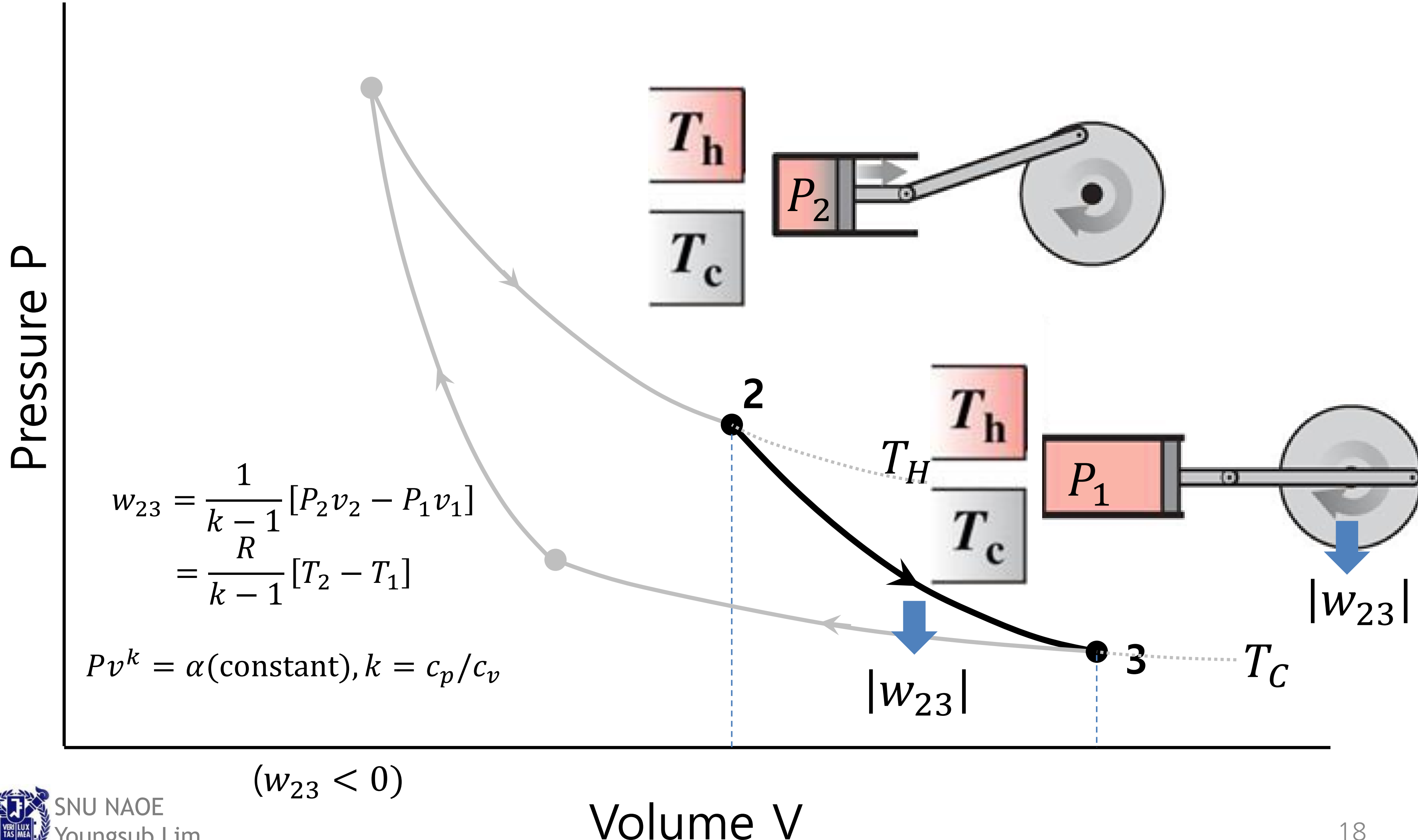
$$w_{12} = RT \ln \frac{v_1}{v_2}$$

$$= RT \ln \frac{P_2}{P_1}$$

$$(w_{12} < 0)$$

http://www.physics.louisville.edu/cldavis/phys298/notes/carnot_thcycle.html

