

# Thermodynamics: First Law

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Subject : Thermodynamics  
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**Part I: First law of thermodynamics for closed system or non-flow system****A. First law of thermodynamics for a closed system undergoing a cycle**

“Algebraic sum of heat transfer is same as algebraic sum of work transfer”.

$$\text{i.e. } (\sum Q)_{\text{cycle}} = (\sum W)_{\text{cycle}}$$

$$\text{or } \oint \delta Q = \oint \delta W$$

**B. First law of thermodynamics for a closed system undergoing a non-cyclic process**

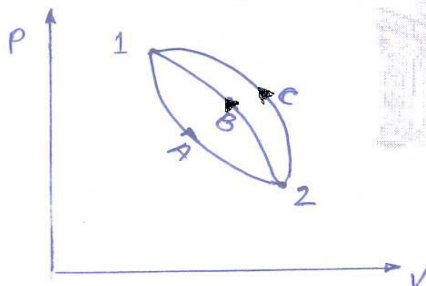
“There exists a property called internal energy whose change is given by difference of heat and work transfer across the system.

$$\text{Mathematically, } \Delta U = Q - W$$

$$\text{For process 1 - 2: } U_2 - U_1 = Q_{1-2} - W_{1-2}$$

**Proof: Internal energy is property of system**

Consider a system which changes its state from state ① to state ② by following path ‘A’ and returns from state ② to state ① by following path ‘B’ i.e. system undergoes a cycle.



Writing the first law of thermodynamics for

$$\text{i) Path 'A': } (\Delta u)_A = Q_A - W_A \dots \dots \dots (1)$$

$$\text{ii) Path 'B': } (\Delta u)_B = Q_B - W_B \dots \dots \dots (2)$$

As path “A” and “B” together constitute a cycle,

$$(\sum Q)_{\text{cycle}} = (\sum W)_{\text{cycle}}$$

$$Q_A + Q_B = W_A + W_B$$

$$Q_A - W_A = -(Q_B - W_B)$$

$$(\Delta u)_A = -(\Delta u)_B \dots \dots \dots (3)$$

Similarly, if the system returned from state ② to state ① by following path 'C' instead of 'B', then

$$(\Delta u)_A = -(\Delta u)_C \dots \dots \dots (4)$$

From equation (3) and (4), we get

$$(\Delta u)_B = (\Delta u)_C$$

Hence we can say that change in internal energy between two states of system is same, whatever path the system follows. It only depends on end states.

Hence internal energy is a point function and therefore a property of the system.

### Characteristic gas equation

$$P \cdot V = m \cdot R \cdot T \quad \text{or}$$

$$P \cdot v = R \cdot T \quad \text{or}$$

$$P \cdot \dot{V} = \dot{m} \cdot R \cdot T$$

Where  $R$  = Specific characteristic gas constant or

= Characteristic gas constant or

= Gas constant

Also,

$$R = \frac{\text{Universal gas constant } \bar{R}}{\text{Molecular weight}}$$

$$= \frac{8.314}{\text{Molecular weight}}$$

$$\frac{P \cdot V}{T} = \text{Constant}$$

### Specific heat at constant pressure ( $C_p$ )

It is rate of change of enthalpy with respect to temperature when pressure is held constant.

$$C_p = \left( \frac{\partial h}{\partial T} \right)_{P=C}$$

### Specific heat at constant volume ( $C_v$ )

It is rate of change of internal energy with respect to temperature when volume is held constant.

$$C_v = \left( \frac{\partial u}{\partial T} \right)_{V=C}$$

**Important relations between  $C_p$ ,  $C_v$  and  $R$** 

By definition of enthalpy,

$$h = u + p \cdot v$$

$$C_p \cdot T = C_v \cdot T + R \cdot T$$

$$C_p - C_v = R \dots \dots \dots (1)$$

Specific heat ratio or adiabatic index ( $\gamma$ ) is given by,

$$\frac{C_p}{C_v} = \gamma \dots \dots \dots (2)$$

From equation (1) and (2), we get

$$C_v \cdot \gamma - C_v = R$$

$$C_v \cdot (\gamma - 1) = R$$

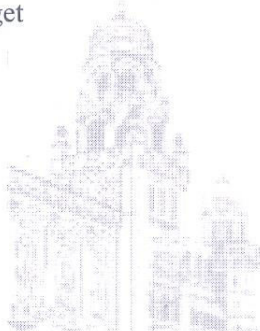
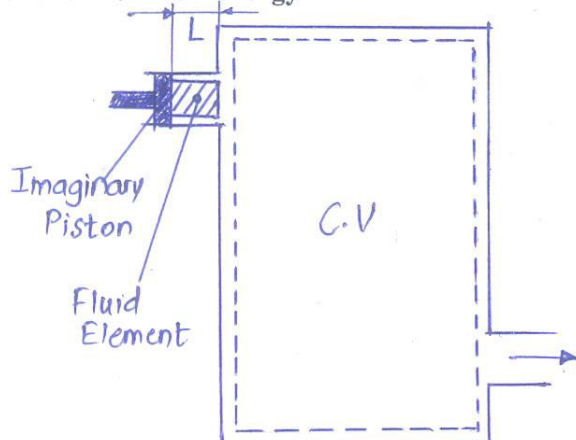
$$C_v = \frac{R}{\gamma - 1} \dots \dots \dots (3)$$

From equation (1), (2) and (3), we get

$$C_p = R + \frac{R}{\gamma - 1}$$

$$= R \cdot \left( 1 + \frac{1}{\gamma - 1} \right)$$

$$= \left( \frac{\gamma \cdot R}{\gamma - 1} \right)$$

**Flow work or Flow energy**

In case of open system of flow system, mass enter or leaves the control volume. Therefore, some work is required to push the mass into and out of control volume. This work is known as “flow work” and is necessary for maintaining a continuous flow.

