Flow Processes in Open Systems

Presentation Outline

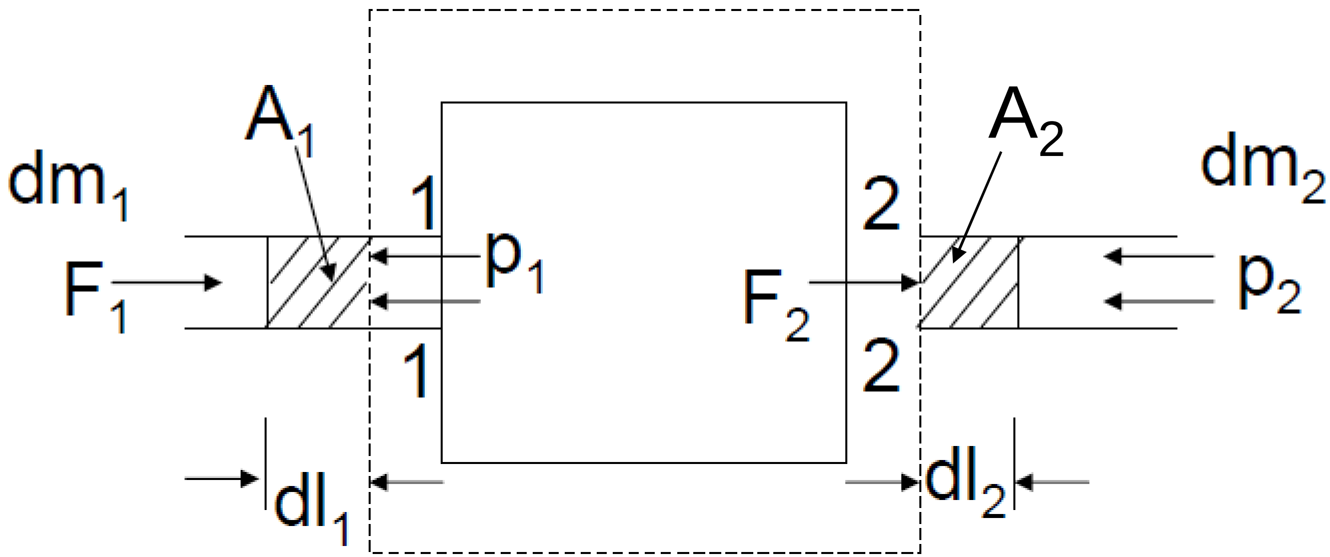
- Overview
- Flow Work
- Concept of Control Volume
- Steady Flow Energy Equation (SFEE)
- Application of SFEE to Flow Processes

Overview

- In the case of closed systems there is only energy transfer across the system boundary.
- However in many engineering applications we come across open systems where both mass and energy transfer take place.
- Let us examine how the First Law of Thermodynamics can be applied to such systems and processes.

Flow Work

- Consider a flow process in which a fluid of mass dm_1 is forced into the system at section 1-1 and a mass dm_2 is forced out of the system at section 2-2 as shown in the figure.



Flow Work contd..

- In order to force the fluid to flow across the boundary of the system against a pressure p_1 , work is done on the boundary of the system.
- The amount of work done is given by

$$\boxed{\delta W = -F_1 . dl_1}$$

where F_1 is the force and dl_1 is the infinitesimal displacement of the fluid mass.

Flow Work contd..

However $F_1 = p_1 A_1$

Hence $\delta W = -p_1 A_1 . dl_1 = -p_1 dv_1$

Therefore, the flow work at section 1-1 is

$$W_1 = \int_0^{W_1} \delta W = \int_0^{W_1} dW = -p_1 \int_0^{v_1} dv_1 = -p_1 v_1$$

Flow Work contd..

- Similarly, the work done by the system to force the fluid out of the system at section 2-2 is expressed by

$$\boxed{W_2 = p_2 v_2}$$

- Hence the Net Flow Work is expressed as

$$\boxed{W_{net} = p_2 v_2 - p_1 v_1}$$

Flow Work contd..

- For unit mass, the flow work is $\left(p_2 v_2 - p_1 v_1\right)$
- Flow work is expressed entirely in terms of the properties of the system.
- The net flow work depends on the initial and final states of the fluid and it is considered as a thermodynamics property.