B: state 2→3 Adiabatic Expansion



$$w_{23} = \frac{1}{k-1}[P_2 v_2 - P_1 v_1]$$
$$= \frac{R}{k-1}[T_2 - T_1]$$

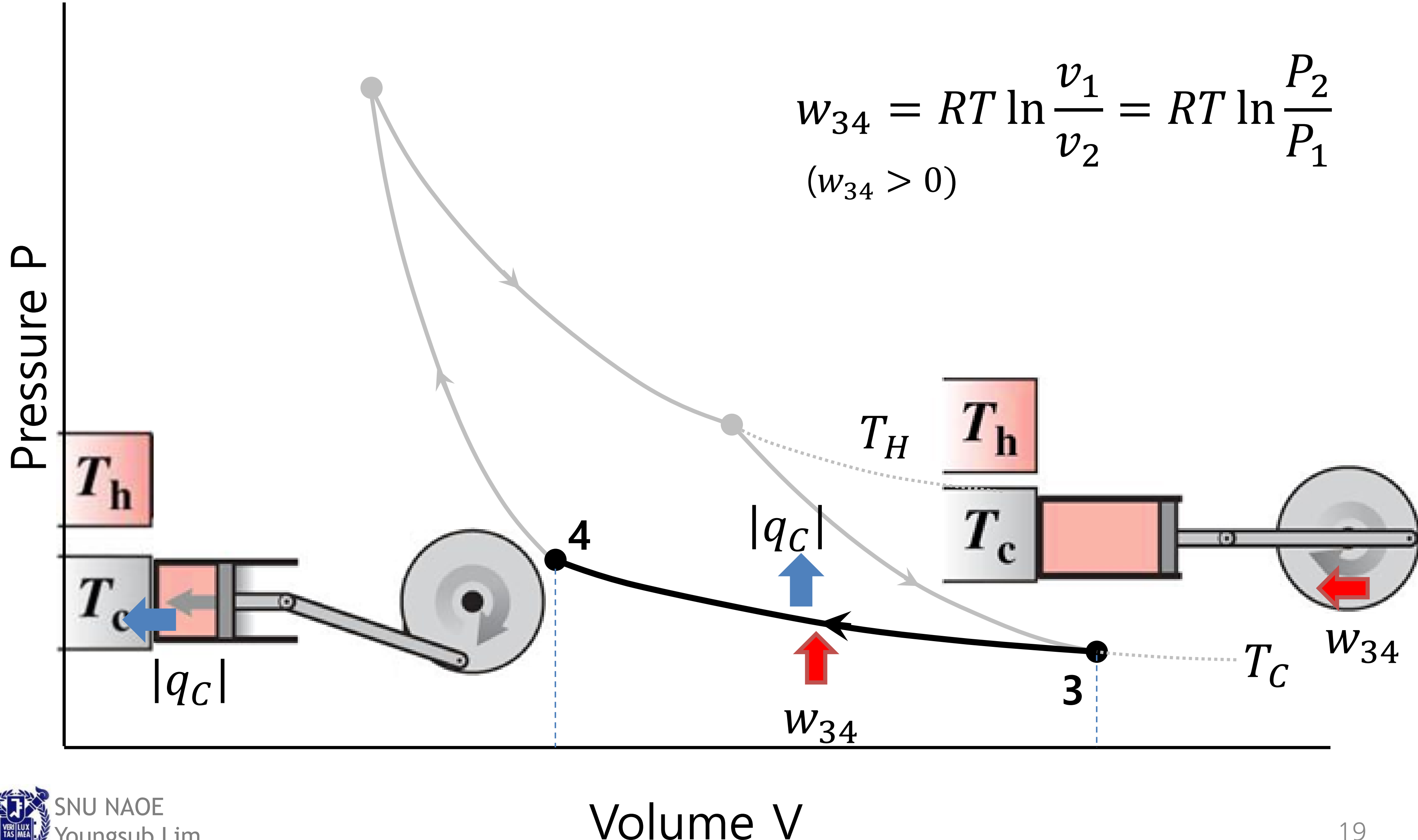
$$Pv^k = \alpha(\text{constant}), k = c_p/c_v$$

