Thermodynamics I

Chapter 3

Energy Transfer by Heat, Work, and Mass

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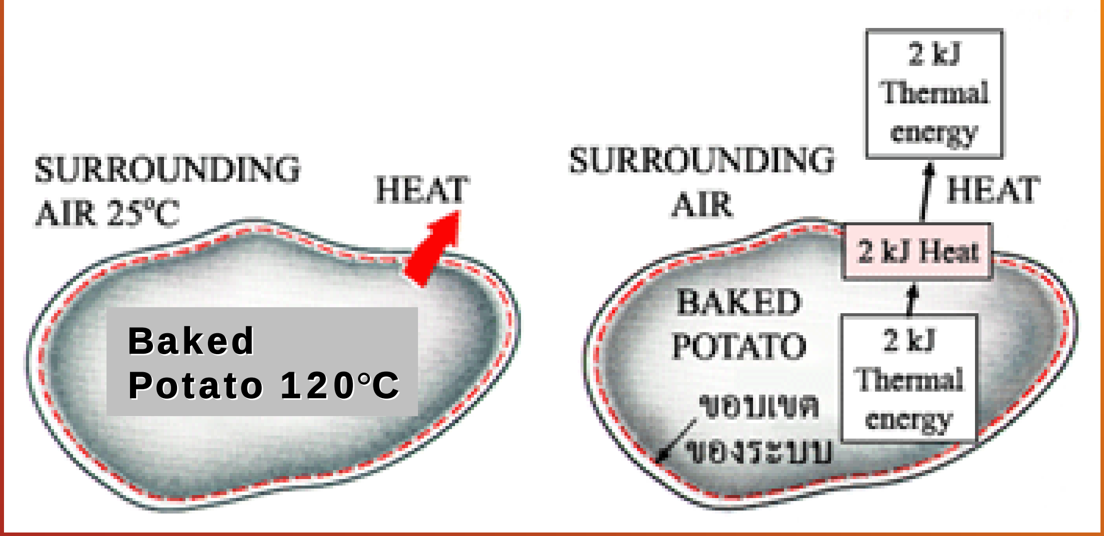
Heat Transfer

- **Heat** :- the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.



Heat Transfer

- Heat has energy unit kJ (or Btu)
- Heat transferred between state 1 and 2 is denoted by Q_{12} or just Q.
- Heat transfer per unit mass of a system is denoted by q.

$$q = \frac{Q}{m} \quad \text{(kJ/kg)}$$

Heat Transfer

- Heat transfer rate :- amount of heat transferred per unit time, denoted by $\dot{Q}$.
- Amount of heat transferred during process determined by

$$Q = \int_{t_1}^{t_2} \dot{Q}\, dt \qquad \text{(kJ)}$$

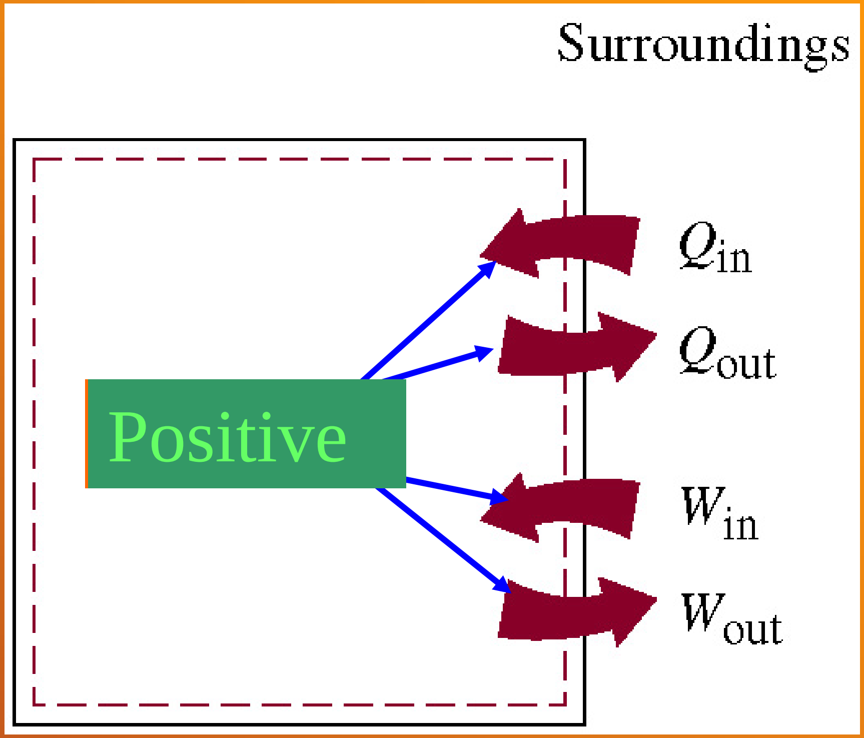
Energy Transfer by Work

- **Work** :- the energy transfer associated with a force acting through a distance.
- Work is also a form of energy transferred like heat, therefore has unit of energy such as kJ.
- Work done during a process between state 1 and 2 is denoted by W_{12} or just W.
- Work done per unit mass

$$w = \frac{W}{m} \qquad \text{(kJ/kg)}$$

Energy Transfer

- Formal sign convention
  - Heat transfer *to* a system and work *done by* a system are positive
  - Heat transfer *from* a system and work *done on* a system are negative



Energy Transfer

- Heat and Work are energy transfer mechanisms between system and its surroundings
  - Both are recognized at boundaries of a system that is both heat and work are *boundary phenomena*
  - System posses energy, but not heat and work
  - Both are associated with *process*, **not a state**. Unlike properties, heat and work has no meaning at a state
  - Both are *path function* (i.e. their magnitudes depend on the path followed during a process as well as the end states (start and end).)