Let  $V$  be volume of fluid element to be pushed. The fluid immediately upstream will force this fluid enter the control volume, thus it can be regarded as an imaginary piston.

If the fluid pressure is ' $P$ ' and cross sectional area of fluid element is ' $A$ ', then force applied by the imaginary piston on fluid element is

$$F = P \cdot A$$

To push the entire fluid element into the control volume, this force must act through a distance ' $L$ '.

$$W_f = F \cdot L$$

$$= P \cdot A \cdot L$$

$$= P \cdot V \dots \dots \dots \text{(kJ)}$$

$$= P \cdot v \dots \dots \dots \text{(kJ/kg)}$$

$$= P \cdot \dot{V} \dots \dots \dots \text{...(kJ/s)}$$

### Enthalpy

It is defined as sum of internal energy and flow energy.

$$H = U + P \cdot V \text{ or}$$

$$h = u + P \cdot v$$

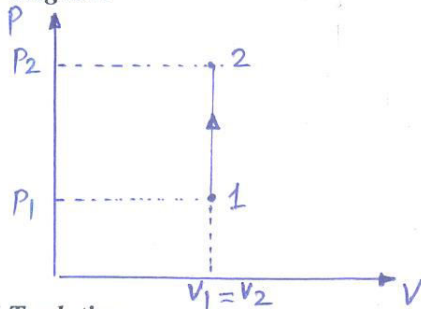
$$\text{Where; } h = \text{specific enthalpy} = \frac{\text{Total enthalpy}}{\text{mass}} = \frac{H}{m}$$

Note: ' $H$ ' is extensive property, whereas specific enthalpy ( $h$ ) is an intensive property.

## Different thermodynamic processes for non-flow system

### 1. Constant volume process / Isochoric process

#### (a) P-V diagram



#### (b) P-V-T relation

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \dots \dots \dots \text{(as } V_1 = V_2 \text{)}$$

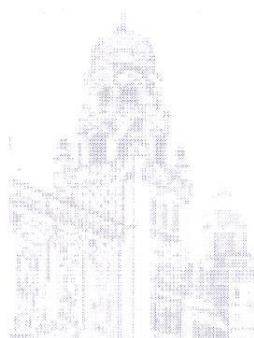
#### (c) Work transfer

We know,

$$W_{1-2} = \int_1^2 P \, dV$$

$$\text{As } dV = 0$$

$$W_{1-2} = 0$$



#### (d) Heat transfer

We know,

$$Q_{1-2} = m \int_{T_1}^{T_2} C_V \, dT$$

$$= m \cdot C_V \cdot (T_2 - T_1)$$

#### (e) Change in internal energy

$$\Delta U = Q_{1-2} - W_{1-2}$$

$$= Q_{1-2} - 0$$

$$= m \cdot C_V \cdot (T_2 - T_1)$$

#### (f) Change in enthalpy

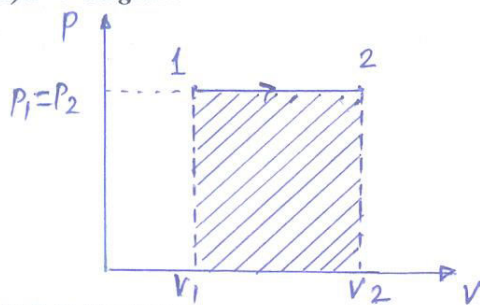
$$\Delta H = H_2 - H_1$$

$$= (U_2 + P_2 \cdot V_2) - (U_1 + P_1 \cdot V_1)$$

$$\begin{aligned}
 &= (P_2 \cdot V_2 - P_1 \cdot V_1) + (U_2 - U_1) \\
 &= m \cdot R \cdot (T_2 - T_1) + m \cdot C_V \cdot (T_2 - T_1) \\
 &= m \cdot (R + C_V) \cdot (T_2 - T_1) \\
 &= m \cdot C_P \cdot (T_2 - T_1)
 \end{aligned}$$

## 2. Constant pressure process / Isobaric process

### (a) P-V diagram



### (b) P-V-T relation

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \dots \dots \dots (\text{as } P_1 = P_2)$$

### (c) Work transfer

We know,

$$\begin{aligned}
 W_{1-2} &= \int_{V_1}^{V_2} P \, dV \\
 &= P \cdot (V_2 - V_1) \dots \dots \dots (\text{kJ})
 \end{aligned}$$

### (d) Heat transfer

We know,

$$\begin{aligned}
 Q_{1-2} &= m \int_{T_1}^{T_2} C_P \, dT \\
 &= m \cdot C_P \cdot (T_2 - T_1)
 \end{aligned}$$

### e) Change in internal energy

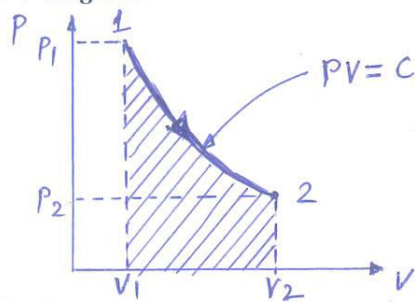
$$\begin{aligned}
 \Delta U &= Q_{1-2} - W_{1-2} \\
 &= m \cdot C_P \cdot (T_2 - T_1) - m \cdot R \cdot (T_2 - T_1) \\
 &= m \cdot (C_P - R) \cdot (T_2 - T_1) \\
 &= m \cdot C_V \cdot (T_2 - T_1)
 \end{aligned}$$

