Engineering Thermodynamics

First Law of Thermodynamics

Dr. Hakam Shehadeh

4.10 APPLICATION OF FIRST LAW TO STEADY FLOW PROCESS

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 :

The following *assumptions* are made in the system analysis :

1. The mass flow through the system remains constant.
2. Fluid is uniform in composition.
3. The only interaction between the system and surroundings are work and heat.
4. The state of fluid at any point remains constant with time.
5. In the analysis only potential, kinetic and flow energies are considered.

4.10 APPLICATION OF FIRST LAW TO STEADY FLOW PROCESS

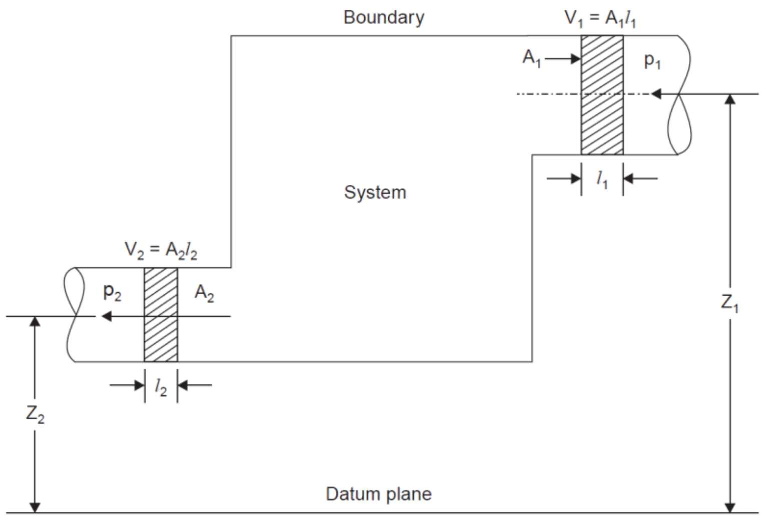

Fig. 4.30

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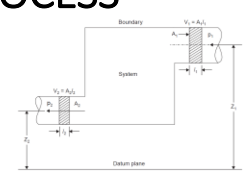
4.10 APPLICATION OF FIRST LAW TO STEADY FLOW PROCESS



The steady flow equation can be expressed as follows :

$$u_1 + \frac{C_1^2}{2} + Z_1 g + p_1 v_1 + Q = u_2 + \frac{C_2^2}{2} + Z_2 g + p_2 v_2 + W \quad ...(4.45)$$

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

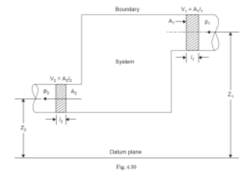
$$h_1 + \frac{C_1^2}{2} + Z_1 g + Q = h_2 + \frac{C_2^2}{2} + Z_2 g + W \quad [\because \quad h = u + pv]$$

If Z_1 and Z_2 are neglected, we get

$$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W \quad ...[4.45\ (a)]$$

4.10 APPLICATION OF FIRST LAW TO STEADY FLOW PROCESS

$$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W \qquad \text{...[4.45 (a)]}$$



Q = Heat supplied (or entering the boundary) per kg of fluid,
W = Work done by (or work coming out of the boundary) 1 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. It is applicable not only to rotary machines such as centrifugal fans, pumps and compressors but also to reciprocating machines such as steam engines.

4.10 APPLICATION OF FIRST LAW TO STEADY FLOW PROCESS

- In a steady flow the rate of mass flow of fluid at any section is the same as at any other section.
- 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 is volume flow divided by specific volume,

$$\therefore \quad \text{Mass flow rate, } \dot{m} = \frac{CA}{v} \qquad \text{...(4.46)}$$

(where v = *Specific volume* at the section)
This equation is known as the **continuity of mass equation**.
With reference to Fig. 4.30.

$$\therefore \quad \dot{m} = \frac{C_1A_1}{v_1} = \frac{C_2A_2}{v_2} \qquad \text{...[4.46 (a)]}$$

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4.11 ENERGY RELATIONS FOR FLOW PROCESS

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

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

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

$$i.e.,\qquad Q=m\left[(u_2-u_1)+g(Z_2-Z_1)+\left(\frac{C_2^{\,2}-C_1^{\,2}}{2}\right)+(p_2v_2-p_1v_1)\right]+W$$

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

where

$$\Delta U=m\,(u_2-u_1)$$
$$\Delta PE=mg\,(Z_2-Z_1)$$
$$\Delta KE=m\left(\frac{C_2^{\,2}-C_1^{\,2}}{2}\right)$$
$$\Delta pv=m(p_2v_2-p_1v_1)$$