$(w_{23} < 0)$

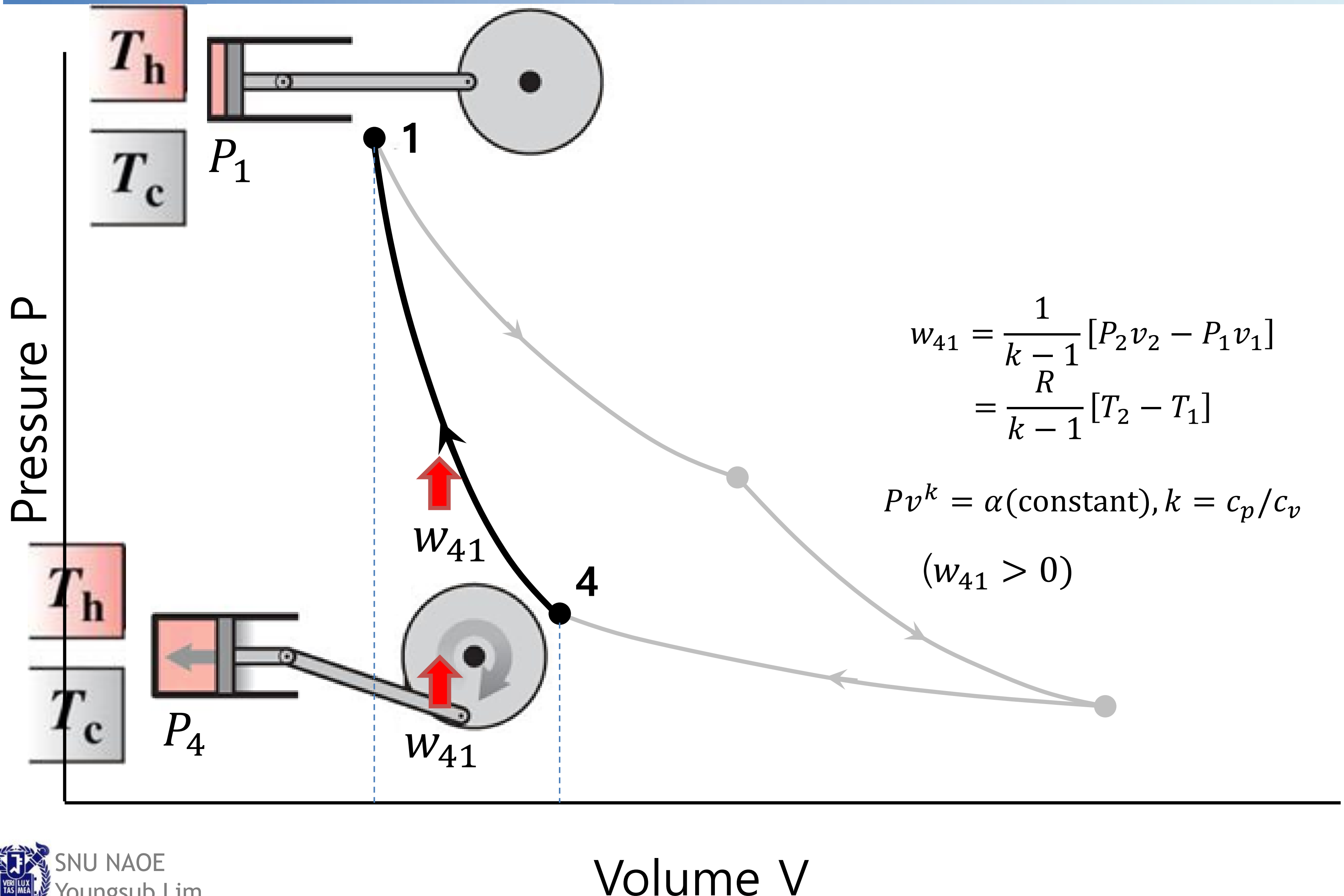
C: state 3→4 Isothermal Compression

$$w_{34} = RT \ln \frac{v_1}{v_2} = RT \ln \frac{P_2}{P_1}$$

$(w_{34} > 0)$



D: state 4→1 Adiabatic Compression

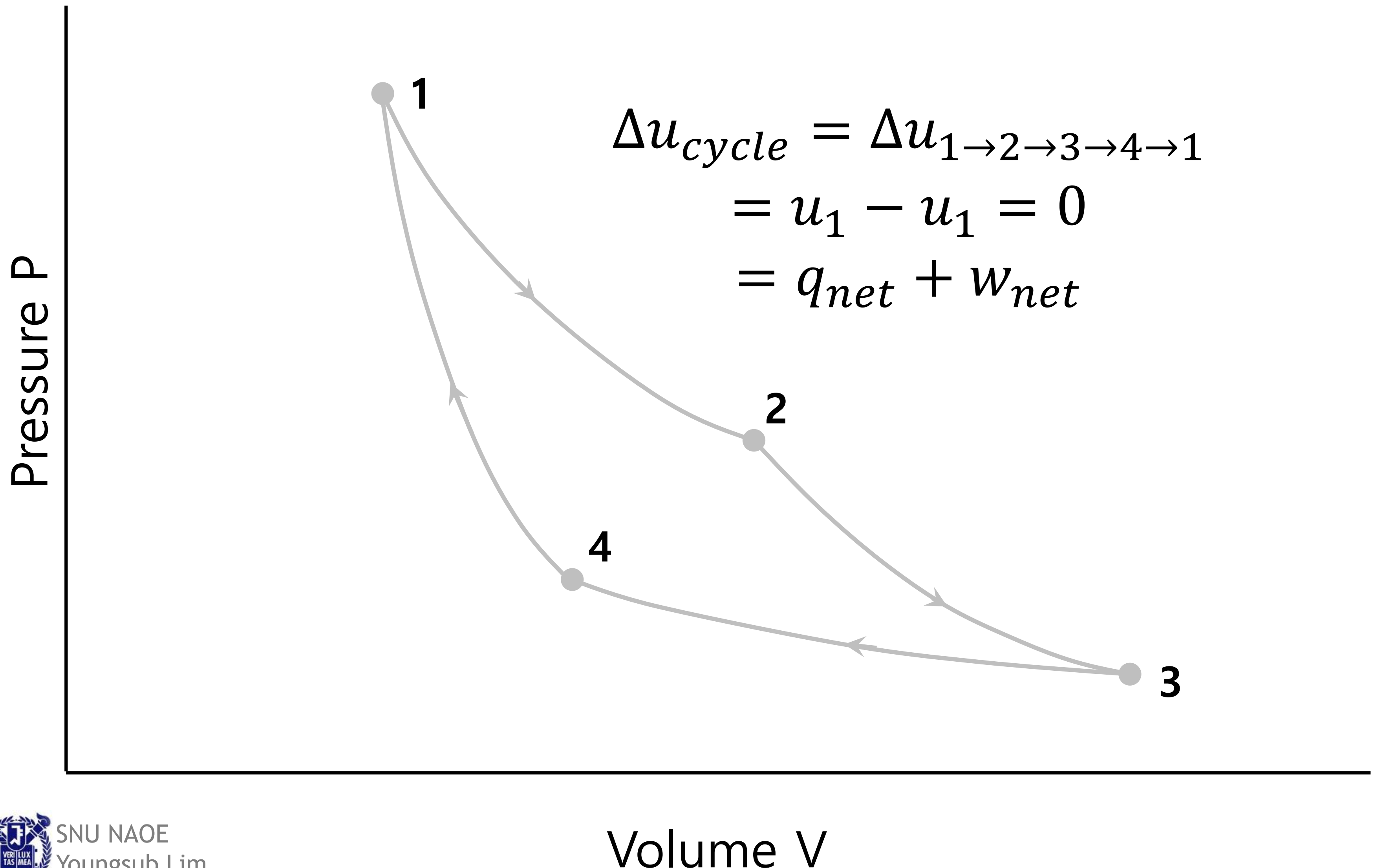


$$w_{41} = \frac{1}{k-1}[P_2 v_2 - P_1 v_1]$$
