

First Law of Thermodynamics

MEE 1003 Thermodynamics

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Outline

- First law of Thermodynamics
- Moving boundary work
- Polytropic process
- Energy balance of closed systems
- Specific heat, Internal Energy, Enthalpy, Specific Heats of Ideal Gases
- Application to steady flow systems

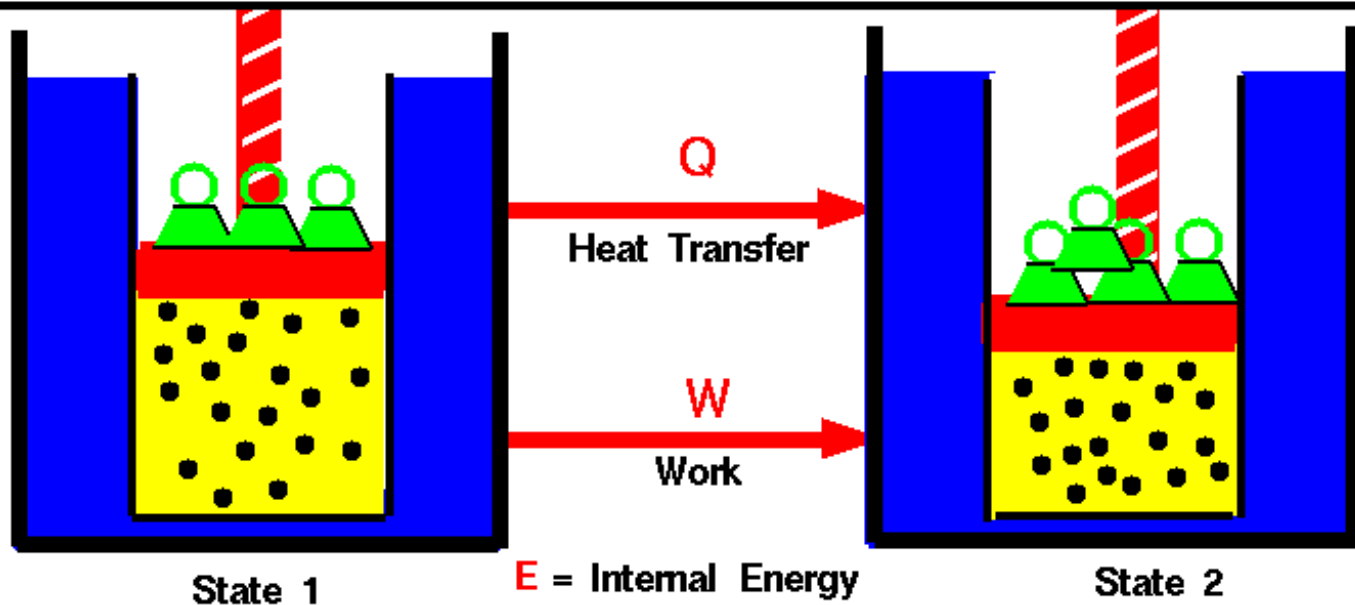
First law of Thermodynamics

- Source: NASA, Glenn research Center



First Law of Thermodynamics

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Any thermodynamic system in an equilibrium state possesses a state variable called the internal energy (E). Between any two equilibrium states, the change in internal energy is equal to the difference of the heat transfer into the system and work done by the system.

- First law statement:

- *Energy can neither be created nor destroyed during a process, it can only change forms.*

$$\oint \delta Q = \oint \delta W \text{ (during any cycle a system undergoes)}$$

- First law principle is the conservation of energy

- Ex: An object of mass m at elevation h has PE = mgh .

- Same object when dropped from height h has KE = $(\frac{1}{2})mV^2$ where $V = (2gh)^{0.5}$

Moving Boundary Work

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- Moving boundary

4-1 Moving Boundary Work

$$W_b = \int_1^2 \delta W_b$$

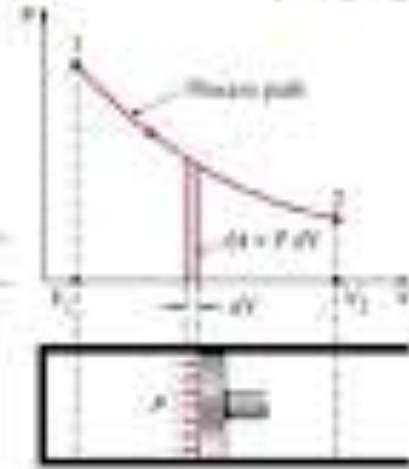
$$= \int_1^2 F ds$$

$$= \int_1^2 \frac{F}{A} A ds$$

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

If P is constant

$$\therefore W = P(V_2 - V_1)$$



- The area under the process curve on a P-V diagram represents the boundary work.

