**Class: Fourth Stage**
**Subject: Refrigeration Systems**
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# CHAPTER NINE

## Applied Engineering Thermodynamics of Steam Jet Refrigeration Systems

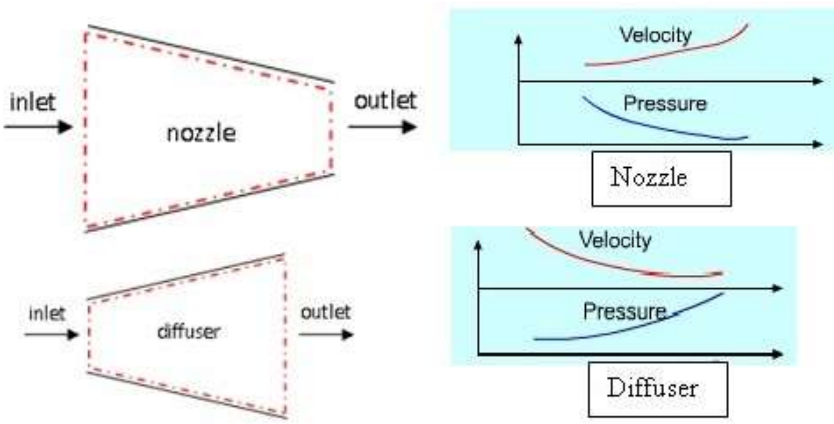
### INTRODUCTION

- The steam jet refrigeration system (also known as ejector refrigeration system) is one of the oldest methods of producing refrigerating effect.
- The basic components of this system are an evaporator, a compression device, a condenser, and a refrigerant control device.
- This system employs a steam ejector or booster (instead of mechanical compressor) to compress the refrigerant to the required condenser pressure level.
- In this system, water is used as the refrigerant.
- Since the freezing point of water is 0°C, therefore, it cannot be used for applications below 0°C.
- The steam jet refrigeration system is widely used in food processing breweries plants for precooling of vegetables and concentrating fruit juices, gas plants, paper mills, breweries etc.

### Principle of Steam Jet Refrigeration System

- The boiling temperature of any liquid can be changed if we changer the external pressure
- At atm (1.013 bar) pressure the boiling temperature of a water is 100 C
- If we reduced the pressure to 0.014 bar the boiling temp. of water will be 12 C
- If we reduced further to 0.01 bar the boiling temp. will be 7 C

**NOTE**: Just to remind you with important **thermodynamics devices** which they are **Nozzle** and **Diffuser** as we need them when we illustrates the working principle of ejector refrigeration systems