$$= \frac{R}{k-1}[T_2 - T_1]$$

$$Pv^k = \alpha(\text{constant}), k = c_p/c_v$$

$$(w_{41} > 0)$$

Internal Energy in Carnot cycle



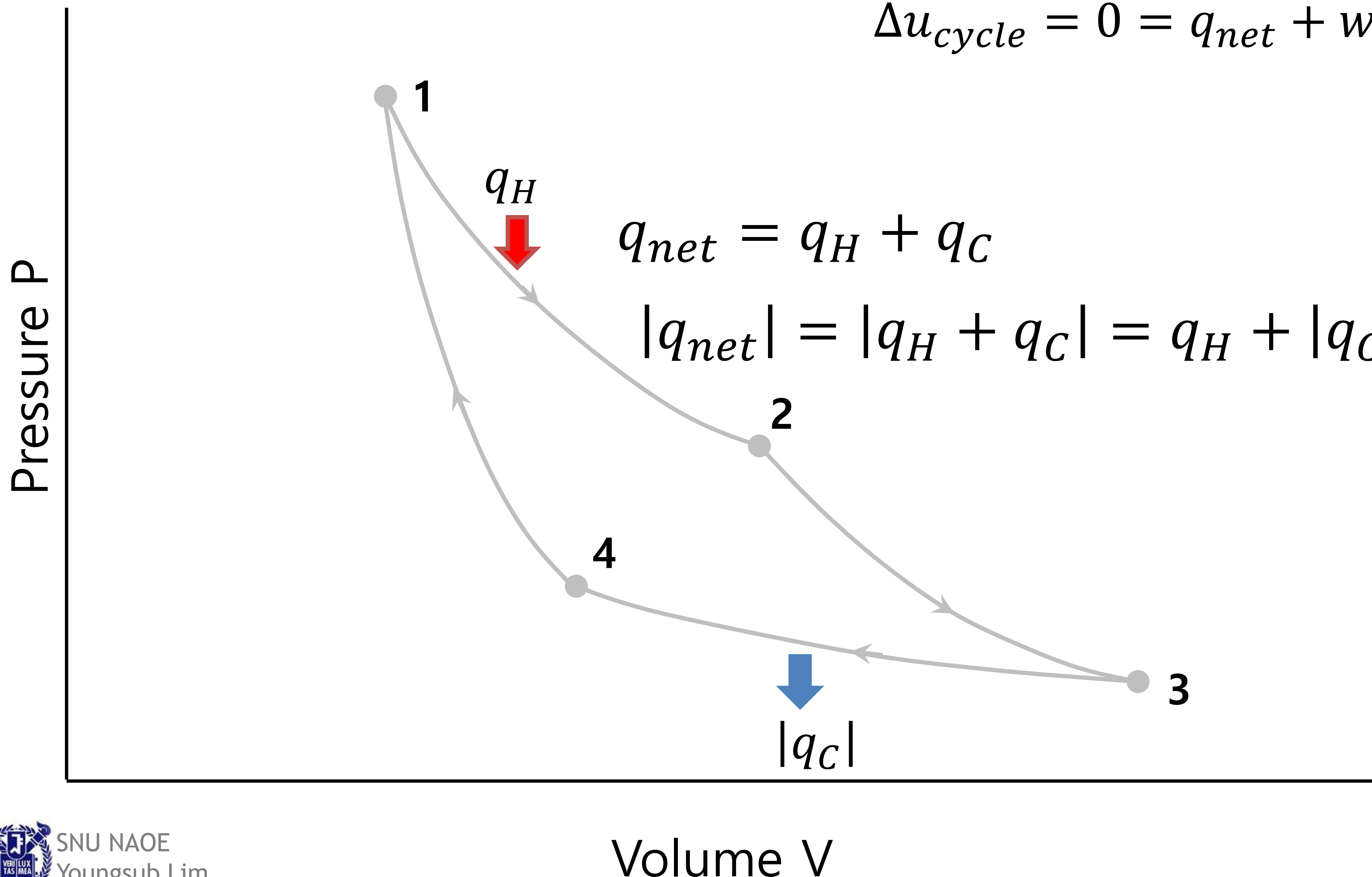
$$\Delta u_{cycle} = \Delta u_{1\to2\to3\to4\to1}$$
$$= u_1 - u_1 = 0$$
$$= q_{net} + w_{net}$$

