Chapter Three

Application of First Law to Steady Flow Process

3.1 Steady Flow Energy Equation (S.F.E.E.)

In many practical problems , the rate at which the fluid flows through a machine or piece of apparatus is constant. This type of flow is called steady flow.

Assumptions :

(i) the mass flow through the system remains constant

(ii) fluid is uniform in composition

(iii) the only interaction between the system and the surroundings are work and heat

(iv) the state of fluid at any point remains constant with time

(v) in the analysis only potential, kinetic and flow work are considered

Fig. 3.1 shows a schematic flow process for an open system. An open system is one in which both mass and energy may cross the boundaries. A wide interchange of energy may take place within an open system.

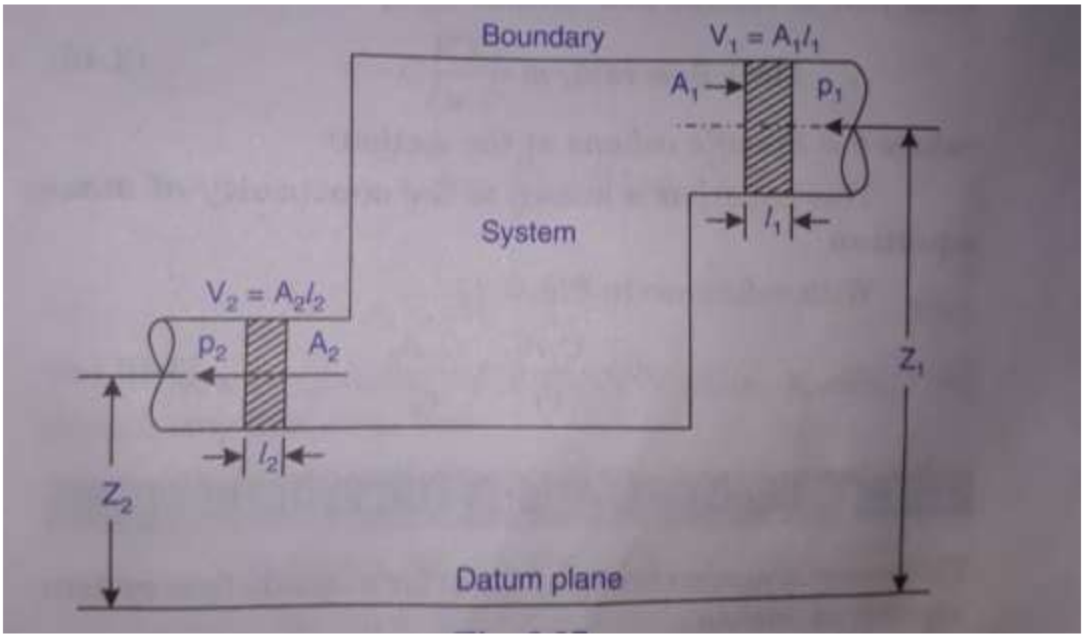

Fig.3.1 : Schematic flow process for an open system

No variation of flow of mass or energy with time across the boundaries of the system.

The steady flow energy equation can be expressed as follows:

$$u_1 + \frac{{C_1}^2}{2} + Z_1 g + p_1 v_1 + Q = u_2 + \frac{{C_2}^2}{2} + Z_2 g + p_2 v_2 + W \quad \ldots\ldots\ldots\ldots (3.1)$$

$$(u_1 + p_1 v_1) + \frac{{C_1}^2}{2} + Z_1 g + Q = (u_2 + p_2 v_2) + \frac{{C_2}^2}{2} + Z_2 g + W$$

$$h_1 + \frac{{C_1}^2}{2} + Z_1 g + Q = h_2 + \frac{{C_2}^2}{2} + Z_2 g + W$$

$$[\therefore \quad h = u + pv]$$

If Z_1 and Z_2 are neglected, we get

$$h_1 + \frac{{C_1}^2}{2} + Q = h_2 + \frac{{C_2}^2}{2} + W \dots\dots\dots\dots (3.2)$$

Where, Q= heat supplied(or entering the boundary) per kg of fluid,

C= velocity of fluid,

Z= height above datum,

P= pressure of the fluid,

u=internal energy per kg of fluid, and

pv=energy required for 1 kg of fluid.

