First Law of Thermodynamics

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Conservation of Energy for a CM System

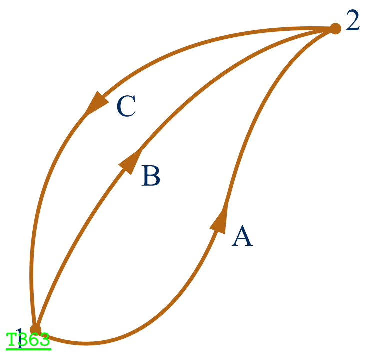
First Law of Thermodynamics (FLT)

When a system undergoes a cyclic change, the net heat to/from the system is equal to the net work from/to the system.

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

$$\text{Mechanical equivalent of heat, } J = \begin{cases} 4.1868 \text{ kJ/kcal} \\ 1.0 \text{ in SI unit} \end{cases}$$

First Law of Thermodynamics for a Change in State



$\Rightarrow \oint \delta W = J \oint \delta Q$

$\Rightarrow \oint \delta Q = \oint \delta W \qquad [J = 1.0 \text{ in SI unit}]$

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

$\Rightarrow \int_1^2 \delta Q_B + \int_2^1 \delta Q_C = \int_1^2 \delta W_B + \int_2^1 \delta W_C \quad ②$

- ①−② : $\int_1^2 \delta Q_A - \int_1^2 \delta Q_B = \int_1^2 \delta W_A - \int_1^2 \delta W_B$

$\Rightarrow \int_1^2 \delta Q_A - \int_1^2 \delta W_A = \int_1^2 \delta Q_B - \int_1^2 \delta W_B$

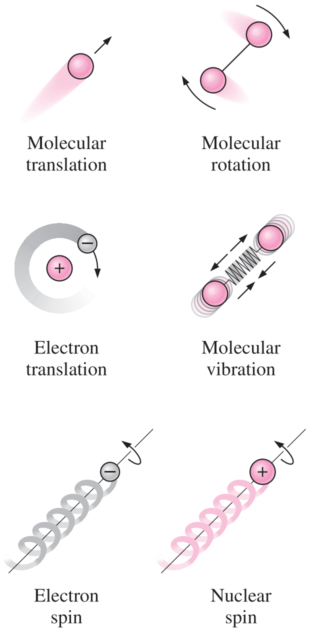
$$\int_1^2 (\delta Q - \delta W)_A = \int_1^2 (\delta Q - \delta W)_B = \cdots$$

$\int_1^2 (\delta Q - \delta W)$ is independent of path and dependent only on the initial and final states; hence, it has the characteristics of a property and this property is denoted by energy, E.

$$\boxed{\delta Q - \delta W = dE \quad \Rrightarrow \quad Q_{12} - W_{12} = \Delta E}$$

- Energy (E): represents all forms energy of the system in the given state. It might be present in a variety of forms, such as:
  - Kinetic Energy (KE): energy of a system associated with motion.
  - Potential Energy (PE): energy associated with a mass that is located at a specified position in a force field.
  - Internal Energy (U): some forms of energy, e.g., chemical, nuclear, magnetic, electrical, and thermal depending in some way on the molecular structure of the substance that is being considered, and these energies are grouped as the internal energy of a system, U.
- KE & PE are external forms of energy as these are independent of the molecular structure of matter. These are associated with the selected coordinate frame and can be specified by the macroscopic parameters of mass, velocity & elevation.
- Internal energy, like kinetic and potential energy, has no natural zero value. So, internal energy of a substance is arbitrarily defined to be zero at some state, known as Reference State.

Internal Energy (U): A Thermodynamic Property



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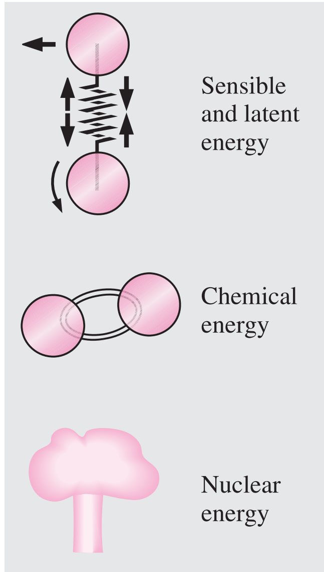
Various forms of microscopic energies making up sensible energy.



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Internal energy is the sum of all forms of the microscopic energies.