Total Net Q in Carnot cycle

$$\Delta u_{cycle} = 0 = q_{net} + w_{net}$$

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

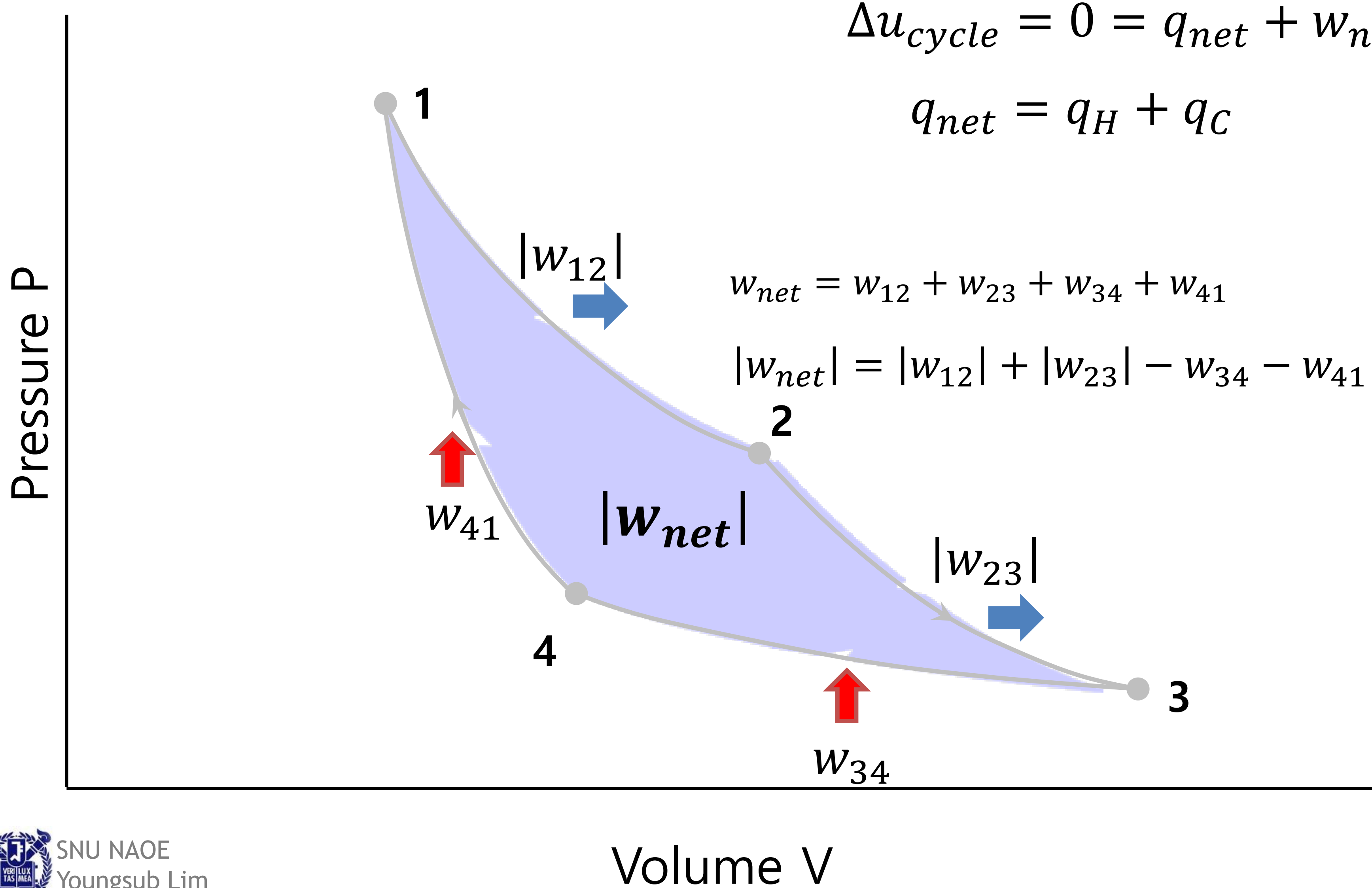
$$|q_{net}| = |q_H + q_C| = q_H + |q_C|$$