Flow Work contdd..

- Also the fluid contains energy forms such as Internal Energy (U), Potential Energy (PE) and Kinetic Energy (KE) in addition to the flow work discussed so far.
- When a fluid enters an open system, these properties will be carried into the system.
- Similarly when the fluid leaves the system, it carries these energy forms out of the system.
- Hence in an open system, there is a change in energy quantity of the system.

Control Volume

- The first and most important step in the analysis of an open system is to imagine a certain region enclosing the system.

- This region having an imaginary boundary is called a control volume, which can be defined as follows.

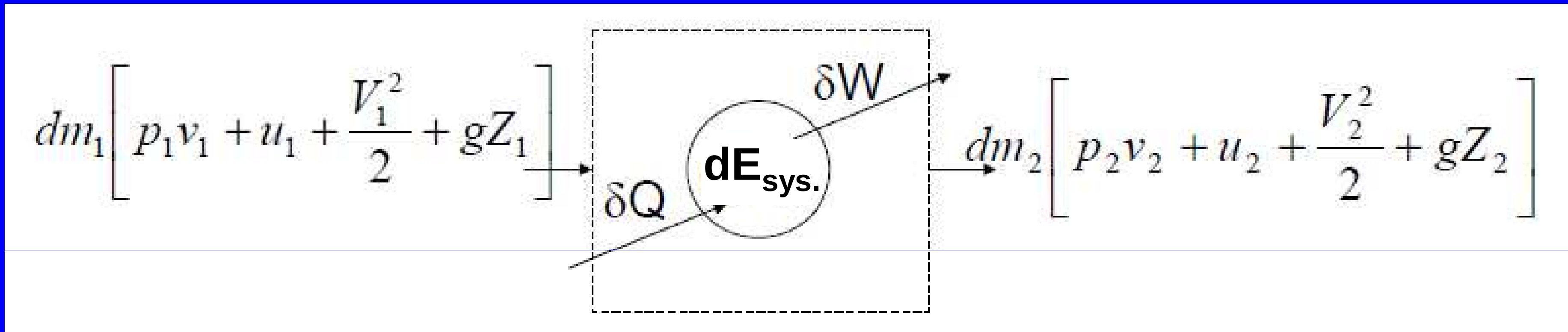
Definition of Control Volume

- A *Control Volume* is any volume of fixed shape and of fixed position and orientation relative to the observer.
- Across the boundaries of the *Control Volume* in addition to mass flow, energy transfer in the form of heat and work can take place.
- The surface enclosing the *Control Volume* is referred to as the *Control Surface*.

Application of First Law to Open Systems

- In the case of open systems, energy is transferred into & out of the system not only by heat and work but also by the fluid that enters into and leaves the boundary of the system in the form of internal energy, gravitational potential energy, kinetic energy and flow work.
- Therefore, when the first law is applied to an open system, the energy entering the system must be equal to the sum of energy leaving the system and any accumulation of energy within the system.

Application of First Law to Open Systems contd..



- This represents a flow process in an open system where mass and energy interactions are taking place.
- This analysis can be expressed mathematically as follows.

Application of First Law to Open Systems contd..

$$\delta Q - \delta W + dm_1\left[p_1 v_1 + u_1 + \frac{V_1^2}{2} + gZ_1 \right]$$

$$= dm_2\left[p_2 v_2 + u_2 + \frac{V_2^2}{2} + gZ_2 \right] + dE_{sys.}$$

Application of First Law to Open Systems contd..

where state 1 is the inlet condition and state 2 is the outlet condition of the fluid.

- $dE_{sys.}$ represents the change in total accumulated energy in the system.
- This is the general equation of the First Law of Thermodynamics applied to an open system.

Energy Equation for Open Systems

- The general form of the First Law of Thermodynamics applied to an open system is called the Steady Flow Energy Equation (SFEE) applicable at steady flow conditions.

- SFEE is developed on the basis of the following assumptions.

Energy Equation for Open Systems contd..

- The mass flow rate at inlet is constant with respect to time, and equal to the mass flow rate at outlet.
- The properties at any point within the open system do not vary with time.
- The properties are constant over the cross-section of the flow at inlet and outlet.
- Any heat or work crossing the boundary does so at a uniform rate.

Energy Equation for Open Systems contd..