- $$\boxed{E = U + KE + PE + \cdots}$$

$\Rightarrow \delta Q - \delta W = dE = dU + d(KE) + d(PE) + \cdots$

$\Rightarrow \frac{\delta Q}{dt} - \frac{\delta W}{dt} = \frac{dE_{CM}}{dt} = \frac{dU}{dt} + \frac{d(KE)}{dt} + \frac{d(PE)}{dt} + \cdots$

- $$\boxed{\frac{dE_{CM}}{dt} = \frac{dQ}{dt} - \frac{dW}{dt} = \dot{Q} - \dot{W}}$$

$\Rightarrow dU \Longrightarrow \int_1^2 dU = U_2 - U_1 = m(u_2 - u_1)$

$\Rightarrow d(KE) = m\mathbb{V}d\mathbb{V} \Longrightarrow \int_1^2 d(KE) = \frac{1}{2}m(\mathbb{V}_2^2 - \mathbb{V}_1^2)$

$\Rightarrow d(PE) = mgdZ \Longrightarrow \int_1^2 d(PE) = mg(Z_2 - Z_1) = mgh$

$$\boxed{Q_{12} - W_{12} = \left[(U_2 - U_1) + \tfrac{1}{2}m(\mathbb{V}_2^2 - \mathbb{V}_1^2) + mg(Z_2 - Z_1) + \cdots\right] \simeq (U_2 - U_1)}$$

$$\boxed{q_{12} - w_{12} = \left[(u_2 - u_1) + \tfrac{1}{2}(\mathbb{V}_2^2 - \mathbb{V}_1^2) + g(Z_2 - Z_1) + \cdots\right] \simeq (u_2 - u_1)}$$

Stationary Systems

$$z_1 = z_2 \rightarrow \Delta PE = 0$$
$$V_1 = V_2 \rightarrow \Delta KE = 0$$
$$\Delta E = \Delta U$$

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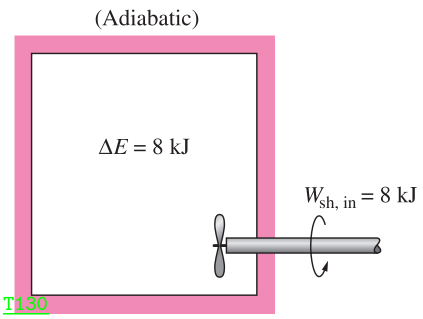

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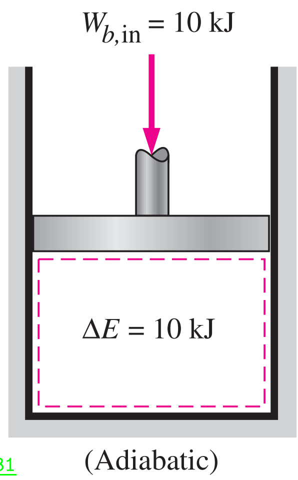

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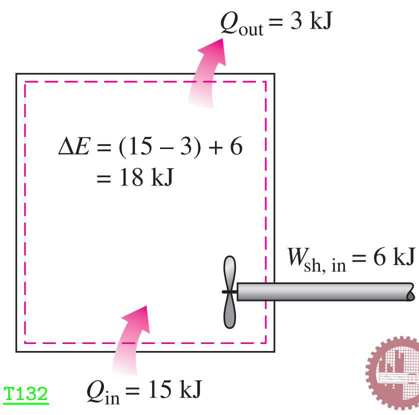

