

## SAMPLE OF THE STUDY MATERIAL

### PART OF CHAPTER 1

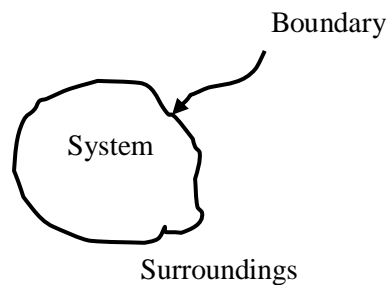
### Basic Thermodynamics

#### 1.1 Thermodynamic systems

Thermodynamic system is a quantity of matter or region in space considered for the analysis of a problem.

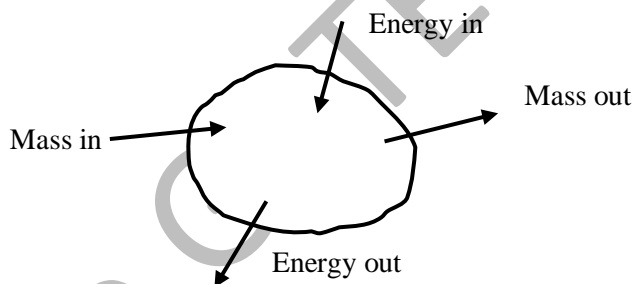
Surroundings: Everything external to the system.

Boundary: It separates system and surroundings

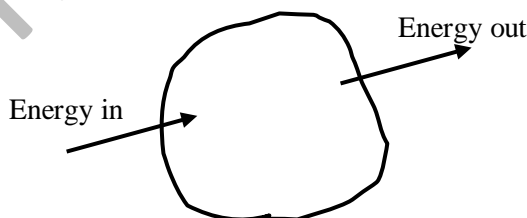


#### Classification of system:

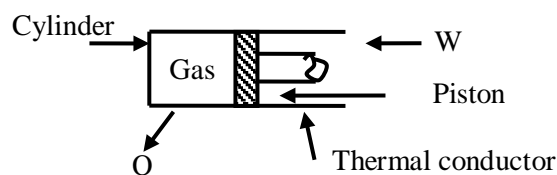
**Open system:** Both energy and mass can transfer across the boundary e.g., Steam turbine, centrifugal pump.



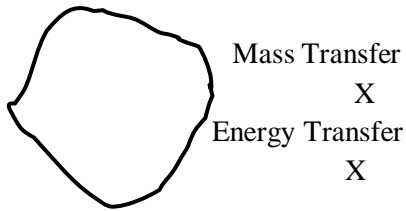
**Closed system:** Energy transfer occurs across the boundary. No mass transfer across the boundary



e.g. Gas compressed in a piston-cylinder assembly



**Isolated system:** Neither mass nor energy transfers across the boundary e.g. Universe



**Thermodynamic property:** Any characteristic of a system by which its physical condition can be described, eg. Pressure, temperature, volume, etc.

**Thermodynamic state:** All the properties have definite values.

**Change of state:** Any operation in which one or more of the properties of the system changes.

**Path of change of state:** The succession of states passed through during a change of state.

## 1.2 Thermodynamic Processes

**Process:** When path is completely specified, the change of state is called process.

Types of thermodynamic properties

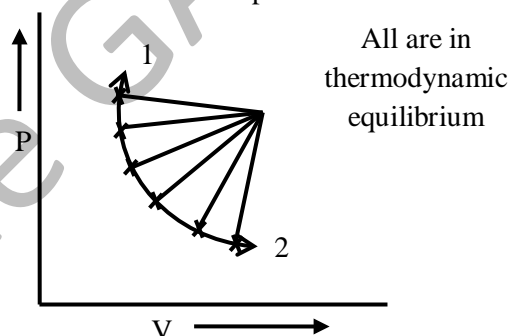
- Intensive properties – independent of mass eg. Pressure, temperature, density.
- Extensive properties – depends on the mass of the system eg. Volume, energy etc.

Thermodynamic equilibrium should satisfy the following.

- Mechanical equilibrium
- Thermal equilibrium.
- Chemical equilibrium

**Quasi – static process:** The departure of the state of the system from the thermodynamic equilibrium is infinitely small.

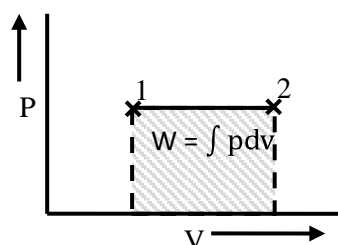
The quasi – static process is an ‘infinite slow’ process.



