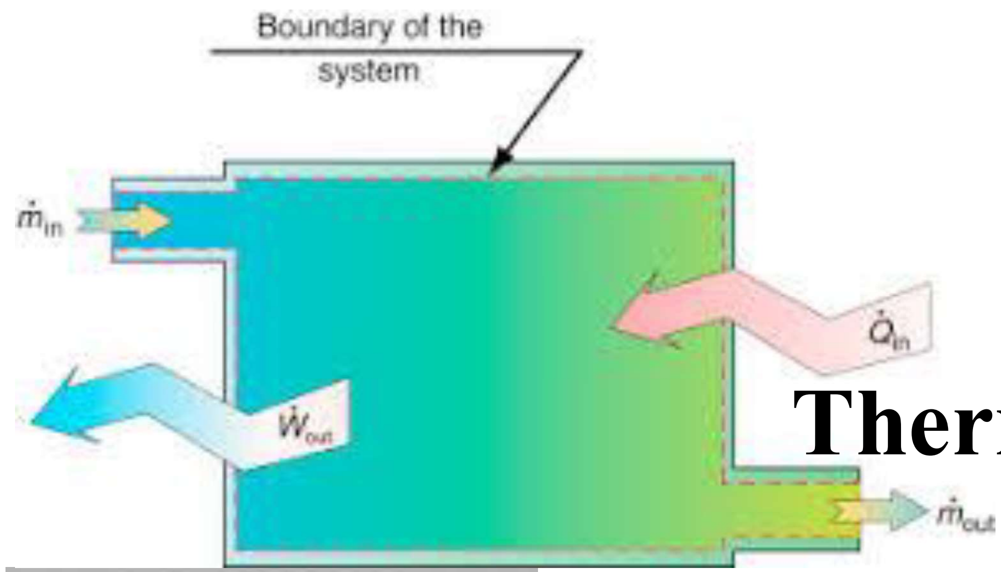
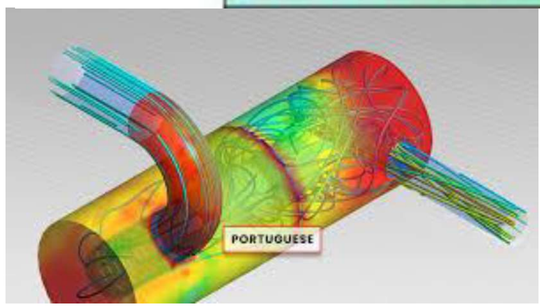
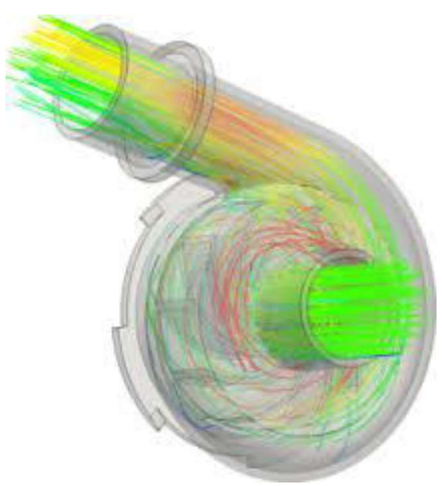






Thermodynamics-I

(MECH-101)

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 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.

For such case 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:

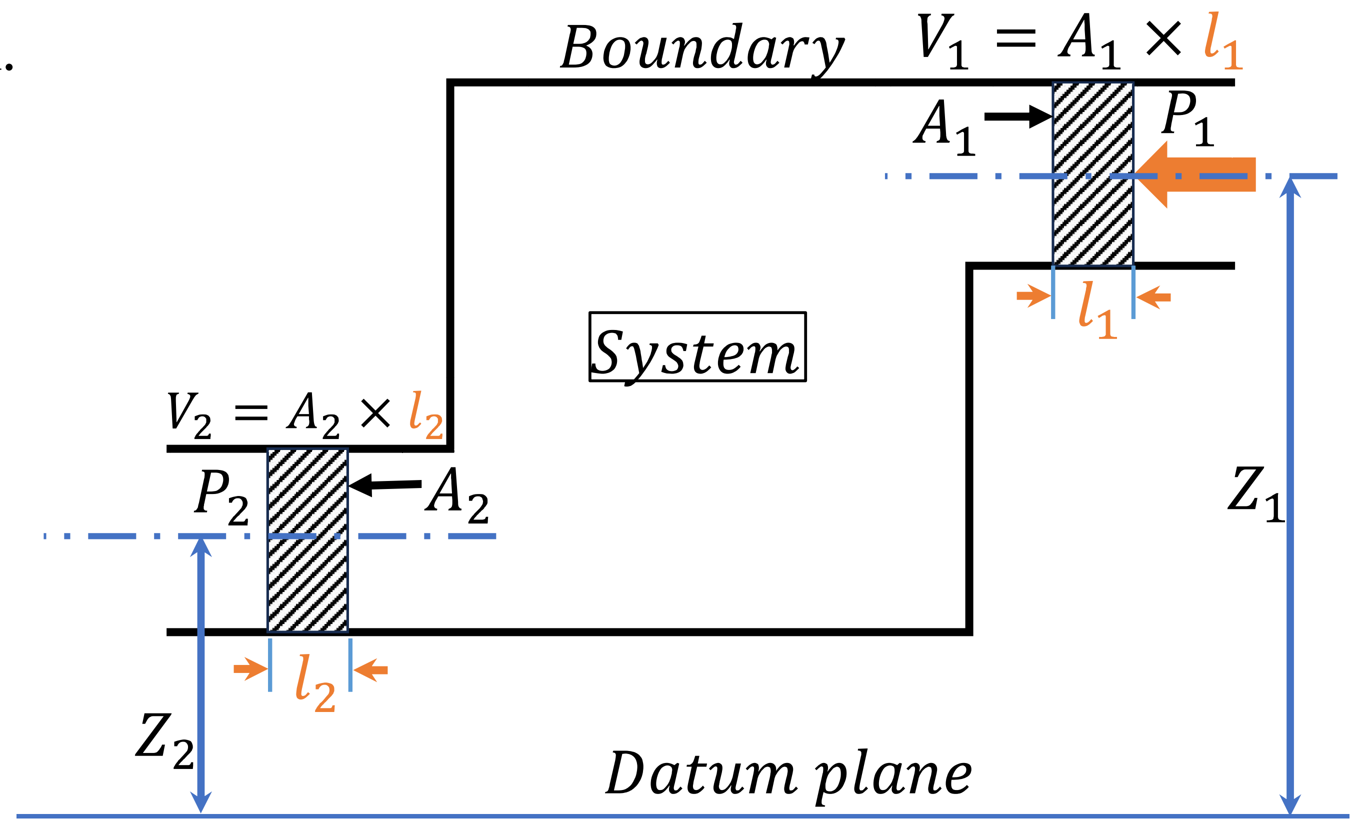


Fig.3.1 : Schematic flow process for an open system

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

$$(u_1+p_1v_1)+\frac{C_1^2}{2}+Z_1\times g+Q=(u_2+p_2v_2)+\frac{C_2^2}{2}+Z_2\times g+W$$

$$\because\ h=u+pv$$

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

When Z_1 and Z_2 are ignored the equation becomes

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

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 $C.A$. Also, since

$$mass\ flow\ rate, \dot{m} = \frac{CA}{v} \ldots\ldots\ldots\ldots\ldots (3.3), \qquad Where\ \ v = Specific\ volume\ at\ a\ section\ (\frac{m^3}{kg})$$

$By\ applying\ the\ mass\ conservation\ on\ flouid\ flow\ in\ \ figure$ 3.1

$$\text{The}\ flow\ rate\ , \dot{m} = \frac{C_1 A_1}{v_1} = \frac{C_2 A_2}{v_2} \ldots\ldots\ldots\ldots\ldots (3.4),$$ ***This equation is known as the continuity of mass equation***.