Energy Transfer

- Heat and work are *path function*.
- Path functions have *inexact differential* designed by symbol δ.
- Differential amounts of heat and work are δQ and δW, respectively.
- Properties are point functions.
- Point functions have *exact differential* designed by symbol d.
- Example of differential of volume is dV.

Energy Transfer

- Total volume change during a process between states 1 and 2 is

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

- Total work done during process 1—2 is

$$\int_1^2 \delta W = W_{12} \qquad (\text{not } \Delta W)$$

Electrical Work

- Electrical power is the rate of work done by electrical charge.
- Electrical work done during a time interval can expressed in terms of current I and potential difference V.

$$W_e = \int_1^2 VI\,dt \quad \text{(kJ)}$$

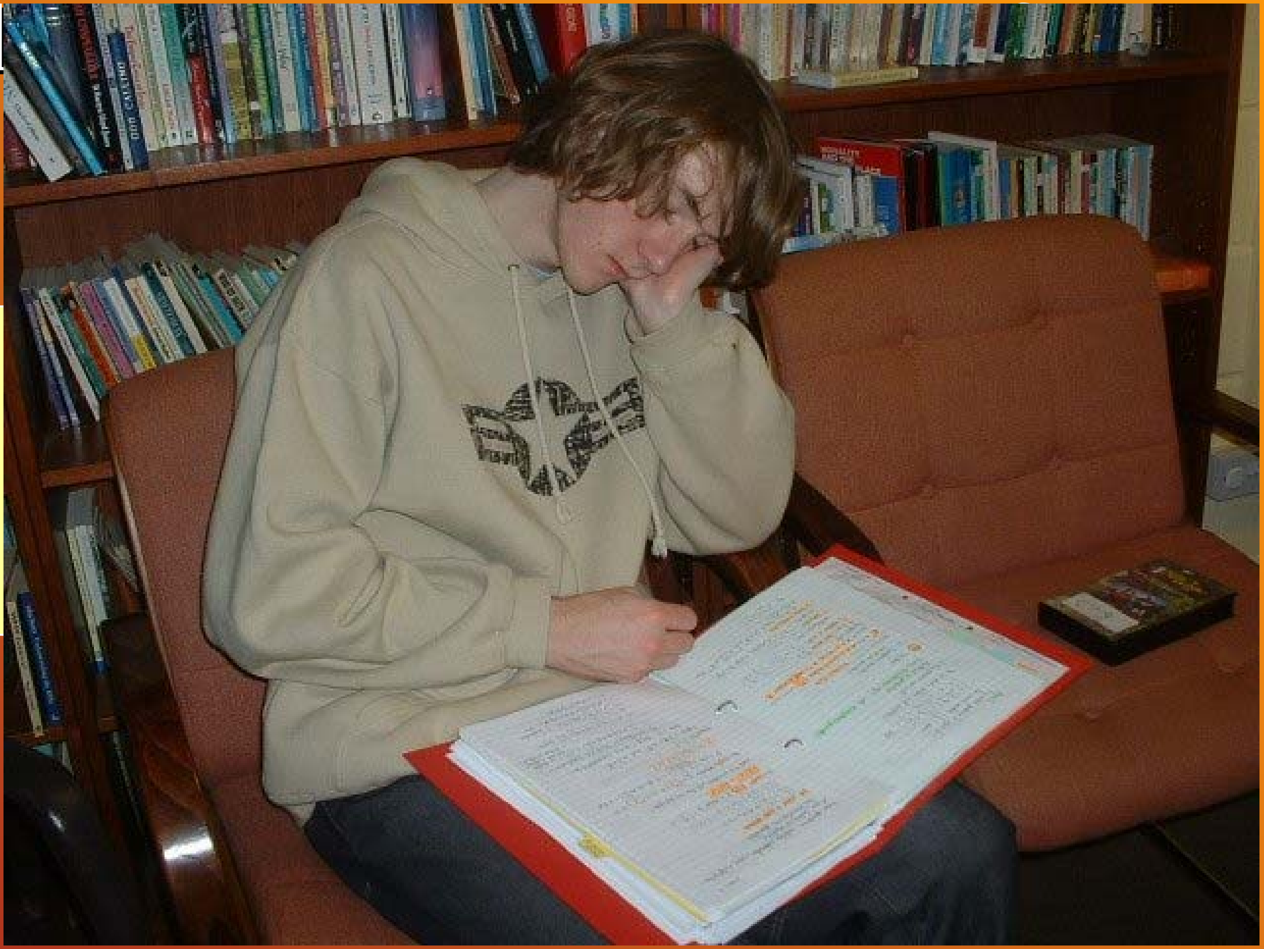
$$\text{or} \quad W_e = VI\Delta t \quad \text{(kJ)}$$

Mechanical Forms of Work

- The work d
  applied (F)