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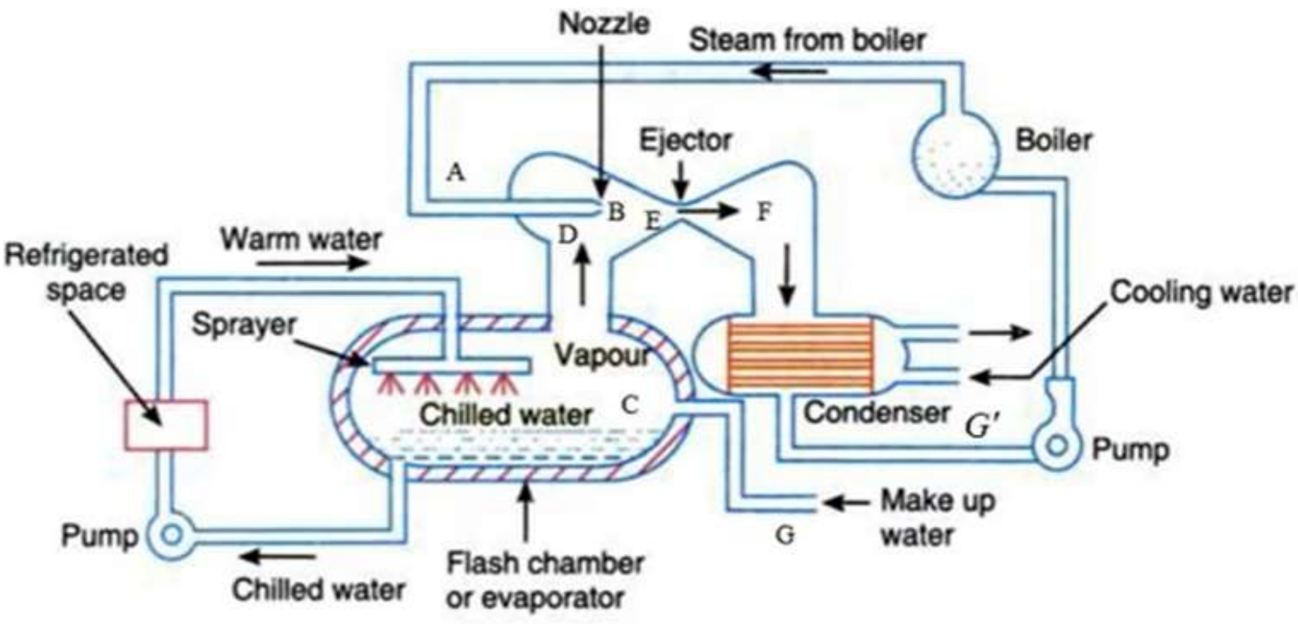
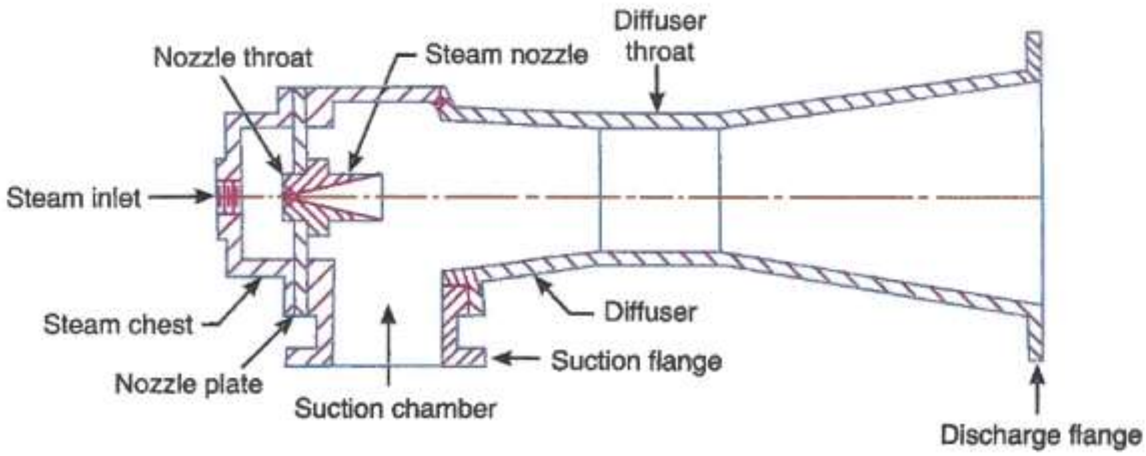
## Working of Steam Jet Refrigeration System

- The main components of the steam jet refrigeration system, as shown in Figure inserted below, are the **flash chamber or evaporator**, **steam nozzles**, **ejector** and **condenser**.
- The flash chamber or evaporator is a large vessel and is heavily insulated to avoid the rise in temperature of water due to high ambient temperature.
- It (flash chamber) is fitted with perforated pipes for spraying water.
- The warm water coming out of the refrigerated space is sprayed into the flash water chamber where some of which is converted into vapours after absorbing the latent heat, thereby cooling the rest of water.
- The high pressure steam from the boiler is passed through the steam nozzles thereby increasing its velocity.
- This high velocity steam in the ejector would entrain the water vapours from the flash chamber which would result in further formation of vapours.
- The mixture of steam and water vapour passes through the venturi-tube of the ejector and gets compressed. (**NOTE**: the ejector works like the compressor of VCRS)
- The temperature and pressure of the mixture rises considerably and fed to the water cooled condenser where it gets condensed.
- The condensate is again fed to the boiler as feed water. A constant water level is maintained in the flash chamber and any loss of water due to evaporation is made up from the make-up water line.