3.2 Energy Relation for Flow Process

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

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

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

$$Q - \Delta U = [\Delta PE + \Delta KE + \Delta pV + W] \ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

$Where: \ \Delta U = \dot{m}(u_2 - u_1)$, $\Delta PE = \dot{m}.g.(Z_2 - Z_1)$, $\Delta KE = \dot{m}\left(\frac{C_2^2}{2} - \frac{C_1^2}{2}\right)$, $\Delta pV = \dot{m}\,(p_2 v_2 - p_1 v_1)$

$$Q = \Delta U + \Delta PE + \Delta KE + \Delta pV + W \ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

For Non-flow system

$$Q - \Delta U = W \ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

$$Q - \Delta U = \int_1^2 p\,dv \ldots\ldots\ldots\ldots\ldots\ldots (3.8)$$

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:

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

In this case,

$Q=0$

$\Delta u = u_2 - u_1 = 0$

$\therefore \quad v_1 = v_2 = v$

$Z_2=0$

$$\therefore \quad \left(p_1v + Z_1g + \frac{{C_1}^2}{2}\right) = \left(p_2v + Z_2g + \frac{{C_2}^2}{2}\right) + W \text{ ......} \quad 3.9$$

$$W = \left[\frac{C_1^2}{2} - \frac{C_2^2}{2}\right] + (Z_1 \times g - Z_2 \times g) + (p_1v - p_2v) \text{ ....} (3.10)$$

$$W = \left[\frac{C_1^2}{2} - \frac{C_2^2}{2}\right] + (Z_1 \times g) + (p_1v - p_2v) \text{ ....} (3.11)$$

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

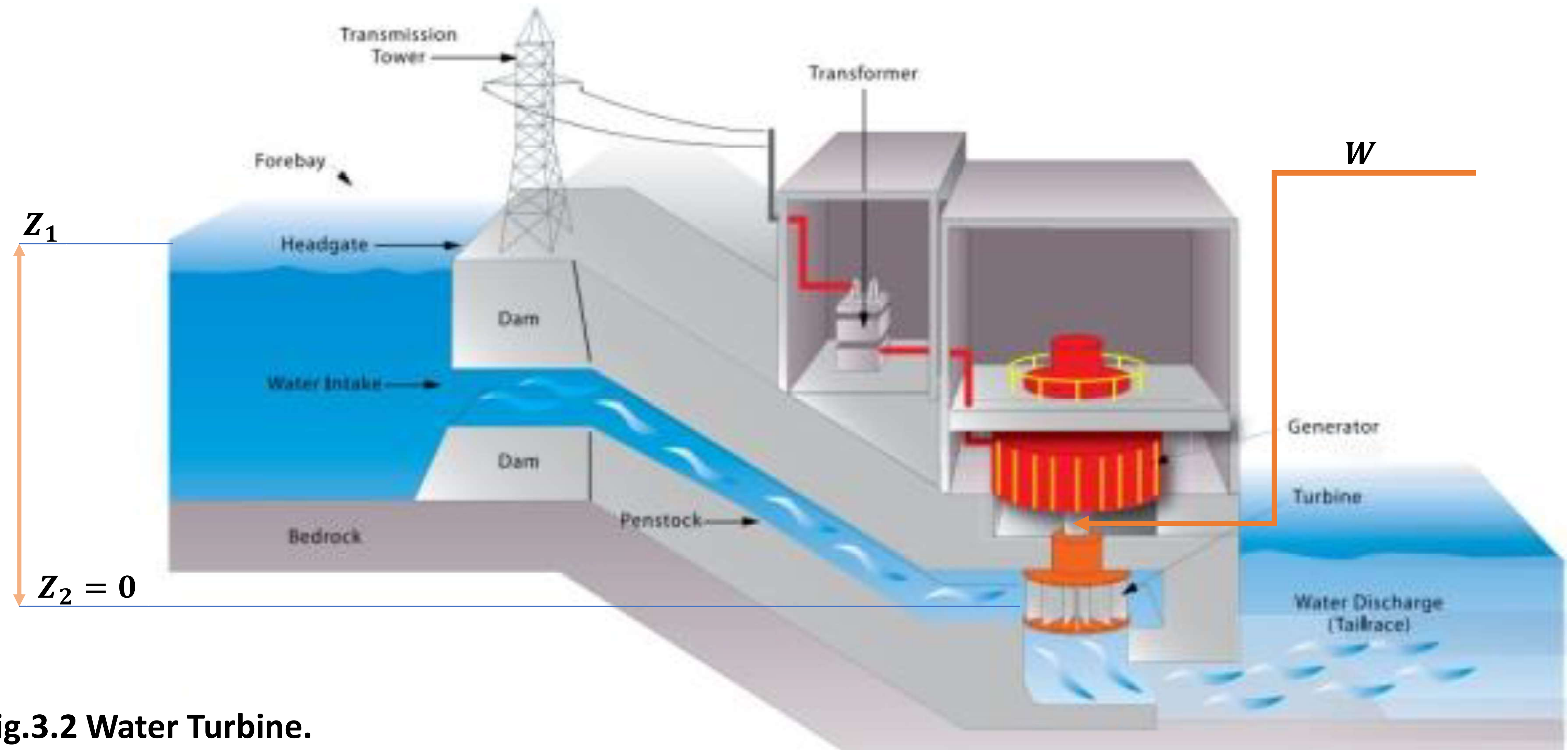


Fig.3.2 Water Turbine.

