Basic Concepts, Work & Heat Transfer

Dr. Md. Zahurul Haq, *Ph.D., CEA, FBSME, FIEB*

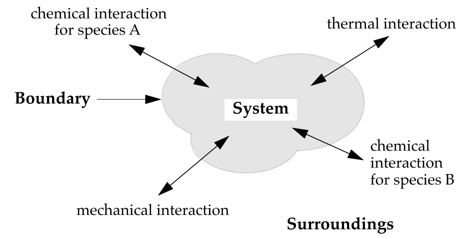
Professor
Department of Mechanical Engineering
Bangladesh University of Engineering & Technology (BUET)
Dhaka-1000, Bangladesh

http://zahurul.buet.ac.bd/

ME 6101: Classical Thermodynamics

http://zahurul.buet.ac.bd/ME6101/

Thermodynamic System



T1566

system – a collection of things with a physical or conceptual boundary between it and the outside world; the particular focus of the thermodynamic analysis at hand
environment or surroundings – what is outside the system
universe/world – everything; the system plus its surroundings
isolated system – a system where absolutely nothing in the surroundings interacts with it and where nothing crosses the system boundaries
closed system – energy (heat) can cross the boundaries, but matter cannot
open system – matter and energy (heat) can cross the boundaries

T1565

change of state – a change in any of the macroscopic thermodynamic properties E, V, N, T, P, or μ; a change to a different set of equilibrium conditions
path – a progression in changes in the state of a system (e.g., changes in variables like E, V, N, T, P, and μ) that describes the process of moving from one equilibrium state to another
adiabatic process – a process in which there is no heat transfer between the system and its surroundings
isothermal process – a process that occurs at constant temperature T
isochoric process – a process that occurs at constant volume V
isobaric process – a process that occurs at constant pressure P
T1567 **isentropic process** – a process in which the entropy S is constant

Boundary or reservoir	Process
Closed	Constant mass
Thermally insulated	Adiabatic
Rigid	Constant volume (isometric)
Closed and rigid	Constant density (isochoric)
Closed, rigid, insulated	Constant energy
Heat reservoir	Constant temperature (isothermal)
Mechanical reservoir	Constant pressure (isobaric)

T1726

Thermodynamic Equilibrium

A system in **Thermodynamic Equilibrium** satisfies the stringent requirements:

1. **Mechanical Equilibrium**: no unbalance forces acting on any part of the system or the system as a whole.
2. **Thermal Equilibrium**: no temperature differences between parts of the system or between the system and the surrounding.
3. **Chemical Equilibrium**: no chemical reactions within the system and no motion of any chemical species from one part to another part of the system.

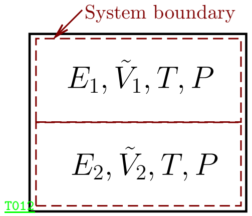
The conditions for equilibrium between two single-component systems are

(1) $T_1 = T_2$ **thermal equilibrium**
(2) $P_1 = P_2$ **mechanical equilibrium**
(3) $\mu_1 = \mu_2$ **chemical equilibrium**

T1369

State & Property

- The description of the condition of a system at a given instant is called its **State**.
- A **Property** is a quantity whose numerical value depends on the state but not on the history of the system. The origin of properties include those
  1. directly measurable
  2. defined by laws of thermodynamics
  3. defined by mathematical combinations of other properties.
- Two states are identical if, and only if, the properties of the two states are identical.
- **Intensive** properties are independent of the size or extent of the system. **Extensive** properties depend on the size or extent of the system. An extensive property is additive in the sense that its value for the whole system is the sum of the values for its parts.

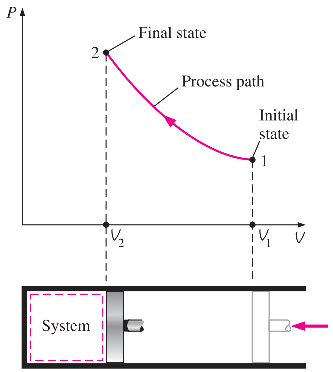


T011

$$\left.\begin{aligned} E_{system} &= E_1 + E_2 \\ \tilde{V}_{system} &= \tilde{V}_1 + \tilde{V}_2 \end{aligned}\right\} \text{Extensive Properties}$$

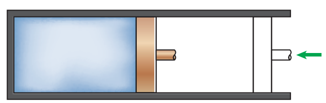
$$\left.\begin{aligned} T_{system} &= T_1 = T_2 \\ P_{system} &= P_1 = P_2 \end{aligned}\right\} \text{Intensive Properties}$$

