- <u>The Carnot Cycle</u>

  Reversible process (가역과정) – ideal process

  한번 발생했던 과정이 역으로도 될 수 있고 이때 계(system)와 주위 (surrounding)에 아무 변화도 남기지 않는 과정

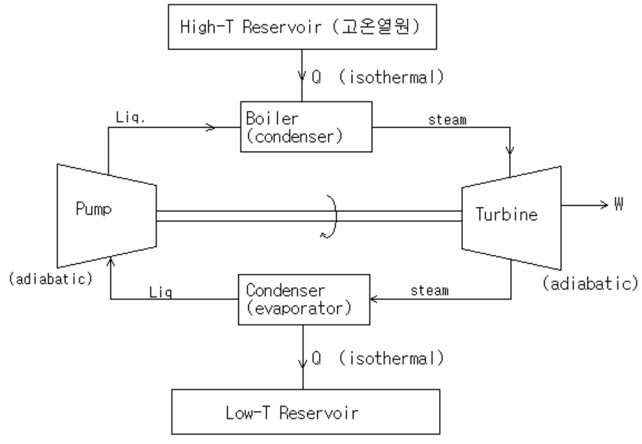
  Irreversible (or Real) process – the opposite

  Consider a heat engine with every process reversible and the cycle is also reversible -> i.e. if a cycle is reversed, the heat engine becomes a refrigerator

  ✓ This is the most efficient cycle that can operate between two constant temperature reservoirs – CARNOT CYCLE –

- A Carnot Cycle (Heat Engine) (working fluid = steam)

  Assume all processes are reversible

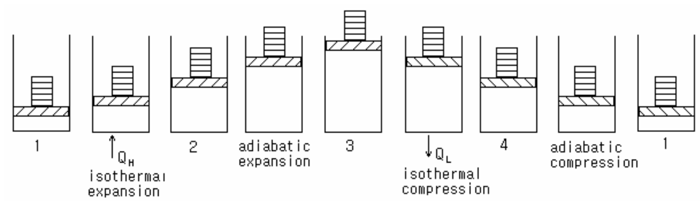


- 4 Processes in a Carnot Cycle

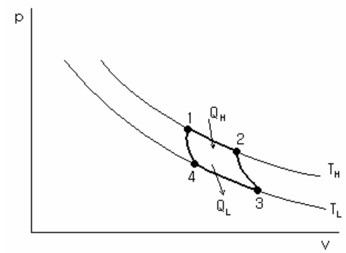
  - A reversible Q_H isothermal process (High-T → Steam)
  - Reversible adiabatic process in turbine – W
  - Reversible isothermal process for – Q_L
  - Reversible adiabatic process on the pump

- → Reverse the flow → Refrigerator

- Carnot Cycle (Working fluid = Gas) 이상기체에 의한 Carnot 사이클



for an ideal gas as working fluid, Carnot cycle can be expressed as

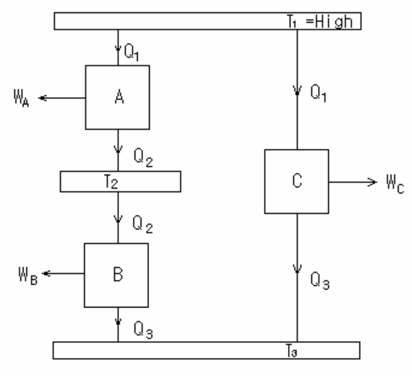


1 → 2 Isothermal expansion
2 → 3 Adiabatic expansion
3 → 4 Isothermal compression
4 → 1 Adiabatic compression

$$W = \int p\,dV$$

- Thermodynamic temperature scale

  Consider 3 engines, 3 Carnot engines



$T_1 > T_2 > T_3$

Q_3 is the same for engine B and C since cycles are reversible

In general term, for a Carnot cycle

$$\frac{Q_1}{Q_3} = \frac{f(T_1)}{f(T_3)} = \frac{T_1}{T_3}$$

`Definition of Absolute Temperature'