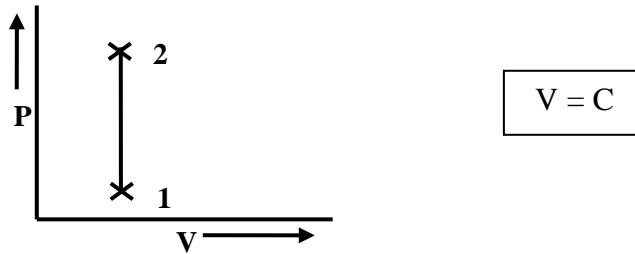
**Thermodynamic processes (non-flow processes):**

**a) Constant pressure or Isobaric process:**

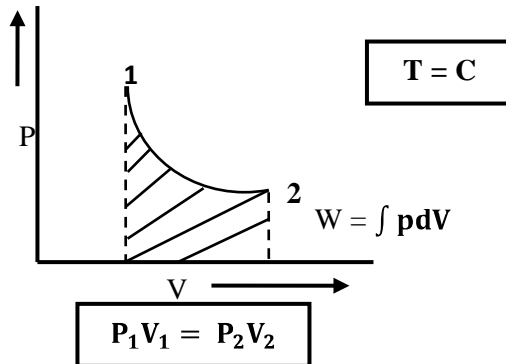
$$P = C$$



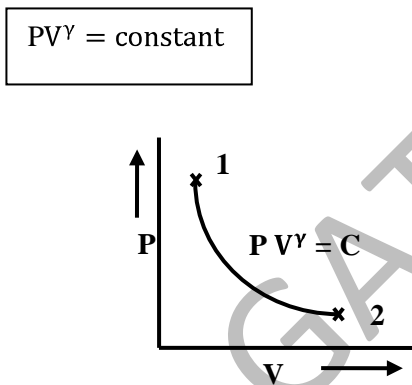
b) Constant volume process or Isochoric process :



c) Isothermal (constant temperature) process:

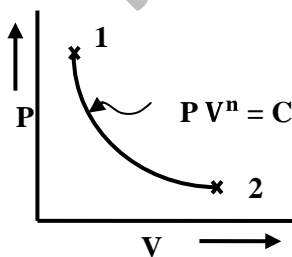


d) Reversible Adiabatic or Isentropic process:



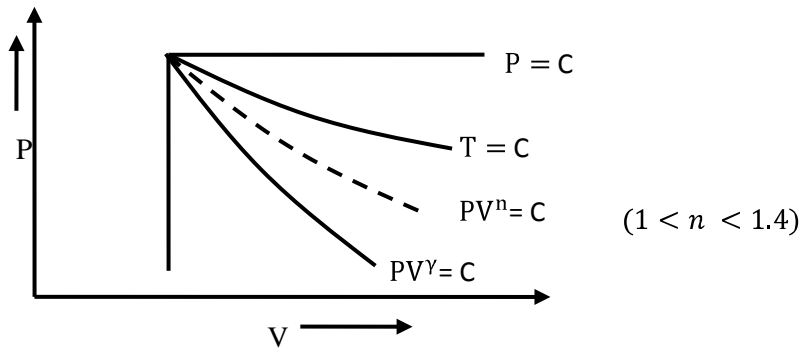
e) Polytropic process (generalized process)

$PV^n = \text{const}$   
n – index of expansion



$$n = \frac{\ln(P_1/P_2)}{\ln(V_2/V_1)}$$

**Representation of thermodynamic processes on P – V diagram:**



**Thermodynamic Process**

- Constant volume ( $V = C$ )
- Constant pressure ( $P = C$ )
- Isothermal ( $T = C$ )
- Polytropic ( $PV^n = c$ )
- Reversible adiabatic ( $PV^r = C$ )

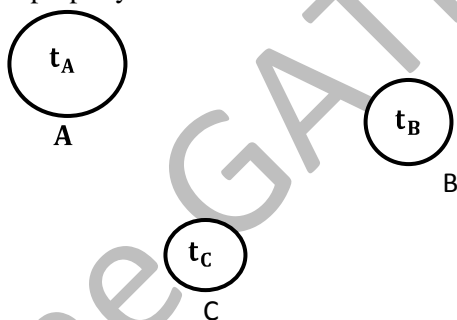
**Index of expansion (n)**

- $\infty$
- 0
- 1
- $1 < n < 1.25$
- $r (= 1.4)$

**1.3 Zeroth law, First law & Second law of thermodynamics**

**Zerth law of thermodynamics (ZLTD):**

- Definition: When a body A is in thermal equilibrium with a body B, and also separately with a body C, then B and C will be in thermal equilibrium with each other.
- ZLTD is the basis for temperature measurement
- A reference body used for quantitative measurement of temperature is called thermometer
- A certain physical characteristic of thermometer which changes with change in temperature is called thermometer property.