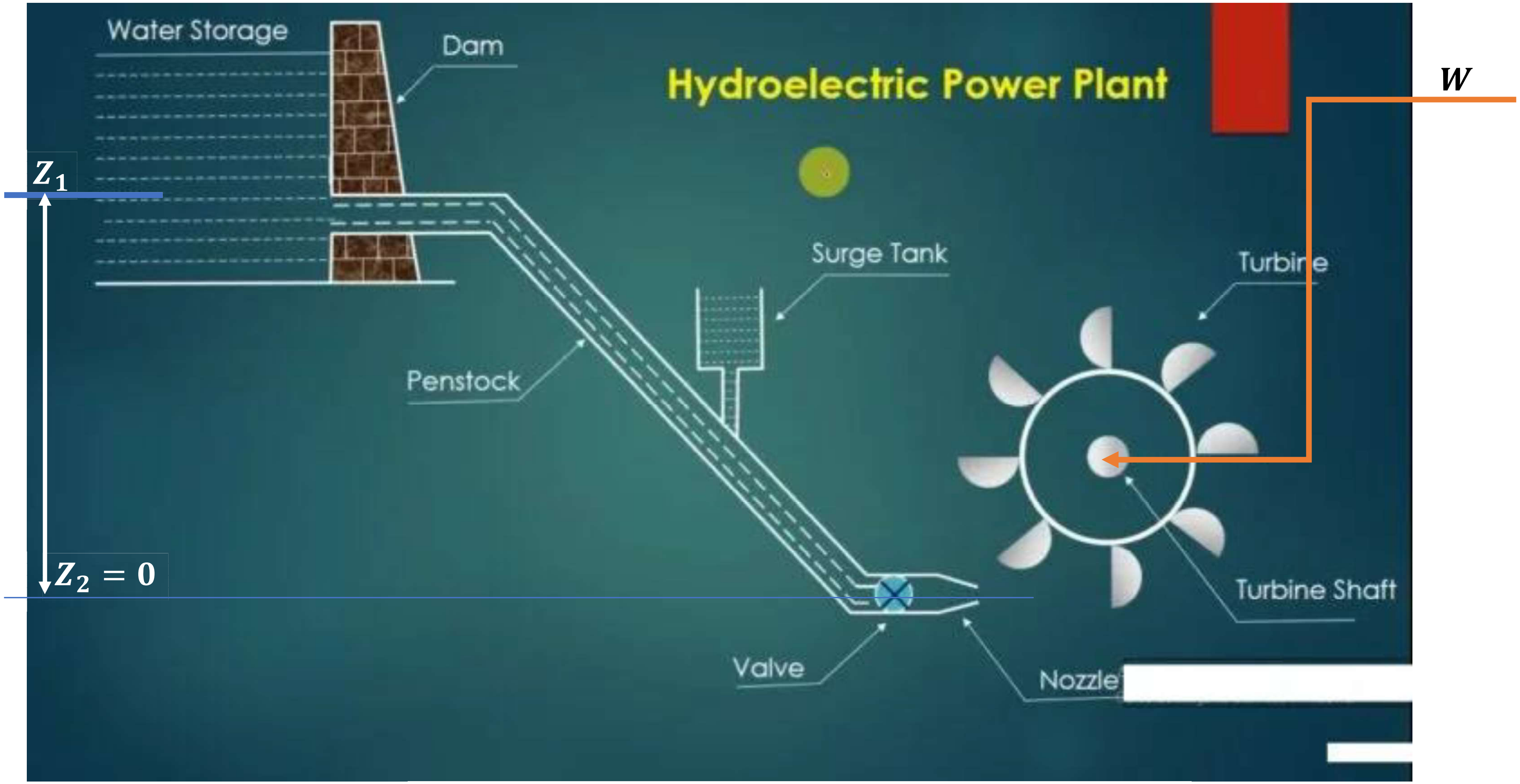


Fig.3.2 Water Turbine.

Example: Consider a river flowing toward a lake at an average velocity of 3 m/s at a rate of 500 m3/s at a location 90 m above the lake surface. Determine the total mechanical energy of the river water per unit mass and the power generation potential of the entire river at that location.

Assumptions **1** The elevation given is the elevation of the free surface of the river.
2 The velocity given is the average velocity.
3 The mechanical energy of water at the turbine exit is negligible.

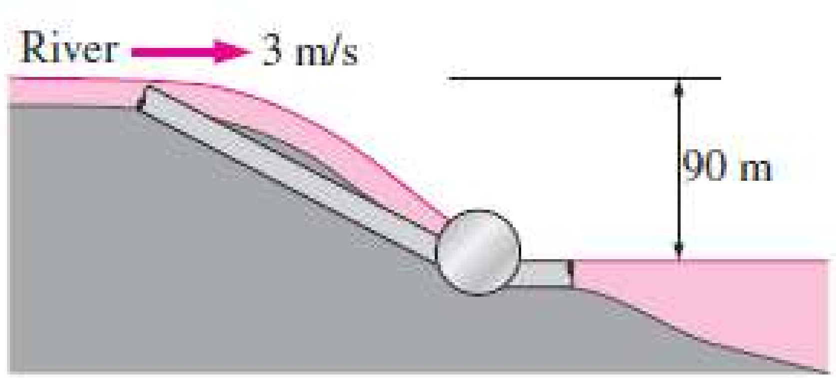
Properties We take the density of water to be ρ = 1000 kg/m3.

Analysis Noting that the sum of the flow energy and the potential energy is constant for a given fluid body, we can take the elevation of the entire river water to be the elevation of the free surface, and ignore the flow energy. Then the total mechanical energy of the river water per unit mass becomes

$$W = KE + PE = \left[\frac{C_1^2}{2}\right] + (Z_1 \times g) = \frac{3^2}{2} + 90 \times 9.81 = 887\ J/kg$$

$$\dot{m} = \rho_w \times \dot{V} = 500,000\,\frac{kg}{s}$$

$$W_{Max} = \dot{m} \times W = 500,000 \times 887 = 4,435,000,00\ W = 444\ MW$$



H.W: Electric power is to be generated by installing a hydraulic turbine–generator at a site 120 m below the free surface of a large water reservoir that can supply water at a rate of 1500 kg/s steadily. Determine the power generation potential.

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.