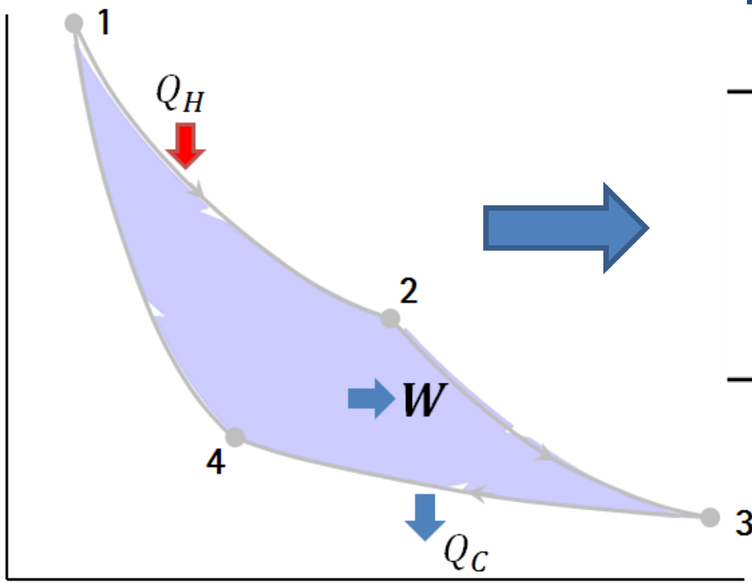
Total Net W in Carnot cycle

$$\Delta u_{cycle} = 0 = q_{net} + w_{net}$$

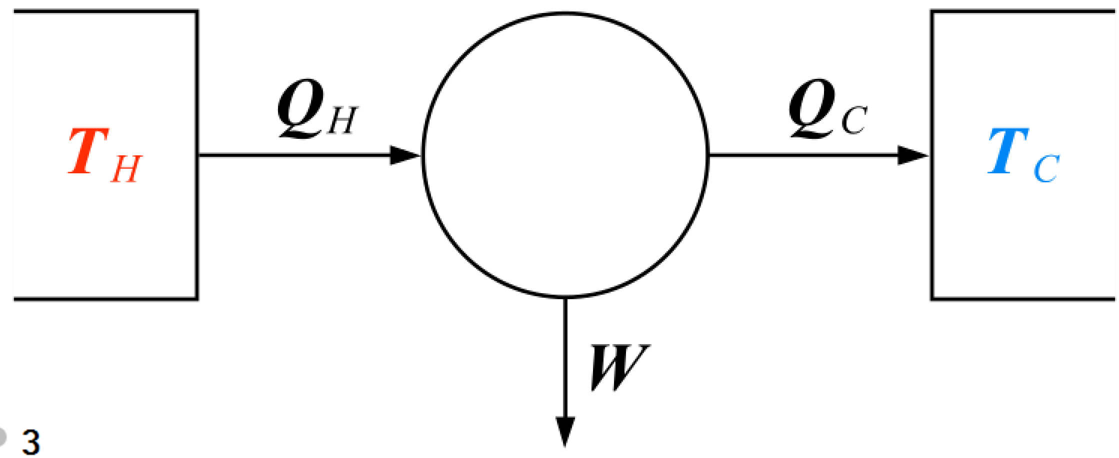
$$q_{net} = q_H + q_C$$



Efficiency of a heat engine



Heat Engine



The first Carnot theorem: all reversible engines operating between the same two baths has the same efficiency