This equation is applicable to any medium in any steady flow.

Consider any section of cross-sectional area A, where the fluid velocity is C, the rate of volume flow past the section is CA. Also, since

$$mass\ flow\ rate, m^{\circ} = \frac{CA}{v} \dots\dots\dots\dots.. (3.3)$$

$$(where\ v = Specific\ volume\ at\ the\ section)$$

This equation is known as the continuity of mass equation.

With reference to Fig.3.1

$$\therefore\ m^{\circ} = \frac{C_1 A_1}{v_1} = \frac{C_2 A_2}{v_2} \dots\dots\dots. (3.4)$$

3.2 Energy Relation for Flow Process

The energy equation(m kg of fluid) for a steady flow system is given as follows:

$$m\left[u_1 + \frac{{C_1}^2}{2} + Z_1 g + p_1 v_1\right] + Q = m\left[u_2 + \frac{{C_2}^2}{2} + Z_2 g + p_2 v_2\right] + W$$

i.e,

$$Q = m\left[(u_2 - u_1) + (Z_2g - Z_1g) + \left(\frac{{C_2}^2}{2} - \frac{{C_1}^2}{2}\right) + (p_2v_2 - p_1v_1)\right] + W$$

$$= \Delta U + \Delta PE + \Delta KE + \Delta(pv) + W$$

Where $\Delta U = m(u_2 - u_1)$

$$\Delta PE = mg(Z_2 - Z_1)$$

$$\Delta KE = m\left(\frac{{C_2}^2 - {C_1}^2}{2}\right)$$

$$\Delta pv = m(p_2v_2 - p_1v_1)$$

$$\therefore Q - \Delta U = [\Delta PE + \Delta KE + \Delta(pV) + W] \ldots\ldots\ldots..(3.4)$$

For non-flow process,

$$Q = \Delta U + W = \Delta U + \int_1^2 pdV$$

$$i.e, \quad Q - \Delta U = \int_1^2 p.dV \ldots\ldots\ldots(3.5)$$

Note :

The internal energy is a function of temperature only and it is a point function. therefore, for the same two temperature, change in internal energy is the same whatever may be the process, non-flow ,or steady flow, reversible or irreversible.

For the same value of Q transferred to non-flow and steady flow process and for the same temperature range, we can equate the values of eqns. (3.4) and (3.5) for $(Q - \Delta U)$.

$$\therefore \int_1^2 p.dV = \Delta\, PE + \Delta\, KE + \Delta\, (pv) + W \ldots\ldots.(3.6)$$

Where, W= Work transfer in flow process

$and \quad \int_1^2 p.dV$=Total change in mechanical energy of reversible steady flow process

3.3 Engineering Applications of Steady Flow Energy Equation (S.F.E.E.)

3.1 Water Turbine

Refer to Fig.3.2. in a water turbine, water is supplied from a height. The potential energy of water is converted into kinetic energy when it enters into the turbine and part of it is converted into useful work which is used to generate electricity

Considering center of turbine shaft as *datum*, the energy equation can be written as follows:

$$\left(u_1 + p_1 v_1 + Z_1 g + \frac{{C_1}^2}{2}\right) + Q = \left(u_2 + p_2 v_2 + Z_2 g + \frac{{C_2}^2}{2}\right) + W$$

In this case,

Q=0

$\Delta u = u_2 - u_1 = 0$

$\therefore \quad v_1 = v_2 = v$

Z_2=0

$$\therefore \quad \left(p_1 v + Z_1 g + \frac{{C_1}^2}{2}\right) = \left(p_2 v + Z_2 g + \frac{{C_2}^2}{2}\right) + W \quad \ldots \ldots (3.6)$$

W *is positive* because work is done by the system(or work comes out of the boundary).