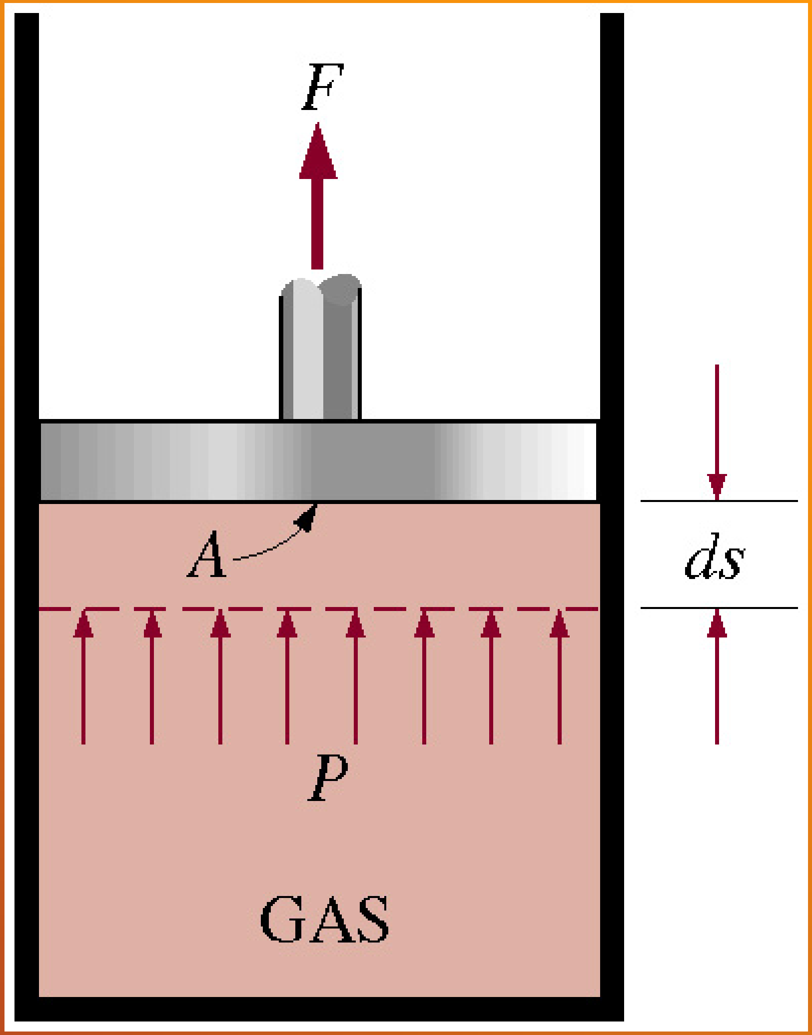
$W =$

If there is no movement, no work is done.

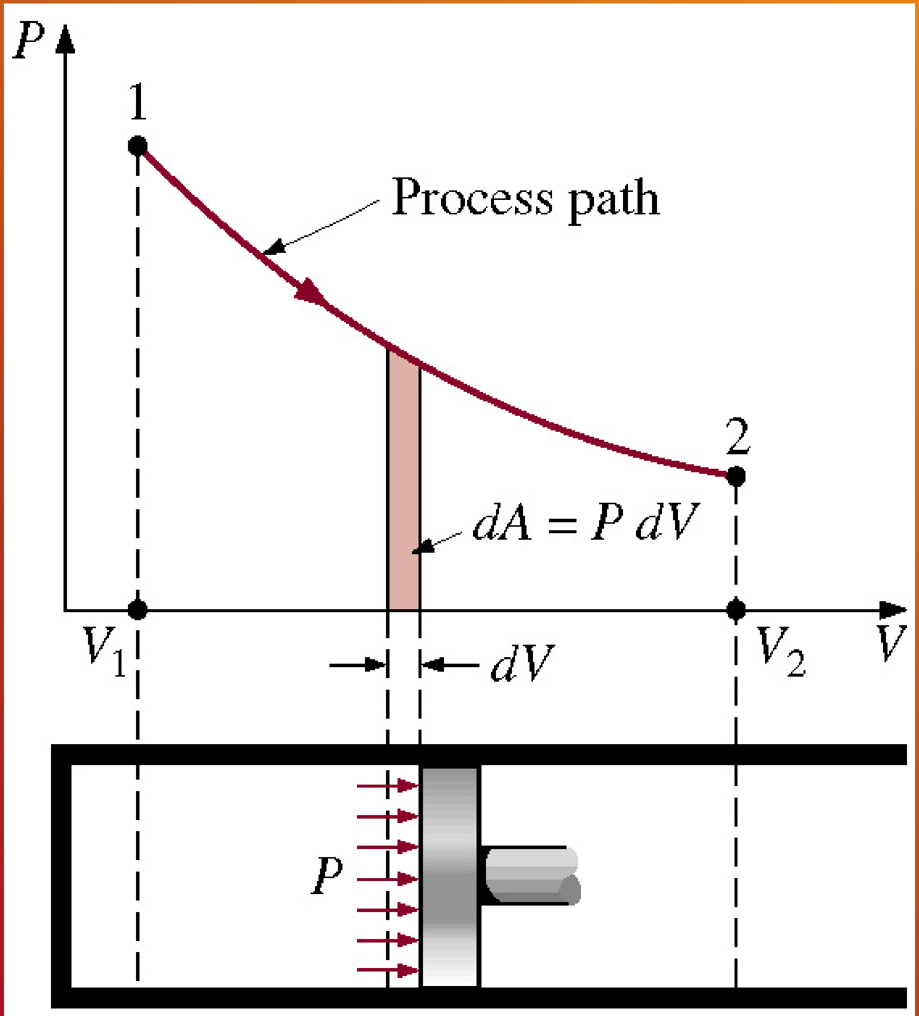


Moving Boundary Work

- The expansion and compression work is often called *moving boundary work* or simply *boundary work*.



