STEAM JET REFRIGERATION SYSTEM

15.1 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 plants for precooling of vegetables and concentrating fruit juices, gas plants, paper mills, breweries etc.

15.2 Principle of Steam Jet Refrigeration System

The boiling point of a liquid changes with change in external pressure. In normal conditions, pressure exerted on the surface of any liquid is the atmospheric pressure. If this atmospheric pressure is reduced on the surface of a liquid, by some means, then the liquid will start boiling at lower temperature, because of reduced pressure. This basic principle of boiling of liquid at lower temperature by reducing the pressure on its surface is used in steam jet refrigeration system.

The boiling point of pure water at standard atmospheric pressure of 760 mm of Hg (1.013 bar) is 100°C. It may be noted that water boils at 12°C if the pressure on the surface of water is kept at 0.014 bar and at 7°C if the pressure on the surface of water is 0.01 bar. The reduced pressure on the surface of water is maintained by throttling the steam through the jets or nozzles.

15.4 Working of Steam Jet Refrigeration System

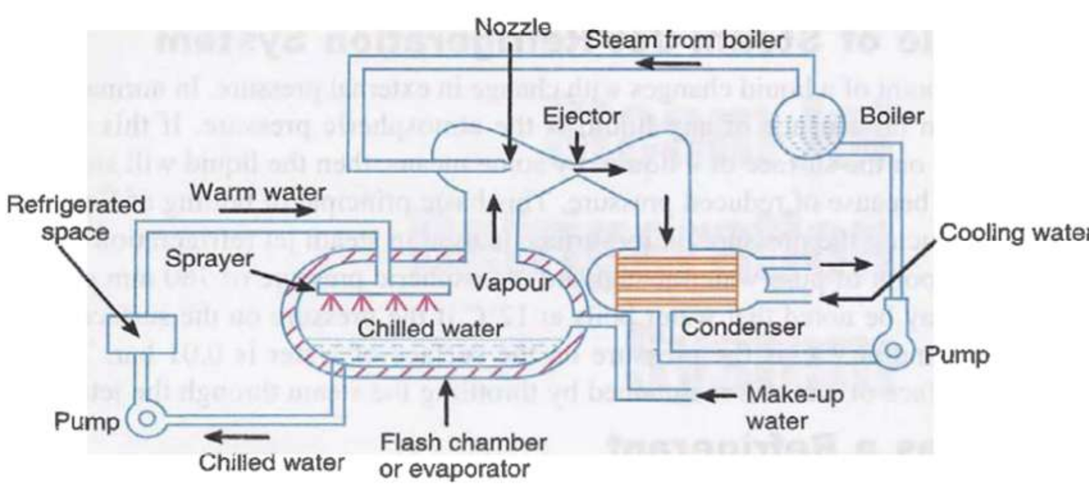


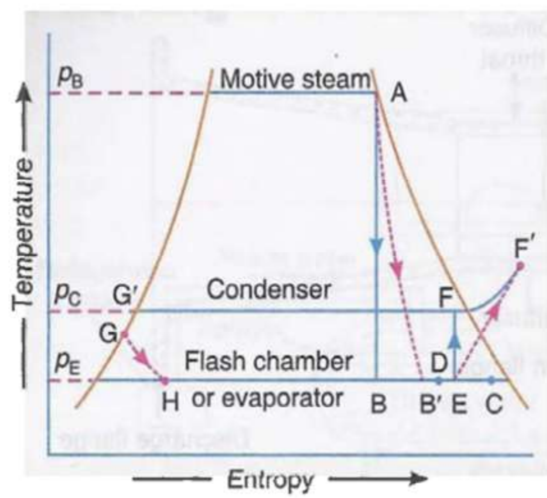
Fig. 15.1. Steam jet refrigeration system.

The main components of the steam jet refrigeration system, as shown in Fig. 15.1, are the flash chamber or evaporator, steam nozzles, ejector and condenser.