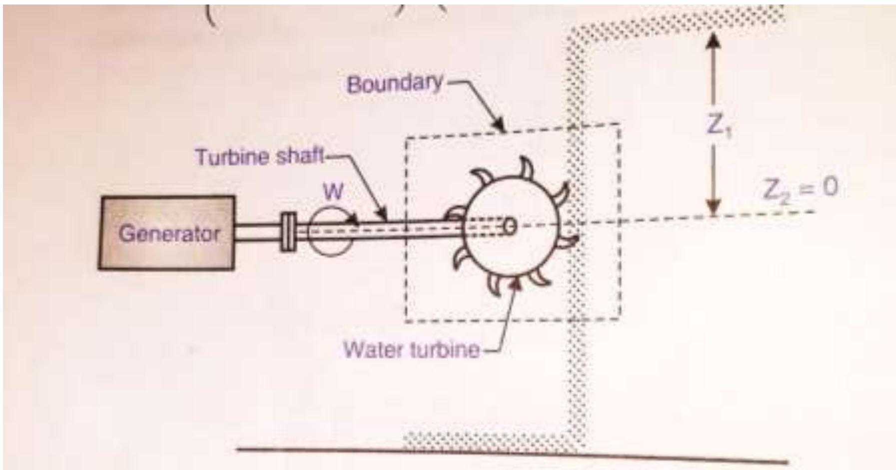

Fig.3.2 Water Turbine.

3.2 Steam or Gas Turbine

In steam or gas turbine steam or gas is passed through the turbine and part of its energy is converted into work in the turbine. This output of the turbine runs a generator to produce electricity as shown in the Fig.3.3. the steam or gas leaves the turbine at lower pressure or temperature.

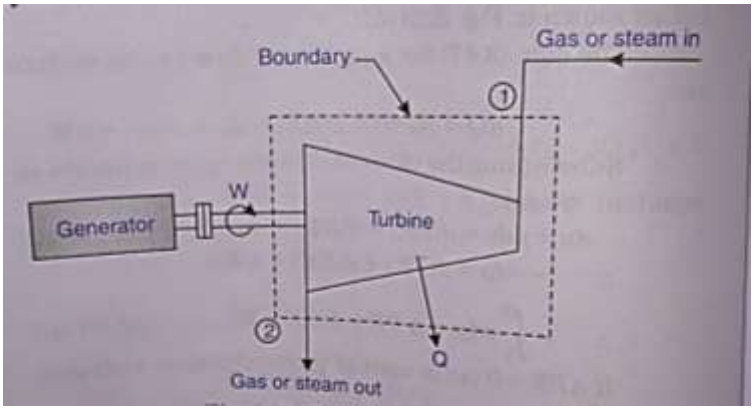

Fig. 3.3 Steam or Gas Turbine.

Applying energy equation to the system.

Here , $Z_1 = Z_2$ (i.e , $\Delta Z = 0$)

$$h_1 + \frac{{C_1}^2}{2} - Q = h_2 + \frac{{C_2}^2}{2} + W \ldots \ldots \ldots (3.7)$$

The sign of Q is negative because heat is rejected (or comes out of the boundary)

The sign of W is positive because the work is done by the system (or work comes out of the boundary)

3.3 Centrifugal Water Pump

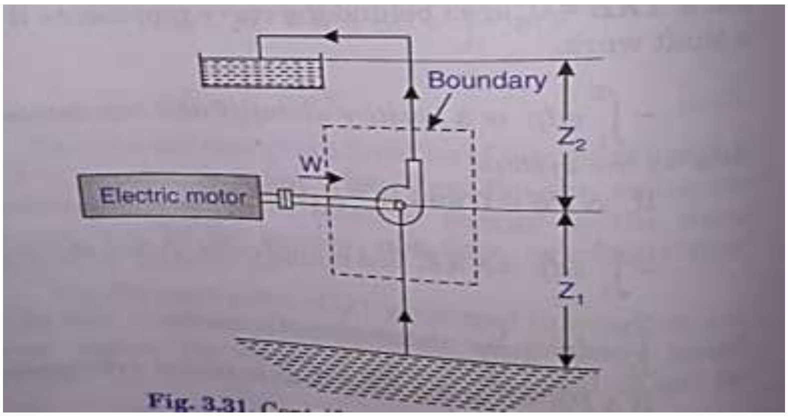

Fig. 3.4. Centrifugal Water Pump

A centrifugal water pump draws water from a lower level and pumps to higher level as shown in Fig.3.4.

Work is required to runs the pump and this may be supplied or external source such as an electric motor or a diesel engine.

Here Q=0 AND $\Delta u = 0$ as there is no change in temperature of water ; $v_1 = v_2 = v$.