Moving Boundary Work



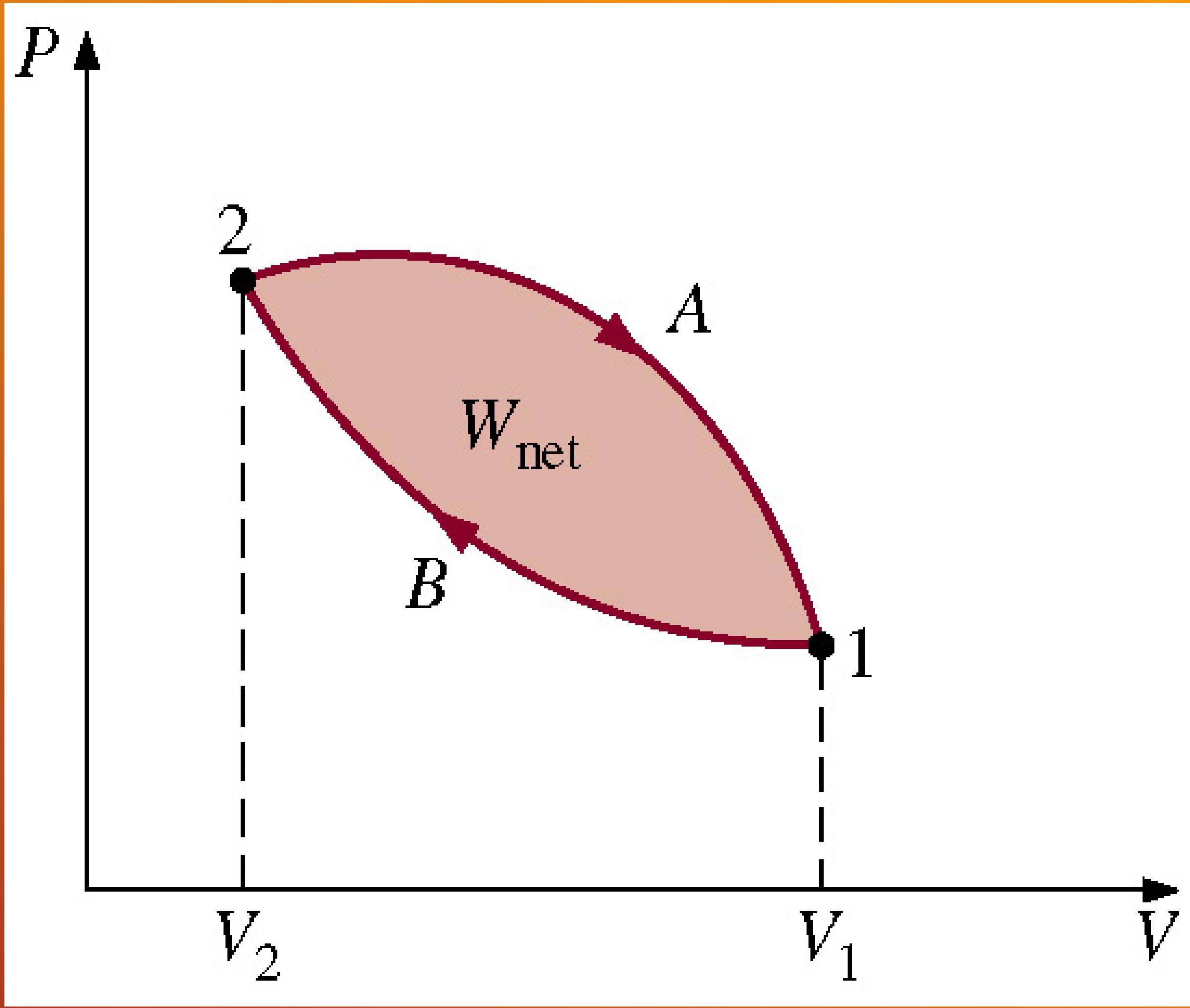
$$\delta W_b = F\,ds = PAds = PdV$$

$$W_b = \int_1^2 PdV \quad \text{(kJ)}$$

Area under the process curve on P-V diagram is equal, in magnitude, to the work done during a quasi-equilibrium expansion or compression process of a closed system.

Boundary Work

The net work done during a cycle is the difference between the work done by the system and the work done on the system.