If  $t_A = t_B$  &  $t_A = t_C$   
Then  $t_B = t_C$

**First law of thermodynamics (FLTD):**

FLTD is postulated by J.P. Joule

It is law of conservation of energy (energy can neither be created nor be destroyed)

Energy is of 2 types

- |                      |                      |
|----------------------|----------------------|
| 1. Energy in transit | 2. Energy in storage |
| e.g. Heat & work     | e.g. Internal energy |

For a closed, system undergoing a cyclic process, FLTD states that

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

For a closed system undergoing non cyclic process, FLTD:

$$\delta Q = \delta W + \Delta U$$

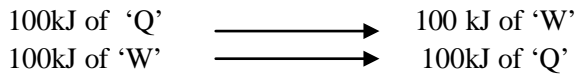
For a cyclic process  $\Delta U = 0$  (i.e.:  $U = \text{constant}$ )

Note: Q – heat supplied/liberated

W= work done

U- internal Energy

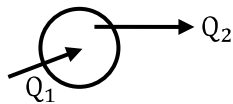
- As per FLTD, heat (Q) and work (W) are mutually convertible



**Sign convention of heat and work:**

Heat supplied to the system (+ve)

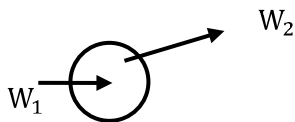
Heat liberated from the system (-ve)



$Q_1 \rightarrow (+ve)$   
 $Q_2 \rightarrow (-ve)$

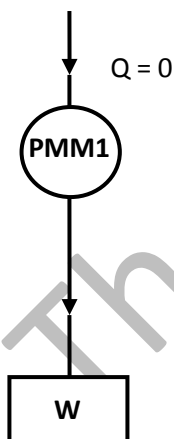
Work done by the system (+ve)

Work done on the system (-ve)



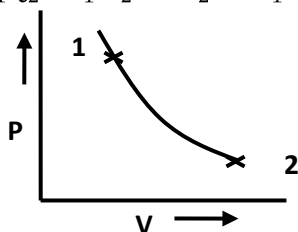
$W_1 \rightarrow (-ve)$   
 $W_2 \rightarrow (+ve)$

Perpetual motion machine of first kind (PMM1) is a fictitious machine which gives continuous output without any input. It violates FLTD



**FLTD for a non cyclic process (non-flow process)**

$${}_1Q_2 - {}_1W_2 = U_2 - U_1$$



**FLTD for a steady flow process**

- Steady flow – properties of the system are constant with respect to time.
- Flow energy or flow work: work done by the fluid on itself to cause the fluid flow.

$$\text{Flow work} = PV \text{ kJ}$$

- Flow work is a point function

- Enthalpy (H):  $H = (U + PV) \text{ kJ}$

Where, U – internal energy(kJ)

PV – flow work (kJ).

Specific enthalpy,  $h = (u + pv) \text{ kJ/kg}$

Where u – specific internal energy (kJ/kg)

pv = flow work per unit mass (kJ/kg)

**Steady Flow Energy Equation (SFEE):**

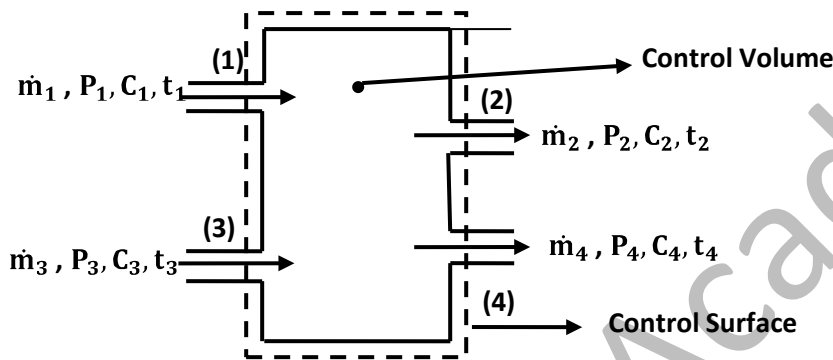


Fig. SFEE

$\dot{m}$  → mass flow rate(kg/s)

P → density ( $\text{kg/m}^3$ ).