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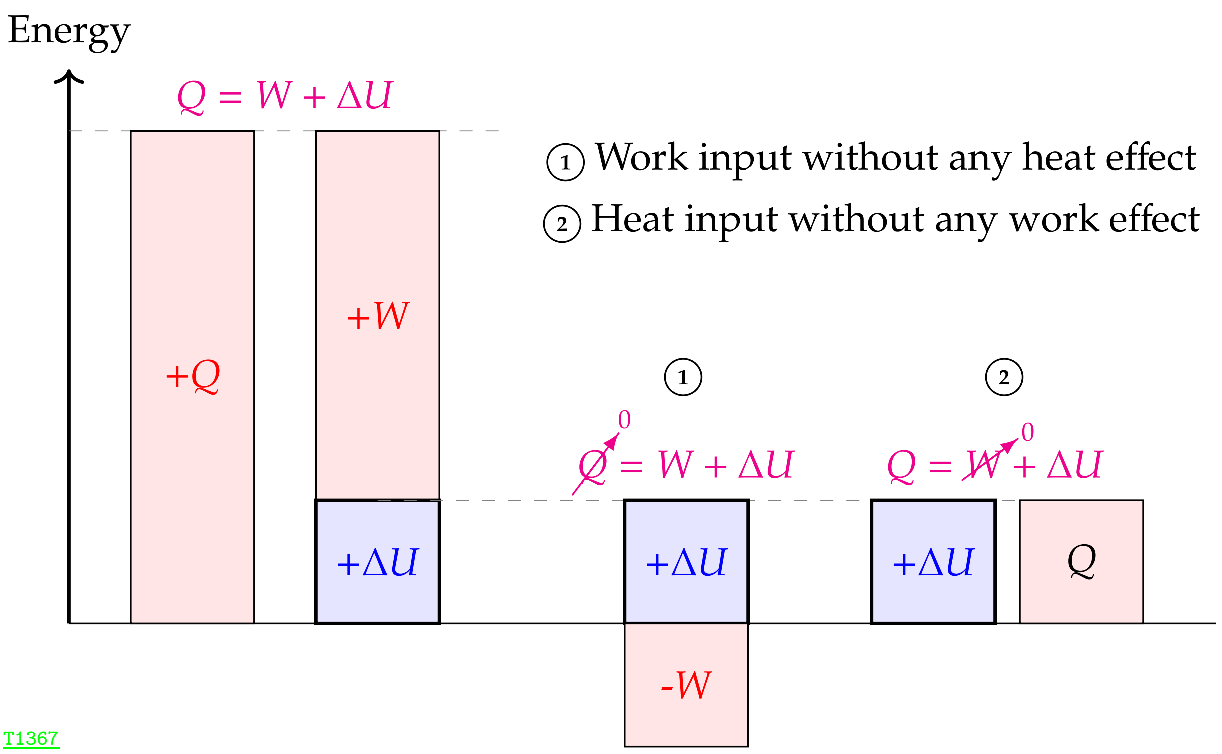

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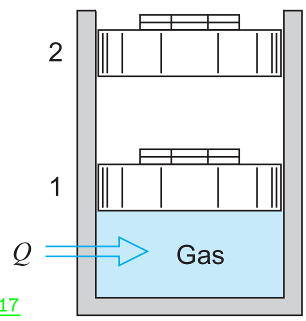
First Law of Thermodynamics for closed system

Enthalpy (H): A Thermodynamic Property

$$\boxed{H \equiv U + PV \quad \Rightarrow \quad h \equiv u + Pv}$$



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$\Rightarrow$ $Q_{12} - W_{12} = \Delta E$

$\Rightarrow$ $Q_{12} - W_{12} = \Delta U$ if $\Delta KE \to 0$, $\Delta PE \to 0$

- $W_{12} = \int_1^2 PdV = P(V_2 - V_1)$

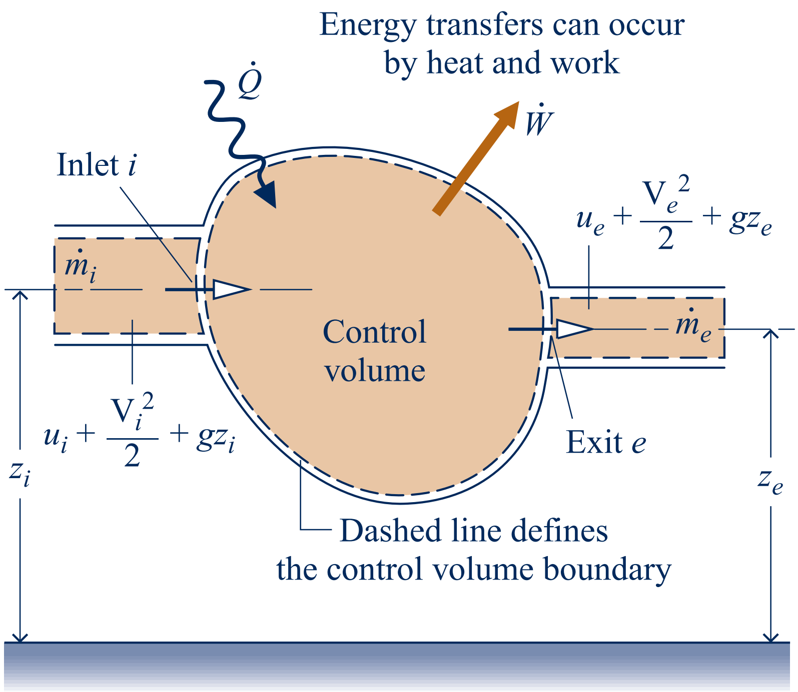
$\Rightarrow$ $Q_{12} = U_2 - U_1 + P(V_2 - V_1)$

$\Rightarrow$ $Q_{12} = (U_2 + P_2 V_2) - (U_1 + P_1 V_1)$

$\Rightarrow$ $Q_{12} = H_2 - H_1$

Heat transfer in a constant-pressure quasi-equilibrium process is equal to the change in enthalpy, which includes both the change in internal energy and the work for this particular process.