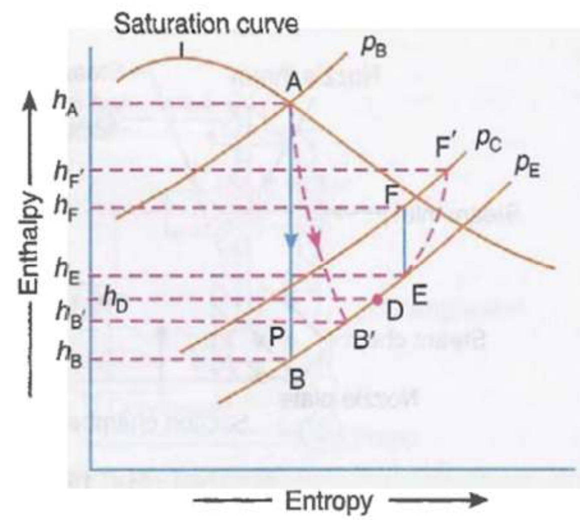
The flash chamber or evaporator is a large vessel and is heavily insulated to avoid the rise in temperature of water due to high ambient temperature. It is fitted with perforated pipes for spraying water. The warm water coming out of the refrigerated space is sprayed into the flash water chamber where 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. 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.

The temperature-entropy (*T-s*) and enthalpy-entropy (*h-s*) diagrams for a steam jet refrigeration system are shown in Fig. 15.3 (*a*) and (*b*) respectively.



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



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

Fig. 15.3

15.7 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,

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

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

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

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

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,

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

15.8 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 = **$m_s + m_v$**

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

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)

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

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

15.9 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 ; [redacted] *; and* **4.** *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 ; $\eta_N = 88\% = 0.88$; $\eta_E = 65\% = 0.65$; $\eta_C = 80\% = 0.8$; $x_E = 92\% = 0.92$

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

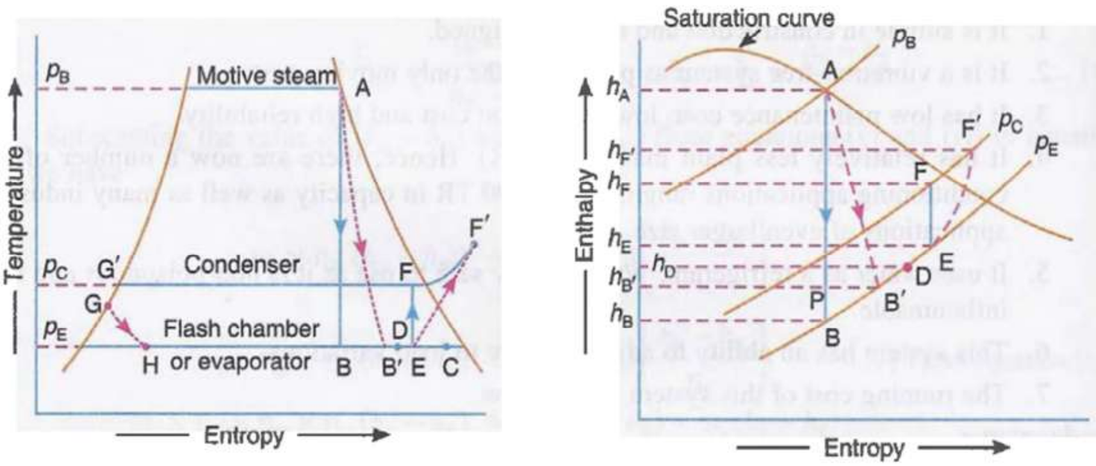
First of all, let us find the dryness fraction of the steam at point *B* (*i.e.* x_B). We know that for isentropic expansion *AB*, Entropy before expansion (s_A)

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

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

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

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.

Fig. 15.4

We know that nozzle efficiency (η_N),

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

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

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′*,

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

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

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

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

x_D = Dryness fraction of steam at *D*.

We know that entrainment efficiency (η_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 ; $h_{fgF} = 2417.5$ kJ/kg

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

Since the compression of the mixture is isentropic, therefore

Entropy before compression (s_E)

$$= \text{Entropy after compression } (s_F)$$

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

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

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 (η_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),

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

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

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

3. *Refrigerating effect per kg of flash vapour*

We know that refrigerating effect per kg of flash vapour,

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

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

4. *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,

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