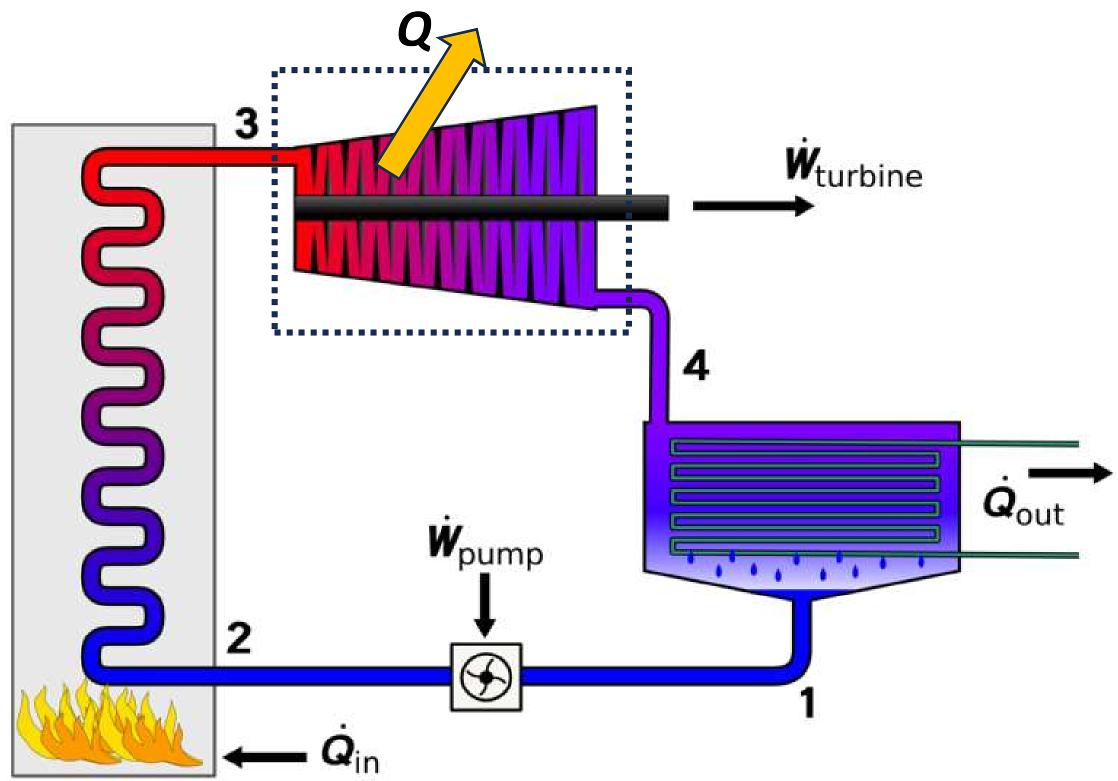


Fig. 3.3 Steam or Gas Turbine.

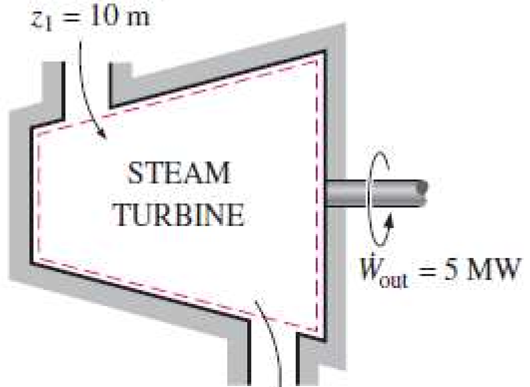
Applying energy equation to the system.

$$Z_3 = Z_4, \qquad \therefore \ \Delta Z = 0$$

$$\left(h_3 + \frac{C_3^2}{2}\right) - Q = \left(h_4 + \frac{C_4^2}{2}\right) + W \ \ldots\ldots\ldots (3.12)$$

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)

Example: The power of an adiabatic steam turbine is 5 MW, and the inlet and the exit conditions of the steam are as indicated in the following figure.
(a) Compare the magnitudes of h, Ke, and Pe.
(b) Determine the work done per unit mass of the steam flowing through the turbine.
(c) Calculate the mass flow rate of the steam.



Solution:

$$\Delta h = h_1 - h_2 = 3248.4 - 2361.01 = 887.39\ kJ/kg$$

$$Ke = \frac{{V_1}^2}{2} - \frac{{V_2}^2}{2} = \frac{50^2 - 180^2}{2} = -14950\frac{J}{kg} = -14.95\frac{\text{kJ}}{\text{kg}}$$

$$\Delta \text{Pe} = g(Z_1 - Z_2) = 9.81(10-6) = 39.25\frac{J}{kg} = 0.03925\frac{kJ}{kg}$$

$Q = 0,$ $\quad$ *Adiabatic*

$$\left(\boldsymbol{h_1 + \frac{C_1^2}{2}}\right) - \boldsymbol{Q} = \left(\boldsymbol{h_2 + \frac{C_2^2}{2}}\right) + \boldsymbol{W} \ldots\ldots\ldots (\mathbf{3.12})$$

$$\boldsymbol{W = \Delta h + \Delta Ke + \Delta Pe =}$$

$$\boldsymbol{W = (h_1 - h_2) + \left(\frac{C_1^2}{2} - \frac{C_2^2}{2}\right) + g(Z_1 - Z_2) =}$$

$$\boldsymbol{W = 887.39 - 14.95} + 0.03925 = \boldsymbol{872.48\ kJ/kg}$$

The required mass flowrate to produce 5MW

$$\boldsymbol{\dot{m} = \frac{5000\ KJ/s}{872.48\ kJ/kg} = 5.7\ kg/sec}$$

3.3 Centrifugal Water Pum

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 run the pump and this may be supplied or external source such as an electric motor or a diesel engine.