**(f) Change in enthalpy**

$$\begin{aligned} \Delta H &= H_2 - H_1 \\ &= (U_2 + P_2 \cdot V_2) - (U_1 + P_1 \cdot V_1) \\ &= (P_2 \cdot V_2 - P_1 \cdot V_1) + (U_2 - U_1) \\ &= m \cdot R \cdot (T_2 - T_1) + m \cdot C_V \cdot (T_2 - T_1) \\ &= m \cdot (R + C_V) \cdot (T_2 - T_1) \\ &= m \cdot C_p \cdot (T_2 - T_1) \end{aligned}$$

**3. Constant temperature process / Isothermal process / Hyperbolic process**

**(a) P-V diagram**



**(b) P-V-T relation**

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$P_1 V_1 = P_2 V_2 \dots \dots \dots \text{(as } T_1 = T_2 \text{)}$$

Governing equation for isothermal process is  $P V = C$

**c) Work transfer**

We know,

$$\begin{aligned} W_{1-2} &= \int_{V_1}^{V_2} P \, dV \\ &= \int_{V_1}^{V_2} \frac{C}{V} \, dV \dots \dots \dots \left[ P V = C, P = \frac{C}{V} \right] \\ &= C \cdot \log_e \left( \frac{V_2}{V_1} \right) \\ &= P_1 \cdot V_1 \cdot \log_e \left( \frac{V_2}{V_1} \right) \dots \dots \dots \left[ \begin{array}{l} C = P_1 V_1 = P_2 V_2 \\ \quad \quad \quad = m R T_1 = m R T_2 \end{array} \right] \\ &= P_1 \cdot V_1 \cdot \log_e \left( \frac{P_1}{P_2} \right) \dots \dots \dots \left[ \begin{array}{l} P_1 V_1 = P_2 V_2 \\ \frac{V_2}{V_1} = \frac{P_1}{P_2} \end{array} \right] \end{aligned}$$



**(d) Heat transfer**

$$\Delta U = Q_{1-2} - W_{1-2}$$

$$0 = Q_{1-2} - W_{1-2}$$

$$Q_{1-2} = W_{1-2} \dots \dots \dots [\Delta U = m \cdot C_v \cdot (T_2 - T_1) = 0 \text{ as } T_1 = T_2]$$

**(e) Change in internal energy**

$$\Delta U = m \cdot C_v \cdot (T_2 - T_1)$$

$$= 0 \dots \dots \dots \text{as } T_1 = T_2$$

**(f) Change in enthalpy**

$$\Delta H = H_2 - H_1$$

$$= (U_2 + P_2 \cdot V_2) - (U_1 + P_1 \cdot V_1)$$

$$= (P_2 \cdot V_2 - P_1 \cdot V_1) + (U_2 - U_1)$$

$$= m \cdot R \cdot (T_2 - T_1) + m \cdot C_v \cdot (T_2 - T_1)$$

$$= m \cdot (R + C_v) \cdot (T_2 - T_1)$$

$$= m \cdot C_p \cdot (T_2 - T_1)$$

$$= 0 \dots \dots \dots \text{as } T_1 = T_2$$

**4. Constant entropy process / Isentropic process / Reversible adiabatic process / Frictionless process / Adiabatic process.*****Derivation of governing differential equation of isentropic process***

First law of thermodynamics applied to closed system executing a non-cyclic process can be written in differential form as,

$$dU = \delta Q - \delta W$$

$$dU + \delta W = \delta Q$$

$$dU + \delta W = 0 \dots \dots \dots [Q = 0, \text{ for adiabatic process}]$$

For unit mass;

$$C_v \cdot dT + P \cdot dv = 0 \dots \dots \dots (1)$$

$$P \cdot v = R \cdot T$$

$$P = \frac{R \cdot T}{v} \dots \dots \dots (2)$$

Substituting equation (2) into equation (1)

$$C_v \cdot dT + R \cdot T \cdot \frac{dv}{v} = 0$$

Dividing the above equation by  $C_V \cdot T$  throughout;

$$\frac{dT}{T} + \frac{R}{C_V} \frac{dv}{v} = 0$$

$$\frac{dT}{T} + (\gamma - 1) \frac{dv}{v} = 0 \dots \dots \dots \left[ C_V = \frac{R}{\gamma - 1} \right]$$