## Steam Ejector

- The steam ejector is one of the important components of a steam jet refrigeration system.
- It is used to compress the water vapours coming out of the flash chamber.
- It uses the energy of fast moving jet of steam to entrain the vapours from the flash chamber and then compress it.
- The essential components of a steam ejector are shown in Figure inserted below




**Q: what is the major functions of the following thermal devices?**

1. **Flash chamber;** it is a large vessel filled with refrigerant which is the water
2. **Steam nozzle;** in which steam is supplied by the boiler at higher pressure and temperature. The higher steam pressure is expanded in the nozzle which convert the thermal energy of the steam into kinetic energy of the steam
3. **Ejector;** it is a pumping device which extract the vapor from the flash chamber
4. **Condenser;** it is shell and tube heat exchanger in which the water flows inside the tube while the refrigerant (which is here the water) is flowing outside the tubes

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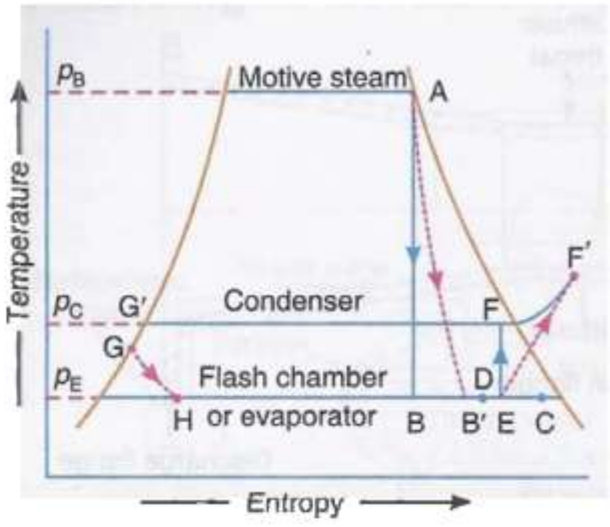
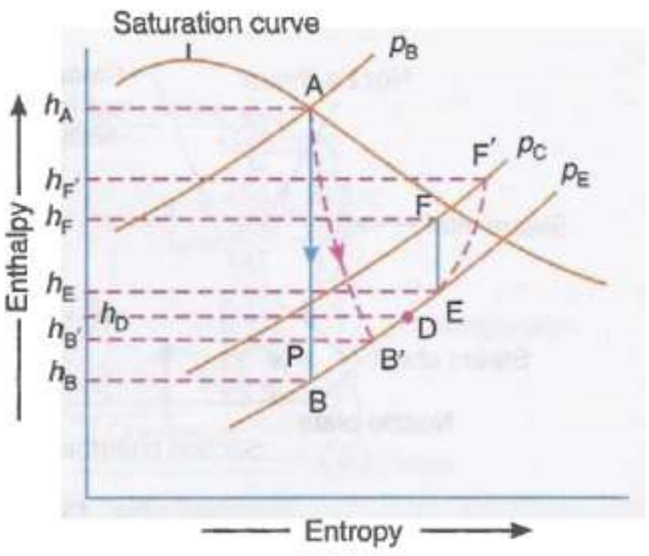
## Analysis of Steam Jet Refrigeration System

- The point A represents the initial condition of the motive steam before passing through the nozzle and the point B is the final condition of the steam, assuming isentropic expansion.
- The point C represents the initial condition of the water vapour in the flash chamber or evaporator and the point E is the condition of the mixture of high velocity steam from the nozzle and the entrained water vapour before compression.
- Assuming isentropic compression, the final condition of the mixture discharged to the condenser is represented by point F.
- The condition of motive steam just before mixing with the water vapour is shown at point D.
- The make-up water is supplied at point G whose temperature is slightly lower than the condenser temperature and is throttled to point H in the flash chamber.