4.11 ENERGY RELATIONS FOR FLOW PROCESS

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$$\Delta KE=m\left(\frac{C_2^{\,2}-C_1^{\,2}}{2}\right)$$
$$\Delta pv=m(p_2v_2-p_1v_1)$$

$$\therefore\qquad Q-\Delta U=[\Delta PE+\Delta KE+\Delta(pV)+W]\qquad\ldots(4.47)$$

For non-flow process,

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

$$i.e.,\qquad Q-\Delta U=\int_1^2 p.dV\qquad\ldots(4.48)$$

4.11 ENERGY RELATIONS FOR FLOW PROCESS

The internal energy is a function of temperature only and it is a point function. Therefore, for the same two temperatures, 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. (4.47) and (4.48) for $(Q - \Delta U)$.

$$\therefore \qquad \int_1^2 p.dV = \Delta\, PE + \Delta\, KE + \Delta\,(pV) + W \qquad \ldots(4.49)$$

where, W = Work transfer in flow process

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

4.11 ENERGY RELATIONS FOR FLOW PROCESS

Property Relations for Energy Equations

We know that

$$h = u + pv$$

Differentiating above equation

$$dh = du + pdv + vdp$$

But $\quad dQ = du + p.dv$ (as per first law applied to closed system)

or $\quad du = dQ - p.dv$

Substituting this value of du in the above equation, we get

$$dh = dQ - p.dv + pdv + vdp$$

$$= dQ + vdp$$

$$\therefore \qquad vdp = dh - dQ$$

$$\therefore \qquad -\int_1^2 vdp = Q - \Delta h \qquad \ldots(4.50)$$

4.11 ENERGY RELATIONS FOR FLOW PROCESS

where $-\int_1^2 v dp$ represents on a *p-v* diagram the area behind 1-2 as shown in Fig. 4.31 (*b*).

The eqn. (4.47) for a unit mass flow can be written as

$$dQ = d(PE) + d(KE) + du + d(pv) + dW$$

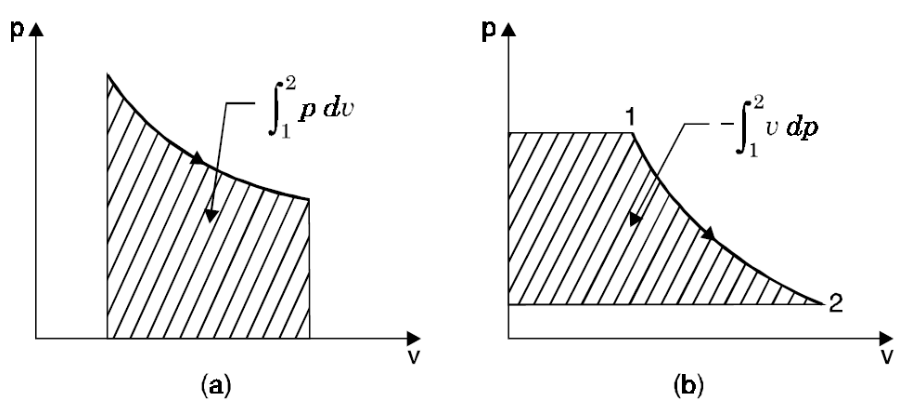
Substituting the value of $dQ = du + p.dv$ in the above equation, we get

$$du + pdv = d(PE) + d(KE) + du + pdv + vdp + dW$$

$$\therefore \quad - vdp = d(PE) + d(KE) + dW$$

$$\therefore \quad -\int_1^2 vdp = \Delta PE + \Delta KE + W \quad \text{...[4.50 (a)]}$$

4.11 ENERGY RELATIONS FOR FLOW PROCESS



(*a*) Work done in non-flow process. (*b*) Work done in flow process.

Fig. 4.31. Representation of work on *p-v* diagram.

4.11 ENERGY RELATIONS FOR FLOW PROCESS

If $\Delta PE = 0$ (as in most of thermodynamic systems)

$$-\int_1^2 vdp = \Delta KE + W \qquad \text{...[4.50 (b)]}$$

If $W = 0$, the area behind the curve represents ΔKE and if $\Delta KE = 0$, area behind the curve represents W which is shaft work.