Conservation of Energy for CV System



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$$\begin{bmatrix}\text{time } \textit{rate of change} \\ \text{of the energy} \\ \text{contained within} \\ \text{the control volume} \\ \textit{at time t}\end{bmatrix} = \begin{bmatrix}\text{net } \textit{rate} \text{ at which} \\ \text{energy is being} \\ \text{transferred in} \\ \text{by heat transfer} \\ \textit{at time t}\end{bmatrix} - \begin{bmatrix}\textit{net} \text{ rate at which} \\ \text{energy is being} \\ \text{transferred out} \\ \text{by work } \textit{at} \\ \textit{time t}\end{bmatrix} + \begin{bmatrix}\textit{net} \text{ rate of energy} \\ \text{transfer } \textit{into} \text{ the} \\ \text{control volume} \\ \text{accompanying} \\ \text{mass flow}\end{bmatrix}$$

T100

$$\begin{aligned}\frac{dE_{cv}}{dt} &= \dot{Q} - \dot{W} + \dot{m}_i e_i - \dot{m}_e e_e \\ &= \dot{Q} - \dot{W} + \dot{m}_i \left(u_i + \frac{\mathbb{V}_i^2}{2} + gz_i\right) - \dot{m}_e \left(u_e + \frac{\mathbb{V}_e^2}{2} + gz_e\right) \\ &= \dot{Q} - \dot{W}_{cv} + \dot{m}_i \left(h_i + \frac{\mathbb{V}_i^2}{2} + gz_i\right) - \dot{m}_e \left(h_e + \frac{\mathbb{V}_e^2}{2} + gz_e\right)\end{aligned}$$

- $\dot{W} = \dot{W}_s + \dot{W}_b + \dot{W}_f = \dot{W}_{cv} + \dot{W}_f$
- $\dot{W}_f = -P(\dot{V}_i - \dot{V}_e) = -P(\dot{m}_i v_i - \dot{m}_e v_e)$
- $h \equiv u + Pv$

First Law of Thermodynamics (FLT) for CV System

$$\boxed{\frac{dE_{CV}}{dt} = \dot{Q} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{\mathbb{V}_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e \left(h_e + \frac{\mathbb{V}_e^2}{2} + gz_e\right)}$$

- Closed System: $\mapsto \dot{m}_i = \dot{m}_e = 0.$

$$\boxed{\frac{dE_{CM}}{dt} = \dot{Q} - \dot{W}_{net}}$$

- Closed & Adiabatic (Isolated) System: $\mapsto \dot{m}_i = \dot{m}_e = 0, \;\; \dot{Q} = 0.$

$$\boxed{\frac{dE_{CM}}{dt} = -\dot{W}_{net} \Longrightarrow \Delta E_{CM} = -W_{ad}}$$

- Steady-State-Steady Flow (SSSF) System:

$$\boxed{\frac{dm_{CV}}{dt} = 0 \Longrightarrow \sum_i \dot{m}_i = \sum_e \dot{m}_e \quad : \quad \frac{dE_{cv}}{dt} = 0}$$

- One-inlet, One-exit & Steady-state: $\mapsto \dot{m}_i = \dot{m}_e = \dot{m}.$

$$\boxed{0 = \dot{Q} - \dot{W}_{CV} + \dot{m}\left[(h_1 - h_2) + \left(\frac{\mathbb{V}_1^2 - \mathbb{V}_2^2}{2}\right) + g(z_1 - z_2)\right]}$$

Bernoulli's Equation

- $h = u + Pv \;\rightarrow dh = du + Pdv + vdP$, so for isothermal process ($du = 0$) and incompressible fluid ($dv = 0$):

$\Rightarrow$ $dh = vdP \rightsquigarrow \boxed{h_2 - h_1 = v(P_2 - P_1) = \frac{P_2 - P_1}{\rho}}$

- For a steady state flow device if $\Delta PE \neq 0$, $\Delta KE \neq 0$, $W_{cv} = 0$ and $Q_{cv} = 0$:

$\Rightarrow$ $0 = 0 - 0 + \dot{m}\left[(h_1 - h_2) + \left(\frac{\mathbb{V}_1^2 - \mathbb{V}_2^2}{2}\right) + g(z_1 - z_2)\right]$

$$\boxed{\frac{P_1}{\rho g} + \frac{\mathbb{V}_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{\mathbb{V}_2^2}{2g} + z_2}$$

$\frac{P}{\rho g}$: pressure head

$\frac{\mathbb{V}^2}{2g}$: velocity head

z : elevation head