For a steady flow process

$$\dot{m} = \dot{m}_1 = \dot{m}_2$$

Also

$$dE_{sys.} = 0 \qquad Q \neq f(T) \qquad W \neq f(T)$$

SFEE Based on Unit Mass

- Energy entering the system = Energy leaving the system

$$Q - W + \left[u_1 + p_1 v_1 + \frac{V_1^2}{2} + gZ_1 \right] = \left[u_2 + p_2 v_2 + \frac{V_2^2}{2} + gZ_2 \right]$$

or

$$Q - W + \left[h_1 + \frac{V_1^2}{2} + gZ_1 \right] = \left[h_2 + \frac{V_2^2}{2} + gZ_2 \right]$$

SFEE Based on Unit Mass contd..

or

$$Q - W = \Delta\left[h + \frac{V^2}{2} + gZ\right]$$

where

Q – Heat transfer across the C.V (kJ/kg)

W – Work across the C.V (kJ/kg)

h – Enthalpy (kJ/kg)

V – Velocity (ms^{-1})

Z – Elevation (m)

g – Acceleration due to gravity (ms^{-2})

SFEE Based on Unit Time

$$\dot{Q} - \dot{W} = \dot{m}\,\Delta\left[h + \frac{V^2}{2} + gZ\right]$$

$$\dot{m}_1 = \rho_1 A_1 V_1$$

and

$$\dot{m}_2 = \rho_2 A_2 V_2$$

$$\dot{m}_1 = \dot{m}_2 = \dot{m}$$

$$\dot{Q} - \dot{W} = \dot{m}\left[(h_2 - h_1) + \frac{\left(V_2{}^2 - V_1{}^2\right)}{2} + g(Z_2 - Z_1)\right]$$

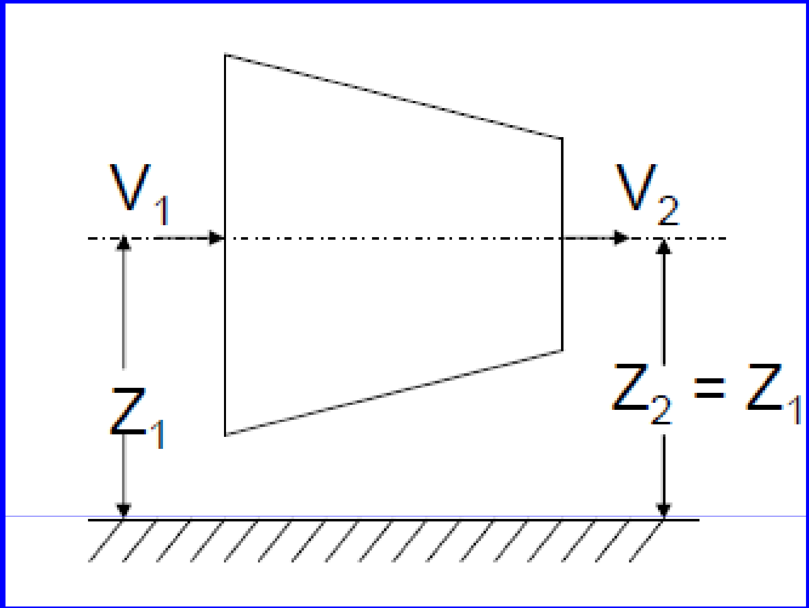
Application of SFEE

1. Nozzle and Diffuser

• Nozzle is a device of varying cross-sectional area in which the velocity increases with a corresponding drop in pressure.

• In a diffuser the pressure increases with a corresponding drop in velocity.

1. Nozzle and Diffuser contd..



$$Q = W = 0$$

Apply SFEE $$Q - W = \Delta h + \Delta PE + \Delta KE$$

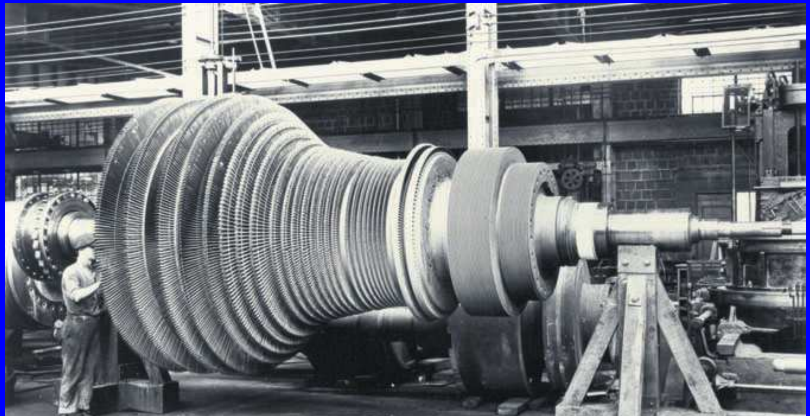
$$0 = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}$$