$-\int_1^2 vdp$ is a *positive quantity and represents work done by the system.*

If $\Delta PE = 0$ and $W = 0$, then

$-\int_1^2 vdp = \Delta KE$, this is applicable in case of a *nozzle.*

$$i.e., \quad \int_1^2 vdp = \frac{C^2}{2} \text{ in the case of a nozzle.}$$

4.11 ENERGY RELATIONS FOR FLOW PROCESS

If $\Delta PE = 0$ and $\Delta KE = 0$, as in case of a *compressor*, $-\int_1^2 vdp = W$

$$\text{or} \qquad W = \int_1^2 vdp \text{ in the case of a } \textit{compressor}.$$

The integral $\int_1^2 pdv$ and $\int_1^2 vdp$ are shown in Fig. 4.31 (*a*) and (*b*).

4.11 ENERGY RELATIONS FOR FLOW PROCESS

The work done during *non-flow process* is given by

$$\int_1^2 pdv = Q - \Delta u \qquad \text{...[4.50 (c)]}$$

For isothermal process, we have

$$\Delta u = 0 \text{ and } \Delta h = 0.$$

Substituting these values in (equations) 4.50 and [4.50 (*c*)]

$$-\int_1^2 vdp = Q \text{ and } \int_1^2 pdv = Q$$

$$\therefore \qquad \int_1^2 pdv = -\int_1^2 vdp$$

The above equation indicates that the *area under both curves is same for an isothermal process.*

Note. In all the above equations '*v*' represents volume per unit mass as mass flow is considered unity.

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4.11 ENERGY RELATIONS FOR FLOW PROCESS

Now let us find out expressions for work done for different flow processes as follows :

(*i*) **Steady flow constant pressure process :**

$$W = -\int_1^2 v \,.\, dp = 0 \qquad [\because \quad dp = 0] \qquad \text{...(4.51)}$$

(*ii*) **Steady flow constant volume process :**

$$W = -\int_1^2 Vdp = -V(p_2 - p_1) = V(p_1 - p_2)$$

i.e., $\qquad W = V(p_1 - p_2) \qquad \text{...(4.52)}$

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4.11 ENERGY RELATIONS FOR FLOW PROCESS

(*iii*) **Steady flow constant temperature process :**

The constant temperature process is represented by

$$pV = p_1V_1 = p_2V_2 = C \text{ (constant)}$$

$$\therefore \quad W = -\int_1^2 V dp$$

$$= -\int_1^2 \frac{C}{p} dp \qquad \left[\because V = \frac{C}{p}\right]$$

$$= -C\int_1^2 \frac{dp}{p} = -C \left| \log_e p \right|_1^2$$

$$= -C \log_e \frac{p_2}{p_1} = C \log_e \frac{p_1}{p_2}$$

i.e., $$W = p_1V_1 \log_e \left(\frac{p_1}{p_2}\right) \qquad \text{...(4.53)}$$

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4.11 ENERGY RELATIONS FOR FLOW PROCESS

Now substituting the values of W in the equation (4.49), considering unit mass flow :

(*a*) The energy equation for *constant pressure flow process*

$$dQ = \Delta PE + \Delta KE + \Delta h$$

$$= \Delta h \text{ (if } \Delta PE = 0 \text{ and } \Delta KE = 0).$$

(*b*) The energy equation for constant volume flow process

$$dQ = -\int_1^2 v dp + \Delta PE + \Delta KE + \Delta u + pdv + vdp$$

$$= \Delta PE + \Delta KE + \Delta u \qquad \left[\because pdv = 0 \text{ and } v \,.\, dp = \int_1^2 v dp\right]$$

$$\therefore \quad dQ = \Delta u \text{ (if } \Delta PE = 0 \text{ and } \Delta KE = 0)$$