C → velocity (m/s)

T → temp( $^{\circ}\text{C}$  or  $^{\circ}\text{K}$ )

SFEE continued

**Mass balance:**

$$\dot{m} = \text{constant}$$

$$\dot{m}_1 + \dot{m}_3 = \dot{m}_2 + \dot{m}_4 \quad (\text{From Fig. SFEE})$$

In general,

$$\sum_{i=1,3,5,\dots} \dot{m}_i = \sum_{e=2,4,6,\dots} \dot{m}_e$$

$\dot{m}_i$  → mass flow rate at inlet

$\dot{m}_e$  → mass flow rate at outlet

**Continuity equations:**

$$\dot{m} = \frac{AC}{v} = PAC$$

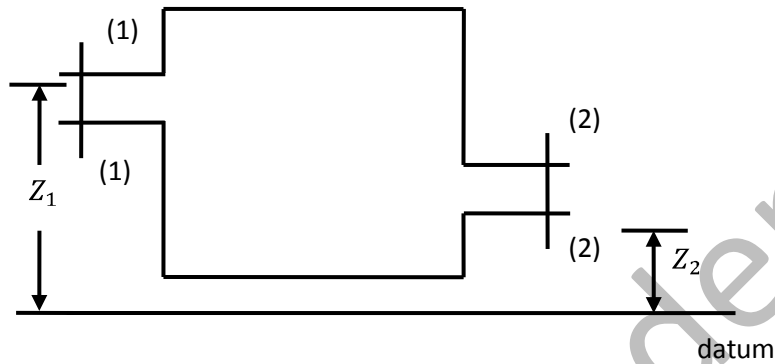
Where A =Xn1 area ( $\text{m}^2$ )

$C = \text{velocity (m/s)}$   
 $v = \text{specific volume (m}^3/\text{kg)}$   
 $P = \text{density (m}^3/\text{kg)}$

$$\dot{m} = \frac{A_1 C_1}{v_1} = \frac{A_2 C_2}{v_2}$$

**Energy balance:**

[Total Energy]<sub>1-1</sub> = [Total Energy]<sub>2-2</sub>



$${}_1\dot{Q}_2 + \dot{m} \left[ p_1 v_1 + u_1 + \frac{1}{2} C_1^2 + g z_1 \right] = {}_1\dot{W}_2 + \dot{m} \left[ p_2 v_2 + u_2 + \frac{1}{2} C_2^2 + g z_2 \right]$$

$$({}_1\dot{Q}_2 - {}_1\dot{W}_2) = \dot{m} \left[ p_2 v_2 + u_2 + \frac{1}{2} C_2^2 + g z_2 - p_1 v_1 - u_1 - \frac{1}{2} C_1^2 - g z_1 \right]$$

$$({}_1\dot{Q}_2 - {}_1\dot{W}_2) = \dot{m} \left[ (h_2 - h_1) + \frac{1}{2} (C_2^2 - C_1^2) + g(z_2 - z_1) \right]$$

----- SFEE

$$({}_1\dot{q}_2 - {}_1\dot{w}_2) = \dot{m} \left[ (h_2 - h_1) + \frac{1}{2} (C_2^2 - C_1^2) + g(z_2 - z_1) \right]$$

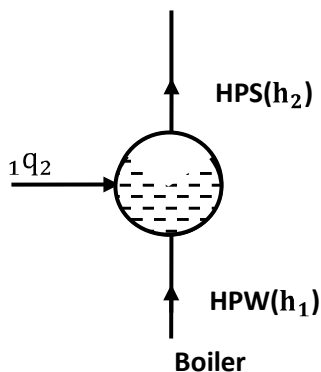
----- SFEE

Where  ${}_1q_2 = \frac{{}_1\dot{Q}_2}{\dot{m}}$  and

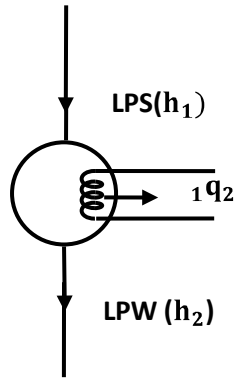
$${}_1w_2 = \frac{{}_1\dot{W}_2}{\dot{m}}$$