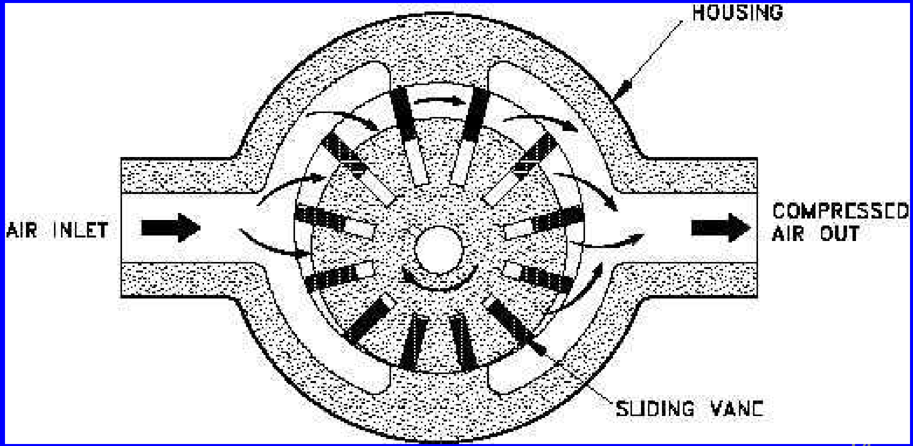
Hence $$h_1 - h_2 = \frac{1}{2}\left(V_2^2 - V_1^2\right)$$

Application of SFEE

2. Turbine and Rotary Compressor

- Turbine is a device which produces work by expanding a high pressure fluid to a low pressure in the rotor.
- A compressor converts low pressure fluid to high pressure fluid by consuming external work.


Turbine Rotor



Rotary Compressor

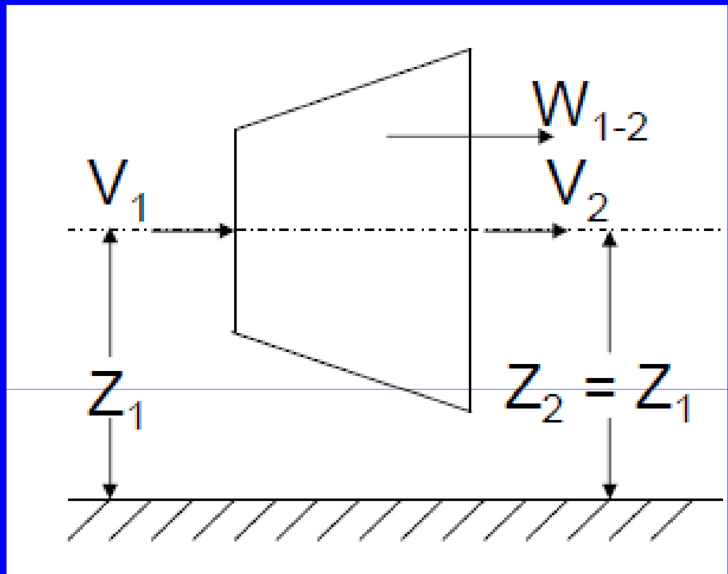
2. Turbine and Rotary Compressor contd..

- Since the velocity of flow of the fluid through the turbine is very high, the flow process is generally assumed to be adiabatic, and hence heat transfer Q = 0.

- The change in Potential Energy is neglected as it is negligible.

- Let us apply the Steady Flow Energy Equation to this scenario.