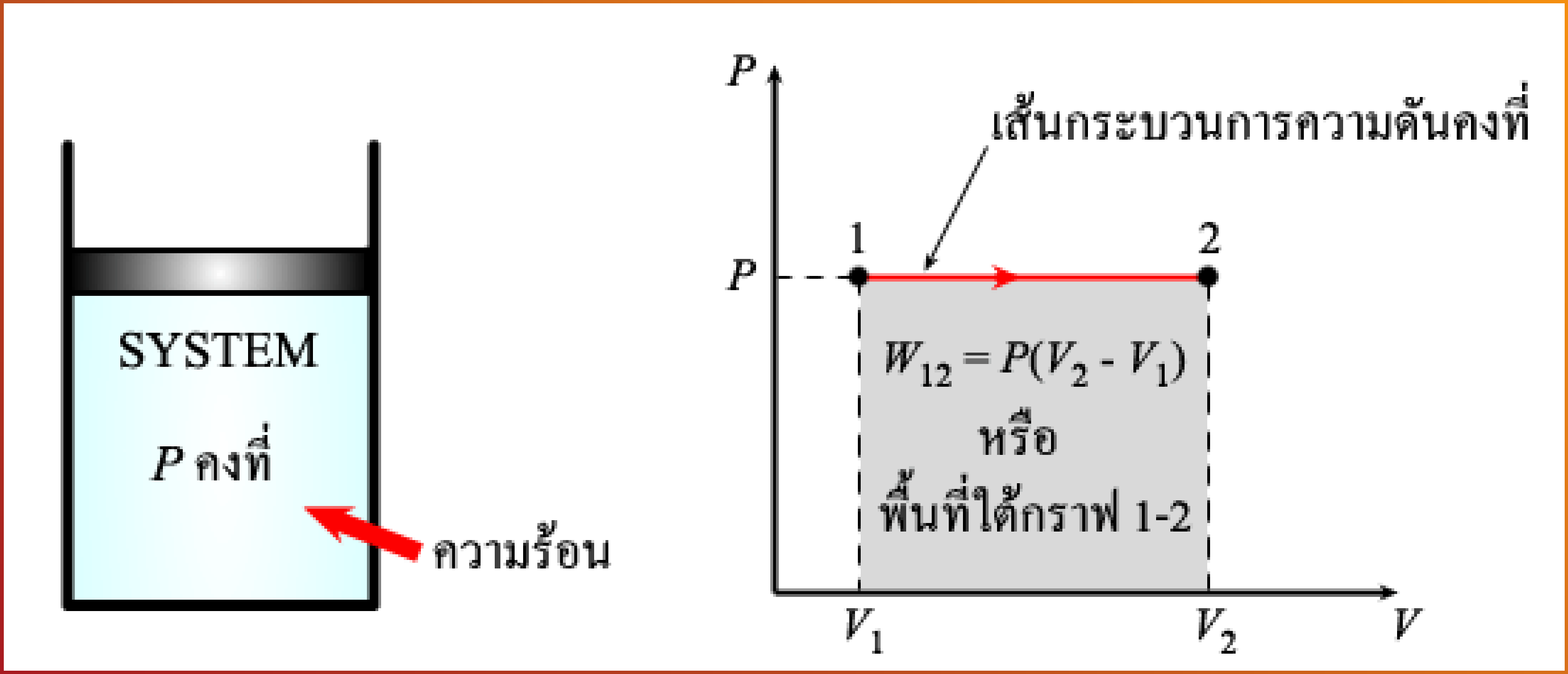
Constant Volume Process

- During a process where volume of the system is kept constant, the boundary work is then equal to zero ($dV = 0$)

$$W_{12} = \int_1^2 P dV = 0$$

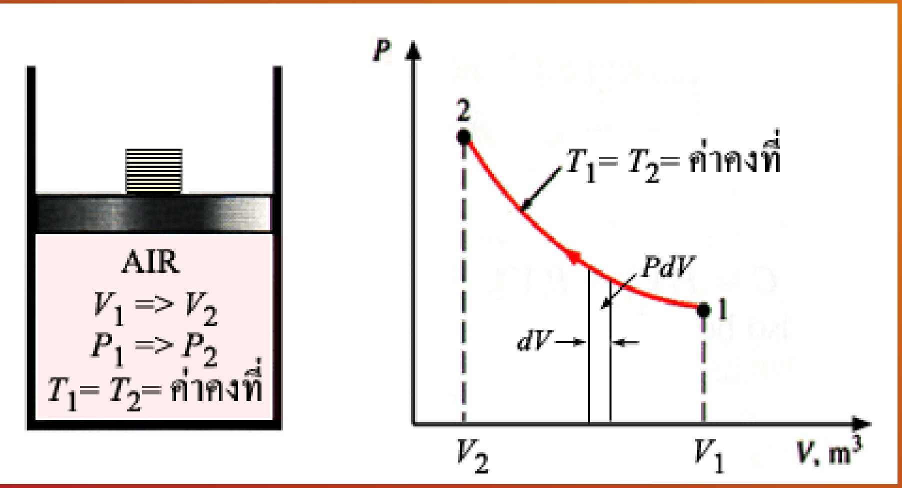
Isobaric Process

- A constant pressure process is called *isobaric process*.



Isothermal Process

- A constant temperature process is called *isothermal process*.



For ideal gas

$$P = \frac{mRT}{V}$$

$$W_b = \int_1^2 \frac{mRT}{V} dV = mRT \ln\left[\frac{V_2}{V_1}\right]$$

Polytropic Process

- During actual expansion and compression processes of gases, pressure and volume are often related by $PV^n = C$, where n and C are constants.
- A process of this kind is called a *polytropic process*.