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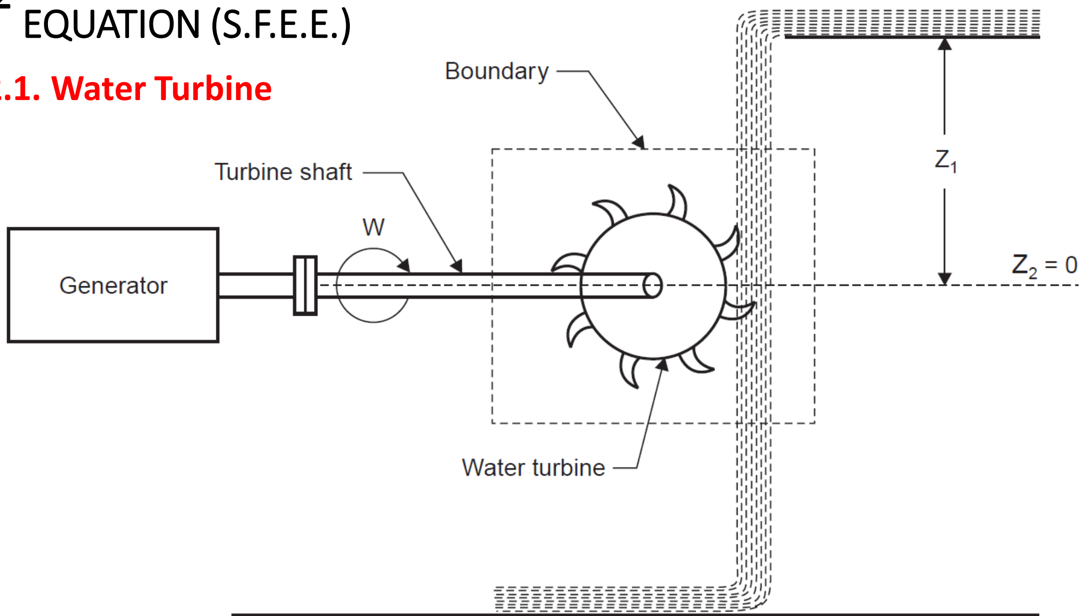
4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.1. Water Turbine



4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.1. Water Turbine

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

In this case,

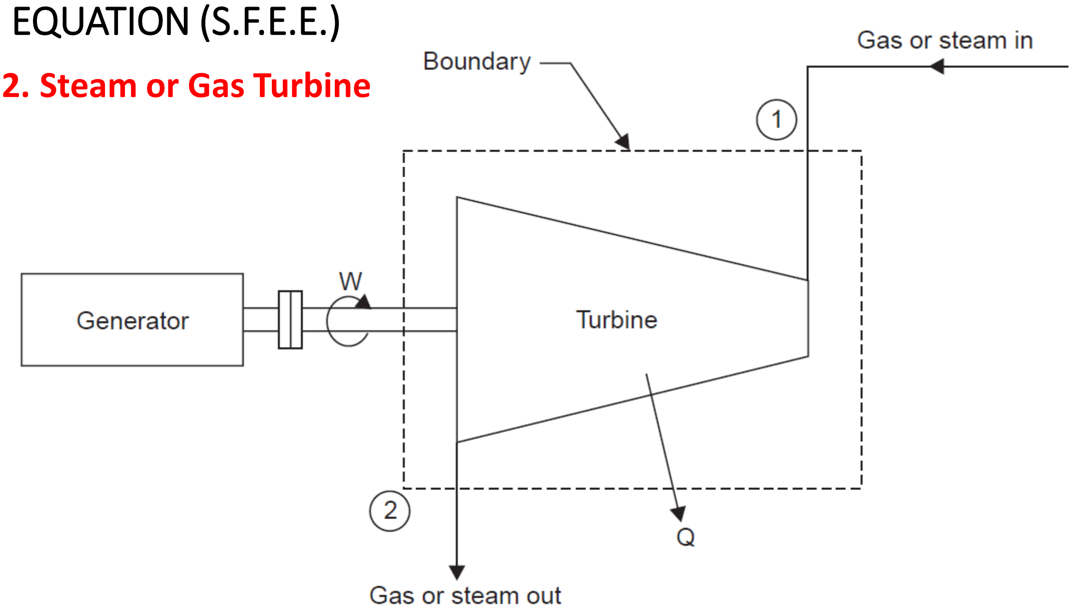
$$Q = 0$$
$$\Delta u = u_2 - u_1 = 0$$
$$\therefore \quad v_1 = v_2 = v$$
$$Z_2 = 0$$

$$\therefore \quad \left(p_1v + Z_1g + \frac{{C_1}^2}{2}\right) = \left(p_2v + Z_2g + \frac{{C_2}^2}{2}\right) + W \quad \text{...(4.54)}$$

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

4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.2. Steam or Gas Turbine



4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.2. Steam or Gas Turbine

Applying energy equation to the system.