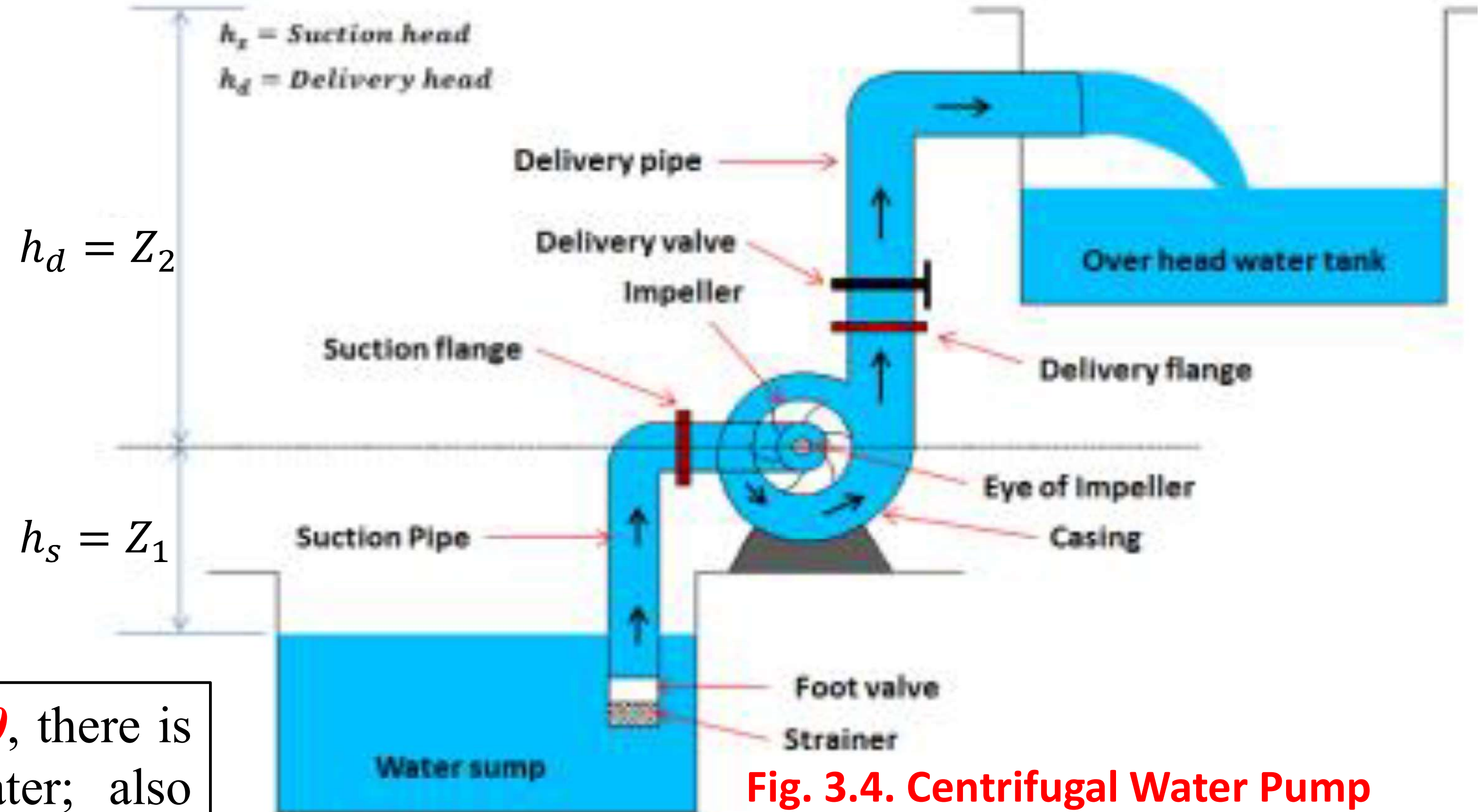


Fig. 3.4. Centrifugal Water Pump

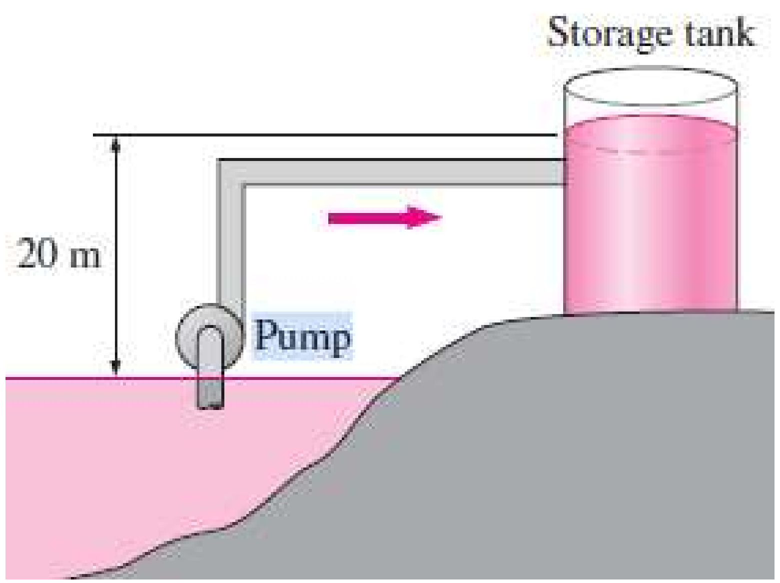
In this application, ***Q=0***, and ***Δu=0***, there is no change in temperature of water; also $v_1 = v_2 = v$

The general equation of energy of this application is

$$p_1v_1 + Z_1 \times g + \frac{C_1^2}{2} = p_2v_2 + Z_2 \times g + \frac{C_2^2}{2} - W \ldots\ldots\ldots..(3.13)$$

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

Example: Water is pumped from a lake to a storage tank 20 m above at a rate of 70 L/s while consuming 20.4 kW of electric power. Disregarding any frictional losses in the pipes and any changes in kinetic energy, determine the overall efficiency of the pump–motor unit.



$$\dot{V}\left(\frac{m^3}{kg}\right) = \frac{70\left(\frac{L}{sec}\right)}{1000} = 0.07\ \frac{m^3}{sec}$$

$$\dot{m} = \rho \times \dot{V} = 1000 \times 0.07 = 70\ \frac{kg}{sec}$$

$$Pe = g.Z_2 = 9.81 \times 20 = 196\frac{J}{kg}$$

$$W_{pump,out} = PE = \dot{m}.g.Z_2 = 70 \times 9.81 \times 20 = 13734W = 13.734kW$$

$$\eta_{pump} = \frac{W_{pump,out}}{W_{in}} = \frac{13.734}{20.4} = 0.67$$

3.4 Compressor

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

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

$$In\ such\ applications\ usually\ \Delta Z = 0$$
$$The\ general\ equation\ of\ this\ application$$

$$\left(h_1 + \frac{C_1^2}{2}\right) - Q = \left(h_2 + \frac{C_2^2}{2}\right) - W \ldots\ldots\ldots\ldots (3.14)$$

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.