2. Turbine and Rotary Compressor contd..



Apply SFEE $$Q - W = \Delta h + \Delta PE + \Delta KE$$

$$-W = (h_2 - h_1) + \frac{\left(V_2^{\,2} - V_1^{\,2}\right)}{2}$$

2. Turbine and Rotary Compressor contd..

$$W = (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2}$$

If mass flow rate is $\dot{m}$ then

Power developed by the Turbine

$$\dot{W} = \dot{m}\left[(h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2}\right]$$ Watts

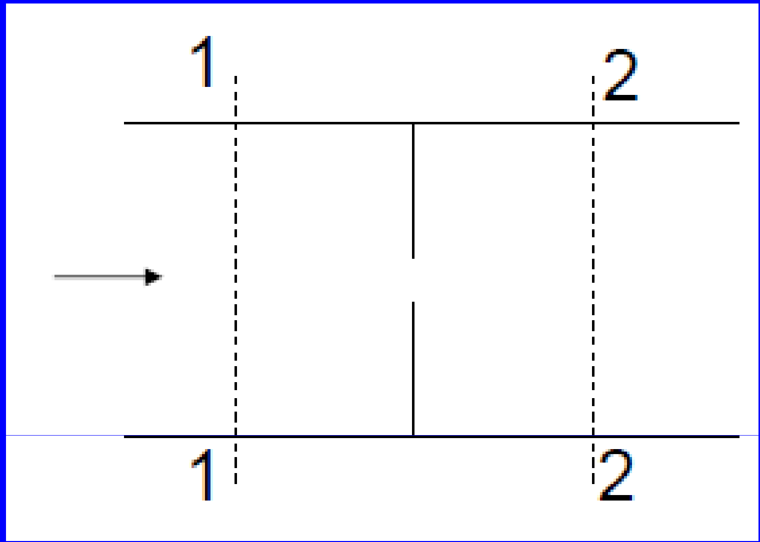
2. Turbine and Rotary Compressor contd..

- Same principle can be applied for the rotary compressor as well.
- Compressor is a device in which work is done on the fluid to raise its pressure.
- A rotary compressor can be regarded as a reversed turbine.
- Since work is done on the system, the rate of work in the above equation is negative and the enthalpy after compression h_2 will be greater than the enthalpy before compression h_1.

3. Throttling Process

- When a fluid steadily flows through a restricted passages such as a partially closed valve, orifice, porous plug etc., the pressure of the fluid drops substantially and the process is called throttling.
- In a throttling process, expansion of the fluid takes place so rapidly that no heat transfer is possible between the system and the surroundings.
- Hence the process is assumed to occur adiabatically.
- The work transfer in this process is zero.

3. Throttling Process contd..



Apply SFEE $\boxed{Q - W = \Delta h + \Delta PE + \Delta KE}$

However $\boxed{Q = 0}$ $\boxed{W = 0}$ $\boxed{Z_1 = Z_2}$ $\boxed{V_1 \cong V_2}$

3. Throttling Process contd..

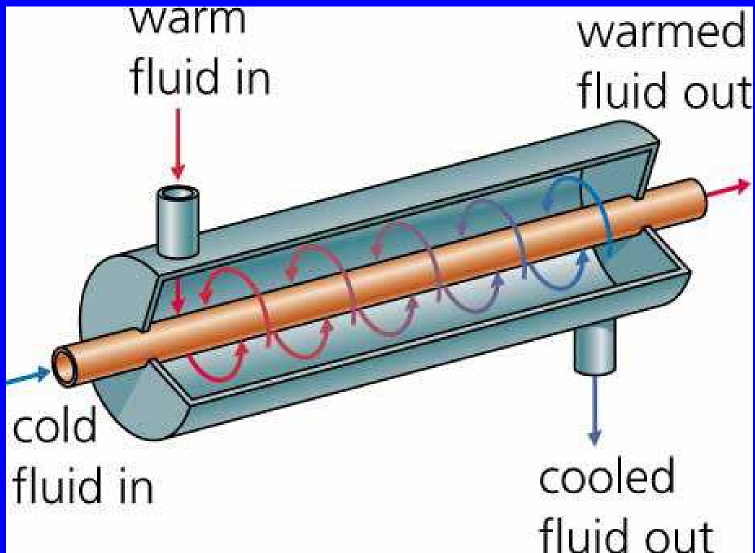
$$0 - 0 = h_2 - h_1 + 0 + 0$$

Hence $\boxed{h_1 = h_2}$

- Therefore in a throttling process, the enthalpy of the system remains constant.
- However throttling process is irreversible.