Note: Due to certain unavoidable losses in the expansion and compression, the actual expansion of motive steam is represented by AB' and the actual compression of the mixture of motive steam and water vapour is represented by EF'.




(a) T-s diagram.




(b) h-s diagram.

## Efficiencies used in Steam Jet Refrigeration System

The various efficiencies used in steam jet refrigeration system are discussed below :

1. *Nozzle efficiency.* It is defined as the ratio of actual enthalpy drop to the isentropic enthalpy drop of the motive steam passing through the nozzle. Mathematically, nozzle efficiency,

$$\eta_N = \frac{\text{Actual enthalpy drop}}{\text{Isentropic enthalpy drop}} = \frac{AP}{AB} = \frac{h_A - h_{B'}}{h_A - h_B}$$

The nozzle efficiency may vary from 85 to 90 per cent.

2. *Entrainment efficiency.* The water vapours formed in the flash chamber or evaporator comes out with a very low velocity as compared to the velocity of the steam ($V$) coming out of the nozzle which is given by

$$* \; V = \sqrt{2000\,(h_A - h_{B'})} = 44.72\sqrt{h_A - h_{B'}}$$

The expression $(h_A - h_B')$ represents the kinetic energy of the motive steam. This kinetic energy gives the required momentum to the water vapours coming out of the flash chamber or evaporator. The process of giving the momentum to the water vapour formed in the flash chamber by the high velocity steam is called *entrainment of vapour*. During the entrainment of water vapour from the flash chamber, the motive steam loses some of its kinetic energy. This process of entrainment is inefficient and part of the original motive force available for compression is reduced. This is taken into consideration by a factor known as entrainment efficiency. Mathematically, entrainment efficiency,

$$\eta_E = \frac{h_A - h_D}{h_A - h_{B'}}$$

The entrainment efficiency may be taken as 65 per cent.

3. *Compression efficiency.* It is defined as the ratio of the isentropic enthalpy increase to the actual enthalpy increase required for the compression of the mixture of motive steam and the water vapours, in the diffuser. Mathematically, compression efficiency,

$$\eta_C = \frac{\text{Isentropic enthalpy increase}}{\text{Actual enthalpy increase}} = \frac{h_F - h_E}{h_{F'} - h_E}$$

The compression efficiency may be taken as 75 to 80 per cent.

**Note :** The compression efficiency is also known as *diffuser efficiency*.

## Mass of motive steam required

According to the law of conservation of energy, the available energy for compression must be equal to the energy required for compression.

Let $m_s$ = Mass of motive steam supplied in kg/min,

$m_v$ = Mass of water vapours formed from the flash chamber or evaporator in kg/min,

$m$ = Mass of the mixture for compression in kg/min = $m_s + m_v$

We know that available energy for compression

$$= m_s (h_A - h_D) \quad \text{... (i)}$$

and energy required for compression

$$= m\,(h_{F'} - h_E) = (m_s + m_v)\,(h_{F'} - h_E) \quad \text{... (ii)}$$

Now according to law of conservation of energy,

$$m_s (h_A - h_D) = (m_s + m_v)\,(h_{F'} - h_E) \quad \text{... (iii)}$$

We have already discussed that the nozzle efficiency,

$$\eta_N = \frac{h_A - h_{B'}}{h_A - h_B} \quad \text{or} \quad h_A - h_{B'} = \eta_N (h_A - h_B) \quad \text{... (iv)}$$