**Applications of SFEE**

(i) **Boiler Condenser**



$${}_1q_2 = h_2 - h_1$$



Condenser

$${}_1q_2 = h_1 - h_2$$

$${}_1W_2 = 0$$

$$C_1 \approx C_2$$

$$Z_1 \approx Z_2$$

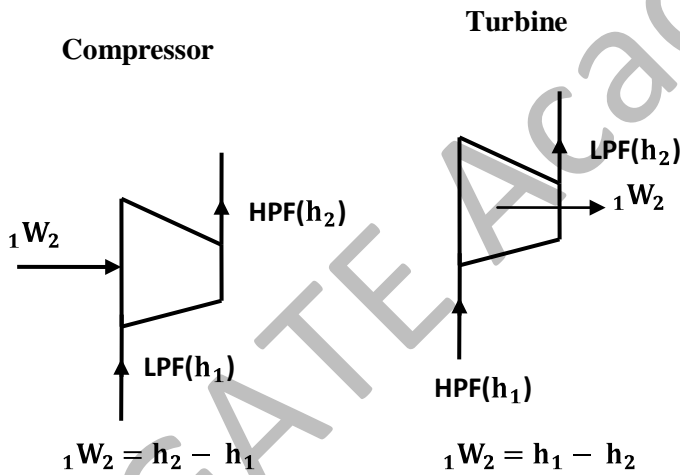
HPW – High Pressure Water

LPW – Low Pressure Water

HPS – High Pressure Steam

LPS – Low Pressure Steam

(ii) **Turbine/Compressor**



$${}_1q_2 = 0$$

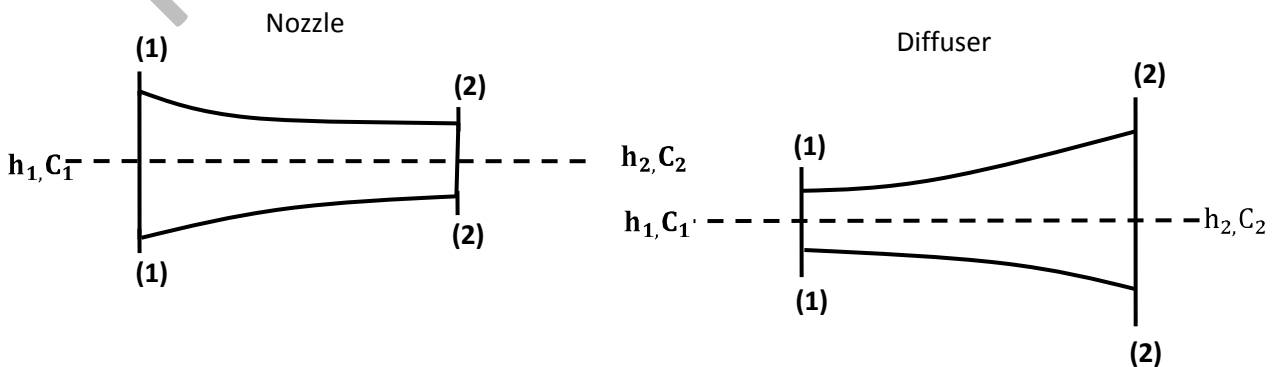
$$C_1 \approx C_2$$

$$Z_1 \approx Z_2$$

HPF – high pressure fluid

LPF - low pressure fluid.

(iii) **Nozzle /Diffuser**



$$h_1 > h_2$$

$$C_1 < C_2$$

$$h_1 < h_2$$

$$C_1 > C_2$$

$$\begin{aligned} {}_1q_2 &= 0 \\ {}_1W_2 &= 0 \\ Z_1 &\approx Z_2 \end{aligned}$$

SFEE: For Nozzle

$$(h_2 - h_1) + \frac{1}{2}(C_2^2 - C_1^2) = 0$$

$$\frac{1}{2}(C_2^2 - C_1^2) = (h_1 - h_2)$$

i.e. gain in KE = drop in enthalpy

$$\text{exit velocity, } C_2 = \sqrt{C_1^2 + 2(h_2 - h_1)}$$

$$(h_2 - h_1) + \frac{1}{2}(C_2^2 - C_1^2) = 0$$

$$(h_2 - h_1) = \frac{1}{2}(C_1^2 - C_2^2)$$

gain in enthalpy = drop in KE

where  $C_2$  = exit velocity, m/s

$(h_1 - h_2)$  = enthalpy drop, J/kg

In general,  $C_1 \ll C_2$

$$C_2 = \sqrt{2(h_1 - h_2)} \text{ m/s}$$

$$= \sqrt{2000(h_1 - h_2)} \text{ where } h_1 \text{ and } h_2 \text{ are given in kJ/kg}$$

$$C_2 = 44.7\sqrt{(h_1 - h_2)}$$

for a gas nozzle  $h = C_p(T_2 - T_1)$

where  $C_p$  = specific heat,  $\frac{J}{kg \cdot K}$

$$C_2 = \sqrt{2C_p(T_2 - T_1)}$$

**(i) SFEE for a throttling process:**

$$\begin{aligned} {}_1q_2 &= 0 \\ {}_1W_2 &= 0 \\ C_1 &\approx C_2 \\ Z_1 &\approx Z_2 \end{aligned}$$