Property	Extensive	Intensive
Mass	m	ρ
Volume	$\tilde{V}$	v
KE	$\frac{1}{2}mV^2$	$\frac{1}{2}V^2$
PE	mgZ	gZ
Total Energy	E	e
Internal Energy	U	u
Enthalpy	H	h
Entropy	S	s

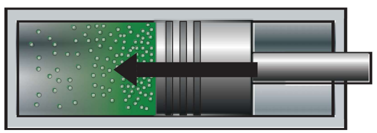


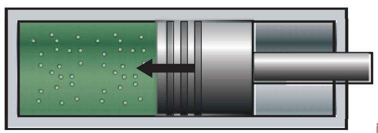
T077


(a) Slow compression (quasi-equilibrium)

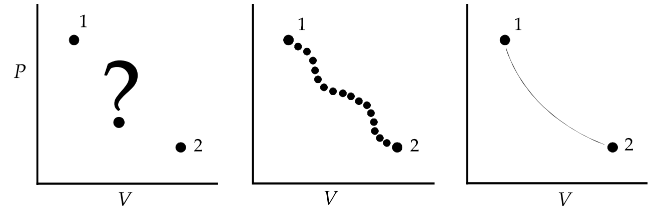

(b) Very fast compression (nonquasi-equilibrium)

T076


T150 (a) Rapid compression requires more work.


(b) Slow compression is ideally reversible.

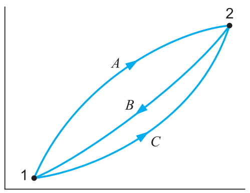
- A system is in **stable/equilibrium State** when no finite change of state can occur unless there is an interaction between the system and its environment which leaves a finite alteration in environmental state.
- During a **Quasi-static Process**, system is at all times infinitesimally near a state of thermodynamic equilibrium; hence, the process should be carried out infinitely slowly to allow the system to settle to a stable state at the end of each infinitesimal step.
- Theoretical calculations must relate to Stable states, since it is only for these we have thermodynamic data.



T1727 (a) finite irreversible process (b) quasi-static process (c) reversible change

Categories of Thermodynamics Quantities

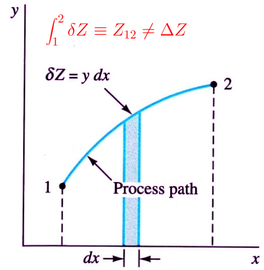
1. **State functions**: all properties are state functions.
2. **Process or Path functions**: quantities whose values depend on the path of the process.



T038

$$\int_1^2 dy = y_2 - y_1 = \Delta y \;\Rightarrow\; \oint dy = 0$$

State function



T013

Path function

Thermodynamic Work & Heat

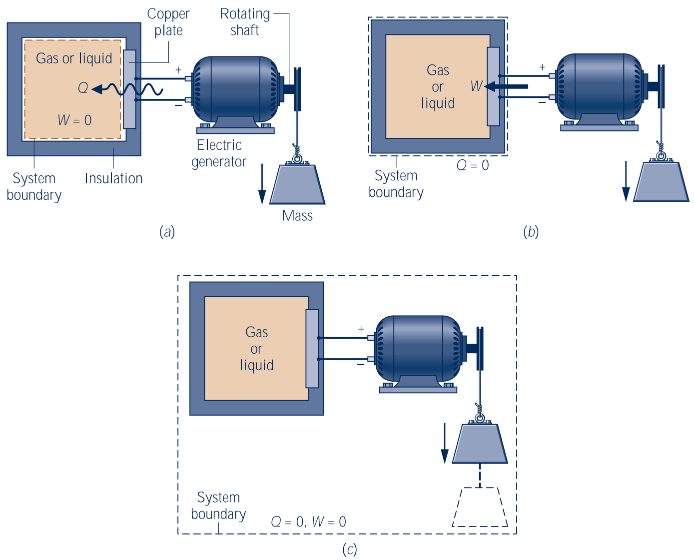
Work

is performed by a system **on** its surroundings during a process if the only effect external to the system **could be** the raising of a weight.