By Lord Kelvin (*)

With this definition, the Carnot efficiency may be expressed in terms of absolute temperature,

$$\eta_{thermal} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H}$$

- Kelvin proposed a Carnot engine that required heat at the temperature of the steam point and rejected heat at the temperature of the ice point.

$$\eta_{th} = 1 - \frac{T_L}{T_H} = 0.2680 \quad \text{or} \quad \frac{T_{ice\ point}}{T_{steam\ point}} = 0.7320 \qquad (1)$$

and use

$$T_{steam\ point} - T_{ice\ point} = 100 \qquad (2)$$

Now solve (1) and (2) simultaneously and find Kelvin Temperature!

$$T_{steam\ pt} = 373.15K$$
$$T_{ice\ pt} = 273.15K$$

Now extending "cycle" to a "process"...

Some examples of a process:

- combustion process in an automobile
- cooling of a cup of coffee
- chemical processes that take place in our body

Energy? Entropy? Both are abstract concept!

- Generalization of 2nd Law for a process (Not cycle limited!)
- Inequality of Clausius says

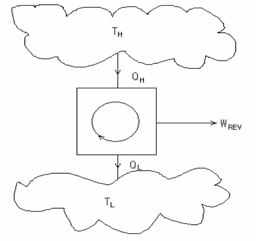
$$\oint \frac{\delta Q}{T} \le 0$$

- Again the Inequality of Clausius says

$$\oint \frac{\delta Q}{T} \le 0 \qquad \text{..(*)}$$

- This is a consequence of the 2nd Law.
- This is true for both reversible + irreversible cycle, heat engines, refrigerators.

- Consider a reversible heat engine system



(*) becomes

$$\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} = 0$$

since $\dfrac{Q_H}{Q_L} = \dfrac{T_H}{T_L}$

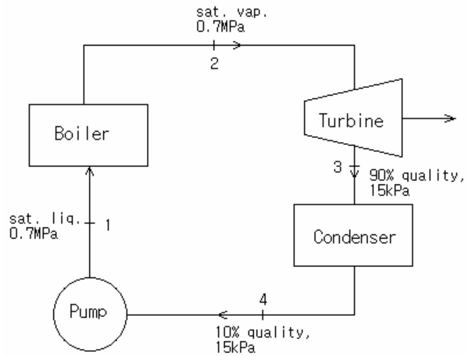
- For all irreversible cycle,

$$\oint \frac{\delta Q}{T} < 0$$

- For both cycles (reversible & irreversible): $\oint \dfrac{\delta Q}{T} \leq 0$

- Example

Consider a simple power plant that demonstrates the inequality of Clausius.



Q: Does this cycle satisfy the inequality of Clausius?

Answer to the previous question:

Heat transfer takes place in two places, the boiler and the condenser.

$$\oint \frac{\delta Q}{T} = \int \left(\frac{\delta Q}{T}\right)_{boiler} + \int \left(\frac{\delta Q}{T}\right)_{condenser}$$

Note T is constant across boiler, condenser.

$$\frac{1}{T_1} Q_{1,2} + \frac{1}{T_3} Q_{3,4} \qquad \text{----------- (*)}$$

For Boiler, look up steam table

At 1) $x = 0,\ p_1 = 0.7MPa,\ h_1 = 697.22\, kJ/kg$

2) $x = 1,\ p_2 = 0.7MPa,\ h_2 = 2763.5\, kJ/kg$

So for 1kg of mass.

1st law for Boiler:

$$q_{1,2} = h_2 - h_1 + \cancel{W}$$
$$= 2763.5 - 697.22 = 2066.28\, kJ/kg$$

$T_1 = 164.97°C$ sat. liq. temperature

Likewise,

$$q_{3,4} = h_4 - h_3 = 463.4 - 2361.8 = -1898\, kJ/kg$$

$$T_3 = 53.97°C$$

$$\therefore (*) \oint \frac{\delta Q}{T} \leq 0$$