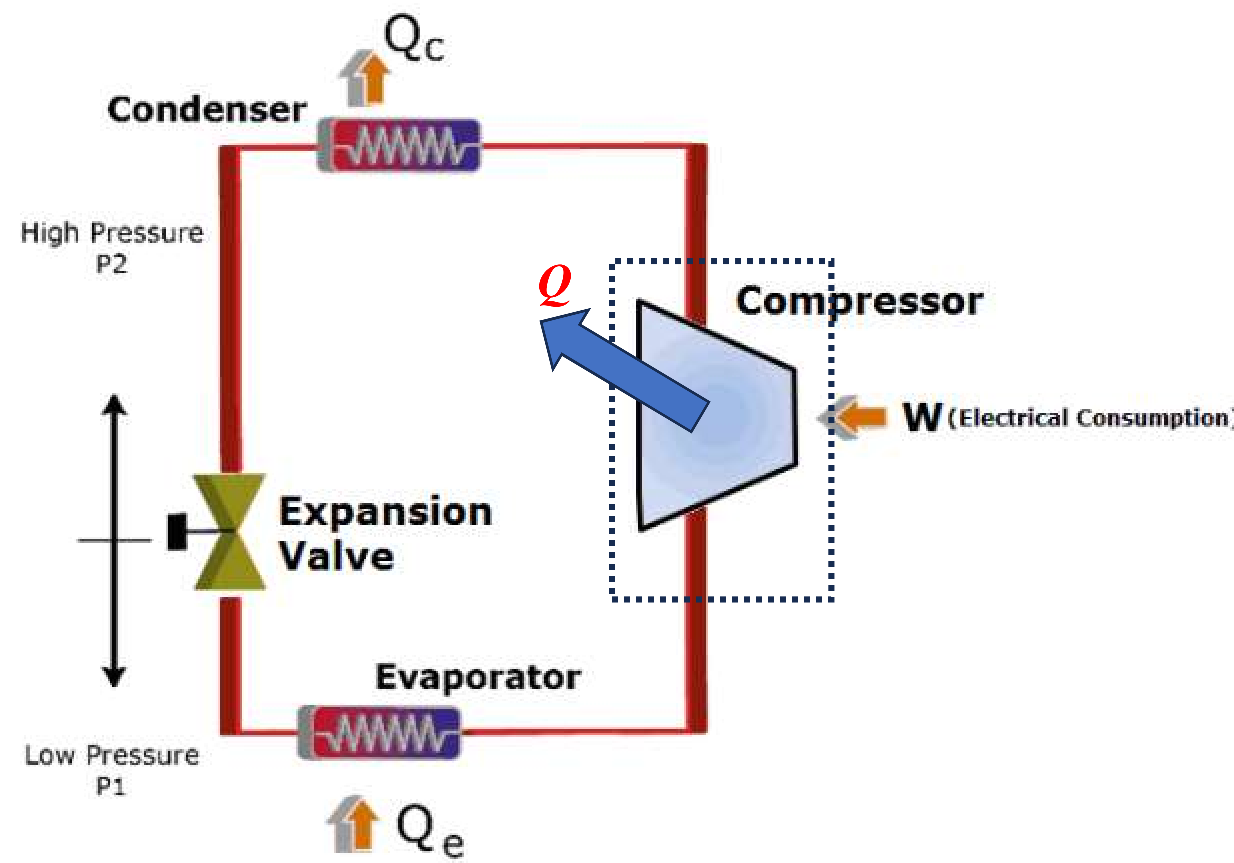
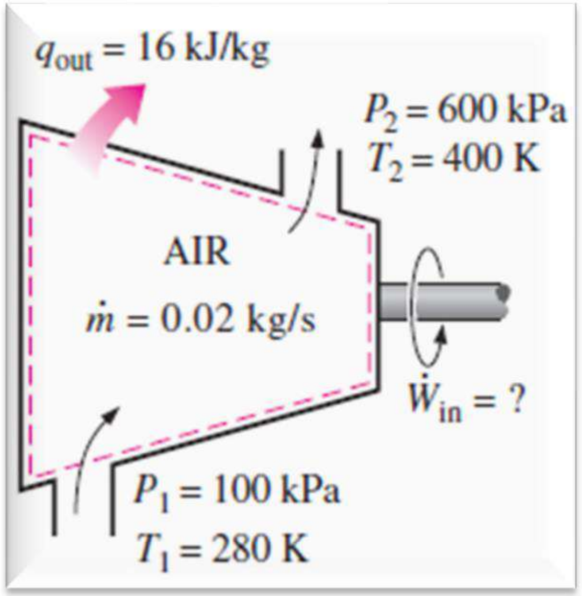


Fig.3.5. Centrifugal Compressor

Example: Air is compressed steadily. The mass flow rate of the air is 0.02 kg/s, and a heat loss of 16 kJ/kg occurs during the process. Assuming the changes in kinetic and potential energies are negligible, determine the necessary power input to the compressor. ($h_1 = 280.13 \frac{kJ}{kg}, and\ h_2 = 400.98\ kJ/kg$)



Solution:

$$\left(h_1 + \frac{C_1^2}{2}\right) - Q = \left(h_2 + \frac{C_2^2}{2}\right) - W \ldots\ldots\ldots\ldots (3.14)$$

$$\left(\frac{C_1^2}{2}\right)\left(\frac{C_2^2}{2}\right) = Ke\ (Negligible)$$

$$\dot{W}_{in} + \dot{m}.h_1 = \dot{Q}_{out} + \dot{m}.h_2$$

$$\dot{W}_{in} = \dot{m}.\dot{Q}_{out} + \dot{m}(h_2 - h_1)$$

$$\dot{W}_{in} = \dot{m}.\dot{Q}_{out} + \dot{m}(h_2 - h_1)$$

$$\dot{W}_{in} = 0.02 \times 16 + 0.02 \times (400.98 - 280.13) = 2.74\ kW$$

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).

Applying energy equation to the system, we have:

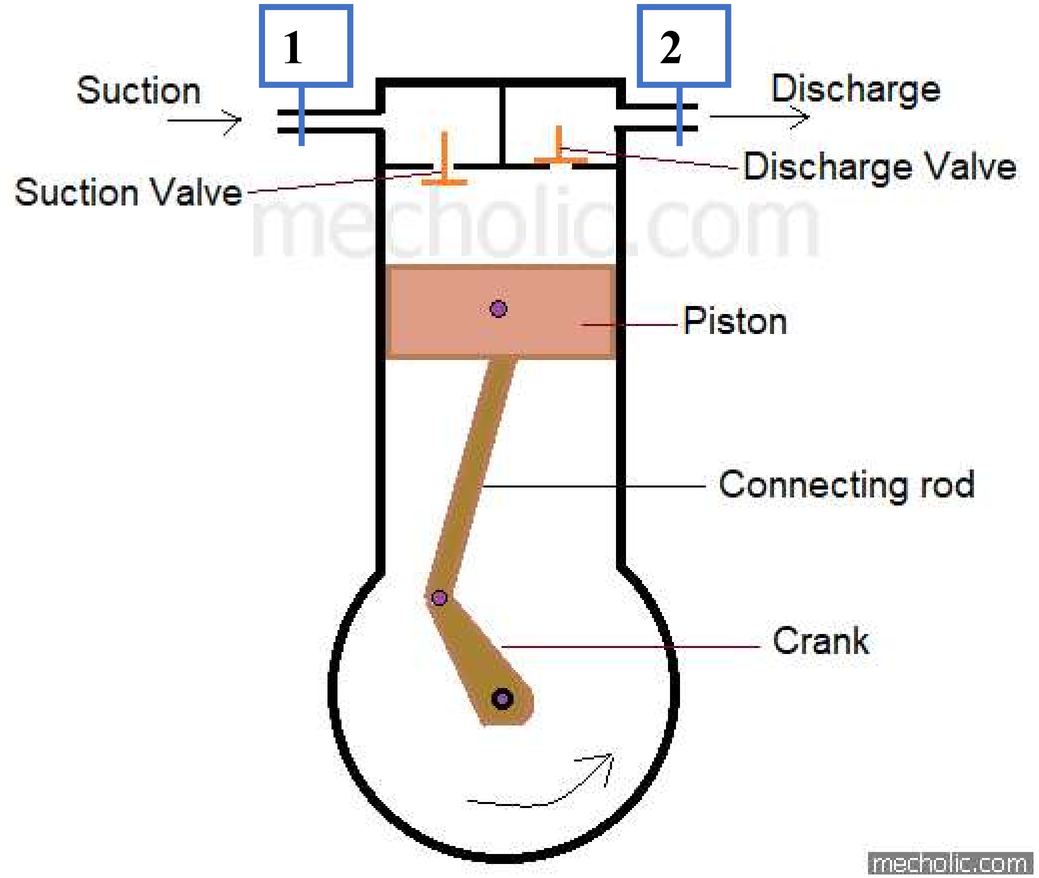


Fig.3.6. Reciprocating Compressor

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

Since these change are negligible compared with other energies.

$$h_1 - Q = h_2 - W \ldots\ldots\ldots\ldots (3.15)$$

3.6 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.