Polytropic Process

$$P = CV^{-n}$$

$$W_b = \int_1^2 PdV = \int_1^2 CV^{-n}dV$$

$$W_b = \left[\frac{CV^{-n}}{-n+1}\right]_1^2 = \left[\frac{CV_2^{-n+1} - CV_1^{-n+1}}{1-n}\right]$$

$$C = P_1V_1^n = P_2V_2^n$$

$$W_b = \frac{P_2V_2^nV_2^{-n+1} - P_1V_1^nV_1^{-n+1}}{1-n}$$

$$W_b = \frac{P_2V_2 - P_1V_1}{1-n}$$

For ideal gas $PV = mRT$

$$W_b = \frac{mR(T_2 - T_1)}{1-n}$$

where $n \neq 1$

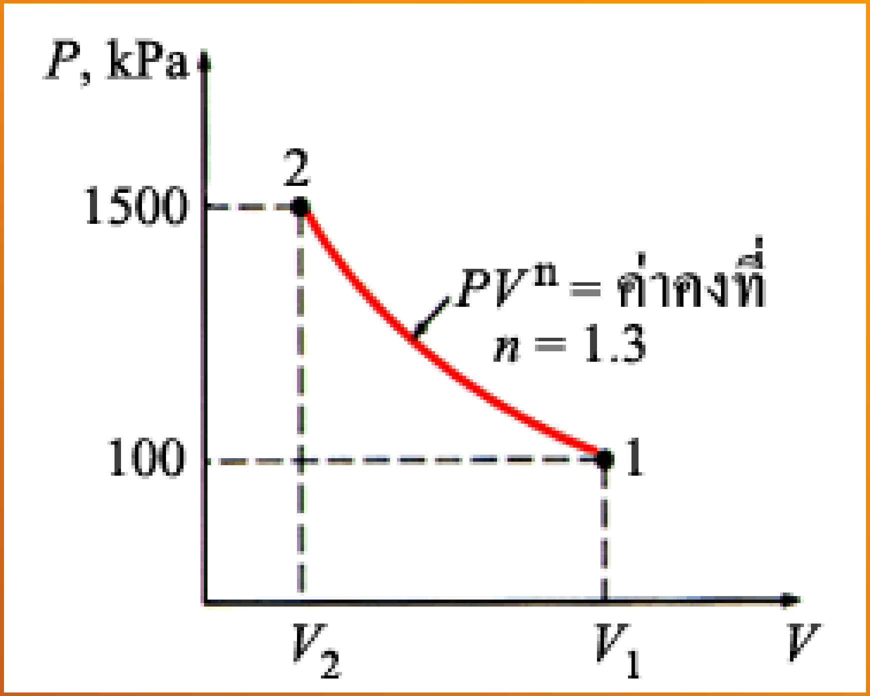
Polytropic Process

- For the special case of *n = 1* the boundary work becomes

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-1}\,dV = PV\ln\left(\frac{V_2}{V_1}\right)$$

Example

A piston-cylinder device initially contains 100 kg of air at 100 kPa and 300 K. The air is now compressed slowly according to the relation $PV^{1.3}$ = constant until it reaches a final pressure of 1500 kPa. Determine the work done during this process.
(R = 0.287 kJ/kg.K)



Gravitational Work

- Potential energy change equation is derived from

$$\vec{F} = m\vec{g}$$

$$W_g = \int_1^2 F dZ = mg\int_1^2 dZ = mg(Z_2 - Z_1)$$

Acceleration Work

- Kinetic energy change equation is derived

$$F = ma$$

$$a = \frac{dV}{dt}$$

$$F = m\frac{dV}{dt}$$

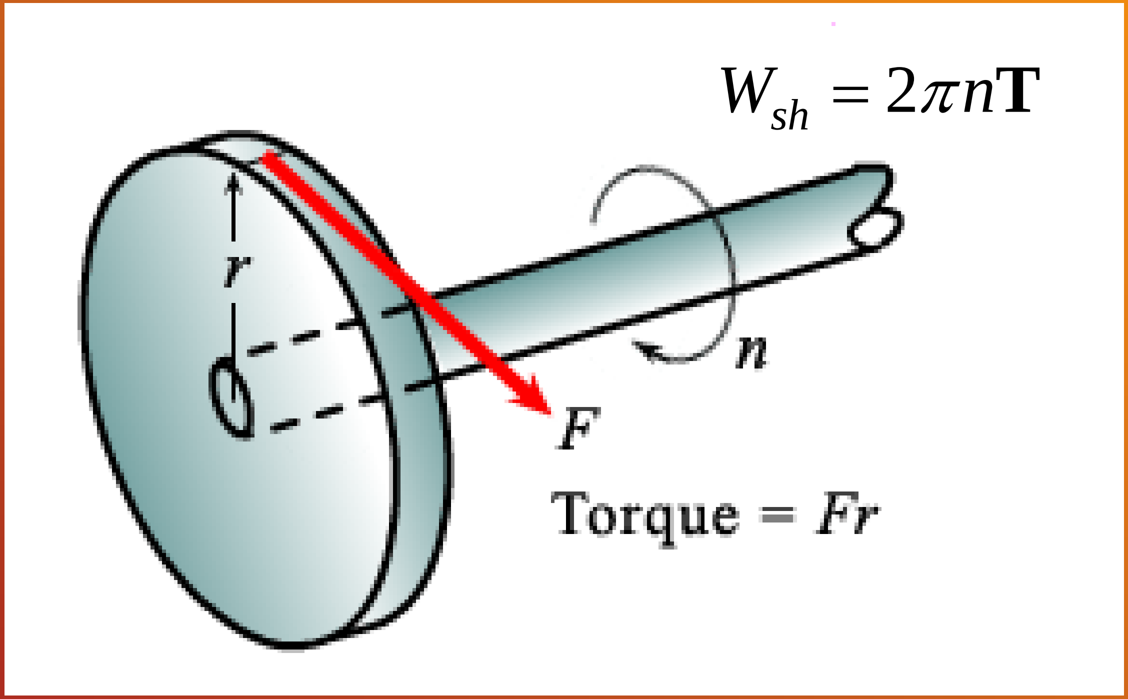
$$V = \frac{ds}{dt}$$

$$ds = Vdt$$

$$W_a = \int_1^2 Fds = \int_1^2 \left[m\frac{dV}{dt} \right] Vdt = m\int_1^2 VdV$$

