First Law of Thermodynamics and Energy Equation (1)

(Lecture 3)

2021년 1학기

열역학 (M2794.001100.002)

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(*) Some texts and figures are borrowed from Sonntag & Borgnakke unless noted otherwise.

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3.1 The Energy Equation

➔ Energy of a substance consists of two main categories:

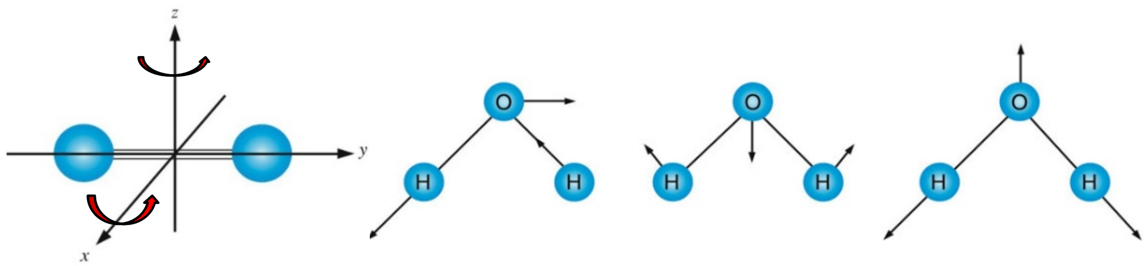
$$E = Microscopic\ Energy + Macroscopic\ Energy$$

(by molecular dynamics in CM) (by mean position or motion of CM)

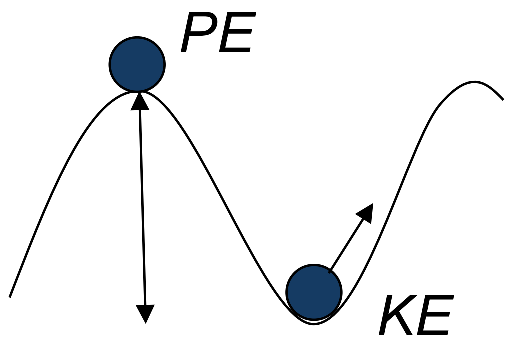
$$E = \boxed{Internal\ Energy} + \boxed{Kinetic\ Energy + Potential\ Energy}$$

$$E = U + KE + PE \quad \leftarrow \quad KE = \frac{1}{2}mV^2,\ PE = mgh$$

$$= m(u + \frac{1}{2}V^2 + gh)$$



Examples of internal (microscopic) energy
(left: rotational modes, right: vibrational modes)

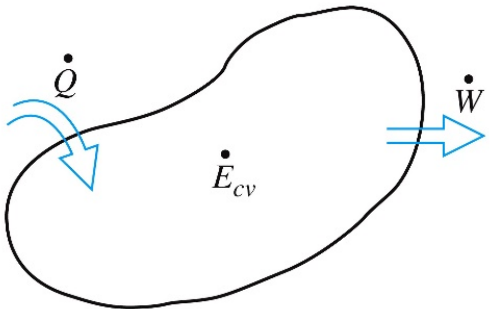


Examples of external (macroscopic) energy
(potential energy vs kinetic energy)

First Law of Thermodynamics and Energy Equation

- Then, energy equation for a control mass can be easily expressed as:

$$\Delta \text{Energy} = +(\text{In}) - (\text{Out})$$ → ***Energy Conservation***



$$\frac{dE_{cv}}{dt} = \dot{E}_{cv} = \dot{Q} - \dot{W} = +in - out$$

→ ***rate basis (per time)***

$$dE_{cv} = dU + d(KE) + d(PE) = \delta Q - \delta W$$ → ***infinitesimal change***

$$\int_1^2 dE_{cv} = \int_1^2 [dU + d(KE) + d(PE)] = \int_1^2 \delta Q - \int_1^2 \delta W$$

$$E_{cv,2} - E_{cv,1} = U_2 - U_1 + \frac{1}{2} m\left(V_2^2 - V_1^2\right) + mg\left(Z_2 - Z_1\right) = {}_1Q_2 - {}_1W_2$$