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

$$h_1 + \frac{C_1^2}{2} - Q = h_2 + \frac{C_2^2}{2} + W \qquad ...(4.55)$$

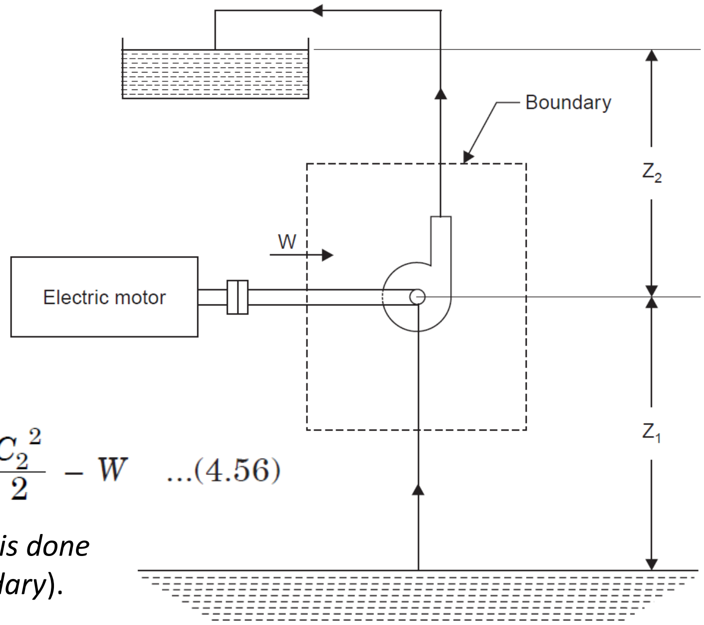
The sign of *Q* is *negative* because heat is *rejected* (or comes out of the boundary).

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

4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.3. Centrifugal Water Pump

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

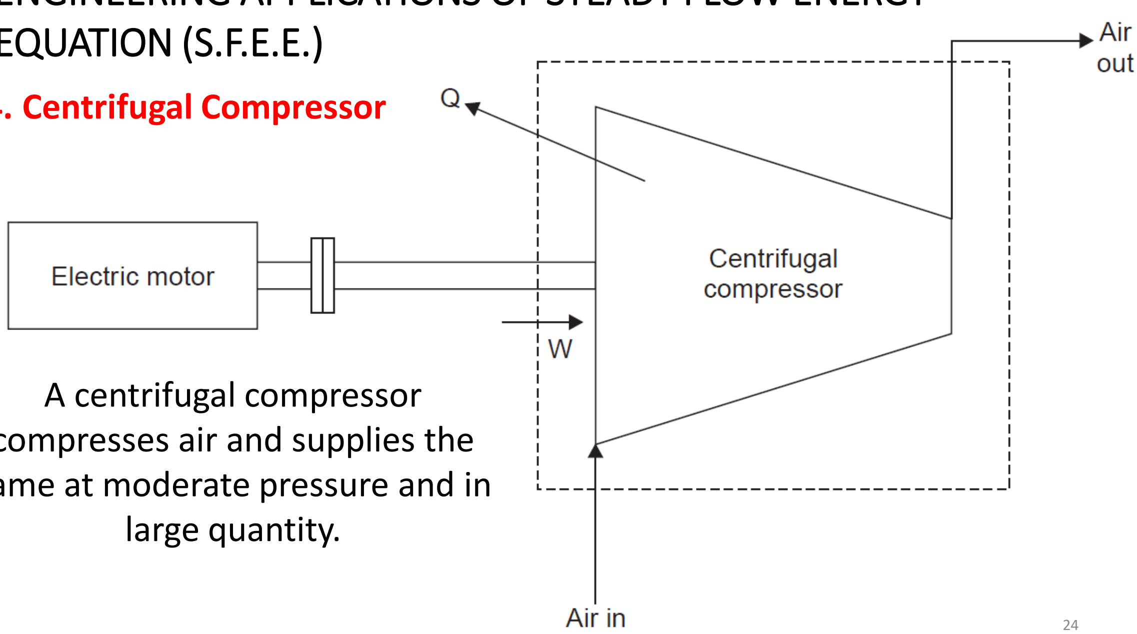


$$p_1v_1 + Z_1g + \frac{C_1^2}{2} = p_2v_2 + Z_2g + \frac{C_2^2}{2} - W \quad ...(4.56)$$

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

4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.4. Centrifugal Compressor



A centrifugal compressor compresses air and supplies the same at moderate pressure and in large quantity.