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

$$h_1 + Q = h_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3.16)$$

$$Q = (h_2 - h_1)$$

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

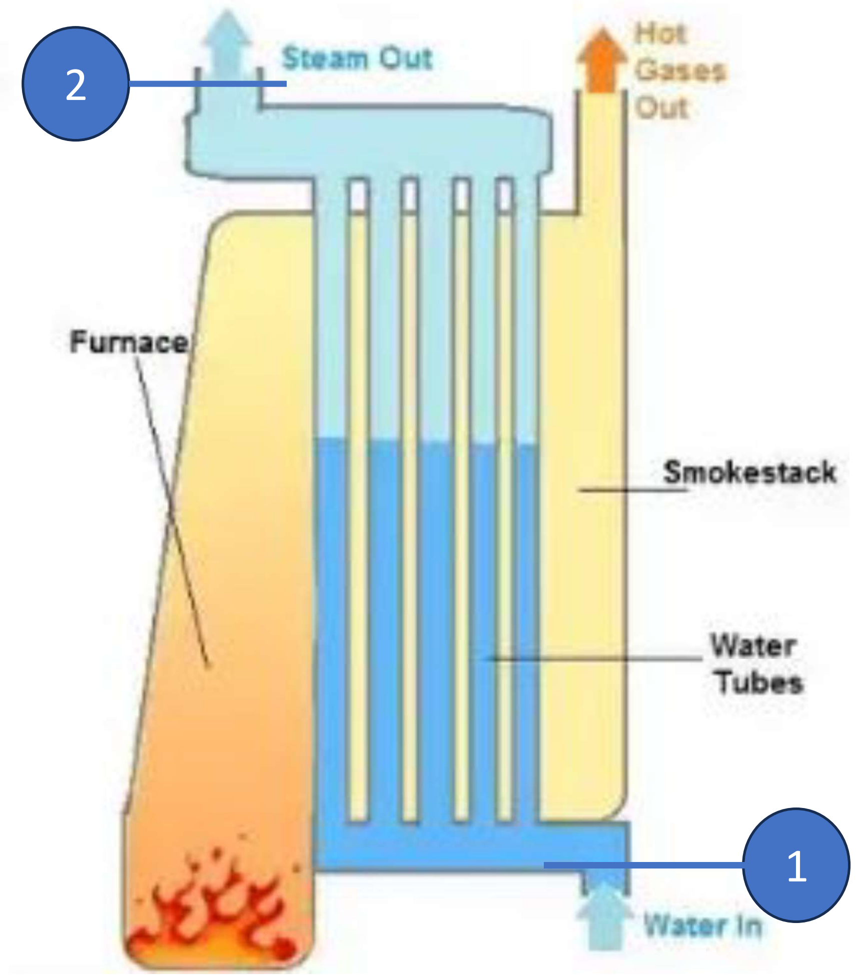
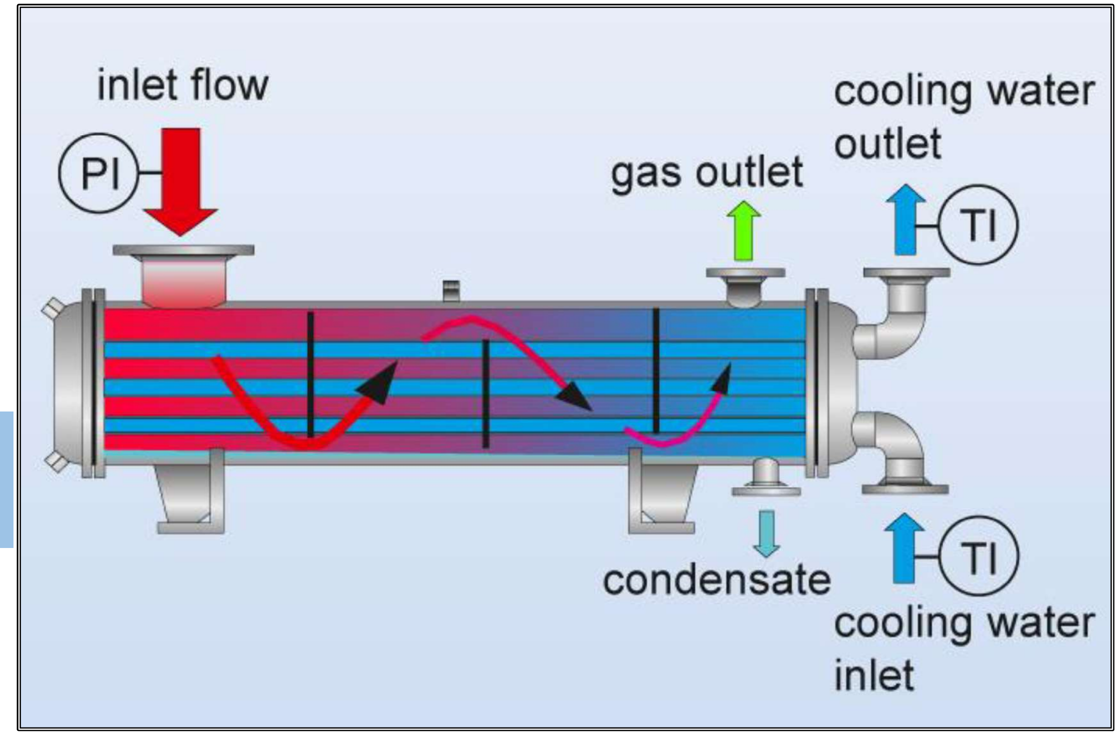


Fig.3.7. Boiler.

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

$Because\ their\ values\ are\ very\ small\ compared\ to\ enthalpies)$

$W = 0,$ $(Since\ neither\ any\ work\ is\ developed\ nor\ absorbed)$

Using energy equation to steam flow

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

$$Q = h_1 - h_2 \dots \dots \dots \dots \dots \dots (3.17)$$

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

$$m_w(h_{w2} - h_{w1}) = m_w . C_w (T_{w2} - T_{w1}), \;\; \therefore Q = m_w . C_w (T_{w2} - T_{w1})$$

Where , ***mw***= mass of cooling water passing through the condenser, and ***Cw***=specific heat of water

3.8 Evaporator

An evaporator is an equipment used in a refrigeration plant to carry heat from the refrigerator to maintain a 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

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

$W = 0,$ (no work is absorbed or supplied)

$$h_1 + Q = h_2 \; \dots \dots \dots \dots \dots \dots (3.18)$$

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.