$$W_a = \frac{1}{2}m(V_2^2 - V_1^2) \;\; \text{kJ}$$

Shaft Work



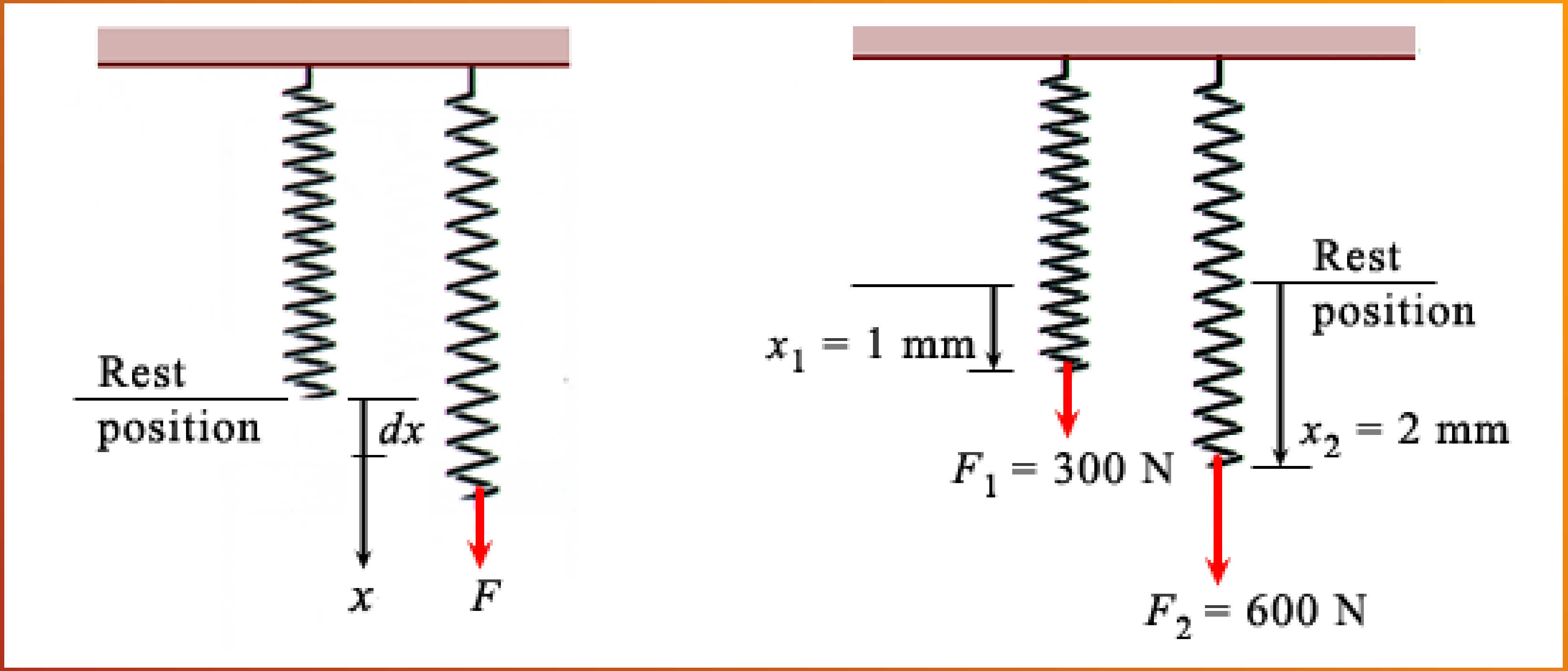
$$\mathbf{T} = Fr$$

$$F = \frac{\mathbf{T}}{r}$$

$$s = (2\pi r)n$$

$$W_{sh} = Fs = \left[\frac{\tau}{r}\right](2\pi rn) = 2\pi n\mathbf{T} \ \ \text{(kJ)}$$