4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.4. Centrifugal Compressor

Applying energy equation to the system (Fig. 4.35)

$$\Delta Z = 0 \text{ (generally taken)}$$

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

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 $$\left(h_1 + \frac{C_1^{\,2}}{2}\right) - Q = \left(h_2 + \frac{C_2^{\,2}}{2}\right) - W \qquad \text{...(4.57)}$$

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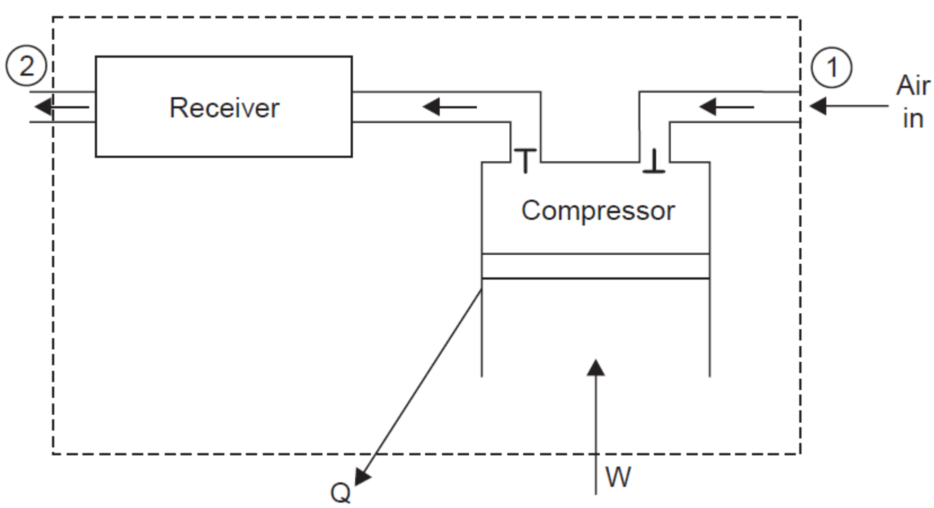
4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.5. Reciprocating Compressor



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4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.5. Reciprocating Compressor

- The reciprocating compressor draws in air from atmosphere and supplies at a considerable higher pressure in small quantities (compared with centrifugal compressor).
- The reciprocating compressor can be considered as steady flow system *provided the control volume includes the receiver which reduces the fluctuations of flow considerably.*

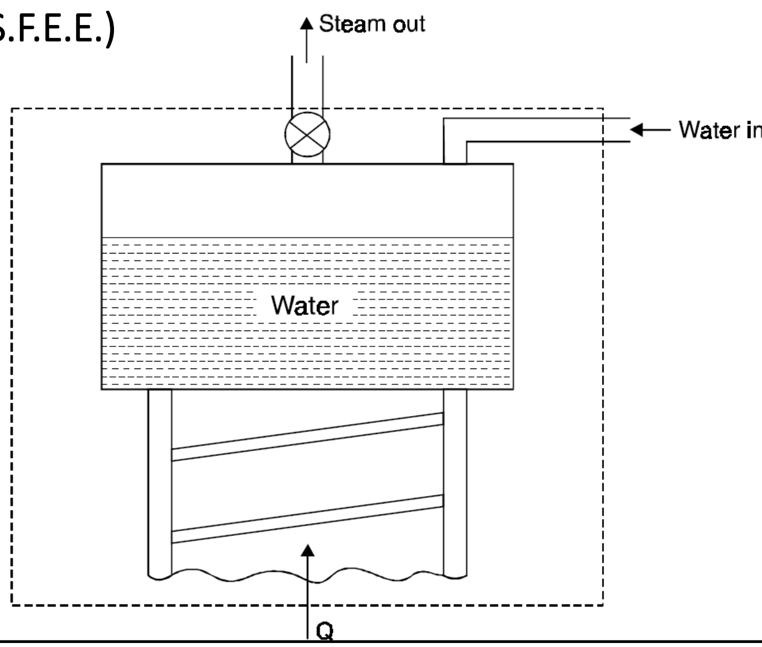
Applying energy equation to the system, we have :