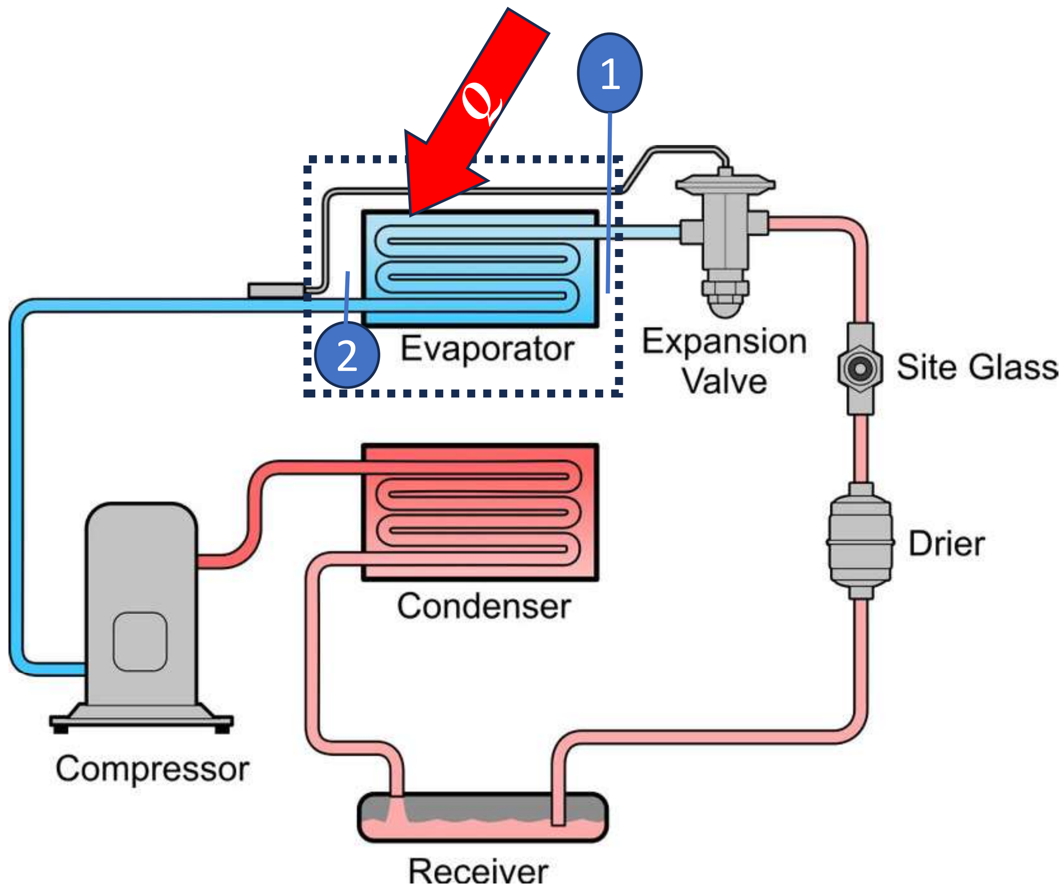


Fig.3.9. Evaporator

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.
For this

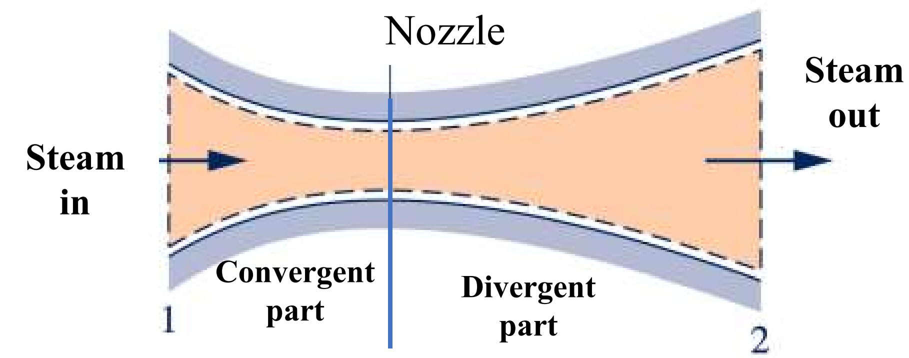


Fig.3.11. Steam Nozzle.

$\Delta PE = 0$

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

The throttling process involves the passage of a higher-pressure fluid through a narrow constriction. The effect is a reduction in pressure and an 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 increases.
Such a process occurs in a flow through a porous plug, a partially closed valve, and a very narrow orifice.

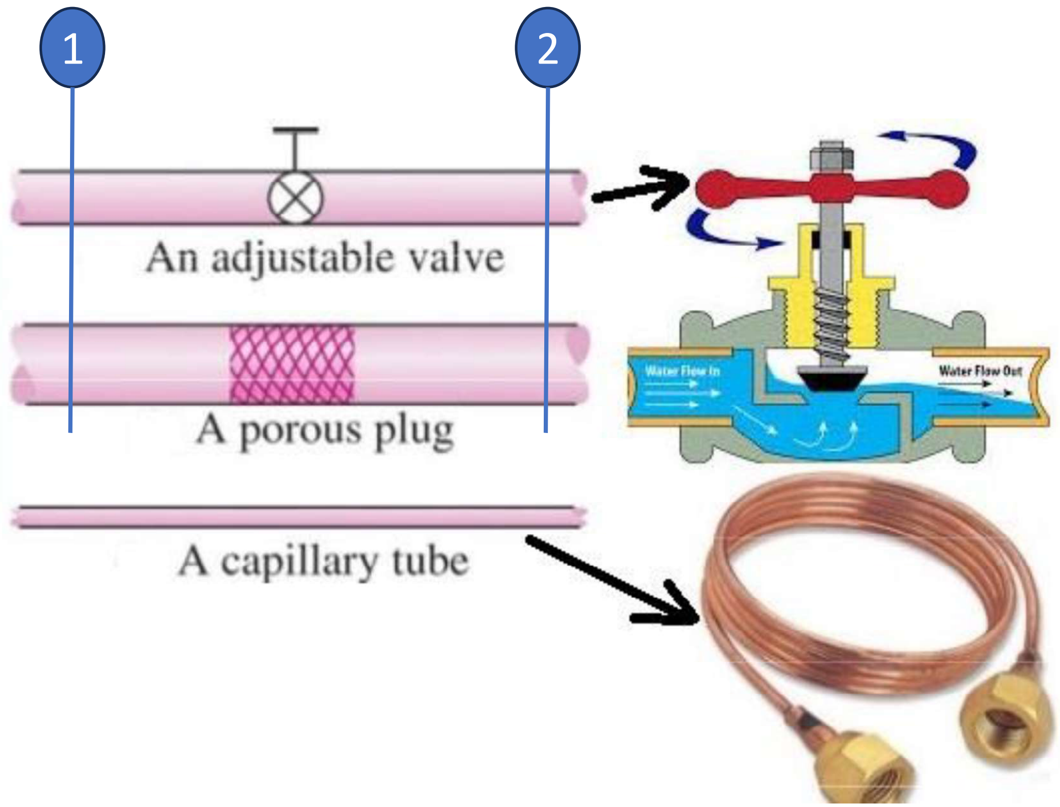


Fig.3.12. Shows Throttling Process

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.