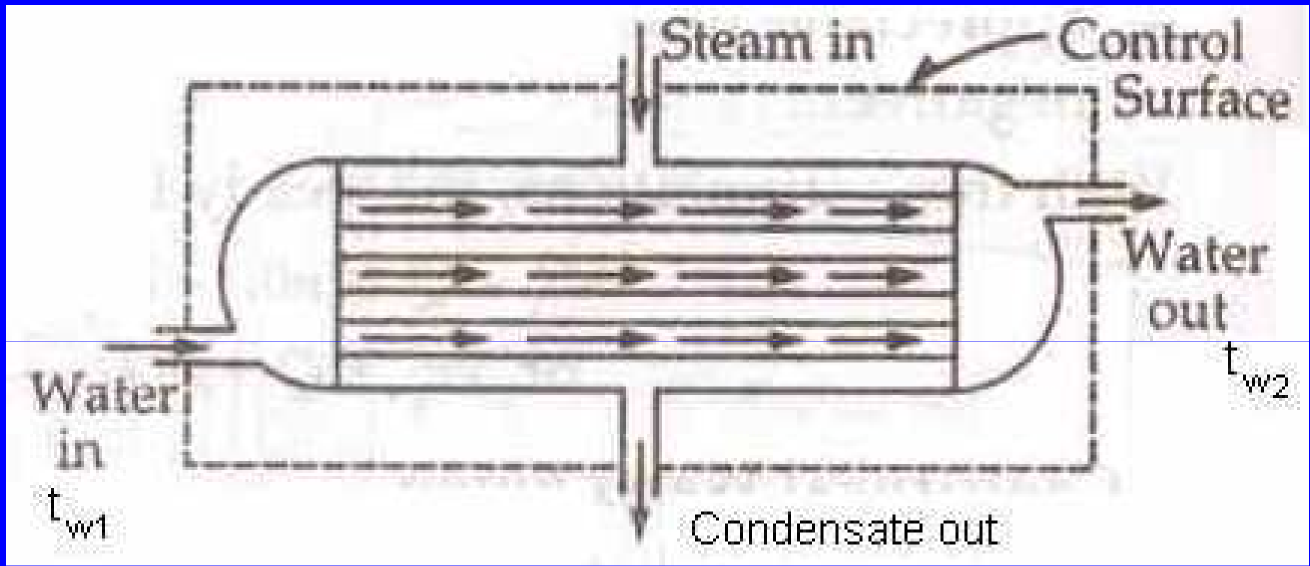
4. Heat Exchanger

- A heat exchanger is a device in which heat is transferred from one fluid to another.
- It is used to add or reduce heat energy from the fluid flowing through the device.
- There will be no work interaction during the flow of fluid through the heat exchanger.



4. Heat Exchanger

(i) Steam Condenser



- ΔKE = 0 and Δ PE = 0 (as their values are very small compared to enthalpies)
- W = 0 (since neither any work is developed nor absorbed)