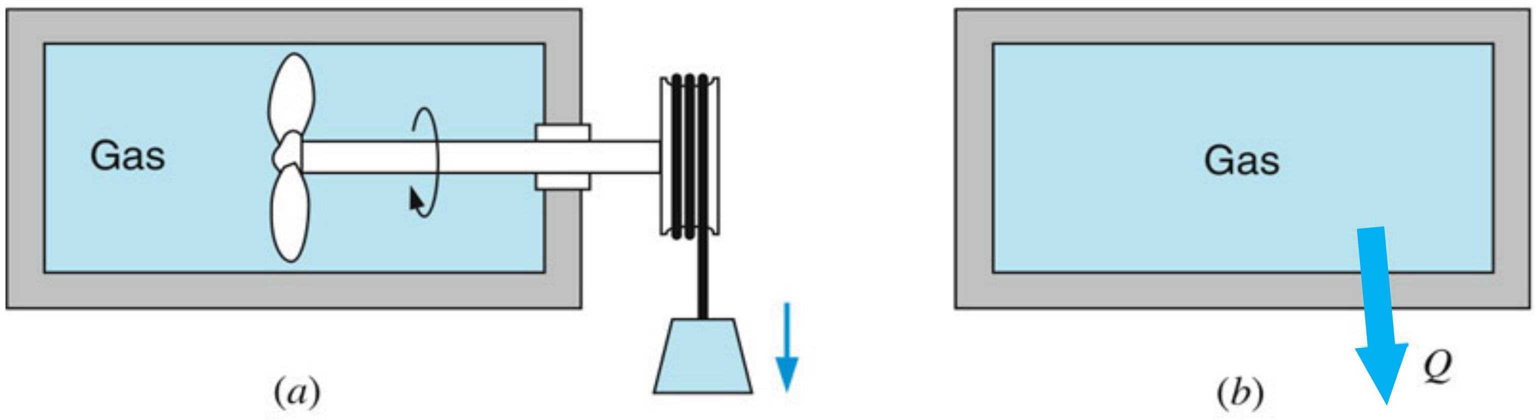
→ ***finite change from state 1 to state 2***

3.2 The First Law of Thermodynamics

➔ The first law of thermodynamics states:

"During any cycle a system undergoes, the cyclic integral of the heat is proportional (or equal) to the cyclic integral of the work."

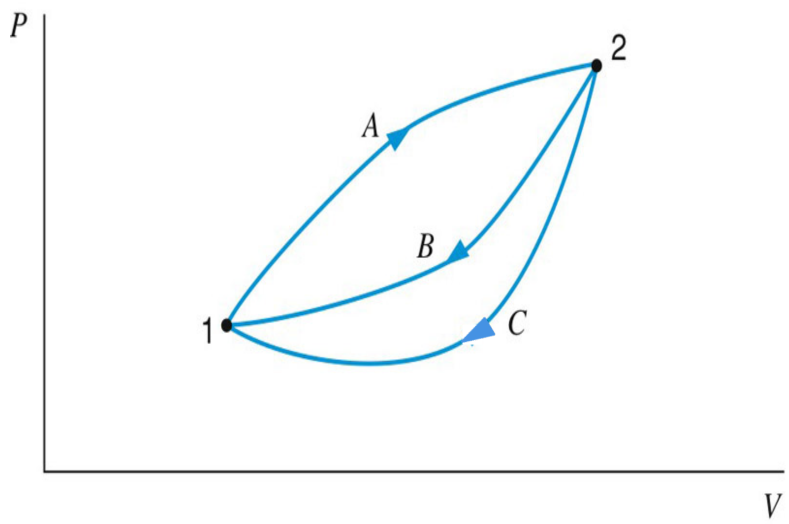
$$\oint \delta Q = \oint \delta W$$



For a thermodynamic cycle, initial gas state should be equal to final gas state.