Integrating above equations,

$$\log_e(T) + (\gamma - 1) \cdot \log_e(v) = \log_e(C_1)$$

$$\log_e(T \cdot v^{\gamma-1}) = \log_e(C_1)$$

$$T \cdot v^{\gamma-1} = C_1$$

$$T = \frac{C_1}{v^{\gamma-1}} \dots \dots \dots (A)$$

Also;  $\frac{P \cdot v}{T} = \text{Constant} = C_2$

$$T = \frac{P \cdot v}{C_2} \dots \dots \dots (B)$$

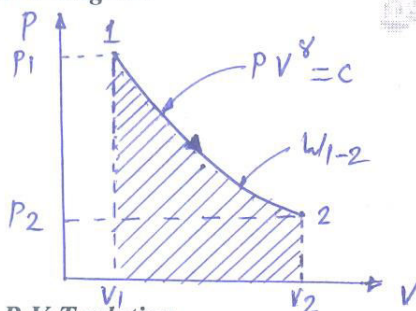
From equation (A) and (B), we get

$$\frac{P \cdot v}{C_2} = \frac{C_1}{v^{\gamma-1}}$$

$$P \cdot v \cdot v^{\gamma-1} = C_1 \cdot C_2 = C$$

$$P \cdot v^\gamma = C$$

(a) P-V diagram



(b) P-V-T relation

$$P \cdot V^\gamma = C$$

$$P_1 \cdot V_1^\gamma = P_2 \cdot V_2^\gamma$$

$$\frac{P_1}{P_2} = \left( \frac{V_2}{V_1} \right)^\gamma \dots \dots \dots (1)$$

$$\frac{V_2}{V_1} = \left( \frac{P_1}{P_2} \right)^{\frac{1}{\gamma}} \dots \dots \dots (2)$$

**Relationship between temperature and pressure at two end points of isentropic process**

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{T_2}{T_1} = \frac{P_2}{P_1} \cdot \frac{V_2}{V_1} \dots \dots \dots (3)$$

$$= \frac{P_2}{P_1} \cdot \left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}} \dots \dots \dots \text{from equation (2)}$$

$$= \frac{P_2}{P_1} \cdot \left(\frac{P_2}{P_1}\right)^{-\frac{1}{\gamma}}$$

$$= \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

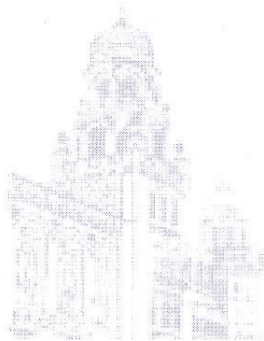
**Relationship between temperature and volume at two end points of isentropic process**

From equation (3) and equation (1) we get,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} \cdot \frac{V_2}{V_1}$$

$$= \left(\frac{V_1}{V_2}\right)^{\gamma} \cdot \left(\frac{V_1}{V_2}\right)^{-1}$$

$$= \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

**(c) Work transfer**

$$W_{1,2} = \int_{V_1}^{V_2} P \, dV$$

$$= \int_{V_1}^{V_2} \frac{C}{V^{\gamma}} \, dV \dots \dots \dots \left[ P V^{\gamma} = C, P = \frac{C}{V^{\gamma}} \right]$$

$$= C \cdot \int_{V_1}^{V_2} V^{-\gamma} \, dV$$

$$= C \cdot \left[ \frac{V^{-\gamma+1}}{-\gamma+1} \right]_{V_1}^{V_2}$$

$$= C \cdot \frac{(V_2^{1-\gamma} - V_1^{1-\gamma})}{1-\gamma}$$

$$= \frac{P_2 \cdot V_2^{\gamma} \cdot V_2^{1-\gamma} - P_1 \cdot V_1^{\gamma} \cdot V_1^{1-\gamma}}{1-\gamma} \dots \dots \dots (P_1 \cdot V_1^{\gamma} = P_2 \cdot V_2^{\gamma} = C)$$

$$= \frac{P_2 \cdot V_2 - P_1 \cdot V_1}{1-\gamma}$$

$$= \frac{P_1 \cdot V_1 - P_2 \cdot V_2}{\gamma-1}$$

$$\begin{aligned}
 &= \frac{m \cdot R \cdot (T_1 - T_2)}{\gamma - 1} \\
 &= m \cdot C_V \cdot (T_1 - T_2) \dots \dots \dots \left( C_V = \frac{R}{\gamma - 1} \right) \\
 &= -\Delta U
 \end{aligned}$$

**d) Heat transfer**

$$Q_{1-2} = 0 \dots \dots \dots [\text{adiabatic process}]$$

**e) Change in internal energy**

$$\begin{aligned}
 \Delta U &= m \cdot C_V \cdot (T_2 - T_1) \\
 &= -W_{1-2}
 \end{aligned}$$

**(f) Change in enthalpy**

$$\begin{aligned}
 \Delta H &= H_2 - H_1 \\
 &= (U_2 + P_2 \cdot V_2) - (U_1 + P_1 \cdot V_1) \\
 &= (P_2 \cdot V_2 - P_1 \cdot V_1) + (U_2 - U_1) \\
 &= m \cdot R \cdot (T_2 - T_1) + m \cdot C_V \cdot (T_2 - T_1) \\
 &= m \cdot (R + C_V) \cdot (T_2 - T_1) \\
 &= m \cdot C_P \cdot (T_2 - T_1)
 \end{aligned}$$

**Proof- Isentropic processes are more steeper than isothermal processes.**

We know that for isentropic process,  $P \cdot V^\gamma = C$

Differentiating above equation,

$$P \cdot \gamma \cdot V^{\gamma-1} \cdot dV + V^\gamma \cdot dP = 0$$

$$V^\gamma \cdot dP = -P \cdot \gamma \cdot V^\gamma \cdot \frac{dV}{V}$$

$$\frac{dP}{dV} = -\gamma \cdot \left( \frac{P}{V} \right)$$

For isothermal process, index of volume = 1. So slope of isothermal process is

$$\frac{dP}{dV} = -\gamma \cdot \left( \frac{P}{V} \right)$$

$$\gamma = \frac{C_P}{C_V}$$

as  $C_p > C_V$ ,  $\gamma > 1$

Therefore slope of isentropic process is more steeper than isothermal process.