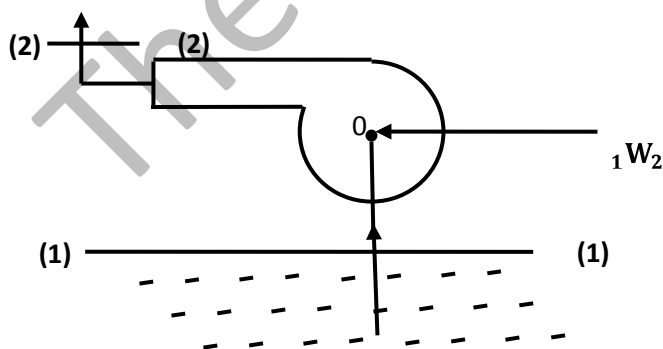
SFEE:

$$h_2 - h_1 = 0$$

$$h_2 = h_1$$

Throttling process is also called isenthalpic process.

**(ii) SFEE for a water pump:**



$$\begin{aligned} {}_1q_2 &= 0 \\ C_1 &\approx C_2 \\ h_1 &\approx h_2 \\ {}_1W_2 &= g(Z_2 - Z_1) \end{aligned}$$

i.e. work input = increase in P.E

**(vi) SFEE for a heat exchanger**

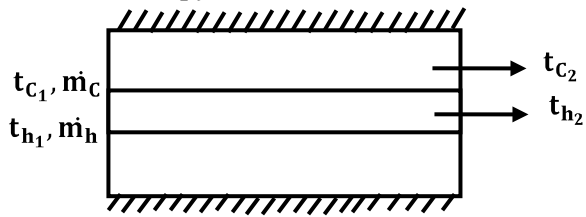
$${}_1q_2 = 0$$

$${}_1W_2 = 0$$

$$Z_1 \approx Z_2$$

$$\text{SFEE: } h_2 - h_1 = 0$$

Increase in enthalpy of cold fluid = decrease in enthalpy of heat fluid



$$(\Delta h)_c = (\Delta h)_h$$

$$\dot{m}_c C_{Pc} (t_{c2} - t_{c1}) = \dot{m}_h (P_n (t_{h1} - t_{h2}))$$

$\dot{m}_h, \dot{m}_c \rightarrow$  mass flow rates of hot and cold fluids respectively

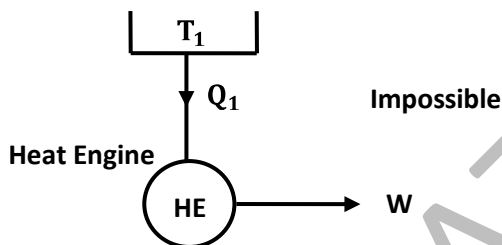
$C_{Ph}, C_{Vc} \rightarrow$  specific heats

$t_h, t_c \rightarrow$  temperatures

**Second law of thermodynamics:**

Also called as “law of degradation of energy”

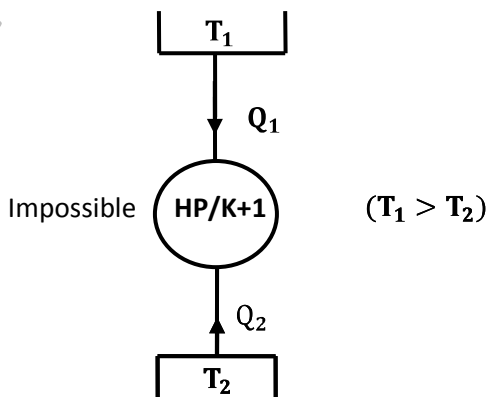
**Kelvin Planck Statement:** It is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.



$$\eta_{HE} = \frac{W}{Q_1}$$

- $Q_1 \neq W$  i.e. ( $W < Q_1$ )
- No heat engine (HE) is 100% efficient
- PMM 2 – fictitious heat engine with 100% efficiency

**Clausius statement:** It is impossible to construct a device, which operating in a cycle, will produce no effect other than the transfer of heat from a cooler to a hotter body



Heat pump (HP)/refrigerator

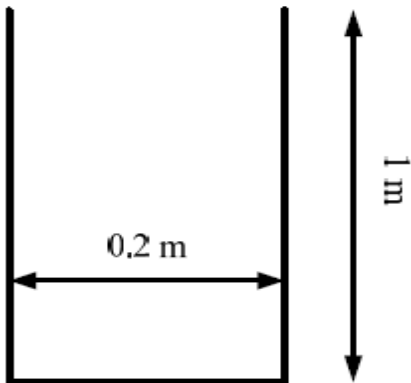
- The performance of heat pump or refrigerator is represented by its COP (coefficient of performance)

### Solved Examples

**Example 1.1:** A cylindrical gas tank 1 m long, inside diameter of 20cm, is evacuated and then filled with carbon dioxide gas at 25°C. To what pressure should it be charged if there should be 1.2 kg of carbon dioxide?