- Now consider a control mass that undergoes a change of state.
  From the first law of thermodynamics,

$$\oint \delta Q = \oint \delta W$$



Case 1: $1 \xrightarrow{A} 2 \xrightarrow{B} 1$

$$\int_1^2 \delta Q_A + \int_2^1 \delta Q_B = \int_1^2 \delta W_A + \int_2^1 \delta W_B$$

Case 2: $1 \xrightarrow{A} 2 \xrightarrow{C} 1$

$$\int_1^2 \delta Q_A + \int_2^1 \delta Q_C = \int_1^2 \delta W_A + \int_2^1 \delta W_C$$

First Law of Thermodynamics and Energy Equation

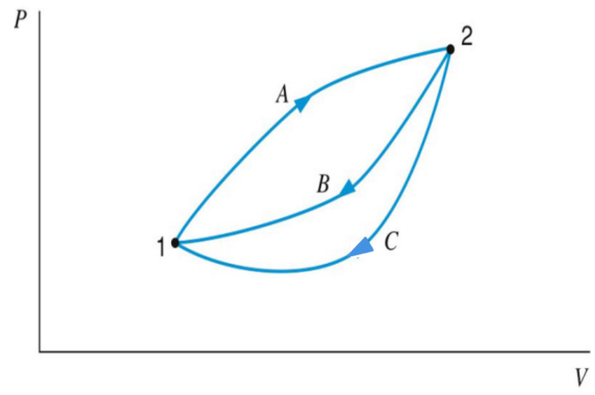
- Here,

$$\int_1^2 \delta Q_A + \int_2^1 \delta Q_B = \int_1^2 \delta W_A + \int_2^1 \delta W_B$$

$$-\Big) \quad \int_1^2 \delta Q_A + \int_2^1 \delta Q_C = \int_1^2 \delta W_A + \int_2^1 \delta W_C$$

$$\int_2^1 \delta Q_B - \int_2^1 \delta Q_C = \int_2^1 \delta W_B - \int_2^1 \delta W_C$$

$$\int_2^1 (\delta Q_B - \delta W_B) = \int_2^1 (\delta Q_C - \delta W_C)$$



Then, the value $\delta Q - \delta W$ doesn't depend on the path, but only on the initial and final state of the process. → Point function!

- Define a thermodynamic property of a substance, Energy(*E*), as:

$$\delta Q - \delta W = dE$$

$${}_1Q_2 - {}_1W_2 = E_2 - E_1$$

$$\Delta \text{Energy} = +(\text{In}) - (\text{Out})$$

→ Same with energy equation

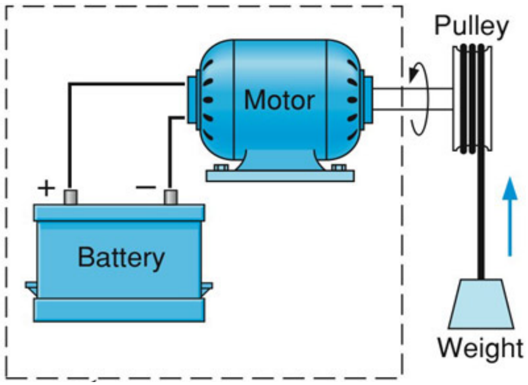
3.3 Definition of Work

- Work is an important way of energy transfer in thermodynamics!
- In general physics, work is defined as a force F acting through a displacement x, where the displacement is in the direction of the force:

$$\delta W = F \cdot dx \;\rightarrow\; W = \int_1^2 F \cdot dx$$

- In thermodynamics, the direction of work transfer across the system boundary is important.

outward : work done by a system (output)
inward : work done on a system (input)



First Law of Thermodynamics and Energy Equation

- Work is the product of force and distance and the unit for work in SI units is *joule (J)*:

$$1\,J = 1\,N \cdot m$$

- Power is the time rate of doing work and the unit for power in SI units is *watt (W)*:

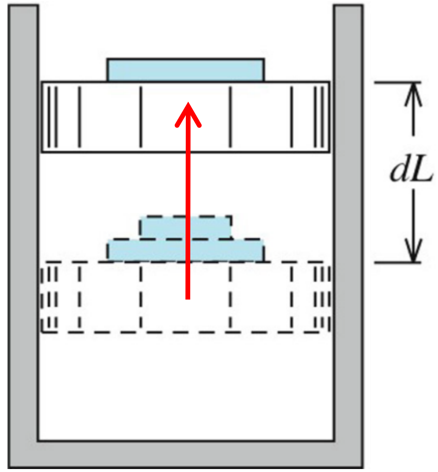
$$\dot{W} \equiv \frac{\delta W}{dt} \quad \rightarrow \quad 1\,W = 1\,\mathrm{J/s}$$

- Specific work is the work per unit mass of the system:

$$w \equiv \frac{W}{m}\,(\mathrm{J/kg})$$

3.4 Work done at the moving boundary of a simple compressible system

➔ Let's consider the moving piston in a cylinder where the volume of a simple compressible substance changes in a quasi-equilibrium process.



$$\delta W = F dL$$

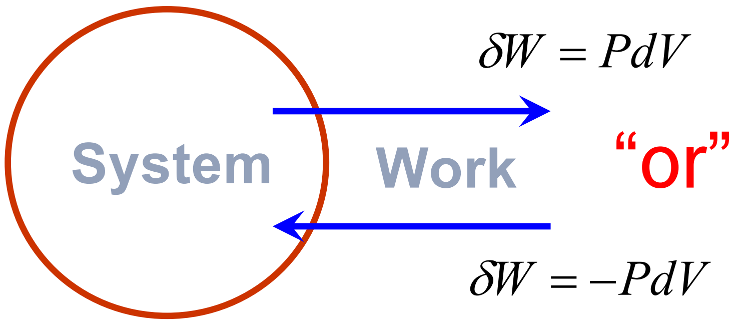
$$\delta W = P\, A\, dL$$

$$\delta W = P\, dV$$

$${}_1W_2 = \int_1^2 F dL = \int_1^2 P dV$$

$$dV : + \quad \Rightarrow \quad W : \text{outward}$$

$$dV : - \quad \Rightarrow \quad W : \text{inward}$$

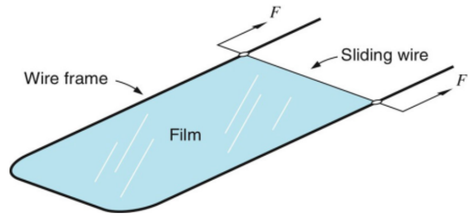


(Ref.) General Systems that Involve Work

Simple compressible system $\quad {}_1W_2 = \int_1^2 P\,dV$

Stretched wire $\quad {}_1W_2 = -\int_1^2 \mathscr{T}\,dL$

Surface film $\quad {}_1W_2 = -\int_1^2 \mathscr{S}\,dA$



System in which the work is completely electrical $\quad {}_1W_2 = -\int_1^2 \mathscr{E}\,dZ$

$$\delta W = P\,dV - \mathscr{T}\,dL - \mathscr{S}\,dA - \mathscr{E}\,dZ + \cdots$$

○ Intensive property

□ Extensive property

$$\dot{W} = \frac{dW}{dt} = P\dot{V} - \mathscr{T}\mathbf{V} - \mathscr{S}\dot{A} - \mathscr{E}\dot{Z} + \cdots$$

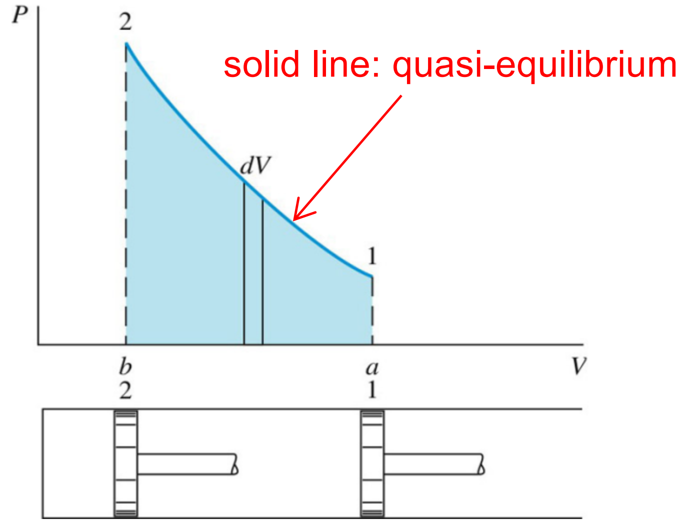
- Pressure-Volume (P-V) diagram is widely used to represent the states and processes of a simple compressible substance.