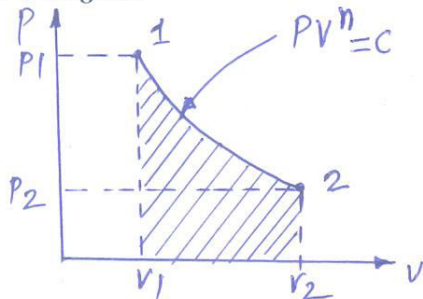
### 5. Polytropic process

It is a general thermodynamic process governed by relation,

$$P \cdot V^n = \text{Constant}$$

- (i) If  $n = 0$ ,  $P = C$
- (ii) If  $n = \infty$ ,  $V = C$
- (iii) If  $n = 1$ ,  $P \cdot V = C$
- (iv) If  $n = \gamma$ ,  $P \cdot V^\gamma = C$

(a) *P-V diagram*



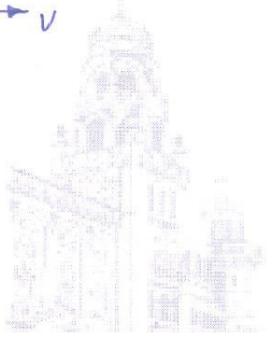
(b) *P-V-T relation*

$$P \cdot V^n = C$$

$$P_1 \cdot V_1^n = P_2 \cdot V_2^n$$

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n \dots\dots\dots (1)$$

$$\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} \dots\dots\dots (2)$$



*Relationship between temperature and pressure at two end points of isentropic process*

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{T_2}{T_1} = \frac{P_2}{P_1} \cdot \frac{V_2}{V_1} \dots\dots\dots (3)$$

$$= \frac{P_2}{P_1} \cdot \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} \dots\dots\dots \text{from equation (2)}$$

$$= \frac{P_2}{P_1} \cdot \left(\frac{P_2}{P_1}\right)^{-\frac{1}{n}}$$

$$= \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

**Relationship between temperature and volume at two end points of isentropic process**

From equation (3) and equation (1) we get,

$$\begin{aligned}\frac{T_2}{T_1} &= \left(\frac{V_1}{V_2}\right)^n \cdot \frac{V_2}{V_1} \\ &= \left(\frac{V_1}{V_2}\right)^n \cdot \left(\frac{V_1}{V_2}\right)^{-1} \\ &= \left(\frac{V_1}{V_2}\right)^{n-1}\end{aligned}$$

**(c) Work transfer**

$$\begin{aligned}W_{1-2} &= \int_{V_1}^{V_2} P \, dV \\ &= \int_{V_1}^{V_2} \frac{C}{V^n} \, dV \dots\dots\dots [P V^n = C, P = \frac{C}{V^n}] \\ &= C \cdot \int_{V_1}^{V_2} V^{-n} \, dV \\ &= C \cdot \left[ \frac{V^{-n+1}}{-n+1} \right]_{V_1}^{V_2} \\ &= C \cdot \frac{(V_2^{1-n} - V_1^{1-n})}{1-n} \\ &= \frac{P_2 \cdot V_2^n \cdot V_2^{1-n} - P_1 \cdot V_1^n \cdot V_1^{1-n}}{1-n} \dots\dots\dots (P_1 \cdot V_1^n = P_2 \cdot V_2^n = C) \\ &= \frac{P_2 \cdot V_2 - P_1 \cdot V_1}{1-n} \\ &= \frac{P_1 \cdot V_1 - P_2 \cdot V_2}{n-1} \\ &= \frac{m \cdot R \cdot (T_1 - T_2)}{n-1}\end{aligned}$$

**(d) Heat transfer**

By first law of thermodynamics applied to closed system executing a non-cyclic process,

$$\Delta U = Q_{1-2} - W_{1-2}$$

$$Q_{1-2} = \Delta U + W_{1-2}$$

$$\begin{aligned}&= m \cdot C_V \cdot (T_2 - T_1) + \frac{m \cdot R \cdot (T_1 - T_2)}{n-1} \\ &= m \cdot \frac{R}{\gamma-1} (T_2 - T_1) - \frac{m \cdot R \cdot (T_2 - T_1)}{n-1} \\ &= m \cdot R \cdot (T_2 - T_1) \left[ \frac{1}{\gamma-1} - \frac{1}{n-1} \right]\end{aligned}$$

$$\begin{aligned}
 &= m \cdot R \cdot (T_2 - T_1) \left[ \frac{n-1-\gamma+1}{(\gamma-1)(n-1)} \right] \\
 &= \left( \frac{\gamma-n}{\gamma-1} \right) \times \frac{m \cdot R \cdot (T_1 - T_2)}{n-1} \\
 &= \left( \frac{\gamma-n}{\gamma-1} \right) \times W_{1-2}
 \end{aligned}$$