**Solution:**

$$T = 298 \text{ K}; m = 1.2 \text{ kg};$$



$$p = 1.2 \times \frac{8314}{44} \times \frac{298}{\pi \times 0.2^2 \times 1} = 2.15 \text{ MPa}$$

**Example 1.2:** A 1-m<sup>3</sup> tank is filled with a gas at room temperature 20°C and pressure 100 kPa. How much mass is there if the gas is

- Air
- Neon, or
- Propane

**Solution:**

Given:

$$T = 273 \text{ K}; P = 100 \text{ KPa}; M_{\text{air}} = 29; M_{\text{neon}} = 20; M_{\text{propane}} = 44;$$

$$m = \frac{P \times V \times M}{R \times T}$$

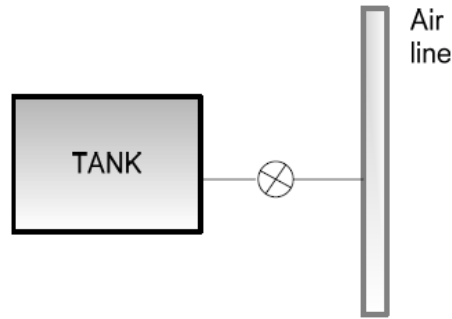
$$m_{\text{air}} = \frac{10^5 \times 1 \times 29}{8314 \times 293} = 1.19 \text{ Kg}$$

$$m_{\text{neon}} = \frac{20}{29} \times 1.19 = 0.82 \text{ Kg}$$

$$m_{\text{propane}} = \frac{44}{20} \times 1.806 \text{ Kg}$$

**Example 1.3:** A 1-m<sup>3</sup> rigid tank with air 1 MPa, 400 K is connected to an air line as shown in fig: the valve is opened and air flows into the tank until the pressure reaches 5 MPa, at which point the valve is closed and the temperature inside is 450 K.

- What is the mass of air in the tank before and after the process?
- The tank is eventually cools to room temperature, 300 K. what is the pressure inside the tank then?



**Solution:**

$$P = 10^6 \text{ Pa}; P_2 = 5 \times 10^6 \text{ Pa}; T_1 = 400\text{K}; T_2 = 450 \text{ K}$$

$$m_1 = \frac{10^6 \times 1 \times 29}{8314 \times 400} = 8.72 \text{ kg}$$

$$m_2 = \frac{5 \times 10^6 \times 29}{8314 \times 450} = 38.8 \text{ kg}$$

$$P = 38.8 \times \frac{8314}{29} \times \frac{300}{1} = 3.34 \text{ MPa}$$

**Example 1.4:** A rigid tank of  $0.568 \text{ m}^3$  volume contains air at 6.895 bar and  $21.1^\circ\text{C}$ . The tank is equipped with a relief valve that opens at a pressure of 8.618 bar and remains open until the pressure drops to 8.274 bar. If a fire causes the valve to operate once as described, determine the air temperature just before the valve opens and the mass of air lost due to fire. Assume that the temperature of the air remains constant during discharge and air in the tank behaves as ideal gas. Assume gas during discharge and air in the tank behave as ideal gas. Assume gas constant =  $294.63 \text{ Nm/kg K}$  for air.

**Solution:**

**Case I:** Before Fire:

Pressure  $p_1 = 6.895 \text{ bar} = 6.895 \times 10^5 \text{ N/m}^2$

Volume,  $V_1 = 0.566 \text{ m}^3$

Temperature,  $T_1 = 21.1 + 273 = 294.1 \text{ K}$

$$\therefore \text{Mass, } m_1 = \frac{p_1 V_1}{RT_1} = \frac{6.895 \times 10^5 \times 0.566}{294.63 \times 294.1} = 4.5 \text{ kg}$$

**Case II:** Just before the valve opens:

Pressure,  $p_2 = 8.618 \text{ bar} = 8.618 \times 10^5 \text{ N/m}^2$

$$V_2 = V_1 = 0.566 \text{ m}^3$$

Mass,  $m_2 = m_1$

Now  $p_2 V_2 = m_2 RT_2 ; T_2 = \frac{p_2 V_2}{m_2 R}$

$$\text{Or } T_2 = \frac{8.618 \times 10^5 \times 0.566}{4.5 \times 294.63} = 367.9 \text{ K}$$