- Total work done during piston movement:

$$W_b = \int_1^2 P dv$$

- Work is process dependent
 - Isobaric ($P = \text{constant}$)
 - Isochoric ($v = \text{constant}$)
 - Isothermal ($T = \text{constant}$)
 - Adiabatic ($Q = 0$)
 - Polytropic ($PV^\gamma = \text{const}$)

Polytropic Process

- Compression and expansion processes in gases that follow the law: $PV^n = C$.
 - Where “n” is an index of exp/comp and C is a constant.

$$PV^n = C \Rightarrow P = CV^{-n}$$

$$\text{Boundary work } W_b = \int_1^2 Pdv = \int_1^2 CV^{-n}dV$$

$$\Rightarrow W_b = C \frac{V_2^{1-n} - V_1^{1-n}}{1-n}; \quad C = P_1 V_1^n = P_2 V_2^n$$

$$\Rightarrow W_b = \frac{P_1 V_1 - P_2 V_2}{n-1}. \quad \because PV = NR_u T$$

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

Energy balance for closed systems

- Energy balance:

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}} \Rightarrow \dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \frac{dE_{\text{system}}}{dt}$$

For a closed system undergoing a cycle,

$$E_1 = E_2 \Rightarrow \Delta E_{\text{system}} = 0 \text{ (initial and final systems are identical)}$$

Hence, energy balance for a closed system is:

$$E_{\text{in}} - E_{\text{out}} = 0. \text{ Since } \dot{m} = 0 \text{ (no mass in or out of a closed system)}$$

$$\dot{W}_{\text{net, out}} = \dot{Q}_{\text{net, in}} \text{ (for a closed cycle)}$$

First law convention: Heat in +ve; Work out +ve.

$$\therefore \dot{Q}_{\text{net, in}} - \dot{W}_{\text{net, out}} = \Delta E_{\text{system}}$$

Specific heat

- Amount of energy required to raise the temperature of a unit mass of substance by one degree.
- Amount of energy depends on process.
- Two types:
 - C_p (specific heat at constant pressure)
 - C_v (specific heat at constant volume)
- C_v : amount of heat to raise temperature of 1 kg substance by 1°C when $V = \text{const.}$
- C_p : amount of heat to raise temperature of 1kg of substance by 1°C when $P = \text{const.}$

Specific heats

- Expressions:

$$V = \text{const}; dV = 0 \Rightarrow \int PdV = W = 0.$$

$$\therefore E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}. \text{ Per unit mass } \dot{e}_{\text{in}} - \dot{e}_{\text{out}} = \Delta \dot{e}_{\text{system}}$$

$$\text{First law in differential form: } \delta e_{\text{in}} - \delta e_{\text{out}} = du$$

$$\text{Definition of } C_v : \delta e_{\text{in}} - \delta e_{\text{out}} = du = C_v dT$$

$$\Rightarrow C_v = \left(\frac{\partial u}{\partial T} \right)_v. \text{ Similarly, } C_p = \left(\frac{\partial h}{\partial T} \right)_p$$

Ideal Gas, Internal Energy, Enthalpy

- Ideal gas law:
 - Any gas that obeys $Pv = RT$ is an ideal gas
- Internal energy is a function of only Temperature

$$u = f(T) = u(T); \quad T \text{ is in K.}$$

- Enthalpy: defined as $h = u + Pv$

Pv : flow work (work done by flow at the boundary)

Since, $Pv = RT$, $h = u + RT$. ($R = R_u/MW$)

$H = mh$; $h = h(T)$ also func of T only.

Ideal gas relations

- Change in enthalpy and internal energy:

$$du = C_v dT; dh = C_p dT$$

- Which means for a process in a closed system:

$$U_{1 \rightarrow 2} = m \int C_v dT; H_{1 \rightarrow 2} = m \int C_p dT$$

Ideal gas relations

- Equations

Since $h = u + RT$; $dh = du + RdT$

$$\Rightarrow C_p dT = C_v dT + RdT$$

$$\therefore C_p = C_v + R \text{ or } C_p - C_v = R$$

$$\text{Specific heat ratio (ideal gas)} \gamma = \frac{C_p}{C_v}$$

$$\Rightarrow C_v = \frac{1}{\gamma - 1} R; C_p = \frac{\gamma}{\gamma - 1} R$$

First law for special processes (Ideal gases)

- Isobaric: $P = \text{const.}$

$$W_b + \Delta U = \Delta H$$

$$\Rightarrow Q - W_{\text{other}} = \Delta H + \Delta KE + \Delta PE \quad (W = W_{\text{other}} + W_b)$$