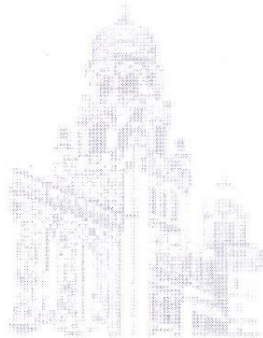
**e) Change in internal energy**

$$\Delta U = m \cdot C_v \cdot (T_2 - T_1)$$

**(f) Change in enthalpy**

$$\Delta H = H_2 - H_1$$

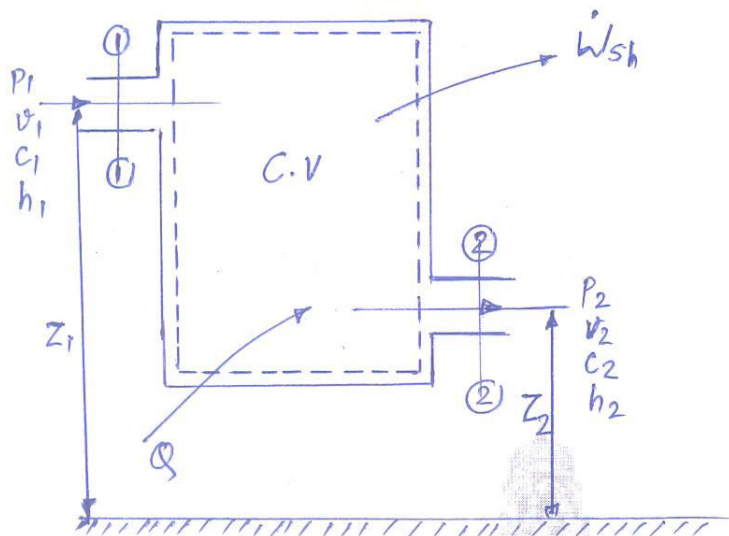
$$\begin{aligned}
 &= (U_2 + P_2 \cdot V_2) - (U_1 + P_1 \cdot V_1) \\
 &= (P_2 \cdot V_2 - P_1 \cdot V_1) + (U_2 - U_1) \\
 &= m \cdot R \cdot (T_2 - T_1) + m \cdot C_v \cdot (T_2 - T_1) \\
 &= m \cdot (R + C_v) \cdot (T_2 - T_1) \\
 &= m \cdot C_p \cdot (T_2 - T_1)
 \end{aligned}$$



**Part I: First law of thermodynamics for open system or flow system**

Steady flow process is defined as a process in which the condition within the control volume do not vary with time.

*Derivation of steady flow energy equation*



Consider any thermodynamic flow system whose inlet is at a height of  $Z_1$  and outlet is at a height of  $Z_2$  from datum.

As per first law of thermodynamics,

Energy entering the system = Energy leaving the system

$$\dot{Q} + (P \cdot \dot{E}_1 + K \cdot \dot{E}_1 + I \cdot \dot{E}_1 + \dot{W}_{f1}) = \dot{W}_{sh} + (P \cdot \dot{E}_2 + K \cdot \dot{E}_2 + I \cdot \dot{E}_2 + \dot{W}_{f2})$$

$$\dot{Q} - \dot{W}_{sh} = (P \cdot \dot{E}_2 - P \cdot \dot{E}_1) + (K \cdot \dot{E}_2 - K \cdot \dot{E}_1) + (I \cdot \dot{E}_2 - I \cdot \dot{E}_1) + (\dot{W}_{f2} - \dot{W}_{f1})$$

$$\dot{Q} - \dot{W}_{sh} = \dot{m} (\Delta pe) + \dot{m} (\Delta ke) + \dot{m} (\Delta u) + \dot{m} (\Delta w_f)$$

$$\dot{Q} - \dot{W}_{sh} = \dot{m} [\Delta(pe) + \Delta(ke) + \Delta u + \Delta w_f] \dots \dots \dots (1)$$

$$\dot{Q} - \dot{W}_{sh} = \dot{m} [\Delta(pe) + \Delta(ke) + \Delta h] \dots \dots \dots (2)$$

Equation (1) and (2) are called steady flow energy equation on time basis.

Where;

$$\Delta(pe) = \frac{gZ_2 - gZ_1}{1000} \dots \dots \dots (kJ/kg)$$

$$\Delta(ke) = \frac{c_2^2 - c_1^2}{2000} \dots \dots \dots (kJ/kg)$$

$$\Delta u = C_v (T_2 - T_1) \dots \dots \dots (kJ/kg)$$



$$\Delta w_f = P_2 V_2 - P_1 V_1 \dots \dots \dots (\text{kJ/kg})$$

$$\Delta h = C_p (T_2 - T_1) \dots \dots \dots (\text{kJ/kg})$$

Dividing equation (1) by  $\dot{m}$  throughout,

$$q - w_{sh} = \Delta(pe) + \Delta(ke) + \Delta u + \Delta w_f \dots \dots \dots (3)$$

$$q - w_{sh} = \Delta(pe) + \Delta(ke) + \Delta h \dots \dots \dots (4)$$

Equation (3) and (4) are called steady flow energy equation on mass basis.

#### *Assumption made in deriving steady flow energy equation*

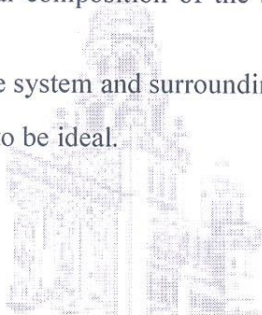
(1) Flow is steady that means,

- (a) Mass flow rate remains constant within the system.
- (b) State of fluid at any point within the control volume is same at all the time.
- (c) Rate at which work and heat transfer across the control surface does not vary with time.

(2) There is no change of chemical composition of the system, so no change in chemical energy involved.

(3) The only interaction between the system and surrounding are work and heat.

(4) If the fluid is gas, it is assumed to be ideal.