Spring Work



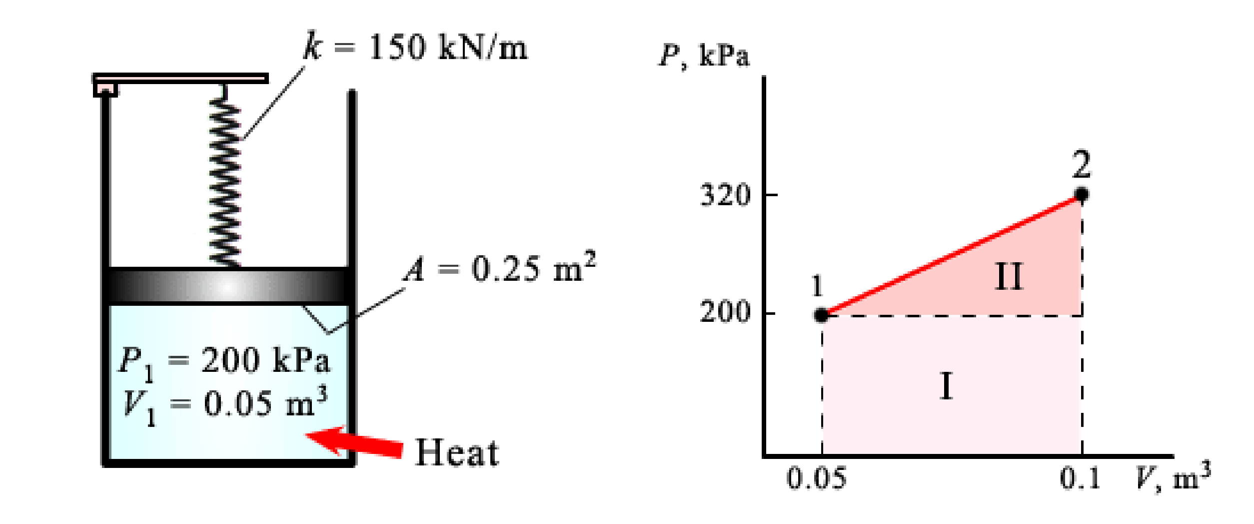
$$\delta W_{\text{spring}} = F\,dx$$

$$F = kx$$

$$W_{\text{spring}} = \frac{1}{2}k(x_2^2 - x_1^2)$$

Example

A piston-cylinder device contains 0.05 m^3 of a gas initially at 200 kPa. At this state a linear spring which has a spring constant of 150 kN/m is touching the piston but exerting no force on it. Now heat is transferred to the gas, causing the piston to rise and to compress the spring until the volume inside the cylinder doubles. If the cross-sectional area of the piston is 0.25 m^2, determine (a) the final pressure inside the cylinder, (b) the total work done by the gas, and (c) the fraction of this work done against the spring to compress it.



Conservation of Mass Principle

- Net mass transfer to or from a system during a process is equal to the net change (increase or decrease) in the total mass of the system during that process

$$\begin{pmatrix} \text{Total mass} \\ \text{entering the system} \end{pmatrix} - \begin{pmatrix} \text{Total mass} \\ \text{leaving the system} \end{pmatrix} = \begin{pmatrix} \text{Net change in mass} \\ \text{within the system} \end{pmatrix}$$

$$m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}} \qquad (\text{kg})$$

Conservation of Mass Principle

- Mass balance for a control volume

$$\sum m_i - \sum m_e = \left(m_2 - m_1 \right)_{\text{system}}$$

- Can be written in rate form

$$\sum \dot{m}_i - \sum \dot{m}_e = dm_{\text{system}} / dt$$

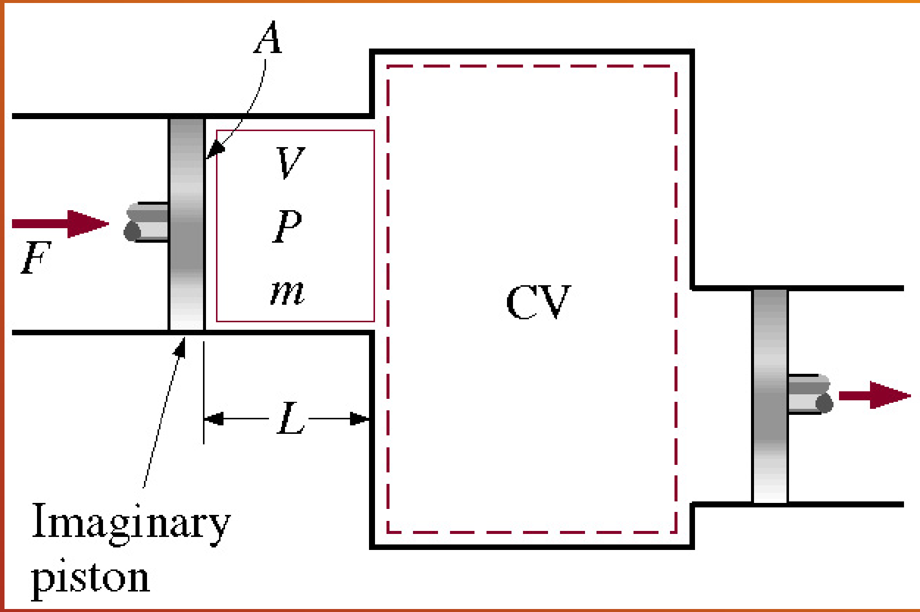
Conservation of Mass Principle

- Mass balance for steady-flow processes

$$\begin{pmatrix}\text{Total mass entering CV}\\ \text{per unit time}\end{pmatrix} = \begin{pmatrix}\text{Total mass leaving CV}\\ \text{per unit time}\end{pmatrix}$$

$$\sum m_i = \sum m_e \quad (\text{kg/s})$$

Flow Work and The Energy of A Flowing Fluid



$$F = PA$$

$$W_{\text{flow}} = FL = PAL = PV \quad \text{(kJ)}$$

$$w_{\text{flow}} = Pv \quad \text{(kJ/kg)}$$

Total Energy of a Flowing Fluid

- Total energy of simple compressible system per unit mass

$$e = u + \mathrm{ke} + \mathrm{pe} = u + \frac{\mathscr{V}^2}{2} + gz \quad (\mathrm{kJ/kg})$$

Total Energy of a Flowing Fluid

- Total energy of a flowing fluid per unit mass

$$\theta = Pv + e = Pv + (u + \mathrm{ke} + \mathrm{pe})$$

$$\theta = h + \mathrm{ke} + \mathrm{pe} = h + \frac{\mathscr{V}^2}{2} + gz \quad (\mathrm{kJ/kg})$$

Total Energy of a Flowing Fluid