Entrainment efficiency,

$$\eta_E = \frac{h_A - h_D}{h_A - h_{B'}} \quad \text{or} \quad h_A - h_D = \eta_E (h_A - h_{B'}) \quad \text{... (v)}$$

and compression efficiency,

$$\eta_C = \frac{h_F - h_E}{h_{F'} - h_E} \quad \text{or} \quad h_{F'} - h_E = \frac{h_F - h_E}{\eta_C} \quad \text{... (vi)}$$

Substituting the value of $(h_A - h_D)$ and $(h_{F'} - h_E)$ from equations (*v*) and (*vi*) in equation (*iii*), we have

$$m_s \times \eta_E\,(h_A - h_{B'}) = (m_s + m_v)\left(\frac{h_F - h_E}{\eta_C}\right)$$

$$m_s \times \eta_E \times \eta_N (h_A - h_B) = (m_s + m_v)\left(\frac{h_F - h_E}{\eta_C}\right) \quad \text{... [ From equation (iv)]}$$

$$m_s \times \eta_E \times \eta_N \times \eta_C (h_A - h_B) = m_s (h_F - h_E) + m_v (h_F - h_E)$$

$$m_s [(h_A - h_B)\,\eta_N \eta_E \eta_C - (h_F - h_E)] = m_v (h_F - h_E)$$

or
$$\frac{m_s}{m_v} = \frac{(h_F - h_E)}{(h_A - h_B)\eta_N \eta_E \eta_C - (h_F - h_E)}$$

where $\frac{m_s}{m_v}$ = Mass of motive steam required per kg of water vapour produced in the flash chamber.

Energy balance of the mixing between steam and vapor (point C,D and E)

$$m_v h_C + m_s h_D = (m_s + m_v) h_E$$

$$h_C + \frac{m_s}{m_v} \times h_D = \left(\frac{m_s}{m_v} + 1\right) h_E$$

$$\boldsymbol{R_E = m_v[h_C - h_{fG}]} \ \textbf{kg/min}$$

If $Q$ tonnes of refrigeration is the refrigerating load, then the heat absorbed or net refrigerating effect,

$$R_E = 210\,Q \text{ kJ/min}$$

From the above expressions, we find that the mass of water vapour formed,

$$m_v = \frac{210\,Q}{[h_C - h_{fG}]} \text{ kg/min}$$

Since one kg of water vapour requires $m_s$ kg of motive steam, therefore,

Mass of motive steam required per $Q$ tonne of refrigerating load

= Mass of water vapour per minute × Motive steam required per kg of vapour

$$= m_v \times m_s$$

$$= \frac{210\,Q}{[h_C - h_{fG}]} \times m_s$$

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**Note :** The coefficient of performance of the system is given by

$$\text{C.O.P.} = \frac{m_v(h_C - h_{fG})}{m_s(h_A - h_{fG'})}$$

## Advantages and Disadvantages of Steam Jet Refrigeration System

Following are the advantages and disadvantages of a steam jet refrigeration system

### Advantages

1. It is simple in construction and rigidly designed.
2. It is a vibration-free system as pumps are the only moving parts.
3. It has low maintenance cost, low production cost and high reliability.
4. It has relatively less plant mass (kg / TR). Hence, there are now a number of air-conditioning applications ranging up to 300 TR in capacity as well as many industrial applications of even larger size.
5. It uses water as a refrigerant. Water is very safe to use as it is non-poisonous and non-inflammable.
6. This system has an ability to adjust quickly to load variations.
7. The running cost of this system is quite low.

### Disadvantages

1. The system is not suitable for water temperature below 4 °C.
2. For proper functioning of this system, maintenance of high vacuum in the evaporator is necessary. This is done by direct vaporisation to produce chilled water which is usually limited as tremendous volume of vapour is to be handled.

**Example 15.1.** A steam ejector refrigeration system is supplied with motive steam at 7 bar saturated with the water in the flash chamber at 4.5°C. The make-up water is supplied to the cooling system at 18°C and the condenser is operated at 0.058 bar. The nozzle efficiency is 88%,

The entrainment efficiency is 65% and the compression efficiency is 80%. The quality of steam and flash vapour at the beginning of compression is 92%.