If KE and PE are negligible, $Q - W_{\text{other}} = \Delta H$

- Isochoric: $V = \text{const}$

$$PV = RT \Rightarrow \frac{P}{T} = \frac{R}{V} = \text{const} \quad (R, V \text{ const})$$

$$\Delta U = m C_v \Delta T; W_b = \int P dV = 0$$

\therefore First law is $\Delta U = \Delta Q = m C_v \Delta T$

- Isothermal

Isothermal $T = \text{const} \Rightarrow PV = RT = \text{const}$

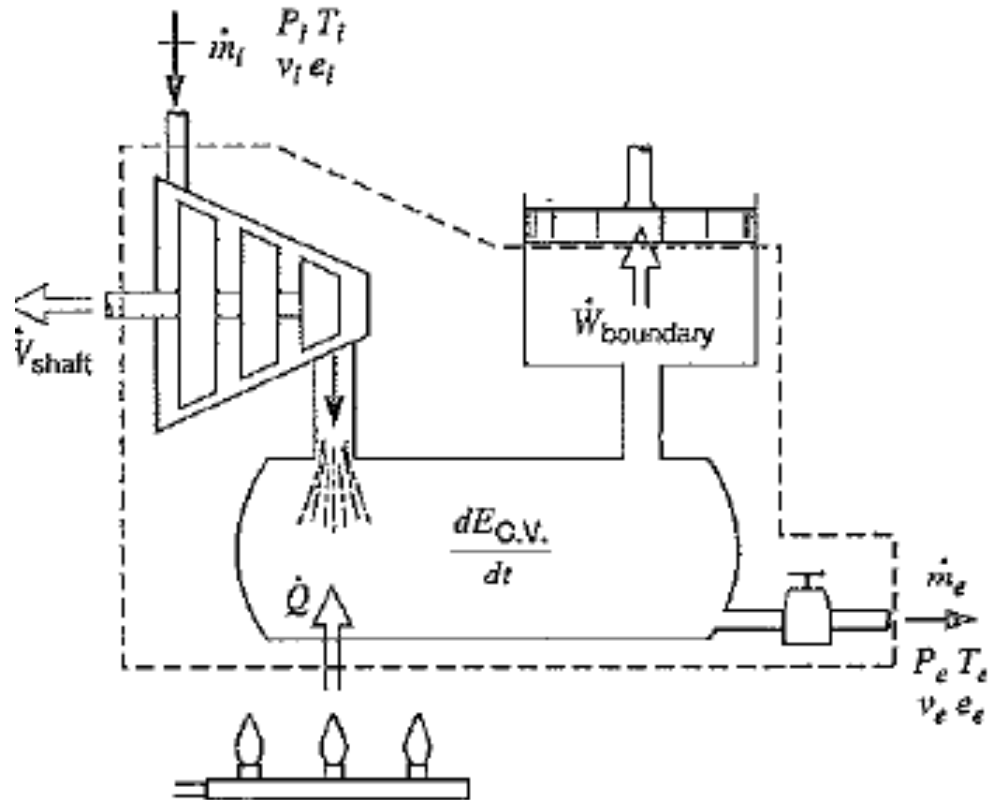
$$\therefore P_1 V_1 = P_2 V_2 = C$$

$$W_b = \int P dV = \int \frac{C}{V} dV = C \ln V \Big|_1^2 = C \ln \frac{V_2}{V_1}$$

$$\Rightarrow W_b = P_1 V_1 \ln \frac{V_2}{V_1} = m R_u T_1 \ln \frac{V_2}{V_1}$$

First law – flow process

- Flow control volume



- (© Wiley and Sons)

- Steady flow process

Energy of the flowing fluid:

$$e = u + \frac{V^2}{2} + gZ. \text{ Flow work } \dot{W}_{\text{flow}} = FV = \int PVdA$$

$$\Rightarrow \dot{W}_{\text{flow}} = P \dot{V} = Pv \dot{m}. \text{ Per unit mass } \dot{w} = Pv$$

Hence, total energy associated with mass flow:

$$e + Pv = u + Pv + \frac{V^2}{2} + gz = h + \frac{V^2}{2} + gZ$$

$$\text{For a steady state process: } \frac{d\dot{m}_{\text{C.V.}}}{dt} = \frac{d\dot{E}_{\text{C.V.}}}{dt} = 0$$

- Steady flow process:

Continuity eqn: $\sum \dot{m}_{\text{in}} - \sum \dot{m}_{\text{exit}} = \frac{d\dot{m}_{\text{C.V.}}}{dt} = 0$

First law:

$$\dot{Q}_{\text{C.V.}} + \sum \dot{m}_{\text{in}} \left(h_{\text{in}} + \frac{V_{\text{in}}^2}{2} + gZ_{\text{in}} \right) = \sum \dot{m}_{\text{exit}} \left(h_{\text{exit}} + \frac{V_{\text{exit}}^2}{2} + gZ_{\text{exit}} \right) + \dot{W}_{\text{C.V.}}$$

Per unit mass: $g + h_{\text{in}} + \frac{V_{\text{in}}^2}{2} + gZ_{\text{in}} = h_{\text{exit}} + \frac{V_{\text{exit}}^2}{2} + gZ_{\text{exit}} + w$

$$q = \frac{\dot{Q}_{\text{C.V.}}}{\dot{m}}, w = \frac{\dot{W}_{\text{C.V.}}}{\dot{m}}$$