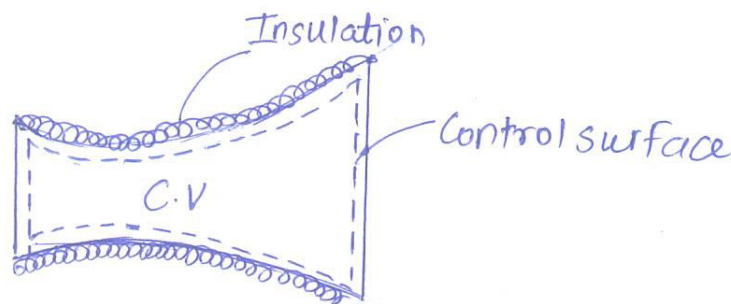


## Application of steady flow energy equation

### (1) Nozzle & Diffuser

Nozzle is a passage of varying cross-section by means of which pressure energy of flowing fluid is changed into kinetic energy. The chief use of nozzle is to produce a jet of high velocity to drive a turbine or to produce thrust. Whereas diffuser increases the pressure of fluid at the expense of its kinetic energy.

Steady flow energy equation on mass basis can be written as,



$$q - w_{sh} = \Delta(pe) + \Delta(ke) + \Delta h$$

Here;

$$w_{sh} = 0$$

$$q = 0$$

$$\Delta(pe) = 0$$

$$\Delta(ke) + \Delta h = 0$$

$$\frac{c_2^2 - c_1^2}{2000} = h_1 - h_2$$

Where;

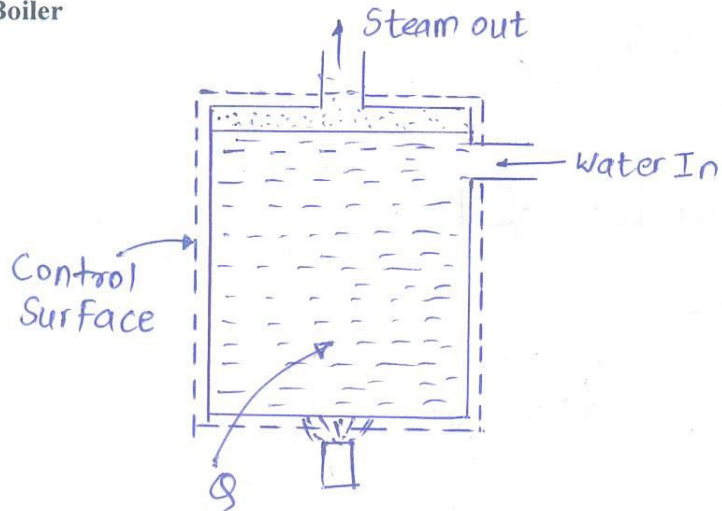
$C_2$  = exit velocity (m/s)

$C_1$  = exit velocity (m/s)

$h_2$  = Specific enthalpy at exit (kJ/kg)

$h_1$  = Specific enthalpy at inlet (kJ/kg)

## 2. Boiler



The Chemical Energy of fuel is released by combustion in the form of heat which is used to generate steam which may be used to drive steam turbine.

Steady flow energy equation on mass basis is given by,

$$q - w_{sh} = \Delta(pe) + \Delta(ke) + \Delta h$$

here,

$$w_{sh} = 0$$

$\Delta(pe)$  and  $\Delta(ke)$  is negligible.

$$q = \Delta h$$

$$q = h_2 - h_1 \dots \dots \dots (\text{kJ/kg})$$

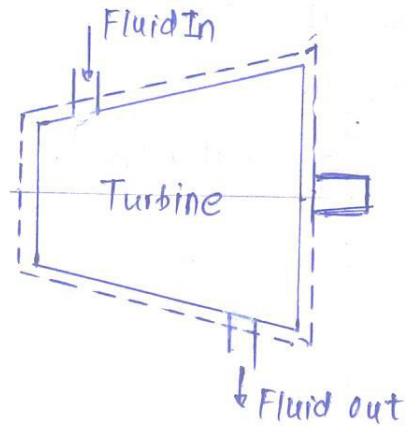
Where;

$q$  = heat supplied to boiler.....(kJ/kg)

$h_2$  = specific enthalpy of steam at exit.....(kJ/kg)

$h_1$  = specific enthalpy of water at inlet.....(kJ/kg)

### 3. Turbine



Turbine converts heat energy of fluid into useful work. It is power producing device.

Steady flow energy equation on mass basis is given by,

$$q - w_{sh} = \Delta(pe) + \Delta(ke) + \Delta h$$

Here;

$$q = 0$$

$\Delta(pe)$  and  $\Delta(ke)$  can be neglected.

$$-w_{sh} = \Delta h$$

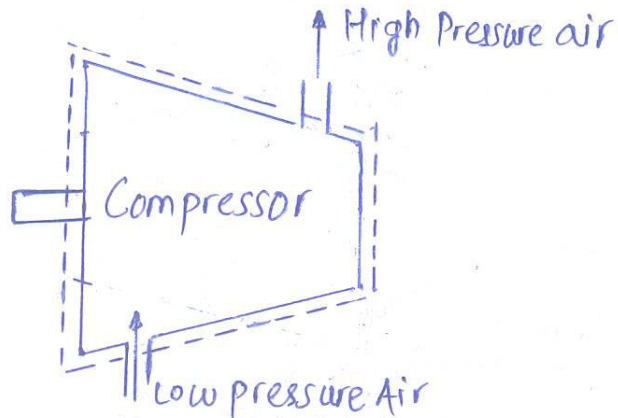
$$= h_2 - h_1$$

$$w_{sh} = h_1 - h_2 \dots \dots \dots (\text{kJ/kg})$$

if  $\dot{m}$  = mass flow rate of fluid (kg/s) then,

$$\text{Power developed} = \dot{W} = \dot{m} w_{sh} = \dot{m} (h_1 - h_2)$$

#### 4. Compressor



Steady flow energy equation on mass basis is given by,

$$q - w_{sh} = \Delta(pe) + \Delta(ke) + \Delta h$$

Here;