Determine : 1. mass of motive steam required per kg of flash vapour ; 2. quality of vapour flashed from the flash chamber ; 3. refrigerating effect per kg of flash vapour ; 4. mass of motive steam required per hour per tonne of refrigeration ; 5. volume of vapour removed from the flash chamber per hour per tonne of refrigeration ,· and 6. Coefficient of performance of the system.

**Solution.** Given : $p_B = 7$ bar ; $t_w = 4.5°C$ ; $t_{mw} = 18°C$ ; $p_C = 0.058$ bar ; $\eta_N = 88\% = 0.88$ ; $\eta_E = 65\% = 0.65$ ; $\eta_C = 80\% = 0.8$ ; $x_B = 92\% = 0.92$

The *T-s* and *h-s* diagrams for the steam ejector refrigeration system is shown in Fig. 15.4.

From steam tables of dry saturated steam, corresponding to a pressure of 7 bar, we find that

$h_A = 2762$ kJ/kg ; $s_A = 6.705$ kJ/kg K ; $t_A = 165°C$

and corresponding to a temperature of *4.5°C, we find that

$h_{fB} = 18.9$ kJ/kg ; $h_{fgB} = 2490.9$ kJ/kg ; $s_{fB} = 0.0685$ kJ/kg K ; $s_{fgB} = 8.9715$ kJ/kg K

First of all, let us find the dryness fraction of the steam at point *B* (*i.e.* $x_B$). We know that for isentropic expansion *AB*,

* From steam tables, pressure corresponding to 4.5°C is 0.008 43 bar.

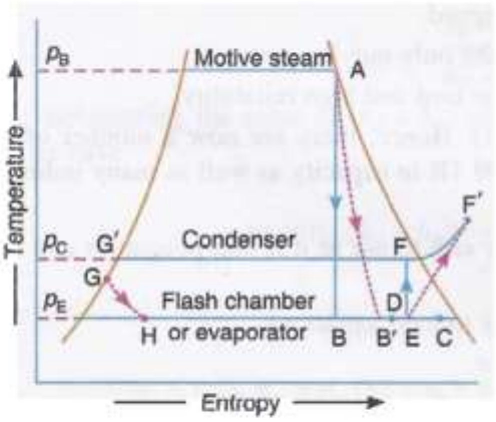
Entropy before expansion ($s_A$)

$$= \text{Entropy after expansion } (s_B)$$

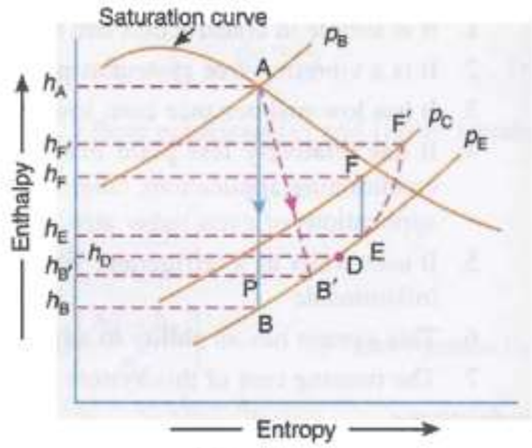
or $$6.705 = s_{fB} + x_B \times s_{fgB} = 0.0685 + x_B \times 8.9715$$

$\therefore$ $$x_B = \frac{6.705 - 0.0685}{8.9715} = 0.74$$

and enthalpy at $B$, $$h_B = h_{fB} + x_B \times h_{fgB} = 18.9 + 0.74 \times 2490.9 = 1862.16 \text{ kJ/kg}$$




(*a*) *T-s* diagram.




(*b*) *h-s* diagram.