Applying the energy equation to the system

$$p_1 v_1 + Z_1 g + \frac{{C_1}^2}{2} = p_2 v_2 + Z_2 g + \frac{{C_2}^2}{2} - W \dots \dots .. (3.8)$$

The sign of work is negative because work is done on the system(or work enters the boundary).

3.4 Centrifugal Compressor

Refer to Fig.3.5. A centrifugal compressor compresses air and supplies the same at moderate pressure and in a large quantity

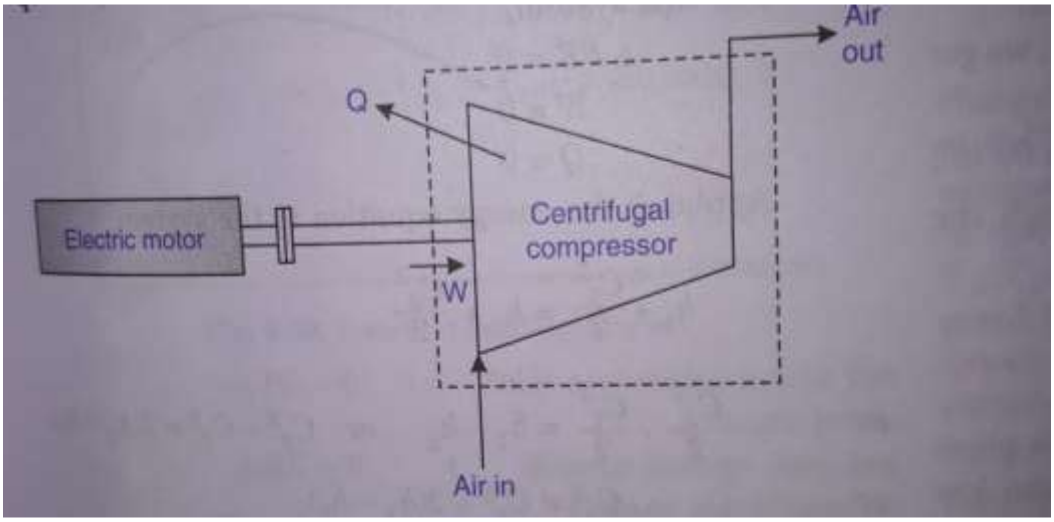

Fig.3.5. Centrifugal Compressor

Applying energy equation to the system (Fig.3.5).

$\Delta Z = 0$(generally taken)

$$\left(h_1 + \frac{{C_1}^2}{2}\right) - Q = \left(h_2 + \frac{{C_2}^2}{2}\right) - W$$

The Q IS taken as negative as heat is lost from the system and W is taken as negative as work is supplied to the system.

Or,

$$\left(h_1 + \frac{{C_1}^2}{2}\right) - Q = \left(h_2 + \frac{{C_2}^2}{2}\right) - W \quad \ldots \ldots .. (3.9)$$

3.5 Reciprocating Compressor

Refer to Fig.3.6. The reciprocating compressor draws in air from atmosphere and supplies the air at a considerable higher pressure in small quantities (compared with centrifugal compressor).

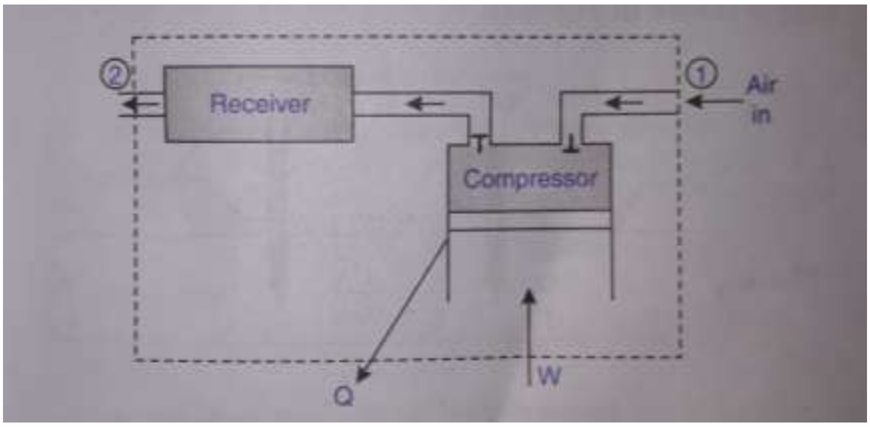

Fig.3.6. Reciprocating Compressor

Applying energy equation to the system, we have:

$\Delta PE = 0$ and $\Delta KE = 0$ since these changes are negligible compared with other energies.

$$\therefore \quad h_1 - Q = h_2 - W \quad \dots \dots (3.10)$$

3.6 Boiler

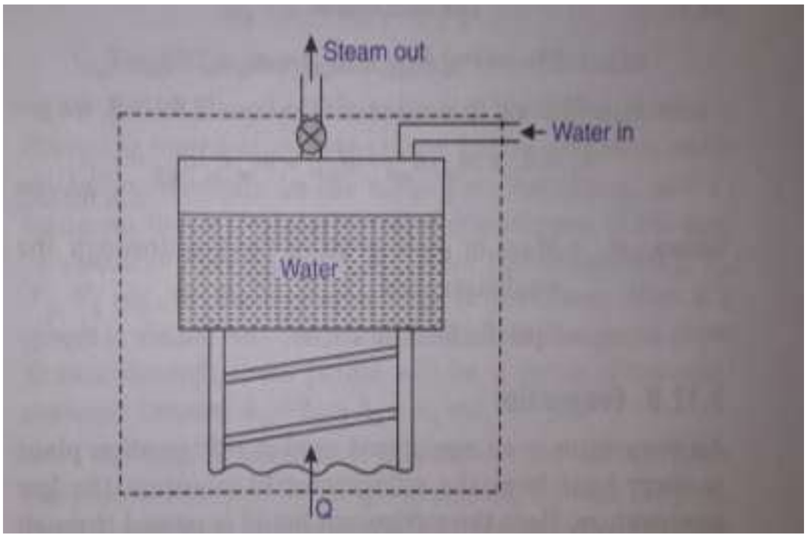

Fig.3.7. Boiler.

Applying energy equation to the system,

$$h_1 + \frac{{C_1}^2}{2} + Z_1 g + Q = h_2 + \frac{{C_2}^2}{2} + Z_2 g + W$$

For boiler :

W=0   since neither any work is developed nor absorbed.

$\Delta PE = 0 \quad and \quad \Delta KE = 0$

Hence , energy equation becomes :

$$h_1 + Q = h_2 \quad \ldots \ldots (3.11)$$

Or ,

$Q = h_2 - h_1$

Q for boiler is always positive value i.e $h_2 > h_1$

Where h_1= inlet enthalpy for water

h_2= outlet enthalpy for steam

3.7 Condenser

The condenser is used in condense the steam in case of steam power plant and condense the refrigerant vapor in the refrigeration system using water or air as cooling medium.

For this system,

$\Delta PE = 0 \, , \Delta KE = 0 (as\ their\ values\ are\ very\ small\ compared\ with\ enthalpies)$
W=0 (since neither any work is developed nor absorbed)

Using energy equation to steam flow

$$h_1 - Q = h_2$$

$$\therefore Q = h_1 - h_2 \quad \ldots \ldots (3.11a)$$

Where Q= heat lost by 1 kg of steam passing through the condenser.

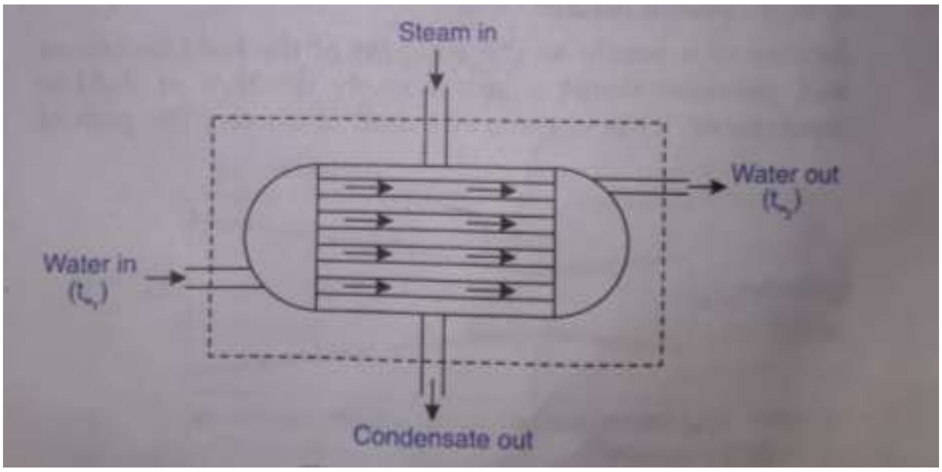

Fig. 3.8. Condenser.