Heat

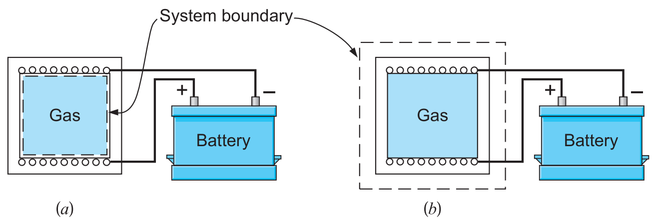
is energy in transition from one body or system to another solely because of a temperature difference between the systems.

- The magnitudes of heat and work depend on the arbitrary selection of boundaries between interacting systems. These are not properties, and it is improper to speak of heat or work 'contained' in a system.
- Heat and work transfers are the **only** mechanisms by which energy can be transferred across the boundary of a closed system.



T010

Comparison of Heat & Work

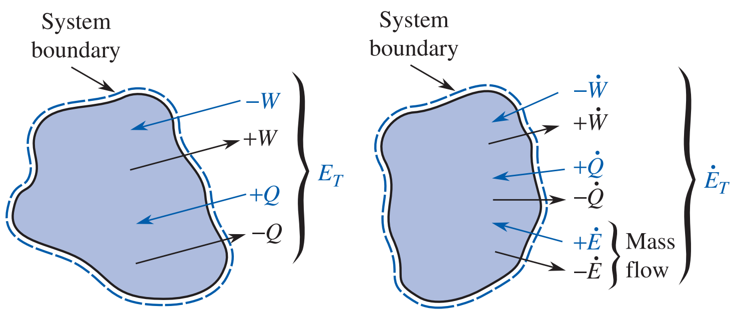


T023

An example of the difference between heat and work.

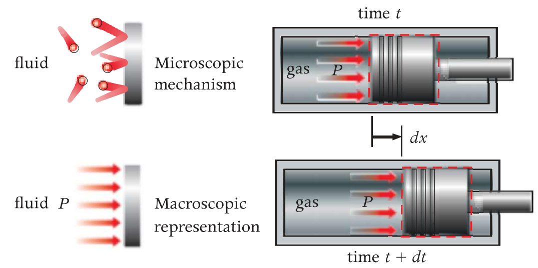
- Heat and work are both transient phenomena. Systems never possess heat or work.
- Both heat and work are boundary phenomena. Both are observed only at the boundary of the system, and both represent energy crossing the boundary.
- Both heat and work are path functions and inexact differentials.

Work & Heat: Sign-Convention



T004 (a) Closed system (b) Open system

Macroscopic work

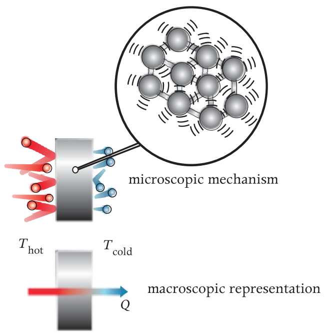


T1364

Pressure on a piston (a) and the macroscopic piston displacement (b)

Energy transfer as work refers to energy transfer (across a boundary) associated with microscopic motions which are observable macroscopically. The observability of the motion means that the motions of individual particles have some overall coherence.

Energy Transfer as Heat



T1365

Energy transfer as heat refers to that energy transfer, across a system boundary, associated with microscopic displacements that are not observable macroscopically. Heat transfer results in microscopic vibrations of the wall atoms, but not in macroscopically observable motion, so we cannot compute it as a force times an observable displacement.

General Work Expressions

- **Thermodynamic work** is generalized to include all forms of work, and a generalized force F_k and generalized displacement $d\delta_k$ can be identified:

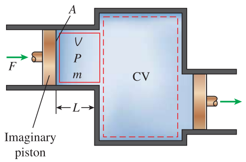
$$W_k = \int F_k d\delta_k$$

- A general system could have many possible work modes, so a general work expression is:

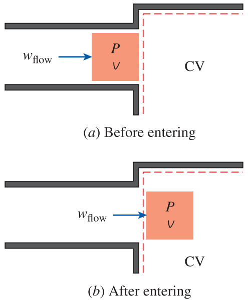
$$W = W_s + W_b + W_f + \cdots = \sum W_k$$

  - $W_s \equiv$ shaft work: rotary useful work
  - $W_b \equiv$ boundary work: due to expansion/compression of system
  - $W_f \equiv$ flow work: interaction required for the mass to cross CS
  - $W_l \equiv$ electrical work
  - ...