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

$$\therefore \qquad h_1 - Q = h_2 - W \qquad ...(4.58)$$

4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.6. Boiler



4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.6. Boiler

For this system, $\Delta Z = 0$ and $\Delta\left(\frac{C_2^{\,2}}{2}\right) = 0$

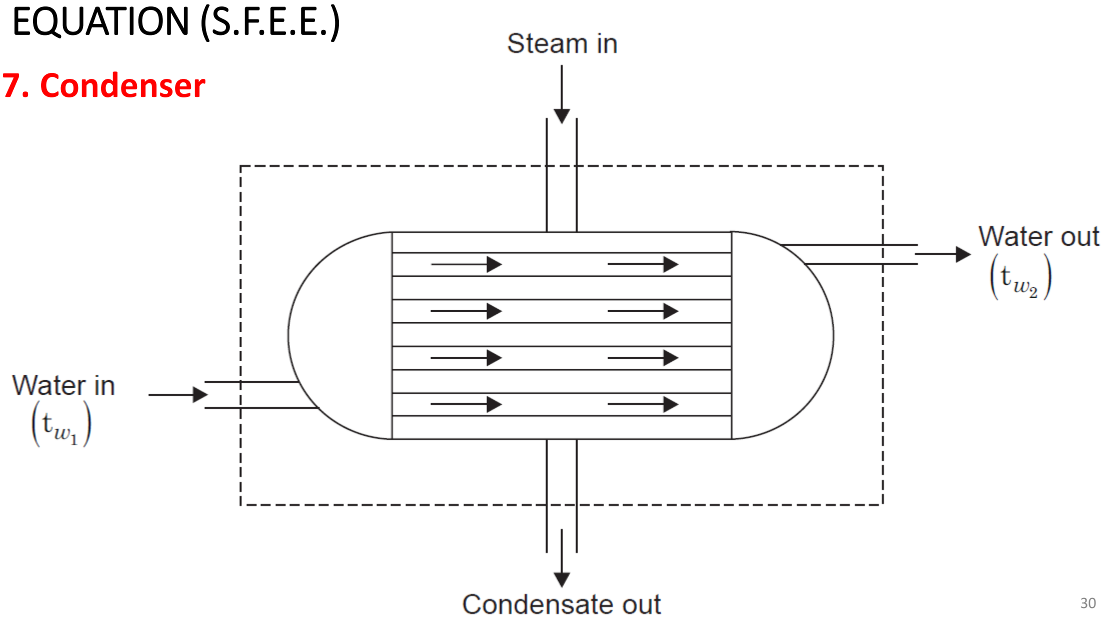
$W = 0$ since neither any work is developed nor absorbed.

Applying energy equation to the system

$$h_1 + Q = h_2 \qquad \ldots(4.59)$$

4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.7. Condenser



4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.7. Condenser

The condenser is used to condense the steam in case of steam power plant and condense the refrigerant vapour 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

$$h_1 - Q = h_2 \qquad \text{...[4.60 (a)]}$$

where Q = Heat lost by 1 kg of steam passing through the condenser.

4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.7. 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. [4.60 (a)], we get

$$h_1 - h_2 = m_w (h_{w2} - h_{w1}) = m_w c_w (t_{w2} - t_{w1}) \qquad \text{...[4.60 (b)]}$$

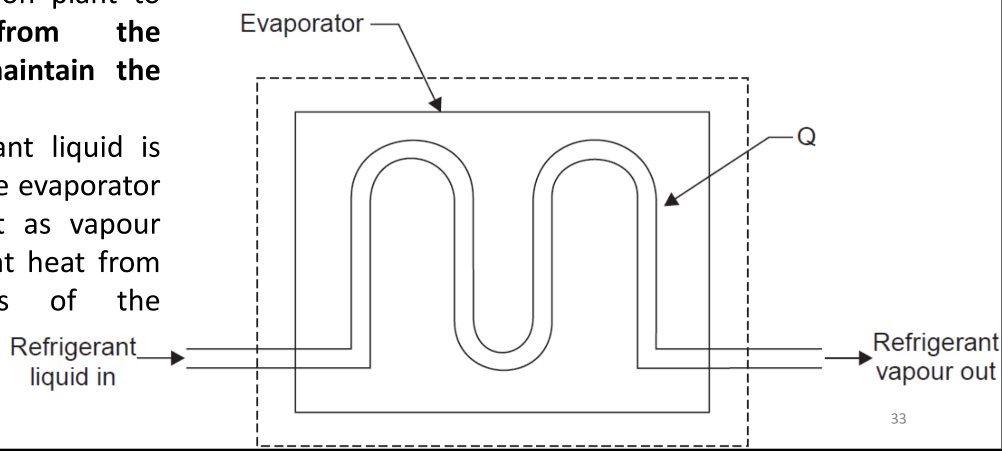
where, m_w = Mass of cooling water passing through the condenser, and

c_w = Specific heat of water.