$$\eta = 1 - \frac{T_C}{T_H}$$

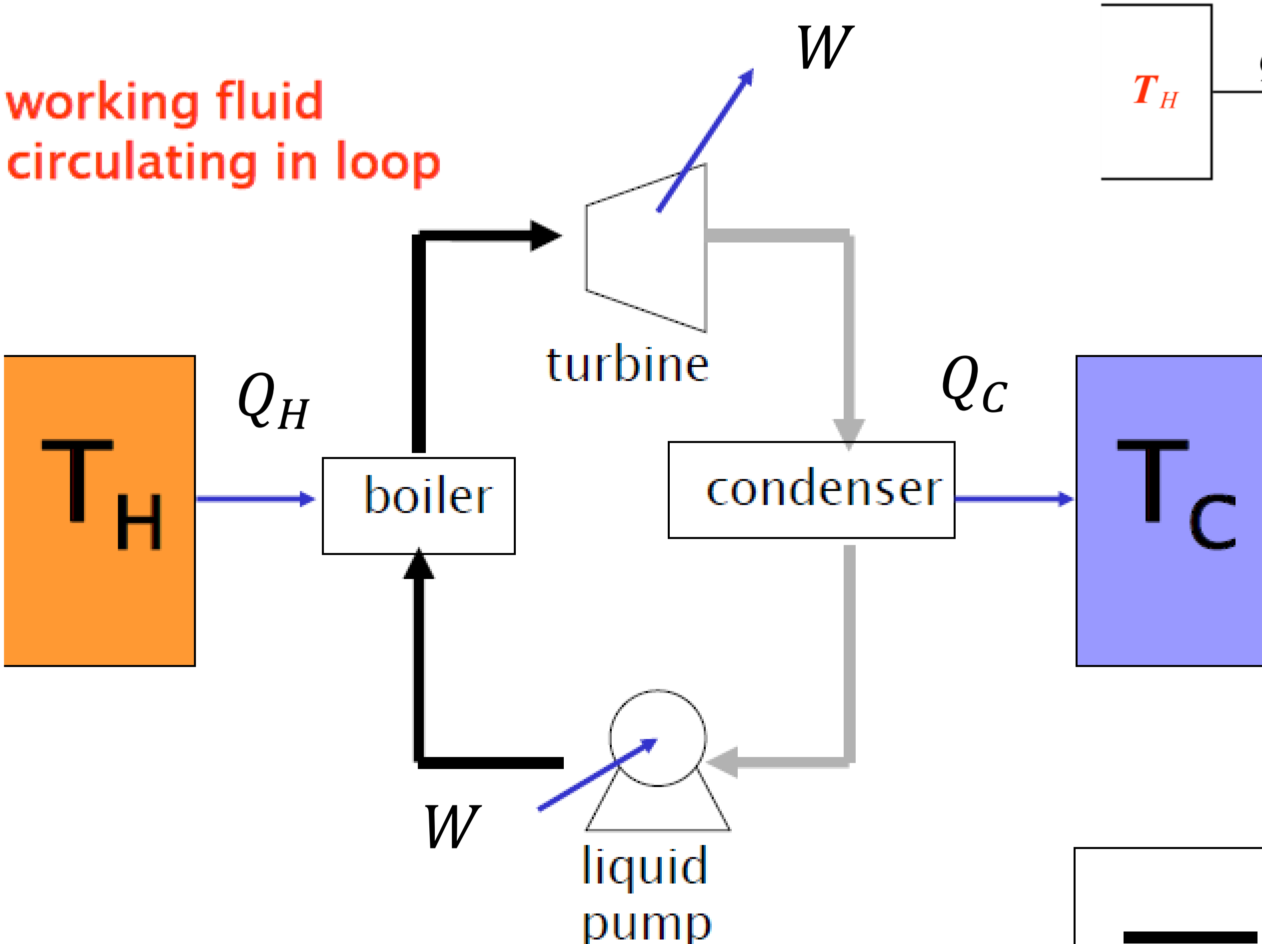
$$efficiency\ \eta \equiv \frac{|W|}{|Q_H|}$$

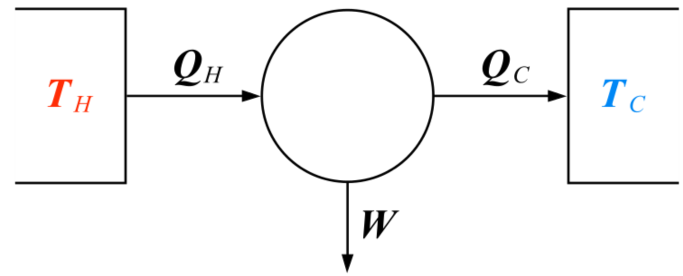
$$|W| = -W = Q = |Q_H| - |Q_C|$$

$$\eta = 1 - \frac{|Q_C|}{|Q_H|}$$

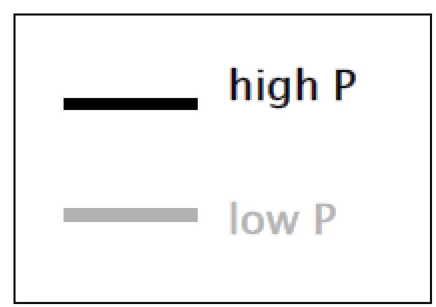
http://www.physics.louisville.edu/cldavis/phys298/notes/carnot_thcycle.html
http://en.wikipedia.org/wiki/Carnot_cycle