Flow Work



T1360



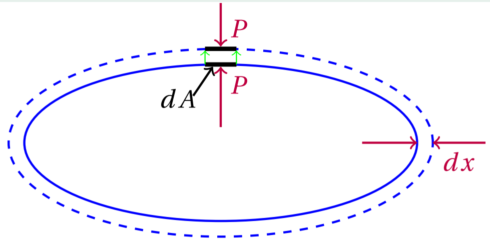
T1361

Flow work, W_f is associated with mass crossing the CS, and represents the work that must be done by fluid outside the control volume to push $\dot{m}$ across the control volume boundary.

- $W_{f,i} = -(PA_i)L_i$: as displacement against PA_i
- $W_{f,e} = +(PA_e)L_e$: as displacement along PA_e

$\Rightarrow W_f = W_{f,i} + W_{f,e} = -P(V_i - V_e)$

Moving System Boundary Work



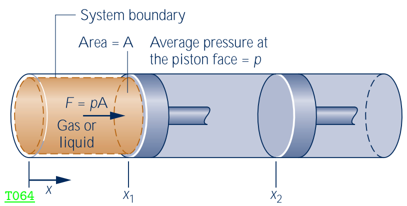
T1362

- Force acting on an element dA of CS $= PdA$
- Work performed as dA recedes by a distance $dx = (PdA)dx$
- Work done $= \delta W_b = \int\int_A PdAdx = P\int\int_A dAdx = PdV$

$$\boxed{\delta W_b = PdV \;\Rightarrow\; W_b = \int_1^2 PdV}$$

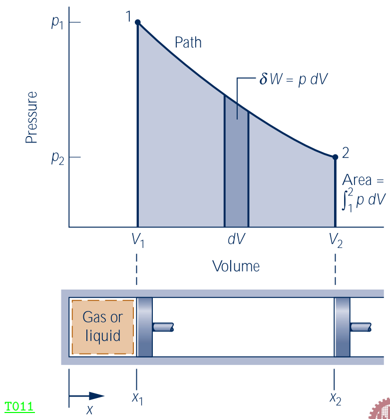
dV is the change in volume represented by the volume enclosed between the full and the broken curves in figure.

Expansion & Compression Work

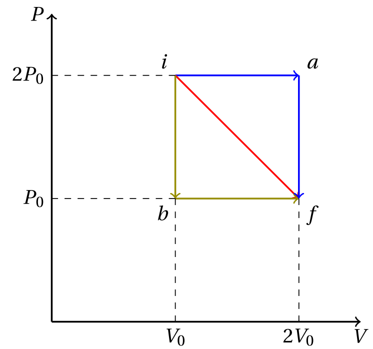


T064

$$\begin{aligned} \longrightarrow \delta W &= Fdx \\ &= PAdx \\ &= PdV \\ \Rightarrow W_{12} &= \int PdV \end{aligned}$$



T011

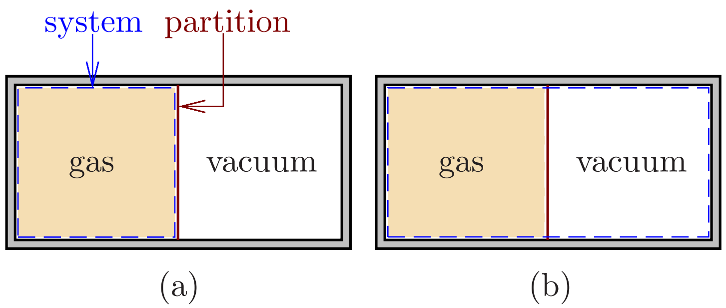


T1363

$$W_{i\to f} = \begin{cases} W_{if} & = \frac{3}{2}P_oV_o \\ W_{ia} + W_{af} & = 2P_oV_o + 0 = 2P_oV_o \\ W_{ib} + W_{bf} & = 0 + P_oV_o = P_oV_o \end{cases}$$

Work done by a system depends not only on the initial and final states but also on the intermediate states $\Rightarrow$ **path function**.

Process involving a change in volume with $W = 0$



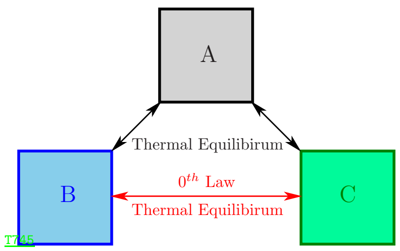
T022

- Work can only be identified at the system boundary.
- If gas & vacuum space is considered as system: no work is done as no work can be identified at the system boundary.
- If the gas is the system: there is a change in volume, but no resistance at the system boundary as the volume increases, and so no work is done in the process of filling the vacuum.