$\Delta(pe)$  and  $\Delta(ke)$  can be neglected.

$$-w_{sh} = \Delta h - q$$

$$= (h_2 - h_1) - q$$

$$w_{sh} = (h_1 - h_2) + q \dots\dots\dots(kJ/kg)$$

In the absence of heat exchange,

$$w_{sh} = (h_1 - h_2) \dots\dots\dots(kJ/kg)$$

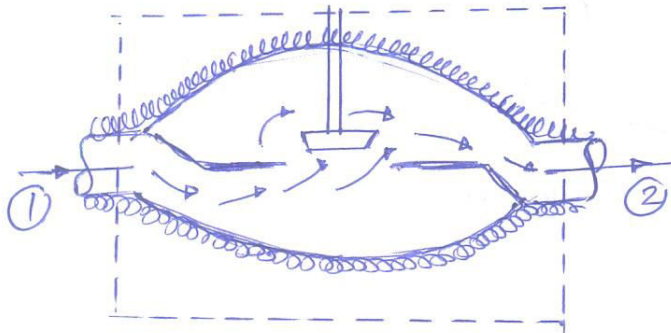
as  $h_2 > h_1$ ,  $w_{sh} = -ve$

Therefore compressor is power consuming device.

### 5. Throttling device

When a fluid flows through a constricted passage, an orifice or a porous plug there is an appreciable drop in pressure and the flow is said to be throttled.

The following figure shows the throttling process by partially opened valve on a fluid flowing through insulated pipe.



Steady flow energy equation on mass basis is given by,

$$q - w_{sh} = \Delta(pe) + \Delta(ke) + \Delta h$$

Here;

$$q = 0$$

$$w_{sh} = 0$$

$\Delta(pe)$  and  $\Delta(ke)$  is negligible.

$$\Delta h = 0$$

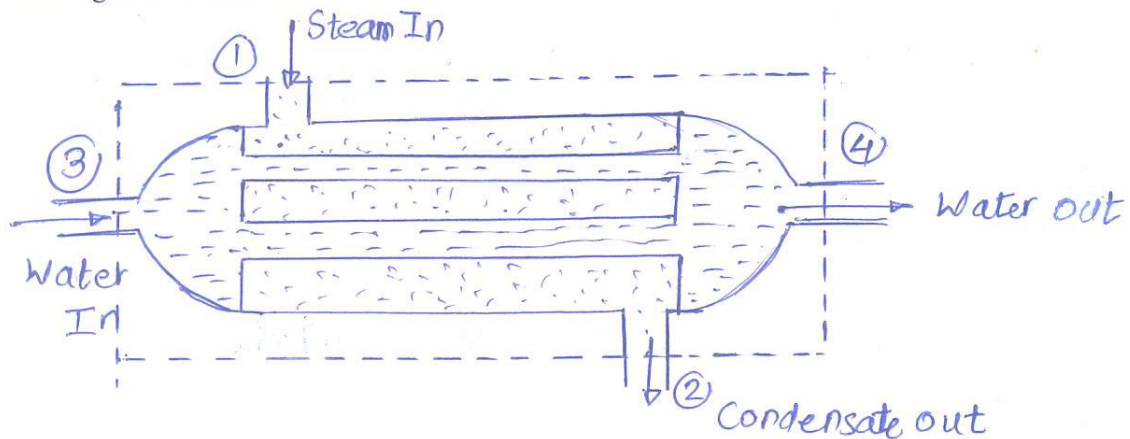
$$h_2 - h_1 = 0$$

$$h_2 = h_1$$

Hence, enthalpy of fluid before throttling is same as enthalpy of fluid after throttling.

## 6. Heat exchanger

A Heat exchanger is a device in which heat is transferred from one fluid to another. Following figure shows steam condenser where steam condenses outside the tubes and cooling water flows inside the tubes.



Applying steady flow energy equation to steam,

$$\dot{Q}_s - \dot{W}_s = \dot{m}_s [\Delta(\text{pe}) + \Delta(\text{ke}) + \Delta h]$$

Here ;

$$\dot{W}_s = 0$$

$$\Delta(\text{pe}) = 0$$

$$\Delta(\text{ke}) = 0$$

$$\dot{Q}_s = \dot{m}_s (h_2 - h_1)$$

$$\text{Heat rejected by steam} = \dot{m}_s (h_1 - h_2)$$

Applying steady flow energy equation to water,

$$\dot{Q}_w - \dot{W}_w = \dot{m}_w [\Delta(\text{pe}) + \Delta(\text{ke}) + \Delta h]$$

Here ;

$$\dot{W}_w = 0$$

$$\Delta(\text{pe}) = 0$$

$$\Delta(\text{ke}) = 0$$

$$\dot{Q}_w = \dot{m}_w (h_4 - h_3)$$

$$\text{Heat absorbed by water} = \dot{m}_w (h_4 - h_3)$$

Assuming that heat exchange is confined only between two fluids (