Assuming there are no other heat interactions except the heat transfer between steam and water, then

Q= Heat gained by water passing through the condenser

$$= m_w(h_{w2} - h_{w1}) = m_w c_w (t_{w2} - t_{w1})$$

Substituting this value of Q in eqn. (3.11a), we get

$$h_1 - h_2 = m_w(h_{w2} - h_{w1}) = m_w c_w (t_{w2} - t_{w1}) \dots \dots (3.11b)$$

Where , m_w= mass of cooling water passing through the condenser, and

C_w=specific heat of water

3.8 Evaporator

An evaporator is an equipment used in refrigeration plant to carry heat from refrigerator to maintain the low temperature. Here the refrigerant liquid is passed through the evaporator and it comes out as vapor absorbing its latent heat from the surroundings of the evaporator.

Fig. 3.9. shows the system. For this system

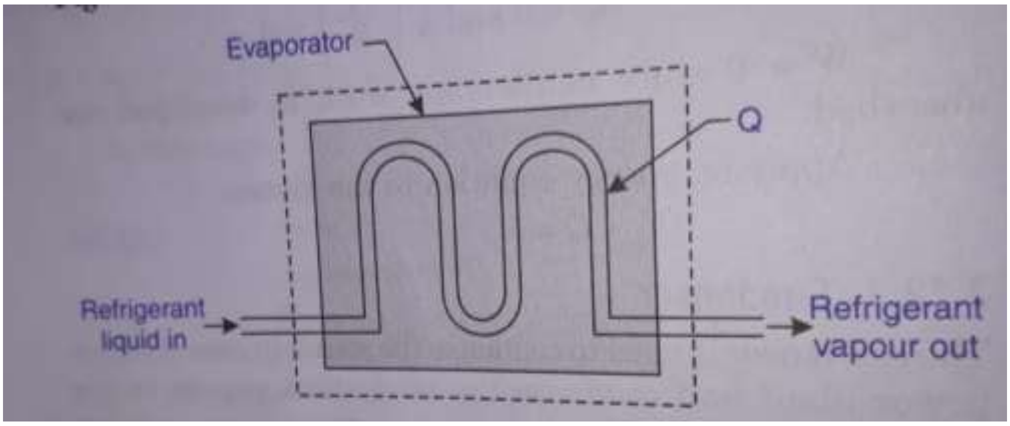

Fig.3.9. Evaporator

$$\Delta PE = 0 \ , \Delta KE = 0$$

W=0 [no work is absorbed or supplied)

Applying the energy equation to the system

$$h_1 + Q = h_2 \quad \ldots \ldots (3.12)$$

Q is taken as +ve because heat flows from the surroundings to the system as the temperature in the system is lower than the surroundings.

3.9 Steam Nozzle

In case of a nozzle as the enthalpy of the fluid decreases and pressure drops simultaneously the flow of fluid is accelerated. This is generally used to convert the part of the energy of steam into kinetic energy of steam supplied to the turbine.

Fig.3.10 shows a commonly used convergent-divergent nozzle.