We know that nozzle efficiency ($\eta_N$),

$$0.88 = \frac{h_A - h_{B'}}{h_A - h_B} = \frac{2762 - h_{B'}}{2762 - 1862.16}$$

$\therefore$ $$h_{B'} = 2762 - 0.88\,(2762 - 1862.16) = 1970.14 \text{ kJ/kg}$$

Now let us find the dryness fraction of steam at point $B'$ (*i.e.* $x_{B'}$). Since the points $B$, $B'$, $D$ and $E$ lie on the same pressure line (corresponding to 4.5°C), therefore

$$h_{fB} = h_{fB'} = h_{fD} = h_{fE} = 18.9 \text{ kJ/kg}$$

and $$h_{fgB} = h_{fgB'} = h_{fgD} = h_{fgE} = 2490.9 \text{ kJ/kg}$$

We know that enthalpy at $B'$,

$$h_{B'} = h_{fB'} + x_{B'} \times h_{fgB'}$$

$$1970.14 = 18.9 + x_{B'} \times 2490.9$$

$\therefore$ $$x_{B'} = \frac{1970.14 - 18.9}{2490.9} = 0.78$$

Let $h_D$ = Enthalpy of steam at $D$, and

$x_D$ = Dryness fraction of steam at $D$.

We know that entrainment efficiency ($\eta_E$),

$$0.65 = \frac{h_A - h_D}{h_A - h_{B'}} = \frac{2762 - h_D}{2762 - 1970.14}$$

Multiple-effect evaporator.

$$\therefore \quad h_D = 2762 - 0.65\,(2762 - 1970.14) = 2247.3 \text{ kJ/kg}$$

We also know that enthalpy at point $D$ ($h_D$),

$$2247.3 = h_{fD} + x_D \times h_{fgD} = 18.9 + x_D \times 2490.9$$

$$\therefore \quad x_D = \frac{2247.3 - 18.9}{2490.9} = 0.894$$

Enthalpy at point $E$,

$$h_E = h_{fE} + x_E \times h_{fgE} = 18.9 + 0.92 \times 2490.9$$
$$= 2310.5 \text{ kJ/kg} \qquad \ldots (\because \text{ It is given that } x_E = 0.92)$$

Now let us find the dryness fraction of the mixture of the motive steam and water vapour after isentropic compression at point $F$.

Let $x_F$ = Dryness fraction at point $F$.

We know that entropy at point $E$,

$$s_E = s_{fE} + x_E \times s_{fgE} = 0.0685 + 0.92 \times 8.9715$$
$$= 8.3223 \text{ kJ/kg K} \qquad \ldots (\because s_{fE} = s_{fB} \text{ and } s_{fgE} = s_{fgB})$$

From steam tables, corresponding to a condenser pressure of 0.058 bar, we find that

$h_{fF} = 148.86$ kJ/kg ; $\quad h_{fgF} = 2417.5$ kJ/kg

$s_{fF} = 0.512$ kJ/kg K ; $\quad s_{fgF} = 7.831$ kJ/kg K

Since the compression of the mixture is isentropic, therefore

Entropy before compression ($s_E$)

= Entropy after compression ($s_F$)

$$8.3223 = s_{fF} + x_F \times s_{fgF} = 0.512 + x_F \times 7.831$$

$$\therefore \quad x_F = \frac{8.3223 - 0.512}{7.831} = 0.997$$

We know that enthalpy at point $F$,

$$h_F = h_{fF} + x_F \times h_{fgF} = 148.86 + 0.997 \times 2417.5 = 2559.1 \text{ kJ/kg}$$

We also know that compression efficiency ($\eta_C$),

$$0.8 = \frac{h_F - h_E}{h_{F'} - h_E} = \frac{2559.1 - 2310.5}{h_{F'} - 2310.5}$$

$$\therefore \quad h_{F'} = \frac{2559.1 - 2310.5}{0.8} + 2310.5 = 2621.2 \text{ kJ/kg}$$