4. Heat Exchanger

(i) Steam Condenser

Apply SFEE $$Q - W = \Delta h + \Delta PE + \Delta KE$$

$$Q = \Delta h = \left(h_2 - h_1\right)$$

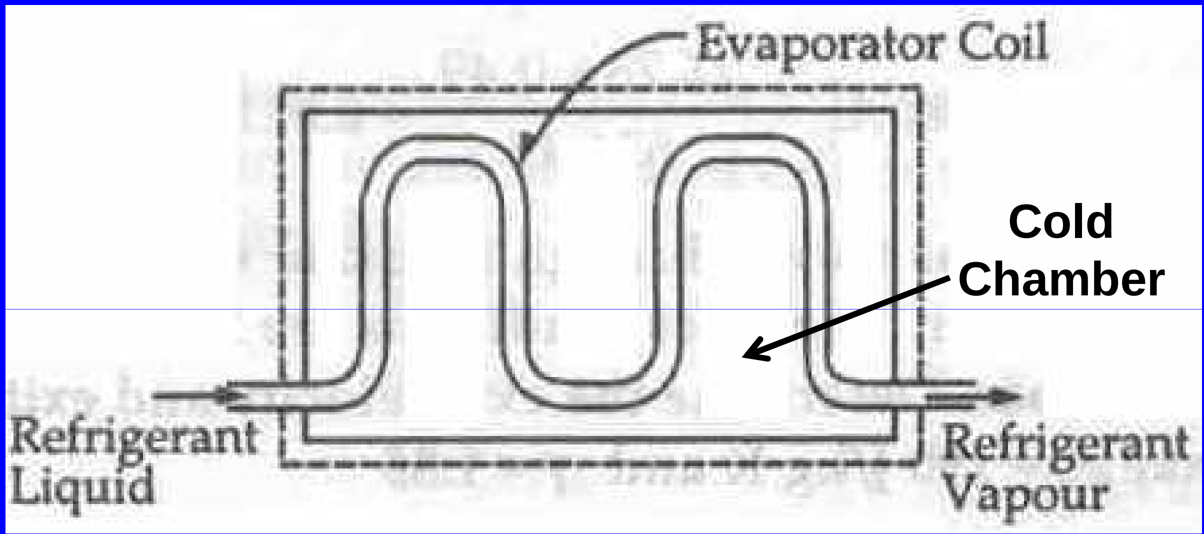
Assuming that there are no other heat interactions except the heat transfer between steam and water, then

Q = Heat gained by unit mass of water passing through the condenser = Heat lost by unit mass of steam passing through the condenser

$$\dot{Q} = \dot{m}_w \left(h_{w_2} - h_{w_1}\right) = \dot{m}_w \, c_w \left(T_{w_2} - T_{w_1}\right)$$

4. Heat Exchanger

(ii) Evaporator



- An evaporator is a component of a refrigeration system and is used to extract heat from the chamber which is to be kept at low temperature.

4. Heat Exchanger

(ii) Evaporator

Apply SFEE $Q - W = \Delta h + \Delta PE + \Delta KE$

$$W = 0 \qquad \Delta PE = \Delta KE = 0$$

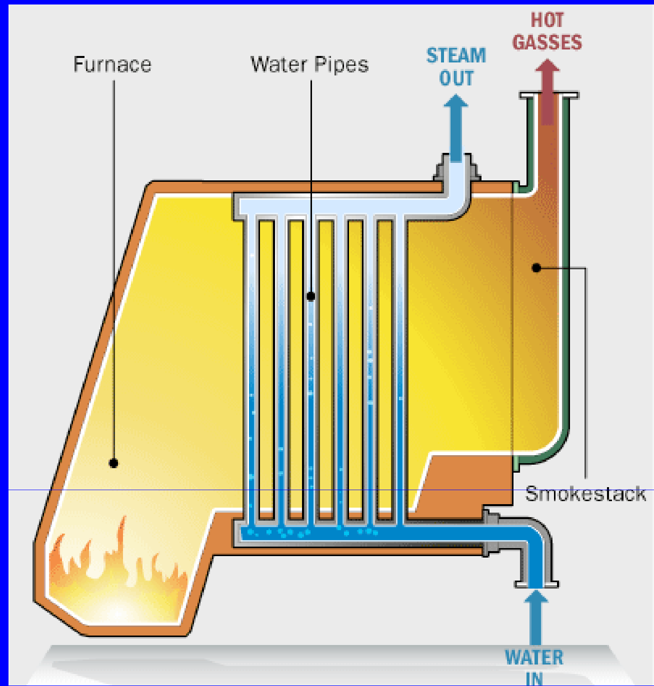
$$Q = \Delta h = \left(h_2 - h_1\right)$$

$$\dot{Q} = \dot{m}_R \left(h_2 - h_1\right)$$

$\dot{m}_R$ is the mass flow rate of the refrigerant

$\dot{Q}$ is taken as positive since the evaporator coil receives heat from the chamber.

5. Boiler



- It is an equipment used for the generation of steam.
- Thermal energy released by the combustion of fuel is transferred to water which gets vapourized and converted into steam at the desired pressure and temperature.

5. Boiler

Apply SFEE $$Q - W = \Delta h + \Delta PE + \Delta KE$$

$$W = 0 \qquad \Delta PE = \Delta KE = 0$$

$$Q = \Delta h = \left(h_2 - h_1\right)$$

$$Q = \left(u_2 - u_1\right) + \left(p_2 v_2 - p_1 v_1\right)$$