**Case III:** Just after the closure of relief valve:

Pressure,  $p_3 = 8.274 \text{ bar} = 8.274 \times 10^5 \text{ N/m}^2$

Volume,  $V_3 = V_2 = V_1 = 0.566 \text{ m}^3$

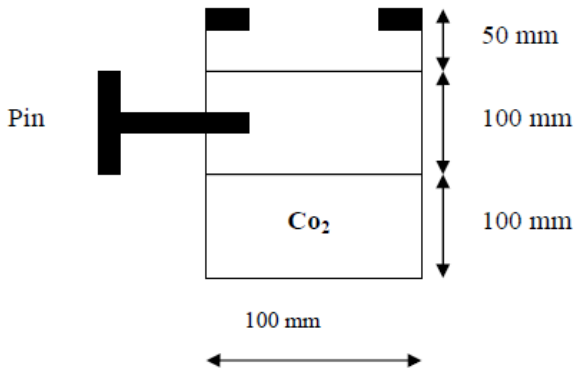
Temperature,  $T_3 = T_2 = 367.9 \text{ K}$  (as calculates above)

$$\therefore \text{Mass, } m_3 = \frac{p_3 V_3}{RT_3} = \frac{8.274 \times 10^5 \times 0.566}{294.63 \times 367.9} = 4.32 \text{ kg}$$

Hence, mass of air lost due to fire =  $m_1 - m_3 = 4.5 - 4.32 = 0.18 \text{ kg}$

**Example 1.5:** A cylinder has a thick piston initially held by a pin as shown in fig. below. The cylinder contains carbon dioxide at 200 kPa and ambient temperature of 290 K. The metal piston has a density of  $8000 \text{ kg/m}^3$  and

the atmospheric pressure is 101 kPa. The pin is now removed, allowing the piston to move and after a while the gas returns to ambient temperature. Is the piston against the stops?



**Solution:**

Given:  $P = 200 \text{ kPa}$ ;

$$V_{\text{gas}} = \frac{\pi}{4} \times 0.1^2 \times 0.1 = 0.7858 \times 10^{-3} \text{ m}^3 : T = 290 \text{ K} : V_{\text{piston}} = 0.785 \times 10^{-3}$$

$$m_{\text{piston}} = 0.785 \times 10^{-3} \times 8000 = 6.28 \text{ kg}$$

$$\text{Pressure exerted by piston} = \frac{6.28 \times 9.8}{\frac{\pi}{4} \times 0.1^2} = 7.848 \text{ kPa}$$

When the metal pin is removed and gas  $T = 290 \text{ K}$

$$v_2 = \frac{\pi}{4} \times 0.1^2 \times 0.15$$

$$= 1.18 \times 10^{-3} \text{ m}^3$$

$$v_1 = 0.785 \times 10^{-3} \text{ m}^3$$

$$p_2 = \frac{200 \times 0.785}{1.18}$$

$$= 133 \text{ kPa}$$

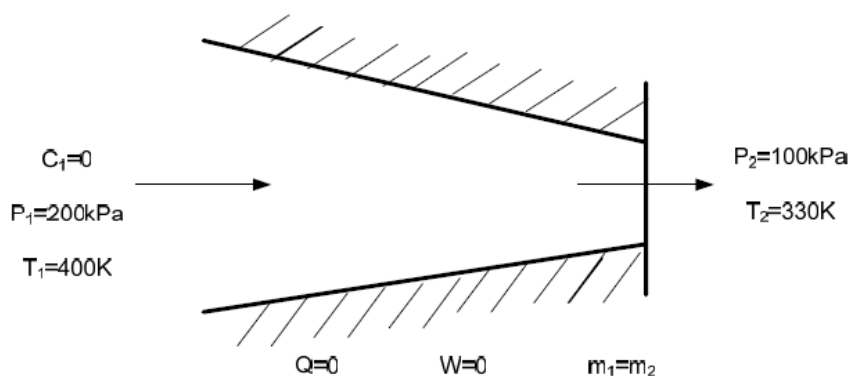
$$\text{Total pressure due to piston + weight of piston} = 101 + 7.848 \text{ kPa}$$

$$= 108.848 \text{ kPa}$$

**Conclusion:** Pressure is greater than this value. Therefore the piston is resting against the stops.

**Example 1.6:** Nitrogen gas flows into a convergent nozzle at 200 kPa, 400 K and very low velocity. It flows out of the nozzle at 100 kPa, 330 K. If the nozzle is insulated, find the exit velocity.

**Solution:**



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

$$\frac{c_2^2}{2} = h_1 - h_2 = 415.31 \times 1000 - 342.4 \times 1000$$

$$c_2 = \sqrt{2(h_1 - h_2)} = 381.8 \text{ m/s}$$

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