**1. *Mass of motive steam required per kg of the flash vapour***

We know that mass of motive steam required per kg of the flash vapour,

$$\frac{m_s}{m_v} = \frac{h_F - h_E}{(h_A - h_B)\eta_N \eta_E \eta_C - (h_F - h_E)}$$

$$= \frac{2559.1 - 2310.5}{(2762 - 1862.16)0.88 \times 0.65 \times 0.8 - (2559.1 - 2310.5)}$$

$$= \frac{248.6}{411.8 - 248.6} = 1.523 \text{ kg/kg of flash vapour} \quad \textbf{Ans.}$$

**2. *Quality of vapour flashed from the flash chamber***

Let $x_C$ = Dryness fraction of the vapour flashed from the flash chamber.

First of all, let us find the enthalpy at point $C$. We know that

$$m_v h_C + m_s h_D = (m_s + m_v)\, h_E$$

$$h_C + \frac{m_s}{m_v} \times h_D = \left(\frac{m_s}{m_v} + 1\right) h_E$$

$$h_C + 1.523 \times 2247.3 = (1.523 + 1)\, 2310.5$$

$$h_C + 3422.6 = 5829.4$$

$$\therefore \quad h_C = 2406.8 \text{ kJ/kg}$$

We also know that enthalpy at point $C$ ($h_C$),

$$2406.8 = h_{fC} + x_C \times h_{fB} = 18.9 + x_C \times 2490.9$$

... ($\because h_{fC} = h_{fB}$ and $h_{fgC} = h_{fgB}$)

$$\therefore \quad x_C = \frac{2406.8 - 18.9}{2490.9} = 0.96 \text{ Ans.}$$

### 3. *Refrigerating effect per kg of flash vapour*

We know that refrigerating effect per kg of flash vapour,

$$R_E = h_C - h_{fG} = 2406.8 - 75.5 = 2331.3 \text{ kJ/kg}$$

. . . ($\because$ From steam tables, $h_{fG}$ at 18°C = 75.5 kJ/kg )

### 4. *Mass of motive steam required per hour per tonne of refrigeration*

We know that mass of motive steam required per hour per tonne of refrigeration

$$= \frac{210\,Q}{h_C - h_{fG}} \times \frac{m_s}{m_v} = \frac{210 \times 1}{2406.8 - 75.5} \times 1.523$$

$$= 0.133 \text{ kg/min/TR} \qquad \ldots (\because Q = 1 \text{ TR})$$

$$= 0.133 \times 60 = 7.98 \text{ kg/h/TR Ans.}$$

### 5. *Volume of vapour removed from the flash chamber per hour per tonne of refrigeration*

We know that volume of vapour (per kg) removed from the flash chamber,

$$v_C = \text{Volume of liquid at } C + x_C \text{ (Volume of saturated vapour} - \text{Volume of liquid)}$$

$$= 1 + 0.95\,(152.22 - 1) = 144.66 \text{ m}^3\text{/kg}$$

. . . (From steam tables, volume of saturated vapour corresponding to 4.5°C = 152.22 m³/kg)

$\therefore$ Volume of vapour removed from the flash chamber per hour per tonne of refrigeration

$$= v_C \times \frac{210\,Q}{h_C - h_{fG}} \times 60$$

$$= 144.66 \times \frac{210 \times 1}{2406.8 - 75.5} \times 60 = 782 \text{ m}^3\text{/h/TR Ans.}$$

### 6. *Coefficient of performance of the system*

From steam tables, corresponding to a condenser pressure of 0.058 bar, we find that enthalpy of liquid at point $G'$,

$$h_{fG'} = 148.8 \text{ kJ/kg}$$

We know that coefficient of performance of the system,

$$\text{C.O.P.} = \frac{m_v (h_C - h_{fG})}{m_s (h_A - h_{fG'})} = \frac{1\,(2406.8 - 75.5)}{1.523\,(2762 - 148.8)} = 0.586 \text{ Ans.}$$