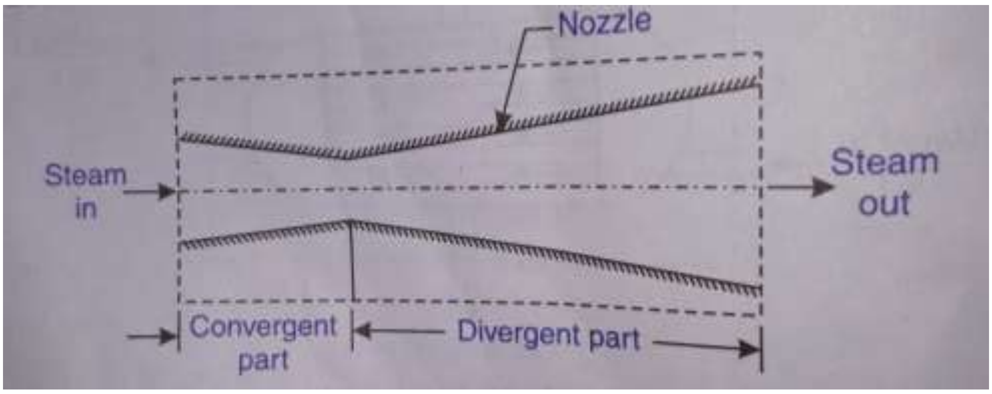

Fig.3.11. Steam Nozzle.

For this system,

$\Delta PE = 0$

W=0

Q=0

Applying energy equation to the system.

$$h_1 + \frac{{C_1}^2}{2} = h_2 + \frac{{C_2}^2}{2}$$

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

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

$${C_2}^2 = {C_1}^2 + 2(h_1 - h_2)$$

$$\therefore \quad C_2 = \sqrt{{C_1}^2 + 2(h_1 - h_2)}$$

Where velocity C is in m/s and enthalpy h in Joules.

If $C_1 \ll C_2$, then

$$C_2 = \sqrt{2(h_1 - h_2)}$$

$$\therefore \quad C_2 = \sqrt{2\Delta h}$$

3.10 Throttling Process

Throttling process involves the passage of a higher pressure fluid through a narrow constriction. The effect is the reduction in pressure and increase in volume. This process is adiabatic as no heat flows from and to the system, but it is not reversible.it is not an isentropic process. The entropy of the fluid actually increases.

Such a process occurs in a flow through a porous plug, a partially closed valve and a very narrow orifice.

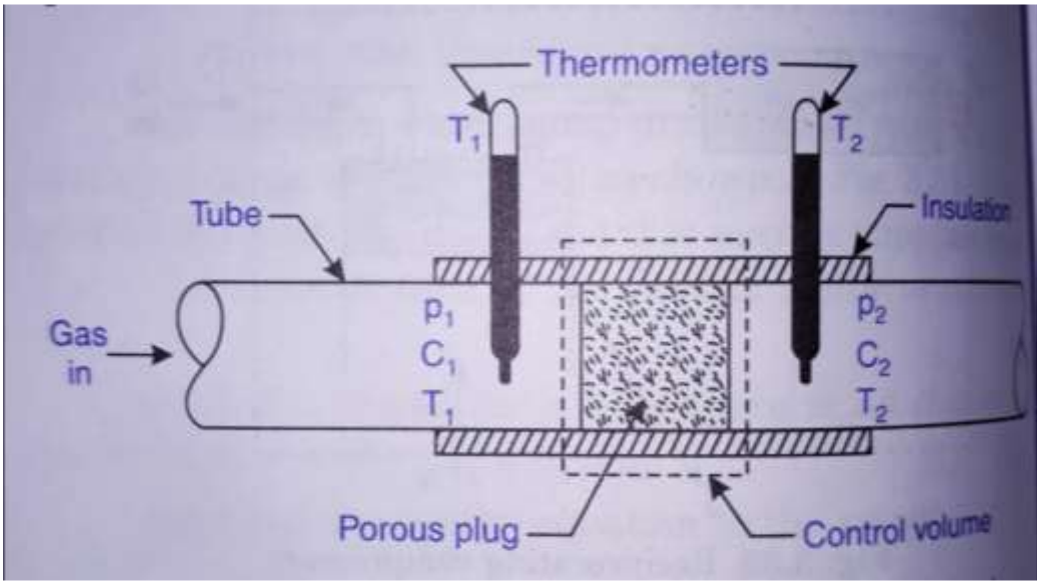

Fig.3.12. Shows Throttling Process

In this system,

Q=0 (system is isolated)

W=0 (there is no work interaction)

$\Delta PE = 0$ $(Inlet\ and\ outlet\ are\ at\ the\ same\ level)$

$\Delta KE = 0$ $(kinetic\ energy\ does\ not\ change\ significantly)$

Applying the energy equation to the system

$h_1 = h_2$

This shows that enthalpy remains constant during adiabatic throttling process.