4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.8. Evaporator

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



4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.8. Evaporator

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

$$W = 0 \qquad [\because \text{ No work is absorbed or supplied}]$$

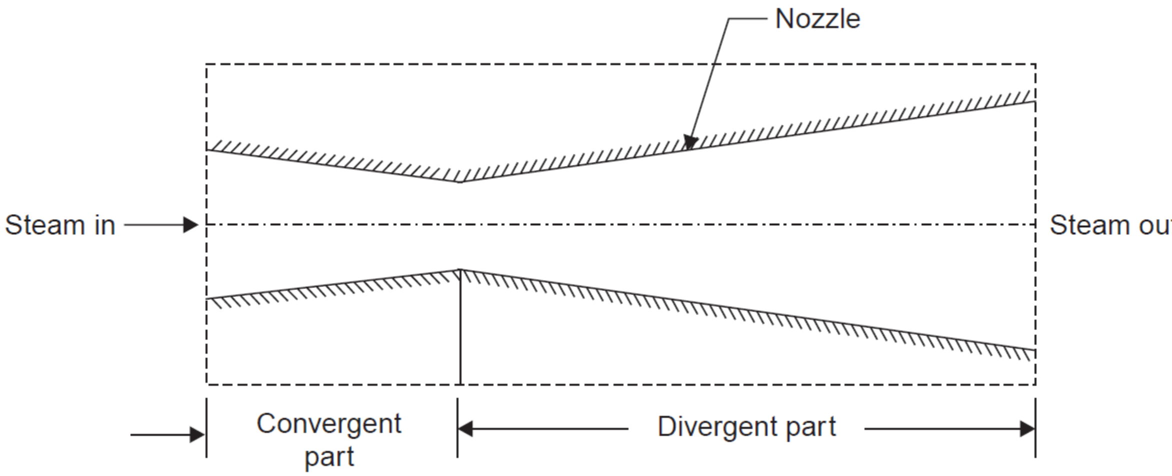
Applying the energy equation to the system

$$h_1 + Q = h_2 \qquad \ldots(4.61)$$

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.

4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.9. Steam Nozzle



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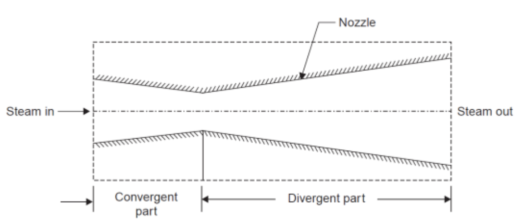
4.12 ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION (S.F.E.E.)

4.12.9. Steam Nozzle



For this system,

$$\Delta PE = 0$$
$$W = 0$$
$$Q = 0$$

Applying the energy equation to the system,

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

or $$\frac{C_2^2}{2} - \frac{C_1^2}{2} = h_1 - h_2 \quad \text{or} \quad C_2^2 - C_1^2 = 2(h_1 - h_2)$$

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

$$\therefore \quad C_2 = \sqrt{C_1^2 + 2(h_1 - h_2)} \quad \text{...(4.62)}$$

where velocity C is in m/s and enthalpy h in joules.

If $C_1 << C_2$, then

$$C_2 = \sqrt{2(h_1 - h_2)} \quad \text{...[4.63 (a)]}$$

$$\therefore \quad C_2 = \sqrt{2\Delta h}\,. \quad \text{...[4.63 (b)]}$$

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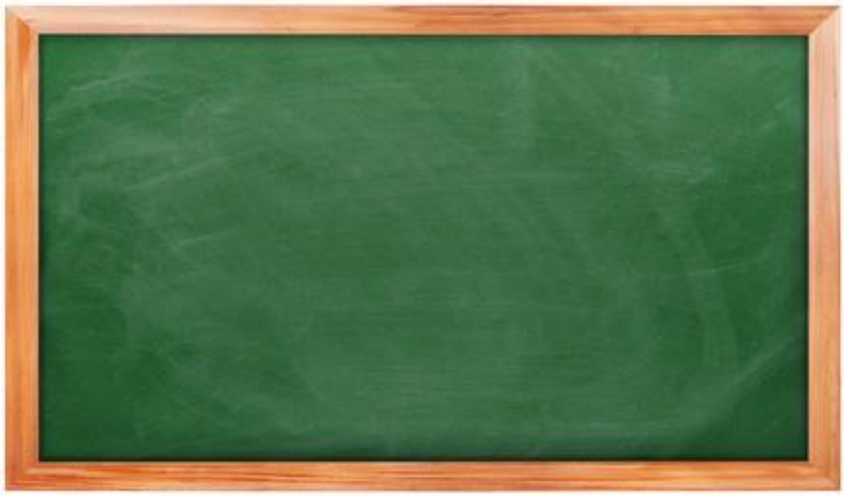
EXAMPLES FOR PART 2



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