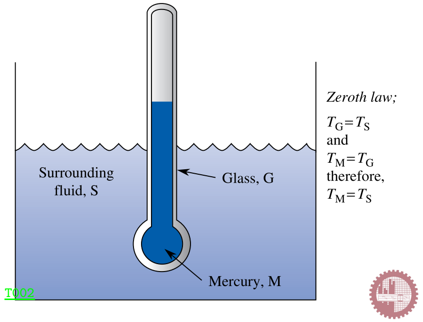
Zero'th Law of Thermodynamics

Zero'th Law of Thermodynamics

Two systems with thermal equilibrium with a third are in thermal equilibrium with each other.

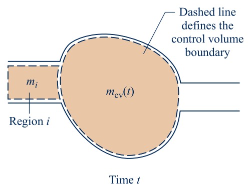


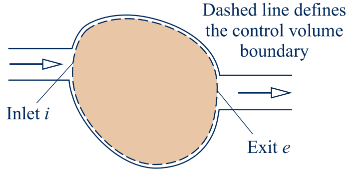
T745



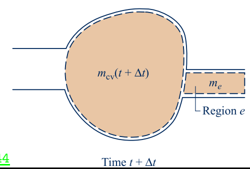
T002

Mass Continuity Equation





T443



T444

$\Rightarrow m_{cv}(t) + m_i = m_{cv}(t + \Delta t) + m_e$

$\Rightarrow m_{cv}(t + \Delta t) - m_{cv}(t) = m_i - m_e$

$\Rightarrow \frac{m_{cv}(t+\Delta t) - m_{cv}(t)}{\Delta t} = \frac{m_i - m_e}{\Delta t}$

- if $\Delta t \to 0 : \Rightarrow \frac{dm_{cv}}{dt} = \dot{m}_i - \dot{m}_e$

$$\boxed{\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e}$$

$$\boxed{\dot{m} = \rho A \mathbb{V} = \frac{A\mathbb{V}}{v} \text{ (for 1D flow)}}$$

Mass Balance: Transient Flow

$$\boxed{\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e \qquad \Rightarrow dm_{cv} = dm_i - dm_e}$$

$\Rightarrow \int_0^t \left(\frac{dm_{cv}}{dt}\right) dt = \int_0^t \left(\sum_i \dot{m}_i\right) dt - \int_0^t \left(\sum_e \dot{m}_e\right) dt$

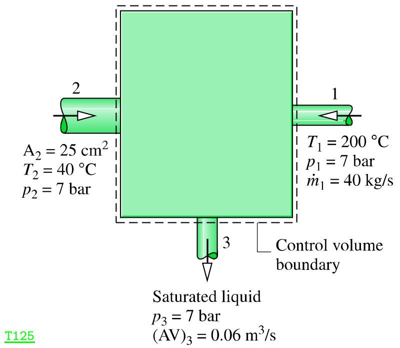
$\Rightarrow \Delta m_{cv} = m_{cv}(t) - m_{cv}(0) = \sum_i \left(\int_0^t \dot{m}_i dt\right) - \sum_e \left(\int_0^t \dot{m}_e dt\right)$

$m_i = \int_0^t \dot{m}_i \, dt$ { amount of mass entering the control volume through inlet i, from time 0 to t

$m_e = \int_0^t \dot{m}_e \, dt$ { amount of mass exiting the control volume through exit e, from time 0 to t

$$\boxed{\Delta m_{cv} = m_{cv}(t) - m_{cv}(0) = \sum_i m_i - \sum_e m_e}$$

Example: ▷ Feed-water heater at steady-state. Determine $\dot{m}_2$ & V_2. Assume, $v_2 \simeq v_f(T_2)$.



- $\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$

$\Rightarrow$ $dm_{cv}/dt = 0$

$\Rightarrow$ $\sum_i \dot{m}_i = \dot{m}_1 + \dot{m}_2$

$\Rightarrow$ $\sum_e \dot{m}_e = \dot{m}_3$

- $\dot{m} = \rho A \mathbb{V}$

$\Rightarrow$ $\dot{m}_3 = \rho_3 (A\mathbb{V})_3$

$\Rightarrow$ $\rho_2 = \rho(T = T_2, P = P_2) \quad \rho_3 = \rho(x = 0.0, P = P_3)$

$\Rightarrow$ $\dot{m}_2 = 14.15 \text{ kg/s}, \quad \mathbb{V}_2 = 5.7 \text{ m/s} \triangleleft.$