$$W = \int_1^2 \delta W = \int_1^2 P dV$$

=area under curve 1-2

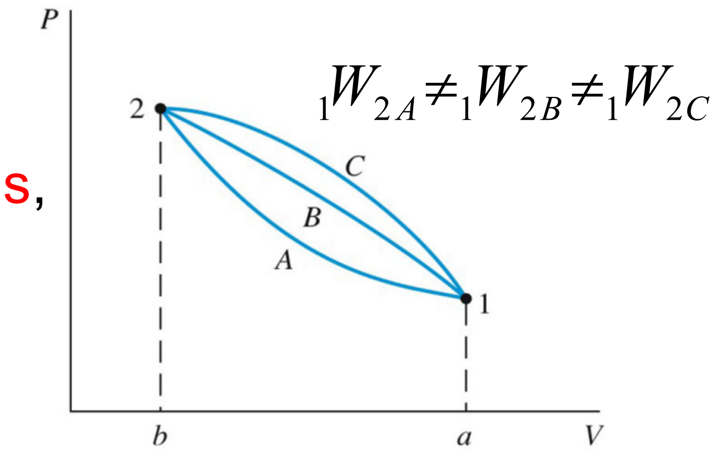
$$dV : + \quad \Rightarrow \quad W : \text{outward} \ \ (2 \rightarrow 1)$$

$$dV : - \quad \Rightarrow \quad W : \text{inward} \ \ (1 \rightarrow 2)$$



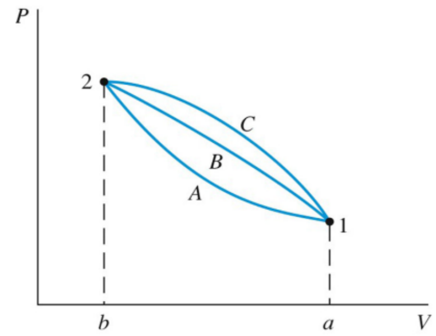
- Work is path function or, in a mathematical term, inexact differential(e.g. δW).
- Thermodynamic properties are point functions, or exact differential(e.g. dV).

$$\Delta V = \int_1^2 dV = V_2 - V_1$$



- To evaluate the following integral, the relationship between P and V should be given:

$$W = \int_1^2 \delta W = \int_1^2 P dV$$



- One common example is a polytropic process, where

$$PV^n = Const. = C \quad \text{or} \quad P = \frac{C}{V^n}$$ n: polytropic coefficient $(-\infty \sim +\infty)$

$n \neq 1$

$$_1W_2 = \int_1^2 \delta W = \int_1^2 P dV = \int_1^2 \frac{C}{V^n} dV = \int_1^2 C V^{-n} dV$$

$$= C \cdot \left[\frac{V^{1-n}}{1-n} \right]_1^2 = \frac{C}{1-n}\left(V_2^{\,1-n} - V_1^{\,1-n} \right) = \frac{P_2V_2 - P_1V_1}{1-n}$$

$n = 1$

$$_1W_2 = \int_1^2 \delta W = \int_1^2 P dV = \int_1^2 \frac{C}{V} dV = C \ln \frac{V_2}{V_1} = P_1V_1 \ln \frac{V_2}{V_1}$$

- For non-equilibrium process in a system, consider external force and volume changes by surroundings.

$$P_{ext} = F_{ext} / A = P_0 + m_p g / A$$

$${}_1W_2 = \int_1^2 P_{ext} dV = P_{ext}(V_2 - V_1)$$