Heat Engine Example(Power Plant)

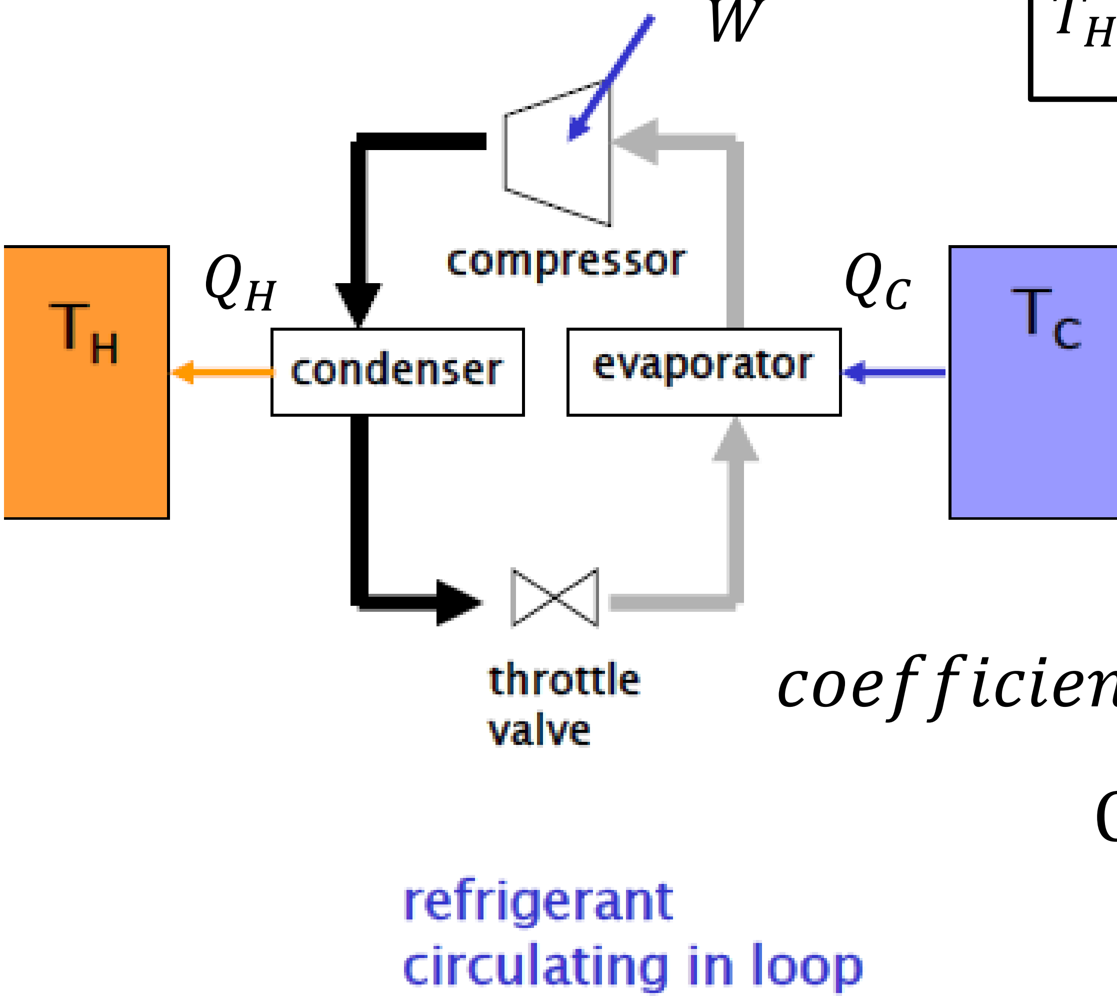


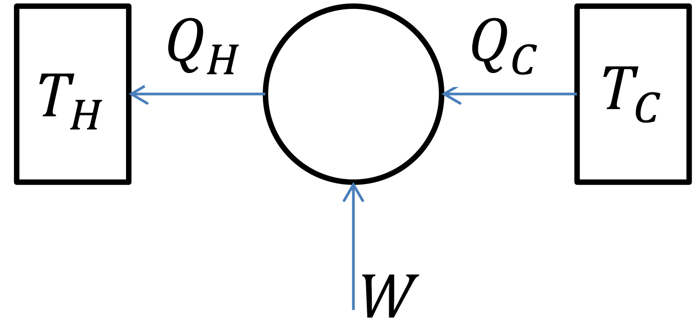


$$efficiency\ \eta \equiv \frac{|W|}{Q_H}$$



Refrigerator Example





coefficient of performance

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